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Earth Tide, Load Effects and Deformation Monitoring Computation

ETideLoad4.5 User Reference

Classroom Teaching, Self-Exercise, Science Research and Engineer Computing

Chinese Academy of Surveying & Mapping
May 2023, Beijing, China

Earth Tide, Load Effects and Deformation Monitoring Computation (ETideLoad4.5) is a large Windows package for scientific computing of geophysical geodetic monitoring, which adopts the scientific uniform numerical standards and analytic compatible geophysical algorithms to compute various tidal and non-tidal effects on various geodetic variations outside the solid Earth, approaches accurately the global or regional load deformation field from surface load observations such as atmosphere, sea level, soil water, lakes, and glaciers, and then monitor collaboratively the land water, temporal gravity field, geological environment and ground stability variations by deep fusing of heterogeneous geodetic and surface load observations.

ETideLoad4.5 includes the basic principles, main formulas and important methods of geodesy on the deforming Earth to popularize and improve higher education, strictly according to the principles of geodesy and solid geodynamics, constrain and assimilate the deep fusion of multi-source heterogeneous monitoring variations, so as to realize the collaborative monitoring of heterogeneous geodesy, improve the science and technology of geodesy, and consolidate the geodetic application.

ETideLoad4.5 is suitable for senior undergraduates, graduate students, scientific researchers, and engineering technicians in geodesy, geophysical, geoscience, geological environment, hydrodynamics, satellite dynamics, seismology, and geodynamics, which can be employed in the classroom teaching, self-exercise, science research and engineer computing.

Key words: Geodesy, Geophysics, Tidal effect, Load deformation, Collaborative Monitoring, Land water, Ground Stability, Geological Disasters.

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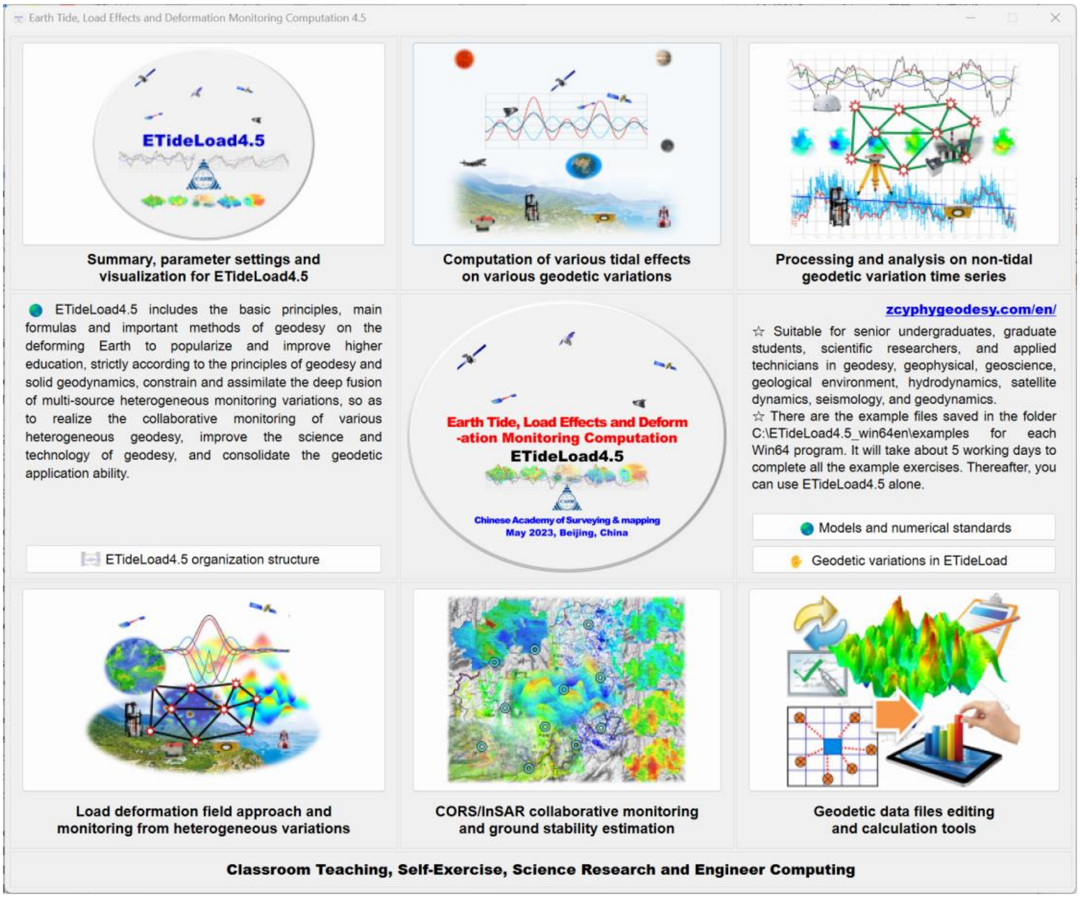
1 ETideLoad4.5's features, strengths, concepts, and usage

Earth Tide, Load Effects and Deformation Monitoring Computation (ETideLoad4.5) is a large Windows package for scientific computing of geophysical geodetic monitoring, which adopts the scientific uniform numerical standards and analytic compatible geophysical algorithms to compute various tidal and non-tidal effects on various geodetic variations outside the solid Earth, approaches accurately the global or regional load deformation field from surface load observations such as atmosphere, sea level, soil water, lakes, and glaciers, and then monitor collaboratively the land water, temporal gravity field, geological environment and ground stability variations by deep fusing of heterogeneous geodetic and surface load observations.



ETideLoad4.5 includes the basic principles, main formulas and important methods of geodesy on the deforming Earth to popularize and improve higher education, strictly according to the principles of geodesy and solid geodynamics, constrain and assimilate the deep fusion of multi-source heterogeneous monitoring variations, so as to realize the collaborative monitoring of various heterogeneous geodesy, improve the science and technology of geodesy, and consolidate the geodetic application ability.

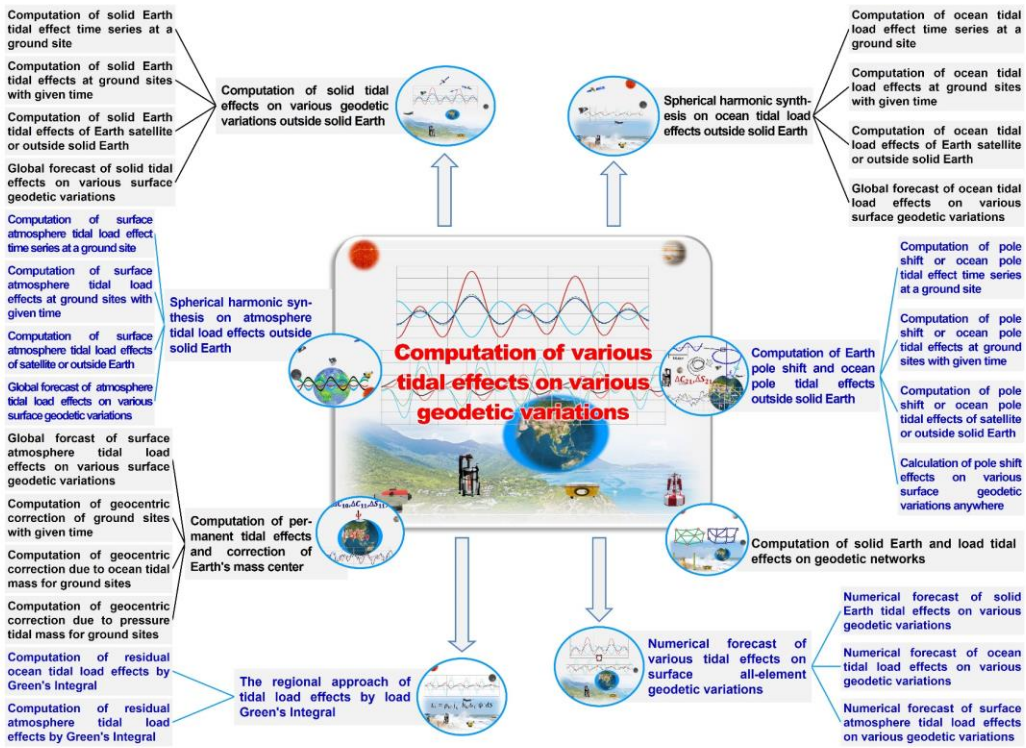
1.1 ETideLoad4.5 structure of computation functions

ETideLoad4.5 has five subsystems, which includes computation of various tidal effects on various geodetic variations, processing and analysis on non-tidal geodetic variation time series, approaching of load deformation field from heterogeneous data, CORS/InSAR collaborative monitoring and ground stability estimation as well as editing, calculating and visualization for geodetic data files.

ETideLoad4.5 were developed by QT C++ (Visual C++) for the user interface, Intel Fortran (Fortran90, 132 Columns fixed format) for the core function modules and mathGL C++ for the geodetic data file visualization in the Visual Studio 2017 x64 integrated environment, which is composed of more than 50 win64 executable programs with nearly 600 function modules.

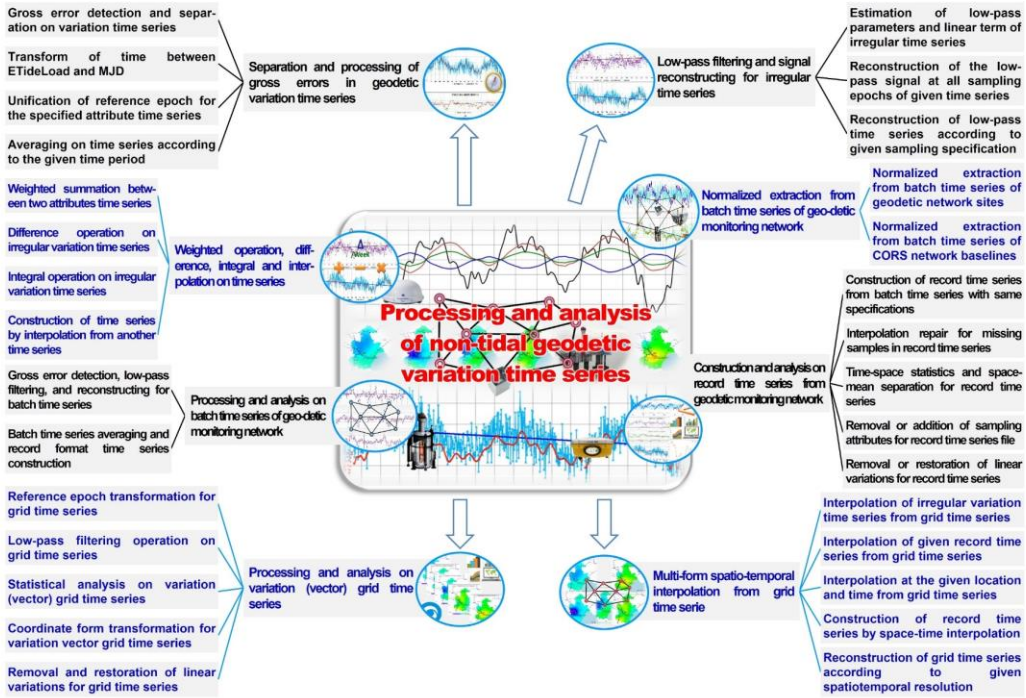
1.1.1 Computation of various tidal effects on various geodetic variations

Using the consistent geophysical models, uniform numerical standards, and compatible geodetic and geodynamic algorithms, compute various geodetic effects of the solid Earth tide, ocean tidal load and surface atmosphere tidal load, which is an important foundation and necessary condition for the collaborative monitoring of multi-geodetic technologies and deep fusion of heterogeneous Earth monitoring data.



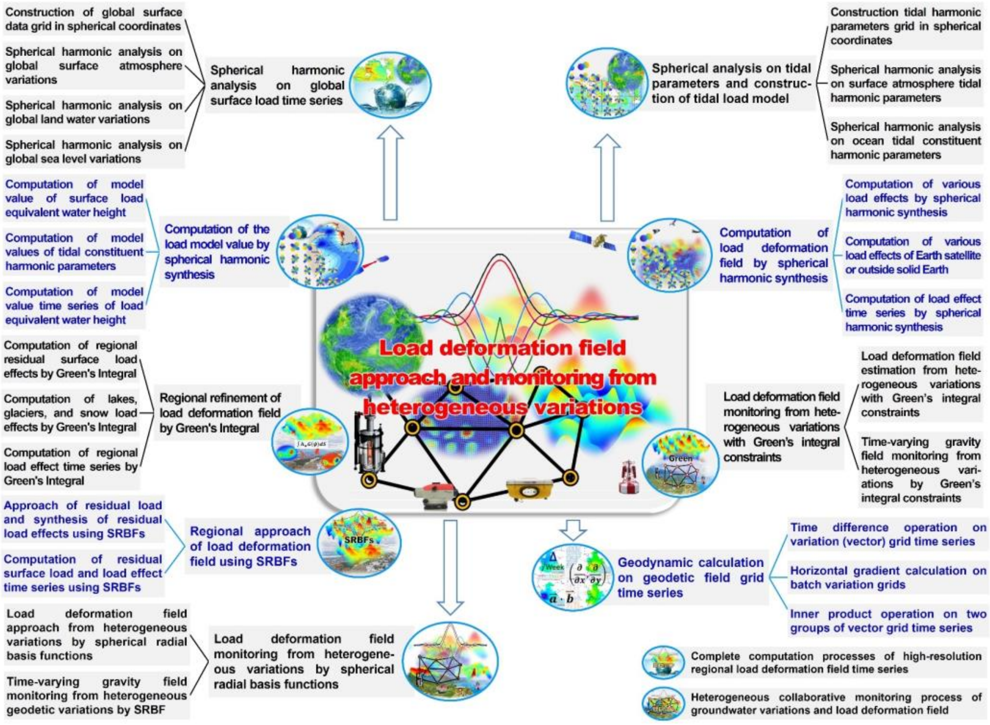
1.1.2 Processing and analysis on non-tidal geodetic variation time series

Based on the characteristics of non-tidal geodetic variations, the group of programs adopts the stable and reliable algorithms uniformly to process and analyze massive various geodetic variation time series.

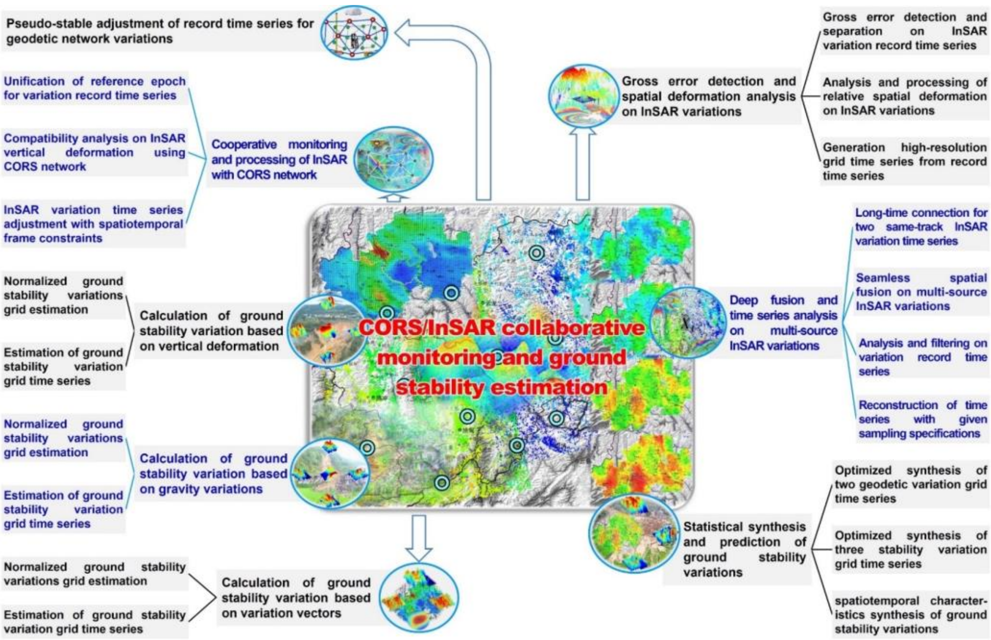


1.1.3 Load deformation field approach and monitoring from heterogeneous variations

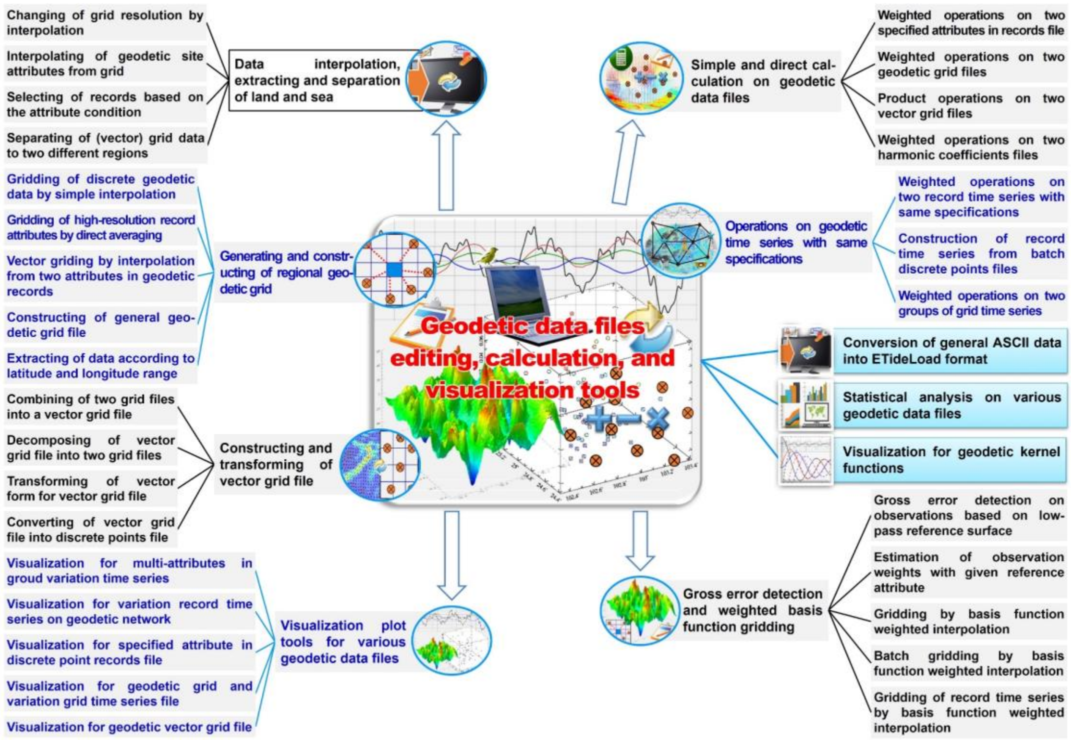
Compute and approach the global and regional non-tidal load effects, and then constrain and assimilate the deep fusion of multi-source heterogeneous data strictly according to the principles of geodesy and solid geodynamics, so as to realize the collaborative monitoring of land water variations and time-varying gravity field from heterogeneous geodesy.



1.1.4 CORS/InSAR collaborative monitoring and ground stability estimation



1.1.5 Geodetic data files editing, calculation, and visualization tools



1.2 Geodetic variations in ETideLoad4.5

1.2.1 Conventions of the geodetic variations

Geodetic variation in ETideLoad is defined as the difference between the geodetic quantity at the current epoch time and the mean of the quantities over a period or the difference between the geodetic quantity at the current epoch time and the geodetic quantity at a certain reference epoch time. The geodetic quantity may be a geodetic observation or a geodetic parameter, and the geodetic variation refers to the difference in the geodetic quantity with time.

1.2.2 Type and unit of the geodetic variations

(1) Height anomaly or geoidal height variation in the unit of mm, ground gravity or gravity disturbance variation in the unit of μGal, and ground tilt or vertical deflection variation (vector) in the unit of mas namely 0.001".

(2) Ground horizontal displacement in the unit of mm, ground radial displacement namely ground ellipsoidal height variation in the unit of mm, and ground normal or orthometric height variation in the unit of mm.

(3) Gravity gradient variation and tangential gravity gradient vector variation in the unit of 10μE for global case, as well as in the unit of mE for regional case.

(4) External (outside the Earth) geopotential perturbation in the unit of $0.1m^2/s^2$, gravity perturbation in the unit of μGal, and gravity gradient perturbation in the unit of 10μE.

(5) Land equivalent water height variation (EWH) in the unit of cm, sea level variation in unit of cm, ocean tidal height in unit of cm, and atmosphere variation in unit of hPa (mbar).

1.2.3 The geodetic variation vectors

(1) Ground tilt or vertical deflection variation vector (SW). The first component points to the south direction, and the second component points to the west direction, which forms a right-handed rectangular coordinate system with the ground gravity direction. This coordinate system is a natural coordinate system.

(2) Ground horizontal displacement vector (EN). The first component points to the east direction, and the second component points to the north direction, which forms a right-handed rectangular coordinate system with the ground radial displacement direction.

(3) Tangential gravity gradient variation vector (NW). The first component points to the north direction, and the second component points to the west direction, which forms a right-handed rectangular coordinate system with the gravity gradient variation direction (radial).

(4) The harmonic parameters of the tidal constituent. The first component is the prograde amplitude for cos(argument), and the second component is the retrograde amplitude for sin(argument).

1.2.4 Expressions of the date and epoch

Time (date and epoch) are agreed to adopt Greenwich Time (zero time zone), which is expressed in modified Julian Date (MJD, in GPS time, and Julian Date 2000.0 = MJD 51544.5) or a long integer agreed by ETideLoad.

In most cases, the long integer agreed by ETideLoad is used. E.g., 20181224122642 represents 12:26:42 on December 24, 2018, 2018122412 represents 12: 0: 0 on December 24, 2018, and 20181224 represents 0: 0: 0 on December 24, 2018. But 201812, 2018 are not valid date and epoch. Here, the epoch is an instantaneous time.

1.3 Science goals and strengths of ETideLoad4.5

1.3.1 Scientific goals of ETideLoad4.5

(1) Using the consistent geophysical models and uniform numerical standards, and constructing analytic compatible geodetic and geodynamic algorithms, compute the various tidal and non-tidal effects on various geodetic variations and then compute and approach accurately global or regional surface load deformation field.

(2) Strictly according to the principles of geodesy and solid geodynamics, constrain and assimilate the deep fusion of multi-source heterogeneous geodetic and surface load observations to realize the collaborative monitoring of land water, temporal gravity field, geological environment, and ground stability variations.

(3) Provide a set of scientific and practical geodetic geodynamic computation tools for construction of heterogeneous spatiotemporal geodetic frames, and deep fusion of heterogeneous Earth observations, collaborative monitoring of multi-geotechnologies,

computation of solid Earth deformation, monitoring of surface hydrology environment, and surveying of geological disasters.

1.3.2 Geodetic features and strengths

(1) Using the scientific uniform numerical standards and analytic compatible geophysical algorithms, compute accurately the Earth tidal, ocean tidal, and surface atmosphere tidal, permanent tidal, polar motions and geocentric motion effects on various geodetic variations, and forecast various tidal effects anytime and anywhere.

(2) Approach global or regional load deformation field from surface load observations such as atmosphere, sea level, soil water, lakes, rivers, glaciers, and snow, and then collaboratively monitor the land water and temporal gravity field by deep fusing of heterogeneous geodetic and surface load observations.

(3) Construct regional uniform spatiotemporal monitoring datum frames with high robustness to fuse the CORS, InSAR, and other geodetic variations. Propose the criteria of the ground stability based on temporal geodetic field to realize quantitative monitoring of the ground stability spatiotemporal variations.

1.4 Dominant concepts and ideas integrated into ETideLoad4.5

1.4.1 Principles of geodetic collaborative monitoring and deep fusion

(1) Using scientific consistent geophysical models, rigorous uniform numerical standards, and analytic compatible geodetic and geodynamic algorithms, unify the space-time monitoring datum and reference epoch to construct the theoretical basis and necessary conditions for geodetic collaborative monitoring.

(2) Based on the principle of geophysical geodesy, deeply fuse or constrainedly assimilate multi-source heterogeneous geodetic data, and then by reconstructing the geodetic or geodynamic space-time relationship between various variations, realize collaborative monitoring with various geometric and physical geodetic technologies.

(3) For the same type of multi-source geodetic monitoring variations, the basic geodetic constraints or joint adjustment methods with additional monitoring datum parameters as needed are used to deep fusion.

(4) For different types of geodetic monitoring variations, physical geodetic, solid geophysical, or environmental geodynamic constraints with additional dynamic parameters as needed are used to deep fusion.

(5) The purpose of geodetic collaborative monitoring is not only to improve the spatiotemporal monitoring capability, but also to further reveal the geodynamic structure and characteristics of the monitored objects and support the massive integration, intelligence and automation of Earth observation.

1.4.2 Tidal deformations of solid Earth and tidal effects on geodetic variations

(1) The external celestial bodies, ocean tide, and atmospheric tide excite the periodic

deformation of the solid Earth and the periodic change of the gravity field, which are called as the tidal deformation of the solid Earth.

(2) The geodetic variations caused by the external celestial bodies, ocean tides, and atmospheric tides are usually called the tidal effects on the geodetic variations.

(3) The geodetic tidal effects include the solid Earth tidal effects and the load tidal effects. The geodetic solid Earth tidal effects are excited by the external celestial bodies, and the tidal load effects are excited by the ocean tide and atmospheric tide.

(4) The geodetic tidal effects can be modeled and accurately removed or restored anytime and anywhere. The geodetic tidal effect is equal to the negative value of the geodetic tidal correction.

The geodetic reference frame with only some tidal effects removed but non-tidal effects neglected is still stationary (unchanged with time). For example, a precision leveling network or a gravity control network, if its observations have been corrected only using some tidal effects, is still stationary.

1.4.3 Non-tidal deformation of solid Earth and their effects on geodetic variations

(1) In the Earth surface system, surface non-tidal load variations such as soil and vegetation water, lake water, glacier and snow, groundwater, atmosphere, and sea level variations can induce the external geopotential variations, and then excite solid Earth deformation, which is manifested as ground displacement, gravity, and tilt variations. Which can be called as the load deformation of the solid Earth, and also takes the form of the variation of the Earth’s gravity field with time.

(2) Groundwater use, underground mining, underground construction, glacier or ice sheet melting, and other natural or artificial surface mass adjustments can break the mechanical balance state of the surface rock and soil layer, and then the surface rock and soil layer will tend slowly to another equilibrium state under the action of its own gravity or internal stress. The process causes plastic or viscous vertical deformation which is also called as the isostatic vertical deformation.

(3) The load deformation is excited by the surface environment load variations, and acts on the entire solid Earth. Which is an elastic deformation and can be quantitatively represented by the load Love numbers. The isostatic vertical deformation is induced by environmental geology change, whose dynamic action is in the underground rock and soil and transmitted by the rock and soil own as the mechanical medium. The isostatic deformation is a slow plastic or viscous vertical deformation.

(4) Non-tidal effects are difficult to be modeled and are measured using geodetic techniques. In most fast or real-time geodetic applications, short-time forecast estimations of the pole shift are adopted. The pole shift is the instantaneous location shift of the Earth pole at the current epoch relative to a certain reference epoch (such as epoch J2000.0) after removing all solid earth tides and load tidal effects. Neither the pole shift nor geocentric

movement should not include various tidal effects.

The geodetic reference frame that needs to account for non-tidal effects can be only dynamic, and the reference value of the dynamic reference frame corresponds to a specific and unique reference epoch time. The reference value at the current epoch time is equal to the sum of the reference value at the reference epoch time and the non-tidal effect correction. The correction here is equal to the difference between the non-tidal effects at the current epoch and that at the reference epoch. The correction process is also called as the (non-tidal effects) epoch reduction.

1.4.4 Types of ground vertical deformation and space-time quantitative natures

There are three forms of ground vertical deformation (or ground subsidence), namely, the elastic load vertical deformation, viscous or plastic isostatic vertical deformation, and plastic tectonic vertical deformation near the compressive geological fracture zone. The latter two are also called as the non-load vertical deformations, both of which are plastic vertical deformations.

(1) The load vertical deformation excited by the surface mass redistribution, firstly causes the Earth geopotential variation called as the direct effect, and then by Earth elastic dynamic action, causes the solid Earth deformation simultaneously to generate an additional geopotential variation called as the indirect effect. The load vertical deformation synchronizes with the time of the load redistribution, whose time-varying characteristics are similar to that of the surface load variations, showing complex nonlinearity and quasi-periodicity.

(2) The isostatic vertical deformation usually manifests as a dynamic process. In the process, the original equilibrium state of the underground rock and soil layer is firstly destroyed by the geology dynamic action, and then under the action of the gravity or internal stress, the rock and soil layer slowly approach another equilibrium state. For example, the compaction effect of the rock and soil layers with voids in the ground after the loss of water and the expansion effect after water infiltration, the deformation of the upper rock layer (wall rock deformation) caused after underground construction and ground plastic isostatic rebound after surface mass migration.

• Spatial quantitative characteristics of the isostatic vertical deformation

The dynamic action is located inside the underground rock and soil layer, and the equilibrium adjustment object is the rock and soil layer above the dynamic action point. The space influence angle of the equilibrium adjustment is about 45°, that is, the spatial range of ground vertical deformation is approximately equal to the buried depth of the action point.

• Temporal quantitative characteristics of the isostatic vertical deformation

The duration of the equilibrium adjustment is approximately proportional to the burial depth of the dynamic action location. The isostatic vertical deformation is the opposite of its acceleration rate sign in a relatively long-period of time (several years), and linear time variation in a short period of time (several months).

(3) The tectonic vertical deformation, driven by the horizontal movement of the lithospheric plate, only appears near the compressive fault zone. Whose spatial influence radius is equivalent to the depth of the fault, and the deformation decays rapidly to zero with the distance of the calculation point away from the fault zone. On a centennial timescale, the tectonic vertical deformation rate remained basically unchanged.

1.4.5 Representation and approach principles of load deformation field

(1) The load deformation field is a form of geodetic non-tidal load effects, which can be uniquely represented by the variations of the Earth's gravity field with time. The relationship between the non-tidal load effects on the parameters of the Earth's gravity field is completely consistent with the relationship between the parameters. Global Earth gravity field can be represented by a geopotential coefficient model (GCM). Similarly, the global load deformation field (namely temporal global gravity field) can be represented by a global surface load spherical harmonic coefficient model (LCM).

(2) From a geopotential coefficient model, you can calculate various gravity field quantities on the surface or outside Earth. Similarly, from a global load spherical harmonic coefficient model, you can calculate load effects on various geodetic variations outside the solid Earth. Regional gravity field (geoid) can be approached by the remove-restore process based on a GCM. Similarly, the regional load deformation field or temporal gravity field can also be approached by the remove-restore process based on an LCM.

(3) The approach theory of Earth's gravity field is linear, so that Earth's gravity field can be approached by the remove-restore scheme and cumulative iteration method. Similarly, the approach theory of load deformation field is also linear, so load deformation field can be also refined by the remove-restore scheme and cumulative approach method. The total deformation effects of various environmental loads (atmospheric pressure, land water, sea level change, etc.) are equal to the deformation effects of the sum of these loads.

(4) The approach methods of the Earth's gravity field can be summarized into two categories, namely, the Stokes / Hotine integral method (geodetic boundary value problem solution) in the spatial domain and the spherical basis function (surface spherical function, radial basis function, spline function, etc.) approach method in the spectral domain, which can integrate various global or regional gravity field data. Similarly, for load deformation field (time-varying gravity field) approach or monitoring, there are two methods of load Green 's function integral constraint in spatial domain and spherical basis function approach in spectral domain, which can also effectively integrate global or regional multi-source heterogeneous variations.

1.4.6 CORS and InSAR collaborative monitoring principle for vertical deformation

(1) Through the gross error detection, spatial filtering, and time series analysis, the InSAR vertical variation is separated into two parts, one part is the vertical deformation of

the rock and soil layer several meters deep, and the other part is the expansion and contraction of the soil own. Only the former is compatible with most geodetic variations, while the latter is mainly affected by the temperature and rainfall and should not be regarded as a solid Earth deformation.

(2) Using the CORS network ellipsoidal height variation time series as the constraints on the multi-source InSAR vertical variation time series, separate the ground vertical deformation signal, and then realize the collaborative monitoring of the CORS network and multi-source InSAR.

(3) Only the vertical deformation of the rock and soil layer several meters deep are the useful information needed for monitoring of the ground subsidence, earthquakes, geological disasters, ground stability variations, solid Earth deformation, groundwater variations, and geodynamics.

1.4.7 Continuous quantitative monitoring scheme of ground stability variations

(1) Construct the quantitative criteria for the ground stability weakening from the regional grid time series of the geodetic vertical deformation, ground gravity and tilt variations, and then continuous quantitatively monitor the ground stability variations.

(2) Quantitative criteria of the ground stability weakening mainly include that the ellipsoidal height increases, the gravity decreases, the horizontal gradient of the height or gravity variation is large, and the inner product of the tilt variations and terrain slope vector is greater than zero.

(3) According to the geological disasters that occurred, optimize and synthesize various geodetic ground stability variation grid time series to adapt to the local environmental geology, and then consolidate regional stability variations monitoring capabilities.

1.4.8 Analytical compatibility between various geodetic algorithms

The consistency and analytical compatibility between various geodetic algorithms are the requirement of geodetic theory and concrete manifestation for the uniqueness of monitoring objects. Which is the smallest requirement for the collaborative monitoring of multi-geodetic technologies and deep fusion of multi-source heterogeneous geodetic data.

Analytical compatibility between geodetic algorithms involves two issues: (1) Compatibility between various geodynamic influences for different types of geodetic variations. (2) Compatibility between different types of geodynamic influences of one kind of geodetic quantity.

The first type of compatibility is the basic requirement of geodetic theory. For example, the load effect on the normal height on a site is equal to the Hotine integral of the load effect on gravity disturbances. For another example, the solid tidal effect on the normal height on a site is equal to the sum of the effects on the ellipsoidal height and geoid.

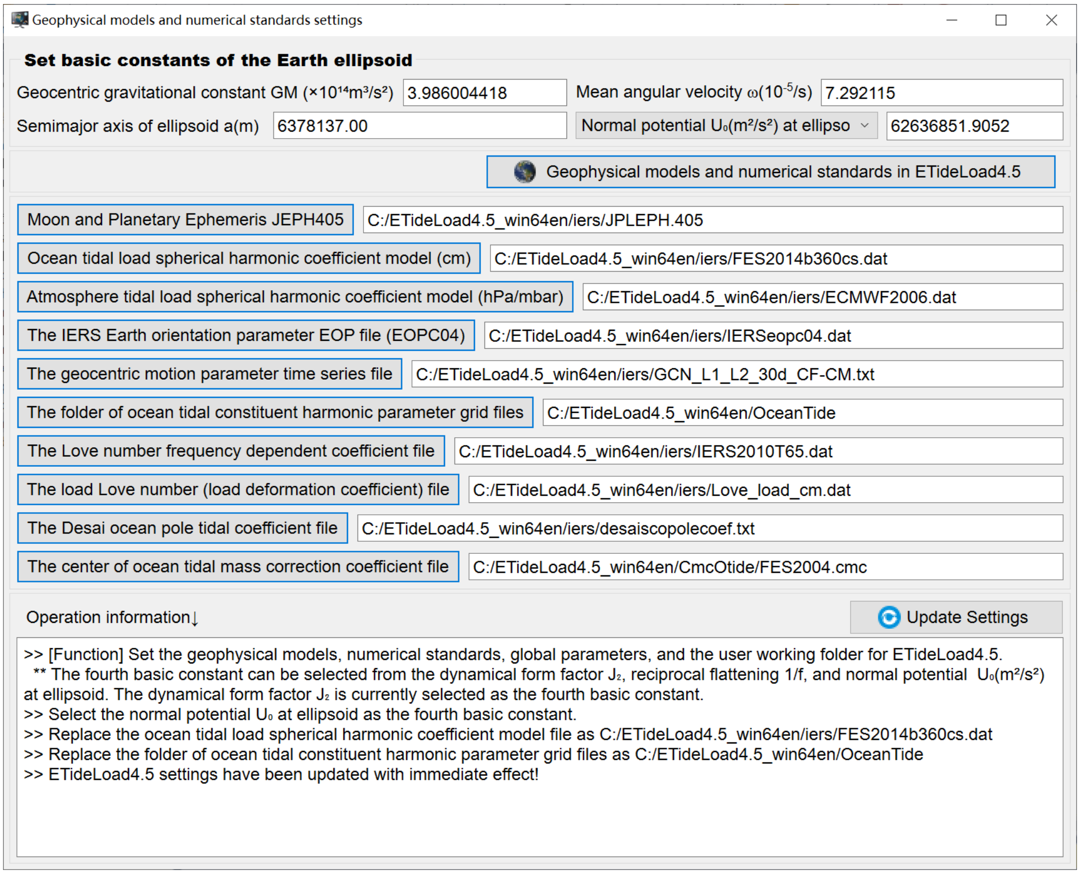
The second type of compatibility is constrained by the solid deformation geodynamic equations (including constitutive equations).

1.5 Conventions, examples and usage in ETideLoad4.5

1.5.1 Geophysical models and numerical standards in ETideLoad4.5

ETideLoad4.5 is mainly based on the geophysical models and numerical standards recommended by IERS Conventions (2010). You can update them by the program [geophysical models and numerical standards settings]. These geophysical models and numerical standards are stored in file form in the folder of C:\ETideLoad4.5_win64en.

Geophysical models and numerical standards in ETideLoad4.5 mainly include the surface atmosphere tidal load spherical harmonic coefficient model, ocean tidal load spherical harmonic coefficient model, Earth's Load Love numbers, IERS Earth orientation parameter time series, geocentric motion parameter time series, ocean tidal constituent harmonic parameters grid model, JPL Moon and Planetary Ephemeris DE405, corrections coefficients of frequency dependence on Love numbers, Desai ocean pole tide coefficients, and center of mass correction coefficients for the ocean tide.



1.5.2 Five kinds of variation time series agreed in ETideLoad4.5

The geodetic variation time series files adopt the ETideLoad own format, which include the ground geodetic variation time series file, geodetic site variation record time series file, geodetic network observation record time series file, variation (vector) grid time series files, and spherical harmonic coefficient (Stokes coefficient) model time series files.

(1) The ground geodetic variation time series

A ground geodetic variation time series file can store the time series data of several kinds of variations on a certain site, a certain baseline or route, and the sampling epochs (here, the epoch is an instantaneous time) of these variations are the same. Such as the CORS station coordinate solution time series, solid tide station observation or analysis result time series, GNSS baseline solution time series, etc.

(2) The geodetic site variation record time series

A geodetic site variation record time series file can store the time series data of one kind of variations for a group of geodetic sites. Such as the station coordinate time series for the CORS network, benchmark height time series for the leveling network, observation time series for the tide station network, and InSAR monitoring time series, etc.

(3) The geodetic network observation record time series

A geodetic network observation record time series file can store the variation record time series of the baseline component for the CORS network, the variation record time series of the height difference for the leveling network, or the variation record time series of the gravity difference for the gravity control network.

(4) The variation grid time series for geodetic field

A group of variation grid time series files is composed of a series of numerical grid model files of one kind of variation (vector), and the seventh attribute of the header in each grid file is agreed to be the sampling epoch time. Such as the grid time series of the land equivalent water height, sea level variation, and the grid time series of various regional load deformation field or temporal gravity field, etc.

(5) The spherical harmonic coefficient model time series

A group of spherical harmonic coefficient model time series files can store the time series of the spherical harmonic coefficient (Stokes' coefficient) models of the global surface load variations, global load deformation field, or temporal global gravity field.

The file header occupies one row and consists of three attributes, namely the geocentric gravitational constant GM($\times 10^{14}$m^3/s^2), equatorial radius of the Earth a(m), and sampling epoch time (in ETideLoad format).

GM, a are the scale parameters of the model. Here, the surface harmonic functions in the spherical harmonic coefficient model are defined on the spherical surface whose radius is equal to the semi-major axis a of the Earth.

The degree n and order m spherical harmonic coefficients are expressed by a record with the format: degree n, order m, C_{nm}, S_{nm} (, C_{nm} error, S_{nm} error). At different sampling epochs, the maximum of the degree need not be the same.

The program [Conversion of general ASCII record data into ETideLoad format], and the function [Normalized extraction of batch time series of geodetic monitoring network] are the important interfaces for ETideLoad to accept external text data. Using the global forecast function program of various tidal effects, a surface geodetic variation time series at a given location and sampling specifications can be constructed. Using the program [Generating and constructing of regional geodetic grid], a numerical grid with the given grid specifications can be constructed. The other programs or functions only accept the format data generated by ETideLoad own.

1.5.3 Full examples for the classroom teaching and self-study exercises

To ease the classroom teaching and self-study exercises, there are the example files saved in the folder C:\ETideLoad4.5_win64en\examples for each Win64 program. Each example includes the operation process file process.txt, some input-output data files and screenshots. The folder name of the example files is the same as the name of the window executable program.

Before using the ETideLoad4.5 programs, it is recommended to perform completely the program example using the input-output example data files by comparing the screenshots according to the process information in process.txt. It will take about 5 working days to complete all the example exercises. Thereafter, you can use ETideLoad4.5 alone.

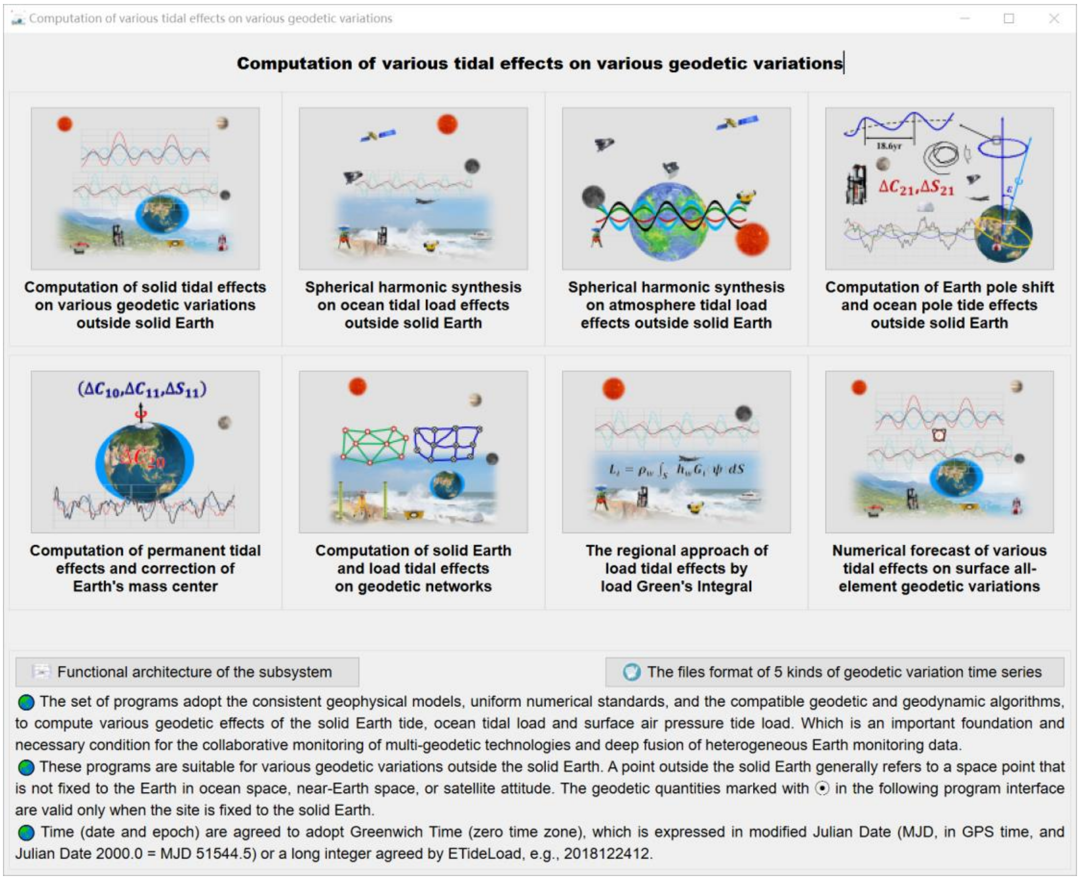
1.5.4 ETideLoad4.5's applicable professional fields and usage instructions

ETideLoad4.5 is suitable for senior undergraduates, graduate students, scientific researchers, and engineering technicians in geodesy, geophysical, geoscience, geological environment, hydrodynamics, satellite dynamics, seismology, and geodynamics, which can be employed in the classroom teaching, self-exercise, science research, and engineer computing.

You can design your own schemes and processes, then organize flexibly the related programs and functions from ETideLoad4.5, perform some scientific computations for various tidal or non-tidal effects, ground deformation field or temporal gravity field approach, land water, ground stability, or surface dynamic environment monitoring, and multi-source heterogeneous geodetic data deep fusion.

2 Computation of various tidal effects on various geodetic variations

The group of programs adopt the consistent geophysical models, uniform numerical standards and the compatible geodetic and geodynamic algorithms, to compute various geodetic effects of the solid Earth tide, ocean tidal load and surface atmosphere tidal load, which is an important foundation and necessary condition for the collaborative monitoring of multi-geodetic technologies and deep fusion of heterogeneous Earth monitoring data.



These programs are suitable for various geodetic variations outside the solid Earth. A point outside the solid Earth generally refers to the space point that is not fixed to the Earth in ocean space, near-Earth space, or satellite altitude. The geodetic variations marked with ⦿ in the following program interface are valid only when the site is fixed to the solid Earth.

2.1 Computation of solid tidal effects on various geodetic variations outside solid Earth

[Purpose] According to the location and time in the input time series file, compute the solid Earth tidal effect time series on various geodetic variations on the ground or outside the solid Earth. Here the point outside the solid Earth generally refers to the space point that is not fixed to the Earth in ocean space, near-Earth space, or satellite altitude.

The solid tidal effects on the physical geodetic variations are computed according to the

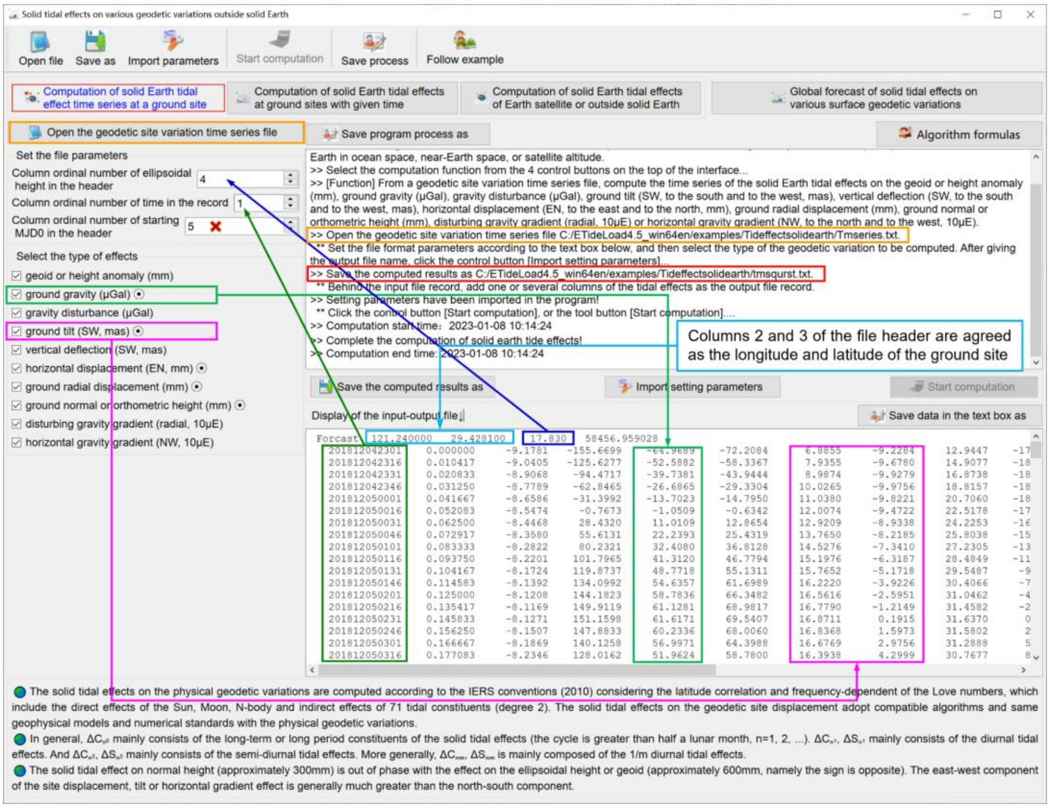
IERS conventions (2010) considering the latitude correlation and frequency-dependent of the Love numbers, which include the direct effects of the Sun, Moon, N-body and indirect effects of 71 tidal constituents (degree 2). The solid tidal effects on the geodetic site displacement adopt compatible algorithms and same geophysical models and numerical standards with the physical geodetic variations.

2.1.1 Computation of solid Earth tidal effect time series at a ground site

[Function] From a geodetic site variation time series file, compute the time series of the solid Earth tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The geodetic site variation time series file.

The file header contains site name, longitude (degree decimal), latitude (degree decimal), height (m) relative to the ellipsoidal surface, the starting MJD0 (optional)……



Starting from the second row of the file, each row in the record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.

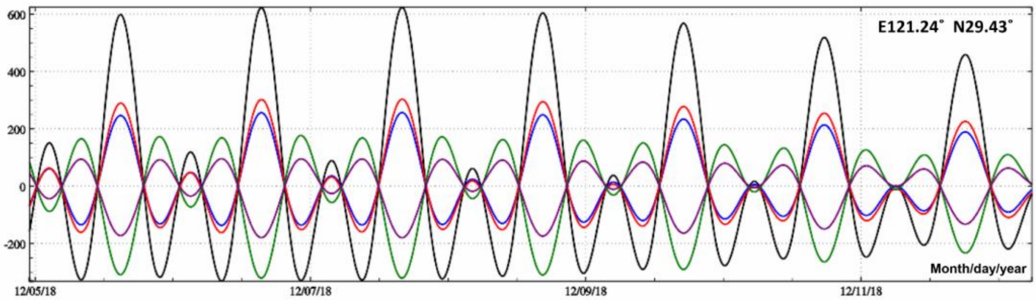
[Parameter settings] Set the input file format parameters, select the type of solid Earth tidal effects.

The geodetic variations marked with ⦿ are valid only when the site is fixed to the solid Earth.

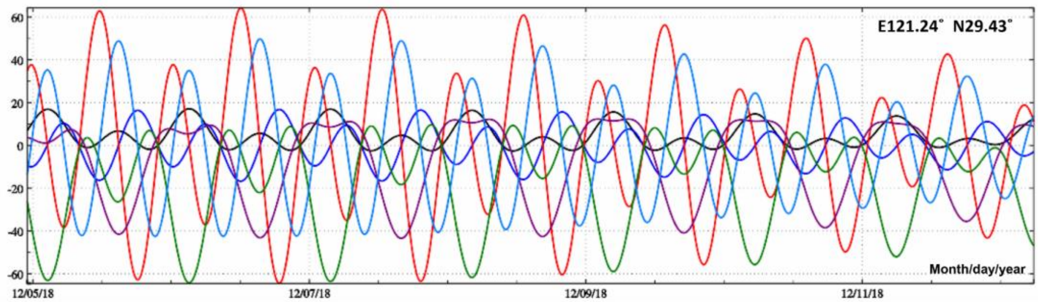
[Output file] The geodetic site solid Earth tidal effect time series file.

The file header is the same as the input time series file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

When the ellipsoidal height of the calculation point is equal to the ellipsoidal height of the geoid, the solid tidal effect on the height anomaly is the effect on the geoid.



Solid tidal effects : geoid or height anomaly (mm) ground gravity (μGal) radial displacement (mm) normal or orthometric height (mm) disturbing gravity gradient (radial, 10μE)



Solid tidal effects : ground tilt (S, mas) tilt (W, mas) horizontal displacement (E, mm) horizontal displacement (N, mm) horizontal gradient (N, 10μE) horizontal gradient (W, 10μE)

The solid tidal effect on normal height (approximately 300mm) is out of phase with the effect on the ellipsoidal height or geoid (approximately 600mm, namely the sign is opposite). The east-west component of the site displacement, tilt or horizontal gradient effect is generally much greater than the north-south component.

2.1.2 Computation of solid Earth tidal effects at ground sites with given time

[Function] According to the location and time in the calculation point file, compute the solid Earth tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

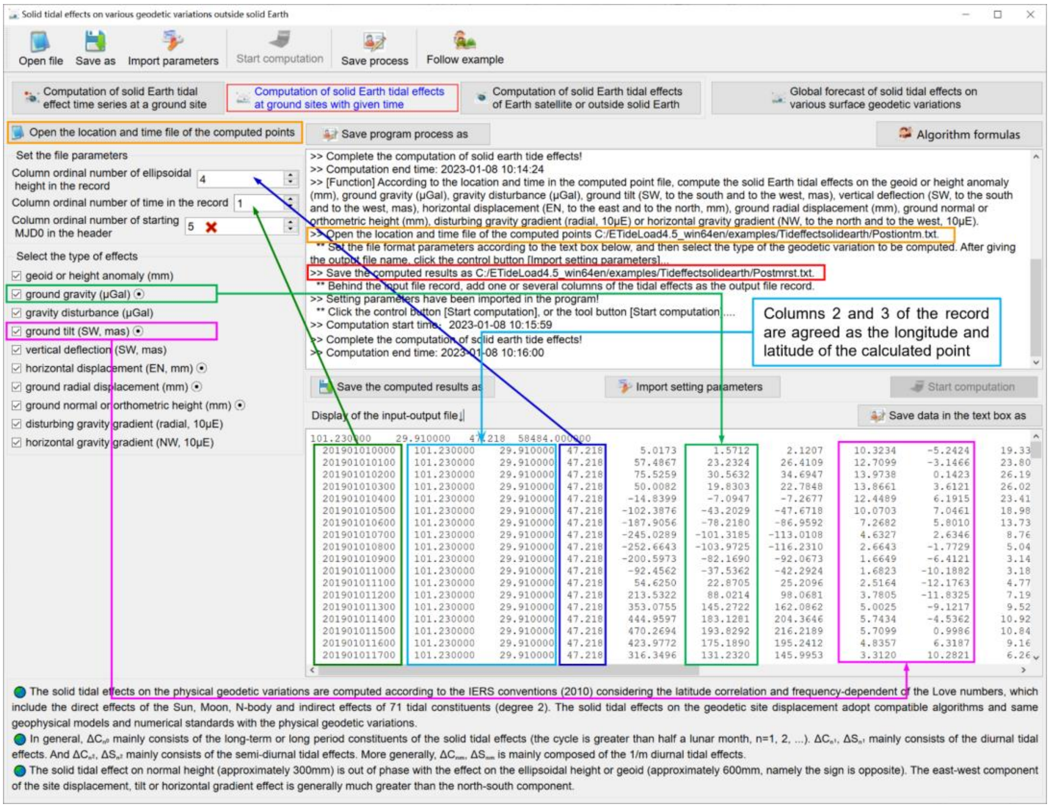
[Input file] The location and time file of the calculation points.

The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

[Parameter settings] Set the input file format parameters, select the type of solid Earth tidal effects.

[Output file] The solid Earth tidal effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.



The start MJD0 attribute in the input file header is required when the date is in MJD format. In this case, the sampling epoch MJD is equal to the sum of the starting MJD0 and the number of days in the record.

If the time (date) is in the long integer format agreed by ETideLoad, it is not necessary for the starting MJD0 attribute in the input file header, and the program automatically recognizes and ignores the selection.

$1+(2h_{nm}-(n+1)k_{nm})/n$ is the solid tidal effect factor of the ground gravity at degree n and order m. $1-(n+1)k_{nm}/n$ is the solid tidal effect factor of the gravity disturbance. $1+k_{nm}-h_{nm}$ is the solid tidal effect factor of the ground tilt. And 1+k_{nm} is the solid tidal effect factor of the vertical deflection or height anomaly.

In general, ΔC_{n0} mainly consists of the long-term or long period constituents of the solid tidal effects (the cycle is greater than half a lunar month, n=1, 2, ...). ΔC_{n1}, ΔS_{n1} mainly consists of the diurnal tidal effects. And ΔC_{n2}, ΔS_{n2} mainly consists of the semi-diurnal tidal effects. More generally, ΔC_{nm}, ΔS_{nm} is mainly composed of the 1/m diurnal tidal effects.

2.1.3 Computation of solid Earth tidal effects of Earth satellite or outside solid Earth

[Function] According to the location and time in the external point file, compute the solid Earth tidal effects on the geopotential (0.1m²/s²), gravity (μGal) or gravity gradient (10μE) outside the solid Earth.

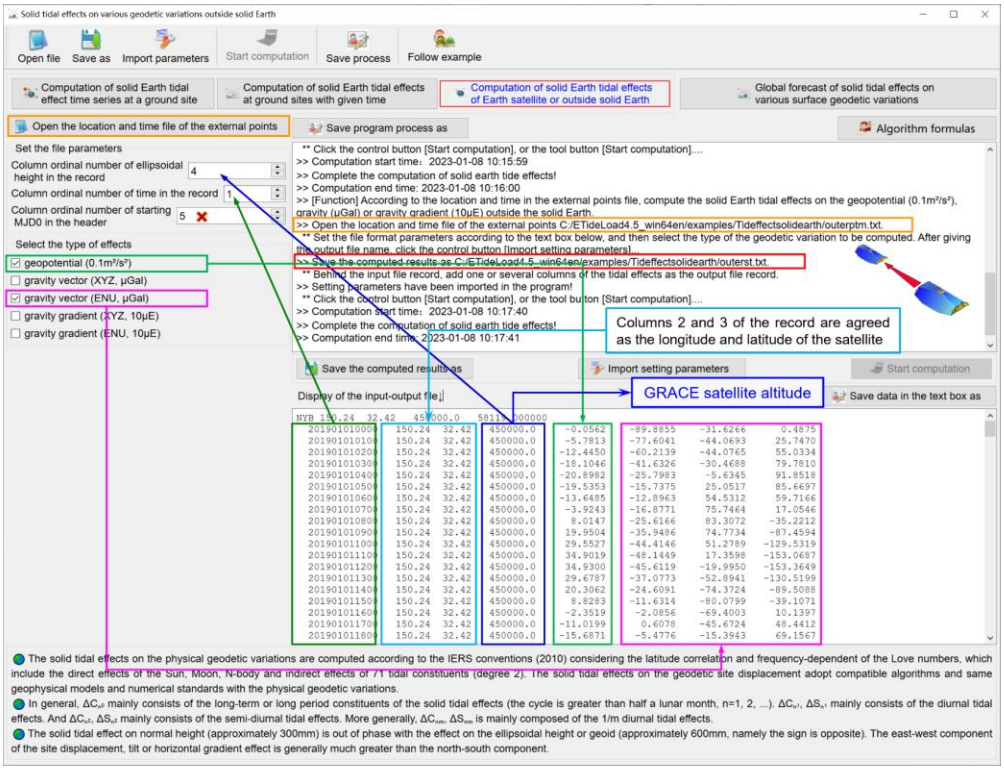
[Input file] The location and time file of the external points.

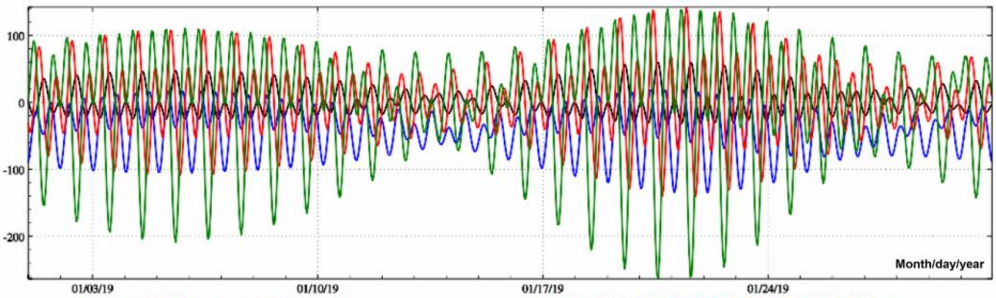
The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

[Parameter settings] Set the input file format parameters, select the type of solid Earth tidal effects.

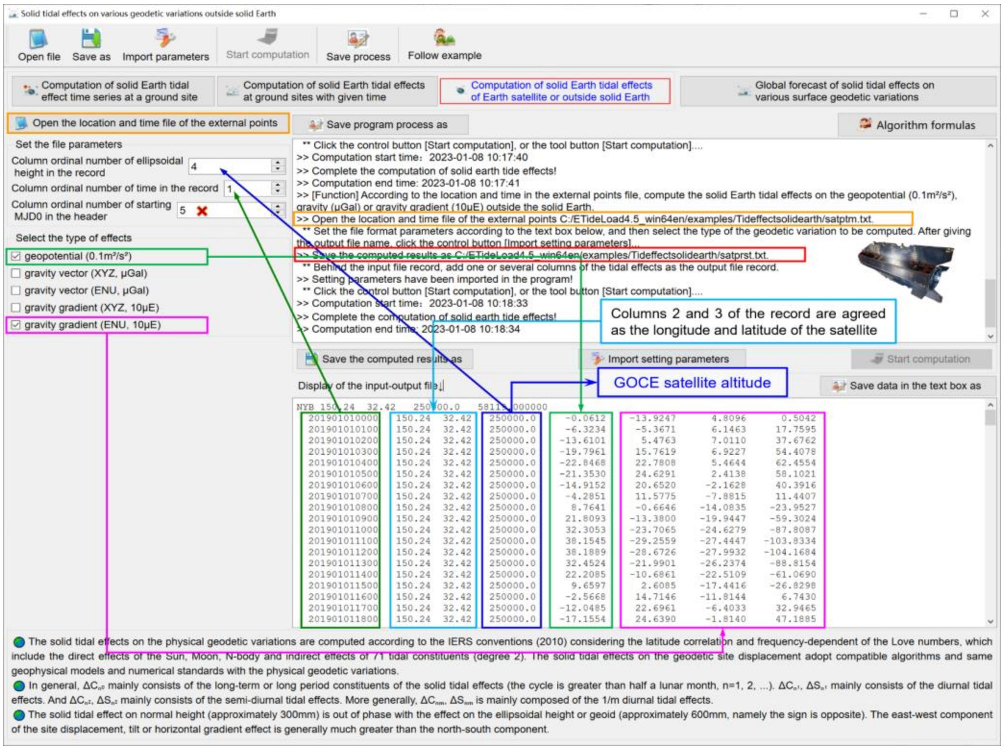
[Output file] The solid Earth tidal effect file.

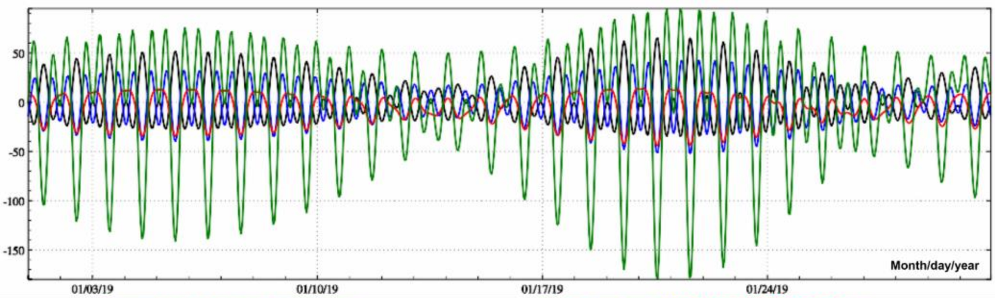
The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, the geopotential and gravity vector are selected, and there are 7 attributes added to the record.





The solid tidal effects at 450km altitude: geopotential (0.1m²/s²), gravity vector (E, N: along the GRACE orbit/SST-II, U, μGal)

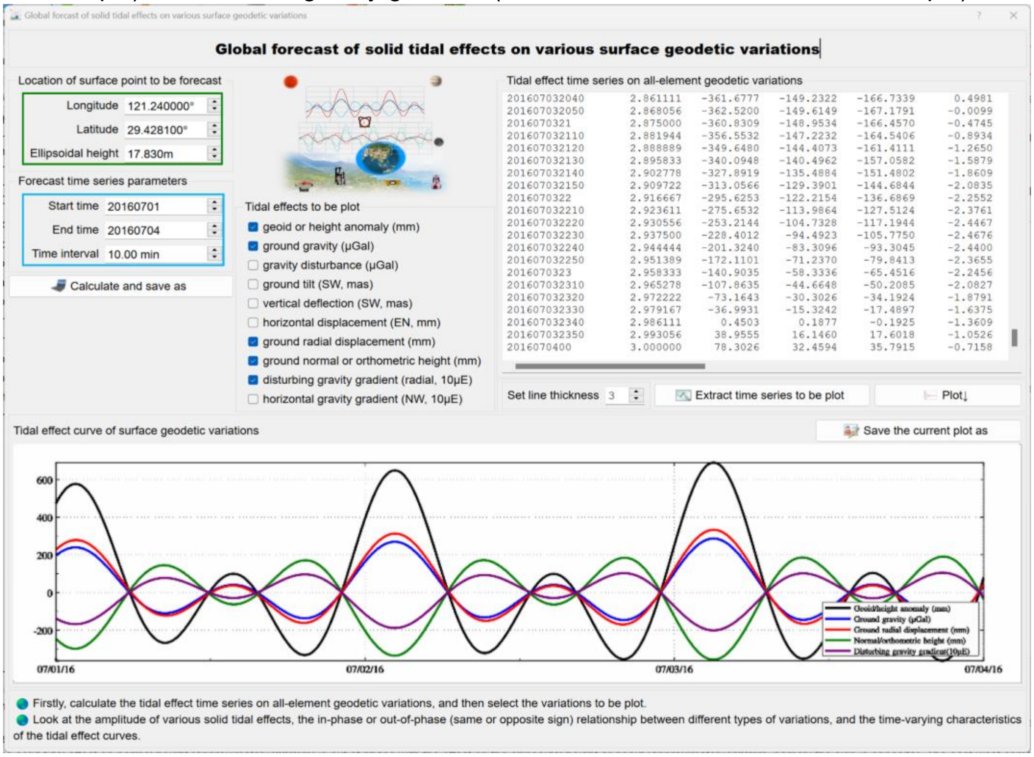


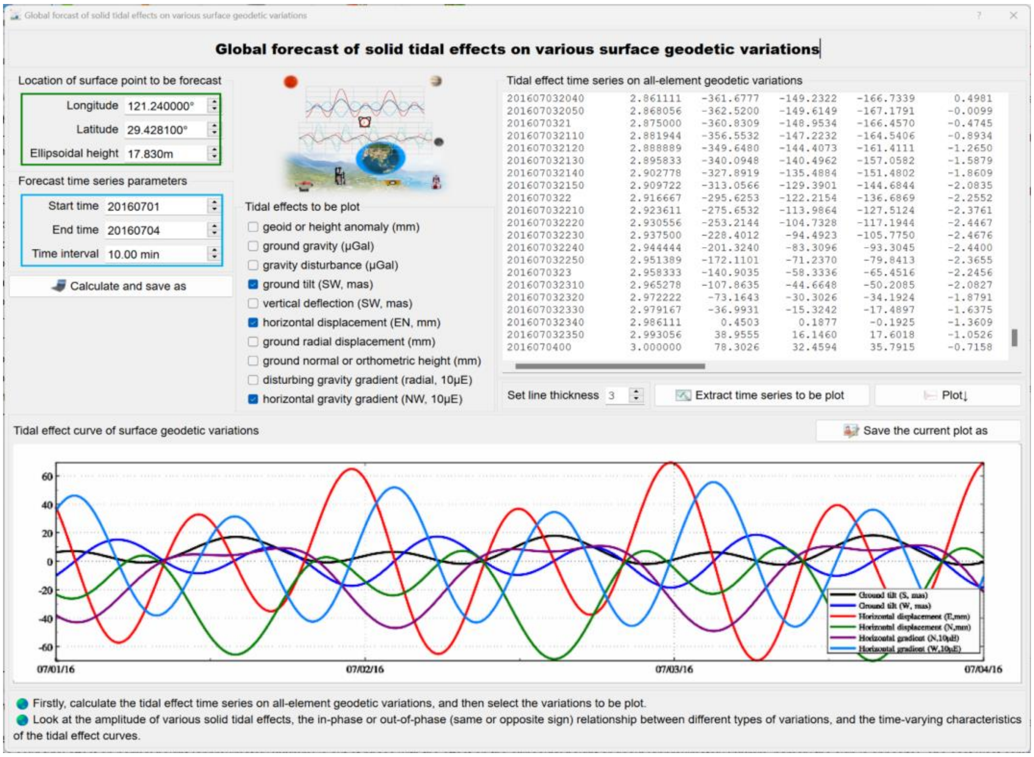


The solid tidal effects at 250km altitude: geopotential (0.1m²/s²), gravity gradient (E, N: along the GOCE orbit, U, 10μE)

2.1.4 Global forecast of solid tidal effects on various surface geodetic variations

[Function] Input the geodetic coordinates of a global anywhere surface point and set the forecast time series parameters, calculate and display the solid Earth tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).





Firstly, calculate the tidal effect time series on all-element geodetic variations, and then select the variations to be plot.

Look at the amplitude of various solid tidal effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying characteristics of the tidal effect curves.

2.2 Spherical harmonic synthesis on ocean tidal load effects outside solid Earth

[Purpose] Using the global ocean tidal load spherical harmonic coefficient model (cm), according to the location and time in the input file, compute the ocean tidal load effects on various geodetic variations on the ground or outside the solid Earth by the spherical harmonic synthesis algorithm. Here the point outside the solid Earth generally refers to the space point that is not fixed to the Earth in ocean space, near-Earth space, or satellite altitude.

2.2.1 Computation of ocean tidal load effect time series at a ground site

[Function] From a geodetic site variation time series file, compute the time series of the ocean tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The geodetic site variation time series file.

The file header contains site name, longitude (degree decimal), latitude (degree decimal), height (m) relative to the sea surface, the starting MJD0 (optional)……

Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.

The height of the calculation point is normal or orthometric height relative to the sea surface since the ocean tidal loads are generally considered to be on the sea surface.

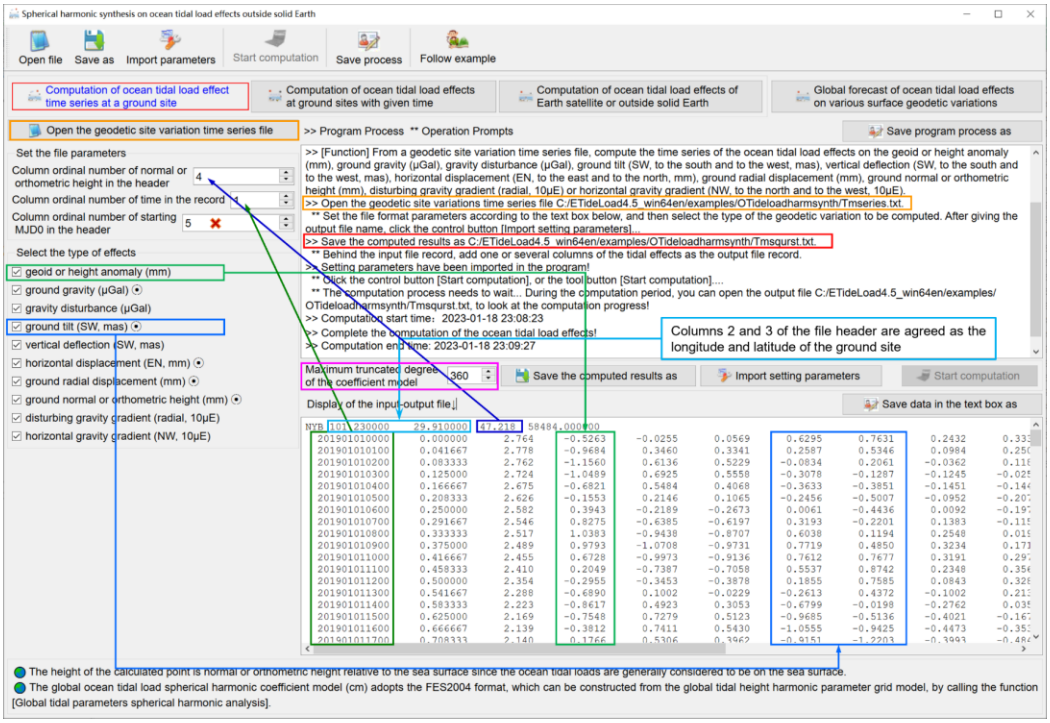
[Parameter settings] Set the input file format parameters, select the type of ocean tidal load effects.

[Output file] The geodetic site ocean tidal effect time series file.

The file header is the same as the input time series file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

The program automatically selects the minimum value between the maximum degree of the spherical harmonic coefficient model and the entered maximum degree as the calculated degree.

The computation process needs to wait. During the computation period, you can open the output file to look at the computation progress!



2.2.2 Computation of ocean tidal load effects at ground sites with given time

[Function] According to the location and time in the calculation point file, compute the ocean tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The location and time file of the calculation points.

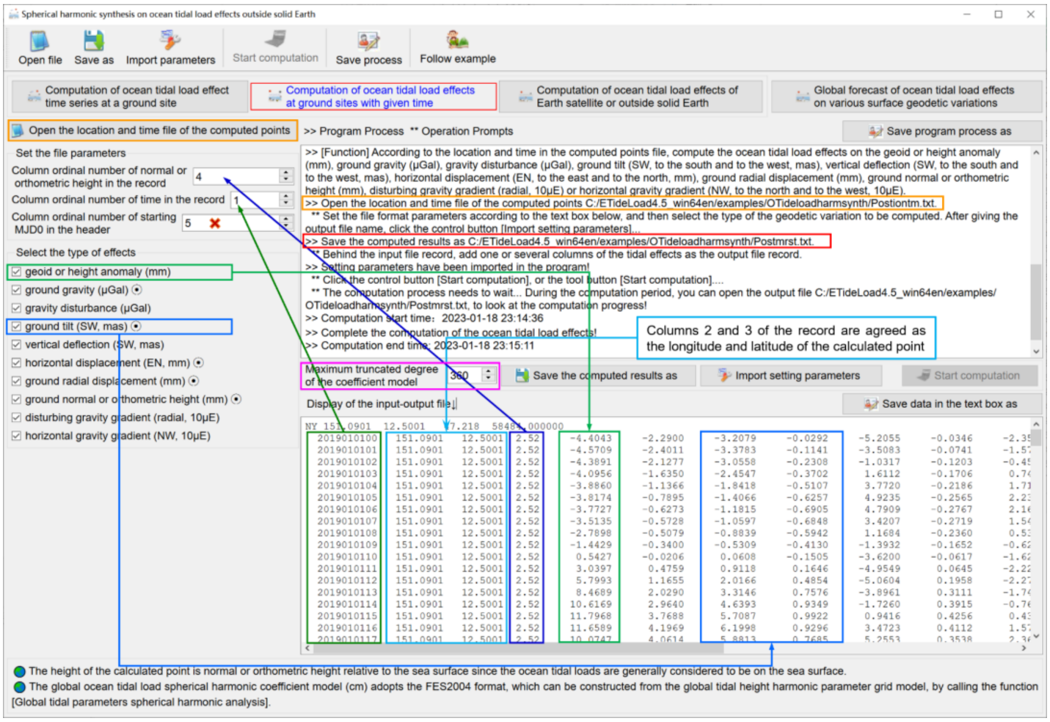
The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and height attributes in the records.

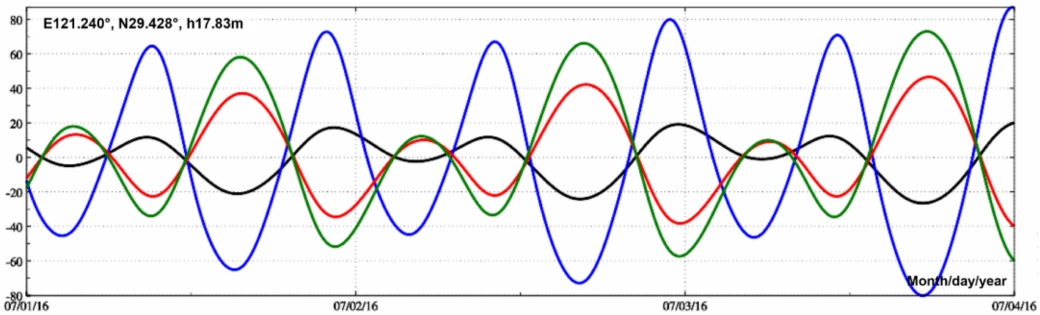
[Parameter settings] Set the input file format parameters, select the type of ocean tidal load effects.

[Output file] The ocean tidal load effect file.

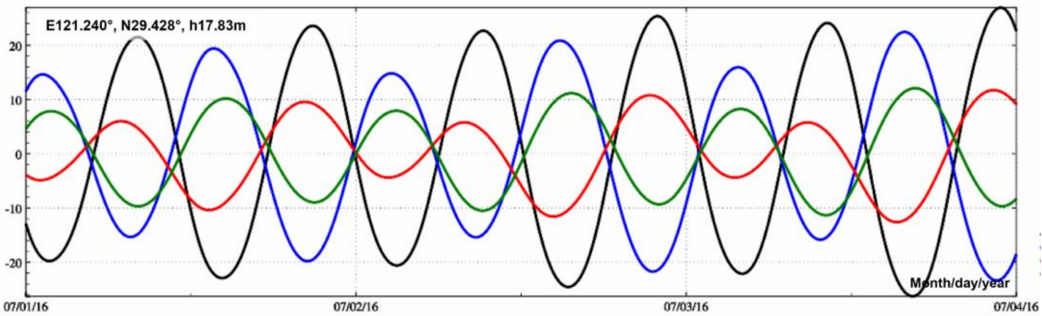
The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

Different from the effect of the solid Earth tide, the load effect on the normal height is in the same phase as the effect on the ellipsoidal height, and the magnitude of effect on the normal height is about 1.75 times that of the ellipsoidal height. The east-west component of the site displacement, tilt or horizontal gradient effect is generally smaller than the north-south component.





The ocean tidal load effects (360-degree) : height anomaly (mm) ground gravity (μGal) radial displacement (mm) orthometric height (mm)



The ocean tidal load effects (360-degree) : ground tilt (S, mas) tilt (W, mas) horizontal displacement (E, mm) horizontal displacement (N, mm)

$1+(2h'_n-(n+1)k'_n)/n$ are the load deformation coefficients of the ground gravity at degree n. $1-(n+1)k'_n/n$ are the load deformation coefficients of the gravity disturbance. $1+k'_n-h'_n$ are the load deformation coefficients of the ground tilt. And $1+k'_n$ are the load deformation coefficients of the vertical deflection or height anomaly.

The global ocean tidal load spherical harmonic coefficient model (cm) adopts the FES2004 format, which can be constructed from the global tidal height harmonic parameters grid model, by calling the function [Global tidal parameters spherical harmonic analysis].

The computation speed of the program depends on the degree of the spherical harmonic coefficient model and the number of the tidal constituents.

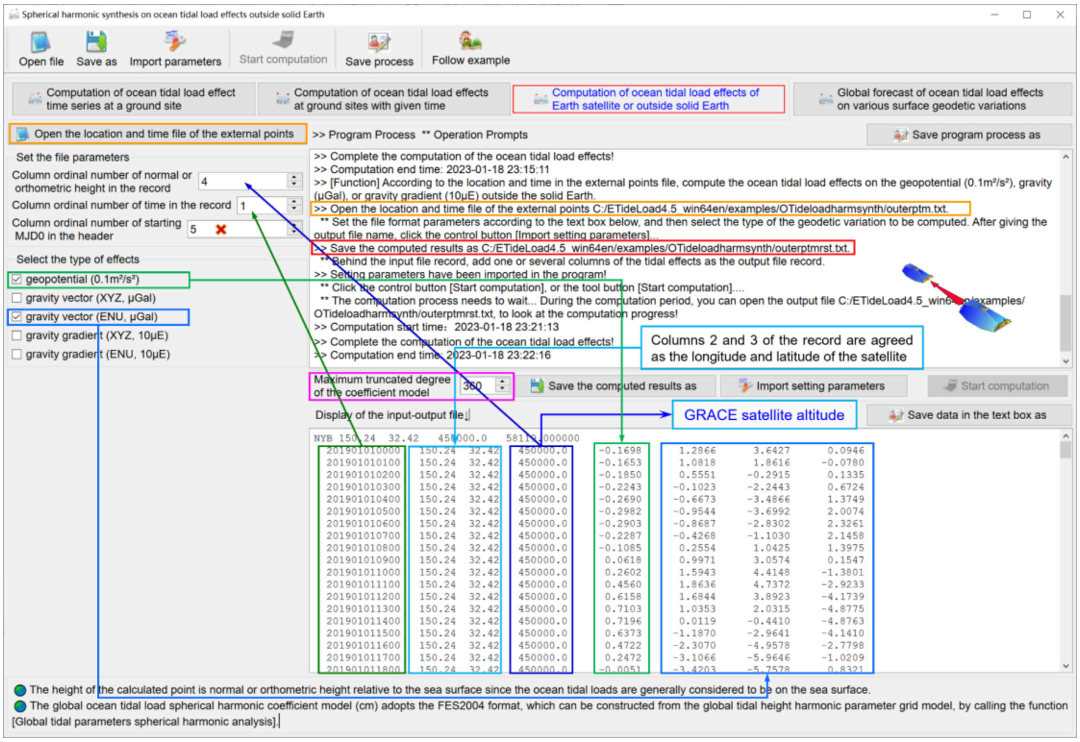
The program adopts the default global ocean tidal load spherical harmonic coefficient model. You can select other global ocean tidal load spherical harmonic coefficient models by the program [geophysical model and numerical standard settings].

2.2.3 Computation of ocean tidal load effects of Earth satellite or outside solid Earth

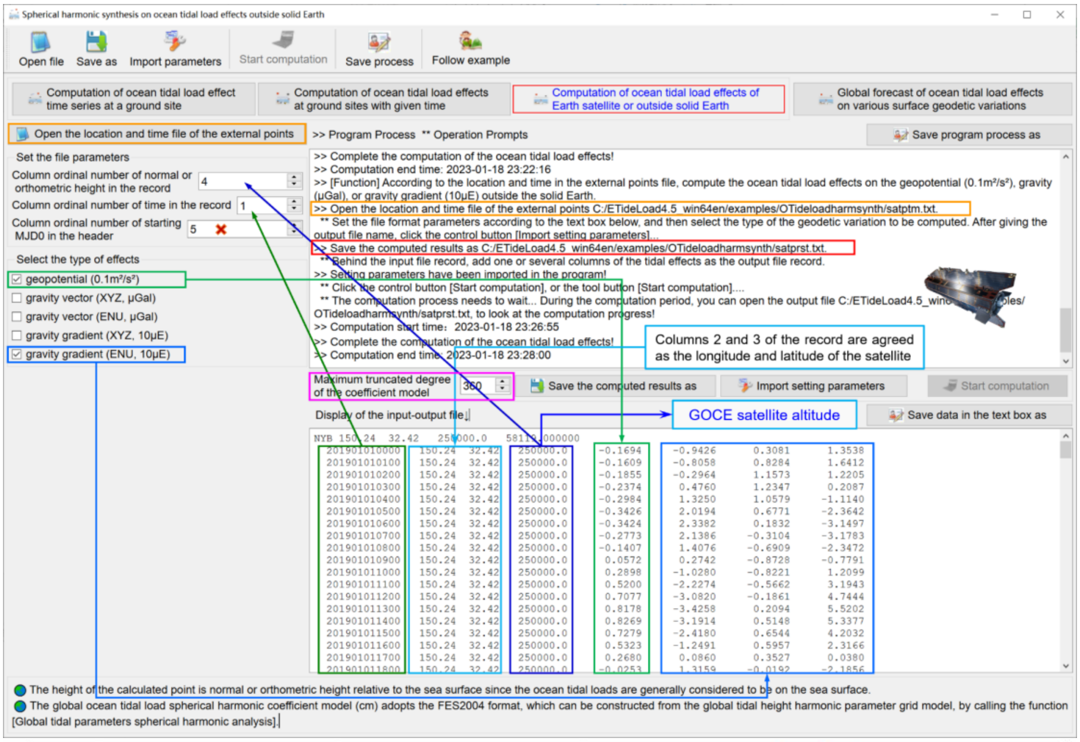
[Function] According to the location and time in the external point file, compute the ocean tidal load effects on the geopotential (0.1m²/s²), gravity (μGal), or gravity gradient (10μE) outside the solid Earth.

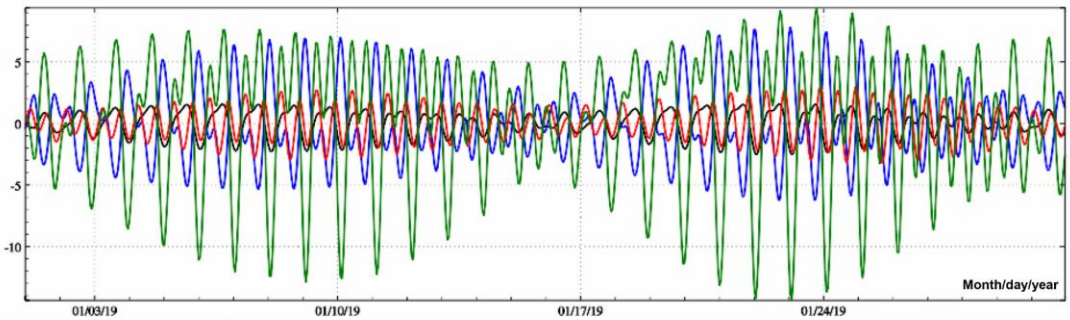
[Input file] The location and time file of the external points.

The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

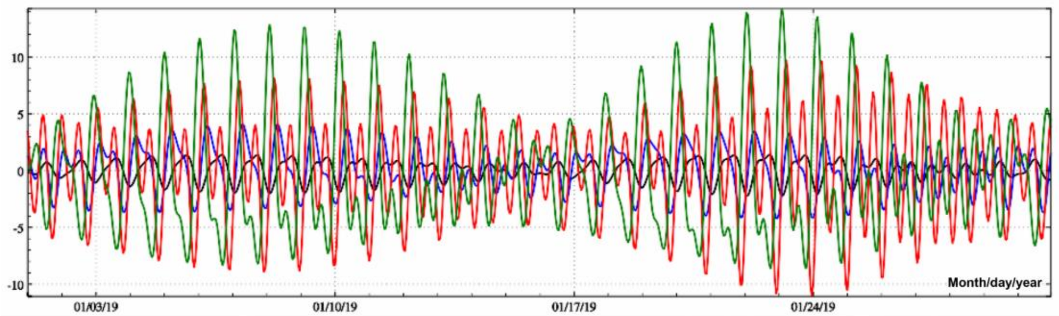


[Parameter settings] Set the input file format parameters, select the type of ocean tidal load effects.





The ocean tidal load effects at 450km altitude: geopotential (0.1m²/s²), gravity vector (E, N: along the GRACE orbit/SST-II, U, μGal)



The ocean tidal load effects at 250km altitude: geopotential (0.1m²/s²), gravity gradient (E, N: along the GOCE orbit, U, 10μE)

[Output file] The ocean tidal load effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, the geopotential and gravity vector are selected, and there are 4 attributes added to the record.

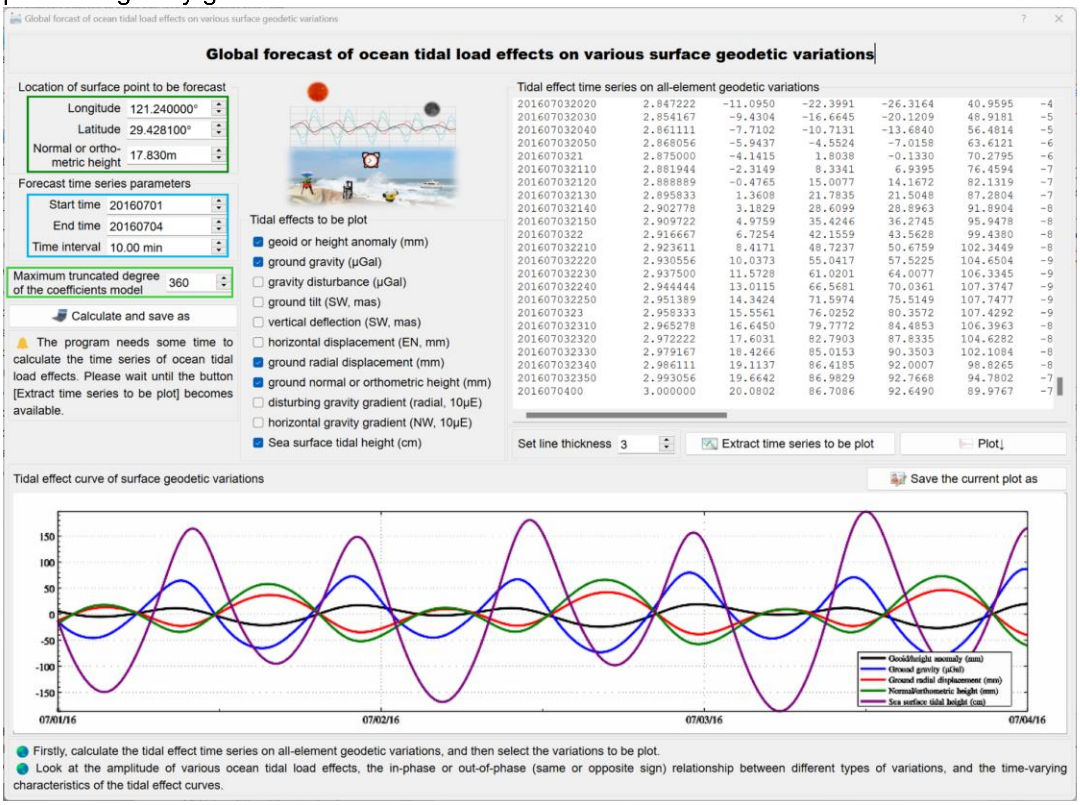
2.2.4 Global forecast of ocean tidal load effects on various surface geodetic variations

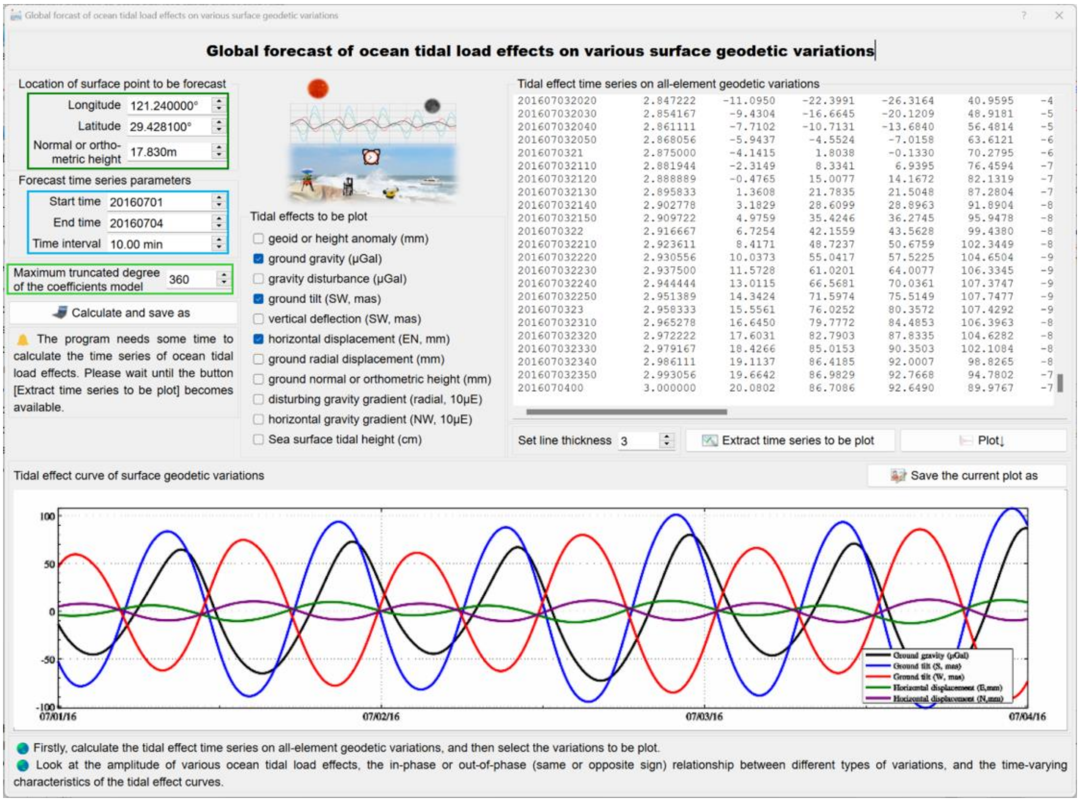
[Function] Input the geodetic coordinates of a global anywhere surface point and set the forecast time series parameters, calculate and display the ocean tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

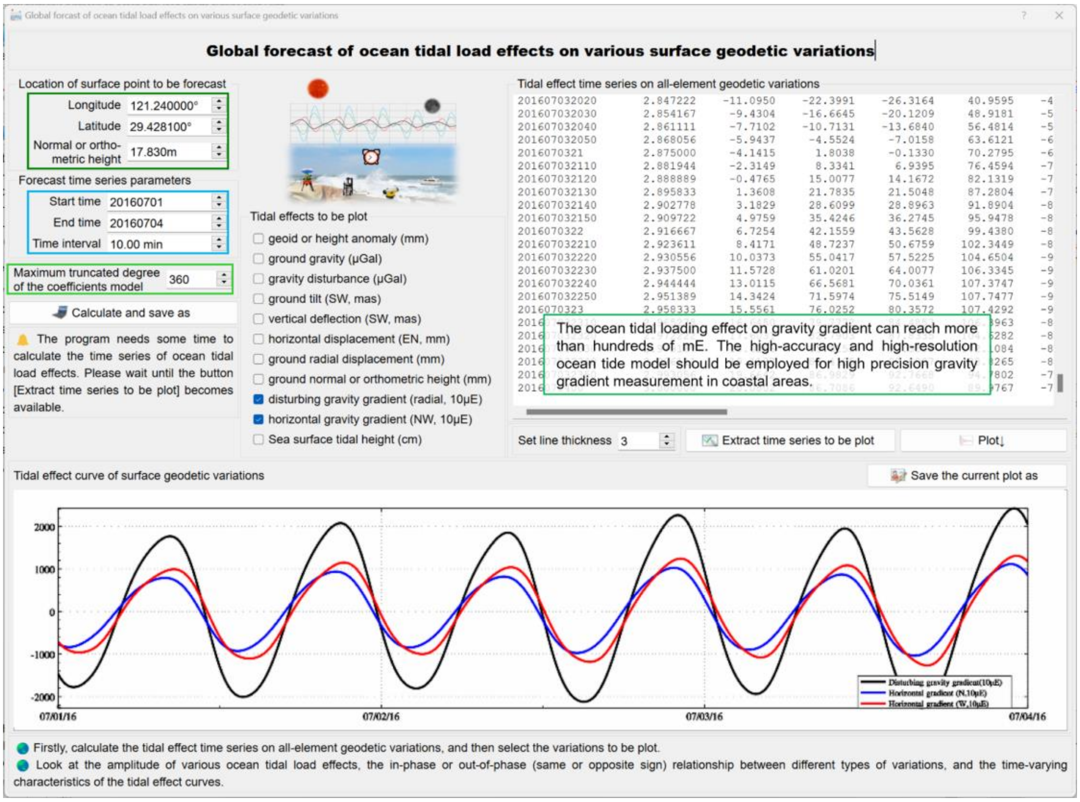
Firstly, calculate the tidal effect time series on all-element geodetic variations, and then select the variations to be plot.

Look at the amplitude of various solid tidal effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying characteristics of the tidal effect curves.

The ocean tidal loading effect on gravity gradient can reach more than hundreds of mE. The high-accuracy and high-resolution ocean tide model should be employed for high precision gravity gradient measurement in coastal areas.




Global forcast of ocean tidal load effects on various surface geodetic variations
Global forecast of ocean tidal load effects on various surface geodetic variations
Location of surface point to be forecast
Longitude 121.240000°
Latitude 29.428100°
Normal or ortho-metric height 17.830m
Forecast time series parameters
Start time 20160701
End time 20160704
Time interval 10.00 min
Maximum truncated degree of the coefficients model 360
Calculate and save as
The program needs some time to calculate the time series of ocean tidal load effects. Please wait until the button [Extract time series to be plot] becomes available.
Tidal effects to be plot
geoid or height anomaly (mm)
ground gravity (μGal)
gravity disturbance (μGal)
ground tilt (SW, mas)
vertical deflection (SW, mas)
horizontal displacement (EN, mm)
ground radial displacement (mm)
ground normal or orthometric height (mm)
disturbing gravity gradient (radial, 10μE)
horizontal gravity gradient (NW, 10μE)
Sea surface tidal height (cm)
Tidal effect time series on all-element geodetic variations
201607032020 2.847222 -11.0950 -22.3991 -26.3164 40.9595 -4
201607032030 2.854167 -9.4304 -16.6645 -20.1209 48.9181 -5
201607032040 2.861111 -7.7102 -10.7131 -13.6840 56.4814 -5
201607032050 2.868056 -5.9437 -4.5524 -7.0158 63.6121 -6
201607032l 2.875000 -4.1415 1.8038 -0.1330 70.2795 -6
201607032110 2.881944 -2.3149 8.3341 6.9395 76.4594 -7
201607032120 2.888889 -0.4765 15.0077 14.1672 82.1319 -7
201607032130 2.895833 1.3608 21.7835 21.5048 87.2804 -7
201607032140 2.902778 3.1829 28.6099 28.8963 91.8904 -8
201607032150 2.909722 4.9759 35.4246 36.2745 95.9478 -8
201607032 2 2.916667 6.7254 42.1559 43.5628 99.4380 -8
201607032210 2.923611 8.4171 48.7237 50.6759 102.3449 -8
201607032220 2.930556 10.0373 55.0417 57.5225 104.6504 -9
201607032230 2.937500 11.5728 61.0201 64.0077 106.3345 -9
201607032240 2.944444 13.0115 66.5681 70.0361 107.3747 -9
201607032250 2.951389 14.3424 71.5974 75.5149 107.7477 -9
2016070323 2.958333 15.5561 76.0252 80.3572 107.4292 -9
201607032310 2.965278 16.6450 79.7772 84.4853 106.3963 -8
201607032320 2.972222 17.6031 82.7903 87.8335 104.6282 -8
201607032330 2.979167 18.4266 85.0153 90.3503 102.1084 -8
201607032340 2.986111 19.1137 86.4185 92.0007 98.8265 -8
201607032350 2.993056 19.6642 86.9829 92.7668 94.7802 -7
2016070400 3.000000 20.0802 86.7086 92.6490 89.9767 -7
Set line thickness 3
Extract time series to be plot
Plot
Tidal effect curve of surface geodetic variations
Save the current plot as
100
50
0
-50
-100
07/01/16
07/02/16
07/03/16
07/04/16
Ground gravity (μGal)
Ground tilt (S, mas)
Ground tilt (W, mas)
Horizontal displacement (E,mm)
Horizontal displacement (N,mm)
Firstly, calculate the tidal effect time series on all-element geodetic variations, and then select the variations to be plot.
Look at the amplitude of various ocean tidal load effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying characteristics of the tidal effect curves.


Global forecast of ocean tidal load effects on various surface geodetic variations
Location of surface point to be forecast
Longitude 121.240000°
Latitude 29.428100°
Normal or ortho-metric height 17.830m
Forecast time series parameters
Start time 20160701
End time 20160704
Time interval 10.00 min
Maximum truncated degree of the coefficients model 360
Calculate and save as
The program needs some time to calculate the time series of ocean tidal load effects. Please wait until the button [Extract time series to be plot] becomes available.
Tidal effects to be plot
geoid or height anomaly (mm)
ground gravity (μGal)
gravity disturbance (μGal)
ground tilt (SW, mas)
vertical deflection (SW, mas)
horizontal displacement (EN, mm)
ground radial displacement (mm)
ground normal or orthometric height (mm)
disturbing gravity gradient (radial, 10μE)
horizontal gravity gradient (NW, 10μE)
Sea surface tidal height (cm)
Tidal effect time series on all-element geodetic variations
The ocean tidal loading effect on gravity gradient can reach more than hundreds of mE. The high-accuracy and high-resolution ocean tide model should be employed for high precision gravity gradient measurement in coastal areas.
Set line thickness 3
Extract time series to be plot
Plot
Tidal effect curve of surface geodetic variations
Save the current plot as
2000
1000
0
-1000
-2000
07/01/16
07/02/16
07/03/16
07/04/16
Disturbing gravity gradient(10μE)
Horizontal gradient (N,10μE)
Horizontal gradient (W,10μE)
Firstly, calculate the tidal effect time series on all-element geodetic variations, and then select the variations to be plot.
Look at the amplitude of various ocean tidal load effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying characteristics of the tidal effect curves.

2.3 Spherical harmonic synthesis on surface atmosphere tidal load effects outside solid Earth

[Purpose] Using the global surface atmosphere tidal load spherical harmonic coefficient model (hPa/mbar), compute the surface atmosphere tidal load effects on various geodetic variations on the ground or outside the solid Earth according to the location and time in the input file by the spherical harmonic synthesis algorithm. Here the point outside the solid Earth generally refers to the space point that is not fixed to the Earth in ocean space, near-Earth space, or satellite altitude.

The program adopts the 360-degree surface atmosphere tidal spherical harmonic coefficient model ECMWF2006.dat, which contains semi-diurnal, diurnal, semi-annual, and annual period constituents. Using this model to compute the surface atmosphere tidal load effects, even if the non-tidal atmosphere load effects are not considered, the surface atmosphere load effects on the geodetic observations or parameters can be controlled to the accuracy level of 1cm.

2.3.1 Computation of surface atmosphere tidal load effect time series at a ground site

[Function] From a geodetic site variation time series file, compute the time series of the surface atmosphere tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The geodetic site variation time series file.

The file header contains site name, longitude (degree decimal), latitude (degree decimal), height (m), starting MJD0 (optional), …

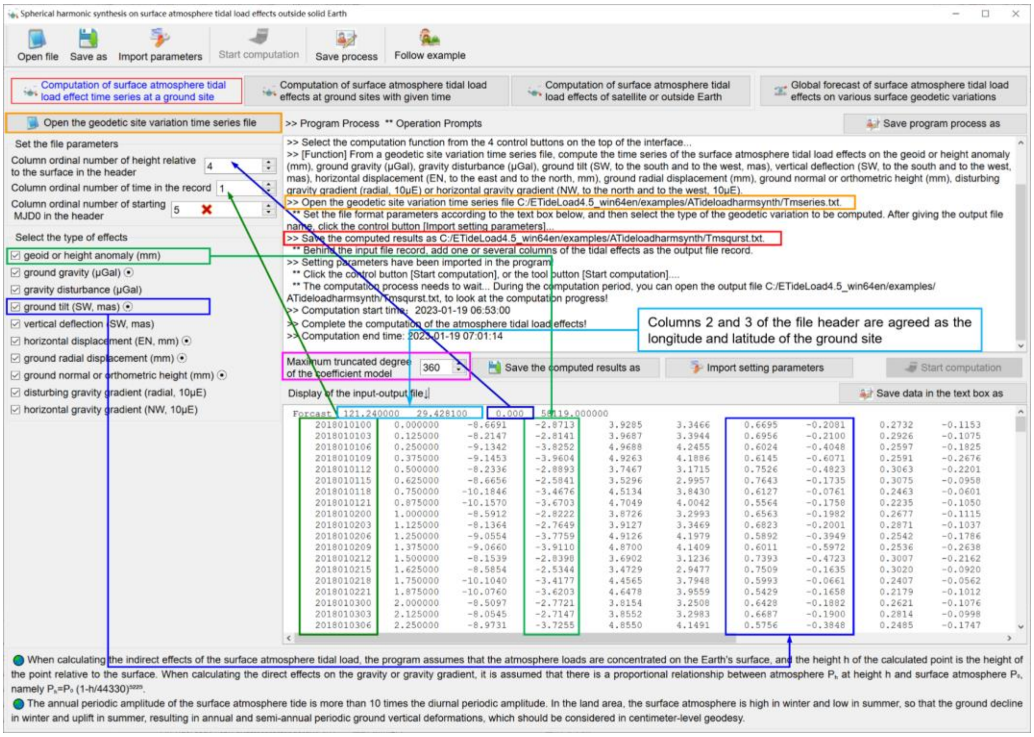
Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.

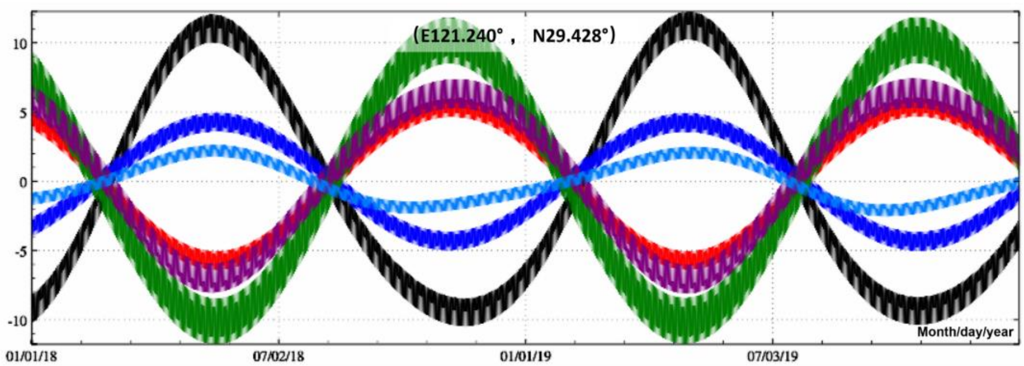
[Parameter settings] Set the input file format parameters, select the type of the surface atmosphere tidal load effects.

[Output file] The geodetic site surface atmosphere tidal load effect time series file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

When calculating the indirect effects of the surface atmosphere tidal load, the program assumes that the atmosphere loads are concentrated on the Earth’s surface, and the height h of the calculation point is the height of the point relative to the surface. When calculating the direct effects on the gravity or gravity gradient, it is assumed that there is a proportional relationship between atmosphere P_h at height h and surface atmosphere P_0, namely $P_h=P_0(1-h/44330)^{5225}$.





The Surface atmosphere tidal load effects (360-degree) : surface atmosphere(hPa/mbar) height anomaly (mm) ground gravity (μGal) orthometric height (mm) gravity gradient (radial 10μE) horizontal displacement (N, 10μE)

The annual periodic amplitude of the surface atmosphere tide is more than 10 times the diurnal periodic amplitude. In the land area, the surface atmosphere is high in winter and low in summer, so that the ground decline in winter and uplift in summer, resulting in annual and semi-annual periodic ground vertical deformations, which should be considered in centimeter-level geodesy.

The surface atmosphere tidal load effects on the east-west component of the site displacement, tilt or horizontal gradient are generally smaller than that on the north-south component.

2.3.2 Computation of surface atmosphere tidal load effects at ground sites with given time

[Function] According to the location and time in the calculation point file, compute the surface atmosphere tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

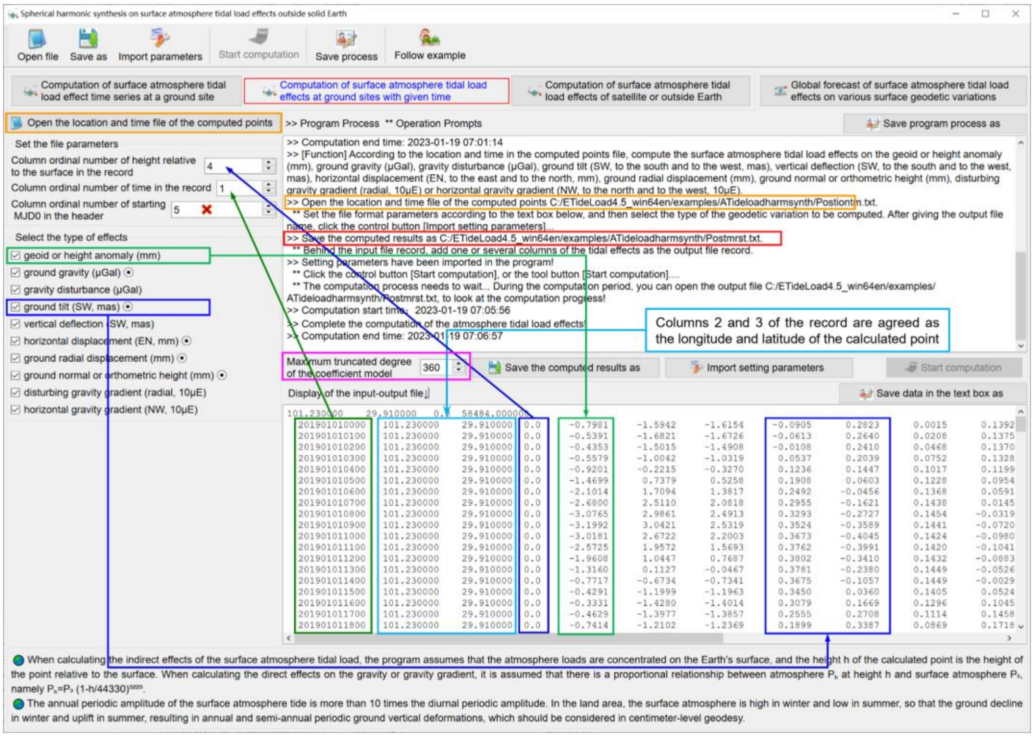
[Input file] The location and time file of the calculation points.

The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and height attributes in the records.

[Parameter settings] Set the input file format parameters, select the type of atmosphere tidal load effects.

[Output file] The surface atmosphere tidal load effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.



The global surface atmosphere tidal load spherical harmonic coefficient model (hPa) adopts the FES2004 format, which can be constructed from the global surface atmosphere harmonic parameters grid model by calling the function [Global tidal parameters spherical harmonic analysis]. In the program [geophysical model and numerical standard settings], you can select the other global spherical harmonic coefficient model of the surface atmosphere tidal load.

2.3.3 Computation of surface atmosphere tidal load effects of satellite or outside Earth

[Function] According to the location and time in the external point file, compute the surface atmosphere tidal load effects on the geopotential (0.1m²/s²), gravity(μGal), or gravity gradient (10μE) outside the solid Earth.

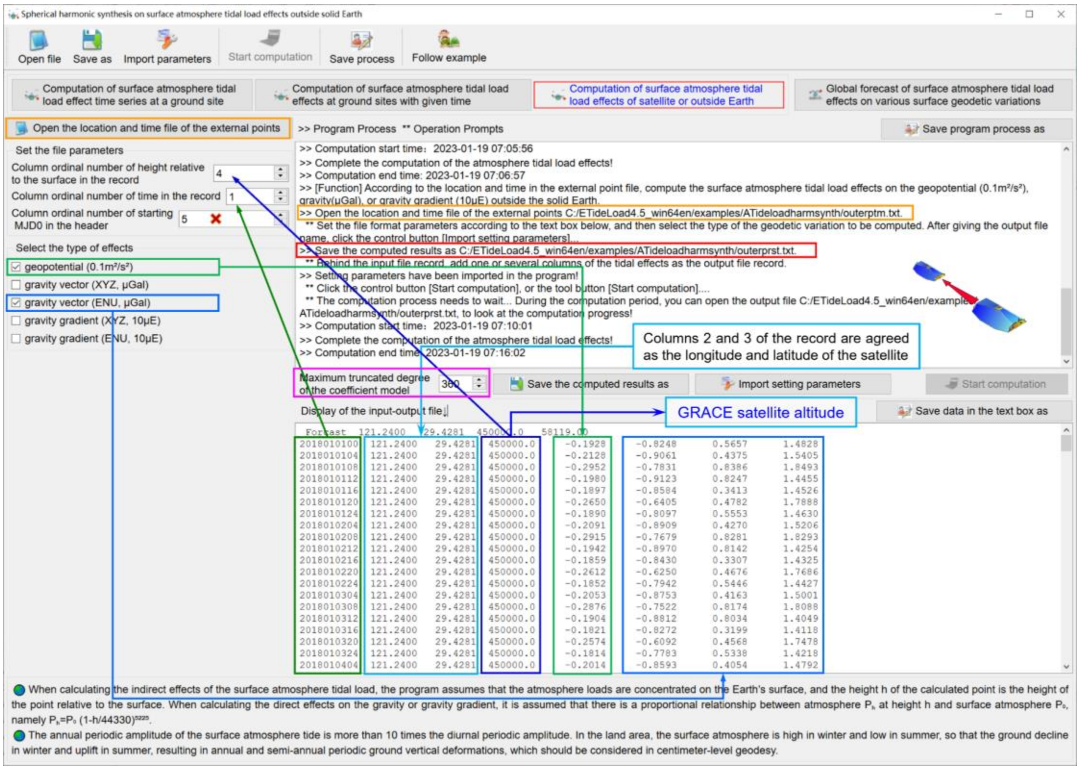
[Input file] The location and time file of the external points.

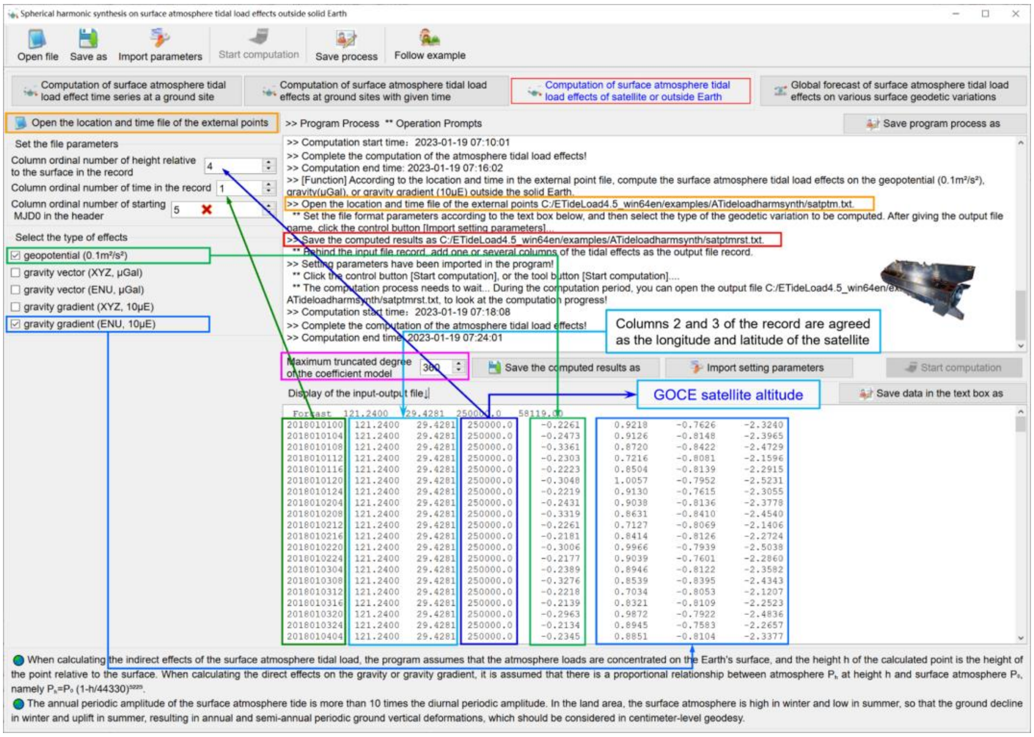
The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and height attributes in the records.

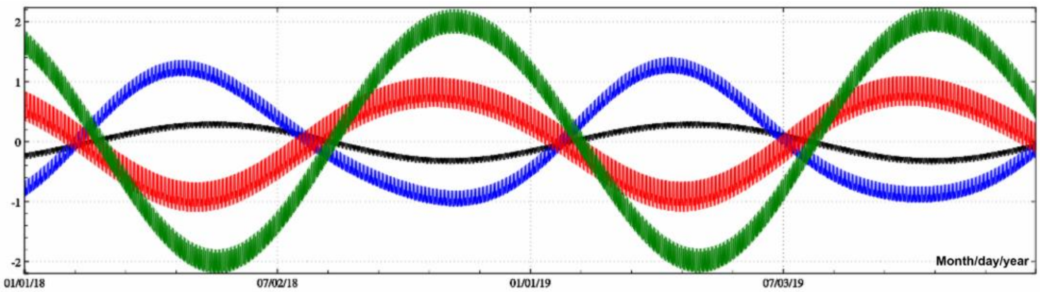
[Parameter settings] Set the input file format parameters, select the type of ocean tidal load effects.

[Output file] The surface atmosphere tidal load effect file.

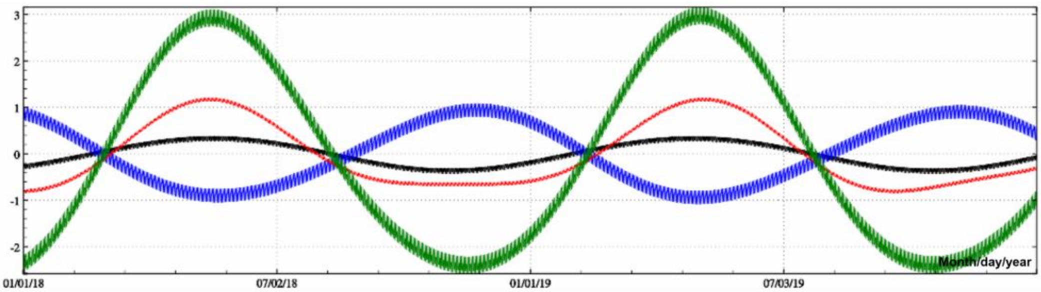
The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, the geopotential and gravity vector are selected, and there are 4 attributes added to the record.







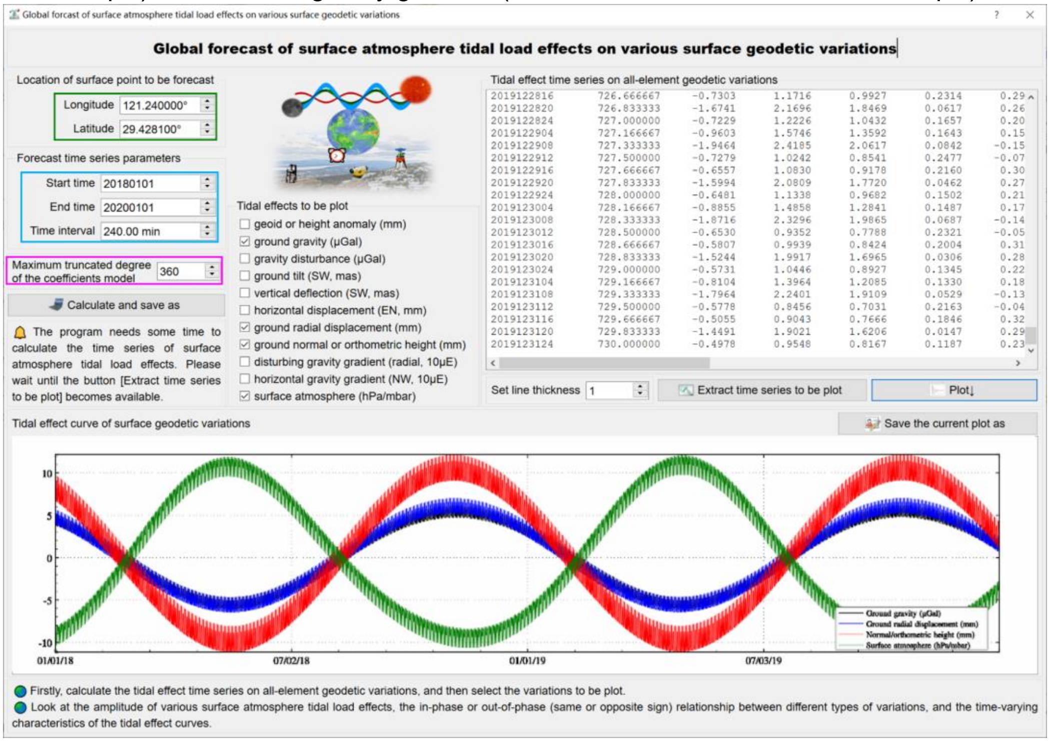
The surface atmosphere tidal effects at 450km altitude：geopotential (0.1m²/s²), gravity vector (E, N: along the GRACE orbit/SST-II, U, μGal)

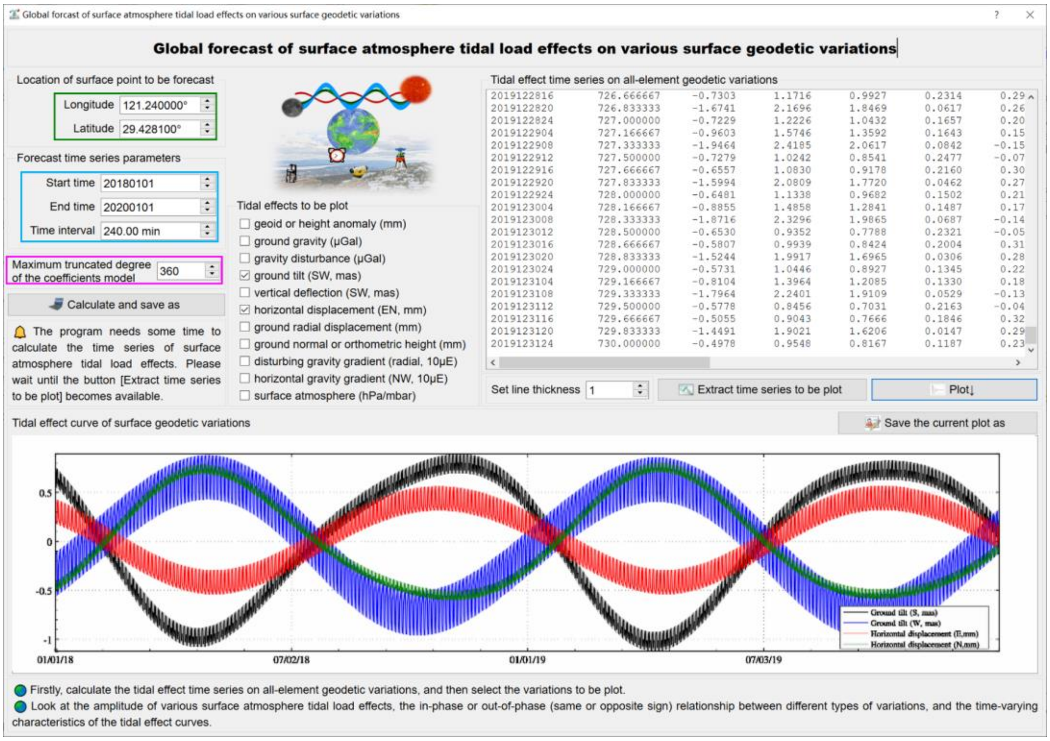


The surface atmosphere tidal effects at 250km altitude：geopotential (0.1m²/s²), gravity gradient (E, N: along the GOCE orbit, U, 10μE)

2.3.4 Global forecast of surface atmosphere tidal load effects on various surface geodetic variations

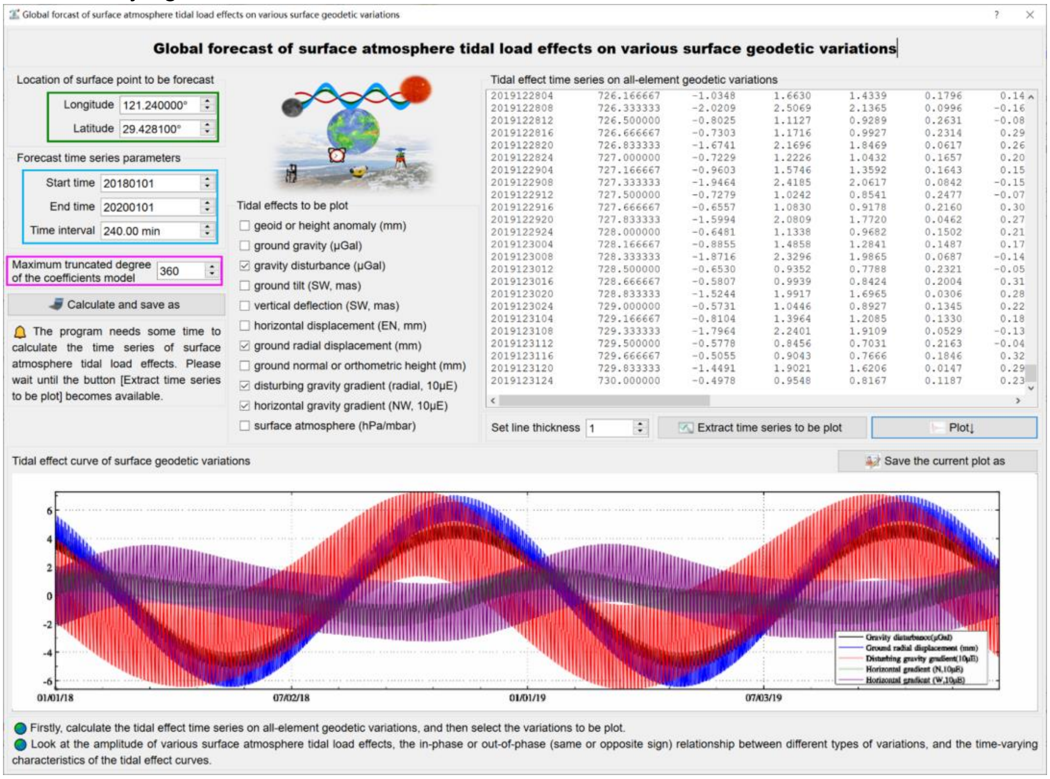
[Function] Input the geodetic coordinates of a surface point and set the forecast time series parameters, calculate and display the surface atmosphere tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).





Firstly, calculate the tidal effect time series on all-element geodetic variations, and then select the variations to be plot.

Look at the amplitude of various surface atmosphere tidal load effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying law of the tidal effect curves.



2.4 Computation of Earth pole shift and ocean pole tidal effects outside solid Earth

[Purpose] Using IERS Earth orientation parameters (EOP) product file IERSeopc04.dat, compute the Earth pole shift and ocean pole tidal effects on various geodetic variations on the ground or outside the solid Earth according to the location and time in the input file.

2.4.1 Computation of pole shift or ocean pole tidal effect time series at a ground site

[Function] From the geodetic site variation time series file, compute the time series of the Earth pole shift or ocean pole tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The geodetic site variation time series file.

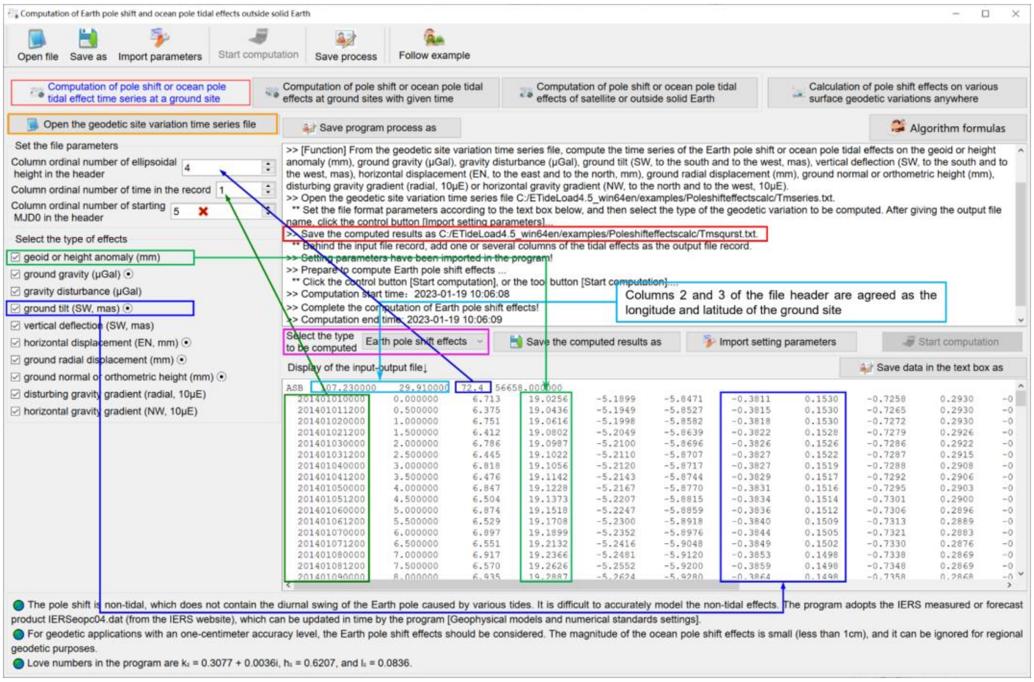
The file header contains site name, longitude (degree decimal), latitude (degree decimal), ellipsoidal height (m), starting MJD0 (optional), …

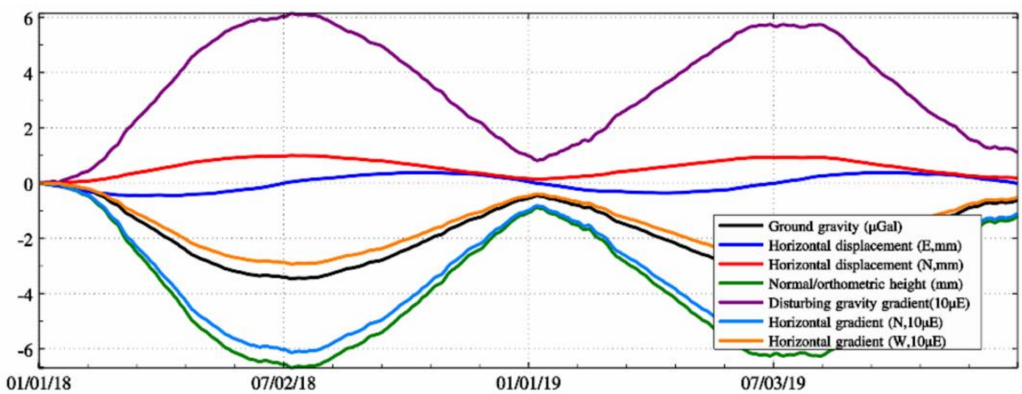
Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.

[Parameter settings] Set the input file format parameters, select the type of the pole shift or ocean pole tidal effects.

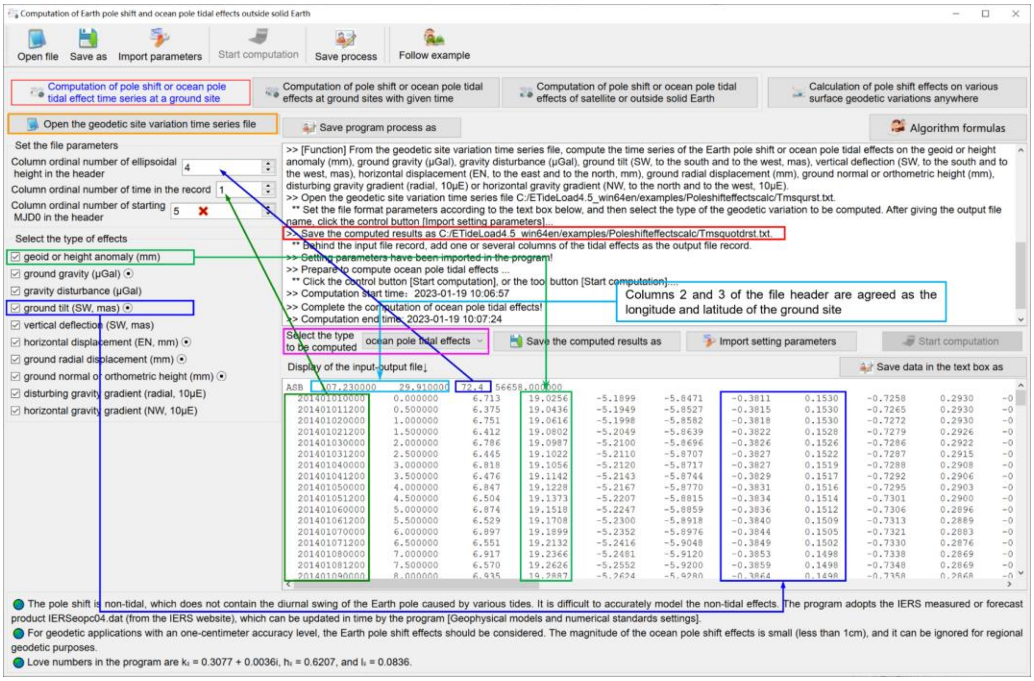
[Output file] The geodetic site Earth or ocean pole-shift effect time series file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.





The effects of the non-tidal pole shift on the ground site (E121.240°, N29.482°, H17.83m)



Love numbers in the program are k_2 = 0.3077 + 0.0036i, h_2 = 0.6207, and l_2 = 0.0836.

If the epoch time to be calculated exceeds the time range of the Earth orientation parameter time series file, please update the parameter time series file.

2.4.2 Computation of pole shift or ocean pole tidal effects at ground sites with given time

[Function] According to the location and time in the calculation point file, compute the Earth pole shift or ocean pole tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

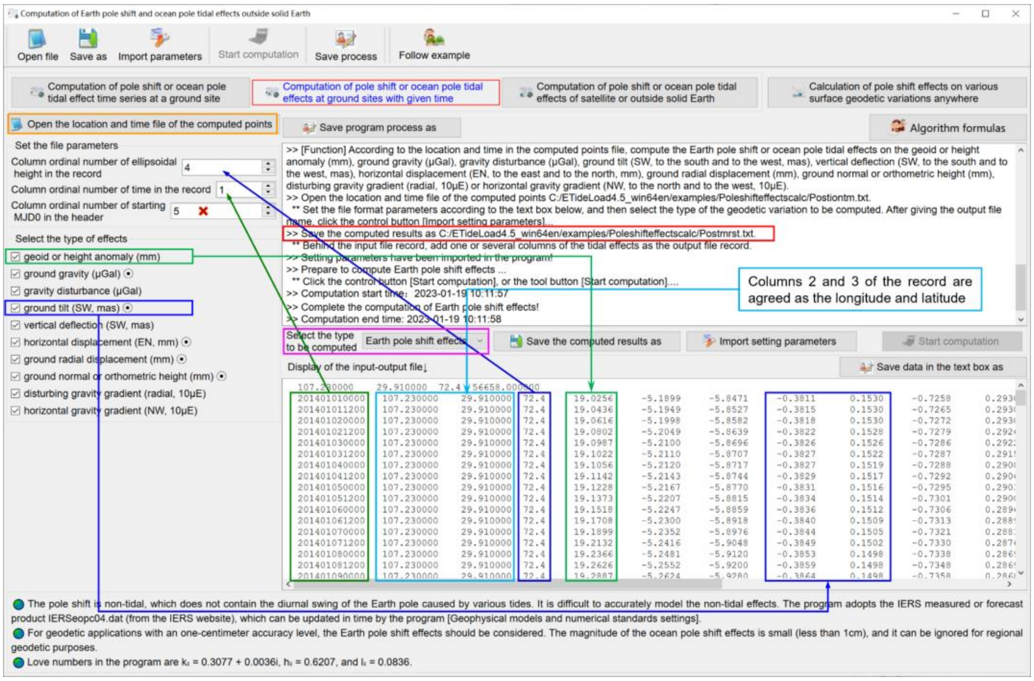
[Input file] The location and time file of the calculation points.

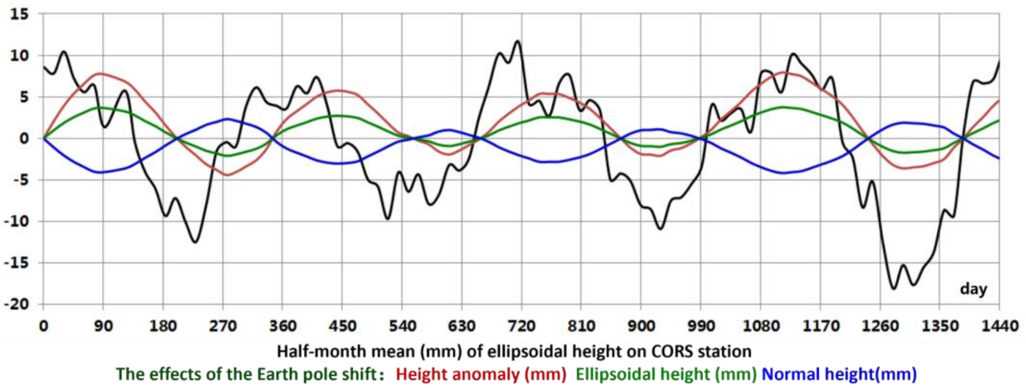
The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

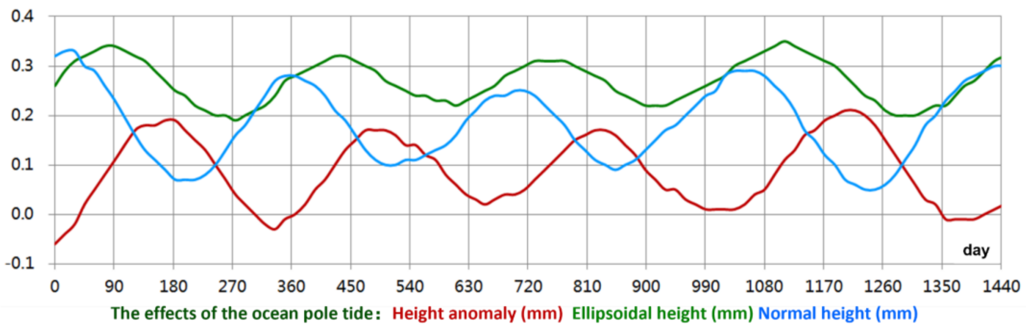
[Parameter settings] Set the input file format parameters, and select the type of the effects.

[Output file] The Earth pole shift or ocean pole tidal effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the Earth pole shift or ocean pole tidal effects selected as the output file record. In this example, select to compute the Earth pole shift effects, and the height anomaly, gravity disturbance, ground radial displacement and ground normal or orthometric height are selected, and there are 4 attributes added to the record.







2.4.3 Computation of pole shift or ocean pole tidal effects of satellite or outside solid Earth

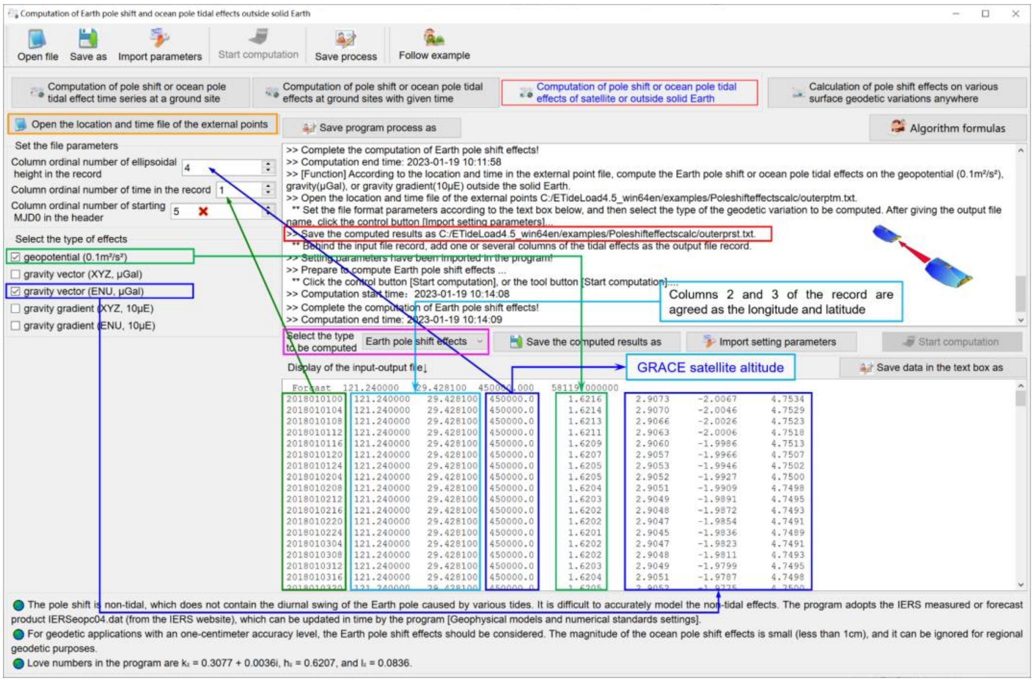
[Function] According to the location and time in the external point file, compute the Earth pole shift or ocean pole tidal effects on the geopotential (0.1m²/s²), gravity(μGal), or gravity gradient(10μE) outside the solid Earth.

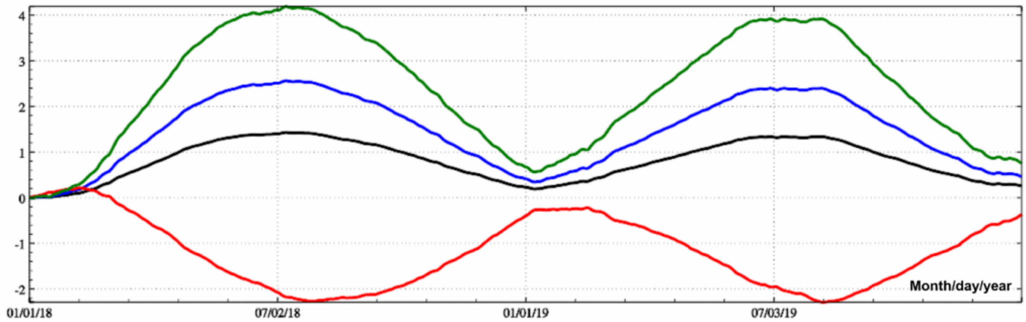
[Input file] The location and time file of the external points.

The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

[Parameter settings] Set the input file format parameters and select the type of the effects.

[Output file] The Earth pole shift or ocean pole tidal effect file.

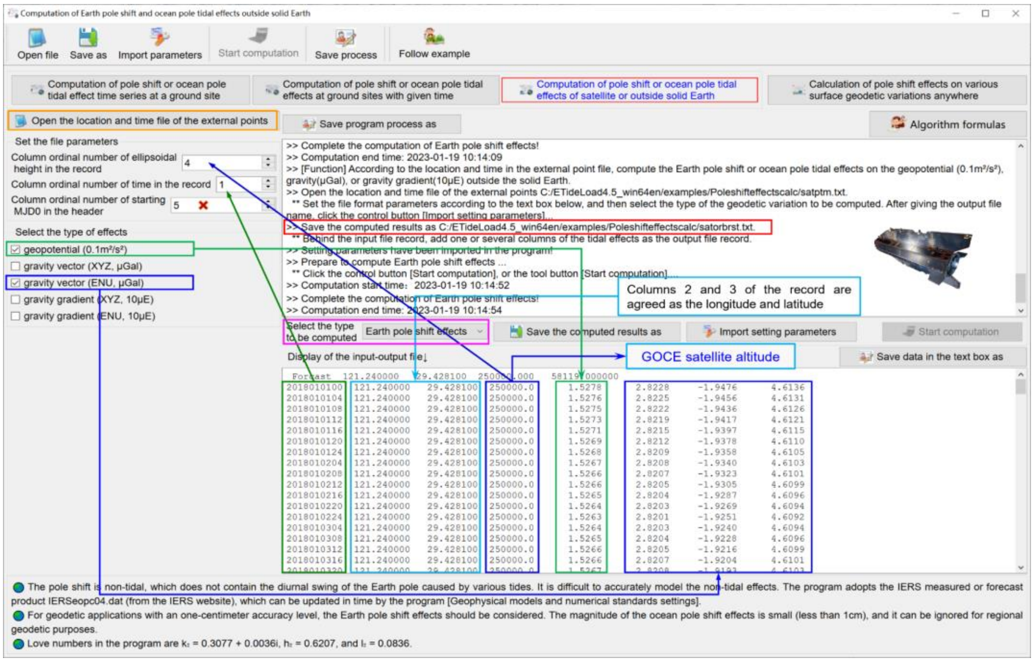


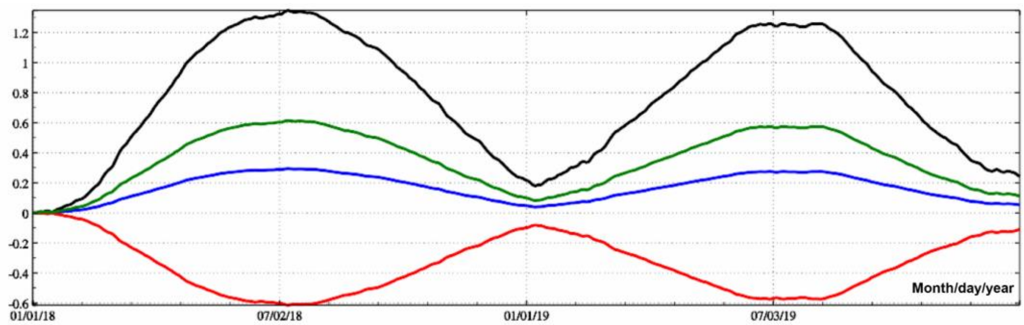


The non-tidal pole shift effects at 450km altitude: geopotential (0.1m²/s²), gravity vector (E, N: along the GRACE orbit/SST-II, U, μGal)

For geodetic applications with an one-centimeter accuracy level, the Earth pole shift effects should be considered. The magnitude of the ocean pole shift effects is small (less than 1cm), and it can be ignored for regional geodetic purposes.

The pole shift is non-tidal, which does not contain the diurnal swing of the Earth pole caused by various tides. It is difficult to accurately model the non-tidal effects. The program adopts the IERS measured or forecast product IERSeopc04.dat (which can be downloaded directly from the IERS website), which can be updated in time by the program [Geophysical models and numerical standards settings].



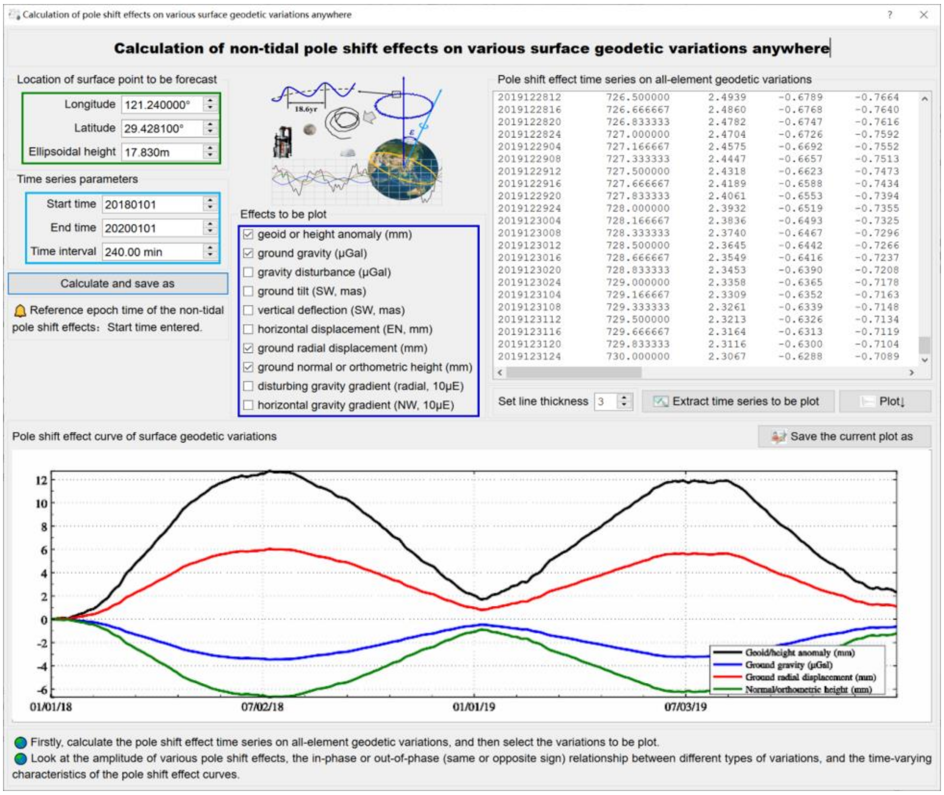


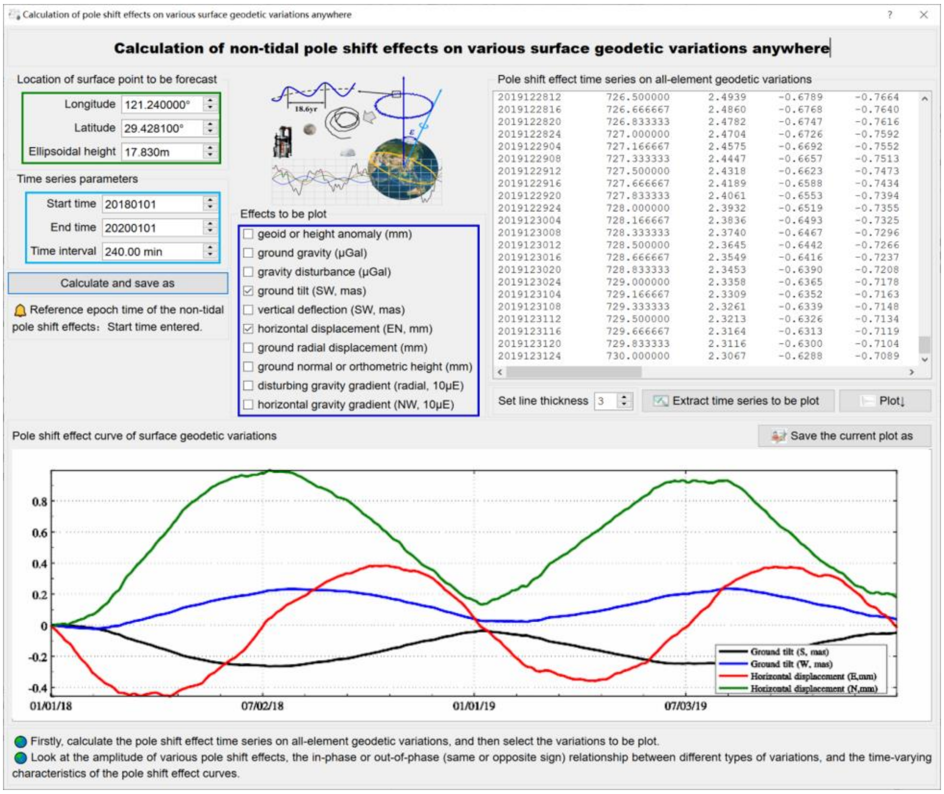
The non-tidal pole shift effects at 250km altitude：geopotential (0.1m²/s²), gravity gradient (E, N: along the GOCE orbit, U, 10μE)

2.4.4 Calculation of pole shift effects on various surface geodetic variations anywhere

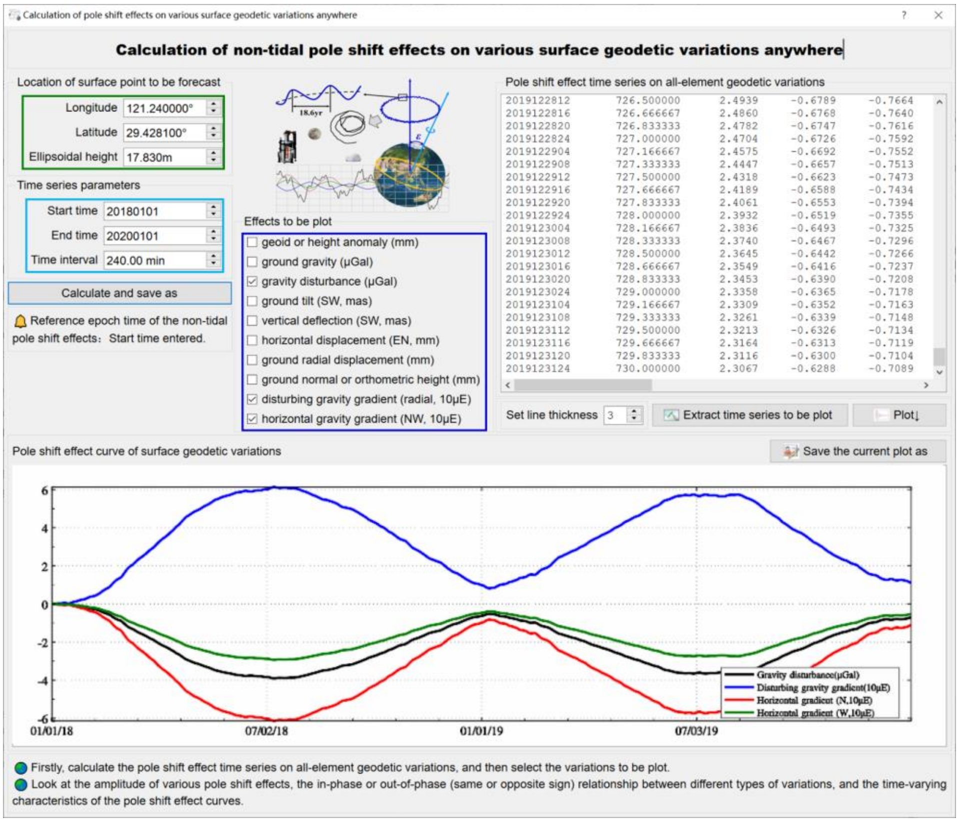
[Function] Input the geodetic coordinates of a global anywhere surface point and set the time series parameters, calculate and display the pole shift effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

Firstly, calculate the pole shift effect time series on all-element geodetic variations, and then select the variations to be plot.





Look at the amplitude of various pole shift effects, the in-phase or out-of-phase (same or opposite sign) relationship between different types of variations, and the time-varying characteristics of the pole shift effect curves.



2.5 Computation of permanent tidal effects and correction of Earth's mass center

[Purpose] Compute the permanent tidal effects on various geodetic variations and the geocentric correction for the coordinates of the ground site.

When calculating the permanent tidal effects, input the geodetic discrete point record file, and when calculating the center of mass correction, input the ground site coordinate file with the epoch time.

2.5.1 Computation of permanent tidal effects on various geodetic variations

[Function] According to the location in the point record file, compute the permanent tidal effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE).

[Input file] The geodetic point record file.

Multi-row file headers are allowed with unlimited content and format.

A row of record stands for geodetic data for a site. Attributes for each record include site number (name), longitude (degree decimal), latitude (degree decimal), …. There is an ellipsoid height attribute in the record.

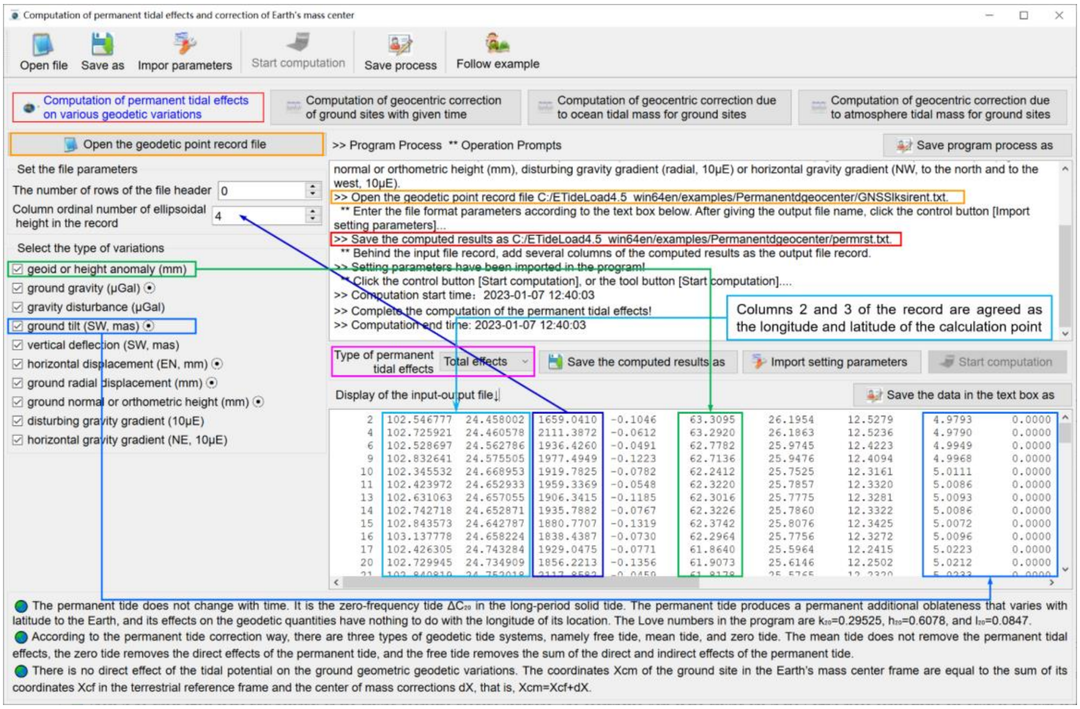
[Parameter settings] Set the input file format parameters, select the type of permanent tidal effects.

[Output file] The permanent tidal effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the permanent tidal effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

The permanent tide does not change with time. It is the zero-frequency tide ΔC_{20} in the long-period solid tide. The permanent tide produces a permanent additional oblateness that varies with latitude to the Earth, and its effects on the geodetic variations have nothing to do with the longitude of its location.

The Love numbers in the program are k_{20}=0.29525, h_{20}=0.6078, and l_{20}=0.0847.



According to the permanent tide correction way, there are three types of geodetic tide systems, namely free tide, mean tide, and zero tide. The mean tide does not remove the permanent tidal effects, the zero tide removes the direct effects of the permanent tide, and the free tide removes the sum of the direct and indirect effects of the permanent tide.

There is no direct effect of the tidal potential on the ground geometric geodetic variations. Therefore, the zero-tide geometric geodetic variations are equal to the mean tide geometric geodetic variations.

2.5.2 Computation of geocentric correction of ground sites with given time

[Function] According to the location and time in the ground site record file, compute the correction (ENU, mm) of Earth center of mass for the coordinates of the ground site using the SLR geocentric motion measurement or prediction parameter time series.

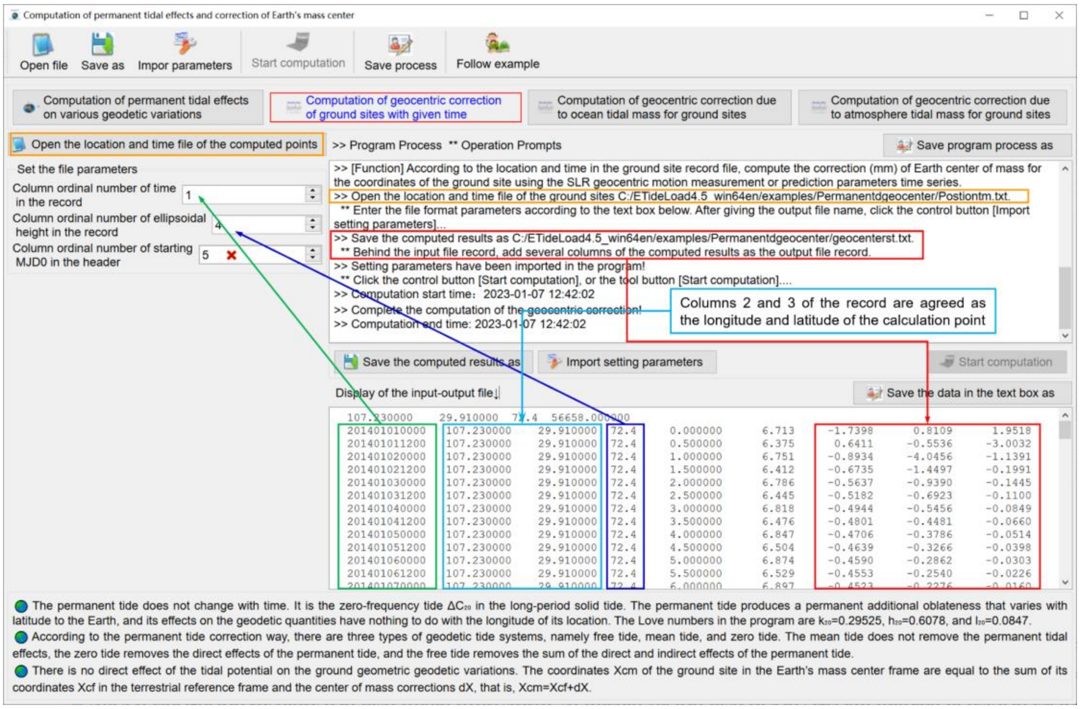
[Input file] The location and time file of the calculation points.

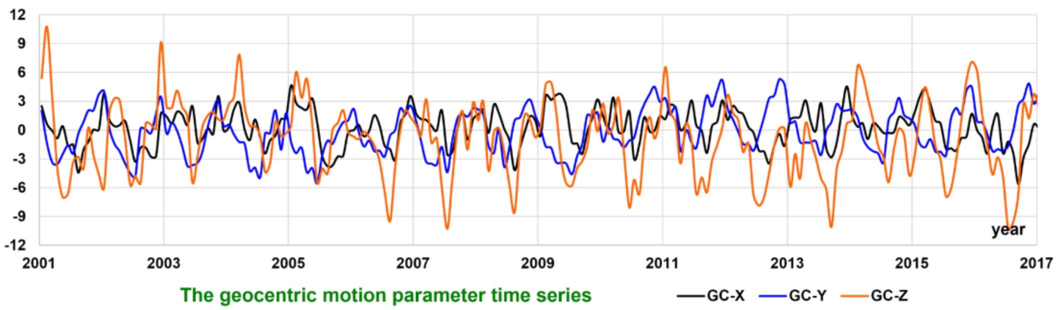
The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and ellipsoidal height attributes in the records.

[Parameter settings] Set the input file format parameters.

[Output file] The correction of Earth center of mass file.

The file header is the same as the input file. Behind the input file record, add 3 columns of the correction of Earth center of mass as the output file record.





The geocentric motion parameter time series

Geocentric motion is non-tidal, which can be represented by the degree 1 geopotential coefficient variations (ΔC_{10}, ΔC_{11}, ΔS_{11}). Physical geodetic observations do not contain geocentric motion information, and the corrections of the center of mass are only for the coordinates of the ground site.

The coordinates Xcm of the ground site in the Earth's mass center frame are equal to the sum of its coordinates Xcf in the terrestrial reference frame and the center of mass corrections dX, that is, Xcm=Xcf+dX.

If the epoch time to be calculated exceeds the time range of the SLR geocentric motion parameter time series, please update the parameter time series file.

2.5.3 Computation of geocentric correction due to ocean tidal mass for ground sites

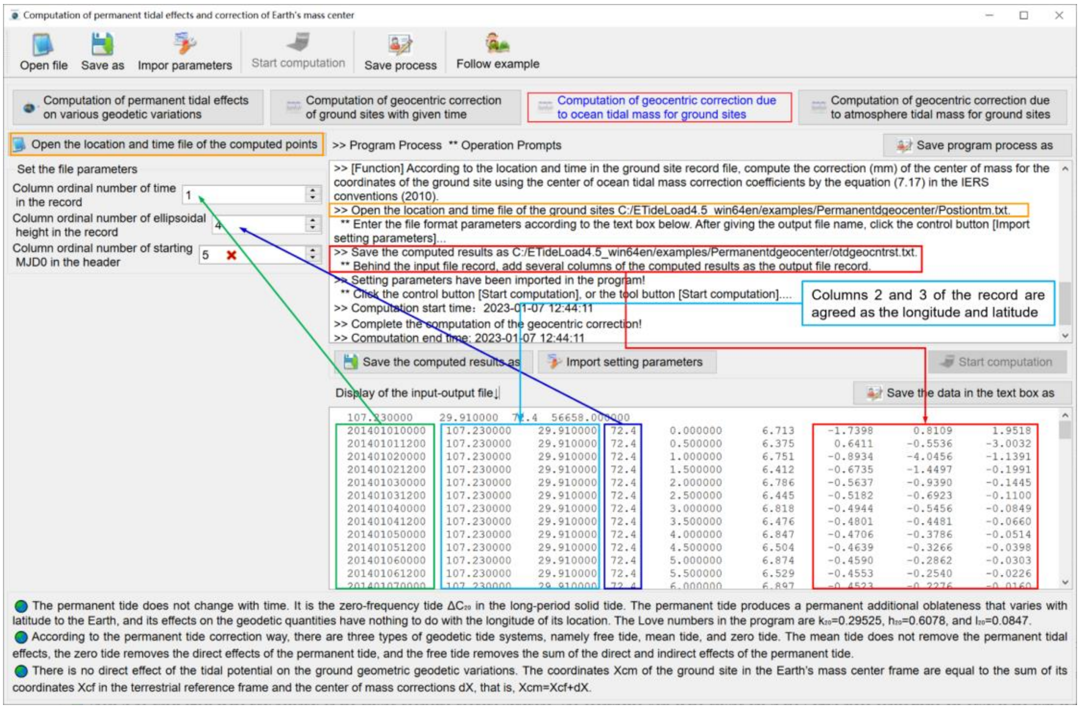
[Function] According to the location and time in the ground site record file, compute the correction (ENU, mm) of the center of mass for the coordinates of the ground site using the center of ocean tidal mass correction coefficients by the equation (7.17) in the IERS conventions (2010).

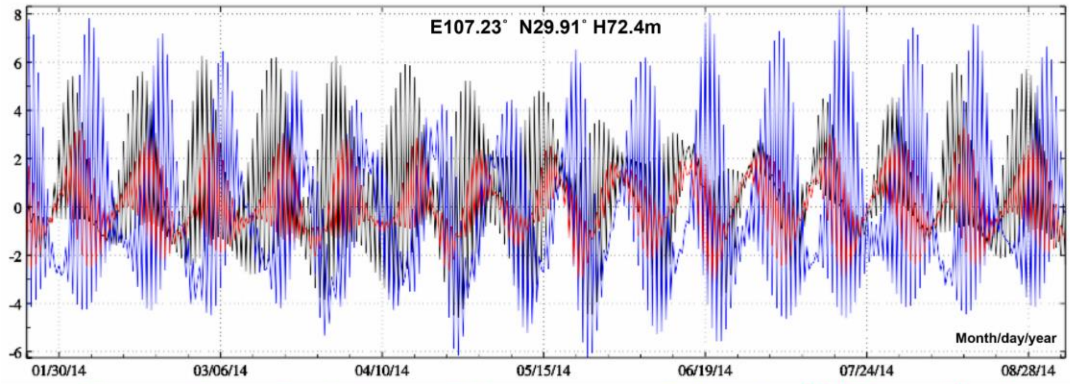
[Input file] The location and time file of the calculation points. The Desai ocean pole tide coefficient file (automatically called by the program without manual input, can be updated from the program [geophysical models and numerical standards settings]).

[Parameter settings] Set the input file format parameters.

[Output file] The geocentric correction due to ocean tidal mass file.

The file header is the same as the input file. Behind the input file record, add 3 columns of the geocentric correction due to ocean tidal mass as the output file record.





The geocentric correction due to ocean tidal mass: East (mm), North (mm), radial displacement (mm)

2.5.4 Computation of geocentric correction due to atmosphere tidal mass for ground sites

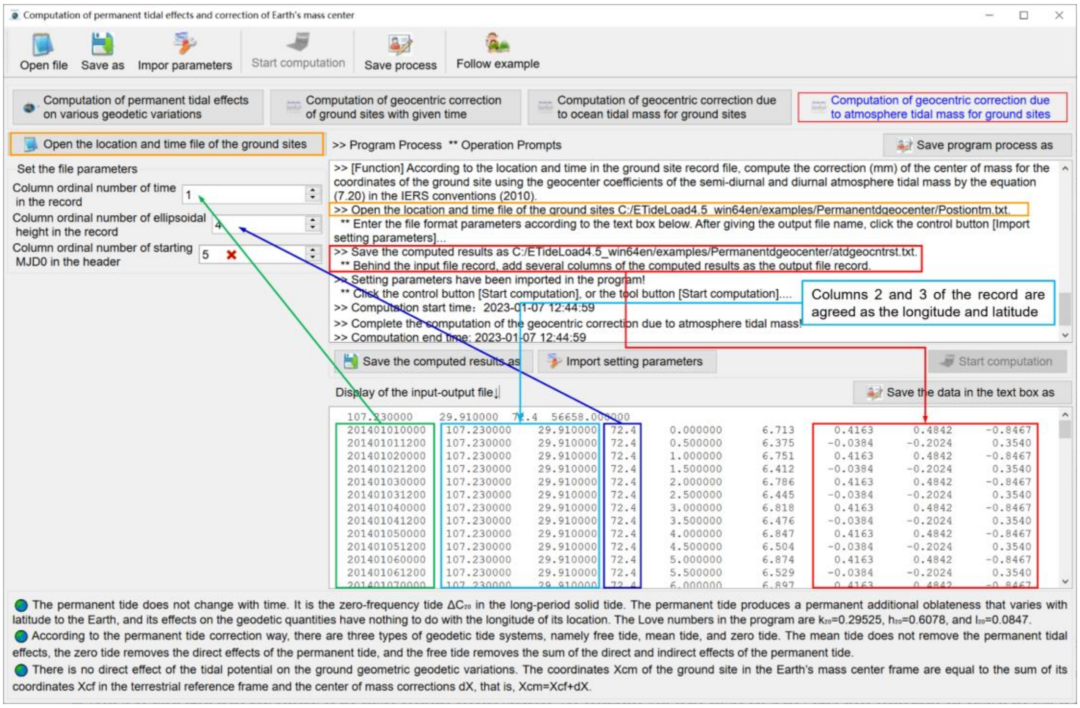
[Function] According to the location and time in the ground site record file, compute the correction (mm) of the center of mass for the coordinates of the ground site using the geocenter coefficients of the semi-diurnal and diurnal atmosphere tidal mass by the equation (7.20) in the IERS conventions (2010).

[Input file] The location and time file of the calculation points.

[Parameter settings] Set the input file format parameters.

[Output file] The geocentric correction due to atmosphere tidal mass file.

The file header is the same as the input file. Behind the input file record, add 3 columns of the geocentric correction due to atmosphere tidal mass as the output file record.



2.6 Computation of solid Earth and load tidal effects on geodetic networks

[Purpose] Compute the solid Earth, ocean tidal load, or atmosphere load tidal effects on the GNSS baseline or level height difference according to the location and observation time in the input geodetic control network record file.

[Input file] The geodetic network observation record file.

The first row is the file header. The record format: the GNSS baseline or leveling route name, starting point longitude, latitude, height, ending point longitude, latitude, height, …, observation time, ….

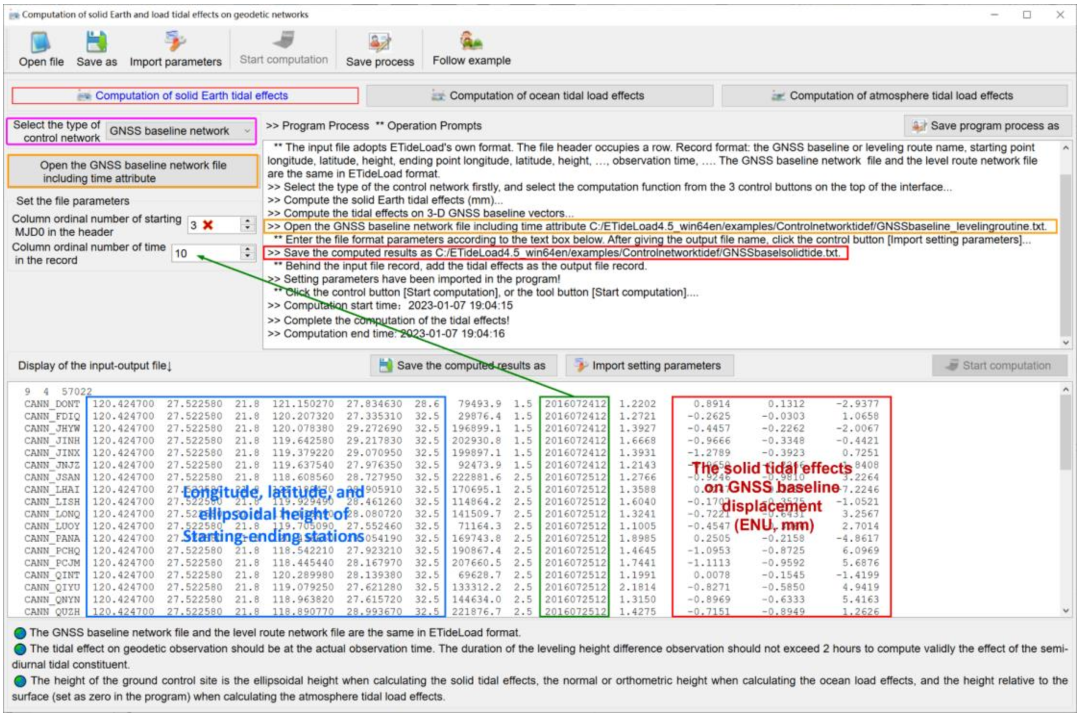
The column ordinal number of the time attribute should not be less than 8.

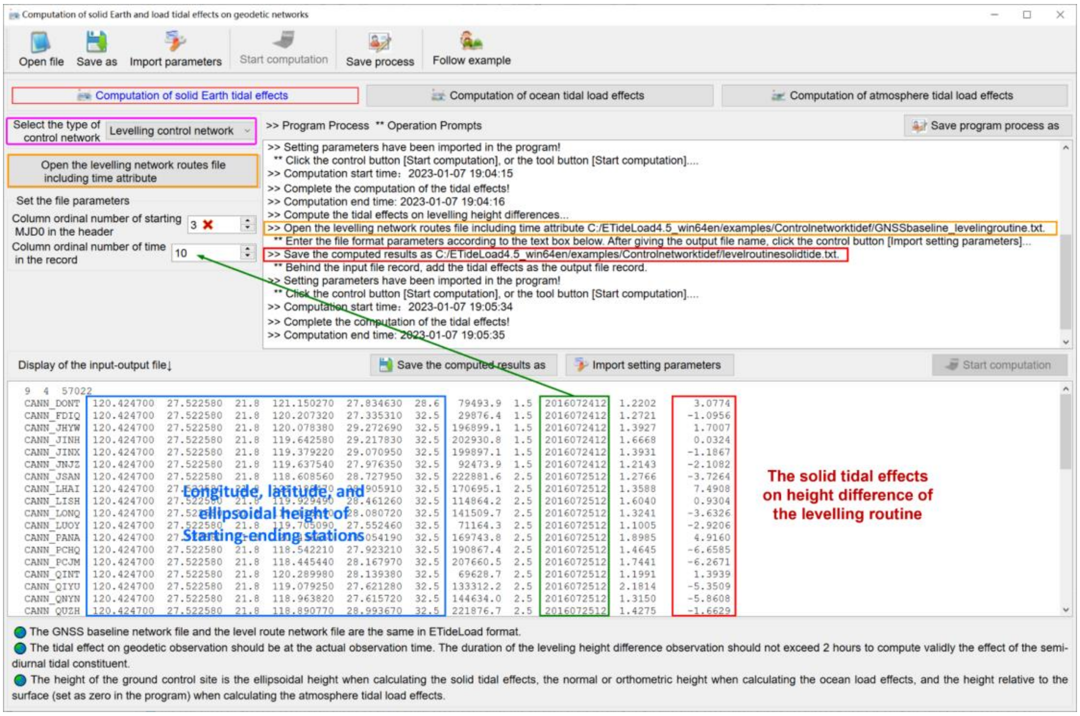
The GNSS baseline network file and the level route network file are the same in ETideLoad format.

[Parameter settings] Select the type of geodetic control network, set the input file format parameters, and enter maximum truncated degree of the coefficient model when computing the tidal load effects.

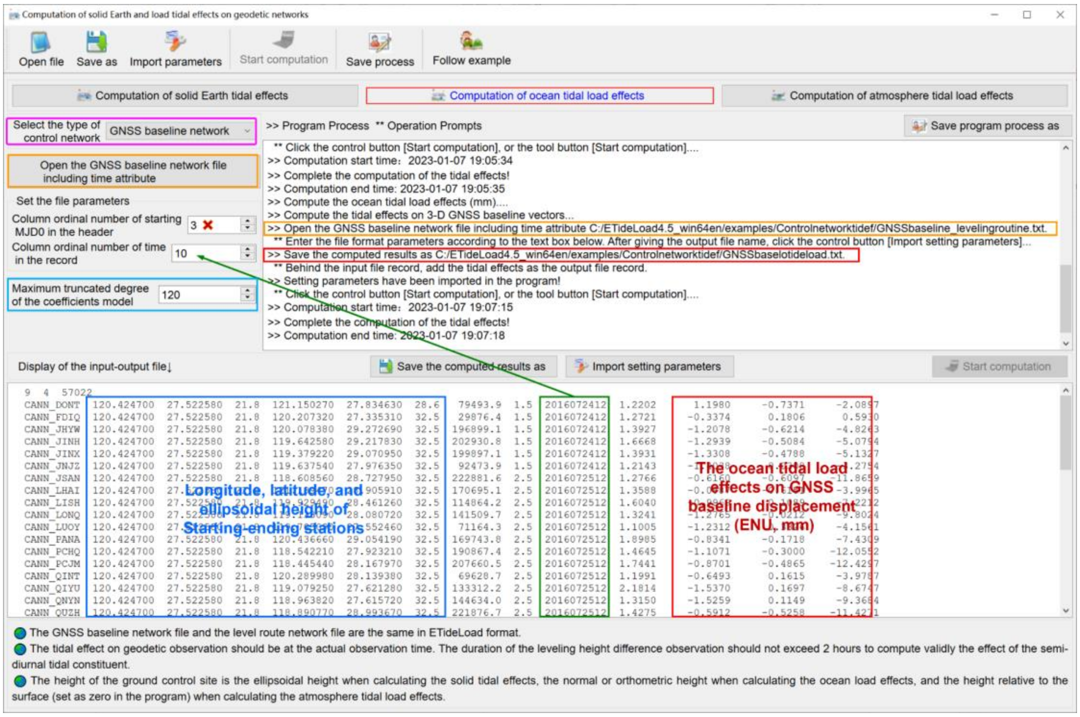
The tidal effect on geodetic observation should be at the actual observation time. The duration of the leveling height difference observation should not exceed 2 hours to compute validly the effect of the semi-diurnal tidal constituent.

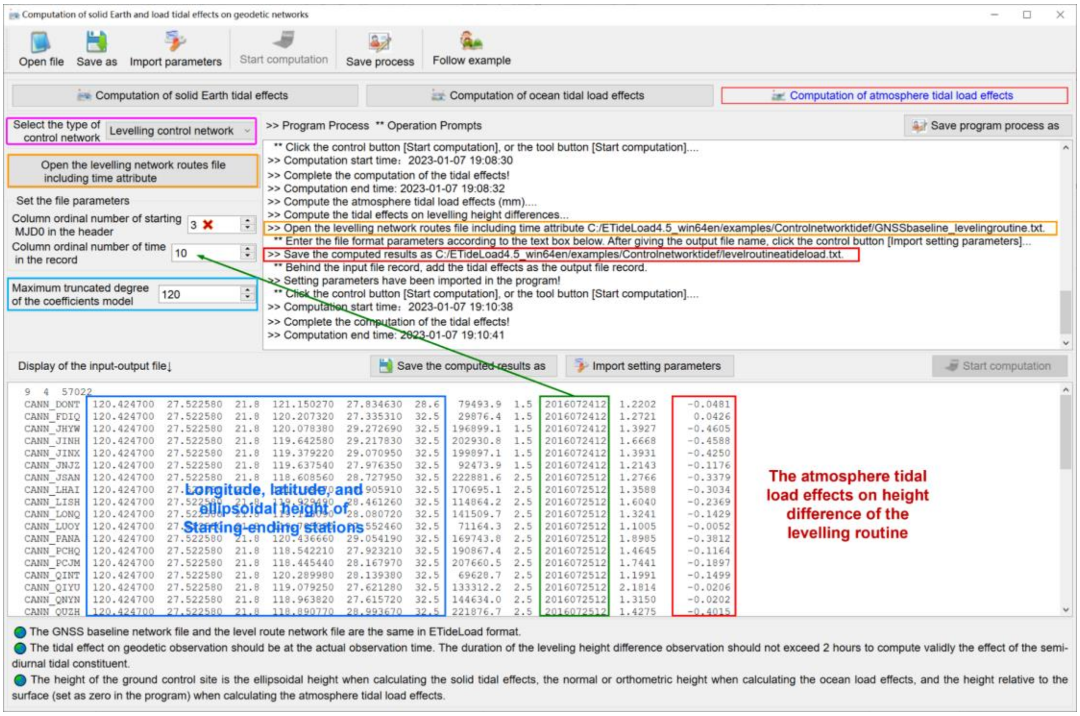
The height of the ground control site is the ellipsoidal height when calculating the solid tidal effects, the normal or orthometric height when calculating the ocean load effects, and the height relative to the surface (set as zero in the program) when calculating the atmosphere tidal load effects.





The gravity observation of the gravity control network need be only operated on the gravity sites, so the solid tidal, ocean tidal load and atmosphere tidal load effects should be calculated according to the site location and actual observation time.





2.7 The regional approach of load tidal effects by load Green's Integral

[Purpose] From the regional residual ocean tide or surface atmosphere tidal harmonic parameters grid, compute the residual ocean or atmosphere tidal load effects near-Earth space by Green's integral.

Here, the residual harmonic parameters are equal to the regional harmonic parameters minus the model value of the harmonic parameters calculated by the global load spherical harmonic coefficient model.

The program requires that residual harmonic parameter grid files of all tidal constituents are stored in a folder. The harmonic parameter grid file is saved in the form of a vector grid, and the seventh attribute of the file header is the Doodson constant.

ETideLoad4.5 takes the regional harmonic parameters grid as the observations, uses global tidal load spherical harmonic coefficient model as a tidal load reference field, and refines the regional residual tidal load effects by Green's integral. Which is also called the remove-restore process. The program only calculates the regional residual value of the tidal load effects in the remove-restore process.

2.7.1 Computation of residual ocean tidal load effects by Green's Integral

[Function] From the regional residual ocean tidal harmonic parameters grid, compute the residual ocean tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE) by Green's Integral.

[Input file] The location and time file of near-Earth points, and the residual ocean tidal harmonic parameters regional grid files.

The location and time file of near-Earth points. The first row is the file header. From the second row onwards, the second and third attributes in the file record are conventionally longitude and latitude (degree decimals), and there are the sampling epoch time and height attributes in the records.

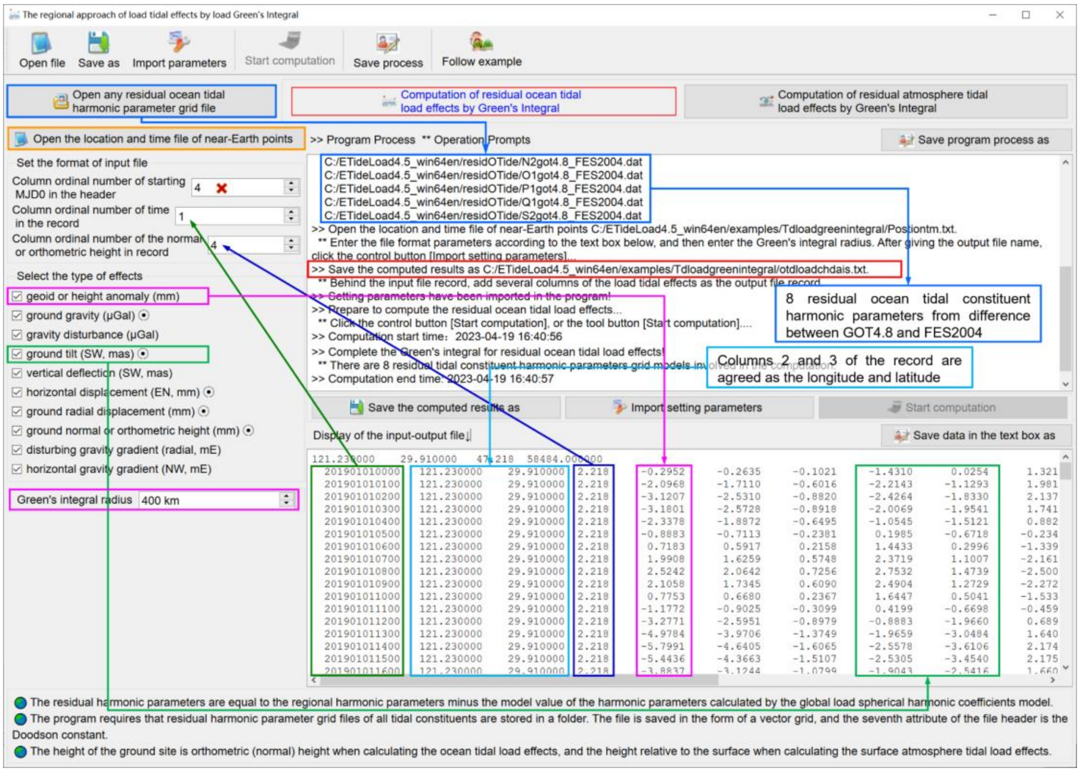
In this example, 8 residual ocean tidal constituent harmonic parameters grid files are selected from the difference between the ocean tide height model GOT4.8 (0.5°×0.5° harmonic parameters grid) and FES2004.

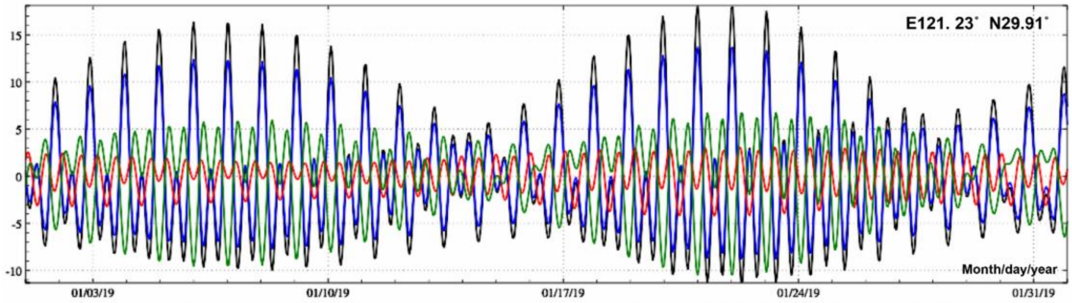
[Parameter settings] Set the input file format parameters, select the type of ocean tidal load effects, and enter Green’s integral radius.

The height of the calculation point is normal or orthometric height relative to the sea surface since the ocean tidal loads are generally considered to be on the sea surface.

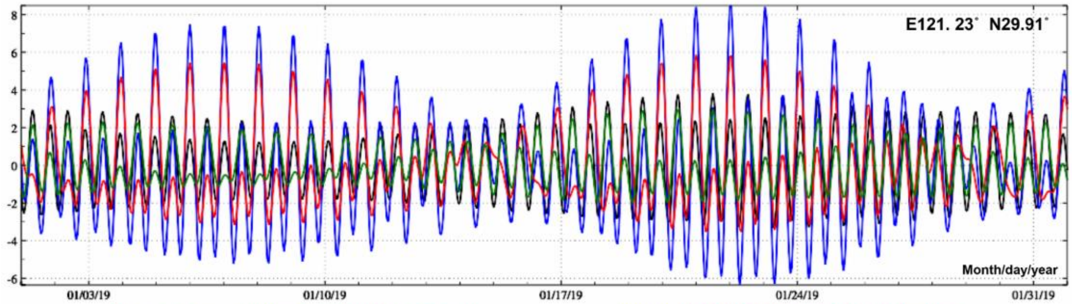
[Output file] The residual ocean tidal load effect file.

The file header is the same as the input file. Behind the input file record, add one or several columns of the residual tidal effects selected as the output file record. In this example, all types are selected, and there are seventeen attributes added to the record.



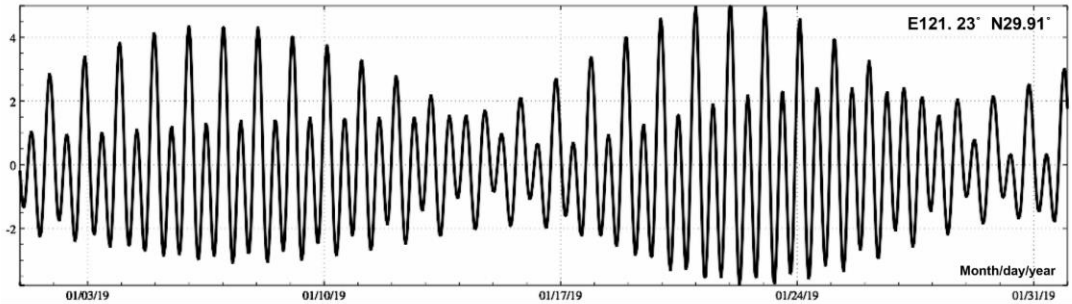


The residual ocean tidal load effects (GOT4.8-FES2004): height anomaly (mm), ground gravity (μGal), radial displacement (mm), orthometric height (mm)

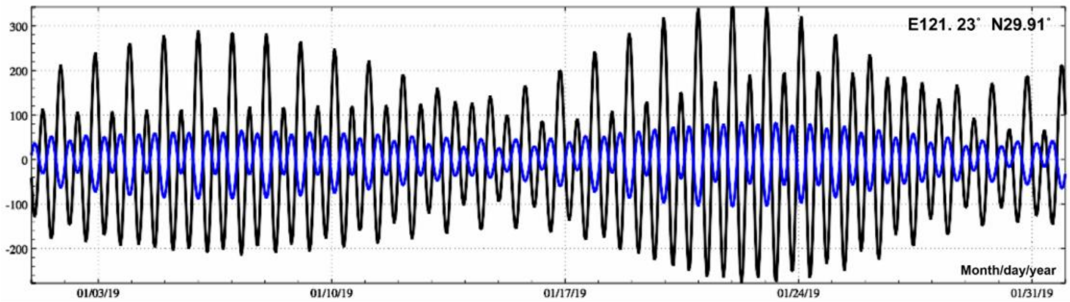


The residual ocean tidal load effects (GOT4.8-FES2004): ground tilt (S, mas), (W, mas), horizontal displacement (E, mm)), (N, mm)

The ocean tidal load is generally considered to be located on the sea surface, and the tidal load effects are all-wavelength. Let the 8 residual tidal constituent harmonic parameters as the ocean tidal modelling error. Since gravity gradient ultrashort waves are dominant, the tide modelling error has great influence on gravity gradient, as shown in the figure.



The residual ocean tidal load effects (GOT4.8-FES2004): disturbing gravity gradient (U, mE)



The residual ocean tidal load effects (GOT4.8-FES2004): horizontal gravity gradient (N, W; mE)

2.7.2 Computation of residual atmosphere tidal load effects by Green's Integral

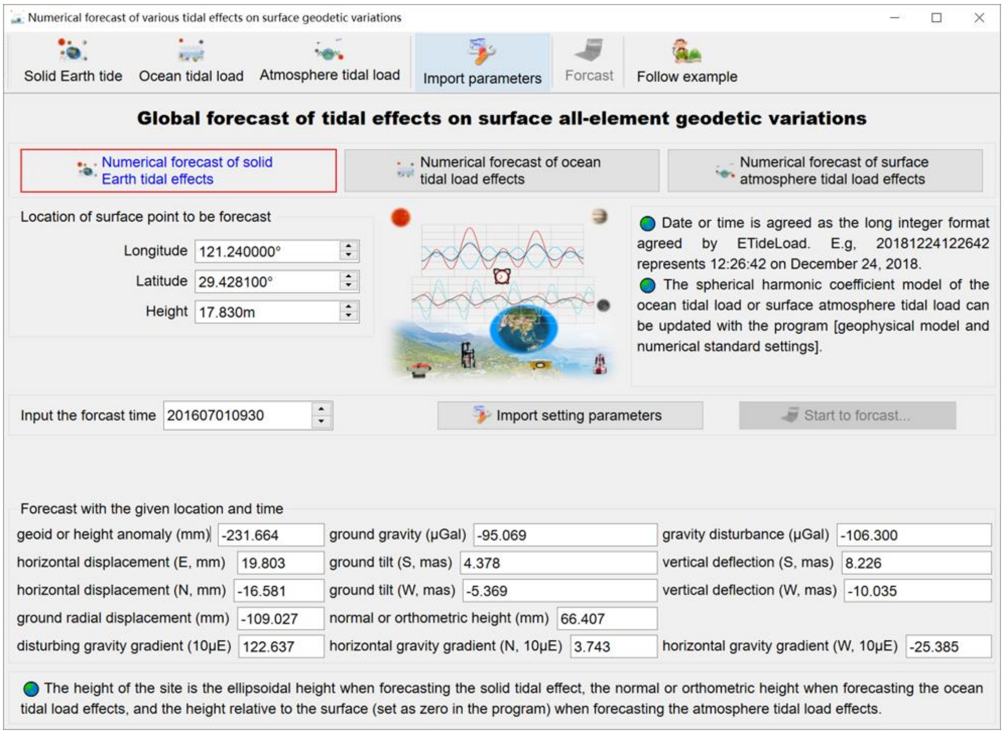
[Function] From the regional residual surface atmosphere tidal harmonic parameters grid, compute the residual tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE) by Green's Integral.

The height of the ground site is the normal or orthometric height when calculating the ocean tidal load effects, and the height relative to the surface (set as zero in the program) when calculating the surface atmosphere tidal load effects.

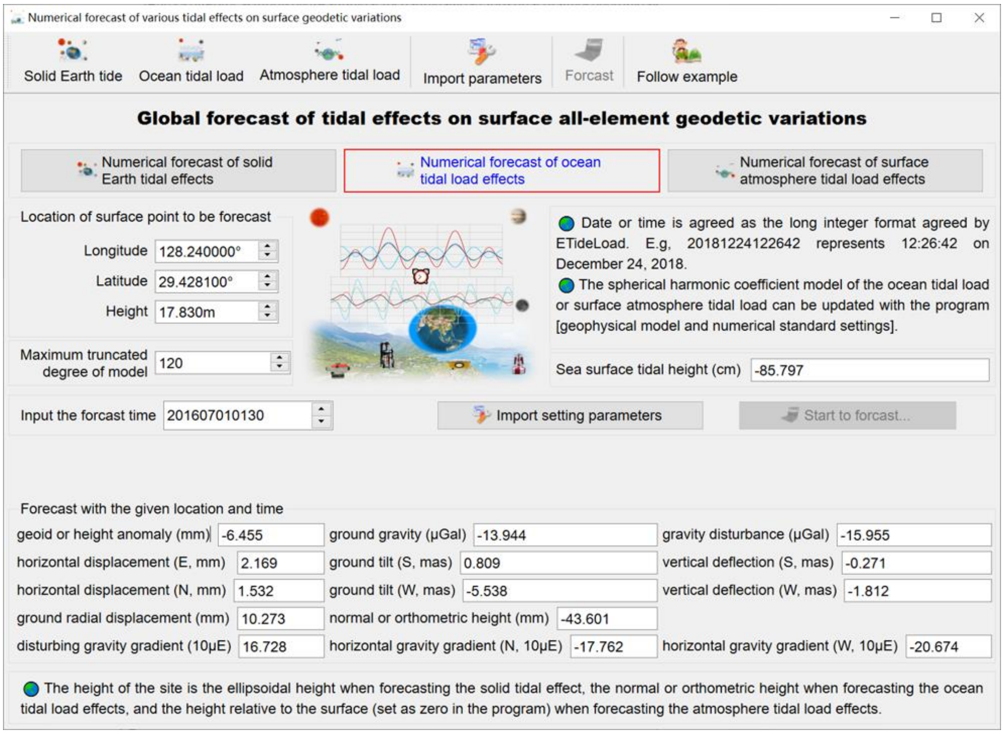
2.8 Numerical forecast of various tidal effects on surface all-element geodetic variations

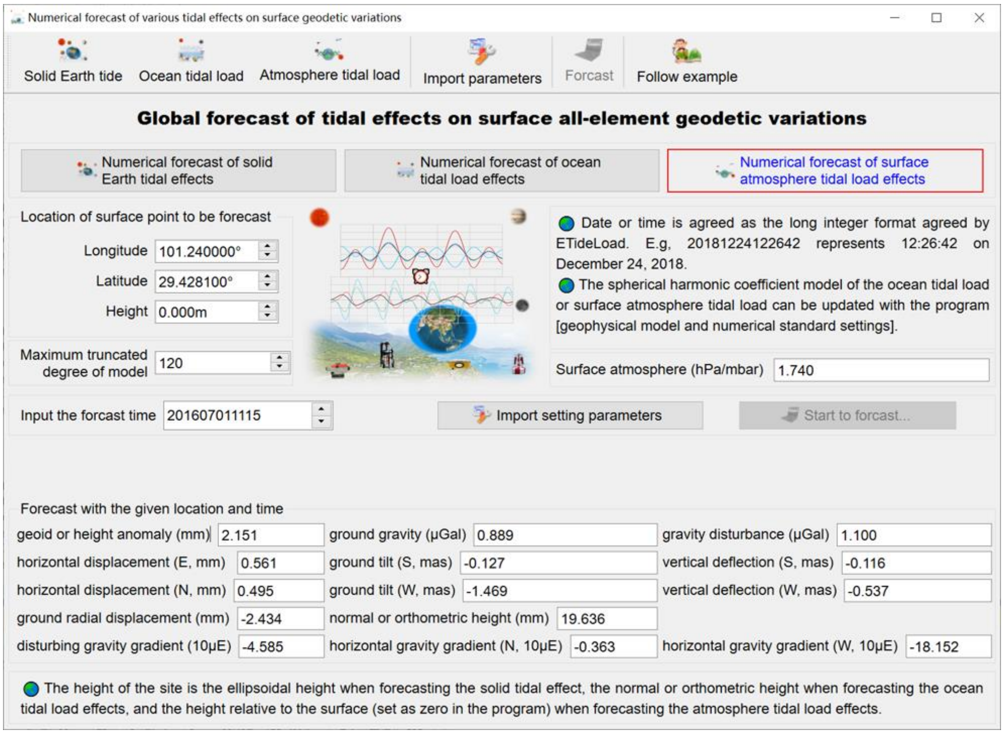
[Purpose] Forecast the solid Earth tidal, ocean tidal load, or surface atmosphere tidal load effects on various surface geodetic variations anywhere and anytime.

The height of the site is the ellipsoidal height when forecasting the solid tidal effect, the normal or orthometric height when forecasting the ocean tidal load effects, and the height relative to the surface (set as zero in the program) when forecasting the atmosphere tidal load effects.



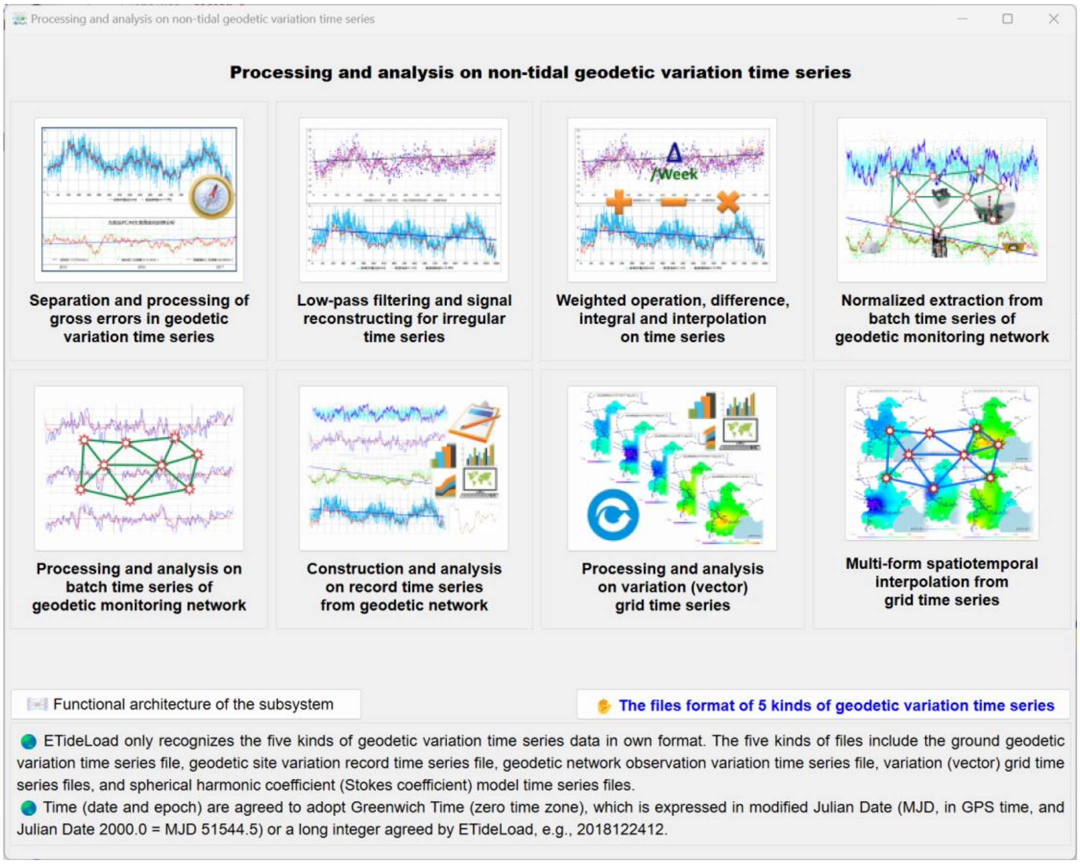
Date or time is agreed as the long integer format agreed by ETideLoad. E.g, 20181224122642 represents 12:26:42 on December 24, 2018, and 2018122412 represents 12: 0: 0 on December 24, 2018.





3 Processing and analysis on non-tidal geodetic variation time series

Based on the characteristics of non-tidal geodetic time series, the group of programs adopt some stable and reliable algorithms to uniformly process and analyze massive various geodetic variation time series data.



ETideLoad only recognizes the five kinds of geodetic variation time series data in own format. The five kinds of files include the ground geodetic variation time series file, geodetic site variation record time series file, geodetic network observation variation time series file, variation (vector) grid time series files, and spherical harmonic coefficient (Stokes coefficient) model time series files.

Time (date and epoch) are agreed to adopt Greenwich Time (zero time zone), which is expressed in modified Julian Date (MJD, in GPS time, and Julian Date 2000.0 = MJD 51544.5) or a long integer agreed by ETideLoad. In most cases, the long integer agreed by ETideLoad is used. E.g., 20181224122642 represents 12:26:42 on December 24, 2018. Here, the epoch is an instantaneous time.

3.1 Separation and processing of gross errors in geodetic variation time series

[Purpose] On the irregular geodetic time series in the given input file, perform preprocessing such as gross error detection and separation, time format transform, reference epoch unification of multi-column time series or averaging according to the given time period.

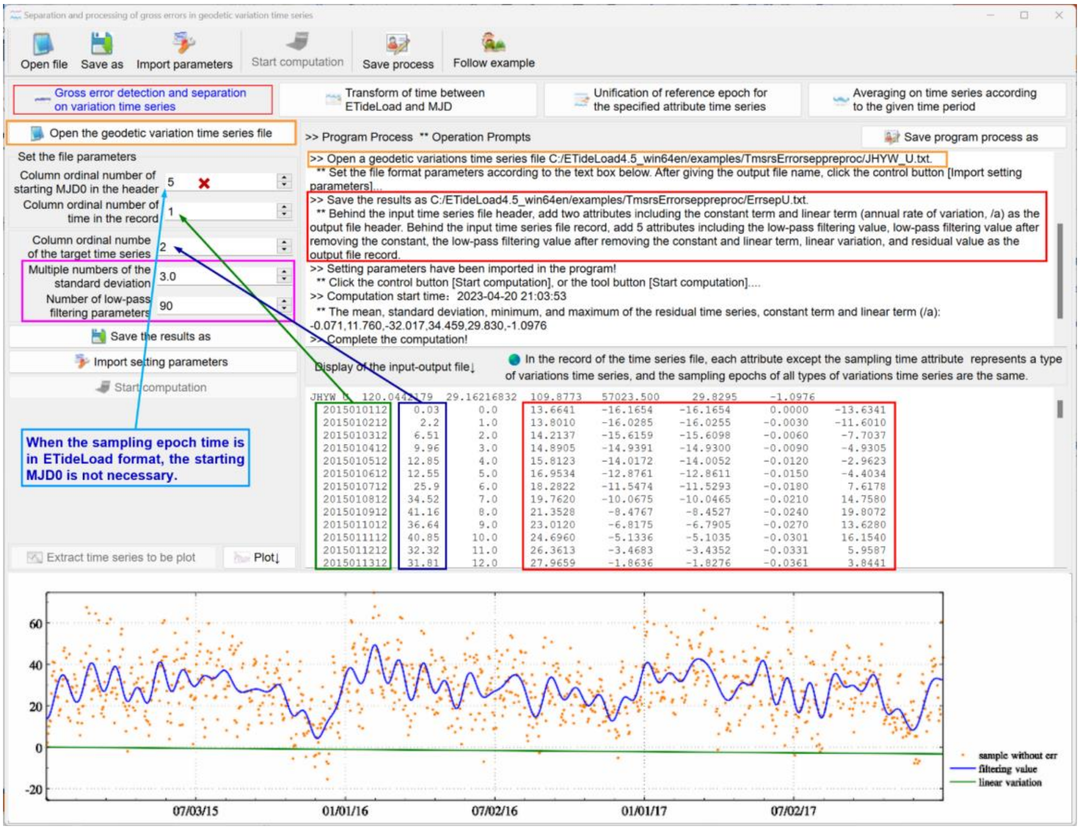
In the record of the geodetic variation time series file, each attribute except the sampling epoch time represents a type of variation time series, and the sampling epoch time of all types of variation time series are the same.

3.1.1 Gross error detection and separation on variation time series

[Function] According to the given number of the low-pass filtering parameters, using the continuous Fourier and Chebyshev combined basis functions, construct the low-pass filtering reference curve from the irregular variation time series of the specified attribute, calculate the difference between the sampling value and the reference value to get the residual time series, and then separate the variation at the corresponding epoch time when the residual is greater than the given multiple of the standard deviation of the residual time series as the gross error. The program performs 5 iterations of the gross error detection and separation.

[Input file] The geodetic variation time series file.

The first row is the file header. Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.



[Parameter settings] Set the input file format parameters, enter column ordinal number of the epoch time and target attribute time series to be detected in the record, and enter the multiple of the standard deviation and the number of low-pass filtering parameters.

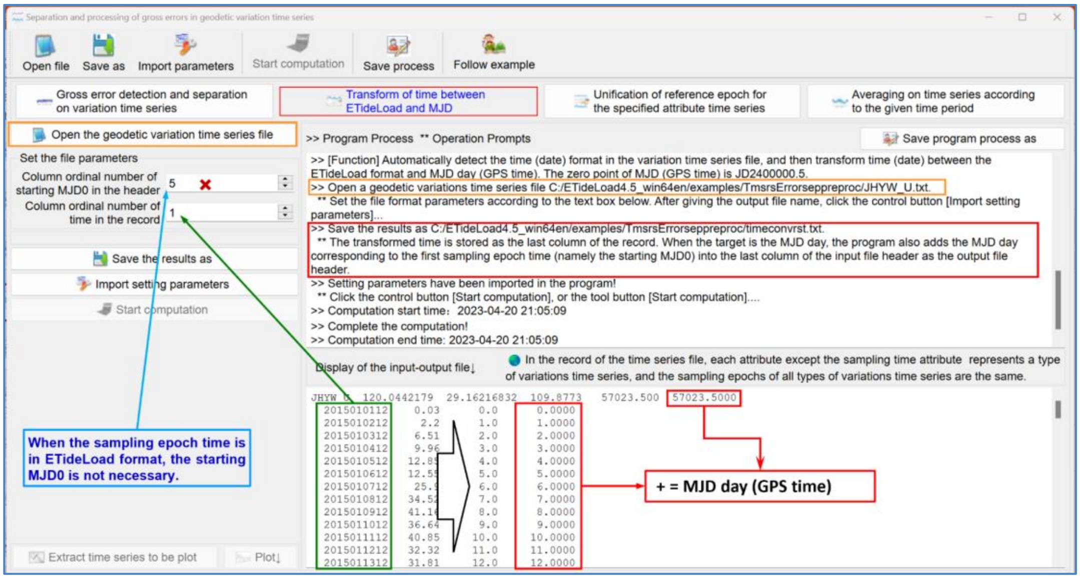
The entered number of the low-pass filtering parameters is not more than 1/2 of the number of time series samples, and not less than 1/30 of the number of samples. When the entered number exceed this range, the program automatically takes the minimum or maximum value.

[Output file] The variation time series analysis file after removing gross errors.

Behind the input time series file header, add two attributes including the constant term and linear term (annual rate of variation, /a) as the output file header. Behind the input time series file record, add 5 attributes including the low-pass filtering value, low-pass filtering value after removing the constant, low-pass filtering value after removing the constant and linear term, linear variation, and residual value as the output file record.

3.1.2 Transform of time between ETideLoad and MJD

[Function] Automatically detect the time (date) format in the variation time series file, and then transform time (date) between the ETideLoad format and MJD day (GPS time). The zero point of MJD (GPS time) is JD2400000.5.



The transformed time is stored as the last column of the record. When the target is the MJD day, the program also adds the MJD day corresponding to the first sampling epoch time (namely the starting MJD0) into the last column of the input file header as the output file header.

3.1.3 Unification of reference epoch for the specified attribute time series

[Function] Using the cubic spline or Gaussian function interpolation method, interpolate the sampling value of the specified attribute time series at the given reference epoch time, and then remove the corresponding sampling values from the time series, thereby unifying the reference epoch time. At the reference epoch time, the sampling value of the specified attribute time series is always zero.

[Input file] The geodetic variation time series file.

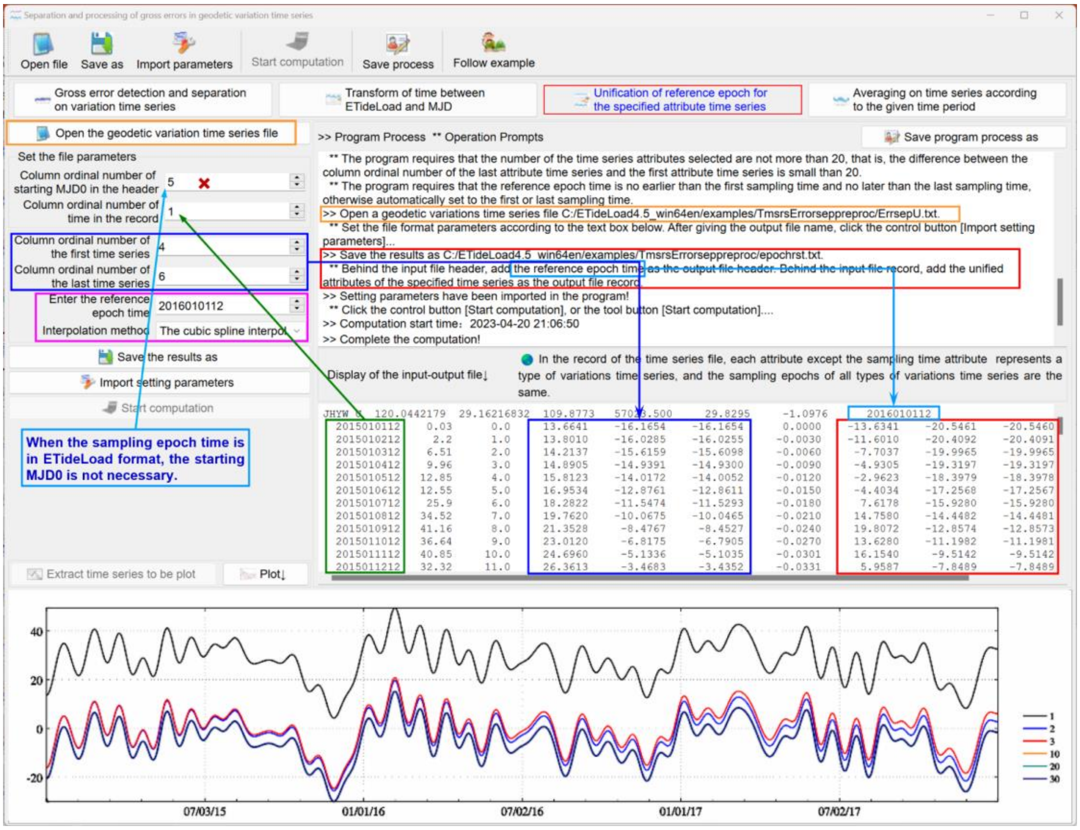
[Parameter settings] Set the input file format parameters, enter column ordinal number of the first and last attribute time series, the reference epoch time (ETideLoad long integer format), and select interpolation method.

The program requires that the reference epoch time is no earlier than the first sampling time and no later than the last sampling time, otherwise automatically set to the first or last sampling time.

The program requires that the number of the time series attributes selected are not more than 20, that is, the difference between the column ordinal number of the last attribute time series and the first attribute time series is small than 20.

The reference epoch time need not be one of the sampling epochs of the input variation time series.

When there are more noise or missing samples in time series signals, Gaussian function interpolation is recommended.



[Output file] The variation time series analysis file.

Behind the input file header, add the reference epoch time as the output file header. Behind the input file record, add the unified attributes of the specified time series as the output file record.

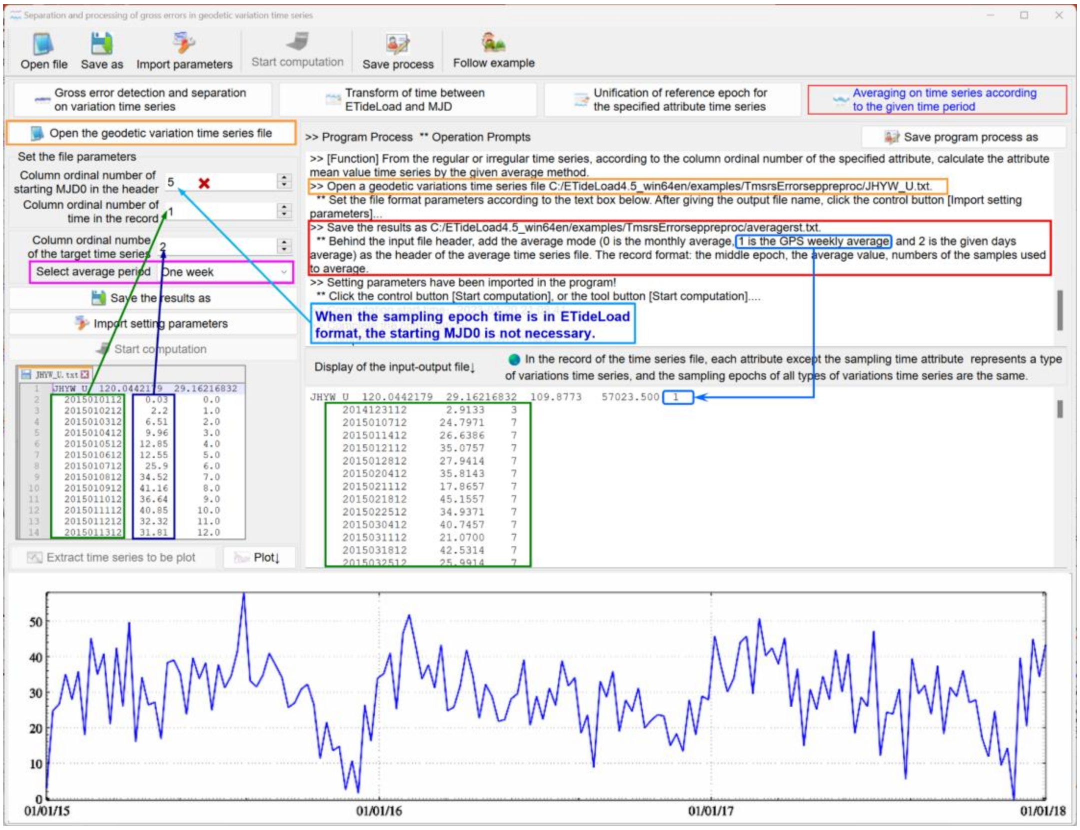
The unification of reference epoch time for multi-source data is the most basic requirement for geodynamics monitoring.

3.1.4 Averaging on time series according to the given time period

[Function] From the regular or irregular time series, according to the column ordinal number of the specified attribute, calculate the attribute mean value time series by the given average method.

[Input file] The geodetic variation time series file.

[Parameter settings] Set the input file format parameters, enter column ordinal number of the specified attribute, and select average period.



[Output file] The variations average time series file.

Behind the input file header, add the average mode (0 is the monthly average, 1 is the GPS weekly average, and 2 is the given days average) as the header of the average time series file. The record format: the middle epoch, the average value, the number of the samples used to average.

3.2 Low-pass filtering and signal reconstructing for irregular time series

[Purpose] Using the continuous Chebyshev and triangular base function combination method, estimate the low-pass parameters of the irregular time series, separate the constant term and linear term, and then reconstruct the time series according to the user's requirements.

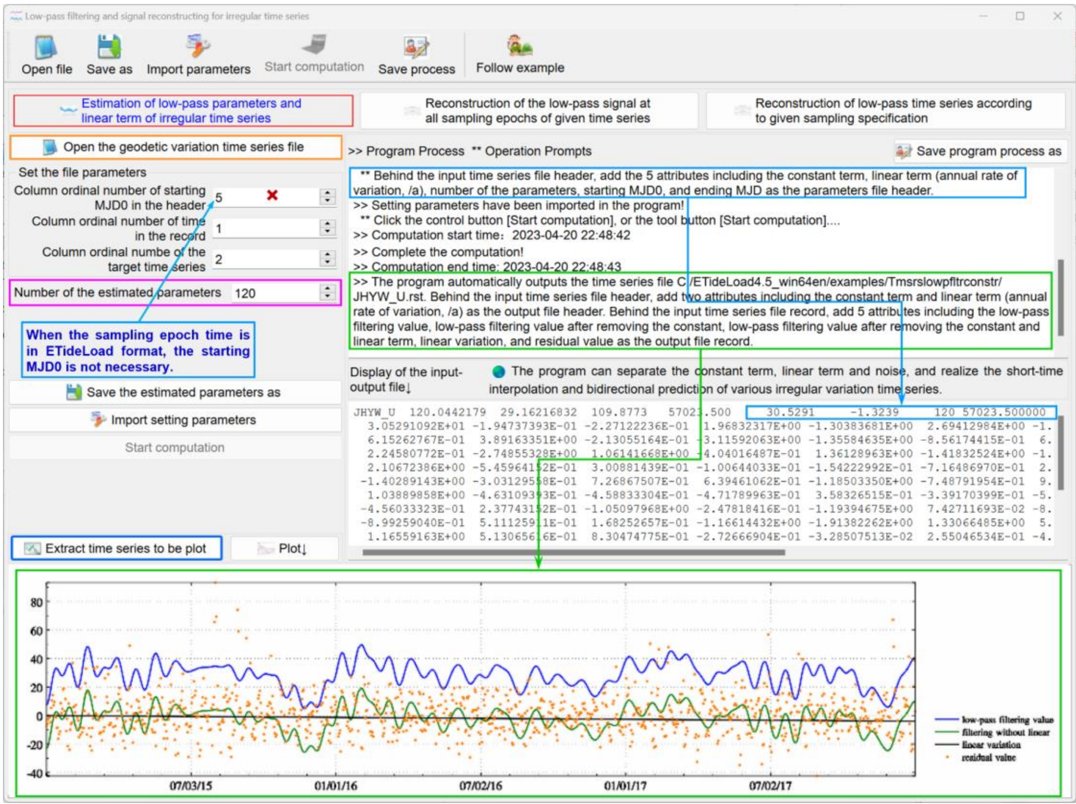
The program can separate the constant term, linear term and noise, and realize the short-time interpolation and bidirectional prediction of various irregular variation time series.

3.2.1 Estimation of low-pass parameters and linear term of irregular time series

[Function] Using the continuous Chebyshev and triangular base function combination method, estimate the constant term, linear term and low-pass parameters of the irregular time series according to the entered number of estimated parameters.

[Input file] The geodetic variation time series file.

The first row is the file header. Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.



[Parameter settings] Set the input file format parameters, enter column ordinal number of the epoch time and target attribute time series in the record, and enter the number of low-pass filtering parameters.

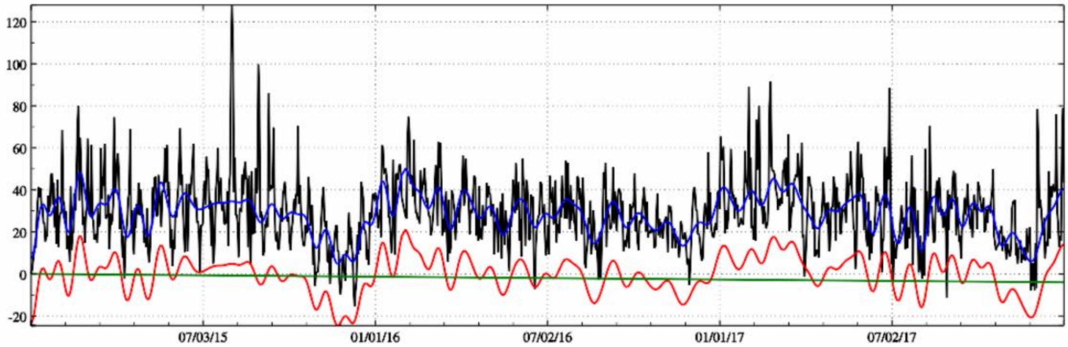
The number of the estimated low-pass parameters should not be greater than 1 / 2 of the number of samples in the input time series and should not be less than 1 / 30 of the number of samples. Otherwise, the program automatically takes the minimum or maximum values.

[Output file] The low-pass filtering parameter file. The low-pass filter variation time series analysis file.

The low-pass filtering parameter file. Behind the input time series file header, add the 5 attributes including the constant term, linear term (annual rate of variation, /a), number of the estimated parameters, starting MJD0, and ending MJD as the parameter file header. And then all low-pass filter parameter values be saved into the file in order.

The low-pass filter variation time series analysis file *.rst. Here, * is the input geodetic variation time series file name.

Behind the input time series file header, add two attributes including the constant term and linear term (annual rate of variation, /a) as the output file header. Behind the input time series file record, add 5 attributes including the low-pass filtering value, low-pass filtering value after removing the constant, low-pass filtering value after removing the constant and linear term, linear variation, and residual value as the output file record.



The original time series Low-pass reconstruction time series Reconstruction time series after removing constant term Linear variation time series

3.2.2 Reconstruction of the low-pass signal at all sampling epochs of given time series

[Function] According to the entered number of the low-pass parameters (here, the entered number should be no greater than the maximum number of the estimated low-pass parameters), reconstruct the low-pass time series with the sampling epochs corresponding to the given time series.

[Input files] The geodetic variation time series file to be reconstructed. The low-pass filtering parameter file, which be automatically called by the program without manual input.

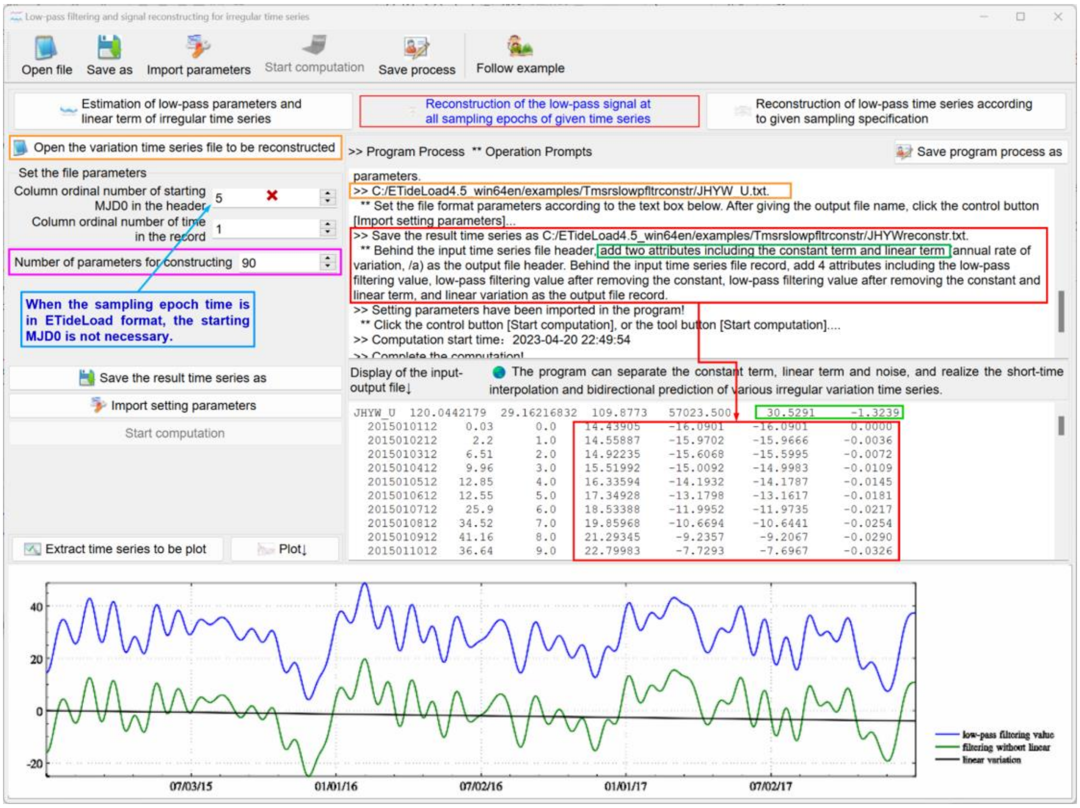
[Parameter settings] Set the column ordinal number of the epoch time in the input file record, enter the number of the low-pass parameters for reconstruction.

The number of the low-pass parameters used for reconstruction should not exceed the estimated number of the low-pass parameters. Otherwise, the program automatically takes the estimated number as the number of the low-pass parameters.

[Output file] The low-pass reconstruction variation time series file.

Behind the input time series file header, add two attributes including the constant term and linear term (annual rate of variation, /a) as the output file header.

Behind the input time series file record, add 4 attributes including the low-pass filtering value, low-pass filtering value after removing the constant, low-pass filtering value after removing the constant and linear term, and linear variation as the output file record.



3.2.3 Reconstruction of low-pass time series according to given sampling specification

[Function] Reconstruct the low-pass time series according to the starting and ending epoch time, sampling interval (hours), and the entered number of the low-pass parameters for reconstruction.

[Input files] The low-pass filtering parameter file, which be automatically called by the program without manual input.

[Parameter settings] Set the starting and ending epoch time, sampling interval (hours), and enter the number of the low-pass parameters for reconstruction.

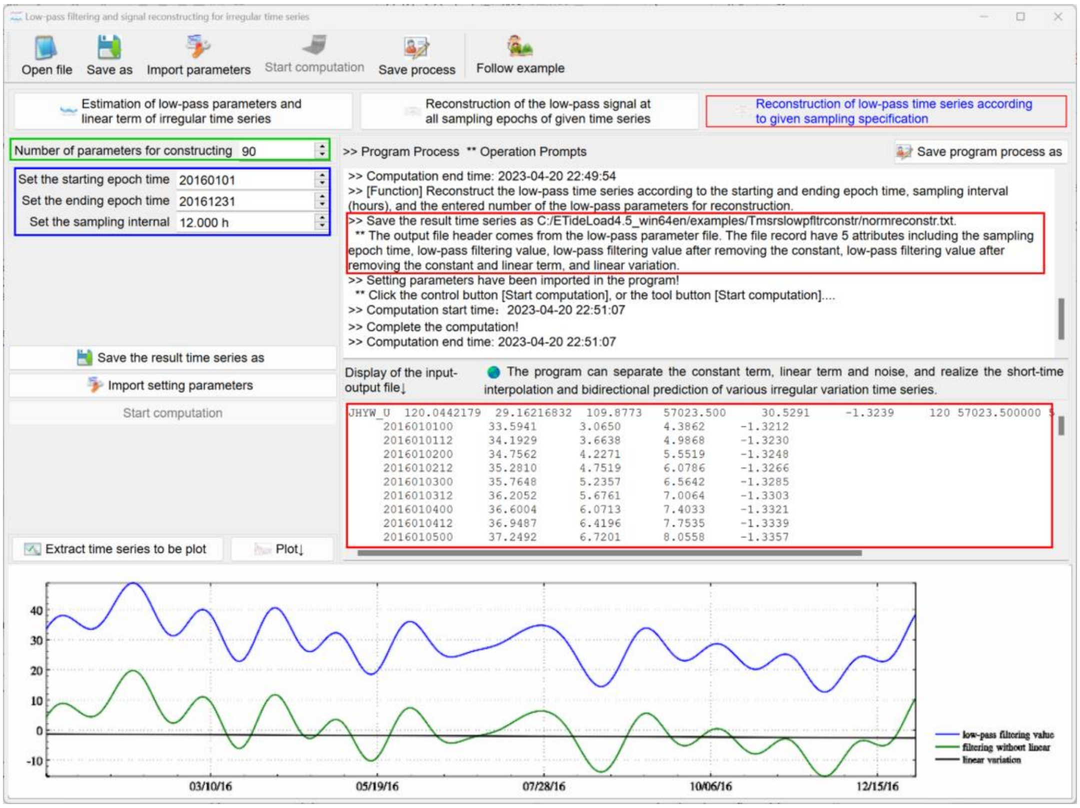
The starting epoch time should not be earlier (may be slightly earlier) than the first sampling epoch time of the variation time series used for parameter estimation.

The ending epoch time should not be later (may be slightly later) than the last sampling epoch time of the variation time series used for parameter estimation.

The starting-ending epoch time should be not earlier (or slightly earlier) than the starting time of the time series used to estimate the low-pass parameters, and not later (or slightly later) than the ending time of the time series.

[Output file] The low-pass reconstruction variation time series file.

The output file header comes from the low-pass parameter file. The file record have 5 attributes including the sampling epoch time, low-pass filtering value, low-pass filtering value after removing the constant, low-pass filtering value after removing the constant and linear term, and linear variation.



3.3 Weighted operation, difference, integral and interpolation on time series

[Purpose] Directly perform weighted operation, difference, integral and interpolation operations on the irregular time series in the given manner.

3.3.1 Weighted operation between two attributes time series

[Function] Perform weighted plus, minus, or multiply operation on two attributes time series in the irregular time series file.

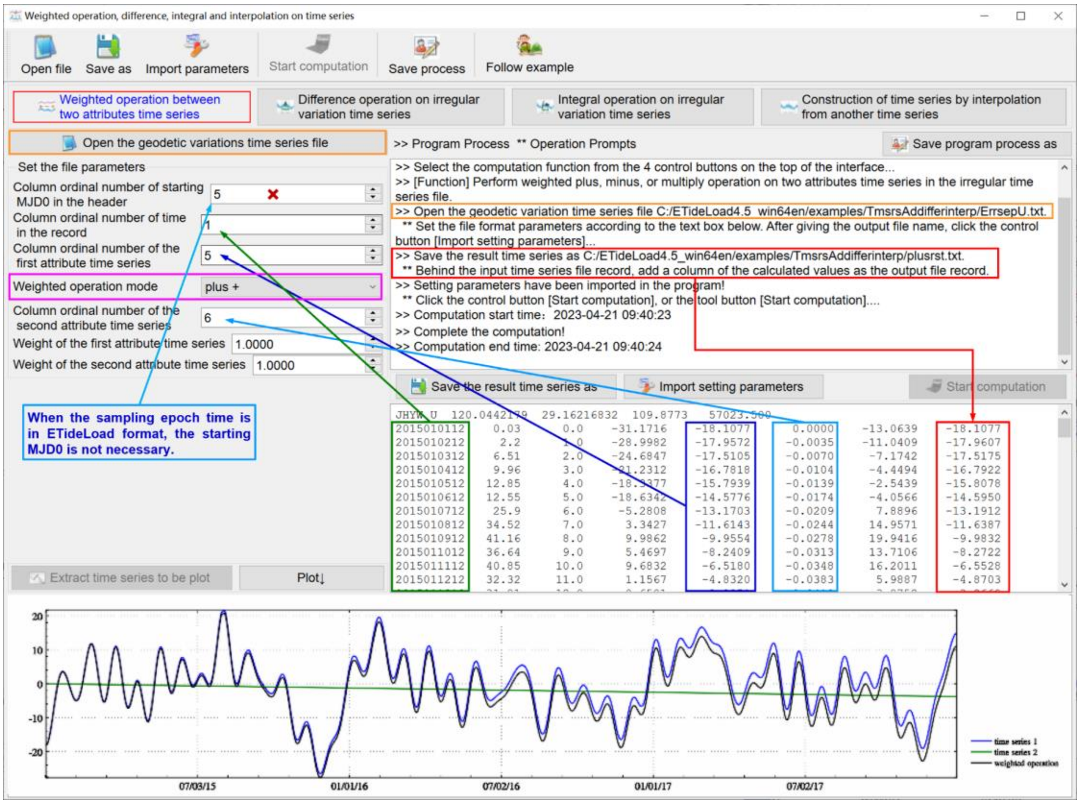
[Input file] The geodetic variation time series file.

The first row is the file header. Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. The attributes in the record include the sampling epoch time and two attributes time series to be operated.

[Parameter settings] Set the input file format parameters, enter column ordinal number of the epoch time and two attributes time series to be operated in the record, and enter the two attribute weights.

[Output file] The weighted operation result variation time series file.

Behind the input time series file record, add a column of the calculated values as the output file record.



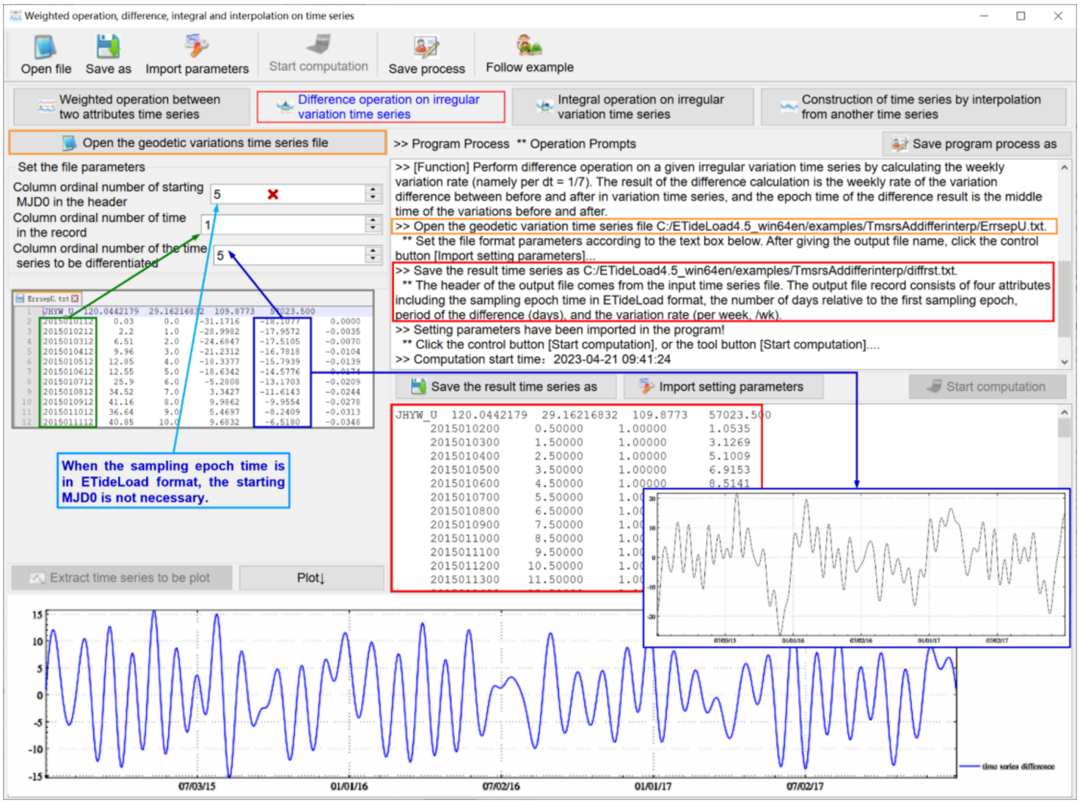
3.3.2 Difference operation on irregular variation time series

[Function] Perform difference operation on a given irregular variation time series by calculating the weekly variation rate (namely per dt = 1/7). The result of the difference calculation is the weekly rate of the variation difference between before and after in variation time series, and the epoch time of the difference result is the middle time of the variations before and after.

[Input file] The geodetic variation difference time series file.

[Output file] The weighted operation result variation time series file.

The output file header comes from the input time series file. The output file record consists of four attributes including the sampling epoch time in ETideLoad format, number of days relative to the first sampling epoch, period of the difference (days), and the variation rate (per week, /wk).



3.3.3 Integral operation on irregular variation time series

[Function] Perform integral operation on a given irregular variation time series by accumulating the weekly variation (namely dt = 7 days). The first sampling epoch value of the integration result time series is always zero, and the weekly rate at the middle epoch time is calculated by the Gaussian function interpolation method from the given time series. The accumulated value of each step is equal to the weekly rate at the middle epoch time multiplied by seven days.

The output file header comes from the input time series file. Behind the input time series file record, add a column of the calculated values as the output file record.

When there is some noise in the time series signal, Gaussian basis function interpolation is recommended.

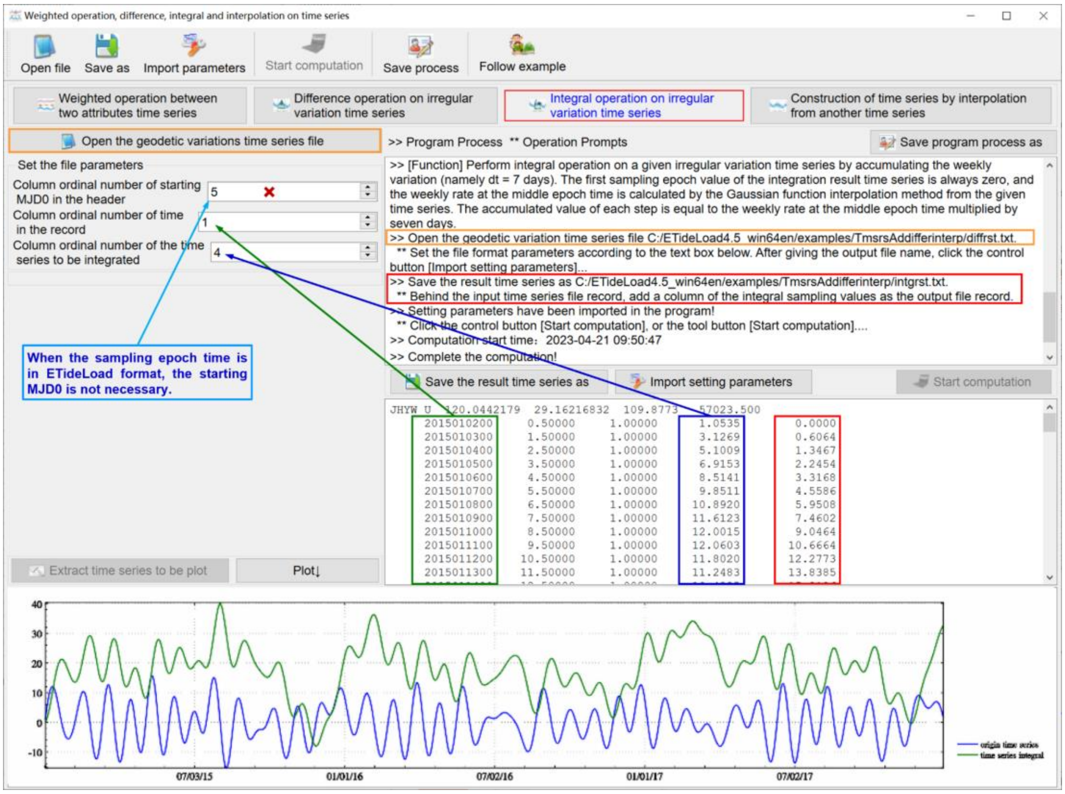
3.3.4 Construction of time series by interpolation from another time series

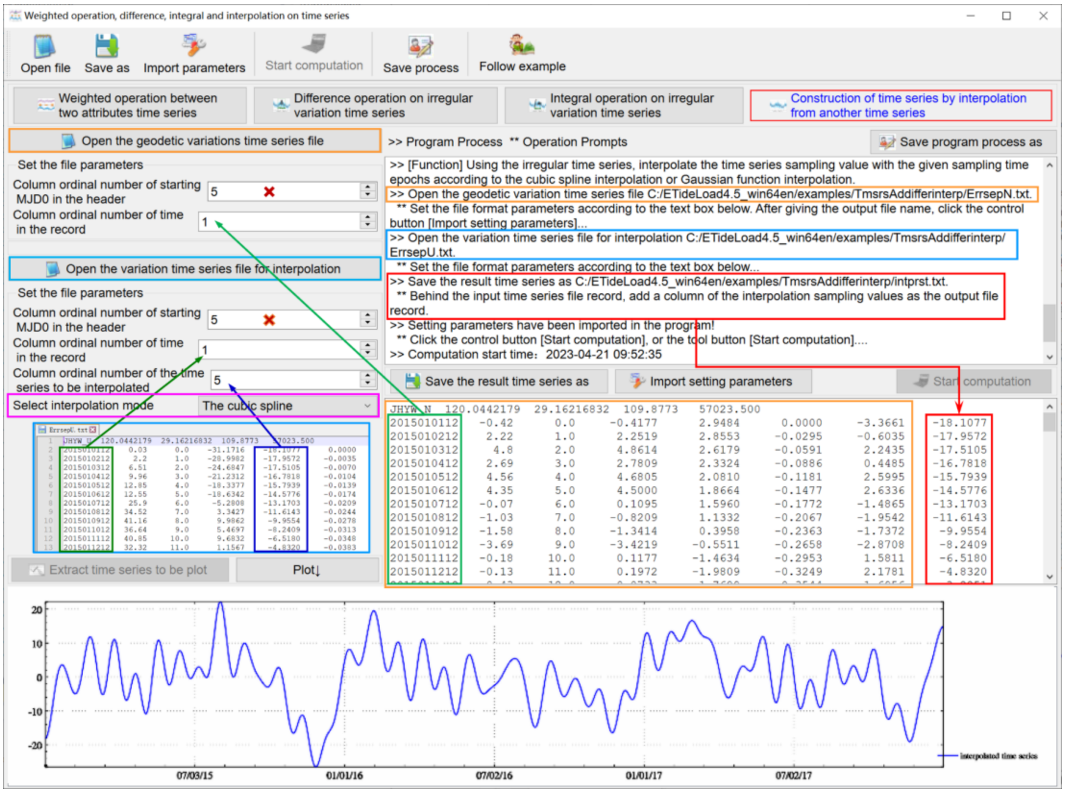
[Function] Using the irregular time series, interpolate the time series sampling value with the given sampling time epochs according to the cubic spline interpolation or Gaussian function interpolation.

[Input file] The geodetic variation time series file to be interpolated. The geodetic variation time series file used for interpolation.

[Output] The interpolation result variation time series file.

The output file header comes from the input time series file. Behind the input time series file record, add a column of the interpolation sampling values as the output file record.





3.4 Normalized extraction from batch time series of geodetic monitoring network

[Purpose] From the text files of batch geodetic sites or batch CORS network baselines that contain the specified time series data with the same format, extract data and generate the corresponding time series files according to the ETideLoad format.

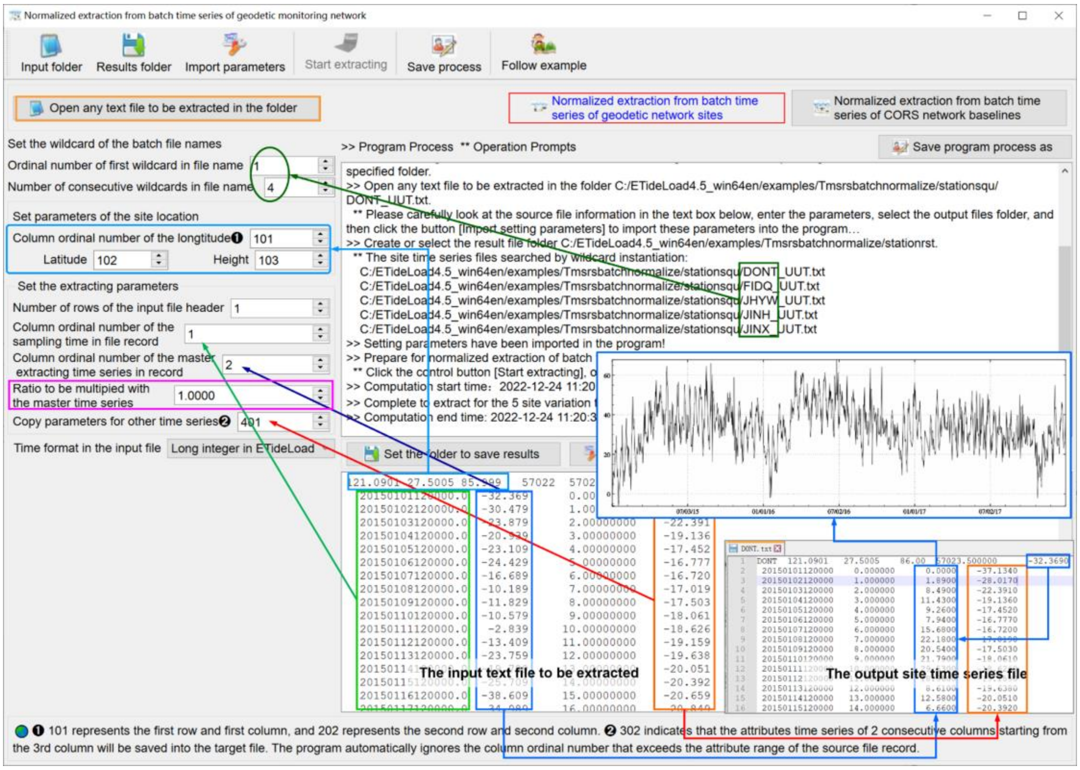
The program requires all the source text files stored in a folder, and the source file name contains the site name or baseline name with the same number of the characters. The extracted time series files are saved into another folder.

3.4.1 Normalized extraction from batch time series of geodetic network sites

[Function] From the text files of batch geodetic network sites that contain the specified time series data with the same file format, according to the ETideLoad format, extract data and generate the corresponding time series files, which are saved in the specified folder.

[Parameter settings]

The program requires that wildcards can uniquely identify files in the folder, and their instance characters will be also used as the extracted time series file name.



If there is no height attribute in the source file, or the entered height column ordinal number exceeds the maximum number of the attributes, the program automatically sets the height to zero.

If there is not the starting MJD0 in the header of the source file, please enter the starting time agreed in ETideLoad format. After entering the epoch time in ETideLoad format, the program would automatically calculate MJD day.

[Output files] Batch geodetic variation time series files in ETideLoad format.

The file header: The site name (instance of the file name wildcard), longitude, latitude, height, starting MJD0, and constant term (the first sampling value of the target time series).

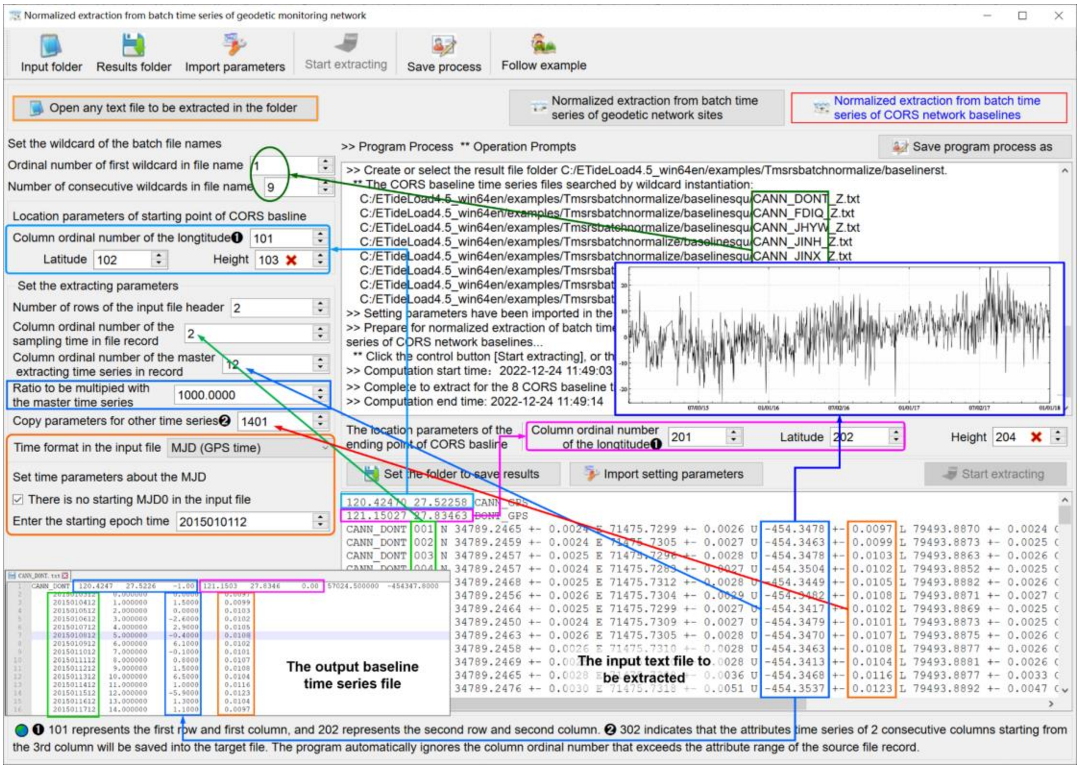
The record format: The sampling epoch time, days relative to the starting MJD0, sampling value which has removed the first sampling value, other copy attributes.

The sum of the starting MJD0 in the header and the sampling epoch time (day) is equal to the sampling epoch time of MJD day in the record. When the sampling epoch time is in ETideLoad format, the starting MJD0 is not necessary for the file header.

3.4.2 Normalized extraction from batch time series of CORS network baselines

[Function] From batch baseline solution files of the CORS network that contain the specified time series data with the same file format, according to the ETideLoad format, extract data and generate the corresponding baseline solution time series files, which are saved in the specified folder.

The program extracts the time series of one-dimension components of the ENU baseline solutions once.



❶ 101 represents the first row and first column, and 202 represents the second row and second column.

❷ 302 indicates that the attribute time series of 2 consecutive columns starting from the 3rd column will be saved into the target file. The program automatically ignores the column ordinal number that exceeds the attribute range of the source file record.

[Output files] Batch CORS baseline solution time series files in ETideLoad format.

The file header: The baseline name (instance of the file name wildcard), starting station longitude, latitude, height, ending station longitude, latitude, height, starting MJD0, and constant term (the first sampling value of the target time series).

The record format: The sampling epoch time, days relative to the starting MJD0, sampling value which has removed the first sampling value, other copy attributes.

3.5 Processing and analysis on batch time series of geodetic monitoring network

[Purpose] On the specified attribute time series from batch variation time series files with the same format, perform gross error detection, linear term separation, low-pass filtering, and signal reconstructing, or calculate the mean time series according to the given period.

The program requires all source time series files saved in a folder. The output time series files are saved into the specified folder.

3.5.1 Gross error detection, low-pass filtering, and reconstructing for batch time series

[Function] On the specified attribute time series from batch time series files with the same format, estimate the low-pass filtering parameters, and use the low-pass filtering curve as a reference curve to detect gross errors, separate linear term, and then reconstruct the low-pass filtering value time series. The output time series files are saved in the specified folder.

[Input files] Batch geodetic variation time series files with the same formats.

The first row is the file header. Starting from the second row of the file, each row record stores the sampling values of all the variations at one sampling epoch time. At least one column of the attributes in the record is the sampling epoch time.

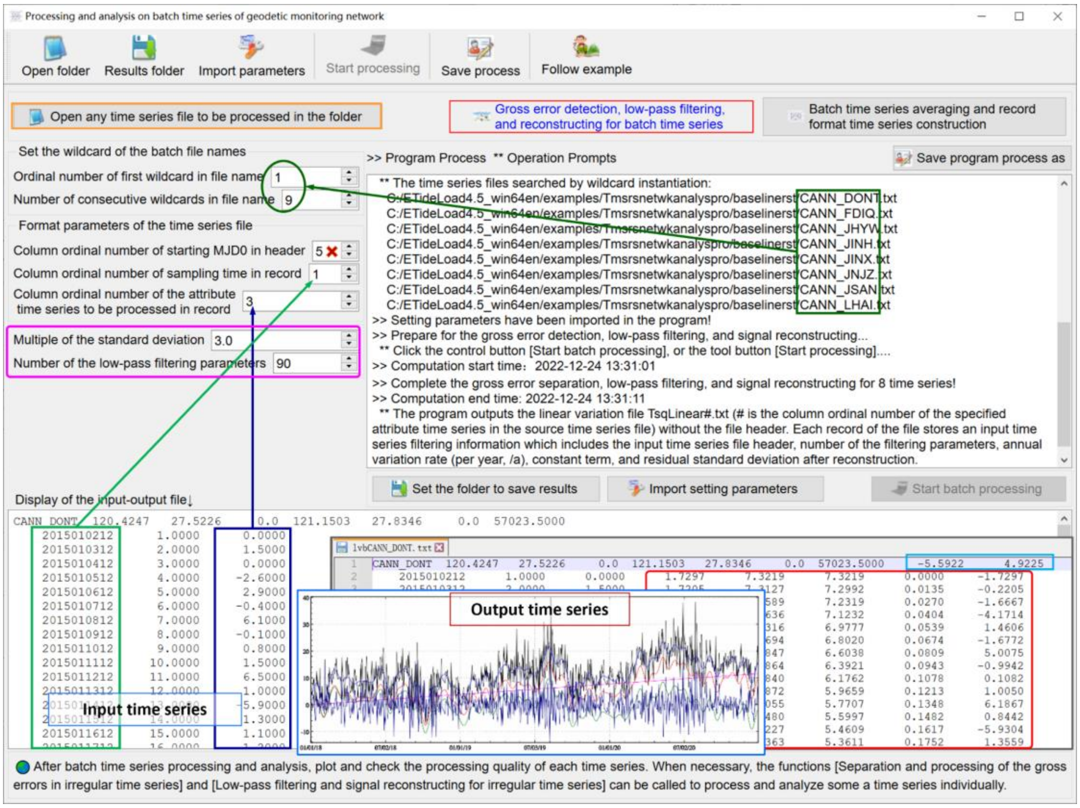
[Parameter settings] Set the wildcard parameters for batch variation time series files, enter column ordinal number of the epoch time and target attribute time series in the record, and enter the multiple of the standard deviation and number of low-pass filtering parameters.

The entered number of the low-pass filtering parameters is not more than 1/2 of the number of time series samples, and not less than 1/30 of the number of samples. When the entered number exceeds this range, the program automatically takes the minimum or maximum value.

[Output files] Batch low-pass filtering time series files. The linear variation file.

The low-pass filtering time series file. Behind the input file header, add two attributes including the constant term and linear term (annual variation rate) as the output file header. Behind the input file record, add 5 attributes including the low-pass filtering value, low-pass filtering value after removing the constant term, low-pass filtering value after removing the constant and linear term, linear variation, and residual value as the output file record.

The linear variation file TsqLinear#.txt (# is the column ordinal number of the specified attribute time series in the source time series file) without the file header. Each record of the file stores an input time series filtering information which includes the input time series file header, number of the filtering parameters, annual variation rate (per year, /a), constant term, and residual standard deviation after reconstruction.



3.5.2 Batch time series averaging and record format time series construction

[Function] On the specified attribute time series from batch time series files with the same format, perform the average according to the given mode. The output time series is stored in two ways. The one is each time series saved as a file. The other is to arrange all the time series in rows, each record store a time series, and all the time series are stored into a record time series file.

[Input files] Batch variation time series files with the same format.

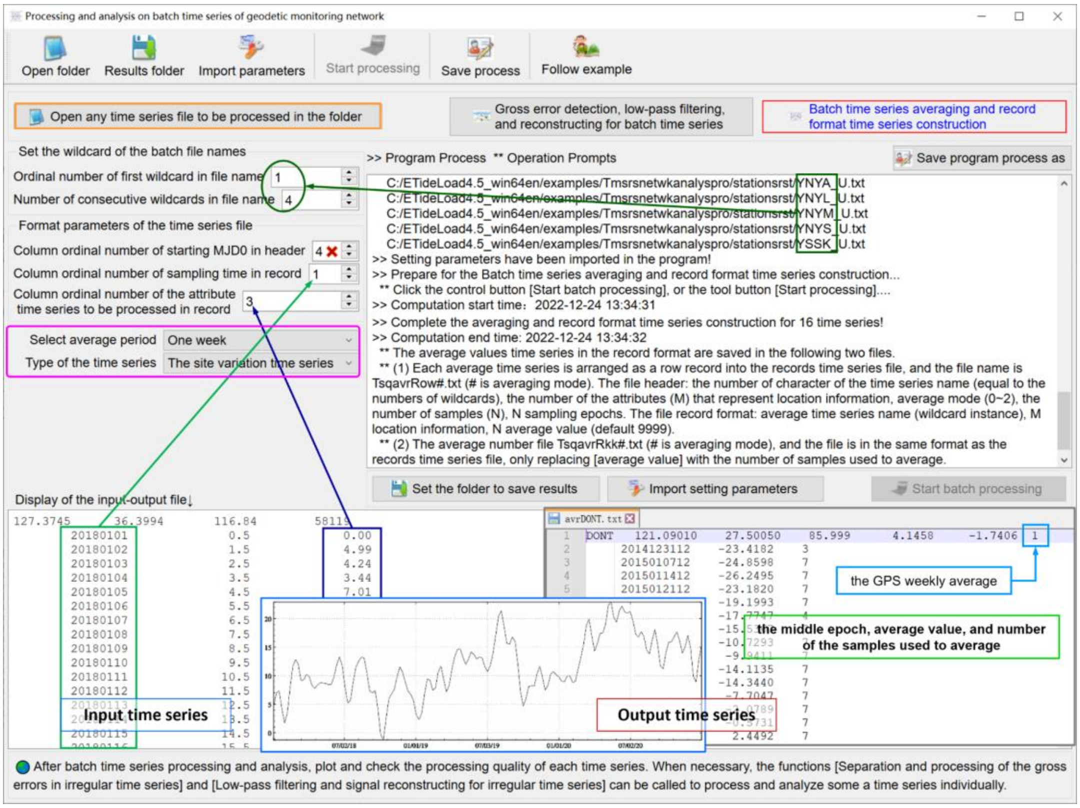
[Parameter settings] Set the wildcard parameters for batch variation time series files and input file format parameters, enter column ordinal number of the epoch time and target attribute time series in the record, and select the average period and type of the input time series files.

"The site variation time series" means that the sample of time series is the coordinate component, gravity, normal (orthometric) height, or tilt component of the ground site.

"Geodetic network time series" means that sample of the time series is the GNSS baseline component, leveling height difference, or gravity difference of the ground geodetic network.

[Output files] Batch mean variation time series files.

Behind the input file header, add the average mode (0 is the monthly average, 1 is the GPS weekly average, and 2 is the average of the given days) as the header of the average time series file. The record format: the middle epoch, average value, and number of the samples used to average.



The program output the average value time series in the record format in the following two files.

(1) The average value record time series file. Each average time series is arranged as a row record into the record time series file, and the file name is TsqavrRow#.txt (# is averaging mode).

The file header: the number of characters of the time series name (equal to the number of wildcards), the number of the attributes (M) that represent location information, average mode (0~2), the number of samples (N), N sampling epochs.

The file record format: average time series name (wildcard instance), M location information, N average value (default 9999).

(2) The average number file TsqavrRkk#.txt (# is averaging mode). The file is in the same format as the record time series file, only replacing "average value" with the number of samples used to average.

After batch time series processing and analysis, plot and check the processing quality of each time series. When necessary, the functions [Separation and processing of the gross errors in irregular time series] and [Low-pass filtering and signal reconstructing for Irregular time series] can be called to process and analyze some a time series individually.

3.6 Construction and analysis on record time series from geodetic network

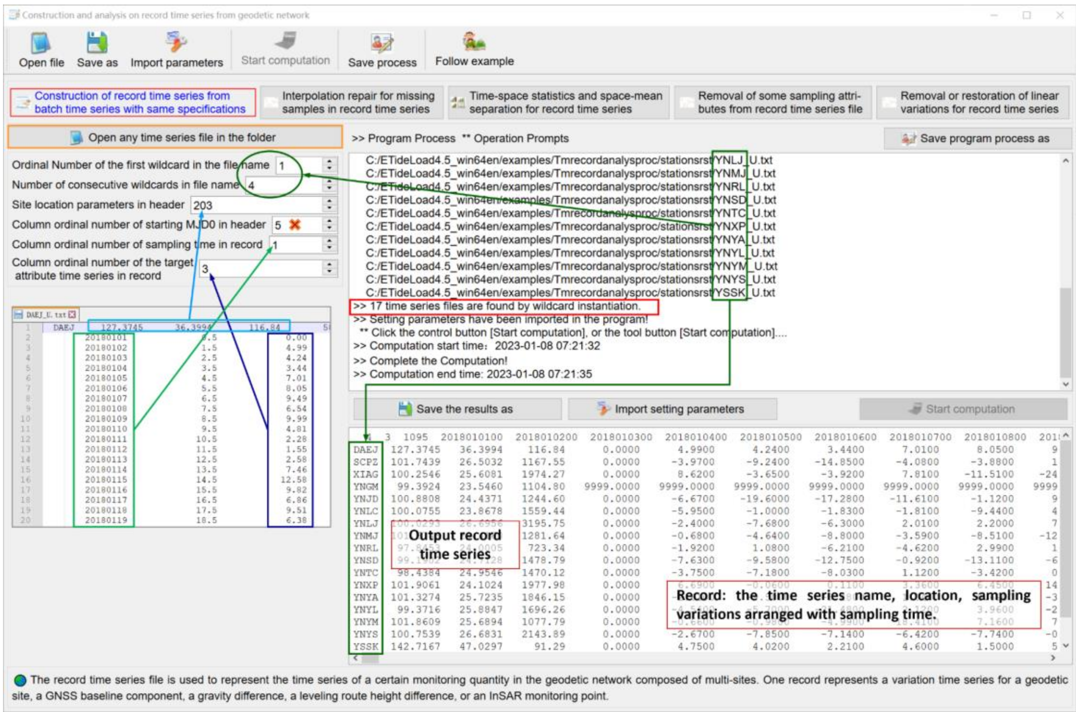
[Purpose] Construct and analyze the variation record time series composed of multi-periods or continuous data from the geodetic monitoring network.

The record time series file is used to represent the time series of a certain monitoring quantity in the geodetic network composed of multi-sites. One record represents a variation time series for a geodetic site, a GNSS baseline component, a gravity difference, a leveling route height difference or an InSAR monitoring point.

3.6.1 Construction of record time series from batch time series with same specifications

[Function] From batch time series files with the same specifications (same sampling time span and interval) stored in a folder, construct a record time series file according to the specified attribute.

The program calculates the maximum-minimum values of the sampling epochs and the minimum sampling interval in all the time series to build a new sampling specification. Each record stores one time series of the specified attribute, whose location information comes from the header of the corresponding input file. An attribute of 9999.000 indicates that there is no valid sampling value at the current epoch time.



[Input files] Batch time series files with the same sampling specifications.

[Parameter settings] Set the wildcard parameters for batch variation time series files and site location parameters in the input file header, enter column ordinal number of the epoch time and target attribute time series in the record.

[Output files] The variation record time series file.

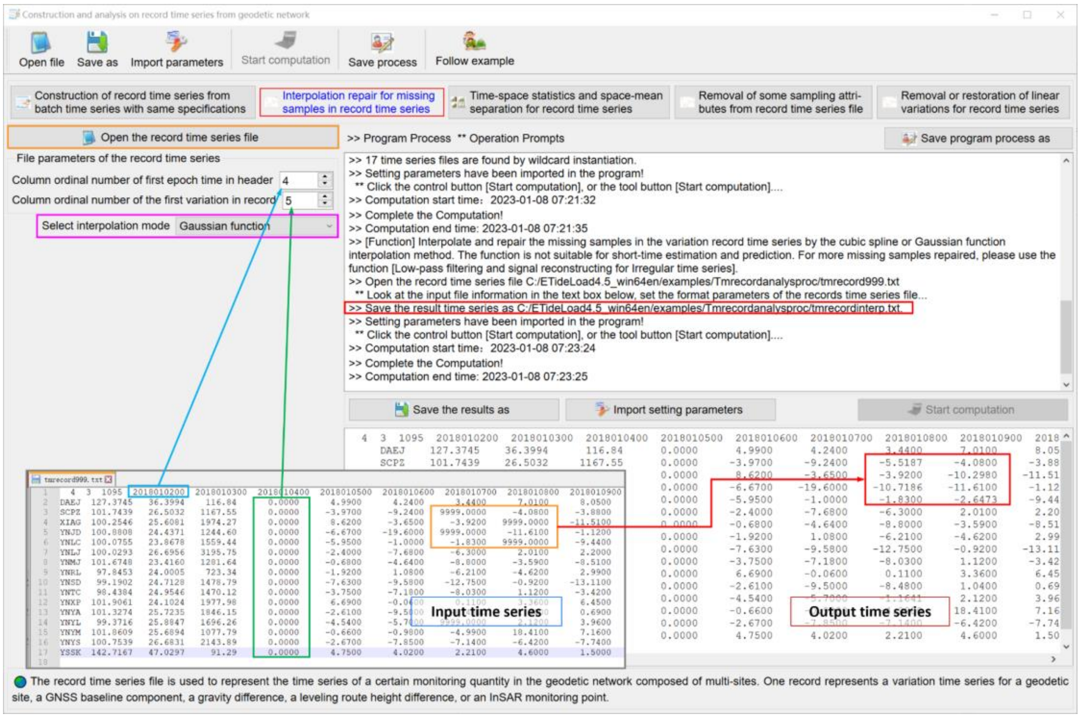
The file header: the number of characters of the time series name, number of columns occupied by the location information of the monitoring object in the record, length of the time series (number of samples), and all the sampling epochs arranged with time.

The file record: the time series name, location information (generally 3 to 4 attributes for a site, 6 to 8 attributes for a baseline or route), sampling variations arranged with sampling time.

3.6.2 Interpolation repair for missing samples in record time series

[Function] Interpolate and repair the missing samples in the variation record time series by the cubic spline or Gaussian function interpolation method. The function is not suitable for short-time estimation and prediction. For more missing samples repaired, please use the function [Low-pass filtering and signal reconstructing for Irregular time series].

When there are more noise or missing samples in time series signals, Gaussian function interpolation is recommended.



3.6.3 Time-space statistics and space-mean separation for record time series

[Function] Firstly, calculate the time average, standard deviation, minimum and maximum of each variation record time series during the entire sampling period. Then calculate the spatial average, standard deviation, minimum and maximum of all variations at each sampling epoch time. Finally, calculate the spatiotemporal average, standard deviation, minimum and maximum of all variations during the entire sampling period.

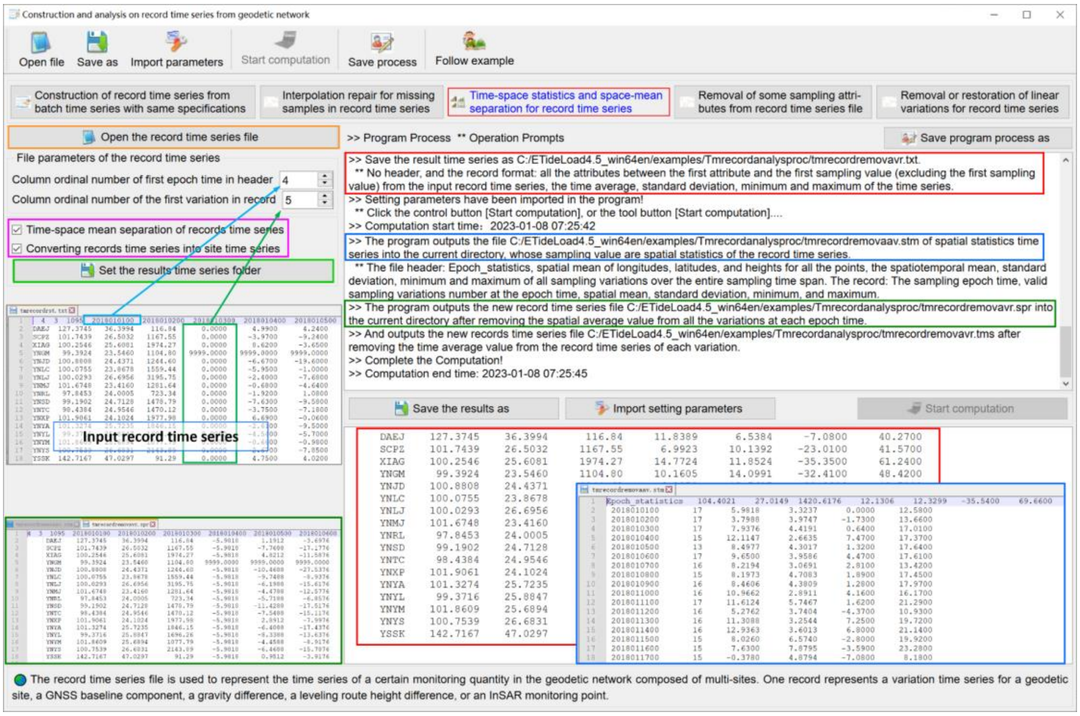
[Input file] The variation record time series file.

The sampling epochs in the file header should be one-by-one correspondence with the sampling variations in the file record.

[Parameter settings] Set the input file format parameters, enter column ordinal number of the epoch time in the header and target attribute time series in the record, and select the checkbox of time-space separation of record time series and converting record time series into site time series.

[Output files] The statistics result file on record time series, the variation record time series file after removing the space average, the variation record time series file after removing the time average, and the spatial statistics time series file.

The statistics result file on record time series file. No file header, and the record format: all the attributes between the first attribute and the first sampling value (excluding the first sampling value) from the input record time series, the time average, standard deviation, minimum and maximum of the time series.



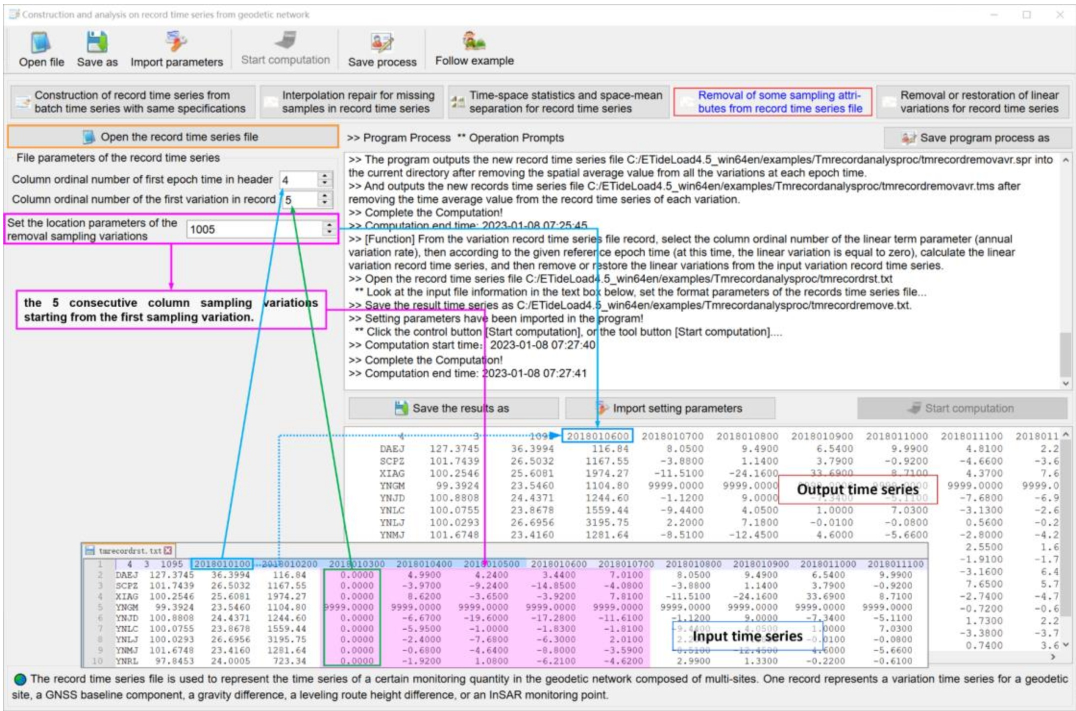
The spatial statistics time series file. The file header: Epoch_statistics, spatial mean of longitudes, latitudes, and heights for all the points, the spatiotemporal mean, standard deviation, minimum and maximum of all sampling variations over the entire sampling time span. The record: The sampling epoch time, valid sampling variations number at the epoch time, spatial mean, standard deviation, minimum, and maximum.

3.6.4 Removal of some sampling attributes from record time series file

[Function] Remove several consecutive columns of the sampling attributes from the record in the record time series file, and then remove the corresponding sampling epoch time in the file header.

[Input file] The variation record time series file.

[Parameter settings] Set the input file format parameters, input the location parameters of the removal sampling variations.



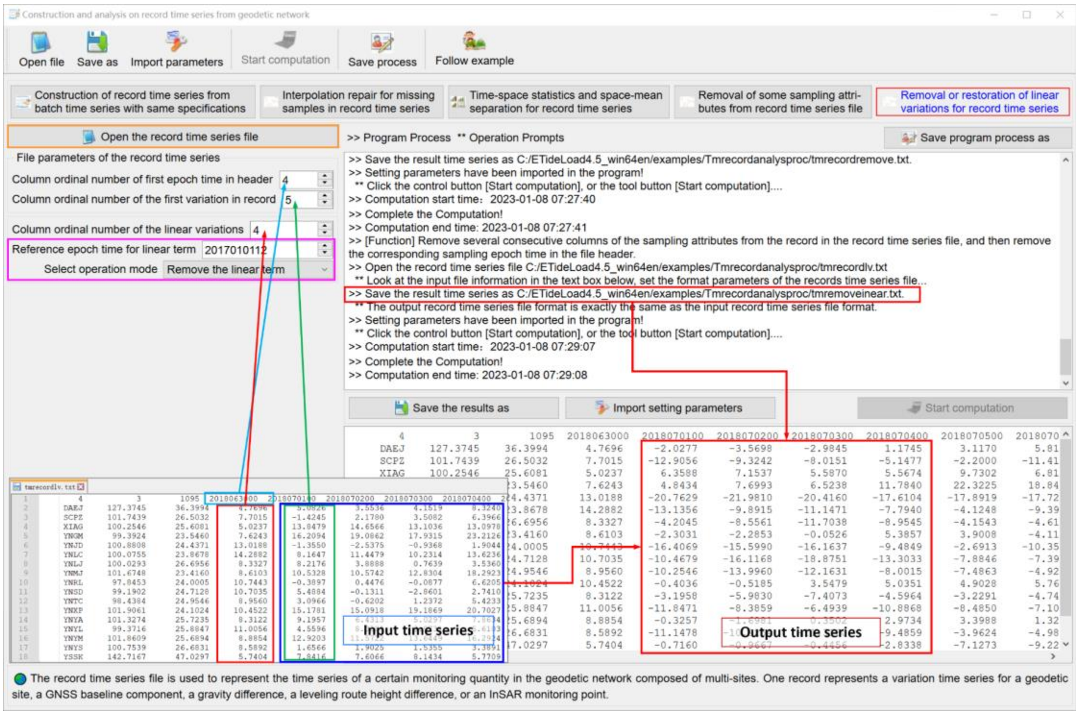
3.6.5 Removal or restoration of linear variations for record time series

[Function] From the variation record time series file record, select the column ordinal number of the linear term parameter (annual variation rate), then according to the given reference epoch time (at this time, the linear variation is equal to zero), calculate the linear variation record time series, and then remove or restore the linear variations from the input variation record time series.

[Input file] The variation record time series file.

[Parameter settings] Set the input file format parameters, enter column ordinal number of the linear term parameter in the record and the reference epoch time, and select to remove or restore the linear term.

[Output files] The result variation record time series file. The result file format is the same as that in the input record time series file.



3.7 Processing and analysis on variation (vector) grid time series

[Purpose] Perform operations such as the reference epoch transformation, difference, and statistical analysis on the variation (vector) grid time series in the specified folder. The variation (vector) grid time series files are extracted according to the given wildcards.

The variation (vector) grid time series is composed of a series of numerical grid files of a certain kind of variation (vector), and the seventh attribute of the file header in each grid file is agreed to be the sampling epoch.

3.7.1 Reference epoch transformation for grid time series

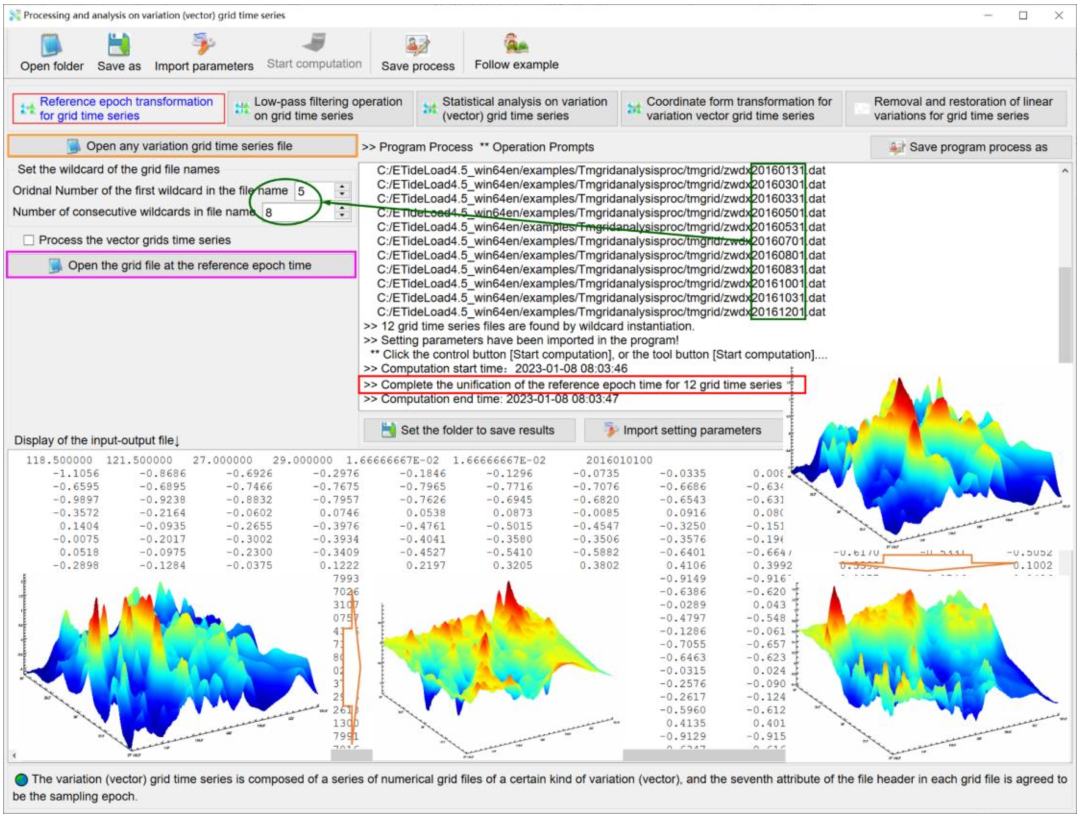
[Function] Unify the reference epoch time for all the variation (vector) grid time series by subtracting the variation (vector) grid at the given sampling time. After the epoch is unified, the variation grid values at the reference epoch time are always zero.

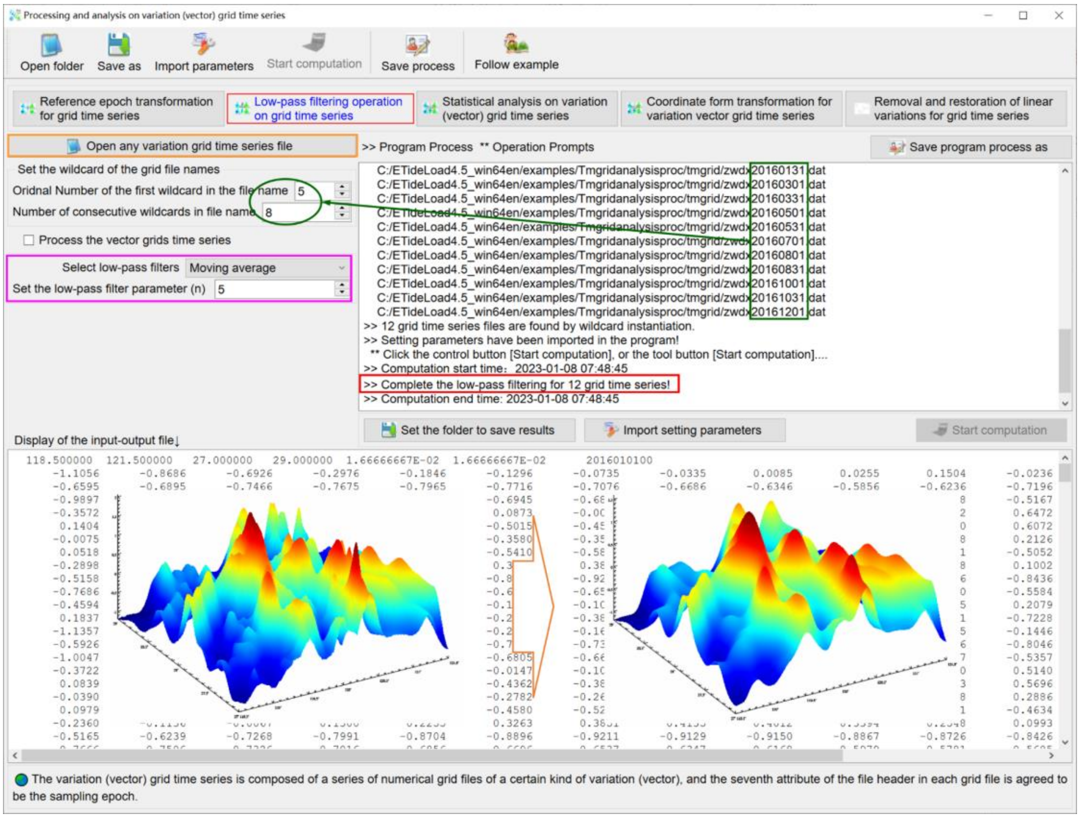
[Input file] The variation grid time series files. The variation grid file at the reference epoch time.

3.7.2 Low-pass filtering operation on grid time series

[Function] Using the low-pass filters such as the moving average, Gaussian, exponential, or Butterworth, perform low-pass filtering on the variation grid time series. Before and after filtering, the grid specifications (Latitude and longitude range and spatial resolution) remain unchanged.

For the moving average filtering, the greater the filtering parameter n, the greater the filtering strength. For "Gaussian", "Exponential" or "Butterworth" filters, the smaller the n, the greater the filtering strength.


Processing and analysis on variation (vector) grid time series
Open folder
Save as
Import parameters
Start computation
Save process
Follow example
Reference epoch transformation for grid time series
Low-pass filtering operation on grid time series
Statistical analysis on variation (vector) grid time series
Coordinate form transformation for variation vector grid time series
Removal and restoration of linear variations for grid time series
Open any variation grid time series file
>> Program Process ** Operation Prompts
Save program process as
Set the wildcard of the grid file names
Ordinal Number of the first wildcard in the file name 5
Number of consecutive wildcards in file name 8
Process the vector grids time series
Open the grid file at the reference epoch time
>> 12 grid time series files are found by wildcard instantiation.
>> Setting parameters have been imported in the program!
** Click the control button [Start computation], or the tool button [Start computation]....
>> Computation start time: 2023-01-08 08:03:46
>> Complete the unification of the reference epoch time for 12 grid time series
>> Computation end time: 2023-01-08 08:03:47
Set the folder to save results
Import setting parameters
Display of the input-output file↓
The variation (vector) grid time series is composed of a series of numerical grid files of a certain kind of variation (vector), and the seventh attribute of the file header in each grid file is agreed to be the sampling epoch.


Processing and analysis on variation (vector) grid time series
Open folder
Save as
Import parameters
Start computation
Save process
Follow example
Reference epoch transformation for grid time series
Low-pass filtering operation on grid time series
Statistical analysis on variation (vector) grid time series
Coordinate form transformation for variation vector grid time series
Removal and restoration of linear variations for grid time series
Open any variation grid time series file
>> Program Process ** Operation Prompts
Save program process as
Set the wildcard of the grid file names
Ordinal Number of the first wildcard in the file name 5
Number of consecutive wildcards in file name 8
Process the vector grids time series
Select low-pass filters Moving average
Set the low-pass filter parameter (n) 5
>> 12 grid time series files are found by wildcard instantiation.
>> Setting parameters have been imported in the program!
** Click the control button [Start computation], or the tool button [Start computation]....
>> Computation start time: 2023-01-08 07:48:45
>> Complete the low-pass filtering for 12 grid time series!
>> Computation end time: 2023-01-08 07:48:45
Set the folder to save results
Import setting parameters
Start computation
Display of the input-output file↓
The variation (vector) grid time series is composed of a series of numerical grid files of a certain kind of variation (vector), and the seventh attribute of the file header in each grid file is agreed to be the sampling epoch.

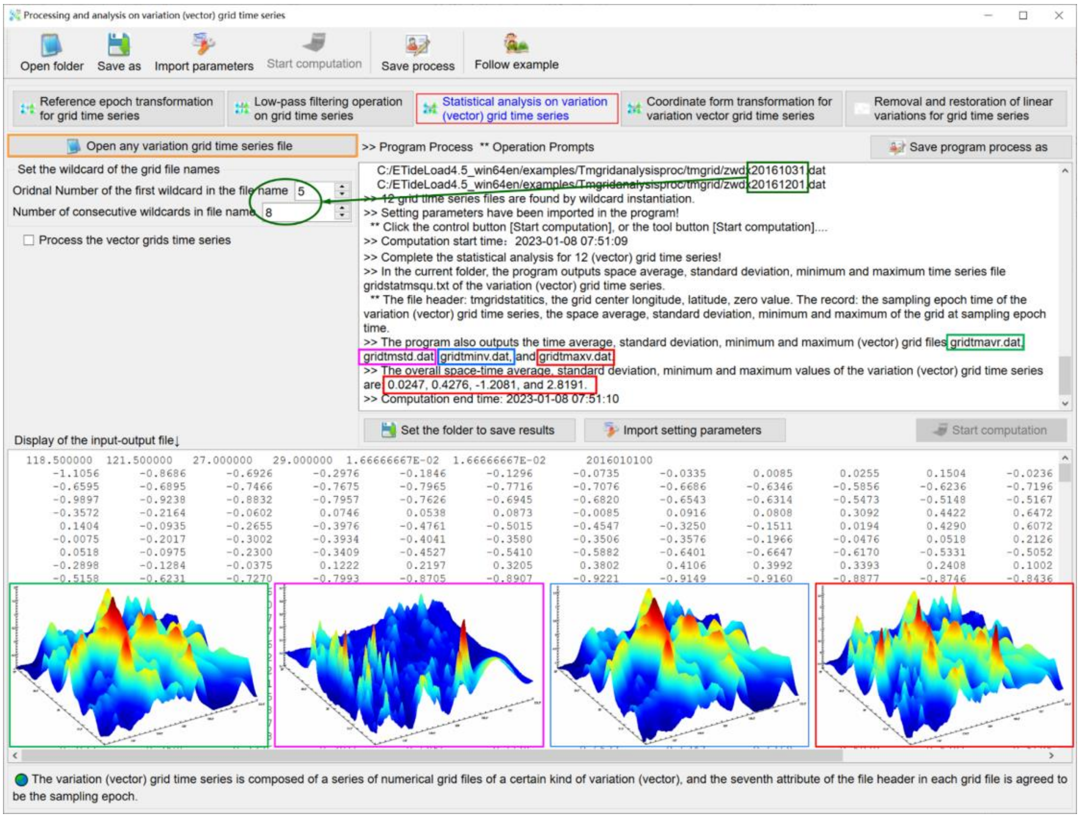
3.7.3 Statistical analysis on variation (vector) grid time series

[Function] Calculate the space average, standard deviation, minimum and maximum of the variation (vector) grid time series at each sampling epoch time, to generate the space average, standard deviation, minimum and maximum (four attributes) time series file. Then generate a new variation (vector) grid time series by removing the space average grid at each epoch time. Finally, calculate the time average, standard deviation, minimum and maximum of the time series of each (vector) grid element, to generate time average, standard deviation, minimum and maximum (vector) four grid files.

The program outputs the space average, standard deviation, minimum and maximum time series file gridstatmsqu.txt of the variation (vector) grid time series.

The file header: tmgridstatitics, the grid center longitude, latitude, zero value. The record: the sampling epoch time of the variation (vector) grid time series, the space average, standard deviation, minimum and maximum of the grid at sampling epoch time.

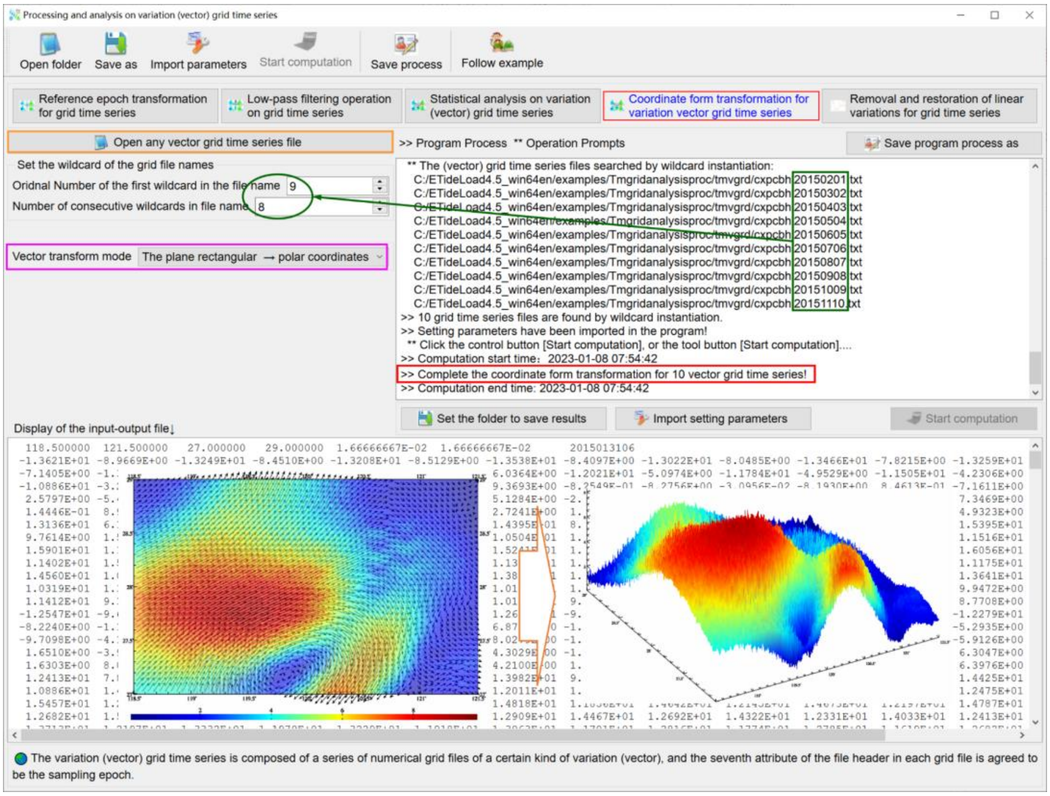
The program also outputs the time average, standard deviation, minimum and maximum (vector) grid files gridtmavr.dat, gridtmstd.dat, gridtminv.dat, and gridtmaxv.dat.



3.7.4 Coordinate form transformation for variation vector grid time series

[Function] The vector in the variation vector grid time series is transformed between the polar coordinate form (r, a) and the plane rectangular coordinate form (E, N).

[Input file] The variation vector grid time series files.



3.7.5 Removal and restoration of linear variations for grid time series

[Function] Using the annual variation (vector) rate grid, calculate the linear variation (vector) grid time series according to the given reference epoch time (the linear variation at reference epoch time is always equal to zero), and then remove or restore the linear variations of the variation (vector) grid time series.

3.8 Multi-form spatiotemporal interpolation from grid time series

[Purpose] From the variation (vector) grid time series files in the specified folder, construct the variation time series according to the location and sampling specifications by the given space and time interpolation method. The variation (vector) grid time series files are extracted according to the given wildcards.

The latitude and longitude of the site to be interpolated should not exceed the latitude and longitude range of the grid time series, and the interpolated epoch should not exceed the sampling time range of the grid time series by too much.

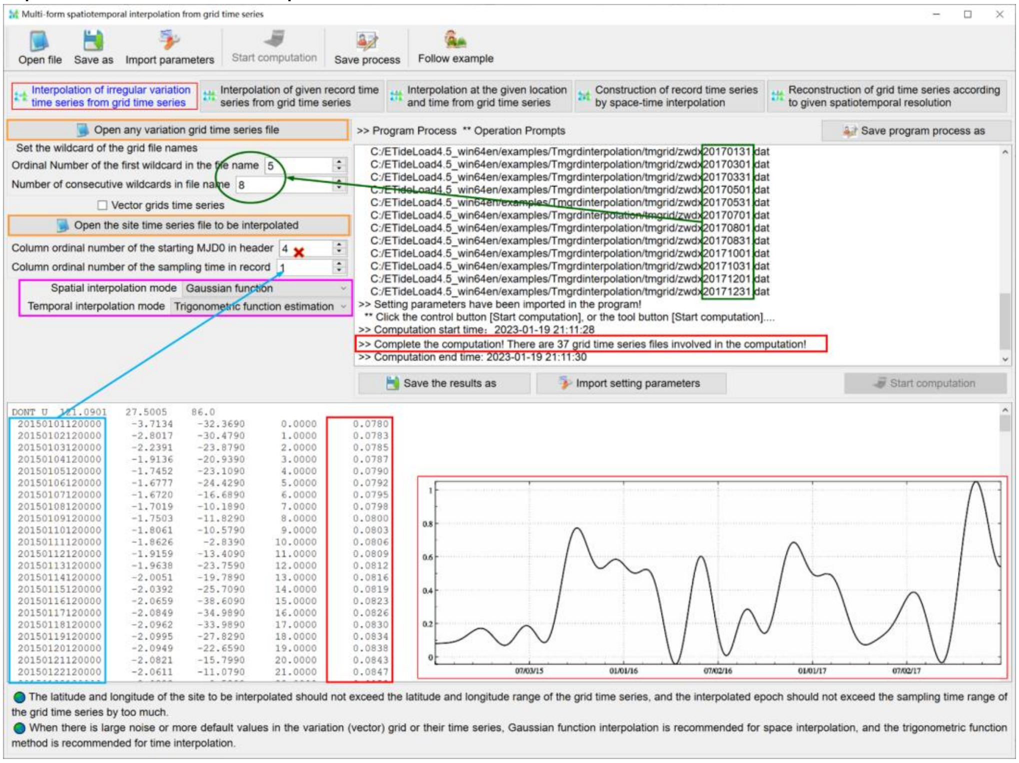
When there is large noise or more default values in the variation (vector) grids or their time series, Gaussian function interpolation is recommended for space interpolation, and the trigonometric function method is recommended for time interpolation.

3.8.1 Interpolation of irregular variation time series from grid time series

[Function] From the variation (vector) grid time series files, construct the irregular variation time series according to the location and sampling specification in the input irregular time series by the given two-dimensional space interpolation and one-dimensional time interpolation method.

[Input file] The variation (vector) grid time series files. The site variation time series file to be interpolated.

[Parameter settings] Set the wildcard parameters for the variation (vector) grid time series files and the site variation time series file format parameters. Select the space interpolation and time interpolation method.



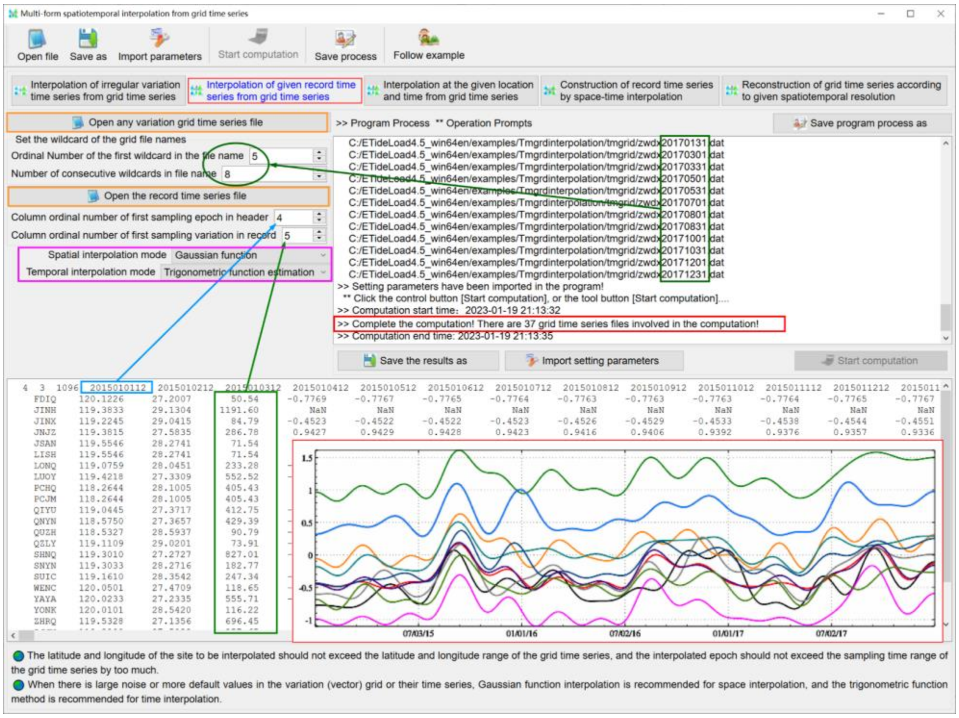
3.8.2 Interpolation of given record time series from grid time series

[Function] Using the given two-dimensional space interpolation and one-dimensional time interpolation method, interpolate to obtain all the sampling values of the input record time series from the variation grid time series files. The output record time series file format is the same as the input record time series file.

The program also outputs the remnant variation record time series file (file extension rnt) into the current folder. The format is the same as the input record time series file. Here the remnant variation is equal to the difference between the input sample value and the interpolation.

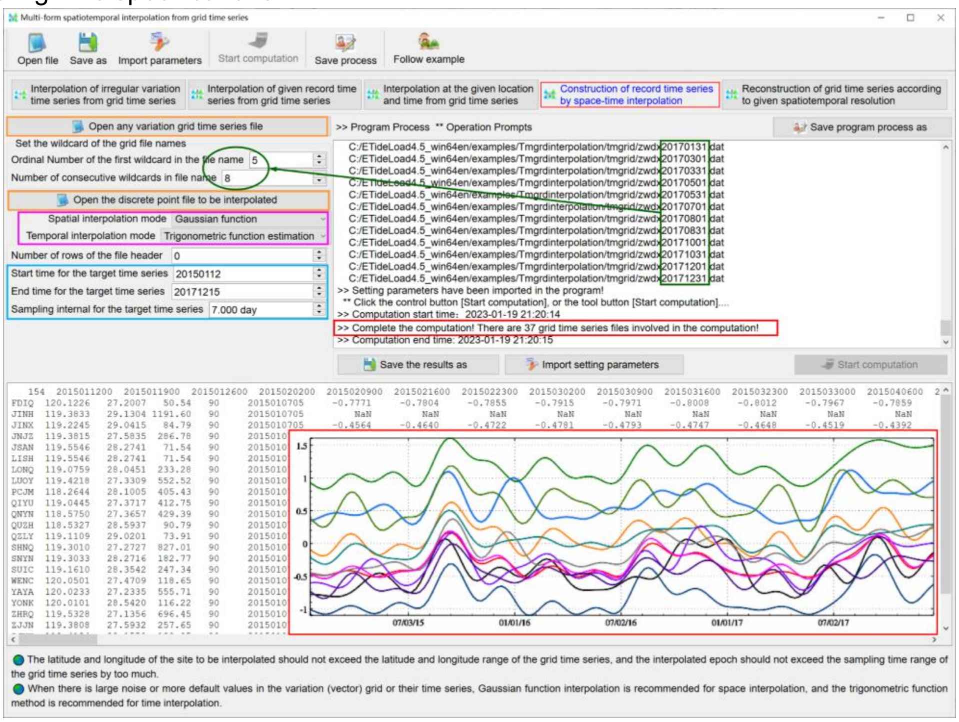
3.8.3 Interpolation at the given location and time from grid time series

[Function] Using the given two-dimensional space interpolation and one-dimensional time interpolation method, interpolate or estimate the sampling value at the given location and epoch time from the variation grid time series files.



3.8.4 Construction of record time series by space-time interpolation

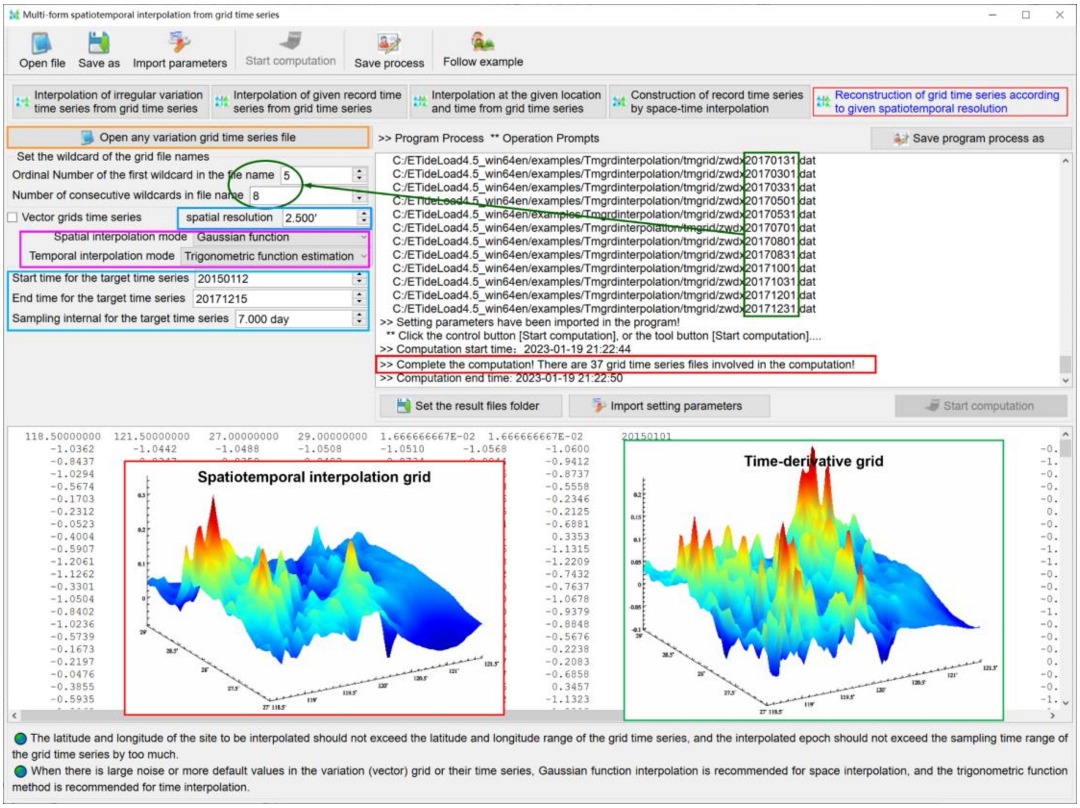
[Function] Using the given two-dimensional space interpolation and one-dimensional time interpolation method, from the variation grid time series files, construct the record time series at the specified location sites in the input discrete point file according to the given sampling time specifications.



3.8.5 Reconstruction of grid time series according to given spatiotemporal resolution

[Function] Using the given two-dimensional spatial interpolation and one-dimensional time interpolation or estimation method, increase or decrease the spatial and temporal resolution of the grid time series according to the given grid spatial resolution and time sampling specification, and then calculate time-derivative (per week, /wk) of the variation grid time series.

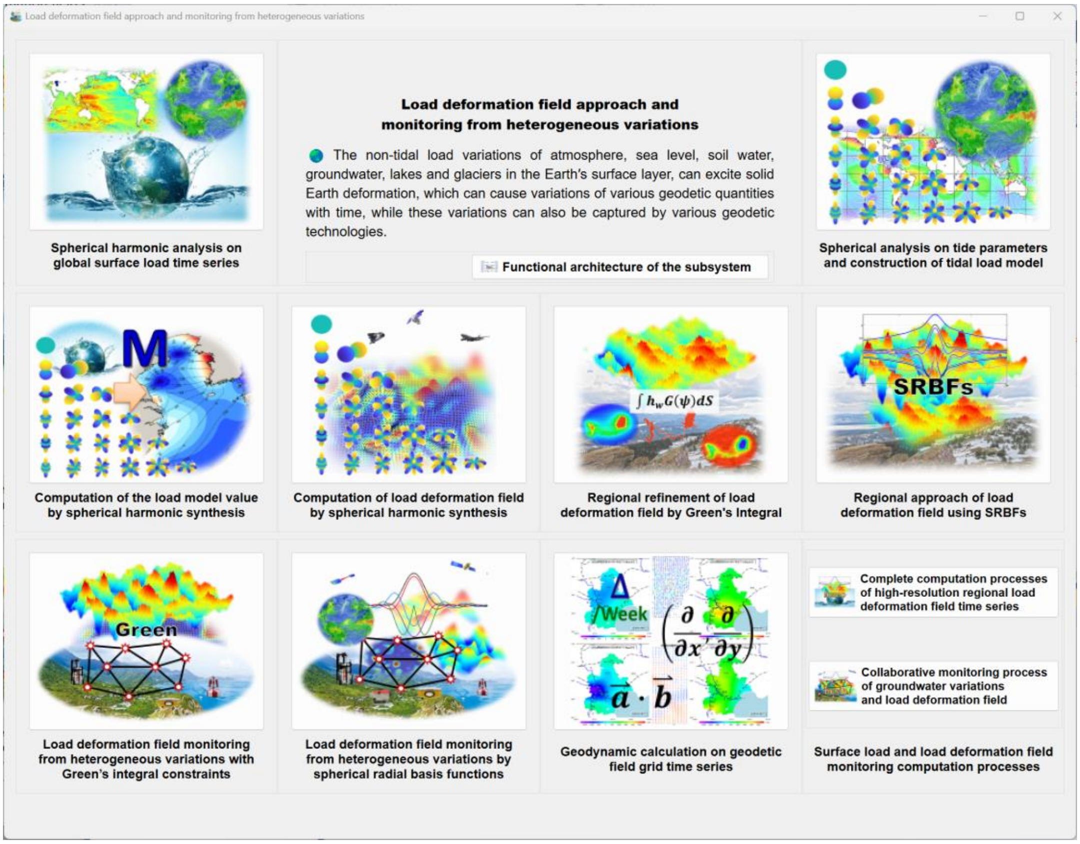
The program output the variation (vector) grid time series files grdtmsp*.dat and their time-derivative (vector) grid time series files grdtmdf.dat (per week, /wk).



4 Load deformation field approach and monitoring from heterogeneous variations

The non-tidal load variations of atmosphere, sea level, soil water, groundwater, lakes and glaciers in the Earth's surface layer, can excite solid Earth deformation, which can cause variations of various geodetic quantities with time, while these variations can also be captured by various geodetic technologies.

The group of programs can be employed to compute and approach the global and regional non-tidal load effects, and then constrain and assimilate the deep fusion of multi-source heterogeneous data strictly according to the principles of geodesy and solid geodynamics, so as to realize the collaborative monitoring of land water variations and time-varying gravity field from heterogeneous geodesy.



Using the consistent geophysical models, uniform numerical standards, and compatible algorithms to monitor and represent various geodetic non-tidal effects, are the important basis for 1cm (20μGal) accuracy level geodesy, and are also necessary conditions to realize the collaboration of the geodetic multi-technologies, the deep fusion of the multi-source heterogeneous geodetic data, and construction and maintenance of high-accuracy geodetic datum frame.

4.1 Spherical harmonic analysis on global surface load time series

[Purpose] From the global grid model of the surface loads such as land/sea surface atmosphere, land water and sea level variation, generate a normalized surface load spherical harmonic coefficient model by spherical harmonic analysis. Using the model, the non-tidal load effects on various geodetic variations outside the solid Earth can be computed by the spherical harmonic synthesis method.

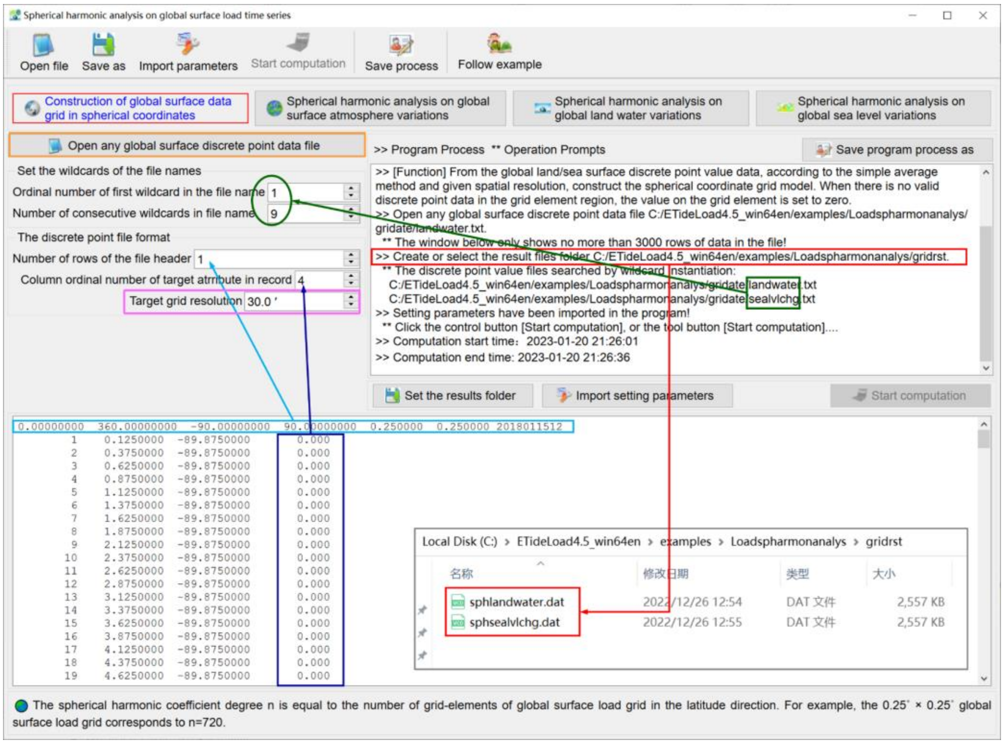
The spherical harmonic coefficient degree n is equal to the number of grid-elements of global surface load grid in the latitude direction. For example, the 0.25° × 0.25° global surface load grid corresponds to n =720.

4.1.1 Construction of global surface data grid in spherical coordinates

[Function] From the global land/sea surface discrete point value data, according to the simple average method and given spatial resolution, construct the spherical coordinate grid model. When there is no valid discrete point data in the grid element region, the value on the grid element is set to zero.

[Input files] A series of global land/sea surface discrete point value data files with the same format.

The file record format: Point number (name), longitude, latitude (decimal degrees), …, attribute to be gridded, ….



[Parameter settings] Set the wildcard parameters of the input file names. enter the number of rows of the input file header, row ordinal number of target attribute in the file record, and grid resolution.

[Output files] A series of spherical coordinate grid files that correspond one-to-one with the input discrete point value files.

4.1.2 Spherical harmonic analysis on global surface atmosphere variations

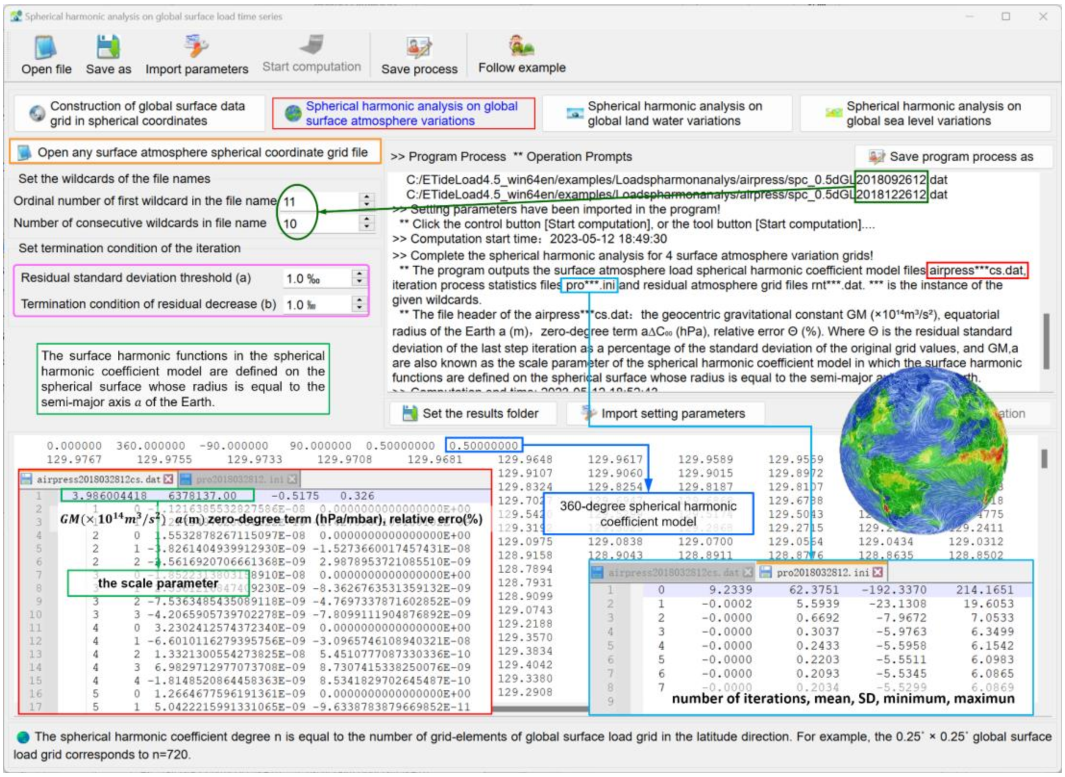
[Function] From the global land/sea surface atmosphere variation (in unit hPa or mbar) spherical coordinate grid time series, compute the non-tidal atmosphere load spherical harmonic coefficient models (in unit m) time series by normalized spherical harmonic analysis.

The spherical coordinate grid time series files are extracted according to the given wildcards.

[Input files] The global land/sea surface atmosphere variation spherical coordinate grid time series files.

[Parameter settings] Set the wildcard parameters for the file names of grid time series and enter the iteration condition parameters.

[Output files] The surface atmosphere load spherical harmonic coefficient model files airpress***cs.dat, iteration process statistics file pro***.ini and residual atmosphere grid file rnt***.dat. Here, *** are the instance of the given wildcards.



The file header of the airpress***cs.dat: the geocentric gravitational constant GM (×10¹⁴m³/s²), equatorial radius of the Earth a (m), zero-degree term $a\Delta C_{00}$ (hPa), relative error Θ (%). Where Θ is the residual standard deviation of the last step iteration as a percentage of the standard deviation of the original grid values, and GM, a are also known as the scale parameter of the spherical harmonic coefficient model in which the surface harmonic functions are defined on the spherical surface whose radius is equal to the semi-major axis a of the Earth.

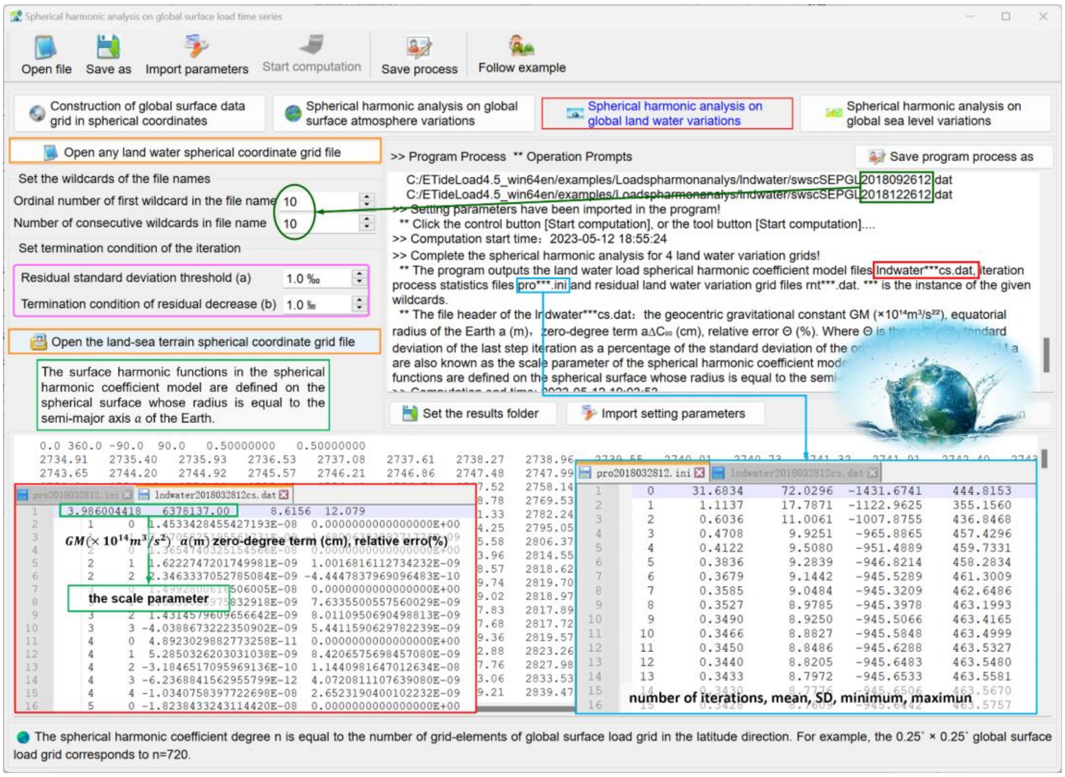
The zero-degree term represents the variations of the total atmospheric mass caused by the variation of global atmospheric pressure, which is meaningless under the condition of Earth's atmospheric mass conservation. The three first-degree spherical harmonic coefficients (ΔC_{10}, ΔC_{11}, ΔS_{11}) represent variations of the Earth's center of mass due to the variations of global atmospheric pressure.

4.1.3 Spherical harmonic analysis on global land water variations

[Function] From the global land equivalent water height variation (in unit cm) spherical coordinate grid time series, compute the land water non-tidal load spherical harmonic coefficient models (in unit m) time series by normalized spherical harmonic analysis.

[Input files] The global land equivalent water height variation spherical coordinate grid time series files. The land-sea terrain spherical coordinates grid file.

The spatial resolution of the land-sea terrain grid should not be lower than the spatial resolution of the surface loads grid.



[Parameter settings] Set the wildcard parameters for the file names of grid time series and enter the iteration condition parameters.

[Output files] The global land water load spherical harmonic coefficient model files lndwater***cs.dat, Iteration process statistics file pro***.ini and residual equivalent water height grid file rnt***.dat. Here, *** are the instance of the given wildcards.

The file header of the lndwater***cs.dat: the geocentric gravitational constant GM ($\times10^{14}m^3/s^2$), equatorial radius of the Earth a (m), zero-degree term $a\Delta C_{00}$ (cm), relative error Θ (%).

The three first-degree spherical harmonic coefficients (ΔC_{10}, ΔC_{11}, ΔS_{11}) represent variations of the Earth's center of mass due to variations of global land water. For global geodetic purposes, the first-degree spherical harmonic coefficients need to be considered. The zero-degree term can be controlled to a small value by adjusting the time datum.

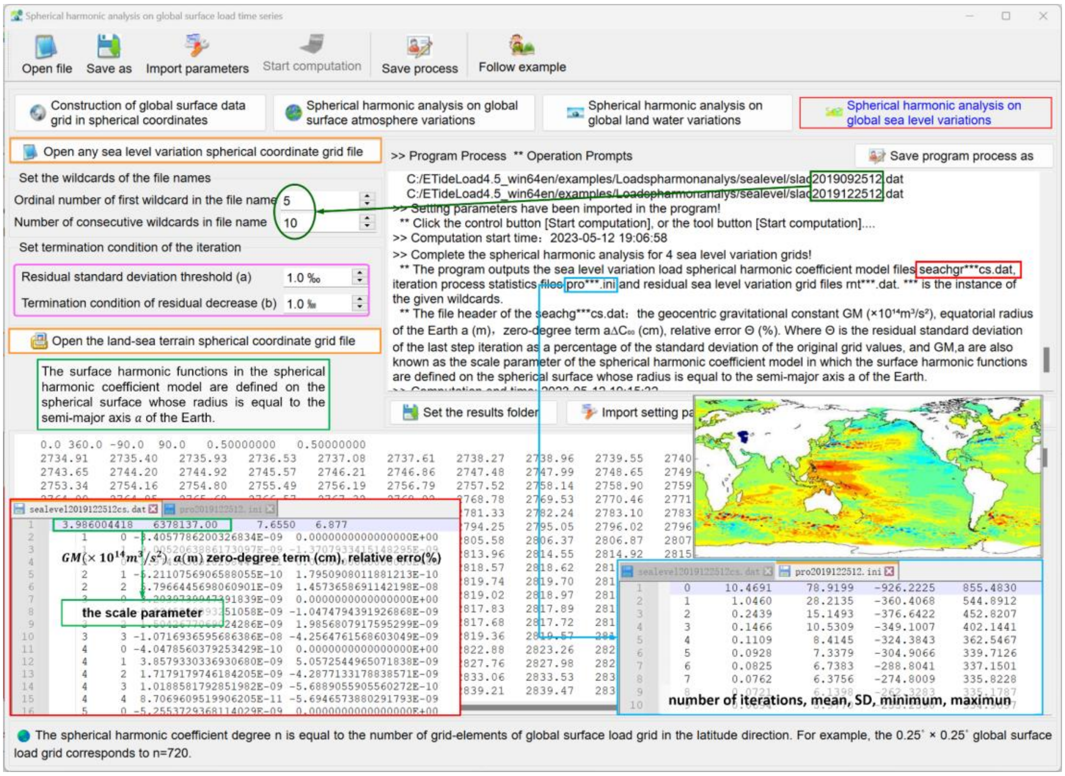
4.1.4 Spherical harmonic analysis on global sea level variations

[Function] From the global non-tidal sea level variation (in unit cm) spherical coordinate grid time series, compute the sea level variation load spherical harmonic coefficient models (in unit m) time series by normalized spherical harmonic analysis.

[Input files] The global sea level variation spherical coordinate grid time series files. The land-sea terrain spherical coordinates grid file.

The spatial resolution of the land-sea terrain grid should not be lower than the spatial resolution of the surface loads grid.

[Parameter settings] Set the wildcard parameters for the file names of grid time series and enter the iteration condition parameters.



Iteration termination condition: The standard deviation of the residual grid value is less than a% of the standard deviation of the original grid value, or the difference of the residual standard deviation of the previous step iteration relative to the current step iteration is less than b‰ of the standard deviation of the original grid values.

[Output files] The global sea level variation load spherical harmonic coefficient model files seachg***cs.dat, iteration process statistics files pro***.ini and residual sea level variation grid files rnt***.dat. Here, *** are the instance of the given wildcards.

The three first-degree spherical harmonic coefficients (ΔC_{10}, ΔC_{11}, ΔS_{11}) represent variations of the Earth's center of mass due to global sea level variations. For global geodetic purposes, the first-degree spherical harmonic coefficients needs to be taken into account. The zero-degree term can be controlled to a small value by adjusting the time datum.

For global geodetic purposes, the zero constraint should be considered that the sum of the zero-degree terms of sea, land and atmosphere at any epoch time is equal to zero, that is, the total loads of sea level, land water and atmospheric pressure variations is conserved.

4.2 Spherical analysis on tide parameters and construction of tidal load model

[Purpose] From the tidal constituent harmonic parameter grid of the global land/sea atmosphere or sea surface height, generate a normalized tidal load spherical harmonic coefficient model by spherical harmonic analysis. The model format is the same as FES2004 ocean tidal load model in the IERS conventions (2010). Using the model, the tidal load effects on various geodetic variations outside the solid Earth can be computed by the spherical harmonic synthesis method.

The unit of the tidal constituent harmonic parameters is the same as the unit of the spherical harmonic coefficients. The unit of the surface atmosphere tidal harmonic parameters and the load spherical harmonic coefficients are hPa or mbar, and the unit of the ocean tidal harmonic parameters and the load spherical harmonic coefficients are cm.

4.2.1 Construction tidal harmonic parameter grid in spherical coordinates

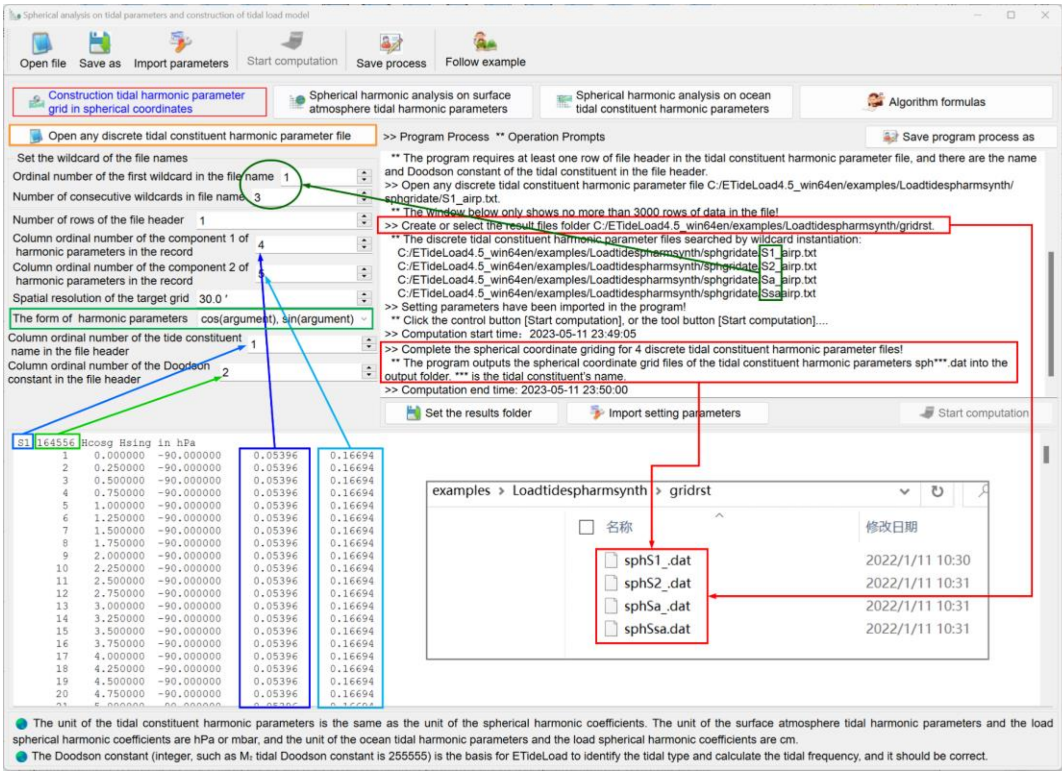
[Function] From the tidal constituent harmonic parameters of the surface atmosphere or sea surface height on the discrete points, according to the simple average method and given spatial resolution, construct spherical coordinate harmonic parameter vector (prograde amplitude, retrograde amplitude) grid model. When there is no valid discrete harmonic parameter data in the grid element region, the vector on the grid element is set to zero.

[Input files] A series of global discrete tidal constituent harmonic parameter files with the same format.

The program requires at least one row of file header in the tidal constituent harmonic parameter file, and there are the name and Doodson constant of the tidal constituent in the file header.

The Doodson constant (integer, such as M_2 tidal Doodson constant is 255555) is the basis for ETideLoad programs to identify the tidal type and calculate the tidal frequency, and it should be correct.

[Parameter settings] Set the wildcard parameters of the input file names. Enter the number of rows of the input file header, column ordinal number of the tidal constituent name and its Doodson constant the input file header, column ordinal number of the component 1 and 2 of harmonic parameters in the record and select the form of harmonic parameters.



[Output files] The spherical coordinate grid files of the tidal constituent harmonic parameters sph***.dat. Here, *** are the tidal constituent's name.

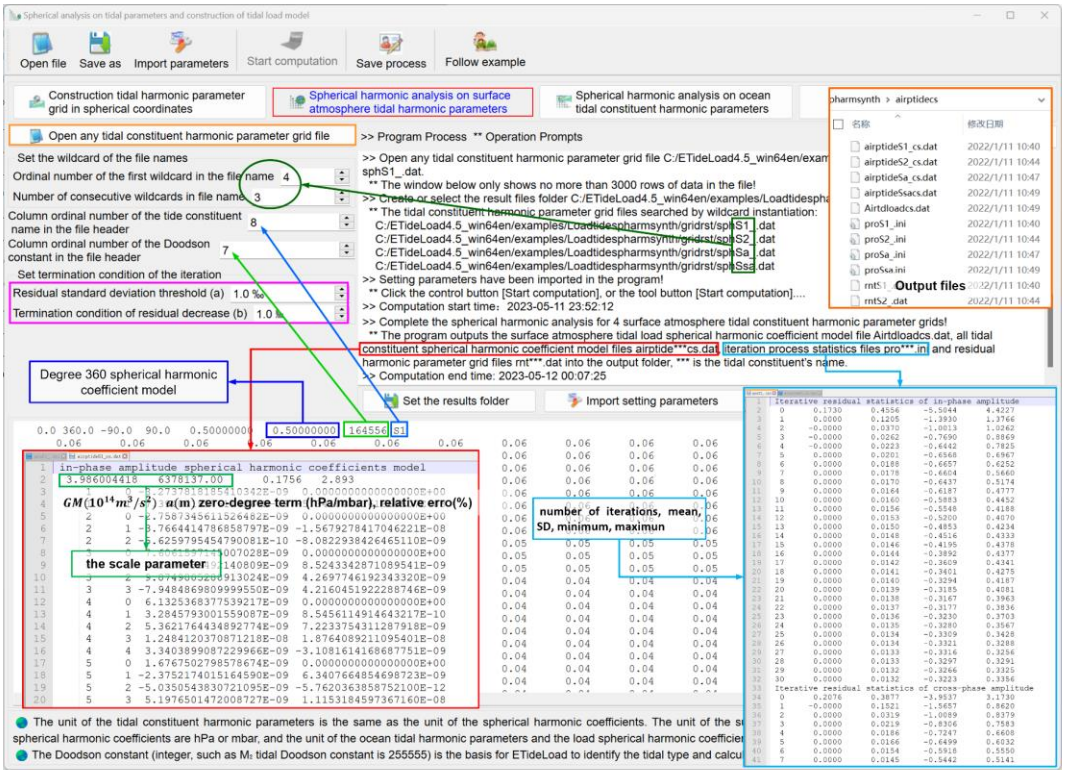
4.2.2 Spherical harmonic analysis on surface atmosphere tidal harmonic parameters

[Function] From the surface atmosphere tidal constituent harmonic parameter (in unit hPa or mbar) spherical coordinate grid, compute the surface atmosphere tidal load spherical harmonic coefficient model (in unit hPa or mbar) in FES2004 format by normalized spherical harmonic analysis.

The tidal constituent harmonic parameter vector spherical coordinate grid files are extracted according to the given wildcards.

[Input files] All the surface atmosphere tidal constituent harmonic parameter vector spherical coordinate grid files.

[Parameter settings] Set the wildcard parameters for the file names, enter the column ordinal number of the tide constituent's name and its Doodson constant the input file header, and set the iteration condition parameters.



[Output files] The surface atmosphere tidal load spherical harmonic coefficient model file Airtdloadcs.dat, all tidal constituent spherical harmonic coefficient model files airptide***cs.dat, iteration process statistics files pro***.ini and residual harmonic parameter grid files rnt***.dat. Here, *** are the tidal constituent's name.

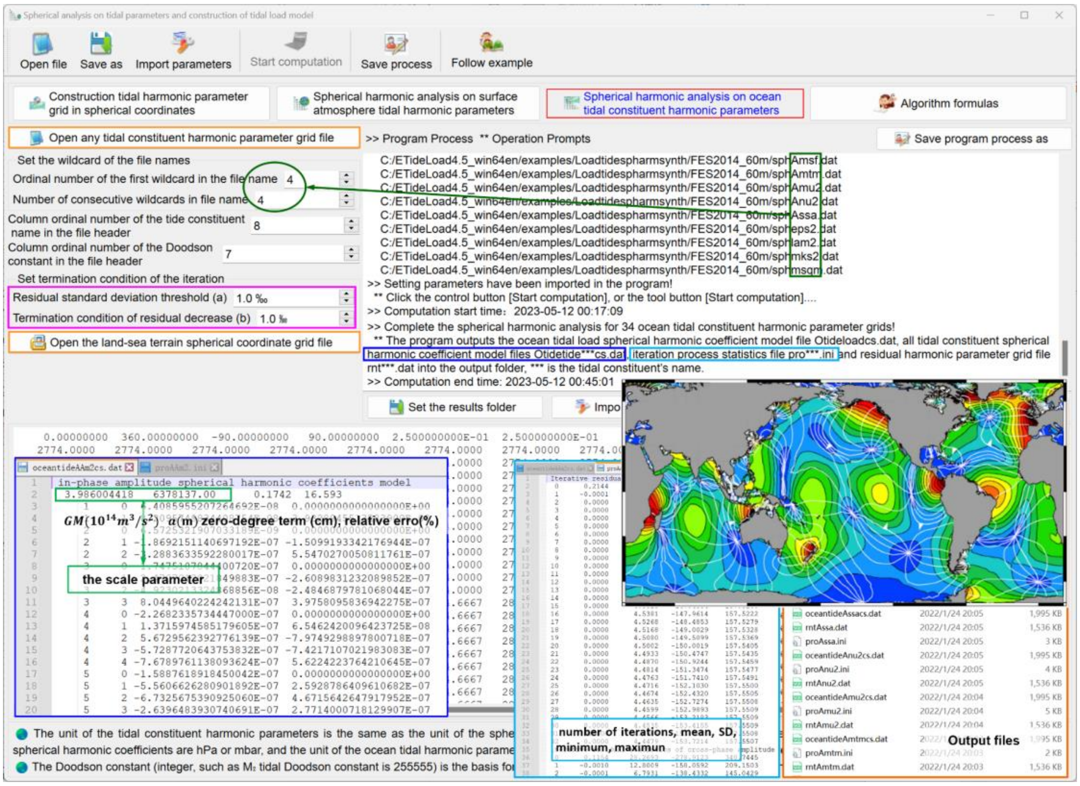
4.2.3 Spherical harmonic analysis on ocean tidal constituent harmonic parameters

[Function] From the ocean tidal constituent harmonic parameter (in unit cm) spherical coordinate grid, compute the ocean tidal load spherical harmonic coefficient model (in unit cm) in FES2004 format by spherical harmonic analysis.

[Input files] All the ocean tidal constituent harmonic parameter vector spherical coordinate grid files. The land-sea terrain spherical coordinate grid file.

The land-sea terrain spherical coordinates grid is used for the land-sea separation for the ocean tidal harmonic parameters, whose resolution should not be lower than the resolution of the ocean tidal constituent harmonic parameter grid.

[Output files] The ocean tidal load spherical harmonic coefficient model file Otideloadcs.dat, all tidal constituent spherical harmonic coefficient model files Otidetide***cs.dat, iteration process statistics file pro***.ini and residual harmonic parameter grid file rnt***.dat. Here, *** are the tide constituent's name.



4.3 Computation of the load model value by spherical harmonic synthesis

[Purpose] From the tidal load spherical harmonic coefficient model or the surface non-tidal load spherical harmonic coefficient model, compute the model values of the tidal harmonic parameters or the non-tidal surface loads by spherical harmonic synthesis.

In the remove-restore process, the program can be employed for regional tidal load effects refinement based on the tidal load spherical harmonic coefficient model, and for regional load deformation field and temporal gravity field approaching based on the surface load spherical harmonic model.

4.3.1 Computation of model value of surface load equivalent water height

[Function] From the surface atmosphere, land water, or sea level variation load normalized spherical harmonic coefficient model (m), compute the model value of the surface atmosphere (hPa/mbar), land equivalent water height (cm), or sea level variation (cm) at the given location.

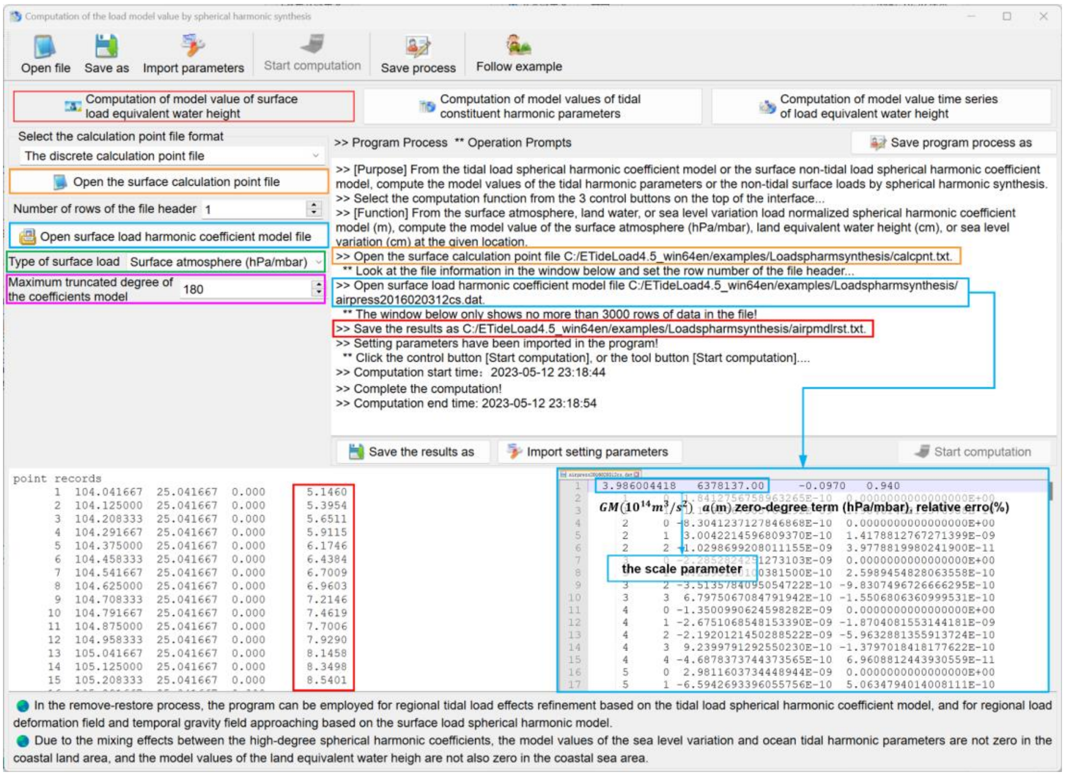
[Input files] The surface calculation point file. The surface load spherical harmonic coefficient model file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

[Parameter settings] Select the format of the calculation point file, enter maximum truncated degree of the coefficient model and select the type of surface loads.

The program automatically selects the minimum value between the maximum degree of the spherical harmonic coefficient model and the entered maximum degree as the calculated degree.



[Output file] The surface load model value file.

When the discrete calculation point file input, the output file header is the same as the input file. Behind the input file record, add a column of the model value of surface load as the output file record.

When the calculation surface height grid file input, the program outputs the surface load model value grid files with the same grid specifications.

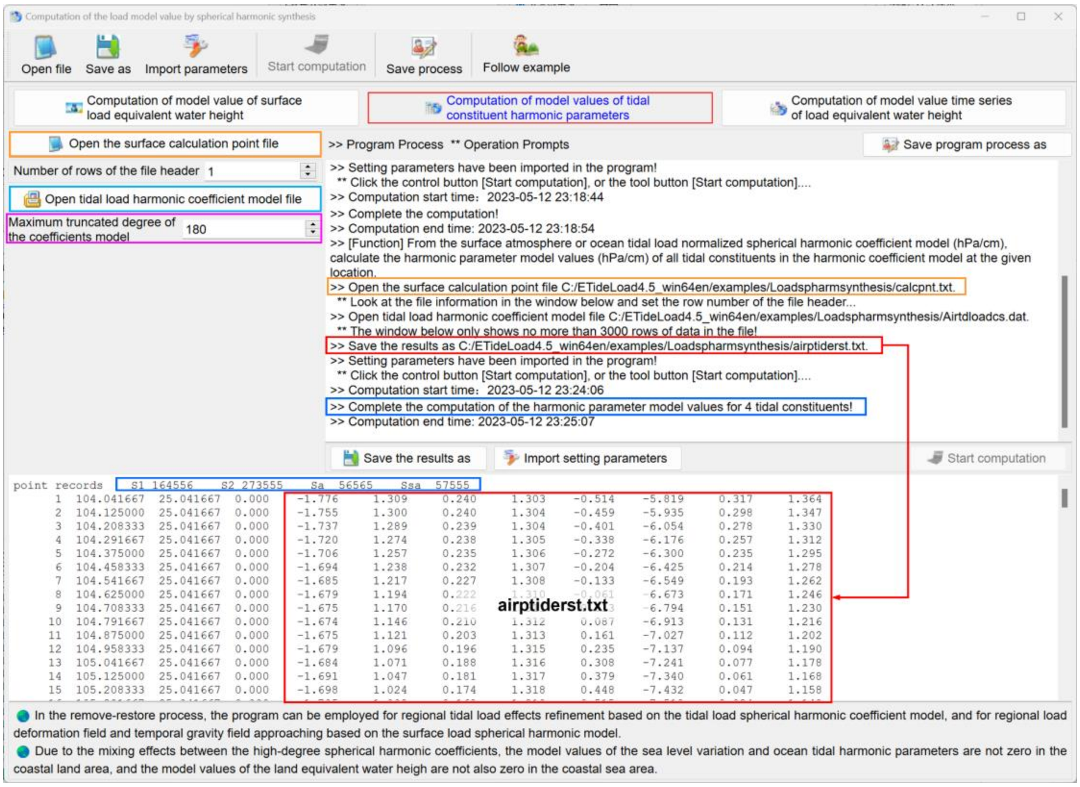
4.3.2 Computation of model values of tidal constituent harmonic parameters

[Function] From the surface atmosphere or ocean tidal load normalized spherical harmonic coefficient model (hPa/cm), calculate the harmonic parameter model values (hPa/cm) of all tidal constituents in the harmonic coefficient model at the given location.

[Input files] The surface calculation point file. The tidal load spherical harmonic coefficient model file.

[Output file] The tidal harmonic parameter model value file.

The output file header comes from the input calculation point file. Behind the input file record, add $2n$ columns of the tidal harmonic parameter model values as the output file record. Here, n is the number of tidal constituents in the harmonic coefficient model.



4.3.3 Computation of model value time series of load equivalent water height

[Function] From the surface atmosphere, land water, or sea level variation load normalized spherical harmonic coefficient model (m) time series, compute the model value record time series of the atmosphere (hPa/mbar), land equivalent water height (cm), or sea level variation (cm) on the given points in the input file.

[Input files] The surface calculation point file. The surface load spherical harmonic coefficient model time series files.

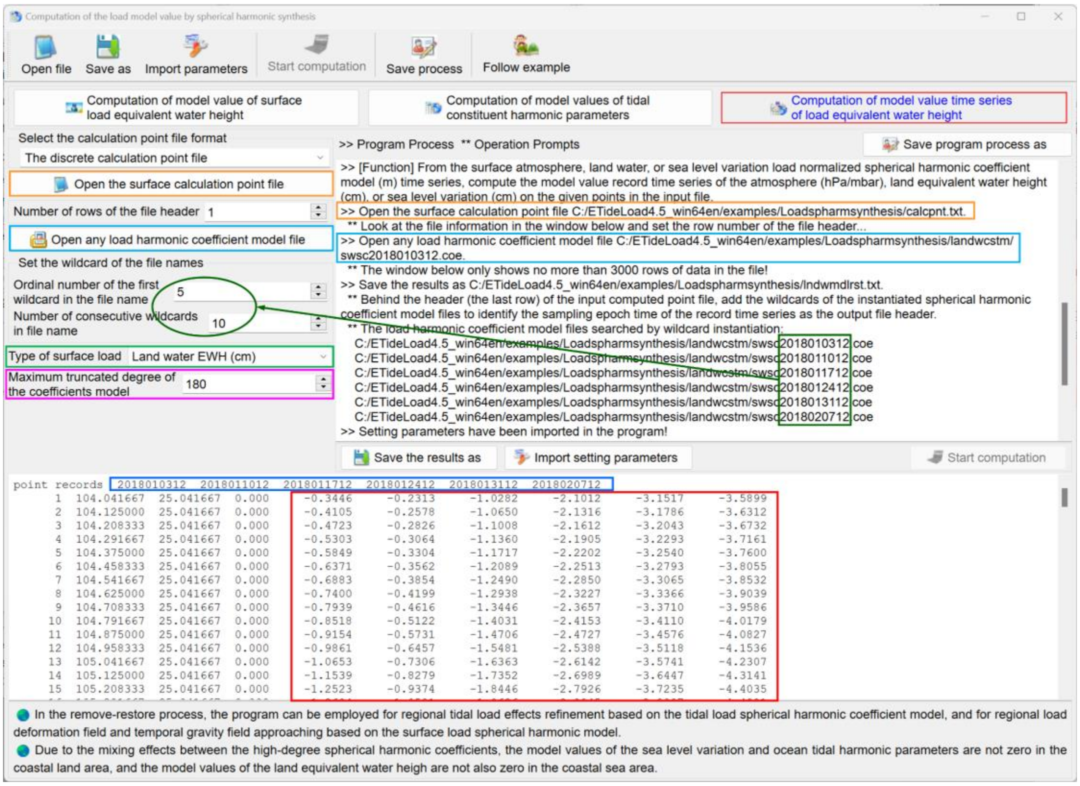
[Parameter settings] Set the wildcard parameters for the surface load spherical harmonic coefficient model time series files. Enter the number of rows of the input file header, row ordinal number of target attribute, and grid resolution.

[Output file] The surface load model value record time series file.

Behind the input file header, add n sampling epoch times of the surface load spherical harmonic coefficient model time series as the output file header. Behind the input file record, add n load model values as the output record. Here, n is the sampling number.

The computation process needs to wait... During the computation period, you can open the output files to look at the computation progress!

The instance wildcards in the file header represent that the computation of the model value at the corresponding epoch time has just been completed.



Due to the mixing effects between the high-degree spherical harmonic coefficients, the model values of the sea level variation and ocean tidal harmonic parameters are not zero in the coastal land area, and the model values of the land equivalent water heigh are not also zero in the coastal sea area.

4.4 Computation of load deformation field by spherical harmonic synthesis

[Purpose] From the surface atmosphere, land water and sea level variation load spherical harmonic coefficient model (m), compute the non-tidal load effects on various geodetic variations on the ground or outside the solid Earth by the spherical harmonic synthesis algorithm.

The time of the load effects is equal to the sampling epoch time of the load spherical harmonic coefficient model.

When computing the load effects of sea level variations, the height of the calculation point is the normal or orthometric height. When computing the load effects of surface atmosphere or land water variations, the height of the calculation point is the height relative to the Earth’s surface.

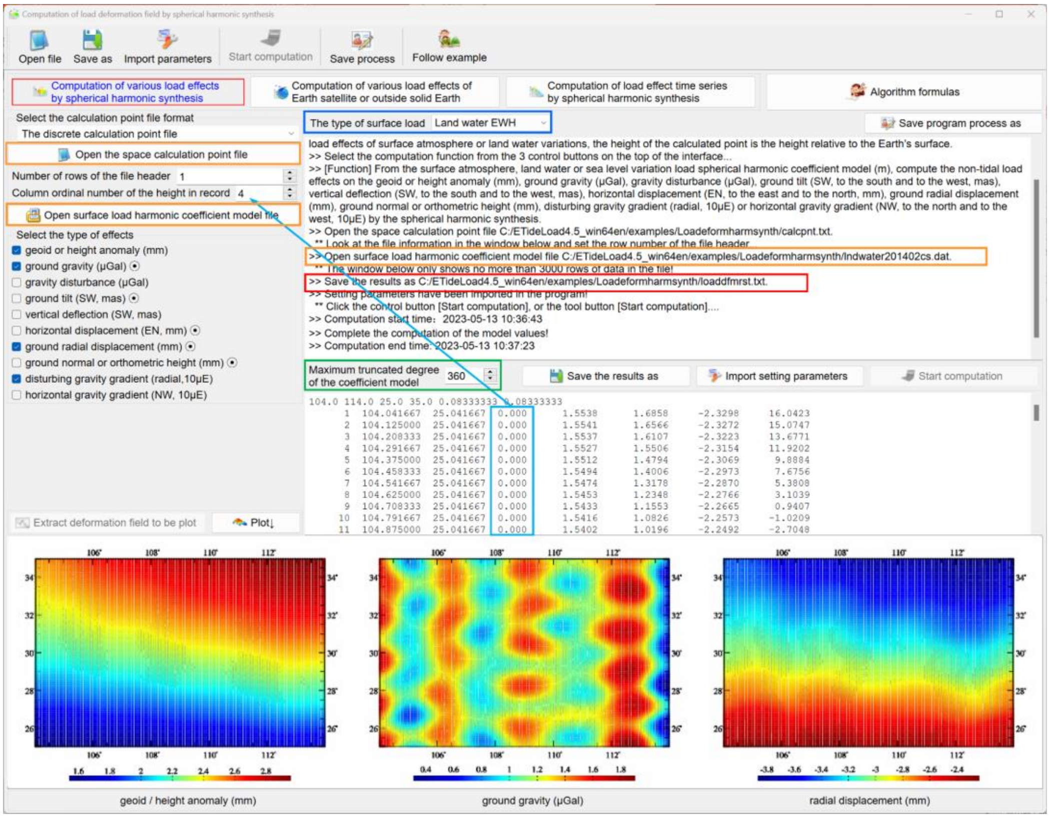
4.4.1 Computation of various load effects by spherical harmonic synthesis

[Function] From the surface atmosphere, land water or sea level variation load spherical harmonic coefficient model (m), compute the non-tidal load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, 10μE) or horizontal gravity gradient (NW, to the north and to the west, 10μE) by the spherical harmonic synthesis.

[Input files] The calculation point file. The surface load spherical harmonic coefficient model file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….



[Parameter settings] Select the format of the calculation point file, enter column ordinal number of the height in the input file record and maximum truncated degree of the spherical harmonic coefficient model and select the type of surface loads.

The program automatically selects the minimum value between the maximum degree of the spherical harmonic coefficient model and the entered maximum degree as the calculation degree.

[Output file] The surface load effect file.

When the discrete calculation point file input, the output file header is the same as the input file. Behind the input file record, add one or several columns of the surface load effects selected as the output file record. In this example, 4 attributes of load effects on height anomaly, ground gravity, ground radial displacement and disturbing gravity gradient are added to the record.

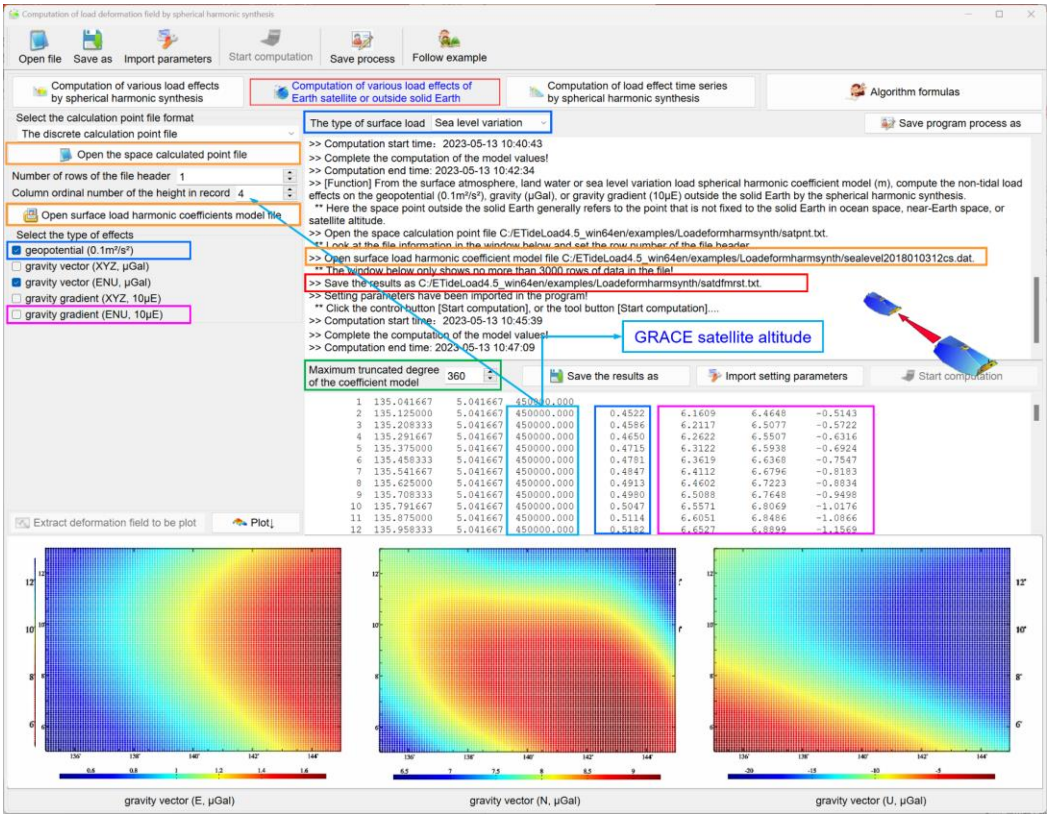
When the calculation surface height grid file input, the program outputs the grid files *.??? of the surface load effects selected, where * is the input file name, and ??? = ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

4.4.2 Computation of various load effects of Earth satellite or outside solid Earth

[Function] From the surface atmosphere, land water or sea level variation load spherical harmonic coefficient model (m), compute the non-tidal load effects on the geopotential (0.1m²/s²), gravity (μGal), or gravity gradient (10μE) outside the solid Earth by the spherical harmonic synthesis.

Here the space point outside the solid Earth generally refers to the point that is not fixed to the solid Earth in ocean space, near-Earth space, or satellite altitude.

[Input files] The discrete calculation point file. The surface load spherical harmonic coefficient model file.



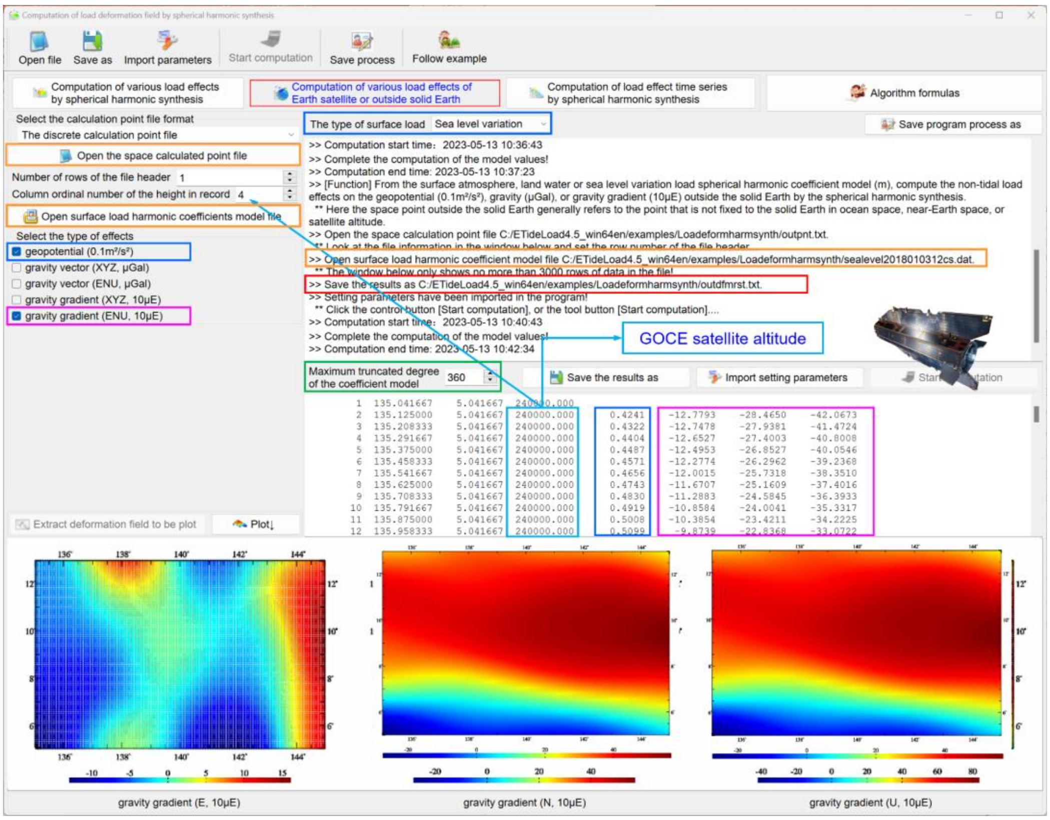
The calculation point file can be a discrete calculation point file or a calculation surface ellipsoidal height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), ellipsoidal height….

[Output file] The surface load effect file.

When the discrete calculation point file input, the output file header is the same as the input file. Behind the input file record, add one or several columns of the surface load effects selected as the output file record. In this example, all types are selected, and there are 14 attributes added to the record.

When the calculation surface ellipsoidal height grid file input, the program outputs the grid files *.??? of the surface load effects selected, where * is the input file name, and ? ? ? = gpv, pvx, pvy, pvz, pve, pvn, pvr, vxx, vyy, vzz, or vee, vnn, vrr, respectively, representing the grid file of load effects on the geopotential, x, y, z components of gravity, E, N, U components of gravity, x, y, z components of gravity gradient or E, N, U components of gravity gradient.



4.4.3 Computation of load effect time series by spherical harmonic synthesis

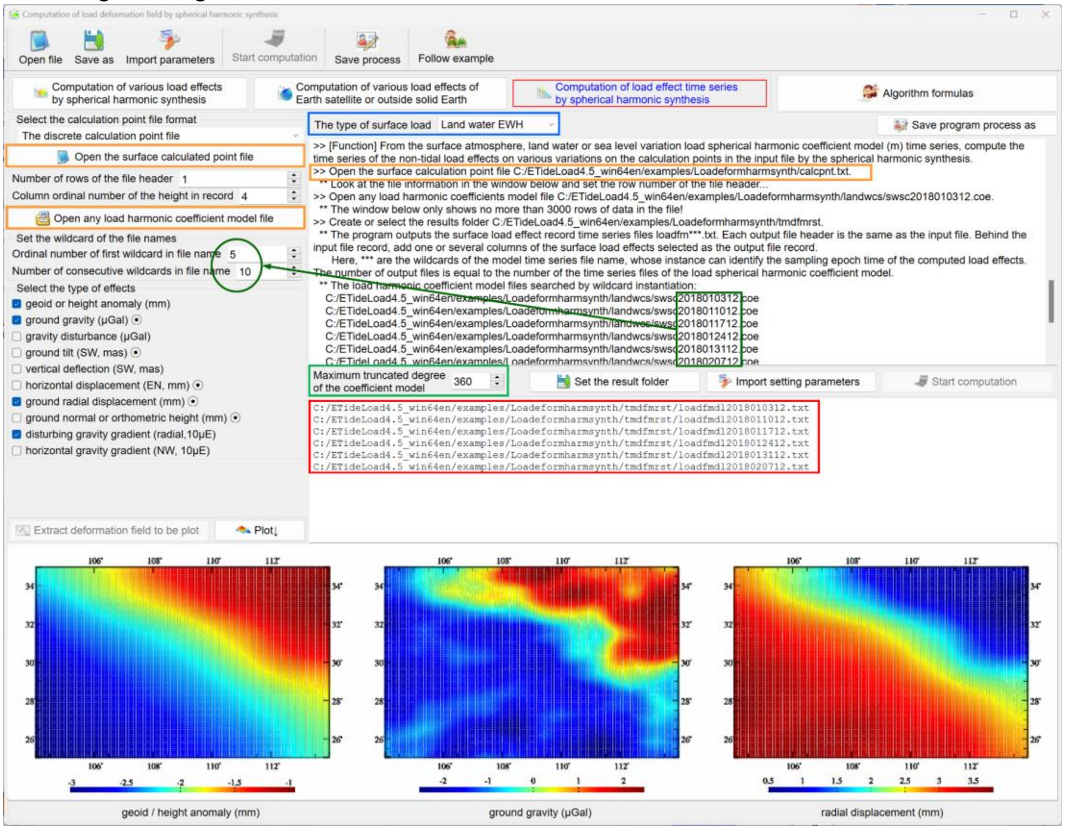
[Function] From the surface atmosphere, land water or sea level variation load spherical harmonic coefficient model (m) time series, compute the time series of the non-tidal load effects on various variations on the calculation points in the input file by the spherical harmonic synthesis.

[Input files] The surface calculation point file. The surface load spherical harmonic coefficient model time series file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

The time series files of the load spherical harmonic coefficient model are extracted according to the given wildcards.



[Output file] The surface load effect time series files.

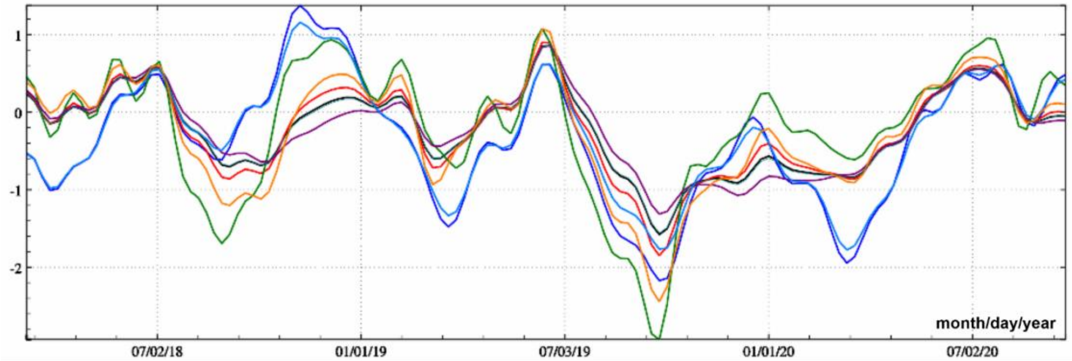
When the discrete calculation point file input, the program outputs the surface load effect record time series files loadfmdl***.txt. Each output file header is the same as the input file. Behind the input file record, add one or several columns of the surface load effects selected as the output file record.

When the calculation surface height grid file input, the program outputs the surface load effect grid time series files loadfmdl***.???, where ??? = ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

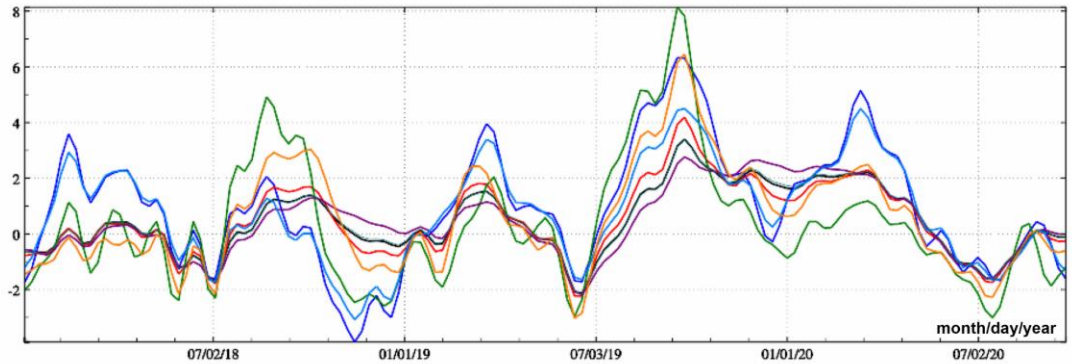
Here, *** are the wildcards of the load spherical harmonic coefficient model time series file name, whose instance can identify the sampling epoch time of the computed load effects. The number of output files is equal to the number of the time series files of the load spherical harmonic coefficient model.

The computation process needs to wait... During the computation period, you can open the output files folder to look at the computation progress!

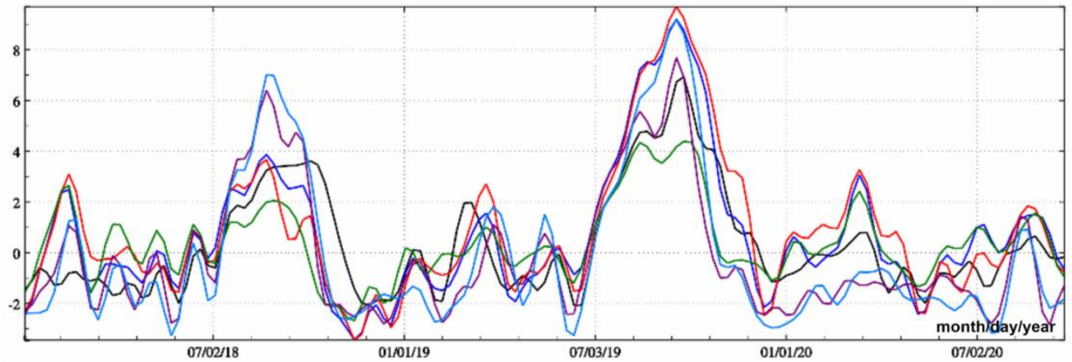
The last column attribute of each output file header is the instance of the wildcards of the file name of the model time series, which represents the sampling epoch time of the output file.



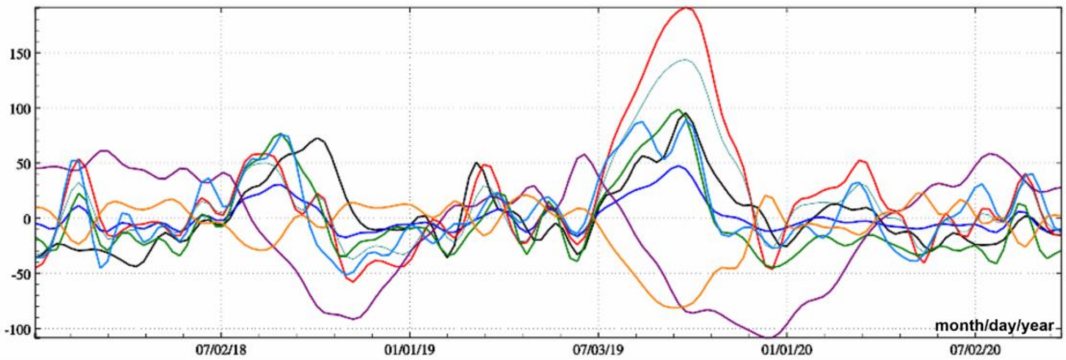
Soil water load effects with time in Chinese mainland (360-degree model): geoidal variation (mm)



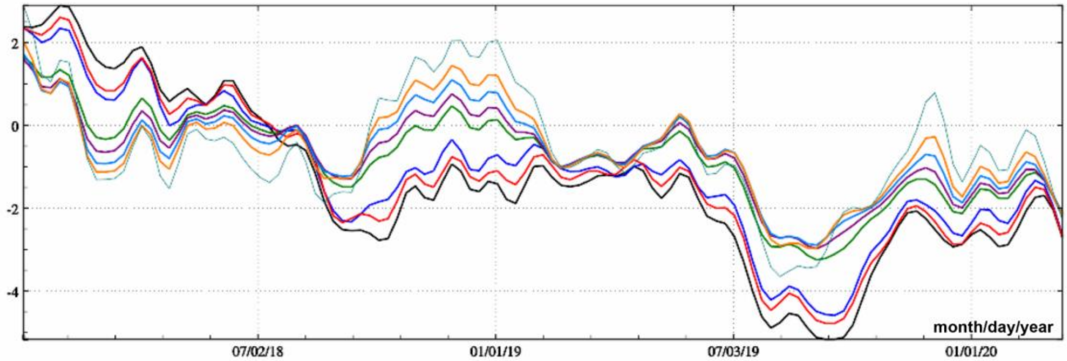
Soil water load effects with time in Chinese mainland (360-degree model): ground normal height variation (mm)



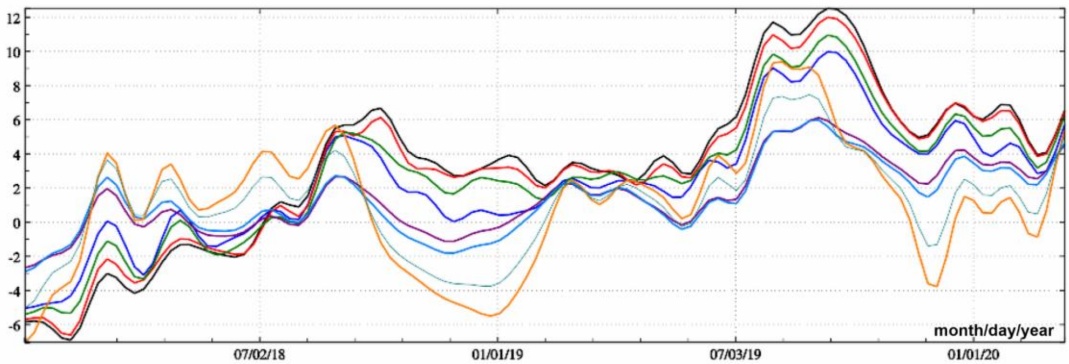
Soil water load effects with time in Chinese mainland (360-degree model): gravity disturbance variation (μGal)



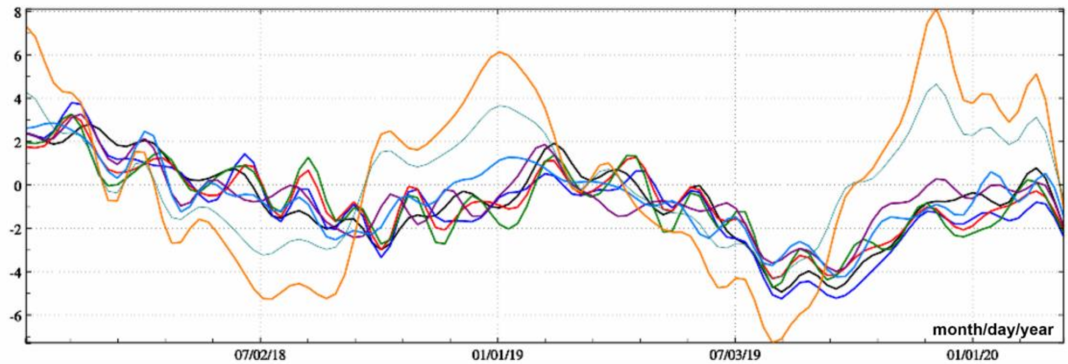
Soil water load effects with time in Chinese mainland (360-degree model): gravity gradient variation (10μE)



Sea level load effects with time in Chinese coastal zone (360-degree model): geoidal variation (mm)

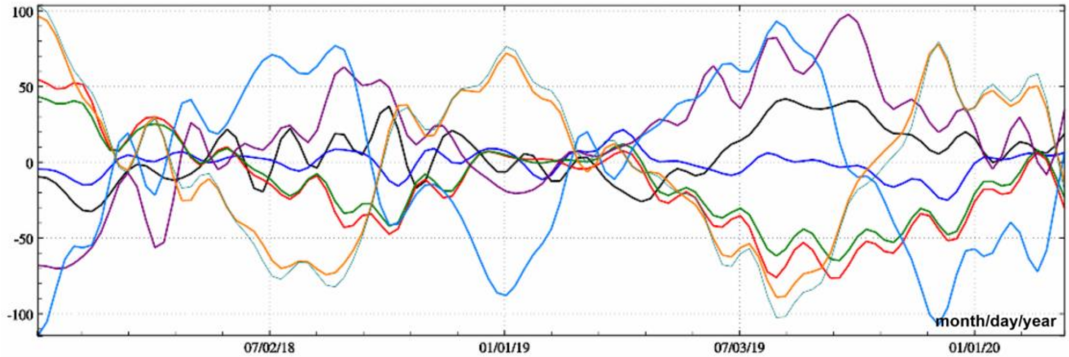


Sea level load effects with time in Chinese coastal zone (360-degree model): normal height variation (mm)



Sea level load effects with time in Chinese coastal zone (360-degree model): gravity disturbance variation (μGal)

Using the monitoring data to global surface atmosphere, land water and sea level variations, determine the non-tidal temporal Earth's gravity field, as well as the non-tidal load effects on the geopotential coefficients, and then you can calibrate various parameters of the gravity satellite's key measurement equipment, and then effectively improve and check the quality, reliability, and accuracy of the time-varying monitoring of satellite gravity field.



Sea level load effects with time in Chinese coastal zone (360-degree model): gravity gradient variation (10μE)

4.5 Regional refinement of load deformation field by Green's Integral

[Purpose] From the regional residual surface load equivalent water height grid which are removed the reference model value with global load spherical harmonic coefficient model, calculate the residual load deformation field grid by Green's integral to refine the regional load deformation field and temporal gravity field.

When computing the load effects of sea level variations, the height of the calculation point is the normal or orthometric height. When computing the load effects of surface atmosphere or land water variations, the height of the calculation point is the height relative to the Earth's surface.

4.5.1 Computation of regional residual surface load effects by Green's Integral

[Function] From the regional residual equivalent water height (EWH) variation grid (cm), compute the residual surface load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE) by Green's Integral.

[Input files] The space calculation point file. The regional residual equivalent water height variation grid file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

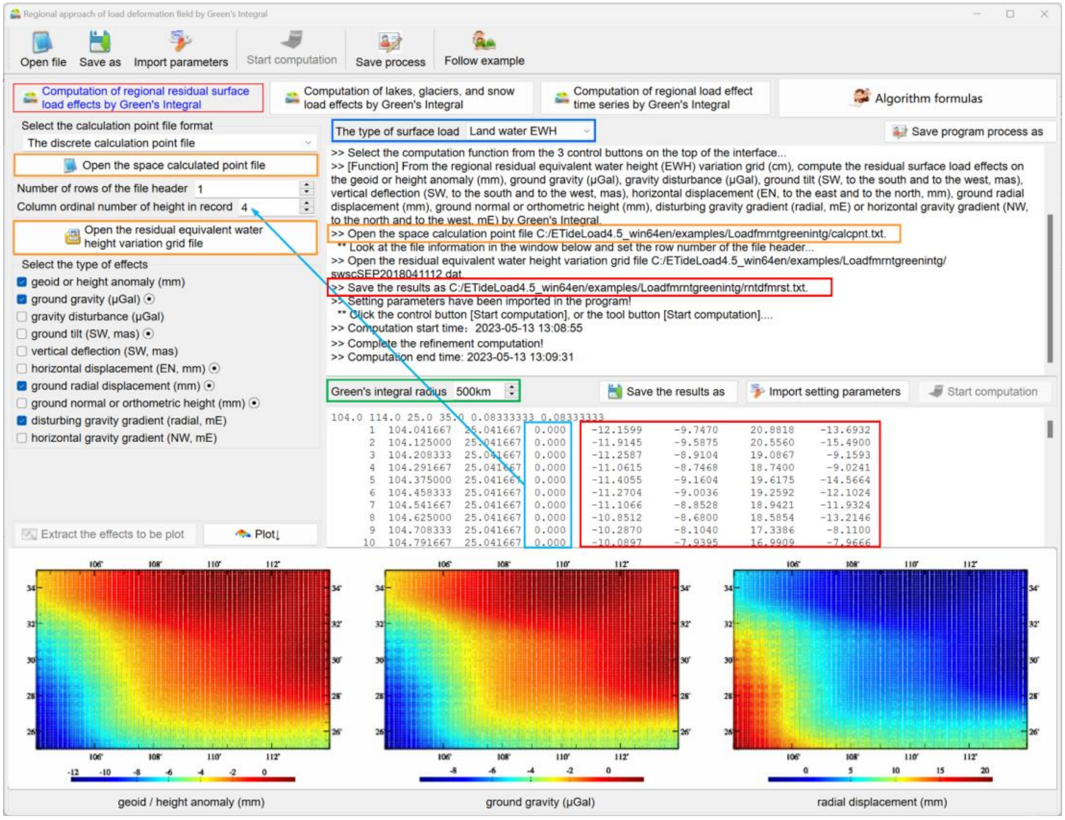
The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

[Parameter settings] Select the format of the calculation point file, enter the load Green's integral radius, and select the type of surface loads.

[Output file] The regional surface load effect file.

When the discrete calculation point file input, the output file header is the same as the input file. Behind the input file record, add one or several columns of the surface load effects selected as the output file record. In this example, 4 attributes of load effects on height anomaly, ground gravity, ground radial displacement and disturbing gravity gradient are added to the record.

When the calculation surface height grid file input, the program outputs the grid files *.??? of the surface load effects selected, where * is the input file name, and ??? = ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.



4.5.2 Computation of lakes, glaciers, and snow load effects by Green's Integral

[Function] From the load equivalent water height variation grid (cm) of the inland water-bodies such as the rivers, lakes, reservoirs, glaciers, and snow-capped mountains, compute the water-bodies load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE) by Green's Integral.

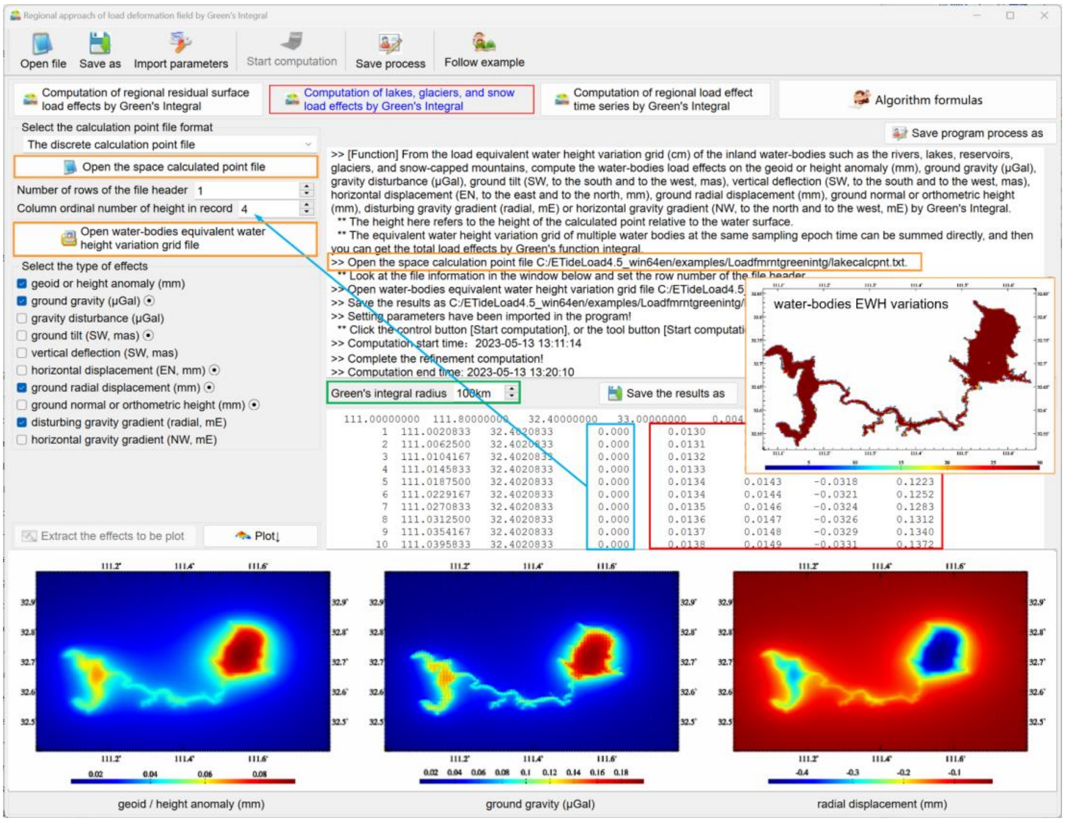
[Input files] The space calculation point file. The water-bodies equivalent water height variation grid file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The height in the calculation point file refers to the height of the calculation point relative to the water surface.

[Parameter settings] Select the format of the calculation point file and enter the load Green’s integral radius.

[Output file] The same with chapter 4.5.1.



The equivalent water height variation grid of multiple water bodies at the same sampling epoch time can be summed directly, and then you can get the total load effects by Green's function integral.

If the changes of the inland water bodies such as the rivers, lakes, reservoirs, glaciers, and snow-capped mountains are represented by the load equivalent water height variations grid, the program can accurately compute these load effects on various geodetic variations.

Due to shortwave dominance of the residual load effects, the residual load equivalent water height grid is required to have an appropriate spatial resolution to reflect the loads shortwave characteristics. Otherwise, Green's function integral may be unstable.

4.5.3 Computation of regional load effect time series by Green's Integral

[Function] From the regional residual equivalent water height (cm) grid time series, compute the time series of the residual value of the load effects on various variations on the calculation points in the input file by Green's integral. The residual equivalent water height variation (cm) grid time series files are extracted according to the given wildcards.

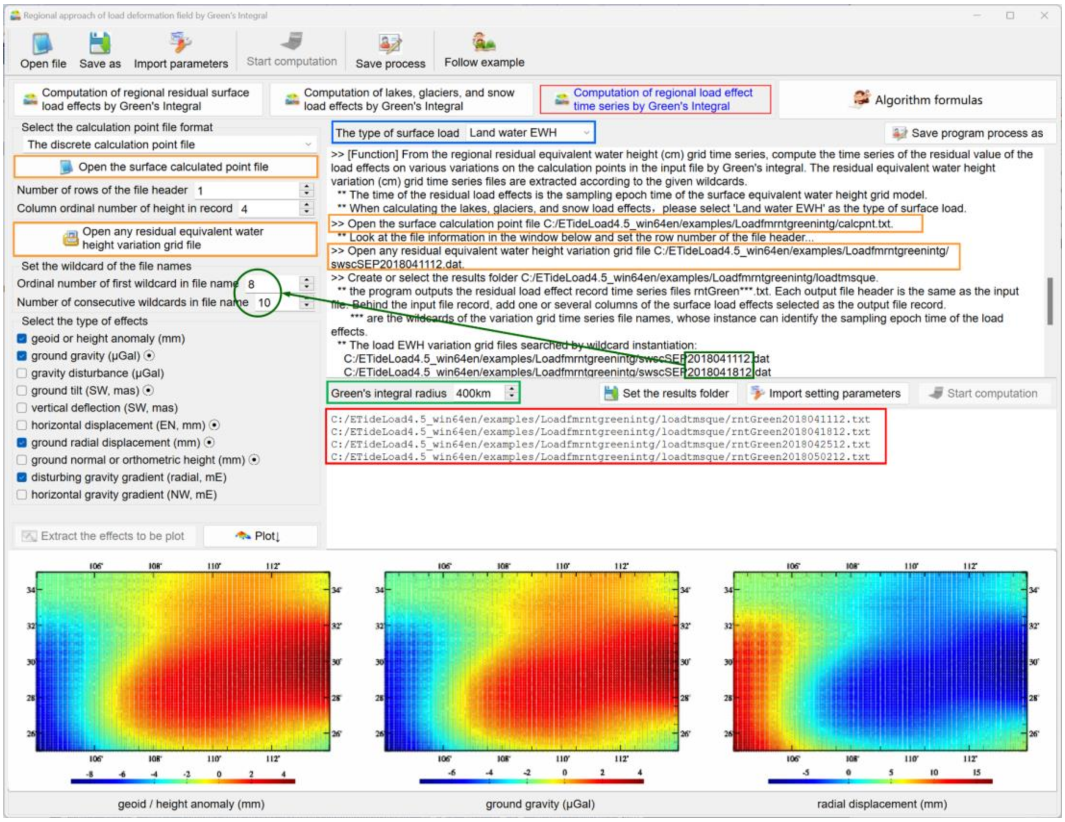
When calculating of the lakes, glaciers, and snow load effects, please select “Land water EWH” as the type of surface load.

[Input files] The surface calculation point file. The regional residual equivalent water height grid time series file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

The time series files of the equivalent water height grids are extracted according to the given wildcards.



[Parameter settings] Select the format of the calculation point file and set the wildcard parameters for the surface load equivalent water height grid time series files, enter the load

Green's integral radius, and select the type of surface loads.

[Output file] The residual surface load effect files.

When the discrete calculation point file input, the program outputs the residual load effect record time series files rntGreen***.txt. Each output file header is the same as the input file. Behind the input file record, add one or several columns of the surface load effects selected as the output file record.

When the calculation surface height grid file input, the program outputs the residual load effect grid time series files rntGreen***.???, where ??? = ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

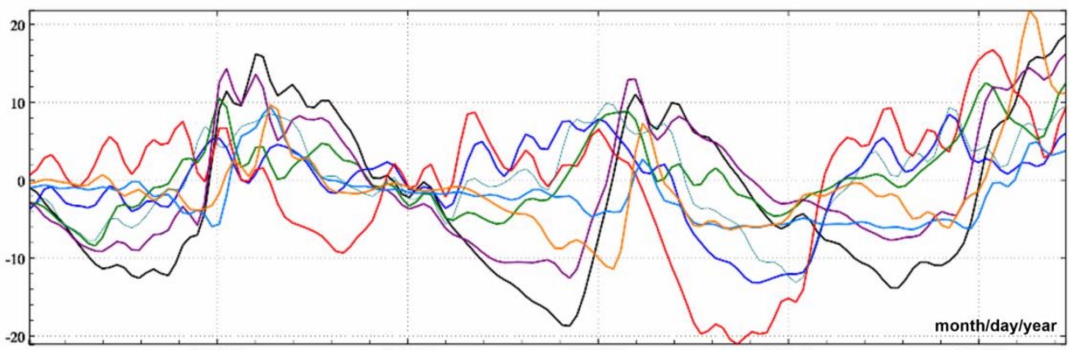
The time of the residual load effects is the sampling epoch time of the surface equivalent water height grid model.

The number of the output files is equal to the number of time series files of the residual equivalent water height variation grid. Here, *** are the wildcards of the variation grid time series file names, whose instance can identify the sampling epoch time of the load effects.

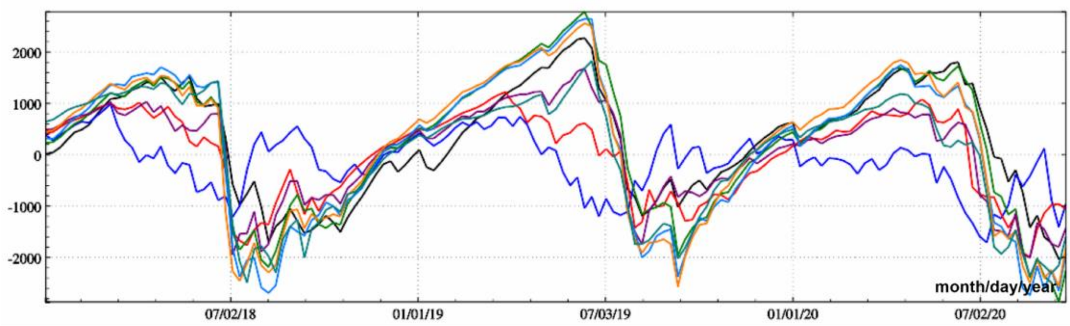
The computation process needs to wait...During the period, you can open the output files folder to look at the computation progress!

The last attribute of each output file header is the instance of the wildcards of the time series file name of the residual equivalent water height grid model, which represents the sampling epoch time of the output file.

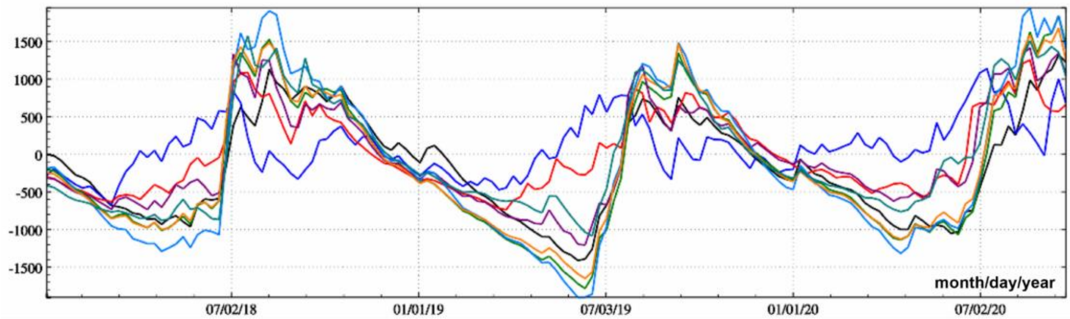
The calculation results show that the residual soil water variation of medium-short wave (30′ spatial resolution) can cause several E magnitudes of gravity gradient variations with time, and the time-varying characteristics are complex and changeable. The variation of soil water in the north and south of Chinese mainland is quite different, and the soil water load effect on horizontal gradient in the north-south direction is significantly greater than that in the east-west direction.



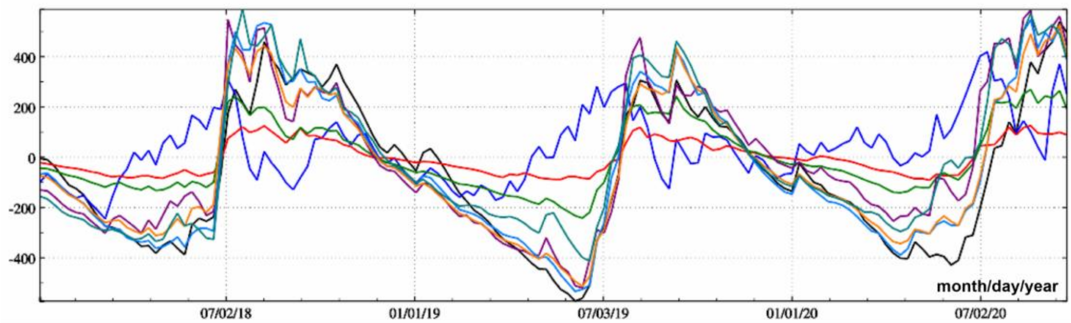
30′×30′ residual soil water load effects in Chinese mainland (Green integral): ground gravity variation (μGal)



30′×30′ residual soil water load effects in Chinese mainland (Green integral): gravity gradient variation (radial, mE)



30′×30′ residual soil water load effects in Chinese mainland (Green integral): horizontal gradient variation (N, mE)



30′×30′ residual soil water load effects in Chinese mainland (Green integral): horizontal gradient variation (W, mE)

After superimposing the load effects of ultrashort wave surface water and groundwater, the variation magnitudes of the ground gravity gradient will increase by more than several times. How to effectively deal with the surface load effects with complex space-time characteristics is a key problem that must be faced in high-precision measurement of ground gravity gradient.

4.6 Regional approach of load deformation field using SRBFs

[Purpose] From the regional residual surface load equivalent water height grid, approach the regional residual surface load in spectral domain using spherical radial basis functions (SRBFs) and then calculate the residual load effects on full-element geodetic variations by SRBF synthesis to solve the high-degree oscillation and poor convergence of Green′s function in the near area around the calculation point.

When computing the load effects of sea level variations, the height of the calculation point is the normal or orthometric height. When computing the load effects of surface atmosphere or land water variations, the height of the calculation point is the height relative to the Earth's surface.

4.6.1 Approach of residual load and synthesis of residual load effects using SRBFs

[Function] From the regional residual equivalent water height (EWH) variation grid (cm), approach the regional residual surface load in spectral domain using spherical radial basis functions (SRBFs) and then calculate the residual EWH estimation and residual load effects on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE).

[Input files] The space calculation point file. The regional residual equivalent water height variation grid file.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

[Parameter settings] Select the calculation point file format and set SRBF approach algorithm parameters.

The effectiveness principle of the parameter optimization and cumulative approach: (1) The estimated load EWH and load effects in space is continuous and differentiable, and (2) the residual standard deviation of the estimated load EWHs is obviously reduced, and the residual statistical mean tends to zero.

Select the spherical radial basis functions: radial multipole kernel function, Poisson wavelet kernel function.

Enter the order m. The order number m of radial multipole kernel function and Poisson wavelet kernel function. The greater the m, the bigger the kurtosis of SRBF. The zero-order radial multipole kernel function is the point mass kernel function, and the zero-order Poisson wavelet kernel function is the Poisson kernel function.

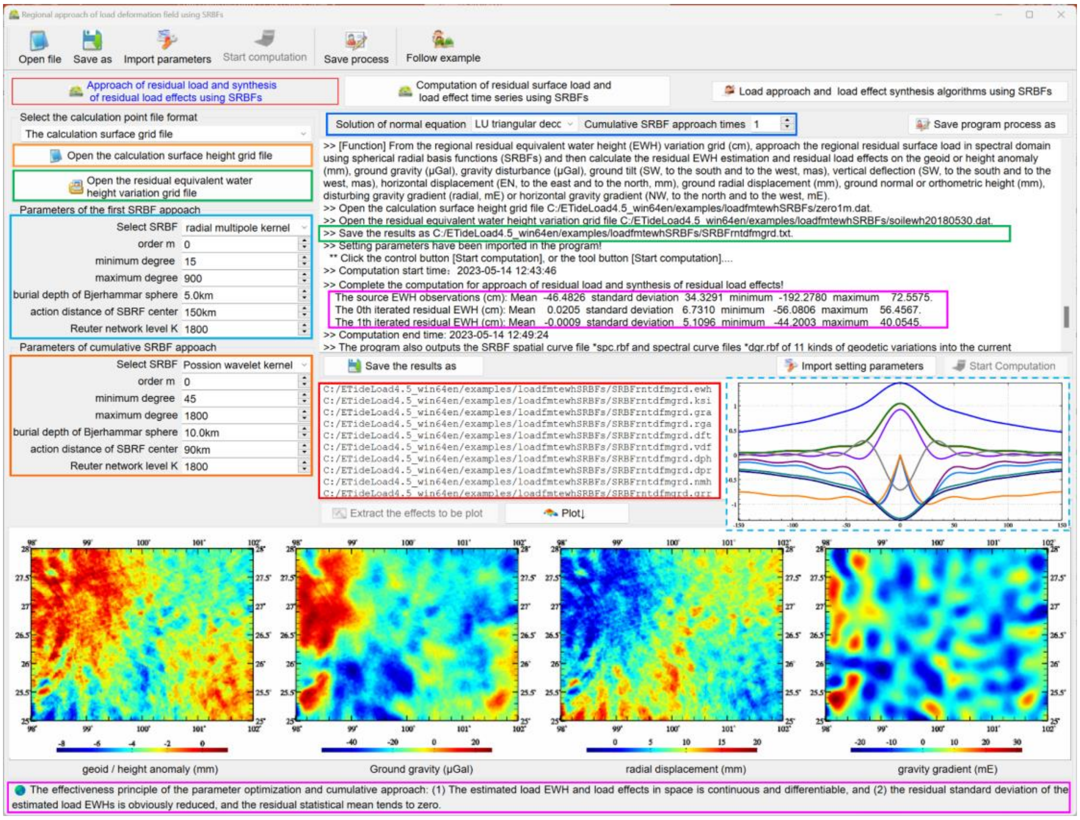
Enter minimum and maximum degree of SRBF Legendre expansion. Minimum and maximum degree can be employed to adjust SRBF bandwidth.

Input the Bjerhammar sphere burial depth: The depth of the Bjerhammar sphere relative to the mean height surface of the observation variations, which can be employed to adjust the spectral center and bandwidth of SRBF when combined with the degree of SRBF Legendre expansion.

The greater the burial depth, the smoother the SRBF, the smaller the kurtosis namely the wider the spectral bandwidth.

Enter the action distance of SRBF center. The action distance is also called as the radius of influence = spherical angular distance × the mean radius of the Earth. Which is equivalent to Green's integral radius in space domain.

A fixed action distance is adopted to ensure the coordination and consistency of the spatial and spectral figure of load deformation field.



Cumulative SRBF approach times. Every cumulative SRBF approach can be considered that the current load deformation field is refined by the remove-restore scheme with the previous load deformation field as the reference field. Generally cumulative 1 ~ 2 times can obtain a stable solution.

Set the Reuter network level K: The spherical surface is divided into K prime vertical circles, and the latitude interval is 180°/K. The larger the K value, the greater the spatial resolution of the spherical Reuter network. The suitable 180°/K is approximately equal to the average distance between observation points.

Select the method of the solution of normal equation. LU triangular decomposition method or Cholesky decomposition. The normal equation here does not need regularization and iterative computation.

[Output file] The residual EWH estimation and residual load effect file.

When the discrete calculation point file input, the output file header is the same as the input file. Behind the input file record, add the residual EWH estimation and residual load effects the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient a total of 14 columns of attributes as the output file record.

When the calculation surface height grid file input, the program outputs the the residual EWH estimation and residual load effect full-element grid files *.???, where * is the input file name, and ??? = ewh, ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of the residual EWH estimation and residual load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

The program also outputs the SRBF spatial curve file *spc.rbf and spectral curve files *dgr.rbf of 11 kinds of geodetic variations into the current directory.

*spc.rbf file header format: SRBF type (0-radial multipole kernel function, 1-Poisson wavelet kernel function), order of SRBF, Minimum and maximum degree of SRBF Legendre expansion, buried depth (km). The record format: spherical distance (km), the normalized SRBF values from the load EWH, height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, orthometric height, gravity gradient and horizontal gradient variations.

The file header of * dgr.rbf is the same as * spc.rbf. The record format: degree n of SRBF Legendre expansion, the degree n normalized SRBF values from the load EWH, height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, orthometric height, gravity gradient and horizontal gradient variations.

4.6.2 Computation of residual surface load and load effect time series using SRBFs

[Function] From the regional residual equivalent water height (EWH) variation grid (cm) time series, approach the regional residual surface load in spectral domain using spherical radial basis functions (SRBFs) and then calculate the residual EWH estimation and residual load effect full-element grid time series on the geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) or horizontal gravity gradient (NW, to the north and to the west, mE).

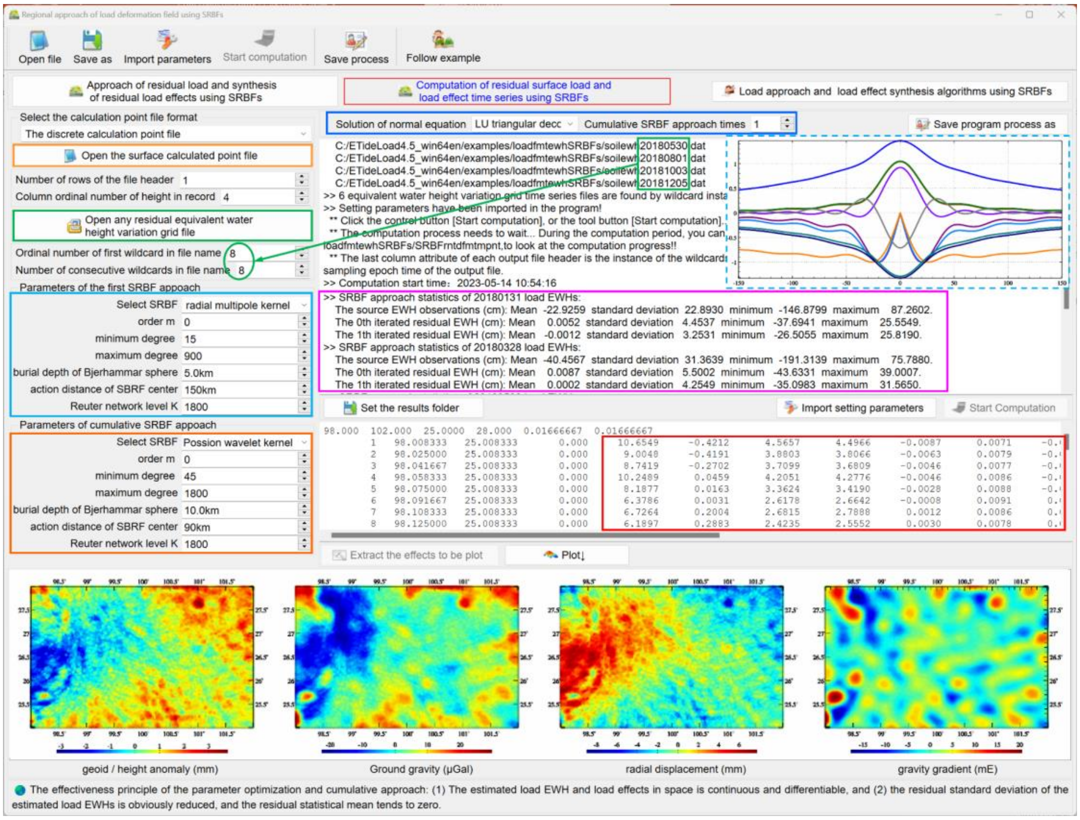
[Input files] The space calculation point file. The regional residual equivalent water height variation grid time series files.

The calculation point file can be a discrete calculation point file or a calculation surface height grid file.

The discrete calculation point file record format: Point number (name), longitude, latitude (decimal degrees), height….

[Parameter settings] Directly employing the Parameter settings from the chapter 4.6.1.

[Output file] The residual EWH estimation and residual load effect full-element grid time series files.



When the discrete calculation point file input, the program outputs the residual load effect record time series files rntSRBFs***.txt. Each output file header is the same as the input file. Behind the input file record, add the residual EWH estimation and residual load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient a total of 14 columns of attributes as the output file record.

When the calculation surface height grid file input, the program outputs the the residual EWH estimation and residual load effect full-element grid time series files rntSRBFs*.???, where ??? = ewh, ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of the residual EWH estimation and residual load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

Here, *** are the wildcards of the variation grid time series file names, whose instance can identify the sampling epoch time of the load effects. The time of the residual load effects is the sampling epoch time of the surface equivalent water height grid model.

The last attribute of each output file header is the instance of the wildcards of the time series file name of the residual equivalent water height grid model, which represents the sampling epoch time of the output file.

The computation process needs to wait...During the period, you can open the output files folder to look at the computation progress!

4.7 Load deformation field monitoring from heterogeneous variations with Green's integral constraints

[Purpose] Using the heterogeneous geodetic variations from the regional CORS network, gravity tide stations and various geodetic monitoring networks as the observations, and the load Green's integral as the geodynamic constraints, estimate the regional land water variation and load effects on full-element load deformation field (time-varying gravity field).

It is technically required that the long wave parts of the load effects on geodetic variations should be removed to satisfy the local Green integral condition.

The geodetic variations here can be one or more of the following five types of variation. (1) Height anomaly variations (mm) from GNSS-leveling monitoring network, (2) disturbance gravity variations (μGal) from GNSS-gravity monitoring network or CORS-gravity tide stations, (3) ground gravity variations (μGal) from gravity monitoring network or gravity tide stations, (4) ellipsoidal height variations (mm) for CORS network or GNSS monitoring network, and (5) normal or orthometric height variations (mm) from leveling monitoring network.

4.7.1 Load deformation field estimation from heterogeneous variations with Green's integral constraints

[Function] Using various heterogeneous geodetic variations as the observations and the load Green's integral as the geodynamic constraints, estimate the regional surface load equivalent water height (EWH) and all-element load effects to obtain the land water EWH, geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) and horizontal gravity gradient (NW, to the north and to the west, mE) variation grids.

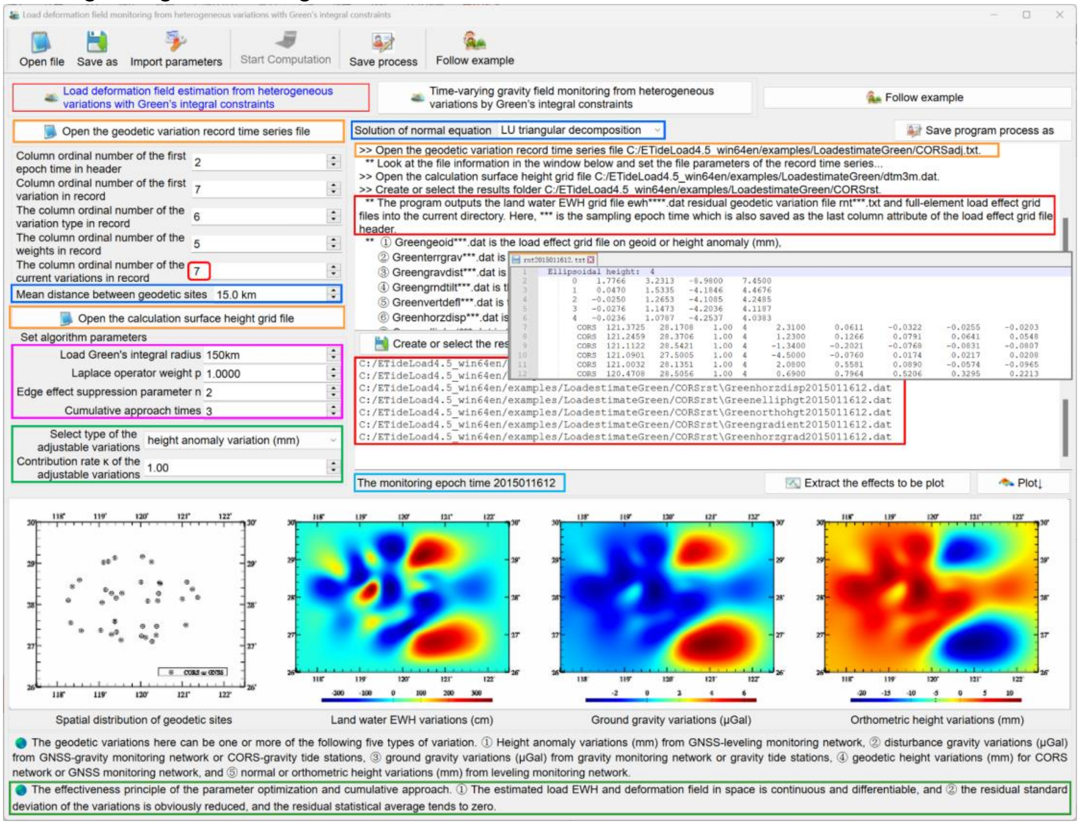
[Input files] The heterogeneous geodetic variation record time series file. The calculation surface height grid file.

The geodetic variation record time series file. The file header contains the time series length and the sampling epoch time arranged with time. Record format: ID (the site name / no), longitude, latitude, …, weight, variation type, ..., variations arranged in time series length (default value is 9999.0000).

Variation type = 1 represents the height anomaly variation (mm), = 2 represents gravity disturbance variation (μGal), = 3 represents ground gravity variation (μGal), = 4 represents ground ellipsoidal height variation (mm), and = 5 represents normal or orthometric height variation (mm).

The calculation surface height is the height of the calculation point relative to the ground surface. When calculating the ground load deformation field, enter the zero-value grid. The calculation surface height grid specification is employed to specify the latitude and longitude range and spatial resolution of the land water EWH grid to be estimated.

The program requires that the grid range of the calculation surface height must be larger than the geodetic site distribution range to absorb the edge effect. The actual effective range of the land water EWH and its load deformation field grid estimated will be less than the coverage range of these geodetic sites.



[Parameter settings] Set the geodetic variation record time series file format parameters, enter the column ordinal number of the current variations, load Green's integral radius and mean distance between geodetic sites, and set the algorithm control parameters.

The weights of variations are employed only to distinguish the quality of variations in the same type.

The column ordinal number of the current variations in the file record. The program estimates an epoch time of the land water EWH and full-element load effect grids once, therefore you need to specify the column ordinal number of the variations at the epoch time.

Mean distance (km) between the geodetic sites. Input the approximate value of the mean distance between the geodetic sites. Which should not be greatly reduced intentionally, otherwise it will seriously affect the speed of parameter estimation and the stability of the solution. The mean distance is not directly related to the spatial resolution of the estimated land water EWH.

Green's integral radius (km). A fixed integral radius is adopted to ensure the coordination and consistency of the spatial and spectral figure of the load deformation field.

The Laplace operator weight p. It is employed to suppress spatial noise. The greater the weight, the greater the spatial filtering intensity. Not smooth when $p = 0$, smooth enhancing when $p > 1$ and smooth weakening when $p < 1$.

Edge effect suppression parameter n. The program lets the unknown EWHs of n cell-grids located in the region edge equal to zero as the observation equations to suppress the edge and far zone effects.

Cumulative approach times. Every cumulative approach can be considered that the current load deformation field is refined by the remove-restore scheme with the previous load deformation field as the reference field. Generally cumulative 1 ~ 3 times can obtain a stable solution.

The effectiveness principle of the parameter optimization and cumulative approach: (1) The estimated load EWH and deformation field in space is continuous and differentiable, and (2) the residual standard deviation of the variations is obviously reduced, and the residual statistical mean tends to zero.

Select the type of adjustable variation and set the contribution rate κ of the adjustable variation.

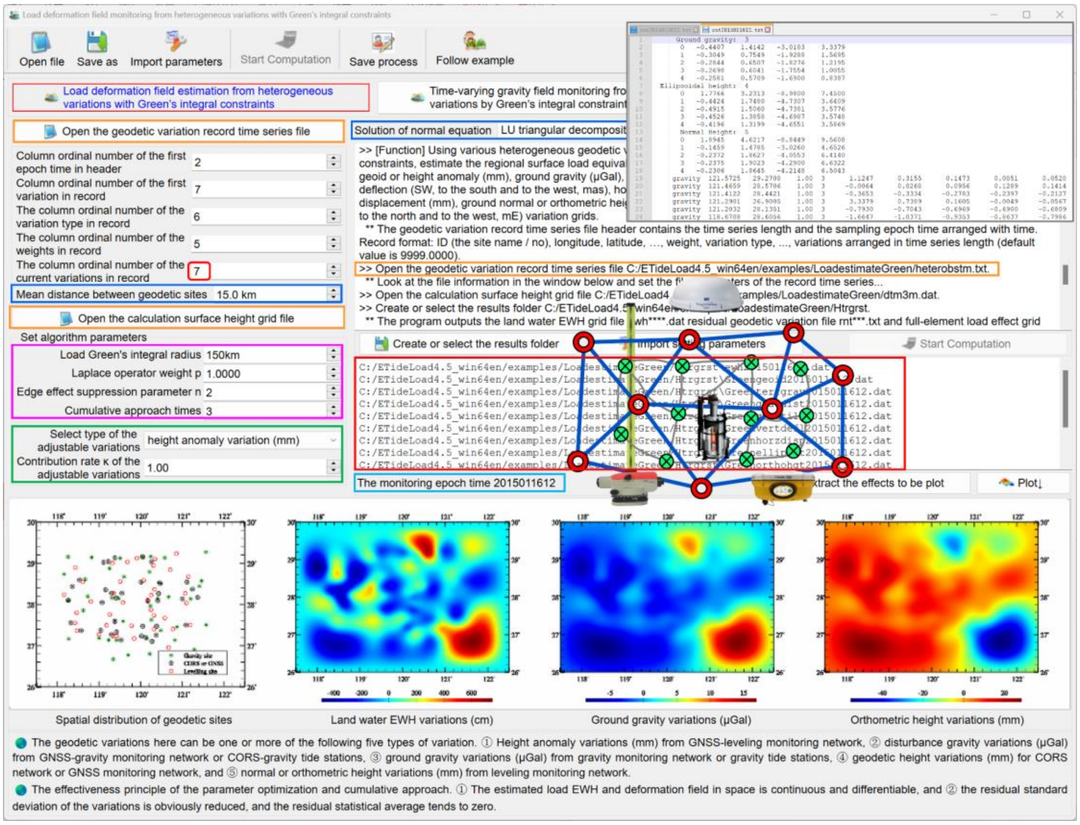
The program multiplies the normal equation coefficient matrix and constant matrix of the adjustable variations by κ, respectively, to increase ($\kappa > 1$) or decrease ($\kappa < 1$) the contribution of the adjustable variation. When $\kappa = 1$, it means that there is not any adjustable variation selected. When $\kappa = 0$, the adjustable variation does not participate in the EWH estimation.

Select the method of the solution of normal equation. LU triangular decomposition method or Cholesky decomposition. The normal equation here does not need regularization and iterative computation.

ETideLoad4.5 proposes a cofactor matrix diagonal standard deviation method to combine different types of heterogeneous geodetic variations for load EWH estimation, so that the properties of the estimation solution are only related to the space distribution of the geodetic variations without influence of various monitoring error, significantly to improve the universality and reliability of the estimation algorithm.

[Output files] The land EWH variation and all-element load effect grid files, the residual geodetic variation file for the cumulative approach process.

The program outputs the land water EWH grid file ewh****.dat, residual geodetic variation file rnt***.txt and various load effect grid files into the current directory.



Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.

①Greengeoid***.dat is the load effect grid file on geoid or height anomaly (mm),

②Greenterrgrav***.dat is the load effect grid file on ground gravity (μGal),

③Greengravdist***.dat is the load effect grid file on gravity disturbance (μGal),

④Greengrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

⑤Greenvertdefl***.dat is the load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),

⑥Greenhorzdisp***.dat is the load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),

⑦Greenelliphgt***.dat is the load effect grid file on ground radial displacement (mm),

⑧Greenorthohgt***.dat is the load effect grid file on ground normal or orthometric height (mm),

⑨Greengradient***.dat is the load effect grid file on gravity gradient (radial, mE) and

⑩Greenhorzgrad***.dat is the load effect vector grid file on horizontal gravity gradient

(NW, to the north and to the west, mE).

After the computation is completed, the residual geodetic variation file should be opened to observe the standard deviation and mean value of the residual variations and their changes with the cumulative number of times to optimize the parameter settings and cumulative number of times, and then recompute.

4.7.2 Time-varying gravity field monitoring from heterogeneous variations by Green's integral constraints

[Function] Using various heterogeneous geodetic variation time series as the observations and the load Green's integral as the geodynamic constraints, estimate the regional surface load equivalent water height (EWH) and all-element load effect grid time series (usually employed to represent regional time-varying gravity field).

[Input files] The heterogeneous geodetic variation record time series file. The calculation surface height grid file.

The geodetic variation record time series file. The file header contains the time series length and the sampling epoch time arranged with time. Record format: ID (the site name / no), longitude, latitude, …, weight, variation type, ..., variations arranged in time series length (default value is 9999.0000).

Variation type = 1 represents the height anomaly variation (mm), = 2 represents gravity disturbance variation (μGal), = 3 represents ground gravity variation (μGal), = 4 represents ground ellipsoidal height variation (mm), and = 5 represents normal or orthometric height variation (mm).

[Parameter settings] All the algorithm parameters that are same as the function [Load deformation field estimation from heterogeneous variations with Green's integral constraints].

During the monitoring period, when the spatial distribution of geodetic monitoring sites or shape of geodetic monitoring networks and the types of geodetic variations are basically unchanged, the algorithm parameters will remain unchanged, which is a typical feature of ETideLoad algorithm of load deformation field approach that is especially useful for automatic processing of multiple heterogeneous multi-period or continuous geodetic monitoring networks.

[Output files] The program outputs the land water EWH grid time series file ewh****.dat, residual geodetic variation time series files rnt***.txt and full element load effect grid time series files.

Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.

①Greengeoid***.dat is the load effect grid file on geoid or height anomaly (mm),

②Greenterrgrav***.dat is the load effect grid file on ground gravity (μGal),

③Greengravdist***.dat is the load effect grid file on gravity disturbance (μGal),

④Greengrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

⑤Greenvertdefl***.dat is the load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),

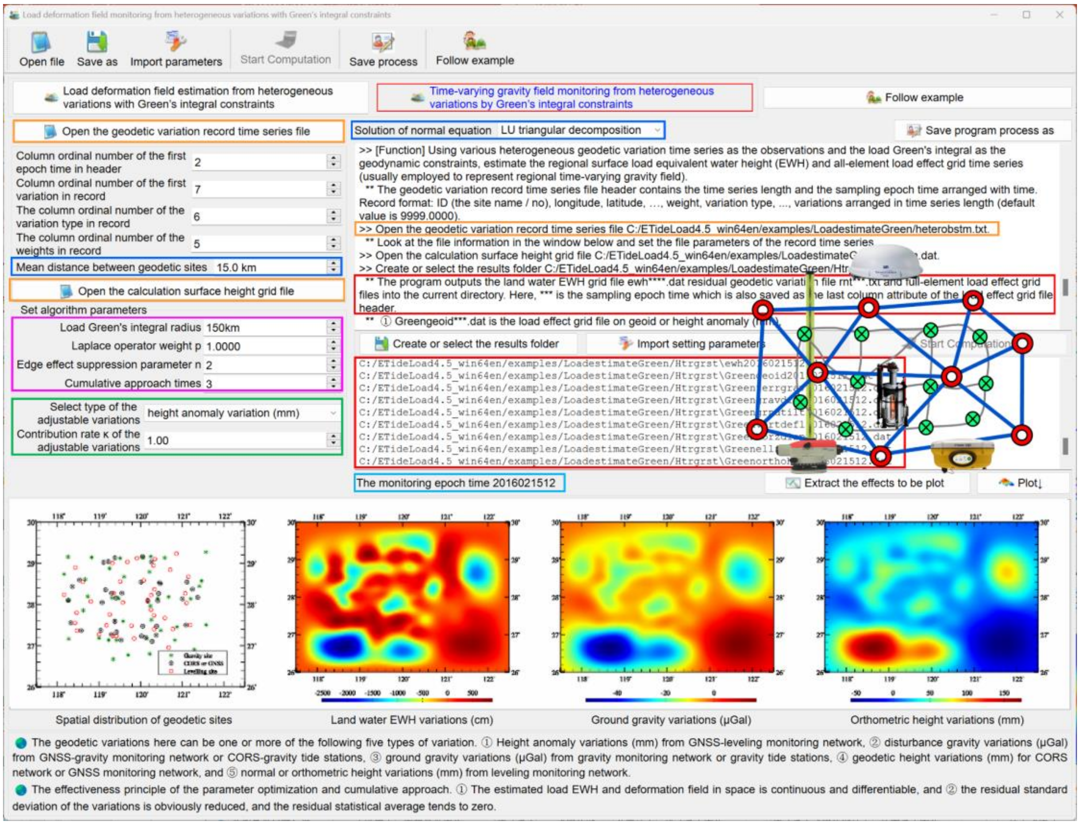
⑥Greenhorzdisp***.dat is the load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),

⑦Greenelliphgt***.dat is the load effect grid file on ground radial displacement (mm),

⑧Greenorthohgt***.dat is the load effect grid file on ground normal or orthometric height (mm),

⑨Greengradient***.dat is the load effect grid file on gravity gradient (radial, mE) and

⑩Greenhorzgrad***.dat is the load effect vector grid file on horizontal gravity gradient (NW, to the north and to the west, mE).



After the estimation is completed, the residual value files should be opened to check the results. The first few rows of the file indicate the change information of the mean and standard deviation of the residual value with the number of iterations. If necessary, the algorithm parameters should be adjusted and recompute for individual epochs without ideal solutions by the function [Load deformation field estimation from heterogeneous variations with Green's integral constraints]. Particular attention should be paid at the monitoring epoch time when the distribution or types of geodetic variations occur obvious changes.

4.8 Load deformation field monitoring from heterogeneous variations by spherical radial basis functions

[Purpose] From the heterogeneous geodetic variations from the regional CORS network, gravity tide stations and various geodetic networks, approach or monitor the regional land water variations and load effects on full-element load deformation field (time-varying gravity field) in spectral domain using spherical radial basis functions (SRBF).

It is technically required that the long wave parts of the load effects on geodetic variations should be removed to satisfy the regional SRBF approach condition.

The variations here can be one or more of the following five types of variation. (1) Height anomaly variations (mm) from GNSS-leveling monitoring network, (2) disturbance gravity variations (μGal) from GNSS-gravity monitoring network or CORS-gravity tide stations, (3) ground gravity variations (μGal) from gravity monitoring network or gravity tide stations, (4) ellipsoidal height variations (mm) for CORS network or GNSS monitoring network, and (5) normal or orthometric height variations (mm) from leveling monitoring network, and (6) equivalent water height variations (cm) from hydrological monitoring stations.

4.8.1 Load deformation field approach from heterogeneous variations using spherical radial basis functions

[Function] Using spherical radial basis functions in spectral domain, approach the regional surface load equivalent water height (EWH) and full-element load to obtain the land water EWH, geoid or height anomaly (mm), ground gravity (μGal), gravity disturbance (μGal), ground tilt (SW, to the south and to the west, mas), vertical deflection (SW, to the south and to the west, mas), horizontal displacement (EN, to the east and to the north, mm), ground radial displacement (mm), ground normal or orthometric height (mm), disturbing gravity gradient (radial, mE) and horizontal gravity gradient (NW, to the north and to the west, mE) variation grids from various heterogeneous geodetic variations.

[Input files] The heterogeneous geodetic variation record time series file. The calculation surface height grid file.

The variation record time series file. The file header contains the time series length and the sampling epoch time arranged with time. Record format: ID (the site name / no), longitude, latitude, …, weight, variation type, ..., variations arranged in time series length (default value is 9999.0000).

Variation type = 1 represents the height anomaly variation (mm), = 2 represents gravity disturbance variation (μGal), = 3 represents ground gravity variation (μGal), = 4 represents ground ellipsoidal height variation (mm), = 5 represents normal or orthometric height variation (mm), and = 6 represents equivalent water height variations (cm).

The calculation surface height is the height of the calculation point relative to the ground surface. When calculating the ground load deformation field, enter the zero-value grid. The calculation surface height grid specification is employed to specify the latitude and longitude range and spatial resolution of the land water EWH grid to be estimated.

The program requires that the grid range of the calculation surface height must be larger than the monitoring site distribution range to absorb the edge effect. The actual effective range of the land water EWH and load effect grid estimated will be less than the coverage range of these monitoring sites.

[Parameter settings] Set the variation record time series file format parameters, enter the column ordinal number of current variations and mean distance between geodetic sites, and set the SRBF parameters and algorithm control parameters.

The weights of variations are employed only to distinguish the quality of variations in the same type.

The column ordinal number of the current variations in the file record. Each time, the program estimates an epoch time of the land water EWH and load deformation field grid, you need to specify the column ordinal number of the variations at the epoch time.

Mean distance (km) between the geodetic sites. Input the approximate value of the mean distance between the geodetic sites. Which should not be greatly reduced intentionally, otherwise it will seriously affect the speed of parameter estimation and the stability of the solution. The mean distance is not directly related to the spatial resolution of the estimated land water EWH.

Select the spherical radial basis functions: radial multipole kernel function, Poisson wavelet kernel function. The zero-order radial multipole kernel function is the point mass kernel function, and the zero-order Poisson wavelet kernel function is the Poisson kernel function.

Enter the order m. The order number m of radial multipole kernel function and Poisson wavelet kernel function. The greater the m, the bigger the kurtosis of SRBF.

Input the Bjerhammar sphere burial depth: The depth of the Bjerhammar sphere relative to the mean height surface of the observation variations, which can be employed to adjust the spectral center and bandwidth of SRBF when combined with the degree of SRBF Legendre expansion.

The greater the burial depth, the smoother the SRBF, the smaller the kurtosis namely the wider the spectral bandwidth.

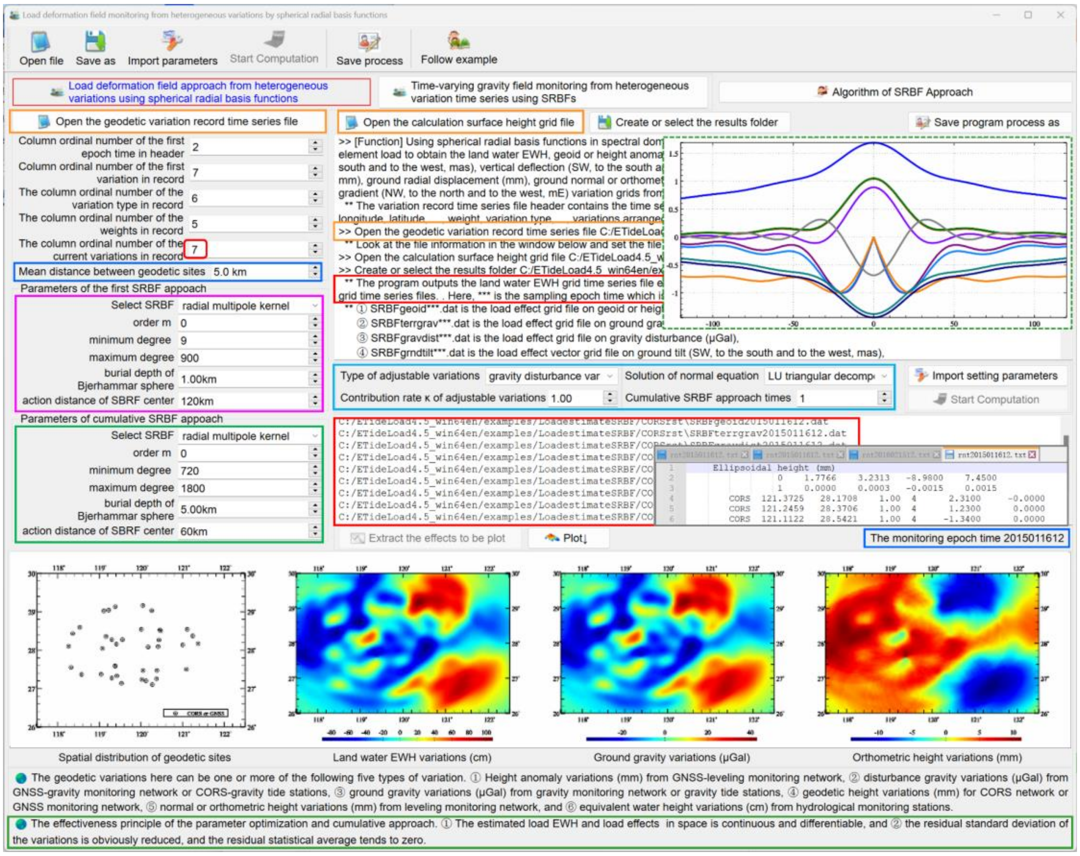
Enter the action distance of SRBF center. The action distance is also called as the radius of influence = spherical angular distance × the mean radius of the Earth. Which is equivalent to Green’s integral radius in space domain.

A fixed action distance is adopted to ensure the coordination and consistency of the spatial and spectral figure of load deformation field.

Enter minimum and maximum degree of SRBF Legendre expansion. Minimum and maximum degree can be employed to adjust SRBF bandwidth.

Cumulative SRBF approach times. Every cumulative SRBF approach can be considered that the current load deformation field is refined by the remove-restore scheme with the previous load deformation field as the reference field. Generally cumulative 1 ~ 3 times can obtain a stable solution.

The effectiveness principle of the parameter optimization and cumulative approach: (1) The estimated load EWH and load effects in space is continuous and differentiable, and (2) the residual standard deviation of the variations is obviously reduced, and the residual statistical mean tends to zero.

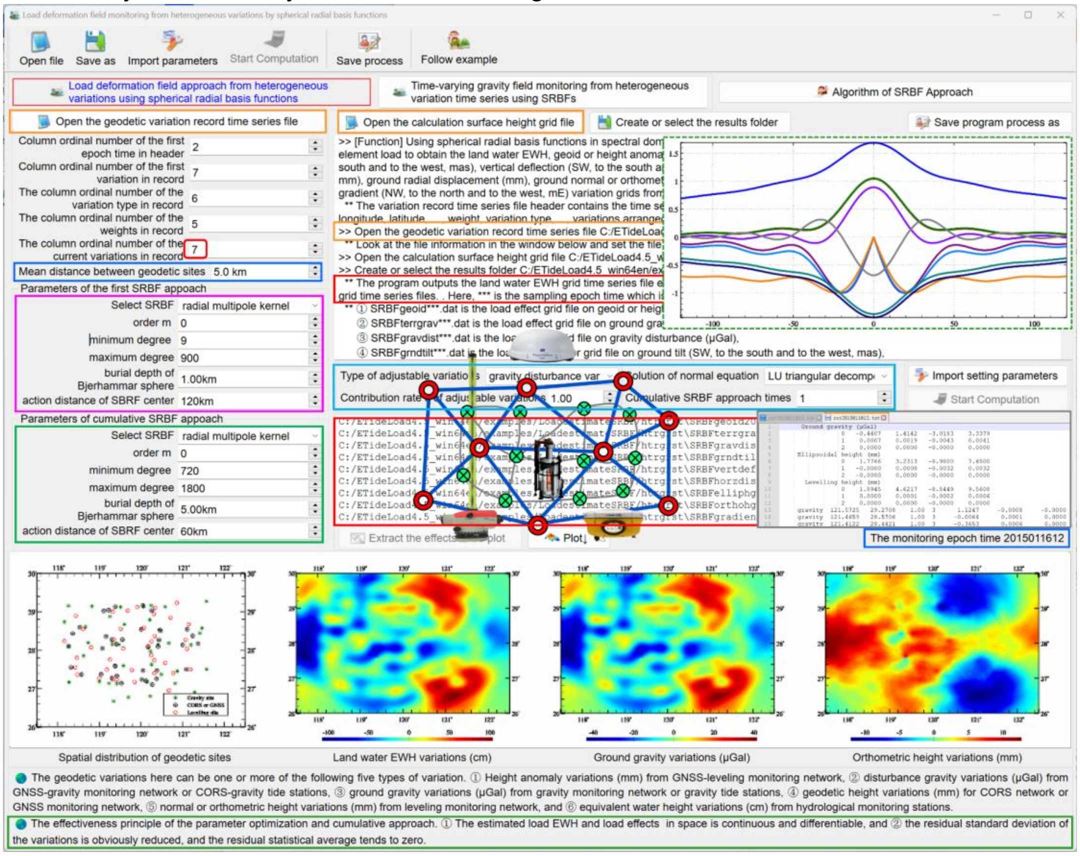


Select the type of adjustable variation and set the contribution rate κ of the adjustable variation.

The program multiplies the normal equation coefficient matrix and constant matrix of the adjustable variations by κ, respectively, to increase ($\kappa > 1$) or decrease ($\kappa < 1$) the contribution of the adjustable variation. When $\kappa = 1$, it means that there is not any adjustable variation selected. When $\kappa = 0$, the adjustable variation does not participate in the EWH estimation.

Select the method of the solution of normal equation. LU triangular decomposition method or Cholesky decomposition. The normal equation here does not need regularization and iterative computation.

ETideLoad4.5 proposes a cofactor matrix diagonal standard deviation method to combine different types of heterogeneous geodetic variations for load EWHs estimation, so that the properties of the estimation solution are only related to the space distribution of the geodetic variations without influence of various monitoring error, significantly to improve the universality and reliability of the estimation algorithm.



[Output files] The land EWH variation and full-element load effect grid files, the residual variation file for the cumulative approach process.

The program outputs the land water EWH grid file ewh****.dat residual variation file rnt***.txt and various load effect grid files into the current directory.

Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.

①SRBFgeoid***.dat is the load effect grid file on geoid or height anomaly (mm),

②SRBFterrgrav***.dat is the load effect grid file on ground gravity (μGal),

③SRBFgravdist***.dat is the load effect grid file on gravity disturbance (μGal),

④SRBFgrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

⑤SRBFvertdefl***.dat is the load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),

⑥SRBFhorzdisp***.dat is the load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),

⑦SRBFelliphgt***.dat is the load effect grid file on ground radial displacement (mm),

⑧SRBForthohgt***.dat is the load effect grid file on ground normal or orthometric height (mm),

⑨SRBFgradient***.dat is the load effect grid file on gravity gradient (radial, mE) and

⑩SRBFhorzgrad***.dat is the load effect vector grid file on horizontal gravity gradient (NW, to the north and to the west, mE).

The program also outputs the SRBF spatial curve file *spc.rbf and spectral curve files *dgr.rbf of 11 kinds of geodetic variations into the current directory.

*spc.rbf file header format: SRBF type (0-radial multipole kernel function, 1-Poisson wavelet kernel function), order of SRBF, Minimum and maximum degree of SRBF Legendre expansion, buried depth (km). The record format: spherical distance (km), the normalized SRBF values from the load EWH, height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, orthometric height, gravity gradient and horizontal gradient variations.

The file header of * dgr.rbf is the same as * spc.rbf. The record format: degree n of SRBF Legendre expansion, the degree n normalized SRBF values from the load EWH, height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, orthometric height, gravity gradient and horizontal gradient variations.

After the computation is completed, the residual geodetic variation file is opened to observe the standard deviation and mean value of the residual variations and their changes with the cumulative number of times to optimize the parameter settings and cumulative number of times, and then recompute.

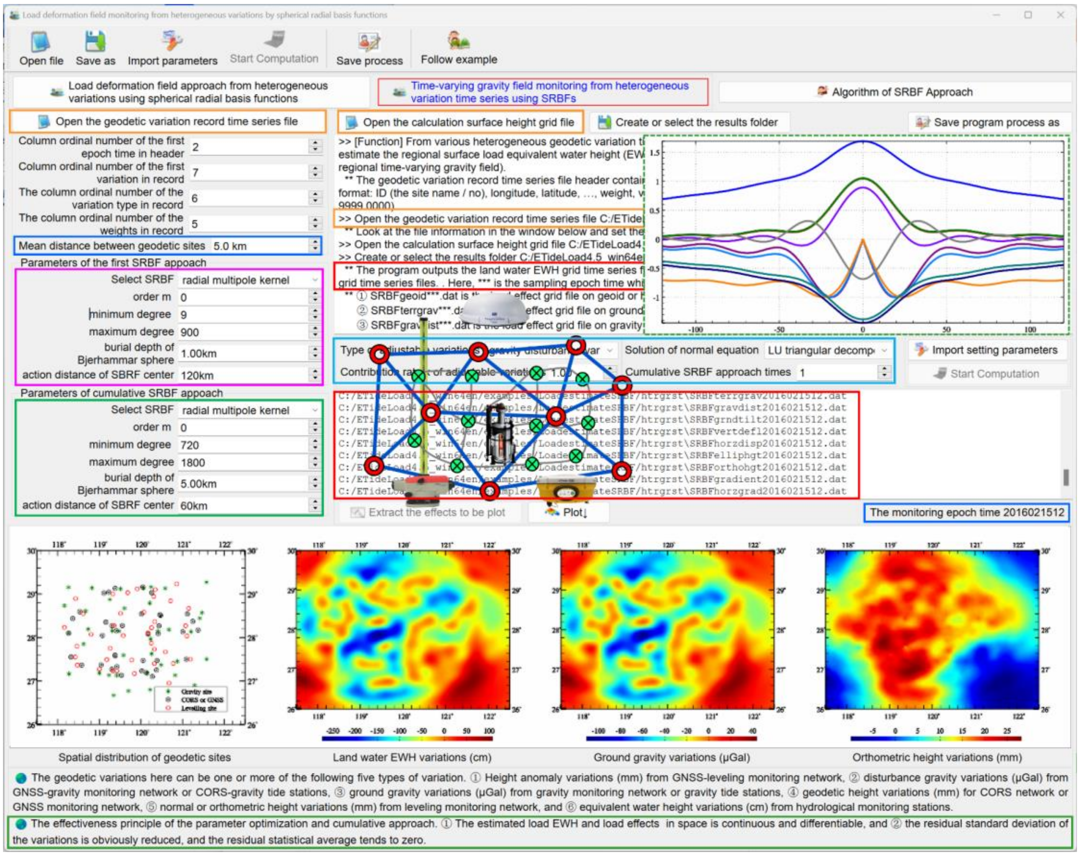
4.8.2 Time-varying gravity field monitoring from heterogeneous variation time series using SRBFs

[Function] From various heterogeneous geodetic variation time series, using spherical radial basis function approach method in spectral domain, estimate the regional surface load equivalent water height (EWH) and full-element load effect grid time series (usually employed to represent regional time-varying gravity field).

[Input files] The heterogeneous variation record time series file. The calculation surface height grid file.

The variation record time series file. The file header contains the time series length and the sampling epoch time arranged with time. Record format: ID (the site name / no), longitude, latitude, …, variation type, weight, ..., variations arranged in time series length (default value is 9999.0000).

Variation type = 1 represents the height anomaly variation (mm), = 2 represents gravity disturbance variation (μGal), = 3 represents ground gravity variation (μGal), = 4 represents ground ellipsoidal height variation (mm), and = 5 represents normal or orthometric height variation (mm), and = 6 represents equivalent water height variations (cm).



[Parameter settings] All the algorithm parameters that are same as the function [Load deformation field approach from heterogeneous variations by spherical radial basis functions].

During the monitoring period, when the spatial distribution of geodetic monitoring sites or shape of geodetic monitoring networks and the type of geodetic variations are basically unchanged, the algorithm parameters will remain unchanged, which is a typical feature of ETideLoad algorithm of load deformation field monitoring that is especially useful for automatic processing of multiple heterogeneous multi-period or continuous geodetic monitoring networks.

[Output files] The program outputs the land water EWH grid time series file ewh****.dat residual variation time series files rnt***.txt and full-element load effect grid time series files. Here, *** is the sampling epoch time which is also saved as the last column attribute of the load effect grid file header.

①SRBFgeoid***.dat is the load effect grid file on geoid or height anomaly (mm),

②SRBFterrgrav***.dat is the load effect grid file on ground gravity (μGal),

③SRBFgravdist***.dat is the load effect grid file on gravity disturbance (μGal), ④SRBFgrndtilt***.dat is the load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

⑤SRBFvertdefl***.dat is the load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),

⑥SRBFhorzdisp***.dat is the load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),

⑦SRBFelliphgt***.dat is the load effect grid file on ground radial displacement (mm),

⑧SRBForthohgt***.dat is the load effect grid file on ground normal or orthometric height (mm),

⑨SRBFgradient***.dat is the load effect grid file on gravity gradient (radial, mE) and

⑩SRBFhorzgrad***.dat is the load effect vector grid file on horizontal gravity gradient (NW, to the north and to the west, mE).

After the estimation is completed, the residual value files should be opened to check the results. The first few rows of the file indicate the change information of the mean and standard deviation of the residual value with the number of iterations.

If necessary, the algorithm parameters should be adjusted and recompute for individual epochs without ideal solutions by the function [Load deformation field approach from heterogeneous variations using spherical radial basis functions]. Particular attention should be paid at the monitoring epoch time when the distribution or types of geodetic variations occur obvious changes.

4.9 Geodynamic calculation on geodetic field grid time series

[Purpose] Calculate the time difference, space horizontal gradient, or two vector grids inner product of the ground deformation field grid time series to display their spatiotemporal geodynamic characteristics.

4.9.1 Time difference operation on variation (vector) grid time series

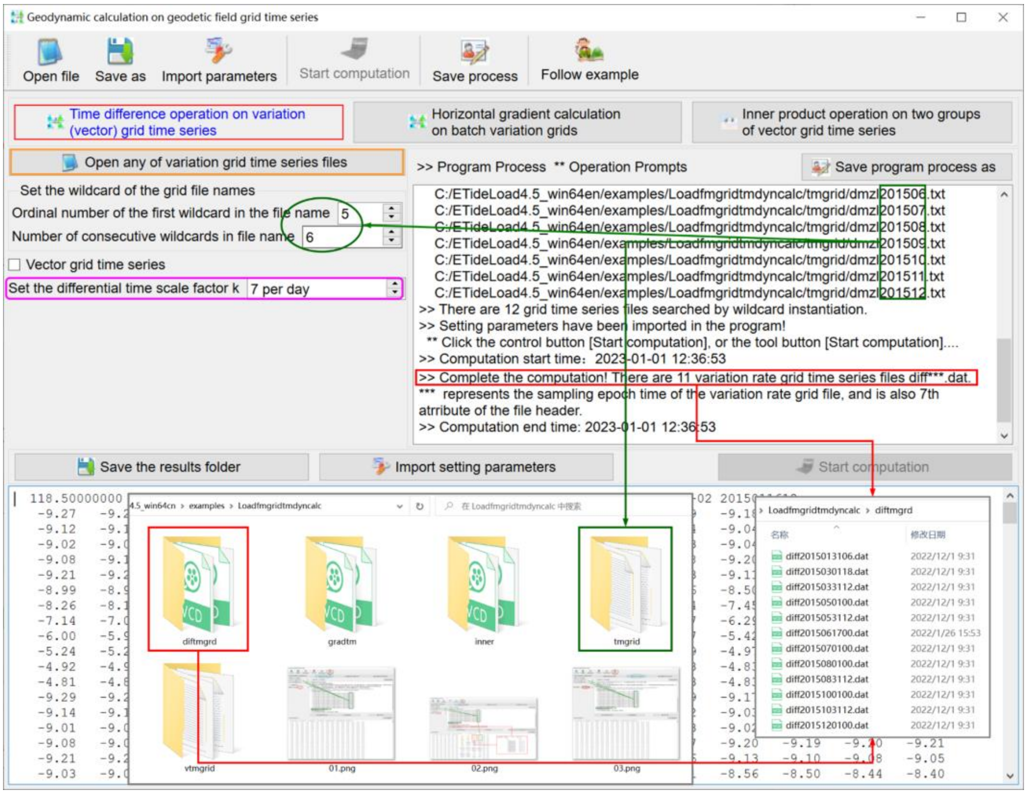
[Function] Sort the input variation (vector) grid time series files according to the sampling epoch time (the seventh attribute of the file header), and then calculate the variation rate at two neighboring sampling epochs to generate the variation (vector) rate grid time series. Here, the sampling epoch time of the current grid is equal to the average of the before and after sampling epochs of the variation (vector) grids, the unit of the variation rate is per k day, and k is the given differential time scale factor.

The variation (vector) grid time series files are extracted according to the given wildcards. For the variation vector grid time series, the program requires them to be in the form of horizontal coordinates.

[Input files] The variation (vector) grid time series files.

[Parameter settings] Set the wildcard parameters for the variation (vector) grid time series files, enter the differential time scale factor k.

[Output files] The variation (vector) rate grid time series files.



4.9.2 Horizontal gradient calculation on batch variation grids

[Function] From batch variation grid files with the same grid specifications in the specified folder, calculate horizontal gradient vector grids (per km). The horizontal gradient vector can be output in the form of polar coordinates or EN horizontal coordinates. The variation grid files are extracted according to the given wildcards.

4.9.3 Inner product operation on two groups of vector grid time series

[Function] Calculate the inner product grid time series from two groups of variation vector grid time series in the form of the EN horizontal rectangular coordinates with the same grid specifications.

The variation vector grid files are extracted according to the given wildcards.

The program allows a group of vector grid files with only one sampling time. When the two groups are both vector grid time series, the program requires one-by-one correspondence between the sampling epochs.

4.10 Surface load and load deformation field monitoring computation processes

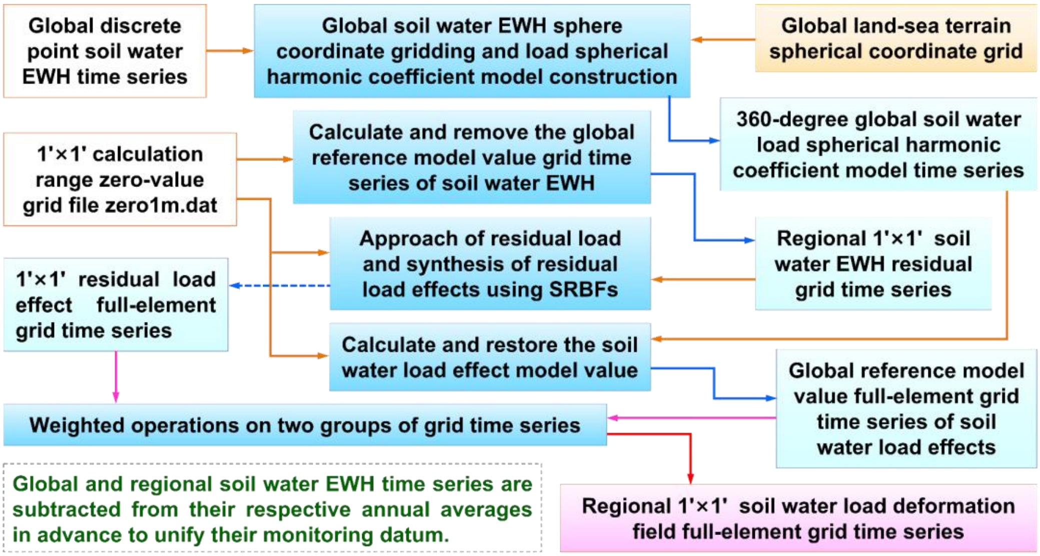
4.10.1 Complete computation processes of high-resolution regional load deformation field time series

Taking the regional soil water variations as the example, the remove-restore scheme combined the global load spherical harmonic coefficient synthesis and regional residual load

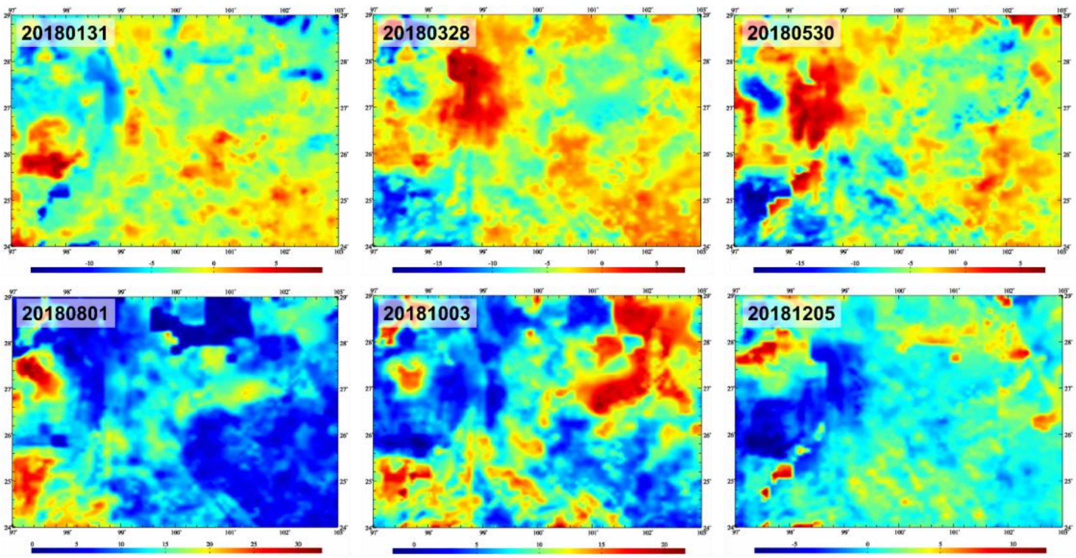
SRBF (spherical radial basis function) approach is employed to compute the high-precision and high-resolution regional load deformation field full-element grid time series in the near-Earth space in the four-step.

The soil water here consists of soil water in 4 m shallow, wetland water, vegetation water, glaciers, and snow mountain water, but does not include lakes, rivers, and groundwater.

The global soil water equivalent water height (EWH) time series and the regional high-resolution soil water EWH time series are subtracted from their respective annual averages in advance to unify the global and regional soil water variation monitoring datum.



Complete computation processes of regional load deformation field full-element grid time series



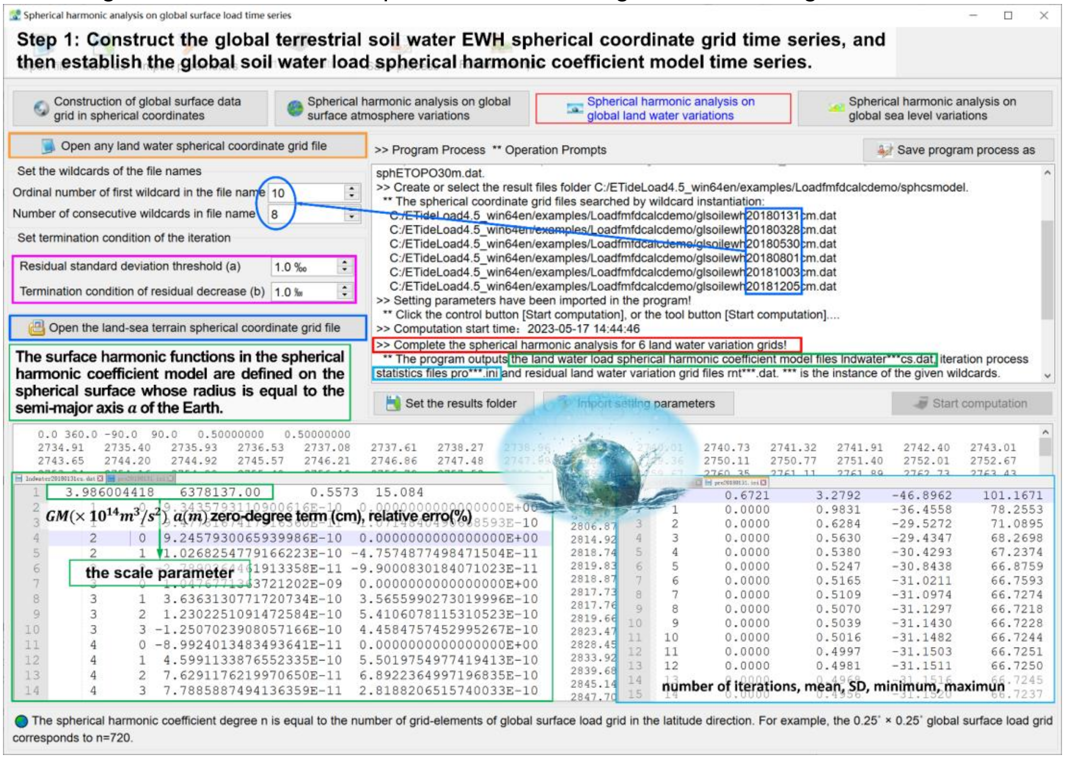
Regional 1′×1′ soil water equivalent water height (EWH, cm) grid time series

The complete computation process of the high-resolution regional load deformation field full-element grid time series consists of four steps usually: global surface load spherical harmonic analysis, load deformation field spherical harmonic synthesis, regional residual load spectral domain SRBF approach and residual load deformation field SRBF synthesis.

Step 1: Construct the global terrestrial soil water EWH spherical coordinate grid time series, and then establish the global soil water load spherical harmonic coefficient model time series.

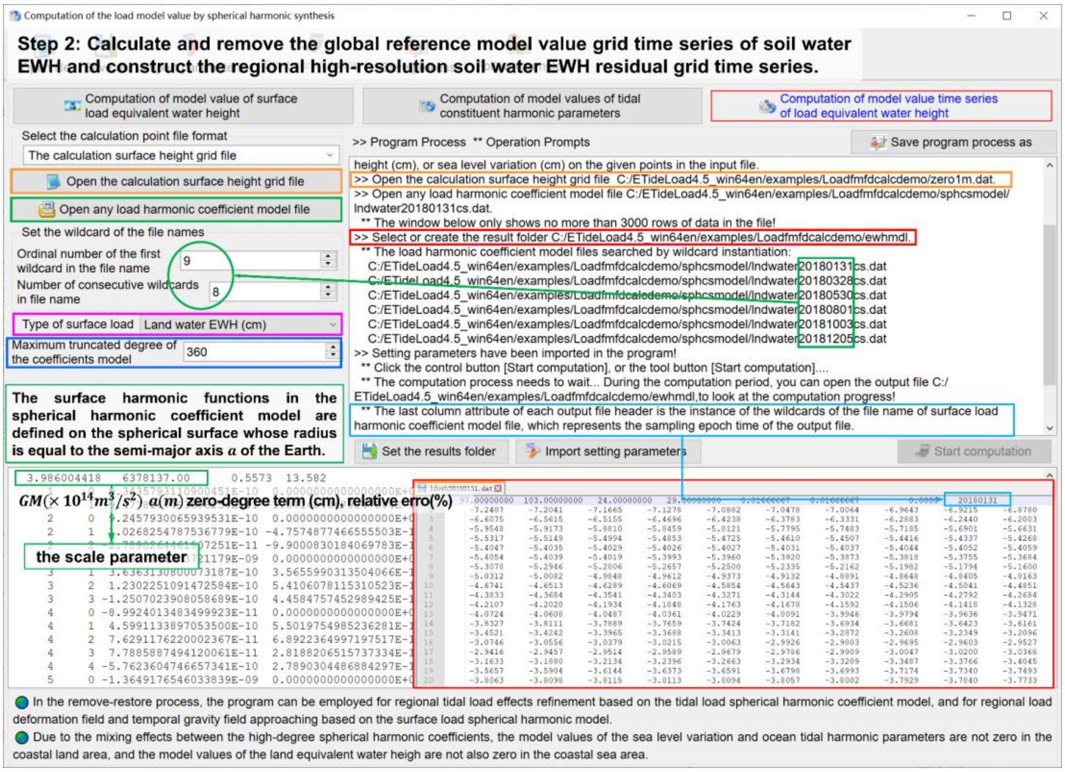
Call the function [Construction of global surface data grid in spherical coordinates], construct the global soil water EWH spherical coordinate grid time series glsoilewh*.dat from global soil water observations, where * is the sample epoch time and * = 20180131 represents January 31, 2018. The process is omitted in this example.

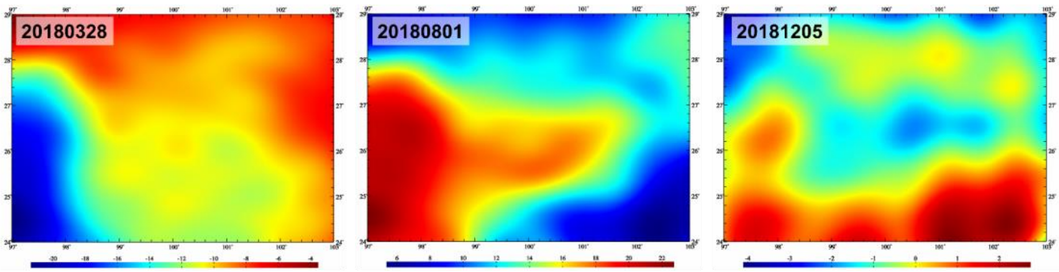
Call the function [Spherical harmonic analysis on global land water variations], input global land-sea terrain spherical coordinate grid sphETOPOnc30m.dat (EWH automatically zero in sea area), whose resolution is not less than the soil water EWH grid, and establish the global soil water load spherical harmonic coefficient model time series lndwater*cs.dat form the global soil water EWH spherical coordinate grid time series glsoilewh*.dat.



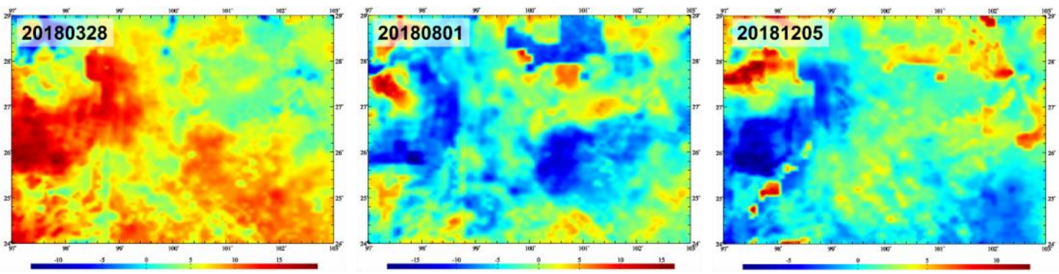
Step 2: Calculate and remove the global reference model value grid time series of soil water EWH and construct the regional high-resolution soil water EWH residual grid time series.

Call the function [Computation of model value time series of load equivalent water height], input the 1'×1' zero-value grid file zero1m.dat, which is employed to give the calculation range and the zero-value represents the calculation surface as the ground, let 'land water EWH (cm)' as the surface load type and the maximum calculation degree 360, calculate the global reference model value grid time series ldewh*.dat of soil water EWH from the global soil water load spherical harmonic coefficient model time series lndwater*cs.dat.





Regional 1′×1′ soil water EWH model reference value (cm) grid time series

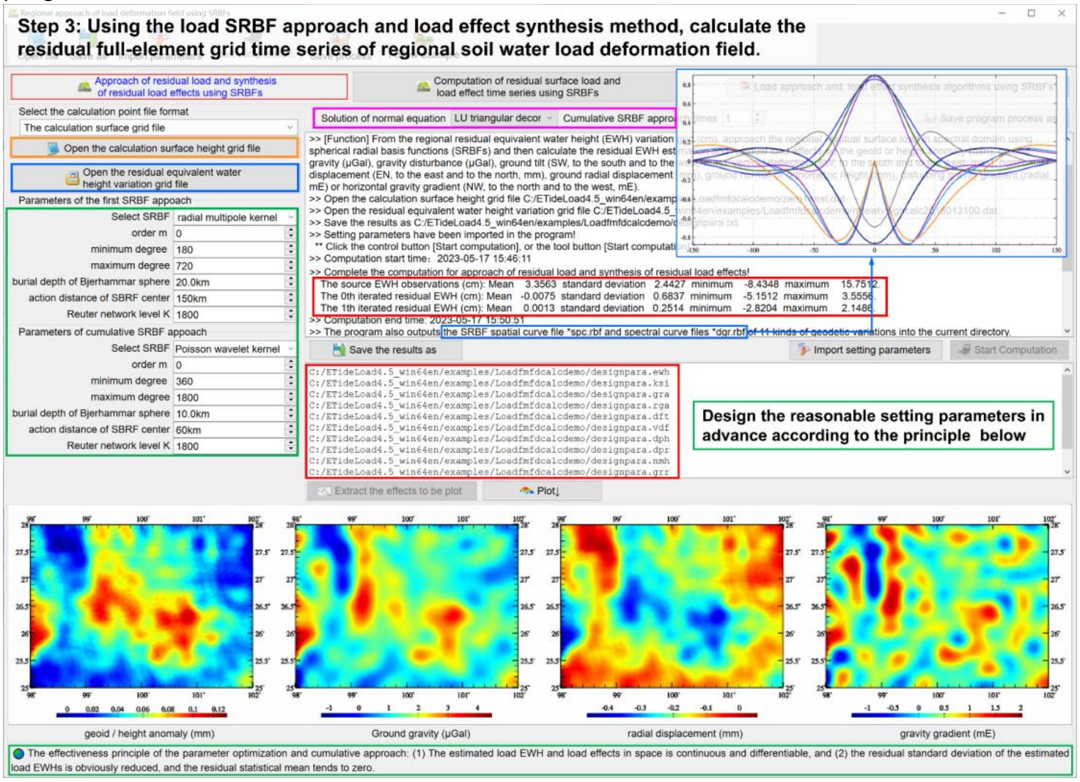


Regional 1′×1′ soil water EWH residual (cm) grid time series

Call the function [Weighted operations on two groups of grid time series], subtract the soil water EWH model value grid time series ldewh***.dat from the 1'×1' soil water EWH grid time series soilewh***.dat to generate the regional 1'×1' soil water EWH residual grid time series rntewh***.dat.

Step 3: Determine the residual full-element grid time series of regional soil water load deformation field by the load SRBF approach and load effect SRBF synthesis.

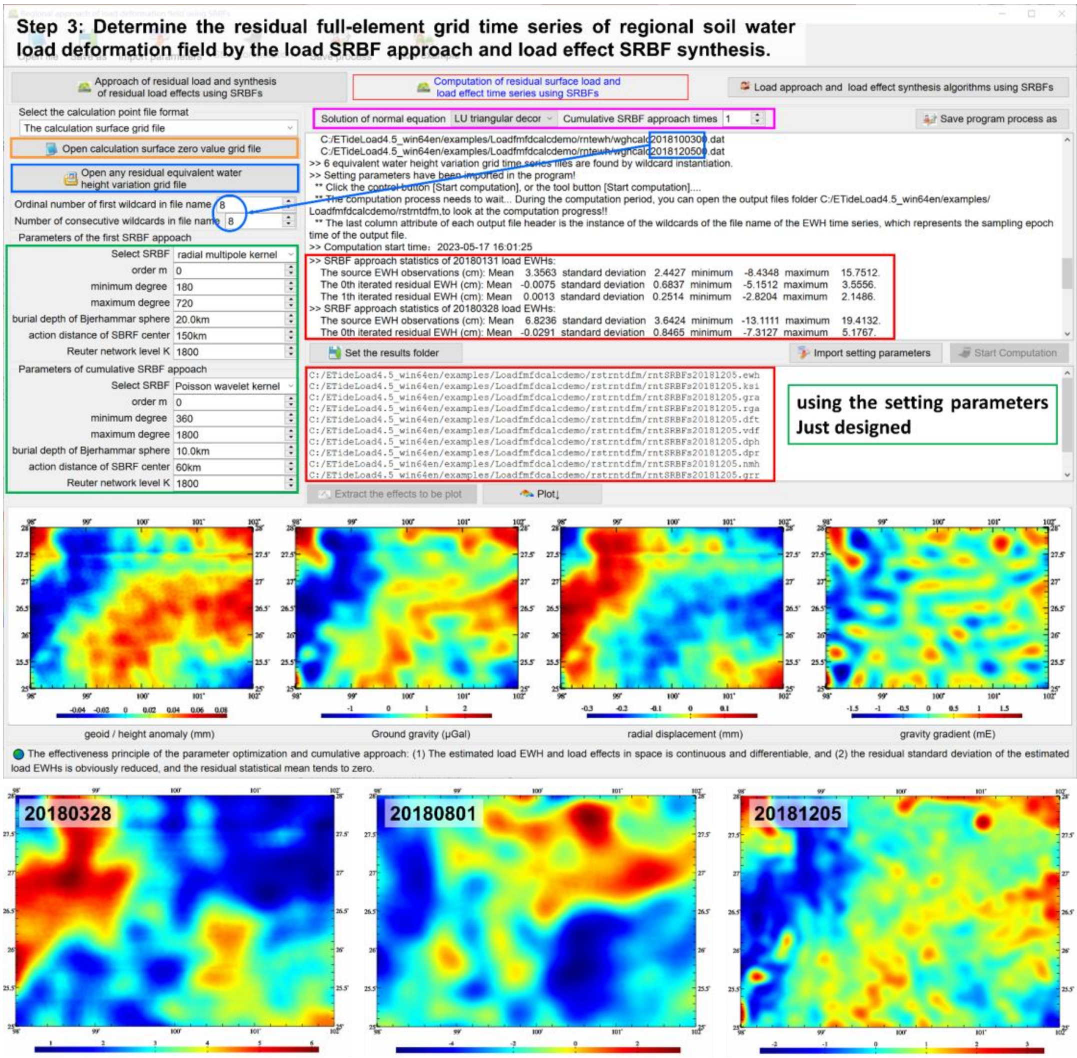
Call the function [Approach of residual load and synthesis of residual load effects using SRBFs], input the calculation result area 1'×1' zero-value grid file zero1mrst.dat removed the 1° edge area around the grid zero1m.dat, and generate the residual load effect full-element grid ttt.??? from regional 1'×1' soil water EWH residual grid rntewh***.dat at any epoch time to design the reasonable setting parameters according to the principle of parameter setting optimization and cumulative approach effectiveness given below the program interface.



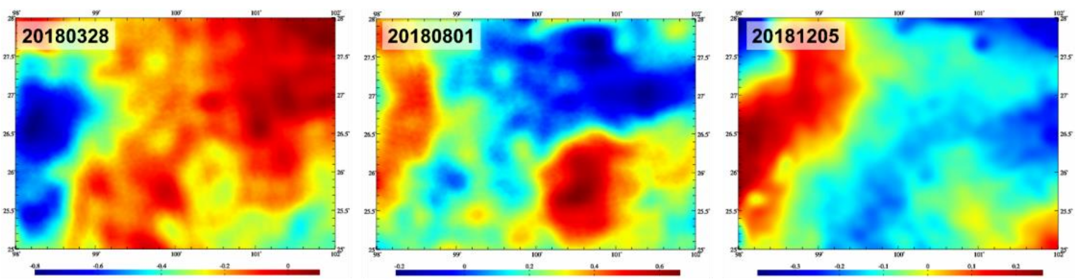
Call the function [Computation of residual surface load and load effect time series using SRBFs], input the 1'×1' zero-value grid file zero1mrst.dat, and generate the residual load effect full-element grid time series rntSRBFs***.??? from regional 1'×1' soil water EWH residual grid time series wghcalc*.dat with the setting parameters above.

Where ??? = ewh, ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of the residual EWH estimation and residual load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

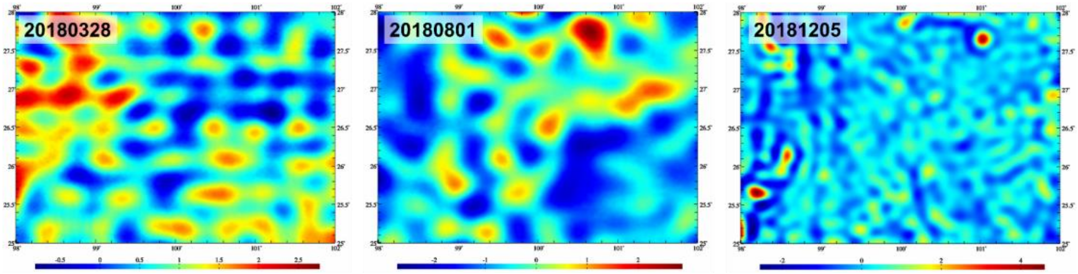
*** are the wildcards of the variation grid time series file names, whose instance can identify the sampling epoch time of the load effects.



Regional 1′×1′ soil water residual load effect (μGal) grid time series on ground gravity



Regional 1′×1′ soil water residual load effect (mm) grid time series on ground ellipsoidal height



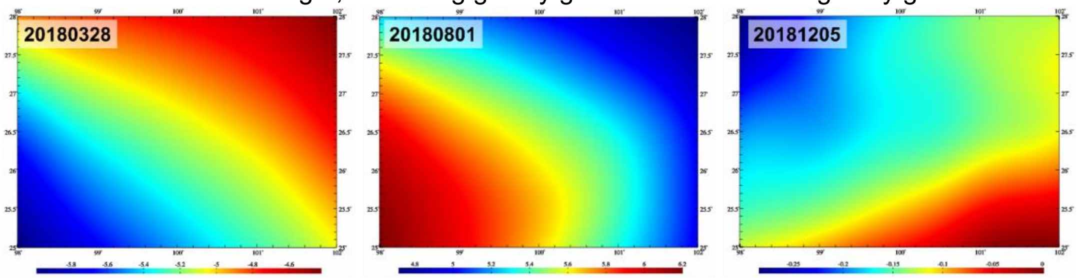
Regional 1′×1′ soil water residual load effect (mE) grid time series on gravity gradient

Step 4: Calculate and restore the soil water load effect model value grid time series and generate the regional high-resolution soil water load effect full-element grid time series.

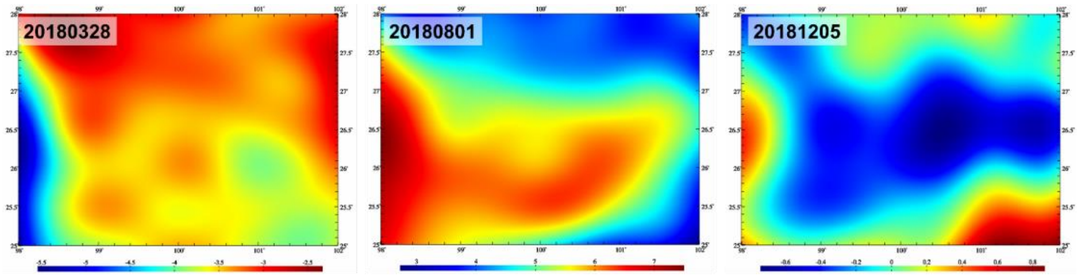
Call the function [Computation of load effect time series by spherical harmonic synthesis], input the calculation result area 1'×1' zero-value grid file zero1mrst, let 'land water EWH (cm)' as the surface load type and the maximum calculation degree is 360, calculate the global reference model value grid time series loadfmdl***.??? of soil water load effects from the global soil water load spherical harmonic coefficient model time series lndwater*cs.dat.

Call the function [Weighted operations on two groups of grid time series], directly add the reference model value grid time series loadfm***.??? to the residual grid time series rntSRBFs***.??? of soil water load effects to generate the regional 1'×1' full-element grid time series soilloadfm***.??? of soil water load effects.

Where ??? = ksi, gra, rga, dft, vdf, dph, dpr, nmh, grr or hgd, respectively, representing the grid file of the soil water load effects on the height anomaly, ground gravity, gravity disturbance, ground tilt, vertical deflection, horizontal displacement, radial displacement, normal or orthometric height, disturbing gravity gradient or horizontal gravity gradient.

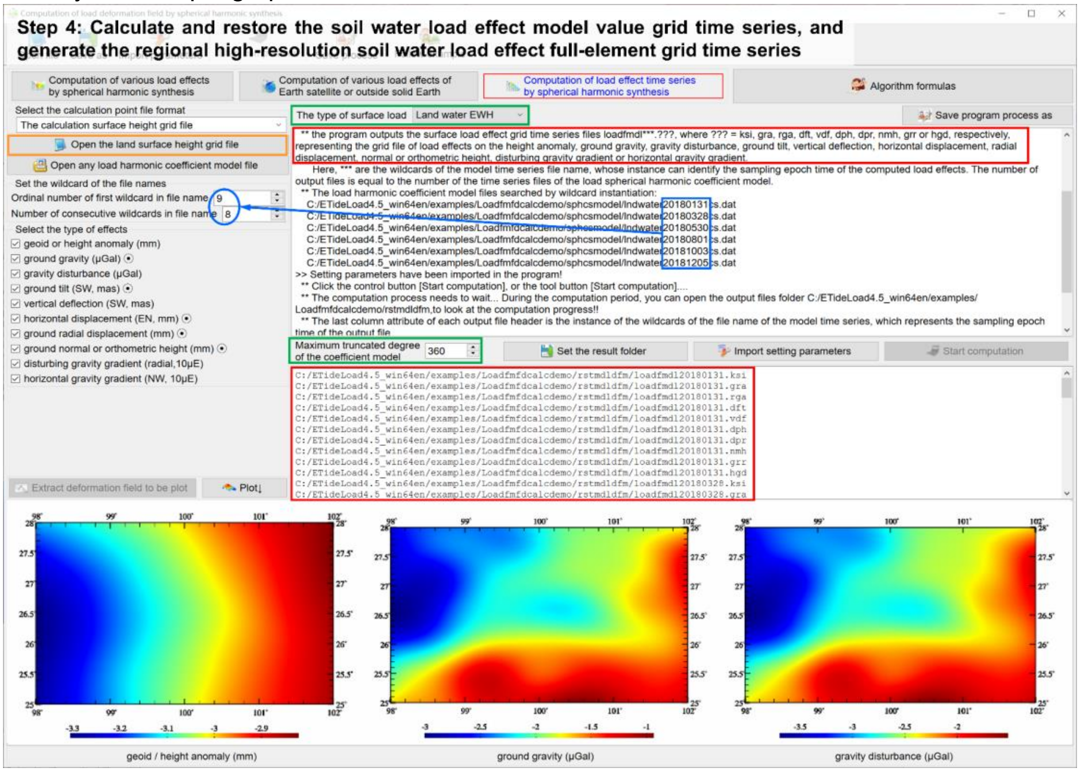


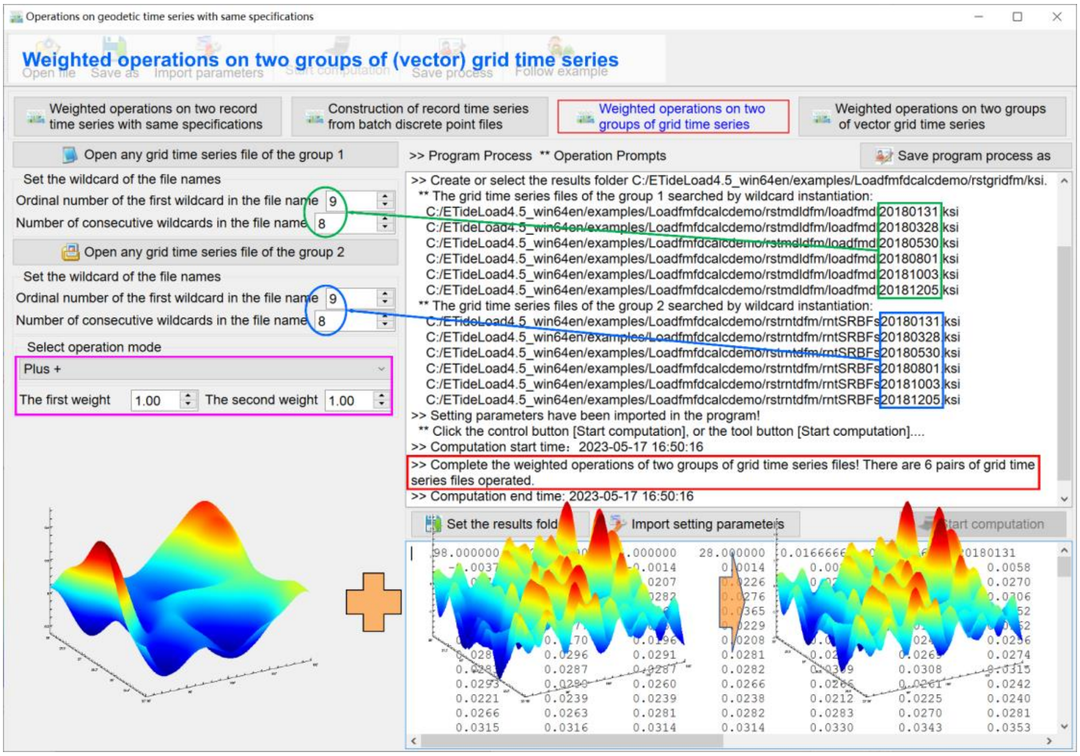
Regional 1′×1′ soil water load effect model value (mm) grid time series on geoid



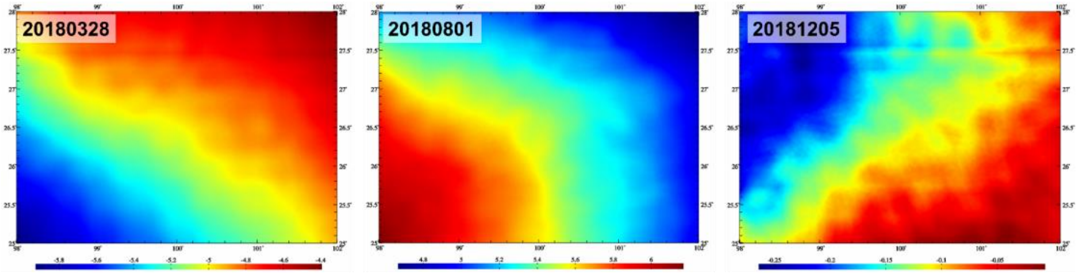
Regional 1′×1′ soil water load effect model value (μGal) grid time series on ground gravity

*** are the wildcards of the variation grid time series file names, whose instance can identify the sampling epoch time of the load effects.

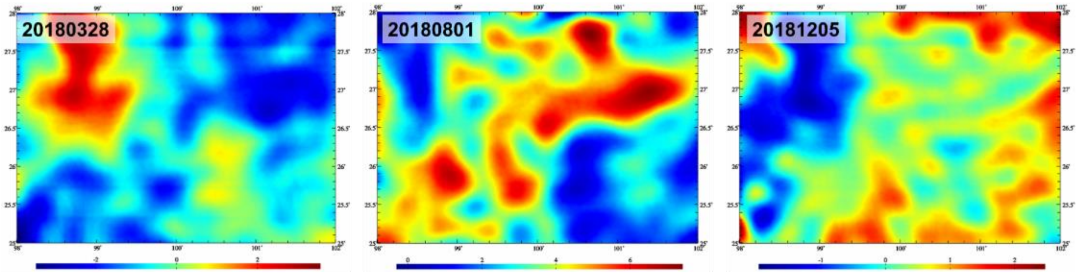




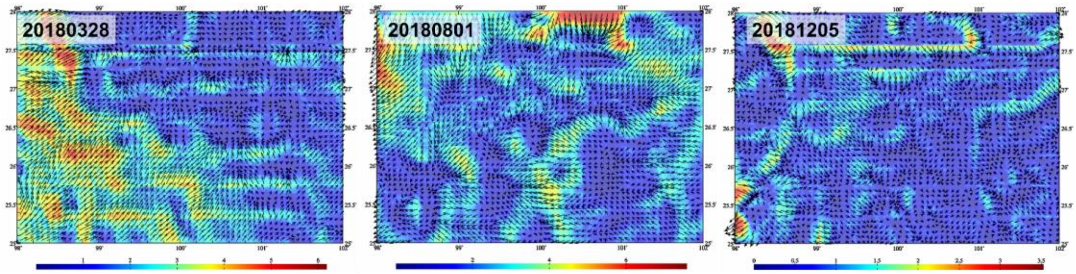
According to the same processes above, you can compute regional atmosphere or sea level variation load deformation field full-element grid time series.



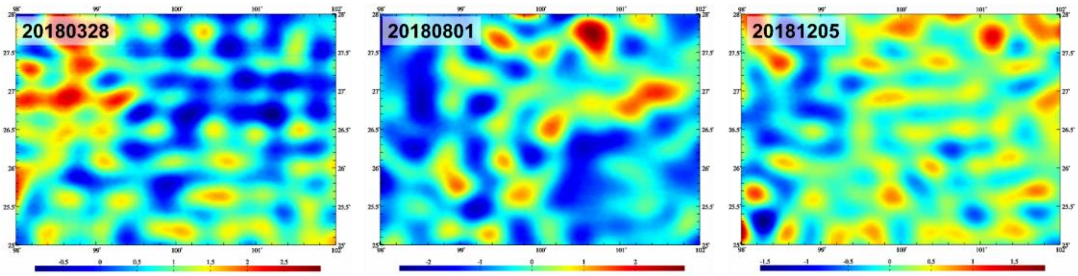
Regional 1′×1′ soil water load effect (mm) grid time series results on geoid



Regional 1′×1′ soil water load effect (μGal) grid time series results on ground gravity



Regional 1′×1′ soil water load effect (mas) vector grid time series results on ground tilt



Regional 1′×1′ soil water load effect (mE) grid time series results on gravity gradient

ETideLoad4.5′s algorithm of the load approach and load effect synthesis using SRBFs can effectively solve the problems of high-degree oscillation and poor convergence of Green′s function and the spectrum leakage and singularity of Green′s integral in the near area around the calculation point.

The full-element load deformation field approached can be used to accurately calibrate the key payloads of geodetic satellite, verify the satellite geodetic monitoring ability, and effectively improve the monitoring performance, reliability, and accuracy level.

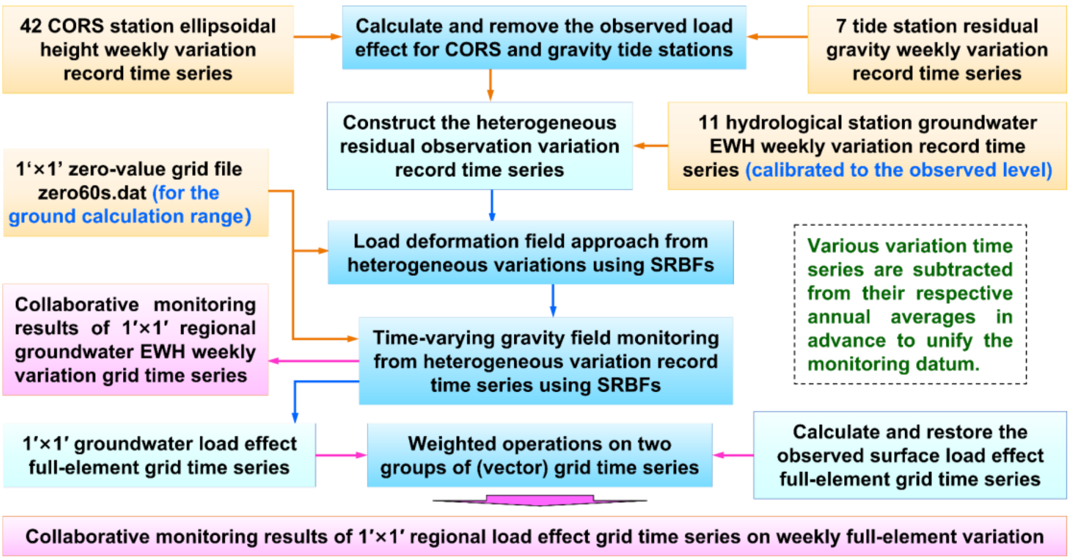
The regional load deformation field approached can be used for the epoch reduction of various high-precision observations such as GNSS, leveling and gravity, which can support the realization and coordinated maintenance of heterogeneous geodetic datum.

It is the basic and lowest requirement of deep fusion of multi-source heterogeneous data and collaborative monitoring of multiple heterogeneous technologies in geodesy to use the surface load deformation field for the unification of monitoring epoch reduction and monitoring datum.

4.10.2 Heterogeneous collaborative monitoring process of groundwater variations and load deformation field

From the heterogeneous observation variation record time series from CORS station, gravity tide station and groundwater monitoring station, compute the groundwater variations and load deformation field full-element grid time series in the five-step to realize the heterogeneous collaborative monitoring to regional groundwater and time-vary gravity field according to the remove-restore scheme based on the observed surface load.

The target monitoring area: 98°~101°E, 24°~26.5°N. Observation point distribution: 97.5°~101.5°E, 23.5°~27.0°N. Monitoring time interval: one week. Starting and ending time: March 2019 to August 2019. Spatial resolution: 1′×1′.



Heterogeneous collaborative monitoring process of groundwater variations and load deformation field

Step 1: Data preparation and preprocessing of various geodetic and surface load observations.

(1) CORS network data processing and calculation of the ellipsoidal height weekly variations time series at 42 CORS stations, and calculation of gravity weekly variation time series at 7 gravity tide stations.

(2) Various geodetic and surface load observation variation time series are subtracted from their respective annual averages in advance to unify variation monitoring datum.

(3) Calculation of groundwater equivalent water height (EWH) weekly variation time series at 11 hydrological monitoring stations.

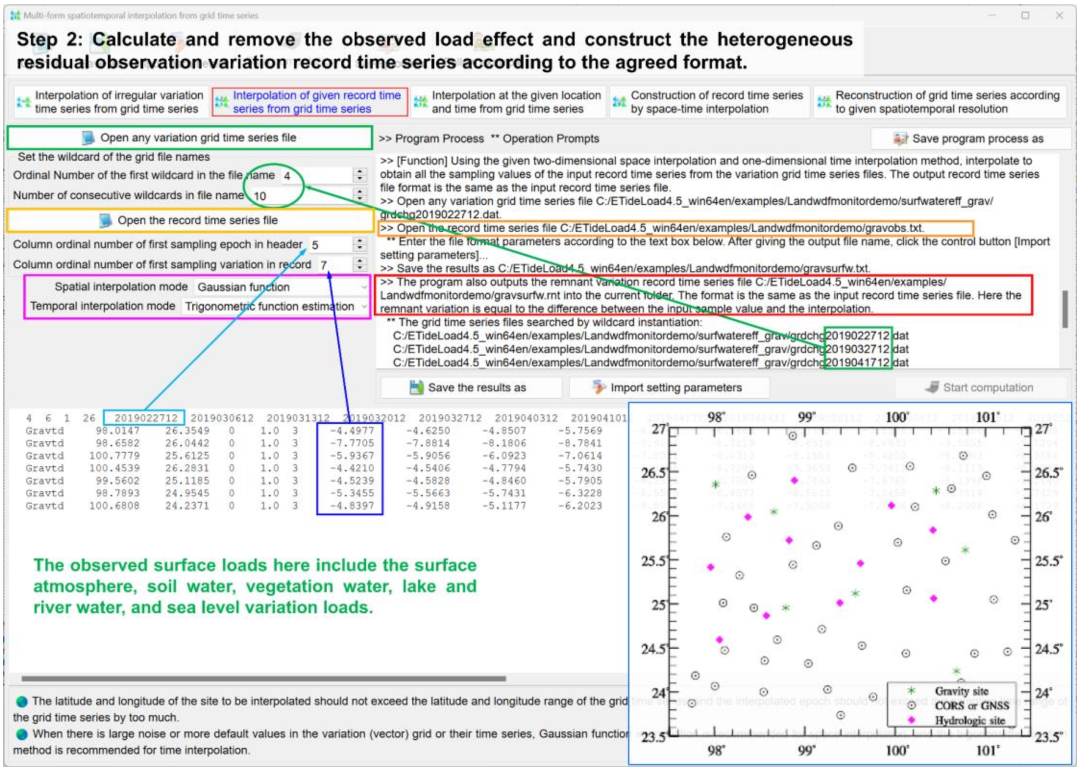
According to the process of this section, calculate the regional groundwater EWH weekly variation grid time series in advance only from CORS and gravity tide monitoring data, whose monitoring time span was not less than two years. Then, interpolate the calculated groundwater EWH grid into the hydrological monitoring station to calibrate the parameters, to transform the variation of observed groundwater level (head) into the variation of groundwater EWH at each hydrological monitoring station.

The process in step 1 is omitted in this example.

Step 2: Calculate and remove the observed load effect and construct the heterogeneous residual observation variation record time series according to ETideLoad4.5 agreed format.

According to the computation process of section 4.10.1, calculate the observed load effect weekly variation grid time series on ground ellipsoidal height and gravity.

Call the function [Interpolation of given record time series from grid time series], remove the observed load effects from the gravity weekly variation time series at gravity tide stations to generate the residual gravity weekly variation time series, and remove the observed load effects from the ellipsoidal height weekly variation time series at CORS stations to generate the residual ellipsoidal height weekly variation time series.



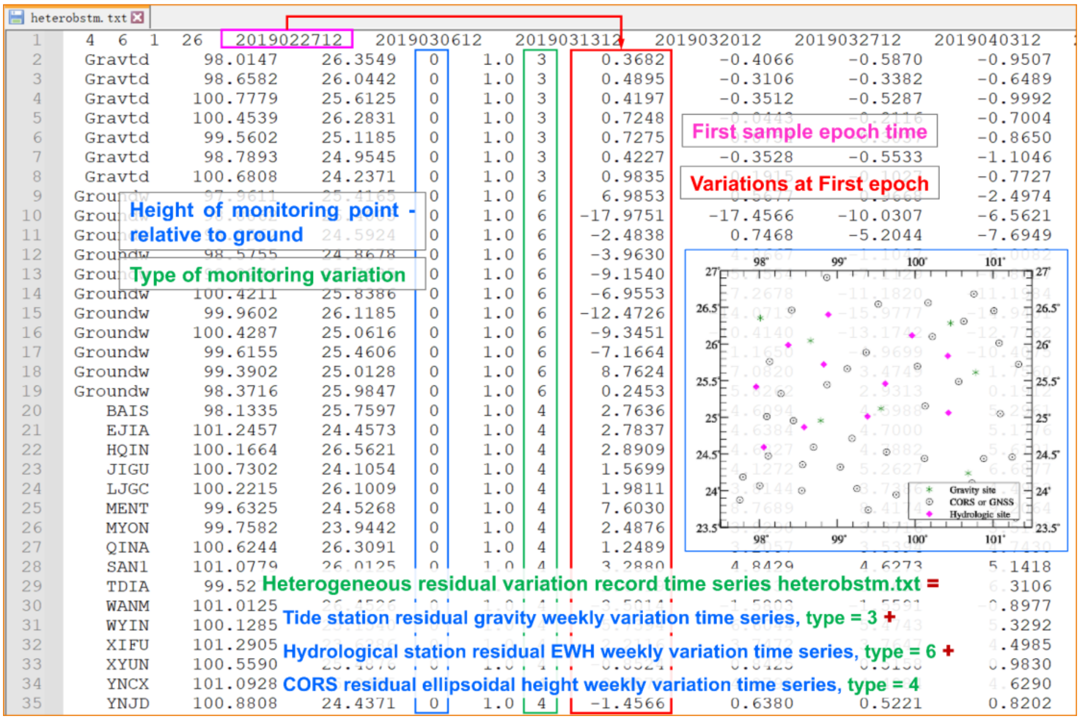
The observed surface loads in this example include surface atmosphere, soil water, vegetation water, lake and river water, and sea level variation loads.

According to the agreed format in ETideLoad4.5, merge the 11 hydrological station groundwater EWH weekly variation, 7 tide station residual gravity weekly variation and 42 CORS residual ellipsoidal height weekly variation record time series to generate the heterogeneous residual observation variation record time series file.

The file header contains the time series length and the sampling epoch time arranged with time. Record format: ID (the site name / no), longitude, latitude, …, weight, variation type, ..., variations arranged in time series length (default value is 9999.0000).

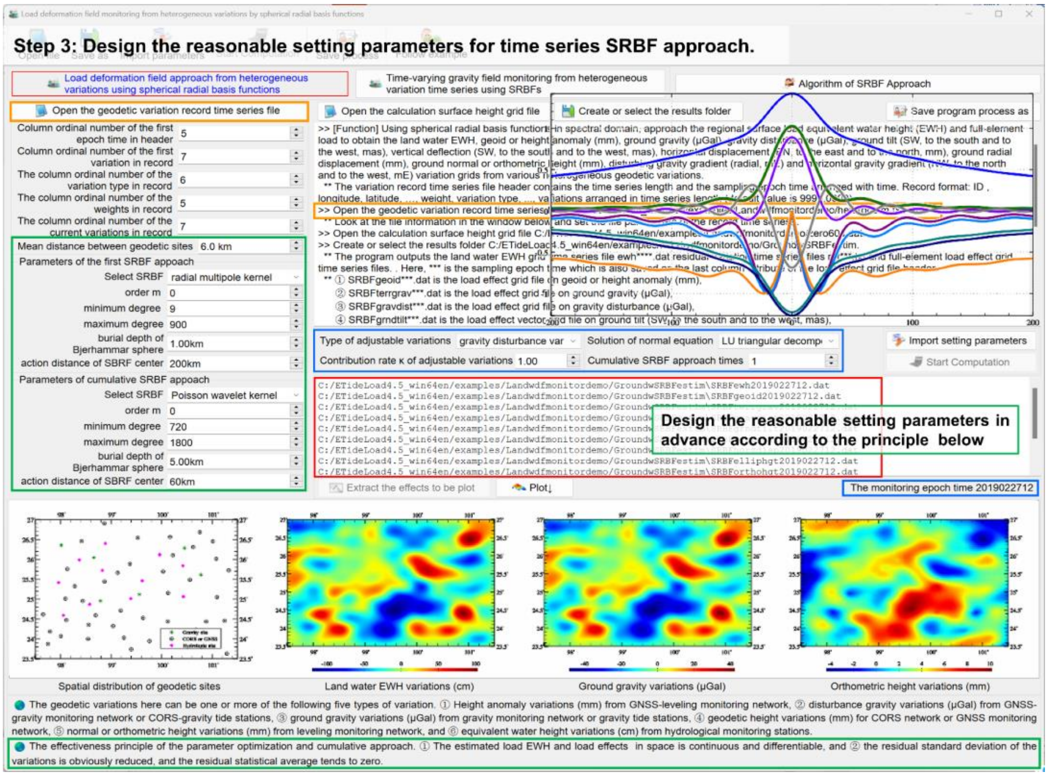
Variation type = 3 represents residual gravity variation (μGal), = 4 represents residual ellipsoidal height variation (mm), = 6 represents EWH variation (cm).

Construct the heterogeneous residual observation variation record time series



Step 3: Call the function [Load deformation field approach from heterogeneous variations using spherical radial basis functions] to design the reasonable setting parameters for time series SRBF approach.

Call the function [Load deformation field approach from heterogeneous variations using spherical radial basis functions], input the 1'×1' zero-value grid file zero60s.dat, which is employed to give the calculation range and the zero value represents the calculation surface as the ground, estimate the residual EWH variation and 10 kinds of load effect grids from the heterogeneous residual observation variation record time series file at any epoch time to design the reasonable setting parameters according to the principle of parameter setting optimization and cumulative approach effectiveness given below the program interface.



Step 4: Estimate the residual EWH and 10 kinds of residual load effect weekly variation grid time series.

Call the function [Time-varying gravity field monitoring from heterogeneous variation time series using SRBFs], input the 1'×1' zero-value grid file zero60s.dat, and estimate the residual EWH weekly variation grid time series ewh***.dat and the following 10 kinds of residual load effect weekly variation grid time series files from the heterogeneous residual observation variation record time series file with the setting parameters above, while output residual variation time series files rnt***.txt.

①SRBFgeoid***.dat is the residual load effect grid file on geoid or height anomaly (mm),

②SRBFterrgrav***.dat is the residual load effect grid file on ground gravity (μGal),

③SRBFgravdist***.dat is the residual load effect grid file on gravity disturbance (μGal),

④SRBFgrndtilt***.dat is the residual load effect vector grid file on ground tilt (SW, to the south and to the west, mas),

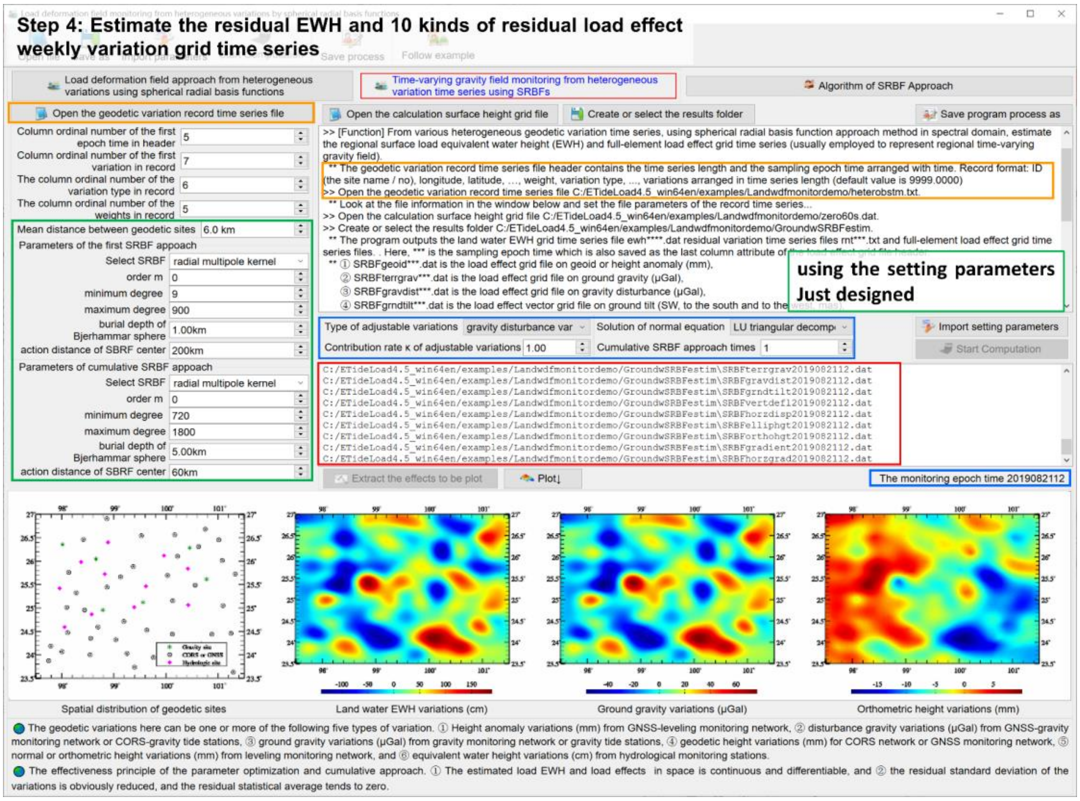
⑤SRBFvertdefl***.dat is the residual load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),

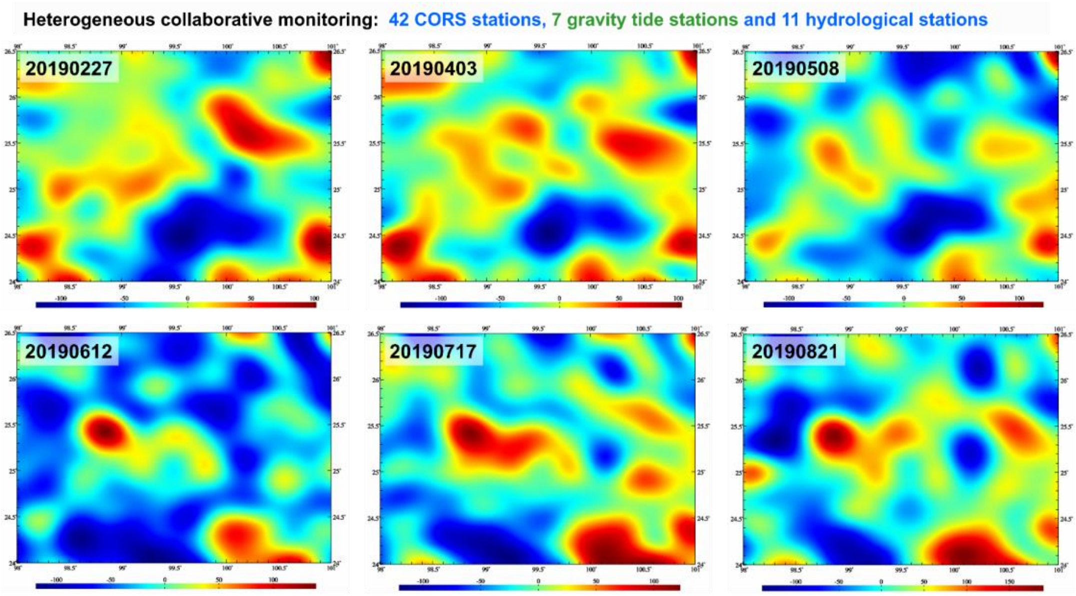
⑥SRBFhorzdisp***.dat is the residual load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),

⑦SRBFelliphgt***.dat is the residual load effect grid file on ground radial displacement (mm),

⑧SRBForthohgt***.dat is the residual load effect grid file on ground normal or orthometric height (mm),

⑨SRBFgradient***.dat is the residual load effect grid file on gravity gradient (radial, mE) and ⑩SRBFhorzgrad***.dat is the residual load effect vector grid file on horizontal gravity gradient (NW, to the north and to the west, mE).

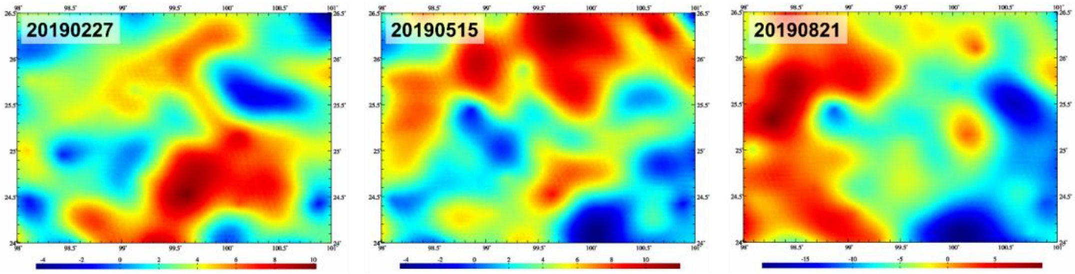




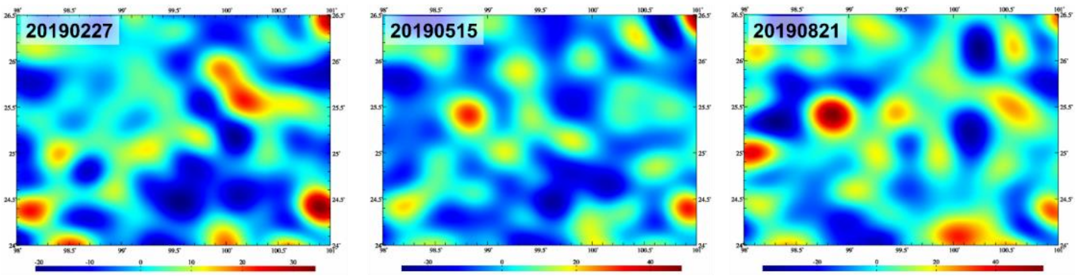
Collaborative monitoring results of 1′×1′ regional groundwater EWH weekly variation grid time series

Where *** is the sampling epoch time from the heterogeneous variation record time series file header, which is also saved as the last column attribute of the load effect grid file header.

The residual load EWH variation here does not contain surface observed load variation, which can be considered as groundwater EWH variation. Therefore ewh***.dat are the heterogeneous collaborative monitoring results of the groundwater EWH weekly variations, while the residual load effect weekly variation can be considered as the groundwater load effect weekly variation.



1′×1′ regional groundwater load effect weekly variation (mm) grid time series on ground orthometric height



1′×1′ regional groundwater load effect weekly variation (mE) grid time series on gravity gradient

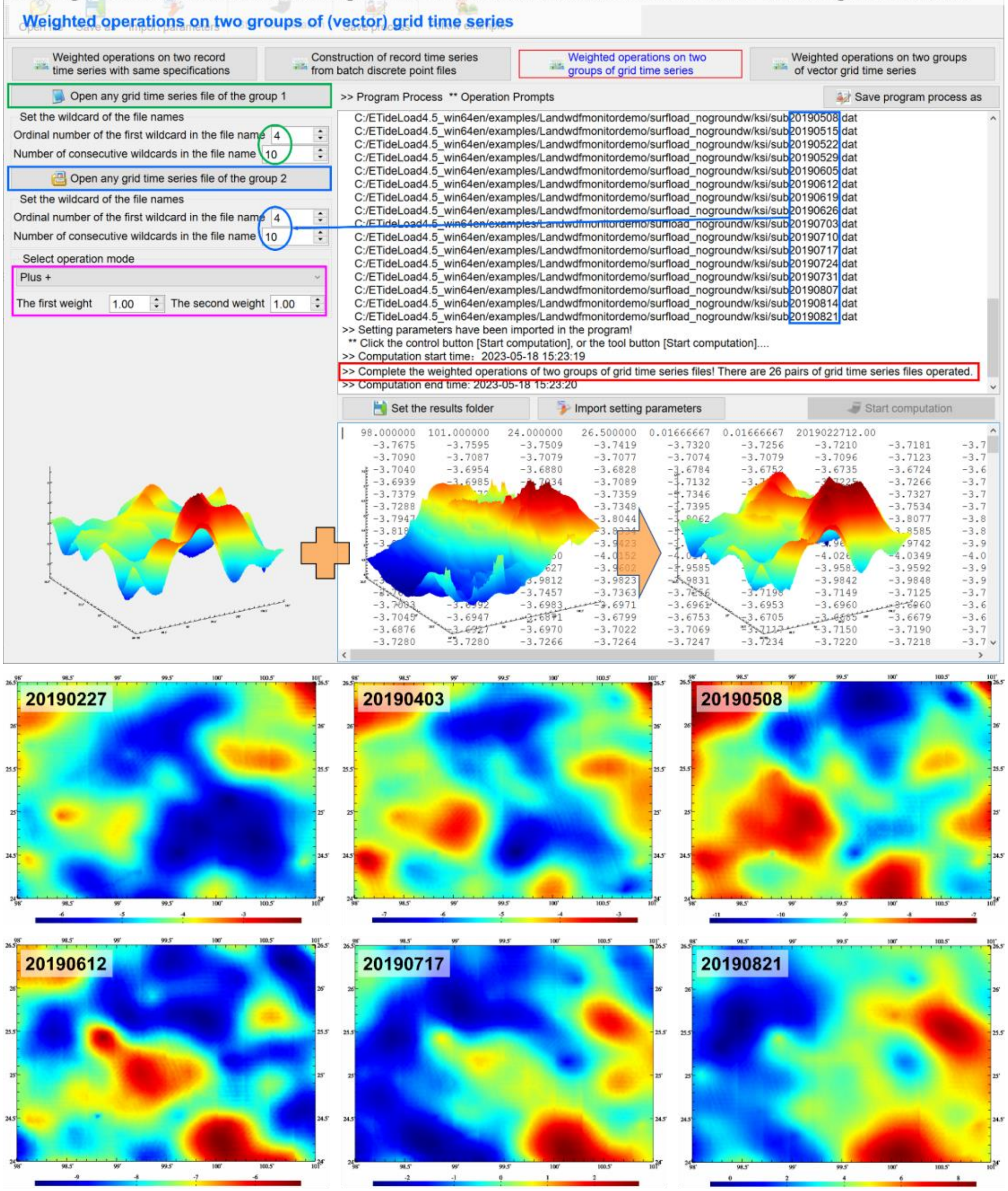
Step 5: Calculate and restore the observed surface load effect full-element grid time series to generate the heterogeneous collaborative monitoring results of land water load deformation field full-element grid time series.

According to the computation process of section 4.10.1, calculate the full element weekly variation grid time series of the observed surface load effect. The process is omitted in this example.

Call the function [Weighted operations on two groups of grid time series], directly add the full element weekly variation grid time series of the observed surface load effects to the full element weekly variation grid time series of the residual (groundwater) load effects, respectively, to generate the regional 1'×1' full-element weekly variation grid time series of land water load effects, which are the heterogeneous collaborative monitoring results of land water full-element load deformation field.

The main technical features of ETideLoad4.5's algorithm of the heterogeneous collaborative monitoring to surface load and time-vary gravity field are in following.

Step 5: Calculate and restore the observed surface load effect full-element grid time series to generate the heterogeneous collaborative monitoring results of land water load deformation field full-element grid time series



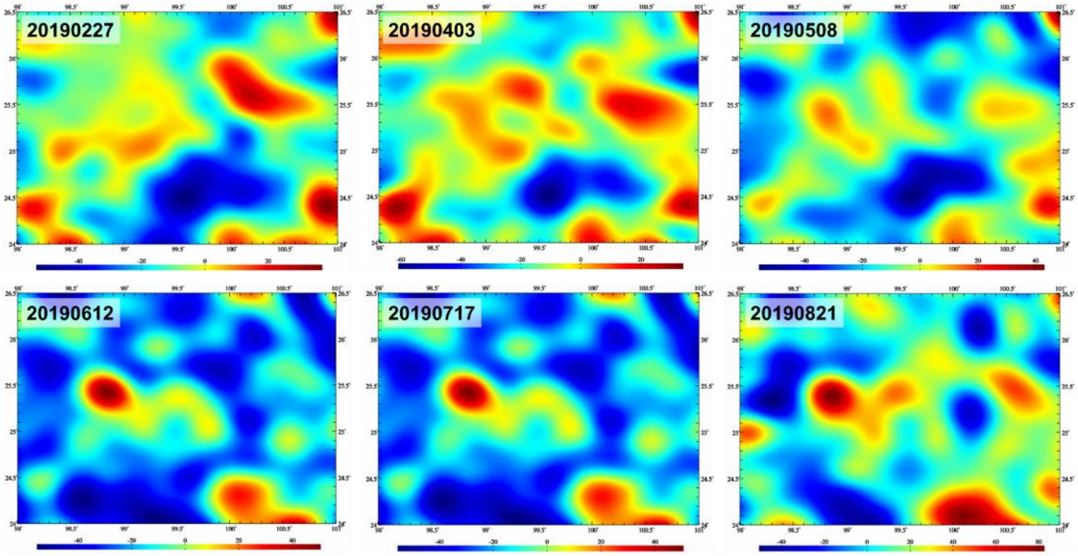
Collaborative monitoring results of 1′×1′ surface load effect weekly variation (mm) grid time series on geoid

(1) The algorithm can effectively solve the problems of high-degree oscillation and poor convergence of Green′s function and spectrum leakage and singularity of Green′s integral in the near area around the calculation point, and then realize the collaborative monitoring of GNSS, gravity, leveling, ground tilt and groundwater strictly according to solid geophysical analytical constraints.

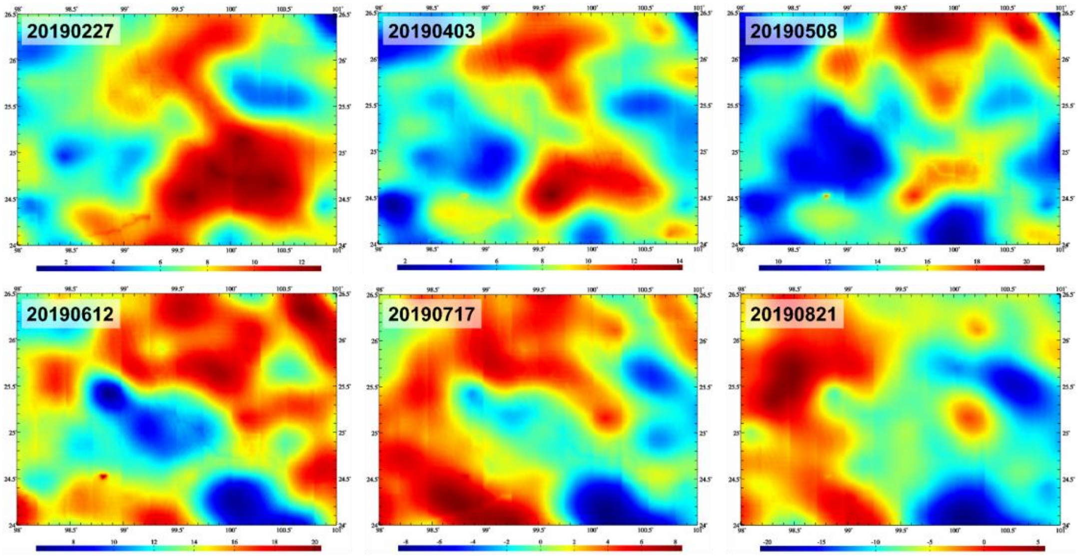
(2) There are rigorous analytical relationships between observation equations in the

algorithm, and heterogeneous observation variations are deeply fused according to the standard deviation of cofactor matrix to avoid the load deformation field affected by the observation errors. The algorithm has high stability and universality, which is suitable for massive computation of multiple time series collaborative monitoring.

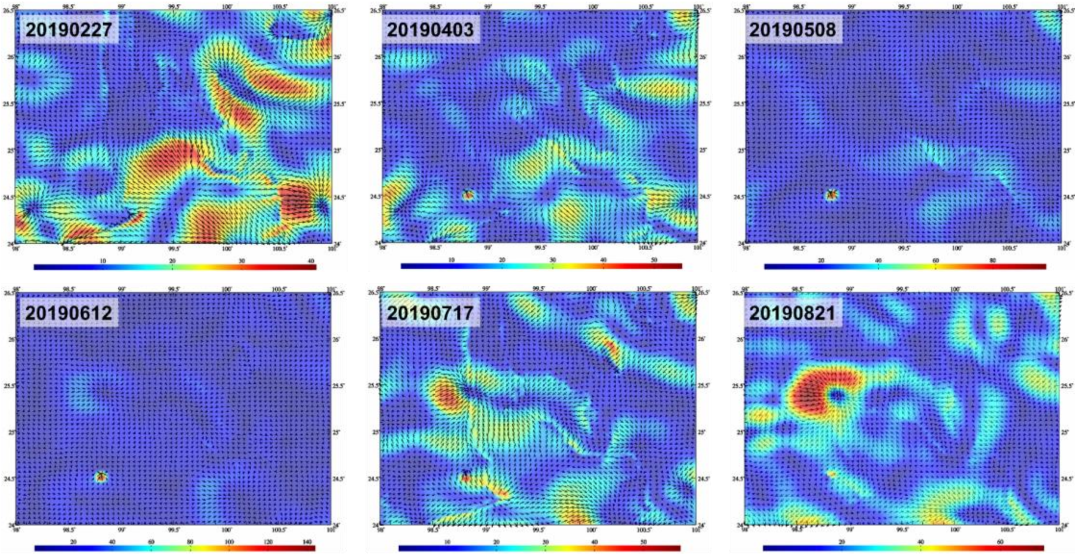
(3) The algorithm has the functions of geophysical signal spatial and spectrum domain separation and measurement equipment parameter calibration, which can improve the medium and long-term monitoring ability of gravity tide station, groundwater monitoring station and ground tilt station, and enhance the level of collaborative monitoring of space, terrestrial and marine geodesy.



Collaborative monitoring results of 1′×1′ load effect weekly variation (μGal) grid time series on ground gravity



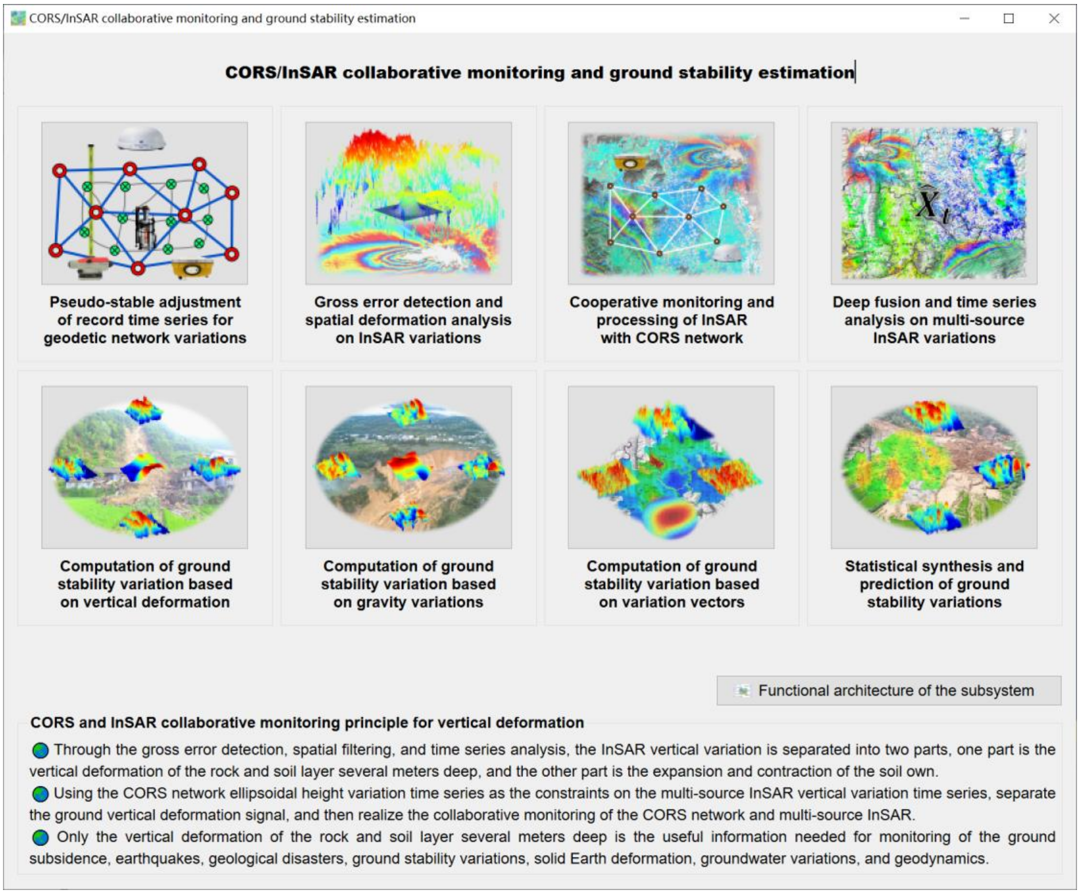
Collaborative monitoring results of 1′×1′ load effect weekly variation (mm) grid time series on ground ellipsoidal height



Collaborative monitoring results of 1′×1′ load effect weekly variation (mas) vector grid time series on ground tilt

5 CORS/InSAR collaborative monitoring and ground stability estimation

The group of programs can be employed to construct an accurate geometric and physical spatiotemporal monitoring frame with regional unification, long-term stability, and high robustness performance, and then fuse the monitoring variation of the CORS network and multi-source InSAR. From the variation grid time series of the geodetic deformation field, quantitatively and continuously monitor the regional ground stability variations by ETideLoad own defined quantitative criteria for the ground stability weakening.



CORS and InSAR collaborative monitoring principle for vertical deformation:

(1) Through the gross error detection, spatial filtering, and time series analysis, the InSAR vertical variation is separated into two parts, one part is the vertical deformation of the rock and soil layer several meters deep, and the other part is the expansion and contraction of the soil own. Only the former is compatible with most geodetic variations, while the latter is mainly affected by the temperature and rainfall and should not be regarded as a solid Earth deformation.

(2) Using the CORS network ellipsoidal height variation time series as the constraints on the multi-source InSAR vertical variation time series, separate the ground vertical deformation signal, and then realize the collaborative monitoring of the CORS network and

multi-source InSAR.

(3) Only the vertical deformation of the rock and soil layer several meters deep is the useful information needed for monitoring of the ground subsidence, earthquakes, geological disasters, ground stability variations, solid Earth deformation, groundwater variations, and geodynamics.

Continuous quantitative monitoring scheme of ground stability variations:

(1) From the grid time series of the geodetic vertical deformation, ground gravity and tilt variations, quantitatively and continuously monitor ground stability variations by constructing the quantitative criteria for the ground stability weakening.

(2) Quantitative criteria of the ground stability weakening can include that the ground ellipsoidal height increases, the gravity decreases, the horizontal gradient of the height or gravity variation is large, and the inner product of the tilt variations and terrain slope vector is greater than zero.

(3) According to the geological disasters that occurred, optimize, and synthesize the geodetic ground stability variation grid time series to adapt to the local environmental geology, and then consolidate regional stability variations monitoring capabilities.

5.1 Pseudo-stable adjustment of record time series for geodetic network variations

[Function] Using the variation time series of the GNSS baseline components, height differences of the leveling route, or gravity differences of the gravity control network as the observations, and a given group of sites as the pseudo-stable reference datum, estimate the variation time series of the coordinate component of the CORS network sites, the height of the leveling network sites or the gravity of the gravity network sites by the indirect least squares adjustment method.

The program can be employed to construct an accurate geometric and physical spatiotemporal monitoring frame with regional unification, long-term stability, and high robustness performance.

The program requires that all the variations are strictly synchronized at each sampling epoch time, and the reference epochs of all the variation record time series should be same and unique.

[Input files] The observed variation record time series file of the geodetic network. The reference variation record time series file of the reference sites.

(1) The observed variation record time series file of the geodetic network (consists of the baselines or routes). The file header includes the number of characters of the baseline or route name, the number of characters of the site name, the sampling length, ……, all the sampling epochs arranged with time.

The record includes the baseline or route name, the starting site (longitude, latitude, height), the ending site (longitude, latitude, height), ……, all the observed variations arranged with sampling time (default value is 9999).

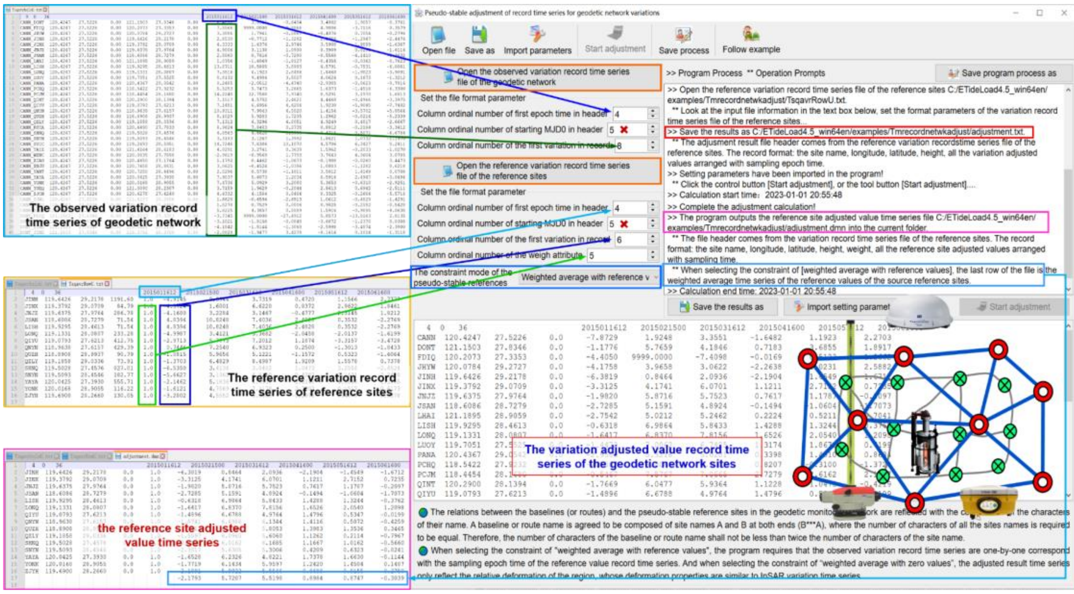
(2) The variation record time series file of the reference sites. The file header contains all the sampling epochs arranged with time. The record format: the site name, longitude, latitude, height, ..., all the variations arranged with sampling time (default value is 9999).

The relations between the baselines (or routes) and the pseudo-stable reference sites in the geodetic monitoring network are reflected with the composition of the characters of their name. A baseline or route name (B***A) is agreed to be composed of site names A and B at both ends, where the number of characters of all the sites names is required to be equal. Therefore, the number of characters of the baseline or route name should not be less than twice the number of characters of the site name.

[Parameter settings] Set the record time series file format parameters for the observed variations of the geodetic network and the reference variations of the reference sites, set the constraint mode of the pseudo-stable references.

When selecting the constraint of "weighted average with reference values", the program requires that the observed variation record time series are one-by-one correspond with the sampling epoch time of the reference value record time series.

When selecting the constraint of “weighted average with zero values”, the adjusted result time series only reflect the relative deformation within the region, whose deformation properties are similar to InSAR variation time series.



[Output files] The variation adjusted value record time series file of geodetic sites.

The file header comes from the reference variation record time series file of the reference sites. The record format: the site name, longitude, latitude, height, all the variation adjusted values arranged with sampling epoch time.

When selecting the constraint of "weighted average with reference values", the program outputs the reference site adjusted value time series file ***.dmn into the current folder.

The file header comes from the variation record time series file of the reference sites. The record format: the site name, longitude, latitude, height, weight, all the reference site adjusted values arranged with sampling time. The last row of the file is the weighted average time series of the reference values of the source reference sites. Here, *** are the output file name of the variation adjusted value record time series.

5.2 Gross error detection and spatial deformation analysis on InSAR variations

[Purpose] Construct InSAR variation spatial analysis algorithms according to the spatial distribution natures of the ground deformation under the action of the environmental geology and load geodynamics, separate the outliers and gross errors from InSAR variations, suppress and weaken the impact of the soil own variations, and then extract the InSAR ground vertical deformation which is compatible with the other geodetic variations.

5.2.1 Gross error detection and separation on InSAR variation record time series

[Function] According to the spatial high-correlation characteristics of the ground deformation, construct a reference surface respectively at each sampling epoch time with the given low-pass filter to separate the outliers, gross error, and abrupt signals from the input InSAR variation record time series.

Before and after gross error separation, the format of InSAR variation record time series, spatial and temporal distribution of monitoring points, number of monitoring points and the value of InSAR variation remain unchanged, and only the gross error variation in the result InSAR variation record time series are replaced by 9999.000.

[Input file] The InSAR variation record time series file.

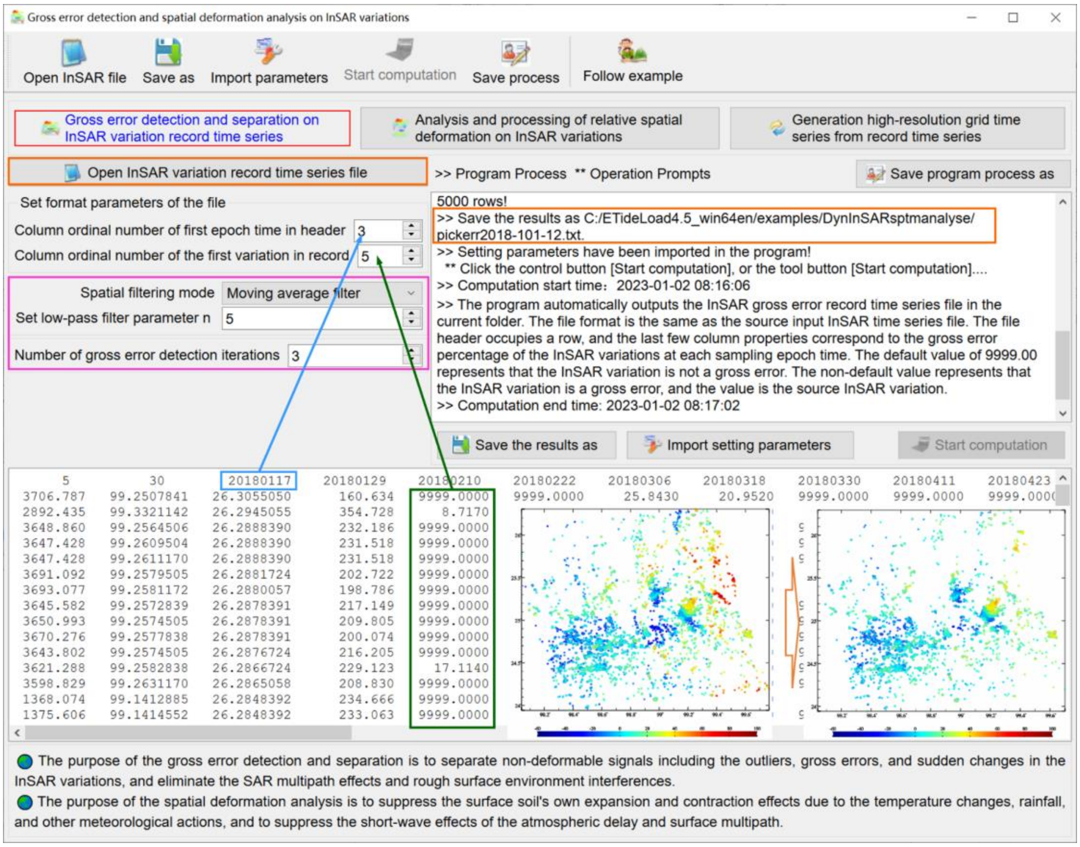
InSAR variation time series is agreed in the record time series format, and the sampling epoch time is agreed in ETideLoad format.

[Parameter settings] Set the InSAR variation record time series file format parameters, select the spatial filtering mode, and enter the number of gross error detection iterations.

[Output file] The InSAR variation record time series file.

The InSAR variation record time series in the output file is the same as that in the input file, with only the gross variations replaced by 9999.000.

The program automatically outputs the InSAR gross error record time series file in the current folder. The file format is the same as the source input InSAR time series file. The file header occupies a row, and the last few column properties correspond to the gross error percentage of the InSAR variations at each sampling epoch time. The default value of 9999.00 in the record represents that the InSAR variation is not a gross error. The non-default value represents that the InSAR variation is a gross error, and the value is the source InSAR variation.



The purpose of the gross error detection and separation is to separate non-deformable signals including the outliers, gross errors, and sudden changes in the InSAR variations, and eliminate the SAR multipath effects and rough surface environment interferences.

5.2.2 Analysis and processing of relative spatial deformation on InSAR variations

[Function] According to the spatial distribution natures that the ground vertical deformation is inversely proportional to the distance away from the dynamic source, suppress or weaken the local changes due to non-geological dynamics on the shallow surface from the input InSAR variation record time series using the specified spatial filtering algorithm.

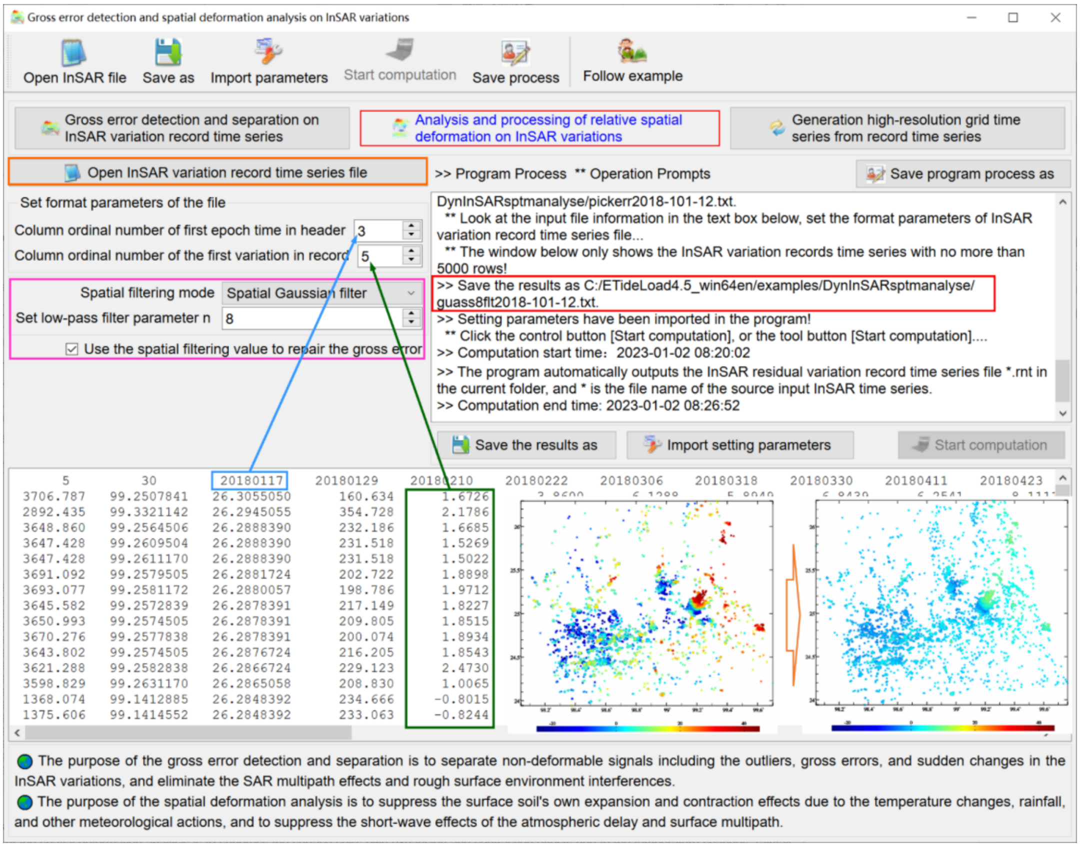
[Input file] The InSAR variation record time series file.

[Parameter settings] Set the InSAR variation record time series file format parameters, select the spatial filtering mode, enter spatial low-pass filter times, and set the checkbox of [use the spatial filtering value to repair the gross error].

For the moving average filter, the greater the filtering parameter n, the greater the filtering strength, and for the spatial Gaussian filter, the smaller the n, the greater the filtering strength.

[Output file] The InSAR variation record time series file.

Before and after filtering, the format, time-space sampling distribution and quantity of the monitoring points of the output InSAR variation record time series file are the same as that of the input InSAR variation record time series file. The output variation = the input variation – the residual variation.



The program automatically outputs the InSAR residual variation record time series file *.rnt in the current folder, and * is the file name of the source input InSAR time series. The file format is the same as the source input InSAR time series file. The residual variation = the input variation – the output variation.

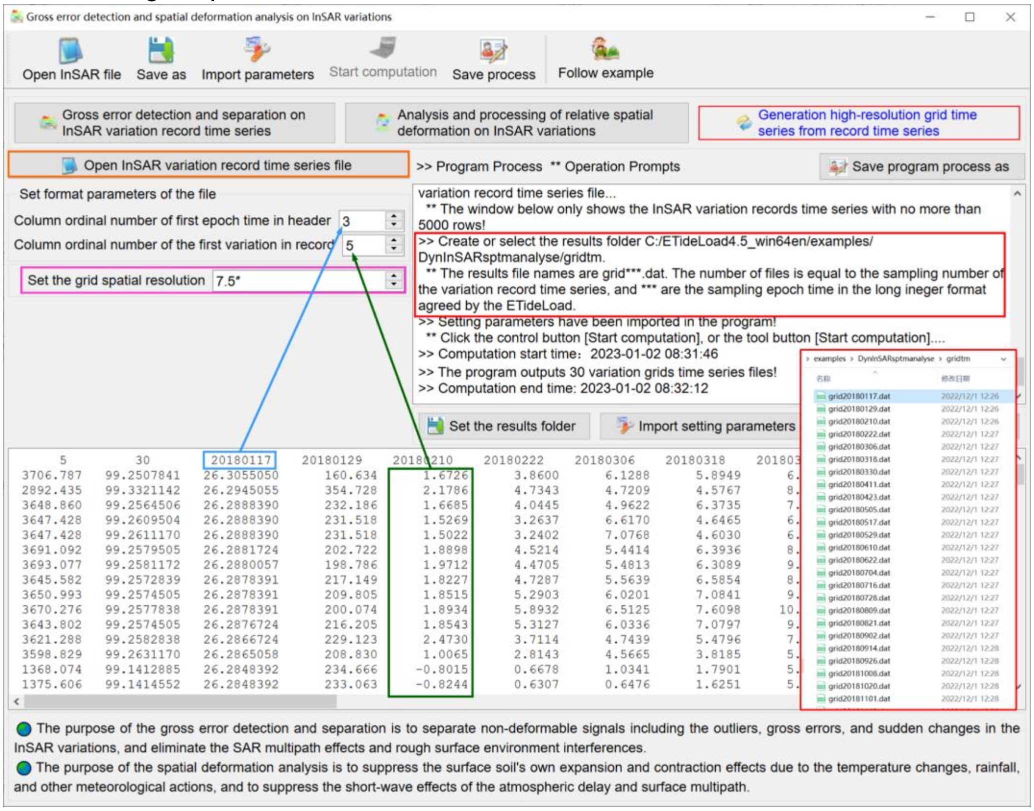
The purpose of the spatial deformation analysis is to suppress the surface soil's own expansion and contraction effects due to the temperature changes, rainfall, and other meteorological actions, and to suppress the short-wave effects of the atmospheric delay and surface multipath.

5.2.3 Generation high-resolution grid time series from record time series

[Function] According to the given minimum number of the effective monitoring points in a grid element, generate the high-resolution variation grid time series by the direct averaging or Gaussian function interpolation method. The number of the output grid time series files are equal to the number of sampling epochs of the variation record time series. The grid value on the invalid grid element is represented by 9999.0.

[Input file] The InSAR variation record time series file.

[Parameter settings] Set the InSAR variation record time series file format parameters and enter the grid spatial resolution.



[Output file] The results file names are grid***.dat. The number of files is equal to the sampling number of the variation record time series, and *** are the sampling epoch time in the long integer format agreed by the ETideLoad.

5.3 Cooperative monitoring and processing of InSAR with CORS network

[Purpose] Unify the reference epoch time of multi-source InSAR variation time series and CORS network height variation record time series, and then through the compatibility analysis of vertical deformation of the CORS network and InSAR, InSAR variation adjustment with the constraint of the CORS network, unify the spatiotemporal monitoring frame of the InSAR variation time series to control the accumulation of the InSAR monitoring errors over time.

The purpose of cooperative monitoring and processing of the CORS network and InSAR: (1) Repair the tidal and non-tidal load effects on the InSAR variations, compensate the spatial long-wave troposphere model errors. (2) Compensate the temporal information which spatial wavelength larger than the InSAR monitoring region, control the cumulative error of the InSAR variations over time. (3) When there are no less than 3 CORS stations, can precisely repair the InSAR differential interference scale error and compensate the other medium-long wave errors.

5.3.1 Unification of reference epoch for variation record time series

[Function] Using the cubic spline interpolation, Gaussian function interpolation, or low-pass filtering method, estimate the reference value of the variation record time series at the given reference epoch time, and then remove the reference value from the variation record time series, thereby unify the reference epoch time of the variation record time series. At the reference epoch time, the sampling values of all the variations are always zero.

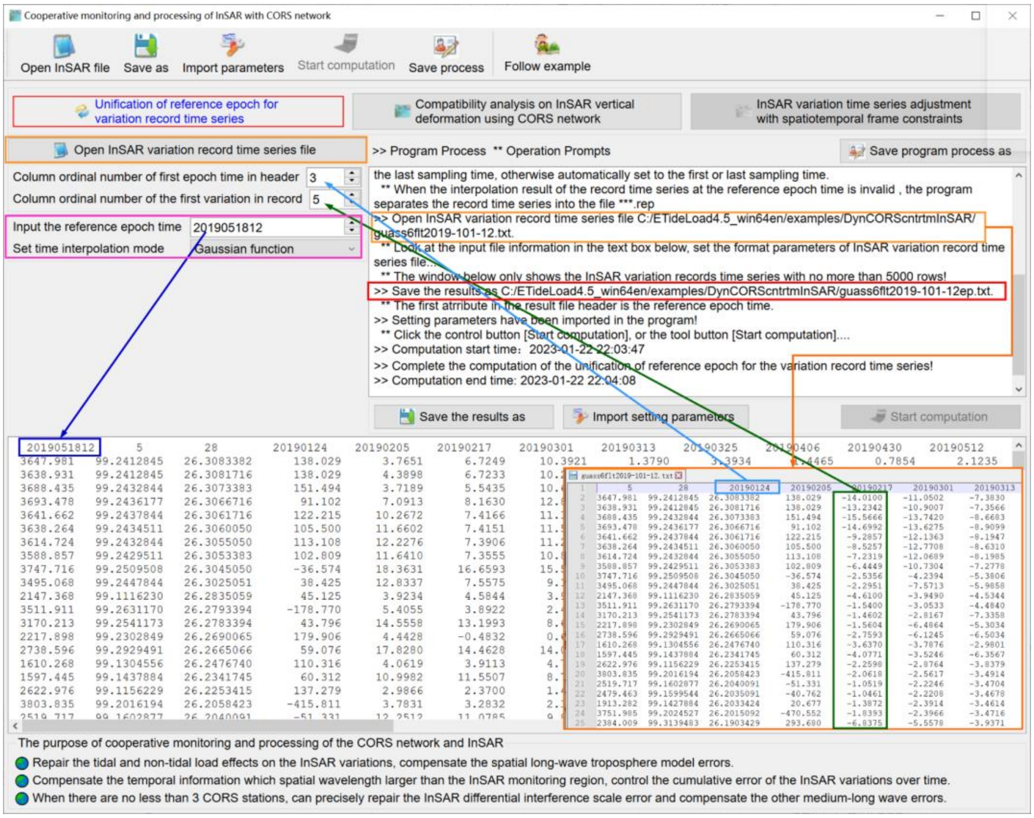
The program requires that the reference epoch time be no earlier than the first sampling time and no later than the last sampling time, otherwise automatically set to the first or last sampling time.

[Input file] The InSAR variation record time series file.

[Parameter settings] Set the InSAR variation record time series file format parameters, select the time interpolation mode, and enter the reference epoch time.

[Output file] The InSAR variation record time series file.

When the interpolation result of the record time series at the reference epoch time is invalid, the program separates the record time series into the file ***.rep.



When there are more noise or missing samples in the variation record time series, Gaussian function interpolation is recommended.

When the reference epoch time exceeds the effective time range of a record time series, if the cubic spline interpolation is still selected, the program automatically extrapolates the sampling value of the reference epoch time of the record time series by the Gaussian basis function method.

The time-varying variation is reflected by the difference between the monitoring quantities at any two moments and has nothing to do with the reference epoch time. Therefore, unifying or transforming the reference epoch time will not change the time-varying monitoring signal of geodetic variation time series.

5.3.2 Compatibility analysis on InSAR vertical deformation using CORS network

[Function] Calculate the ellipsoidal height variation time series on the CORS site from InSAR variation time series near the CORS site by the direct average method. Interpolate the CORS site ellipsoidal height variations at sampling epochs of the InSAR time series from the CORS site ellipsoidal height variation time series. And then construct the CORS baselines by the complete combinations of the CORS sites, calculate all the double-difference time series respectively from the two kinds of CORS site ellipsoidal height variation time series. Evaluate the compatibility of the vertical deformation between the CORS network and InSAR and analyze the effectiveness of the InSAR variations gross error detection and spatial analysis algorithm.

[Input file] The InSAR variation record time series file. The CORS site ellipsoidal height variation record time series file.

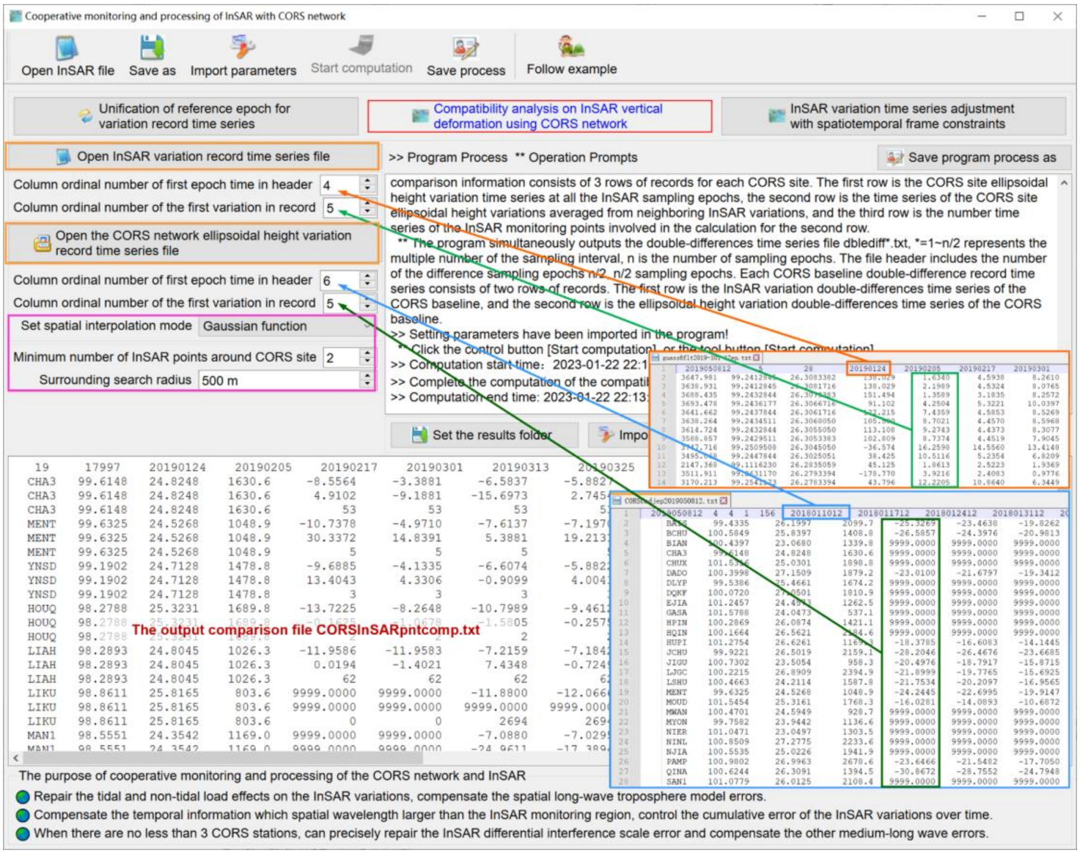
[Parameter settings] Set the InSAR and CORS site variation record time series file format parameters, select the time interpolation mode, and enter the minimum number of InSAR points around CORS site and surrounding search radius.

When there are more noise or missing samples in the CORS height variation record time series, Gaussian function interpolation is recommended.

The double-difference algorithm of the InSAR variation time series on the CORS baseline: Firstly, calculate the InSAR variation at the current epoch time on the CORS site by the direct average method using the InSAR variations around the CORS site, and then calculate the InSAR variation difference between the two ends of the CORS baseline at the current epoch time, and finally calculate the time difference between the InSAR variation differences after and before the epoch time to obtain the InSAR variation double-difference time series of the CORS baseline.

[Output file] The comparison file CORSInSARpntcomp.txt between the CORS site ellipsoidal height and InSAR variation time series.

The file header contains the total number of the CORS sites in the InSAR monitoring range, the number of InSAR monitoring points, and all the sampling epochs. The comparison information consists of 3 rows of records for each CORS site. The first row is the CORS site ellipsoidal height variation time series at all the InSAR sampling epochs, the second row is the time series of the CORS site ellipsoidal height variations averaged from neighboring InSAR variations, and the third row is the number time series of the InSAR monitoring points involved in the calculation for the second row.



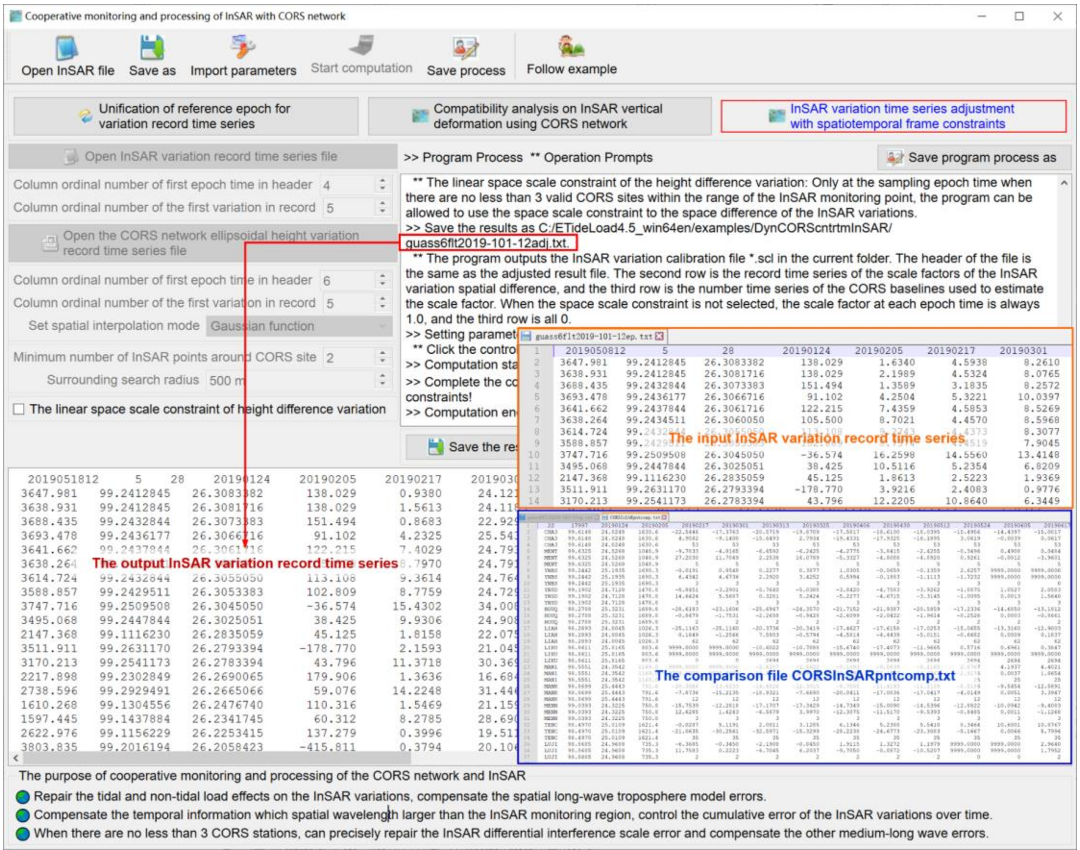
The program simultaneously outputs the double-difference time series file dbledif*.txt, *=1~n/2 represents the multiple number of the sampling interval, n is the number of sampling epochs. The file header includes the number of the difference sampling epochs n/2, n/2 sampling epochs. Each CORS baseline double-difference record time series consists of two rows of records. The first row is the InSAR variation double-difference time series of the CORS baseline, and the second row is the ellipsoidal height variation double-difference time series of the CORS baseline.

5.3.3 InSAR variation time series adjustment with spatiotemporal frame constraints

[Function] From the comparison file CORSInSARpntcomp.txt output by the function [Compatibility analysis of vertical deformation from CORS network and InSAR], estimate spatiotemporal monitoring datum transfer parameters, construct spatiotemporal frame constraint equations, perform the adjustment for the InSAR variation record time series, so as to unify the spatiotemporal monitoring frame of the InSAR variation record time series into the CORS network spatiotemporal monitoring frame.

[Input files] The InSAR variation record time series file. The geodetic variation time series file to be reconstructed. The comparison file CORSInSARpntcomp.txt between the CORS site ellipsoidal height variations and InSAR variation time series. The two files can be automatically called by the program without manual input.

[Parameter settings] Set the checkbox [The linear space scale constraint of the height difference variation].



[Output file] The InSAR variation adjusted value record time series file. Whose format is same as the input InSAR variation record time series file.

The program outputs the InSAR variation calibration file ***.scl in the current folder. Here *** are the output adjusted result file name.

The header of the file is the same as the adjusted result file. The second row is the record time series of the scale factors of the InSAR variation spatial difference, and the third row is the number time series of the CORS baselines used to estimate the scale factor. When the space scale constraint is not selected, the scale factor at each epoch time is always 1.0, and the third row is all 0.

The scale factor is an important quantitative indicator to evaluate the performance of the InSAR deformation monitoring. At sampling epoch time whose scale factor exceeds (0.5, 2.0), the vertical deformation separation of the InSAR variations is insufficient, or the quality of the InSAR variations is poor.

The linear space scale constraint of the height difference variation: Only at the sampling epoch time when there are no less than 3 valid CORS sites within the range of InSAR monitoring points, program can be allowed to use the space scale constraint to the space difference of the InSAR variations.

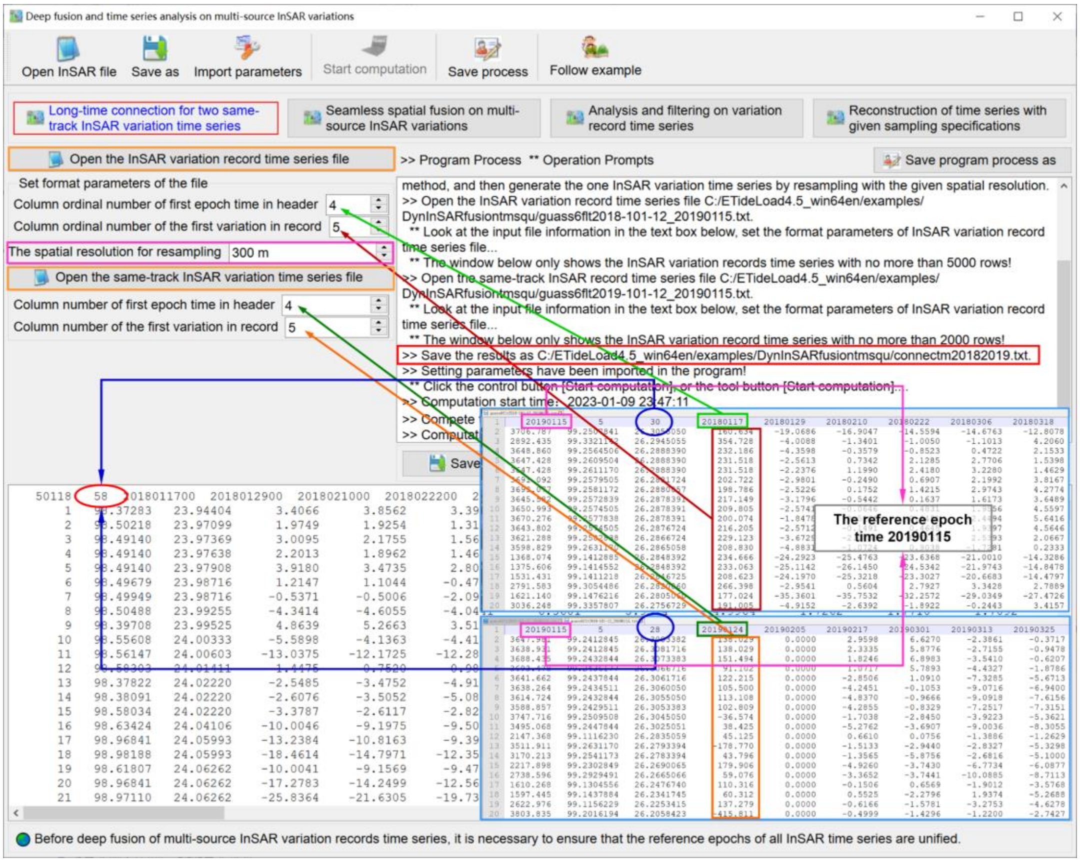
5.4 Deep fusion and time series analysis on multi-source InSAR variations

[Purpose] Firstly, deeply fuse multi-source InSAR variation record time series into the uniform spatiotemporal monitoring frame and reference epoch represented by the CORS variation time series respectively in time and space, and then perform time series analysis for all InSAR variation monitoring points, to realize multi-source InSAR collaborative monitoring.

5.4.1 Long-time connection for two same-track InSAR variation time series

[Function] From the two InSAR variation record time series in the same region and with the same reference epoch time, respectively supplement the sampling values of each time series by the Gaussian interpolation method, and then generate the one InSAR variation time series by resampling with the given spatial resolution.

[Input files] The two InSAR variation record time series files in the same region and with the same reference epoch time.



[Parameter settings] Set the two InSAR variation record time series file format parameters and enter the resampling spatial resolution.

[Output file] The connected InSAR variation record time series file.

The output file format and reference epoch are same as that of the input InSAR variation record time series file.

5.4.2 Seamless spatial fusion on multi-source InSAR variations

[Function] According to the given spatial resolution, resample the input multi-source InSAR variation record time series to generate a new InSAR variation record time series. The input InSAR variation record time series files are extracted according to the given wildcards, and all the input files are in the same format.

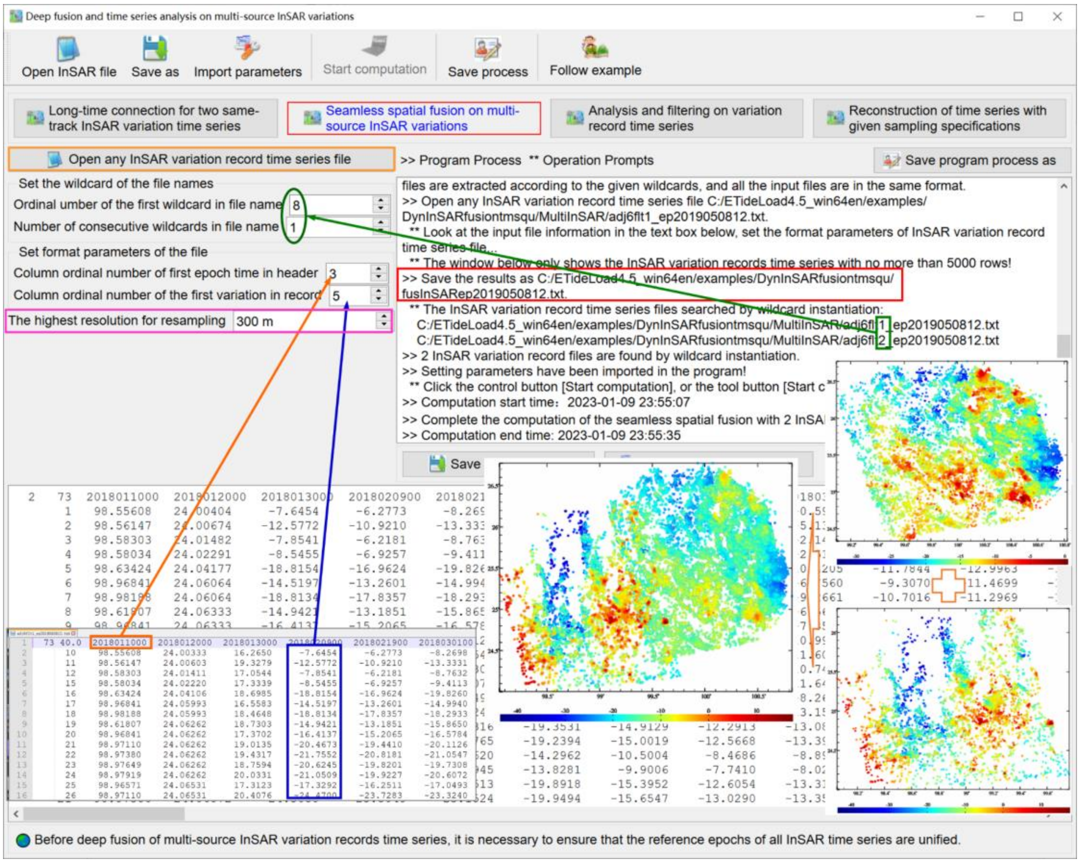
Before deep fusion of multi-source InSAR variation record time series, it is necessary to ensure that the reference epochs of all InSAR time series are unified.

[Input files] Multi-source InSAR variation record time series files.

In this example, two InSAR variation record time series are on adjacent areas, and a small number in the two groups of InSAR monitoring points are cross-distributed.

[Parameter settings] Set the file name wildcards and file format parameters of multi-source InSAR variation record time series and enter the resampling spatial resolution.

[Output file] The fused InSAR variation record time series file. The format is the same as that of the input InSAR variation record time series file.



5.4.3 Analysis and filtering on variation record time series

[Function] Using the continuous Chebyshev and triangular basis function combination method, estimate the low-pass filtering parameters for variation record time series on each monitoring point, and then calculate the filtering value and the linear variation (per year, /a) at source sampling epochs.

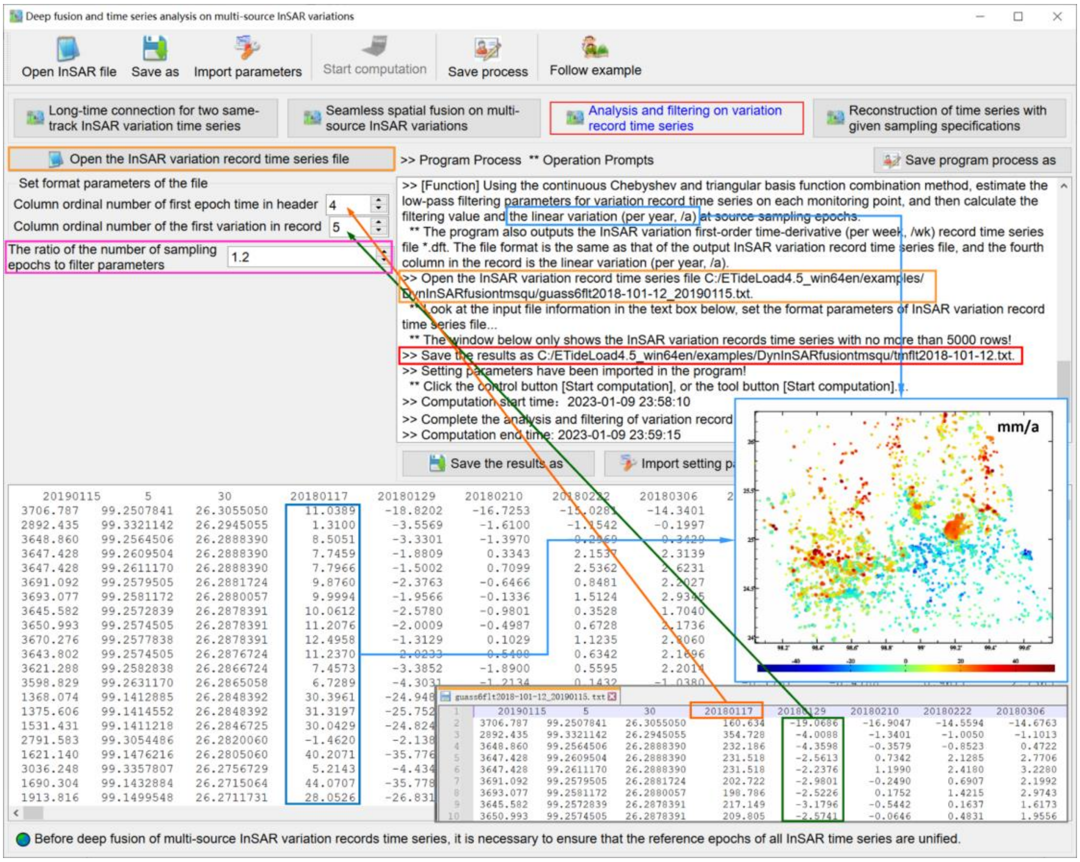
[Input files] The InSAR variation record time series files.

[Parameter settings] Set the file format parameters of InSAR variation record time series and enter the ratio of the number of sampling epochs to filter parameters.

[Output file] The filtered InSAR variation record time series file ***.txt. The InSAR variation first-order time-derivative (per week, /wk) record time series file ***.dft. Here, *** are the output file name.

The filtered variation record time series file. The file format is the same as that of the input InSAR variation record time series file and the fourth column in the file record is the linear variation (per year, /a).

The InSAR variation first-order time-derivative (per week, /wk) record time series file *.dft. The file format is the same as that of the output InSAR variation record time series file, and the fourth column in the record is the linear variation (per year, /a).



5.4.4 Reconstruction of time series with given sampling specifications

[Function] Using the continuous Chebyshev and triangular basis function combination method, estimate the filtering parameters for variation record time series of each monitoring point, and then reconstruct the variation record time series according to the given time series sampling specifications.

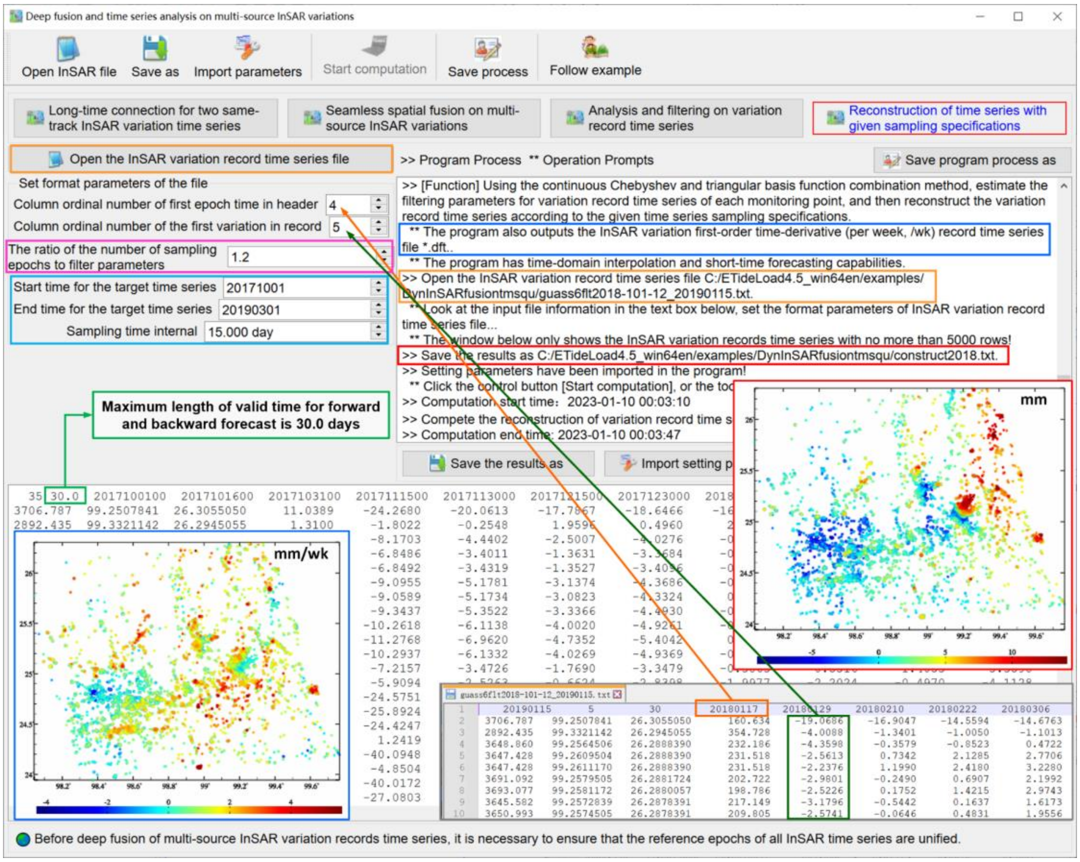
The program has time-domain interpolation and short-time forecasting capabilities.

[Input files] The InSAR variation record time series files.

[Parameter settings] Set the file format parameters of InSAR variation record time series and enter the ratio of the number of sampling epochs to filter parameters and time series sampling specifications.

When the starting time is earlier than the first sampling epoch time of the source variation record time series, the program lets the starting time = the first sampling epoch time - sampling interval * total number of the samples * 5%.

When the ending time is later than the last sampling epoch time of the source variation record time series, the program lets the ending time = the last sampling epoch time + sampling interval * total number of the samples * 5%.



[Output file] The reconstructed InSAR variation record time series file ***.txt. The InSAR variation first-order time-derivative (per week, /wk) record time series file ***.dft. Here, *** are the output file name.

The filtered variation record time series file. The file format is the same as that of the input InSAR variation record time series file and the fourth column in the file record is the linear variation (per year, /a).

The InSAR variation first-order time-derivative (per week, /wk) record time series file *.dft. The file format is the same as that of the output InSAR variation record time series file, and the fourth column in the record is the linear variation (per year, /a).

5.5 Computation of ground stability variation based on vertical deformation

[Purpose] From the ground vertical deformation rate and its horizontal gradient grid model, using the normalized statistical synthesis algorithm, quantitatively estimate the ground stability variation grid according to the quantitative criteria of the ground stability weakening defined by ETideLoad.

Ground stability variation grid time series here is used to quantitatively express the time and location, continuous time influence period and space influence range of ground stability weakening.

Quantitative criteria defined by ETideLoad for the ground stability weakening based on the vertical deformation grid time series are in the following.

(1) The ground vertical deformation rate is relatively large (greater than zero). At this time, the ground here is rising upward.

(2) The horizontal gradient (modulus) of the vertical deformation rate is relatively large. At this time, the ground is twisting locally.

(3) The terrain slope value is relatively large.

The ground stability variation is a dimensionless continuous real variable. At any sampling epoch time, the stability variation of a grid element is greater than zero, indicates that the stability currently on the location of the grid element is decreasing, and less than zero indicates that the stability is improving.

5.5.1 Estimation of normalized ground stability variation grid

[Function] From the ground vertical deformation rate grid and ground digital elevation model with the same grid specifications, calculate the horizontal gradient of the ground vertical deformation rate and the terrain slope vector grid, and then quantitatively estimate the ground stability variation grid by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

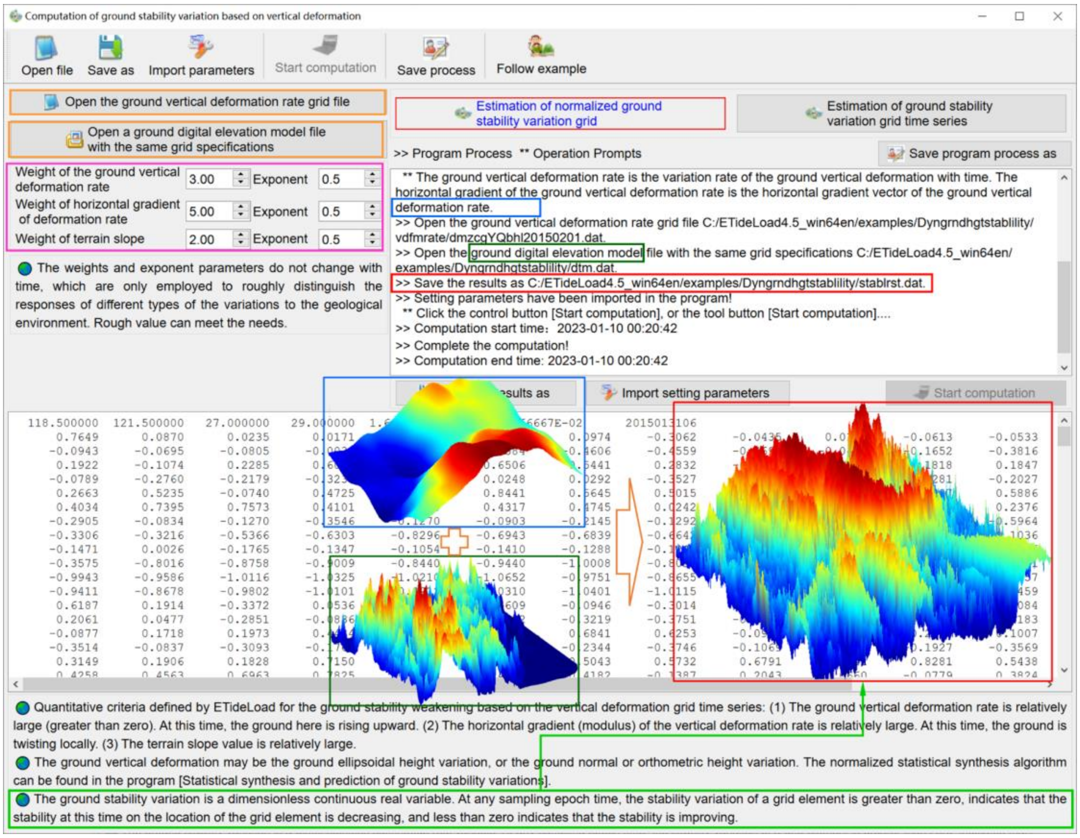
[Input files] The ground vertical deformation rate grid file and ground digital elevation model file with the same grid specifications.

[Parameter settings] Set the weights and exponents for ground vertical deformation rate, horizontal gradient of the ground vertical deformation rate and terrain slope.

The ground vertical deformation rate is the variation rate of the ground vertical deformation with time. The horizontal gradient of the ground vertical deformation rate is the horizontal gradient vector of the ground vertical deformation rate.

The weights and exponent parameters do not change with time, which are only employed to roughly distinguish the responses of different types of the variations to the geological environment. Rough value can meet the needs.

[Output file] The normalized ground stability variation grid file.



5.5.2 Estimation of ground stability variation grid time series

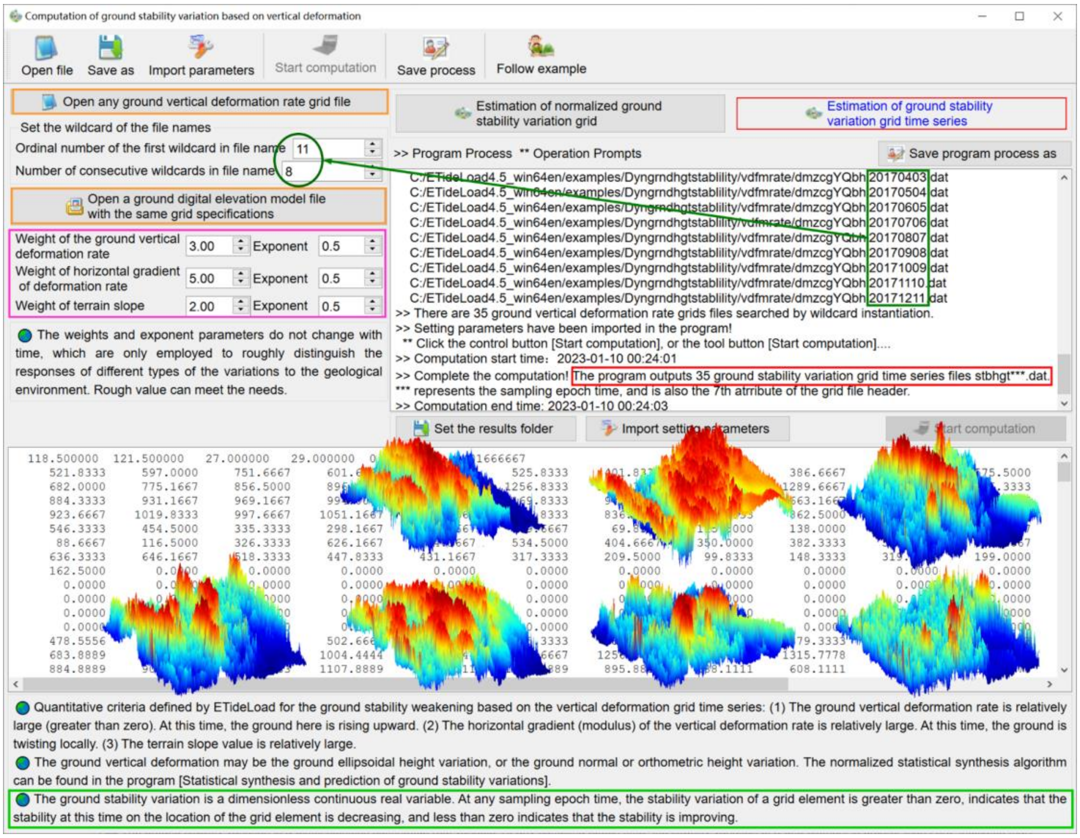
[Function] From the ground vertical deformation rate grid time series and ground digital elevation model with the same grid specifications, calculate the terrain slope vector grid and the vector grid time series of the horizontal gradient of the ground vertical deformation rate, and then quantitatively estimate the ground stability variation grid time series by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

[Input files] The ground vertical deformation rate grid time series files and ground digital elevation model file with the same grid specifications.

[Parameter settings] Set the wildcard parameters for the deformation rate grid time series files, enter the weights and exponents for ground vertical deformation rate, horizontal gradient of the ground vertical deformation rate and terrain slope.

[Output file] The normalized ground stability variation grid time series files.

The ground vertical deformation may be the ground ellipsoidal height variation, or the ground normal or orthometric height variation. The normalized statistical synthesis algorithm can be found in the program [Statistical synthesis and prediction of ground stability variations].



5.6 Computation of ground stability variation based on gravity variations

[Purpose] From the ground gravity (or gravity disturbance) variation rate and its horizontal gradient grid model, using the normalized statistical synthesis algorithm, quantitatively estimate the ground stability variation grid according to the quantitative criteria of the ground stability weakening defined by ETideLoad.

Quantitative criteria defined by ETideLoad for the ground stability weakening based on the gravity variation grid time series are in the following.

(1) The ground gravity variation rate is relatively large (less than zero). At this time, the ground here is rising upward.

(2) The horizontal gradient (modulus) of the gravity variation rate is relatively large. At this time, the ground is twisting locally.

(3) The local terrain effect on the gravity disturbance is relatively large (less than zero).

The ground gravity variation may be the ground gravity variation, or the ground gravity disturbance variation.

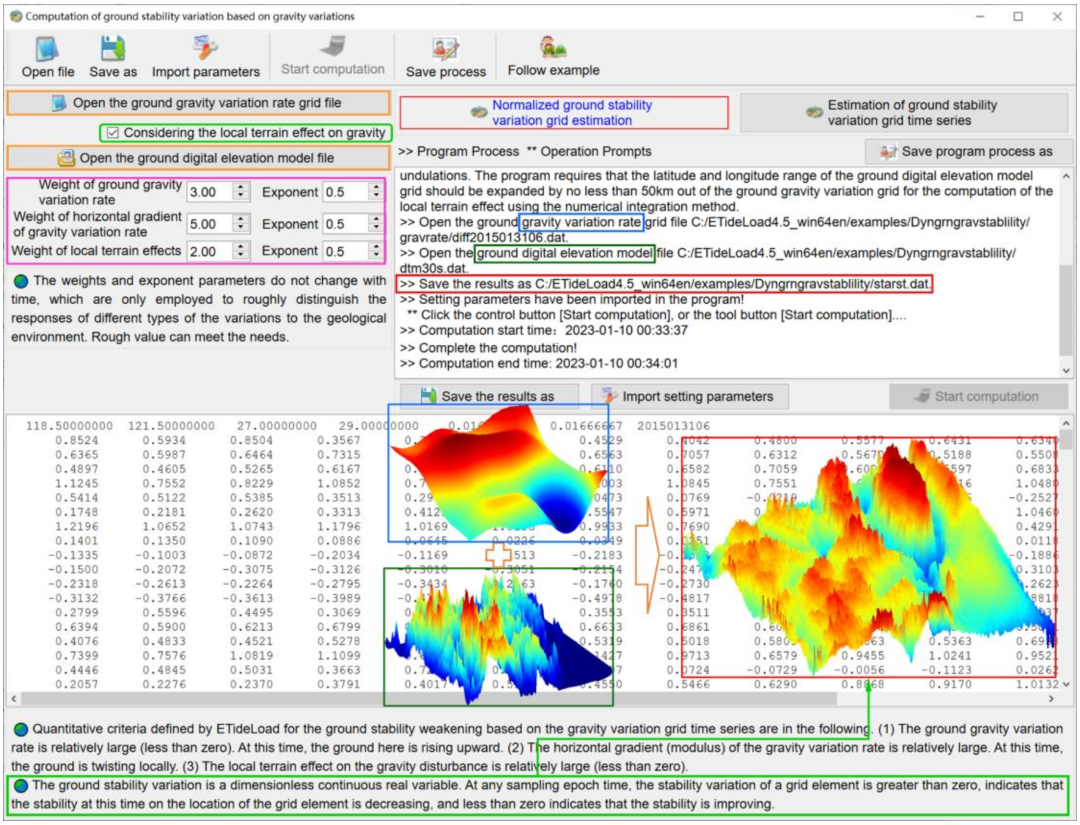
5.6.1 Normalized ground stability variation grid estimation

[Function] From the ground gravity variation rate grid and ground digital elevation model, calculate the horizontal gradient vector grid of the ground gravity variation rate and the local terrain effect grid of the gravity disturbance, and then quantitatively estimate the ground stability variation grid by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

[Input files] The ground gravity variation rate grid file. The ground digital elevation model grid file.

[Parameter settings] Set the weights and exponents for ground gravity variation rate, horizontal gradient of the ground gravity variation rate and local terrain effect, set the checkbox [Considering the local terrain effect on gravity].

The ground gravity variation is the variation rate of the ground gravity variation with time. The horizontal gradient of the ground gravity variation rate is the horizontal gradient vector of the ground gravity variation rate.



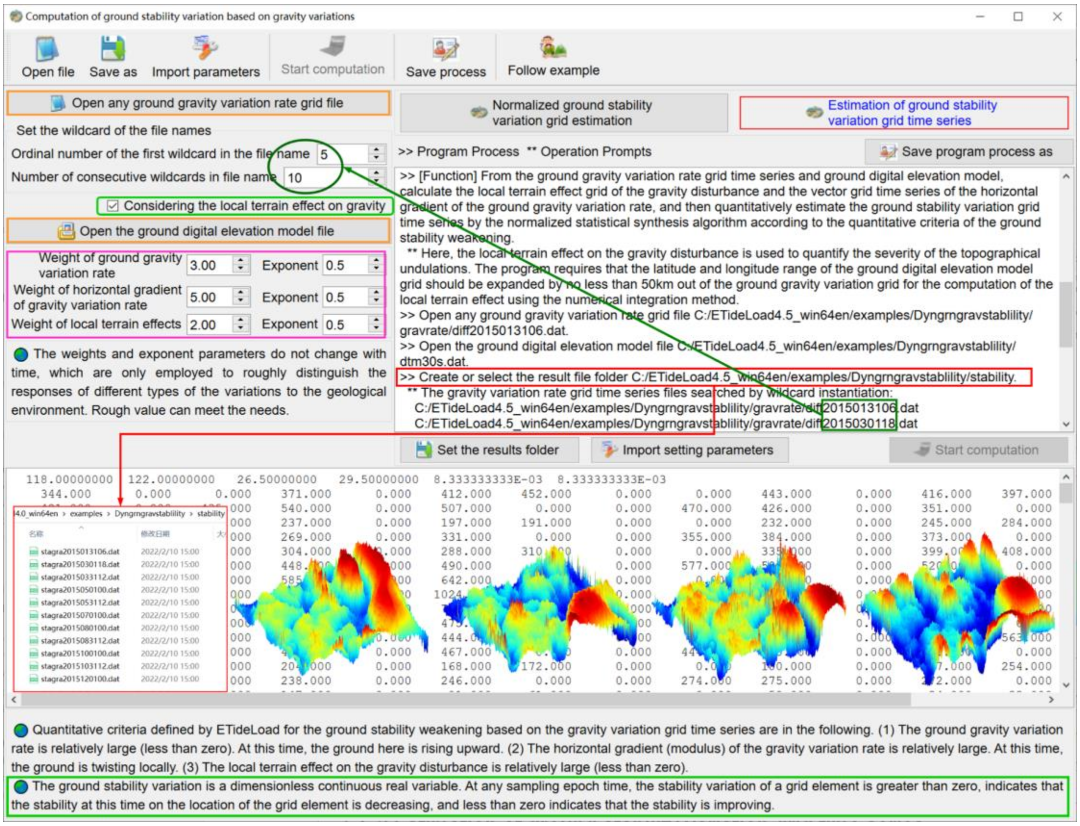
[Output file] The normalized ground stability variation grid file.

5.6.2 Estimation of ground stability variation grid time series

[Function] From the ground gravity variation rate grid time series and ground digital elevation model, calculate the local terrain effect grid of the gravity disturbance and the vector grid time series of the horizontal gradient of the ground gravity variation rate, and then quantitatively estimate the ground stability variation grid time series by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

[Input files] The ground gravity variation rate grid time series files and ground digital elevation model file.

[Parameter settings] Set the wildcard parameters for the gravity variation rate grid time series files, enter the weights and exponents for ground gravity variation rate, horizontal gradient of the ground gravity variation rate and local terrain effect.



Here, the local terrain effect on the gravity is used to quantify the severity of the topographical undulations. The program requires that the latitude and longitude range of the ground digital elevation model grid should be expanded by no less than 50km out of the ground gravity variation grid for the computation of the local terrain effect using the numerical integration method.

The weights and exponent parameters do not change with time, which are only employed to roughly distinguish the responses of different types of the variations to the geological environment. Rough value can meet the needs.

[Output file] The normalized ground stability variation grid time series files.

5.7 Computation of ground stability variation based on variation vectors

[Purpose] From the ground tilt (vertical deflection or horizontal displacement) variation rate vector grid and ground digital elevation model, using the normalized statistical synthesis algorithm, quantitatively estimate the ground stability variation grid according to the quantitative criteria of the ground stability weakening defined by ETideLoad.

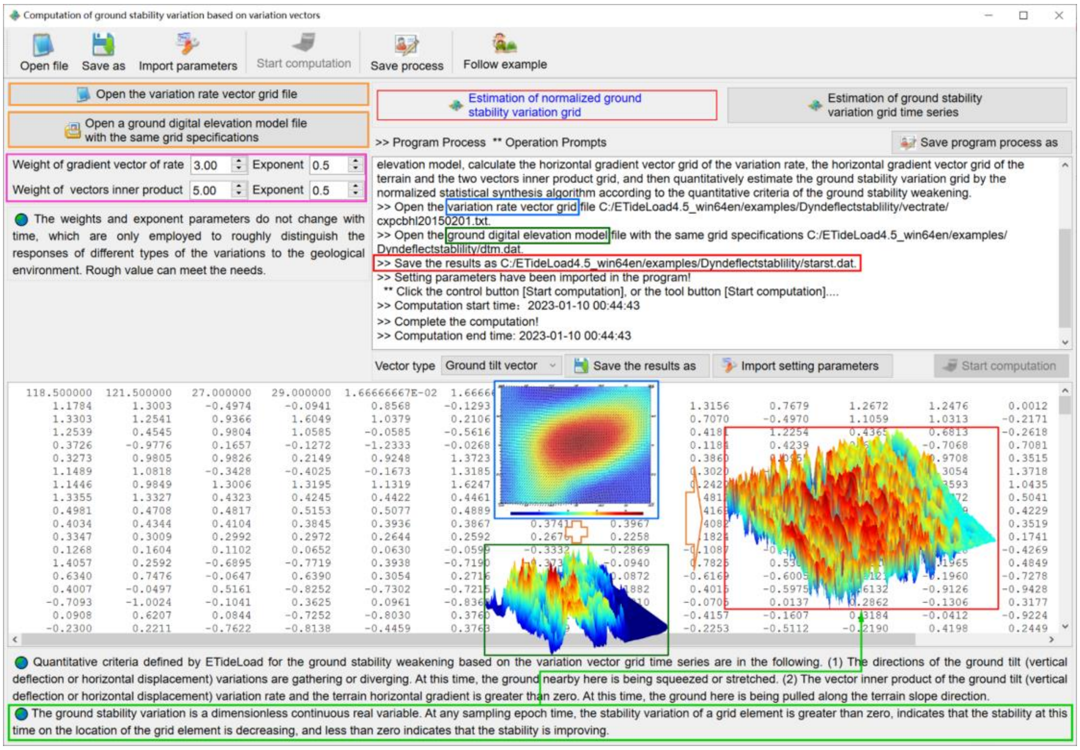
5.7.1 Estimation of normalized ground stability variation grid

[Function] From the ground tilt (vertical deflection or horizontal displacement) variation rate vector grid and ground digital elevation model, calculate the horizontal gradient vector grid of the variation rate, the horizontal gradient vector grid of the terrain and the two vectors inner product grid, and then quantitatively estimate the ground stability variation grid by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

[Input files] The ground variation rate vector grid file and ground digital elevation model file with the same grid specifications.

[Parameter settings] Set the weights and exponents for the rate gradient and two vectors inner product, select the vector type.

[Output file] The normalized ground stability variation grid file.



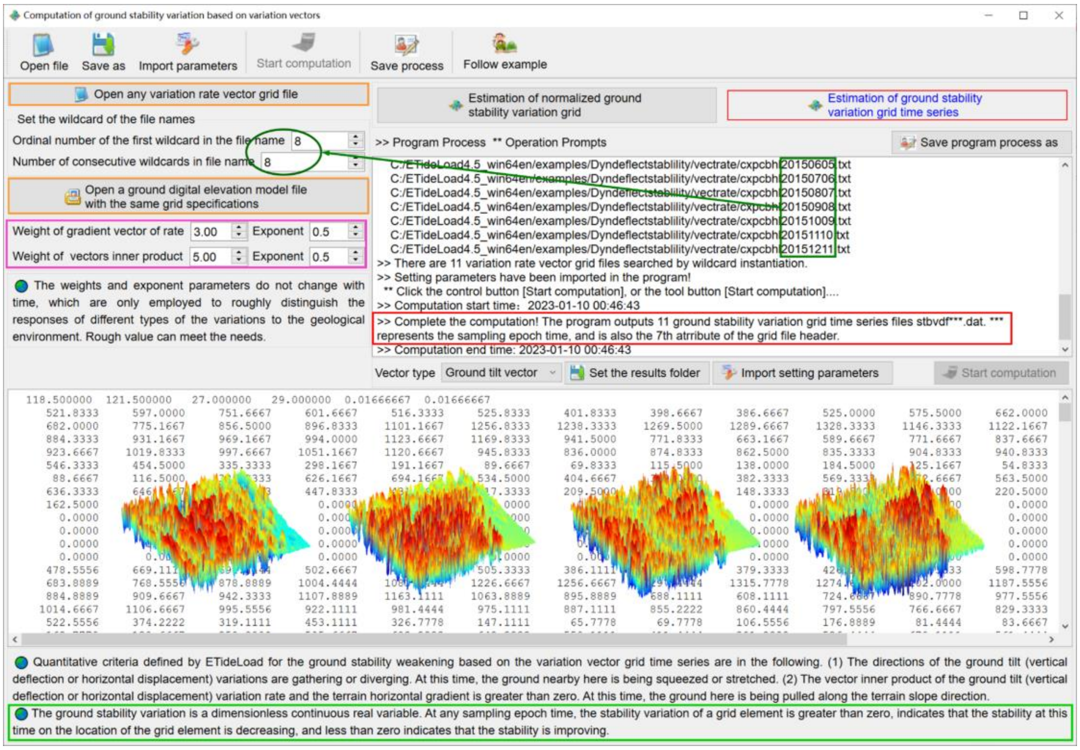
5.7.2 Estimation of ground stability variation grid time series

[Function] From the ground tilt (vertical deflection or horizontal displacement) variation rate vector grid time series and ground digital elevation model, calculate the horizontal gradient vector grid time series of the variation rate, the horizontal gradient vector grid of the terrain, and the two vectors inner product grid time series, and then quantitatively estimate the ground stability variation grid time series by the normalized statistical synthesis algorithm according to the quantitative criteria of the ground stability weakening.

[Input files] The ground variation rate vector grid time series files and ground digital elevation model file with the same grid specifications.

[Parameter settings] Set the wildcard parameters for the rate vector grid time series files, enter the weights and exponents for the rate gradient and two vectors inner product, select the vector type.

[Output file] The normalized ground stability variation grid time series files.



Quantitative criteria defined by ETideLoad for the ground stability weakening based on the variation vector grid time series are in the following.

(1) The directions of the ground tilt (vertical deflection or horizontal displacement) variations are gathering or diverging. At this time, the ground nearby here is being squeezed or stretched.

(2) The vector inner product of the ground tilt (vertical deflection or horizontal displacement) variation rate and the terrain horizontal gradient is greater than zero. At this time, the ground here is being pulled along the terrain slope direction.

The variation vector may be the ground tilt variation, vertical deflection variation, or ground horizontal displacement.

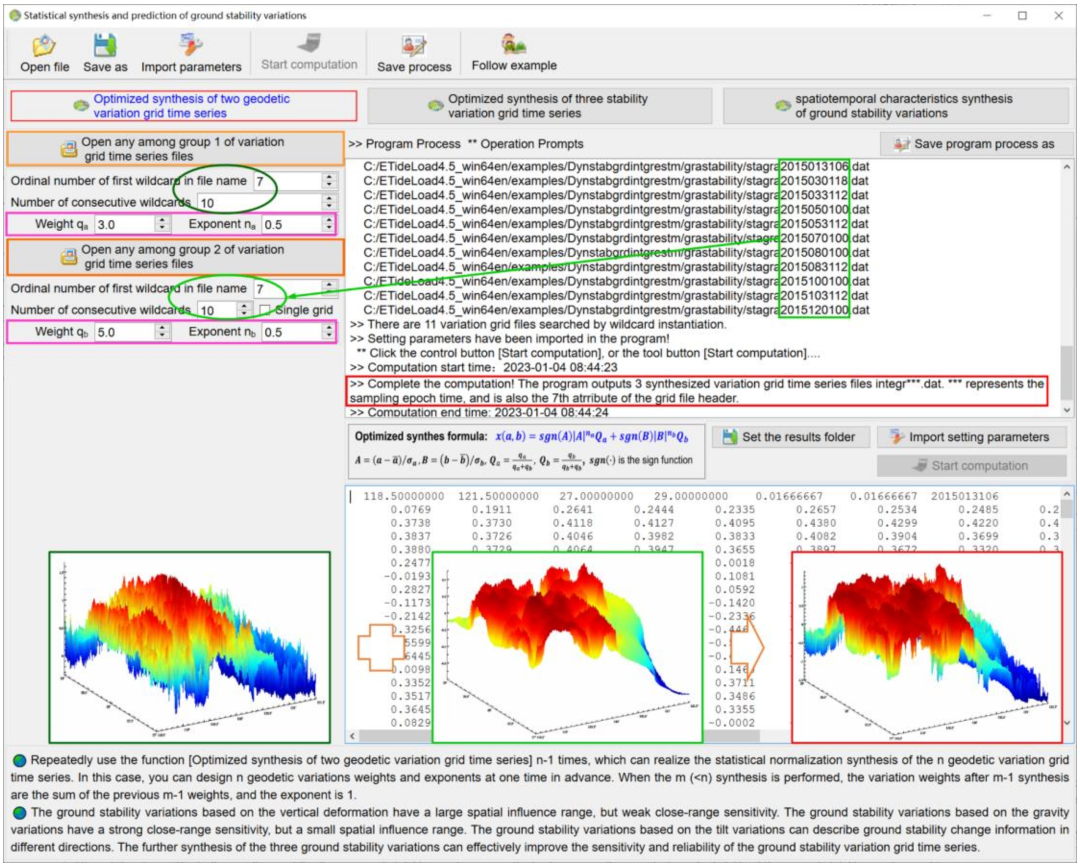
5.8 Statistical synthesis and prediction of ground stability variations

[Purpose] According to historical disasters events during the monitoring period, by adjusting the weights and exponents of multiple stability variations based on various geodetic variations, optimize the ground stability variation grid time series by the statistical normalized synthesis algorithms, to reveal the spatial distribution and temporal natures of the regional ground stability variations.

5.8.1 Optimized synthesis of two geodetic variation grid time series

[Function] From two groups of geodetic variation grid time series with the same space-grid and time-sampling specifications, generate the coupled geodetic variation grid time series by the statistical normalized synthesis algorithms, to reveal the spatiotemporal dynamic effects of the two kinds of geodetic joint monitoring.

[Input files] The two groups of geodetic variation grid time series files with the same space-grid and time-sampling specifications.



[Parameter settings] Set the wildcard parameters for grid time series files, enter the weights and exponents.

[Output file] The synthesized variation grid time series files.

If all the characters of the file name are set as wildcards, the variation grid time series only is an epoch sampling grid. In this case, the program can realize the normalized synthesis between a group of the grid time series and a single grid.

With the two geodetic variation grid time series $\boldsymbol{a}$, $\boldsymbol{b}$, the synthesized variation grid time series $\boldsymbol{x}$ can be calculated by the following formula.

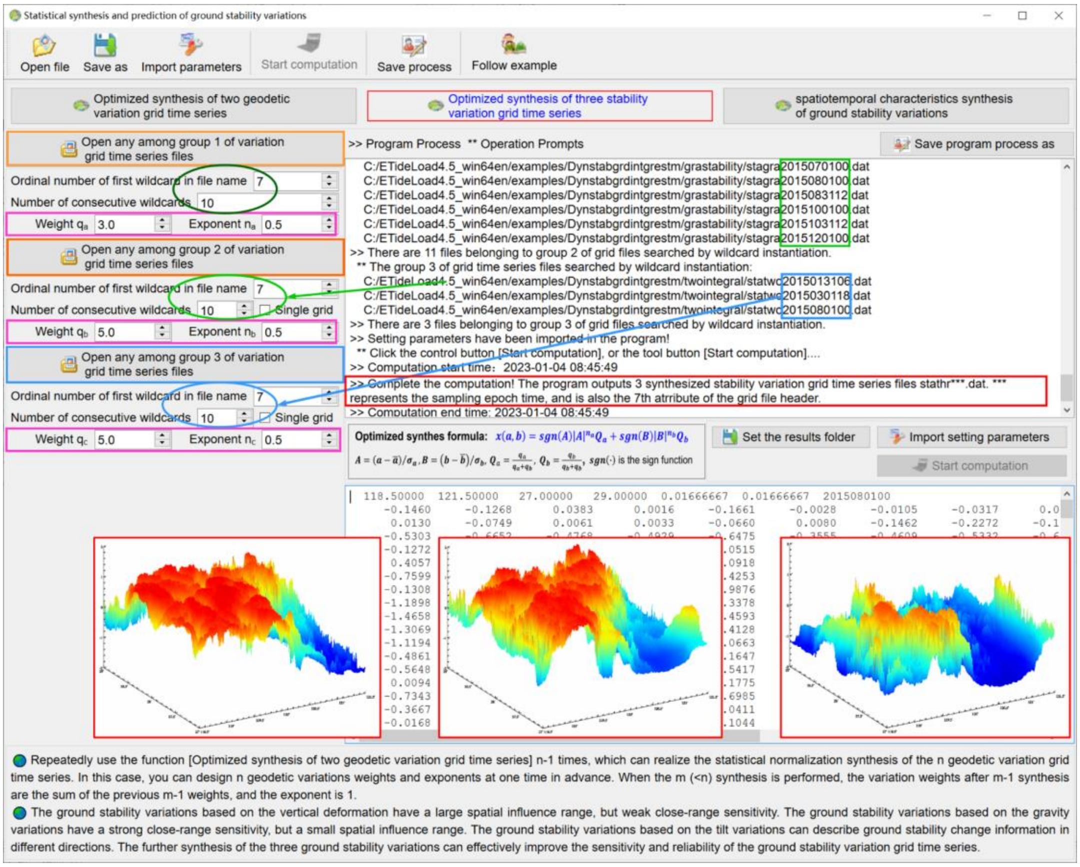
$\boldsymbol{x} = \boldsymbol{sgn}(\boldsymbol{A})|\boldsymbol{A}|^{n_a}\boldsymbol{Q_a} + \boldsymbol{sgn}(\boldsymbol{B})|\boldsymbol{B}|^{n_b}\boldsymbol{Q_b}$ where $\boldsymbol{sgn}(*)$ is the sign function,

$\boldsymbol{A} = (\boldsymbol{a} - \overline{\boldsymbol{a}})/\boldsymbol{\sigma_a}, \boldsymbol{B} = \left(\boldsymbol{b} - \overline{\boldsymbol{b}}\right)/\boldsymbol{\sigma_b}, \boldsymbol{Q}_a = \frac{q_b}{q_a+q_b}, \boldsymbol{Q}_a = \frac{q_b}{q_a+q_b}$.

5.8.2 Optimized synthesis of three stability variation grid time series

[Function] From three groups of ground stability variation grid time series with the same space-grid and time-sampling specifications, generate the ground stability variation grid time series with spatiotemporal dynamic feature information, higher sensitivity, and reliability by the statistical normalized synthesis algorithms.

[Input files] The three groups of stability variation grid time series files with the same space-grid and time-sampling specifications.



[Parameter settings] Set the wildcard parameters for grid time series files, enter the weights and exponents.

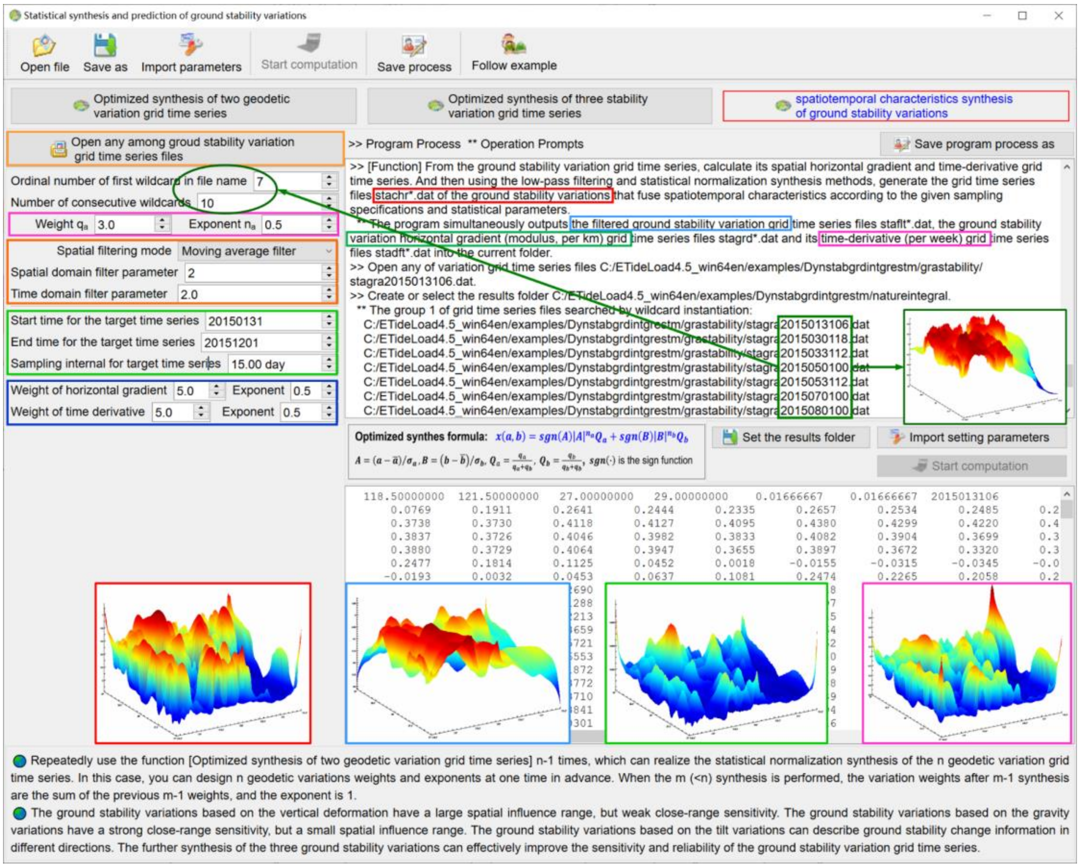
[Output file] The synthesized stability variation grid time series files.

5.8.3 Spatiotemporal characteristics synthesis of ground stability variations

[Function] From the ground stability variation grid time series, calculate its spatial horizontal gradient and time-derivative grid time series. And then using the low-pass filtering and statistical normalization synthesis methods, generate the grid time series files stachr*.dat of the ground stability variations that fuse spatiotemporal characteristics according to the given sampling specifications and statistical parameters.

[Input files] The ground stability variation grid time series files.

[Parameter settings] Enter the weights and exponents for the ground stability variation, its horizontal gradient and time-derivative, set spatial and time domain filter parameters, and set the sampling specifications parameters.



When the starting time is earlier than the first sampling epoch time of the source variation grid time series, the program lets the starting time = the first sampling epoch time - sampling interval * total number of the samples * 5%.

When the ending time is later than the last sampling epoch time of the source variation grid time series, the program lets the ending time = the last sampling epoch time + sampling interval * total number of the samples * 5%.

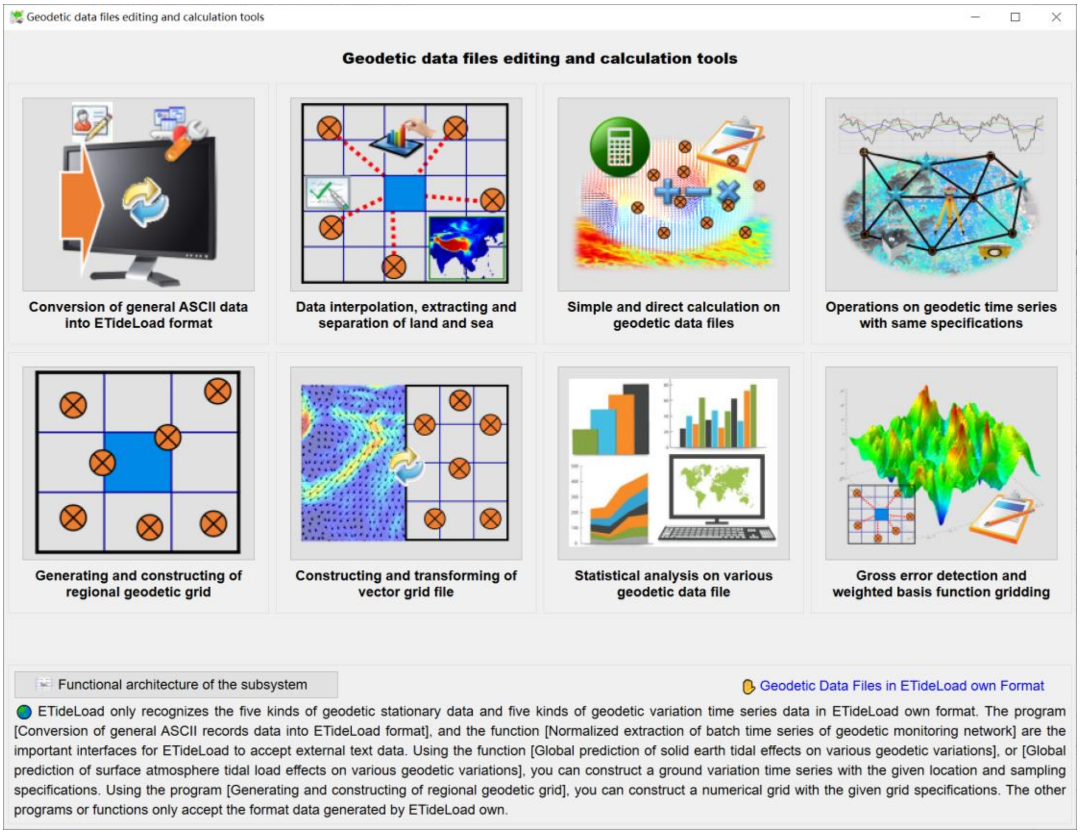
[Output file] The synthesized ground stability variation grid time series files stachr*.dat, filtered ground stability variation grid time series files staflt*.dat, ground stability variation horizontal gradient (modulus, per km) grid time series files stagrd*.dat and its time-derivative (per week) grid time series files stadft*.dat.

Repeatedly use the function [Optimized synthesis of two geodetic variation grid time series] n-1 times, which can realize the statistical normalization synthesis of the n geodetic variation grid time series. In this case, you can design n geodetic variations weights and exponents at one time in advance. When the m (<n) synthesis is performed, the variation weights after m-1 synthesis are the sum of the previous m-1 weights, and the exponent is 1.

The ground stability variations based on the vertical deformation have a large spatial influence range, but weak close-range sensitivity. The ground stability variations based on the gravity variations have a strong close-range sensitivity, but a small spatial influence range. The ground stability variations based on the tilt variations can describe ground stability change information in different directions. The further synthesis of the three ground stability variations can effectively improve the sensitivity and reliability of the ground stability variation grid time series.

6 Editing, calculation and visualization for geodetic data files

The group of programs can be employed to construct of geodetic data files in ETideLoad format, edit, interpolate, grid, extract, separate and merge geodetic data, and simply calculate and visualize on geodetic data files.



ETideLoad only recognizes the five kinds of geodetic stationary data and five kinds of geodetic variation time series data in ETideLoad own format. The program [Conversion of general ASCII record data into ETideLoad format], and the function [Normalized extraction of batch time series of geodetic monitoring network] are the important interfaces for ETideLoad to accept external text data. Using the function [Global prediction of solid earth tidal effects on various geodetic variations], or [Global prediction of surface atmosphere tidal load effects on various geodetic variations], you can construct a ground variation time series with the given location and sampling specifications. Using the program [Generating and constructing of regional geodetic grid], you can construct a numerical grid with the given grid specifications. The other programs or functions only accept the format data generated by ETideLoad own.

6.1 Conversion of general ASCII data into ETideLoad format

[Function] Convert the general ASCII data record file from different sources and non-standard formats into the discrete geodetic record file in ETideLoad format.

[Input file] The general ASCII data record file.

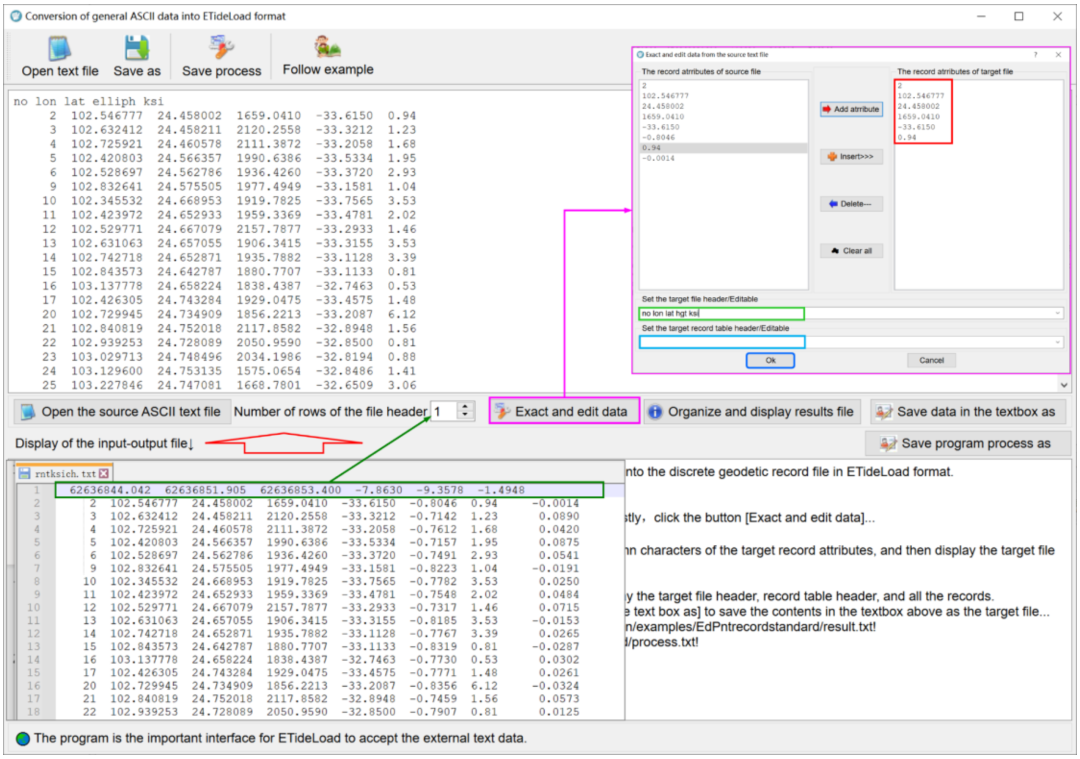
After entering the number of rows of the input file header, click the control button [Exact and edit data] to open the dialog [Exact and edit data from the source text file].

Set the format parameters about the target file header, record table header, and record attributes.

When the target file does not need the record table header, please clear the text corresponding to the input text box.

Click the button [Ok] to close the dialog. Click the control button [Organize and display result file] to count the maximum number of each column characters of the target record attributes, then the program will display target file header, record table header and all the records in the editable textbox. The program need take some time to organize the target record attributes, please wait…

Complete the statistics of the maximum number of characters of the target record attributes, and display the target file header, record table header, and all the records in the editable textbox.



[Output file] The discrete geodetic record file in ETideLoad format.

Check the target record file displayed in the editable textbox. Click the control button [Save data in the textbox as] to save the contents in the textbox above as the target file...

The program is the important interface for ETideLoad to accept the external text data.

6.2 Data interpolation, extracting and separation of land and sea

6.2.1 Changing of grid resolution by interpolation

[Function] Increase or decrease the grid spatial resolution according to the given grid resolution and specified interpolation method.

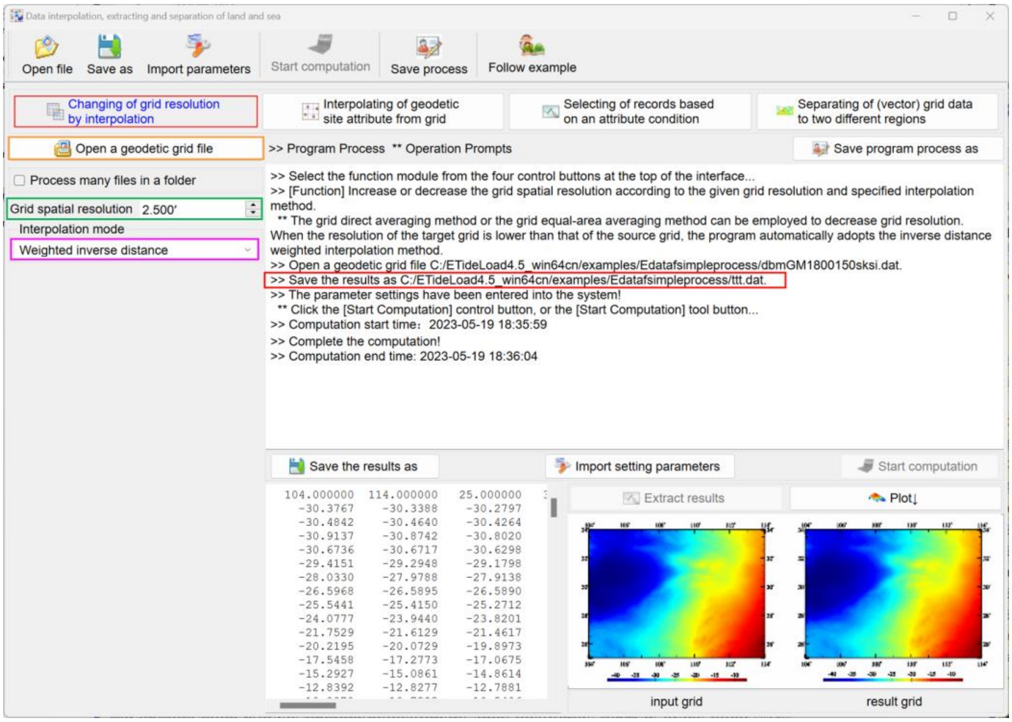
[Input file] The geodetic numerical grid file.

[Parameter settings] Enter the spatial resolution for target grid and select the interpolation mode.

[Output file] The target geodetic numerical grid file.

The grid direct averaging method is that sums up all the effective source grid element values within the target grid element, and then divided them by the number of the effective source elements. The grid equal-area averaging method is that sums up all the effective source grid element values within the target element, and then divided by the total number of source elements.

It is recommended to adopt the grid equal-area averaging method when decreasing the spatial resolution of the surface loads.



The grid direct averaging method or the grid equal-area averaging method can be employed to decrease grid resolution. When the resolution of the target grid is lower than that of the source grid, the program automatically adopts the inverse distance weighted interpolation method.

6.2.2 Interpolating of geodetic site attributes from grid

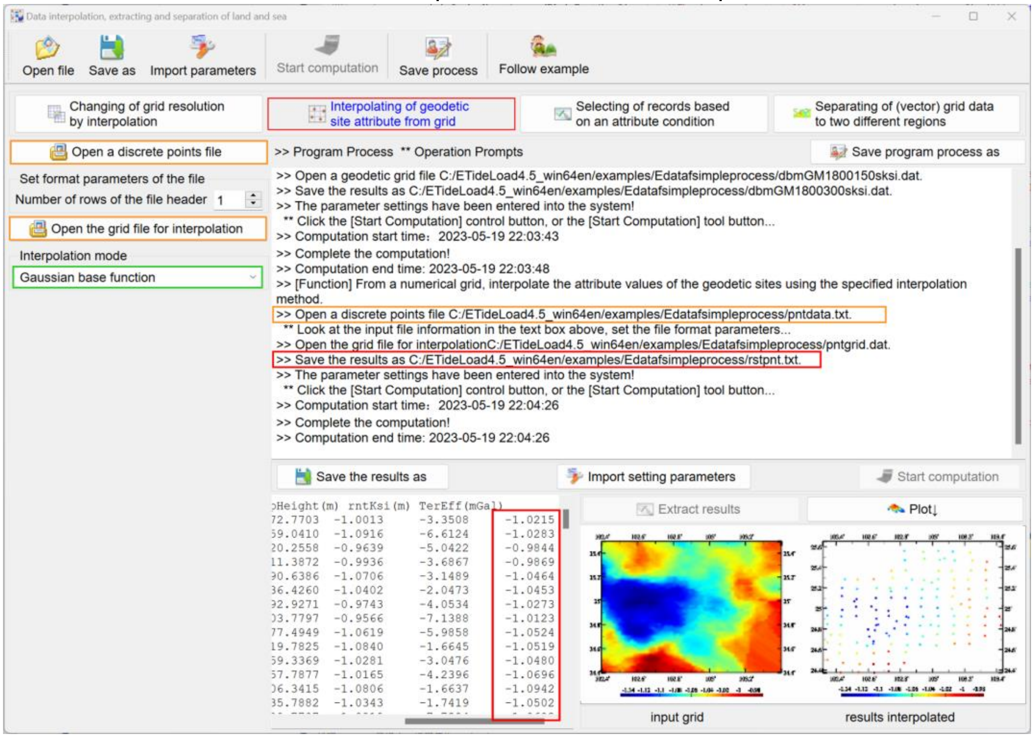
[Function] From a numerical grid, interpolate the attribute values of the geodetic sites according to the specified interpolation method.

[Input files] The discrete geodetic point file to be interpolated. The geodetic numerical grid file for interpolation.

[Parameter settings] Enter number of rows of the discrete geodetic point file header and select the interpolation mode.

[Output file] The interpolated discrete geodetic point file.

The file format is the same as the input discrete geodetic point file file. Behind the input file record, add one column of the interpolated value as the output file record.



6.2.3 Selecting of records based on the attribute condition

[Function] Select the geodetic records from a geodetic record file according to the maximum and minimum range of the specified attribute.

[Input files] The discrete geodetic point.

[Parameter settings] Enter number of rows of the input file header, column ordinal number of the condition attribute in the file record, and minimum and maximum of the attribute.

[Output file] The selected discrete geodetic point file.

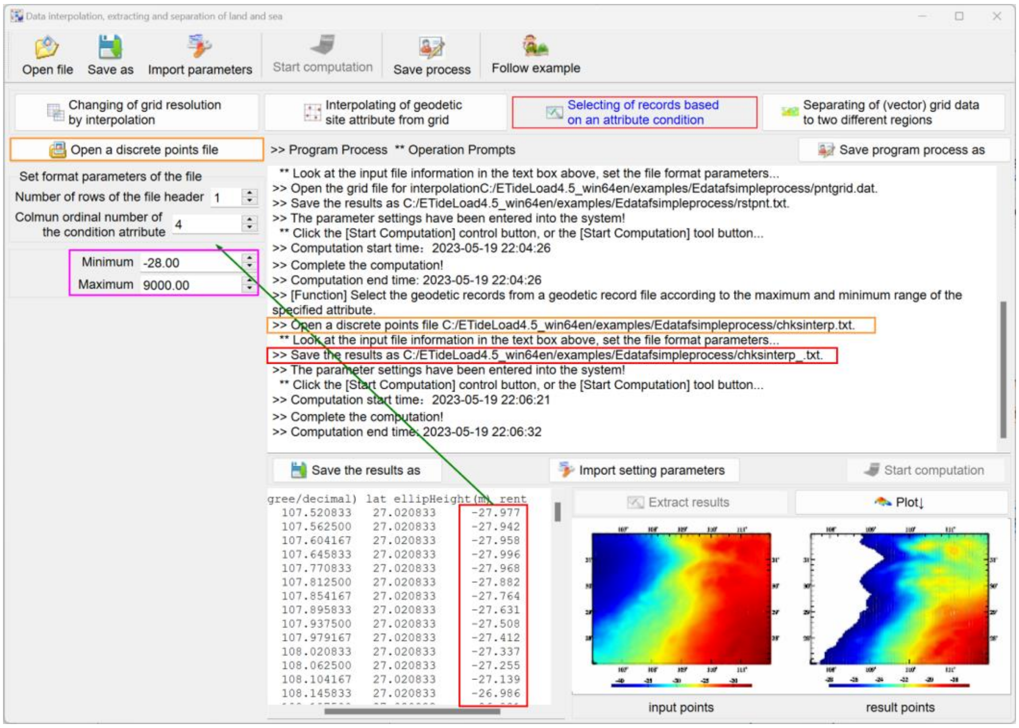
The file format is the same as the input discrete geodetic point file file.

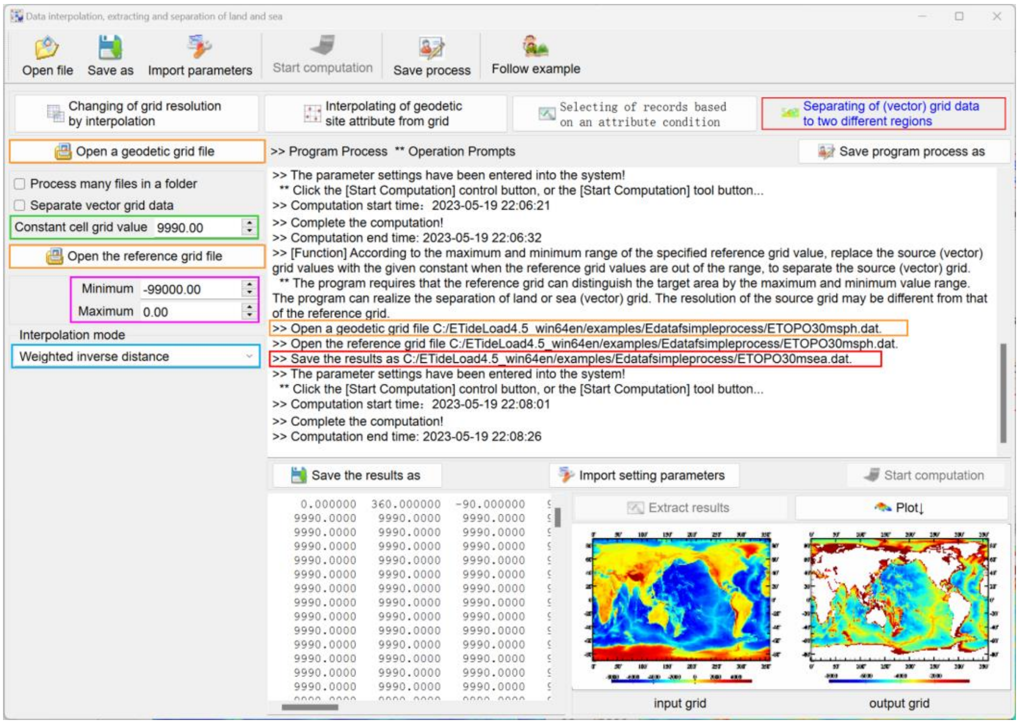
6.2.4 Separating of (vector) grid data to two different regions

[Function] According to the maximum and minimum range of the specified reference grid value, replace the source (vector) grid values with the given constant when the reference grid values are out of the range, to separate the source (vector) grid.

The program requires that the reference grid can distinguish the target region by the maximum and minimum value range.

The program can realize the separation of land or sea (vector) grid.





[Input files] The source geodetic (vector) grid file. The reference grid file whose grid range and resolution are not smaller than that of the source grid file.

[Parameter settings] Enter the maximum and minimum value range and the constant grid value to replace the grid value out of the range. Select the interpolation mode.

[Output file] The separated geodetic (vector) grid file.

6.3 Simple and direct calculation on geodetic data files

6.3.1 Weighted operations on two specified attributes in record file

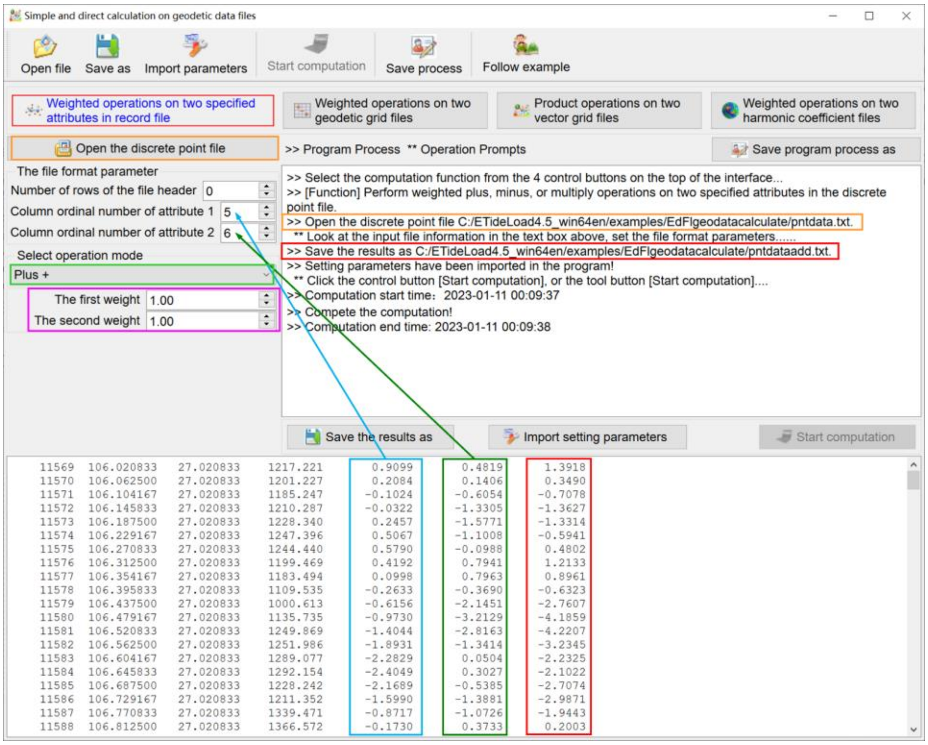
[Function] Perform weighted plus, minus, or multiply operations on two specified attributes in the discrete point file.

[Input file] The discrete geodetic point file.

[Parameter settings] Enter number of rows of the discrete geodetic point file header, column ordinal number and weight of the attribute 1, and column ordinal number and weight of attribute 2. Select the operation mode.

[Output file] The operated discrete geodetic point file.

The file format is the same as the input discrete geodetic point file file. Behind the input file record, add one column of the computed result as the output file record.

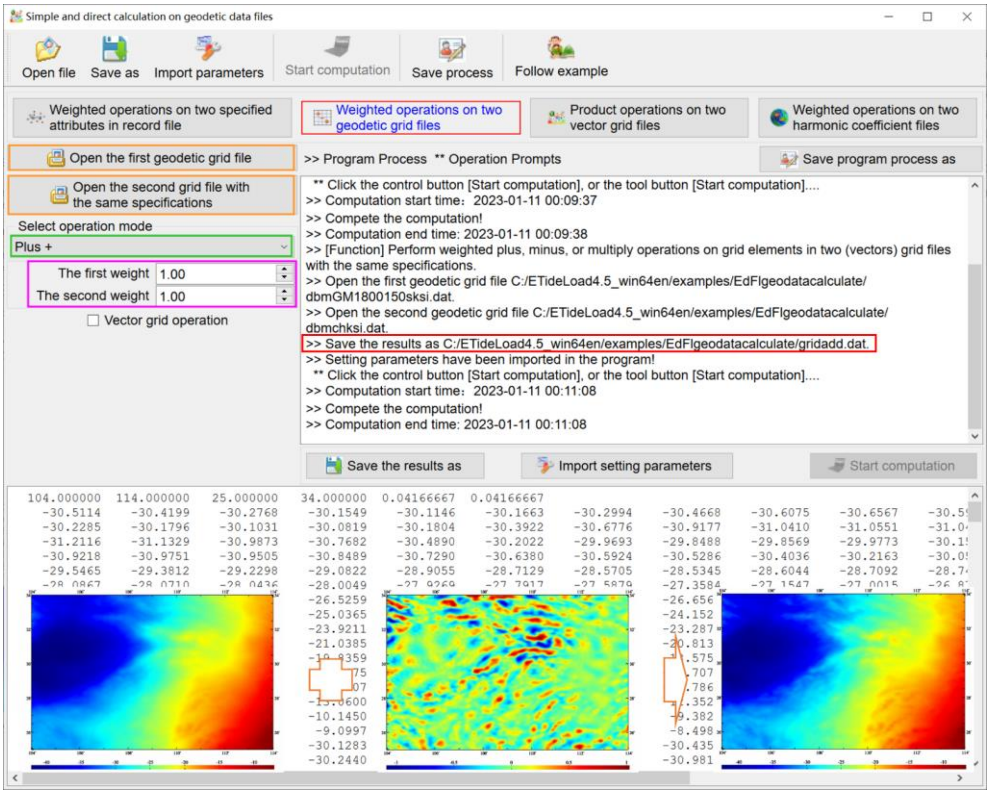


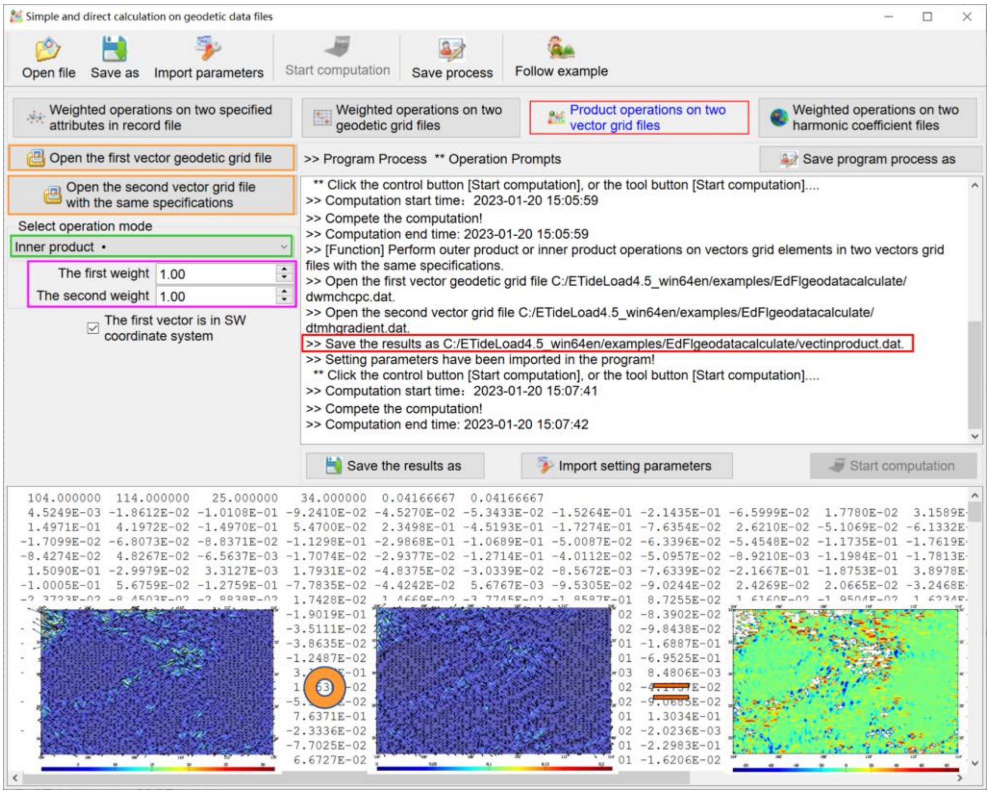
6.3.2 Weighted operations on two geodetic grid files

[Function] Perform weighted plus, minus, or multiply operations on grid elements in two (vectors) grid files with the same specifications.

6.3.3 Product operations on two vector grid files

[Function] Perform outer product or inner product operations on vectors grid elements in two vectors grid files with the same specifications.





6.3.4 Weighted operations on two harmonic coefficient files

[Function] Perform weighted operations on two normalized spherical harmonic coefficient model files.

The file header occupies a row and consists of two attributes for scaling parameters of the spherical harmonic coefficient model, namely the geocentric gravitational constant GM ($\times10^{14}$m^2/s^2) and equatorial radius of the Earth a (m).

6.4 Operations on geodetic time series with same specifications

6.4.1 Weighted operations on two record time series with same specifications

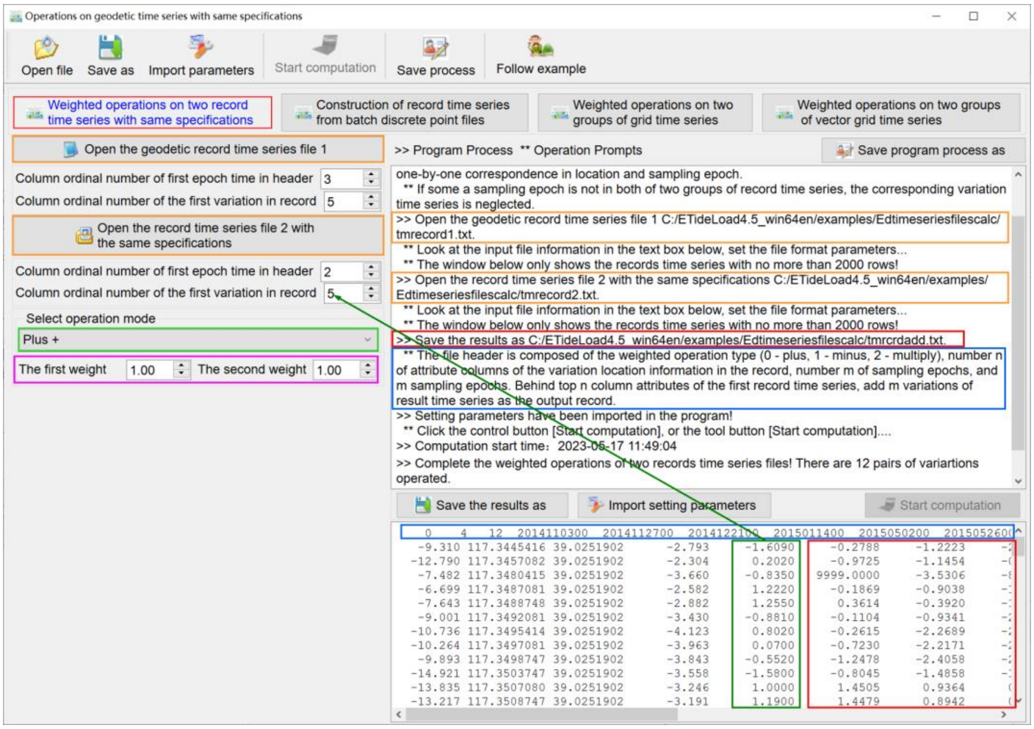
[Function] Perform weighted plus, minus, or multiply operations on two variations at the same sampling epochs from two records time series.

The program requires that the records of two groups of time series are one-by-one correspondence in location and sampling epoch.

[Input files] The two groups of variation record time series files.

[Parameter settings] Set the record time series file format parameters, enter the weighs, and select operation mode.

If some a sampling epoch is not in both of two group of records time series, the corresponding variation time series is neglected.



[Output file] The operated discrete geodetic point file.

The file header is composed of the weighted operation type (0 - plus, 1 - minus, 2 - multiply), number n of attribute columns of the variation location information in the record, number m of sampling epochs, and m sampling epochs.

Behind top n columns attributes of the first record time series file record, add m variations of result time series as the output record.

6.4.2 Construction of record time series from batch discrete point files

[Function] From a series of discrete point files with the same specifications including the sampling epoch time, extract the specified attribute variation, and compose a time series by sorting with time, and then generate a record time series file with several kinds of variations.

[Input files] A series of discrete point files with the same specifications.

The program requires that the file header occupies a row that contains a sampling epoch in ETideLoad format.

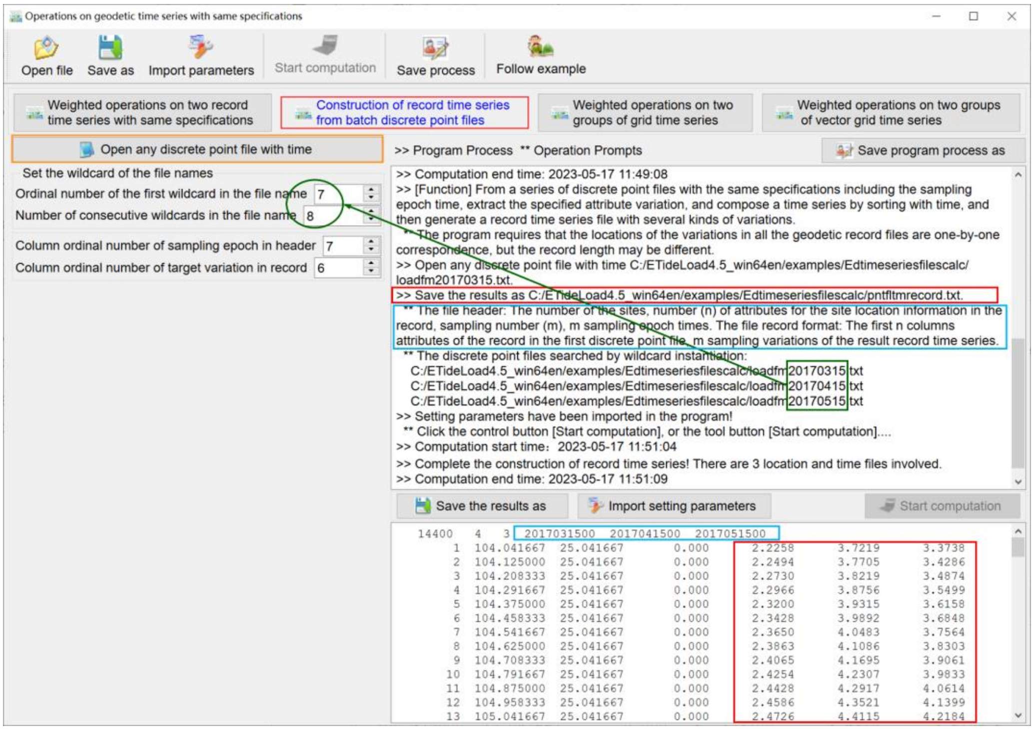
The program also requires that the locations of the variations in all the geodetic record files are one-by-one correspondence, but the record length may be different.

[Parameter settings] Set the wildcard parameters for a series of discrete point files and the file format parameters, enter column ordinal number of the epoch time in the input file header and target attribute time series in the input file record.

[Output file] The variation record time series file.

The output file header: The number of the sites, number (n) of attributes for the site location information in the record, sampling number (m), m sampling epoch times.

The output file record format: The first n columns of attributes of the record in the first discrete point file, m sampling variations of the result record time series.



6.4.3 Weighted operations on two groups of grid time series

[Function] From two groups of variation grid time series with the same grid specifications, sort the two groups of grids with time and then perform weighted plus, minus, or multiply operations.

The program automatically ignores the grid file whose sampling epoch is not one-by-one correspondence.

6.4.4 Weighted operations on two groups of vector grid time series

[Function] From two groups of variation vector grid time series with the same grid specifications, sort the two groups of vector grids with time and then perform weighted plus, minus, or outer production operations.

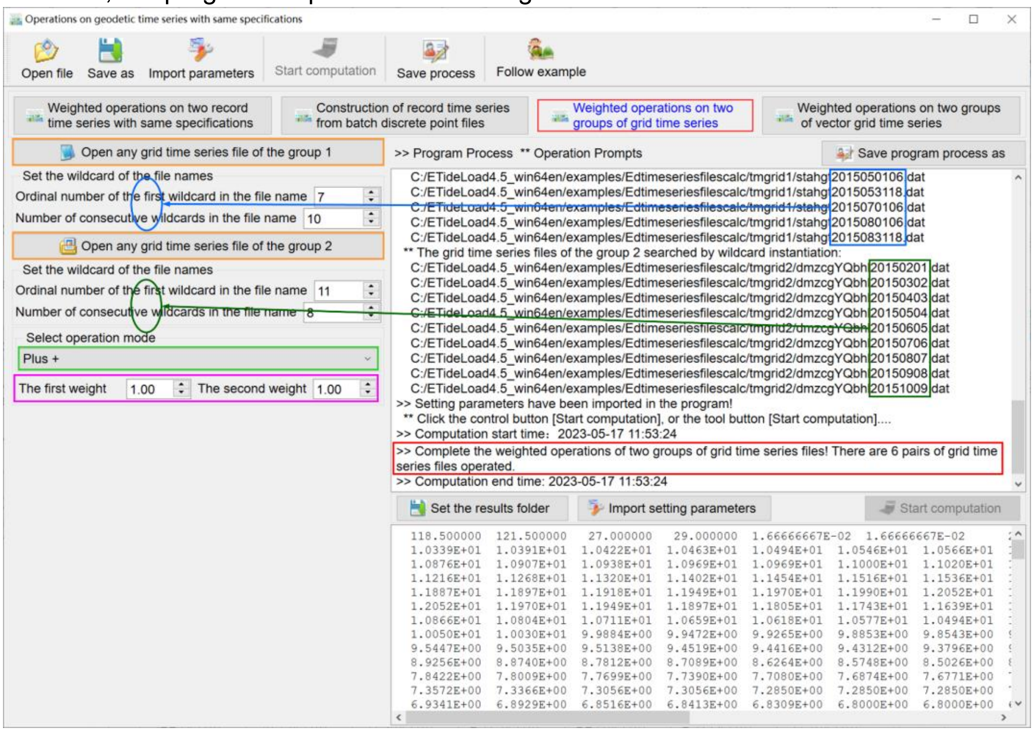
The program automatically ignores the vector grid file whose sampling epoch is not one-by-one correspondence.

[Input files] The two groups of variation vector grid time series files with the same grid specifications.

[Parameter settings] Set the wildcard parameters for variation vector grid time series files, enter the weighs, and select operation mode.

The weighted (w_1, w_2) outer product of two vectors is defined as $(a_1, a_2) \times (b_1, b_2) = w_1 a_1 b_2 - w_2 a_2 b_1$, which is a scalar.

[Output file] The variation (vector) grid time series files. Only when outer production operations, the program outputs the variation grid time series files.



6.5 Generating and constructing of regional geodetic grid

6.5.1 Gridding of discrete geodetic data by simple interpolation

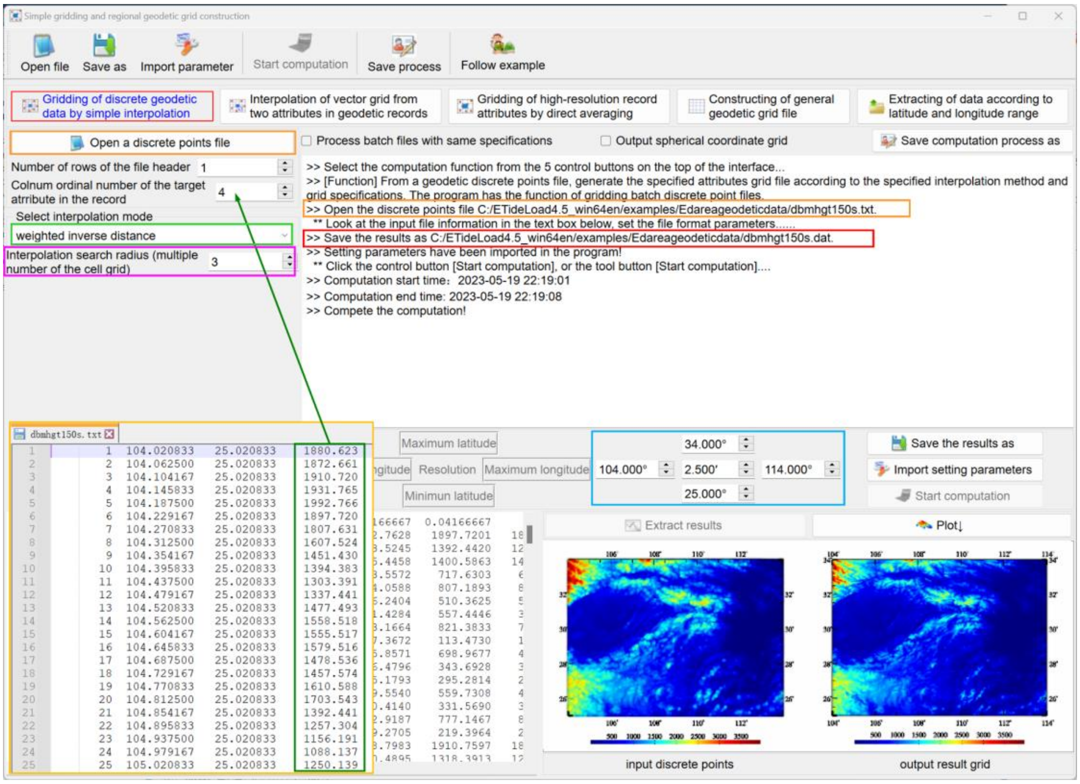
[Function] From a geodetic discrete point record file, generate the specified attribute grid file according to the specified interpolation method and grid specifications.

[Input files] The discrete geodetic point file to be interpolated. The geodetic numerical grid file for interpolation.

[Parameter settings] Enter number of rows of the discrete point file header, column ordinal number of the target attribute in the file record, interpolation search radius (multiple of the grid element) and grid specifications parameters. Select the interpolation mode.

[Output file] The operated discrete geodetic point file.

The file format is the same as the input discrete point file. Behind the input file record, add one column of the interpolated result as the output file record.



6.5.2 Vector griding by interpolation from two attributes in geodetic records

[Function] From a geodetic discrete point file, generate the vector grid file according to the two specified component attributes, specified interpolation method, and given grid specifications.

6.5.3 Gridding of high-resolution record attributes by direct averaging

[Function] Using the direct averaging method, grid the high-resolution discrete observations.

6.5.4 Constructing of general geodetic grid file

[Function] According to the given latitude and longitude range and spatial resolution, generate the constant, random number, 2D array index value, or Gaussian surface grid file.

6.5.5 Extracting of data according to latitude and longitude range

[Function] According to the given latitude and longitude range, extract data from the discrete point file, grid file, or vectors grid file. The program can extract data from batch files.

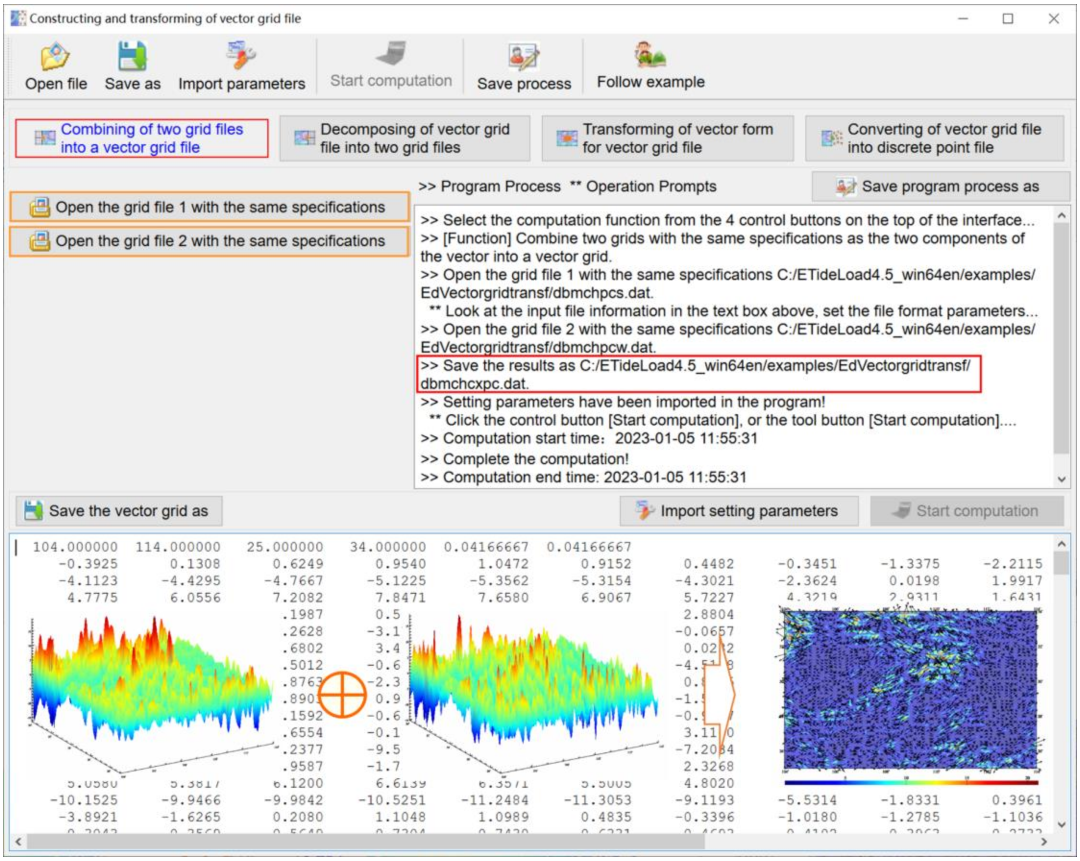
6.6 Constructing and transforming of vector grid file

6.6.1 Combining of two grid files into a vector grid file

[Function] Combine two grids with the same specifications as the two components of the vector into a vector grid.

[Input files] The two geodetic grid files.

[Output file] The geodetic vector grid file.



6.6.2 Decomposing of vector grid file into two grid files

[Function] Decompose a vector grid file into two components grid files.

[Input file] The geodetic vector grid file.

[Output files] The two geodetic grid files.

6.6.3 Transforming of vector form for vector grid file

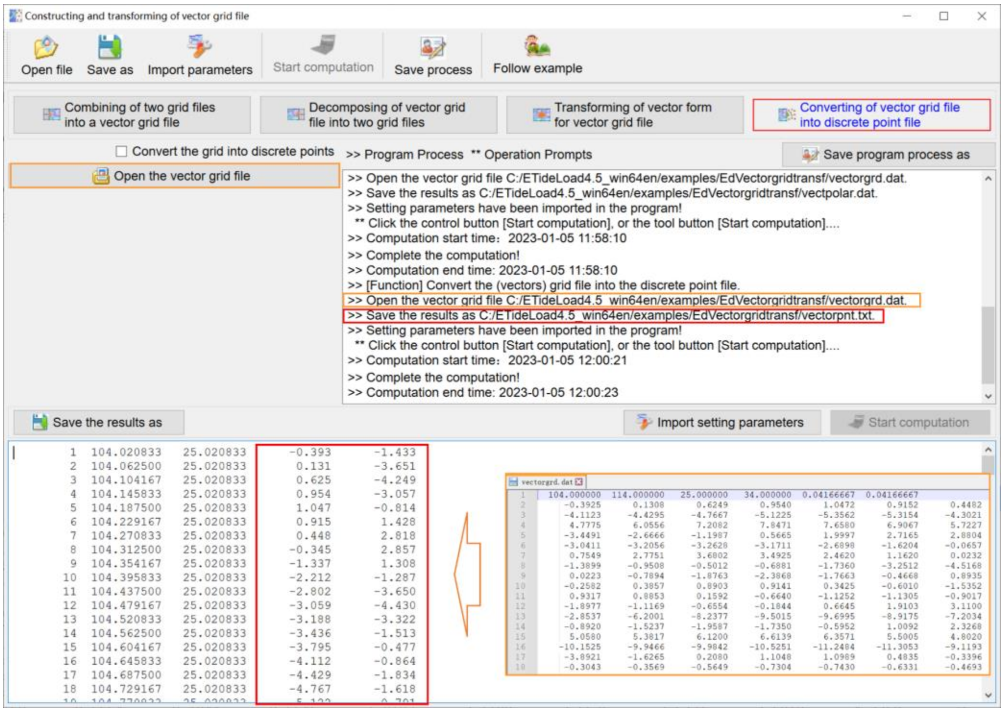
[Function] Transform the vectors in a vector grid file between plane coordinates (in-phase/cross-phase amplitude) and polar coordinates (amplitude/phase).

6.6.4 Converting of vector grid file into discrete point file

[Function] Convert the (vectors) grid file into the discrete point file.

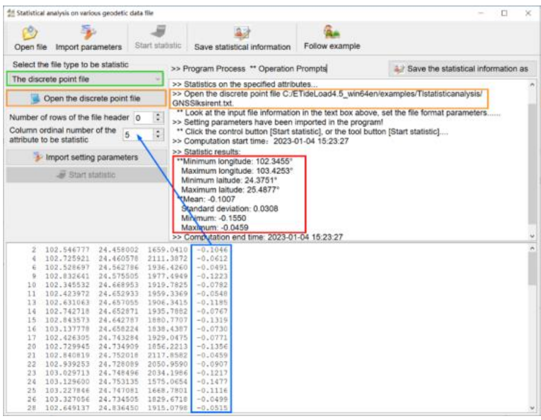
[Input file] The geodetic (vector) grid file.

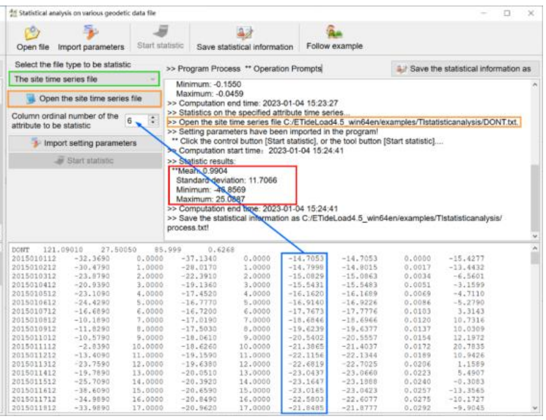
[Output file] The discrete point record file.



6.7 Statistical analysis on various geodetic data files

[Purpose] Extract the latitude and longitude range, mean, standard deviation, minimum, maximum, and other statistical information from the specified attributes of the discrete point file, geodetic grid file, or vector grid file.





6.8 Gross error detection and weighted basis function gridding

6.8.1 Gross error detection on observations based on low-pass reference surface

[Function] Select the low-pass grid as the reference surface, interpolate the reference value of the specified attribute value at the discrete point, and then detect and separate the gross error records according to the statistical properties of the differences between the specified attribute value and reference value.

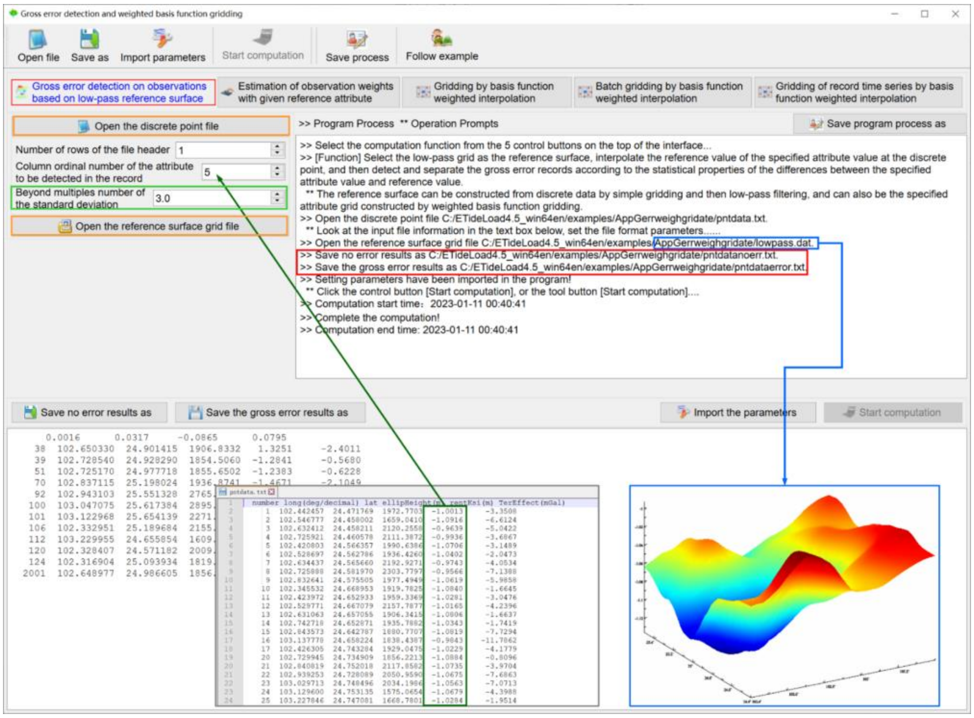
[Input files] The discrete geodetic point file to be detected. The low-pass reference surface grid file.

The reference surface can be constructed from discrete data by simple gridding and then low-pass filtering, and can also be the specified attribute grid constructed by weighted basis function gridding.

[Parameter settings] Enter number of rows of the discrete geodetic point file header, column ordinal number of the attribute to be detected in the record, and beyond multiples of the standard deviation.

When the absolute value of the difference between the attribute and its mean is greater than n times standard deviation, the record in which attribute is a gross error record.

[Output file] The operated discrete geodetic point file without gross error, whose format is the same with the input discrete point file. The gross error point file, whose file header include the average, standard deviation, minimum and maximum of the differences.



6.8.2 Estimation of observation weights with given reference attribute

[Function] Using the weight function defined by ETideLoad, estimate the observation weight according to the statistical property of the specified reference attribute in the input geodetic record file.

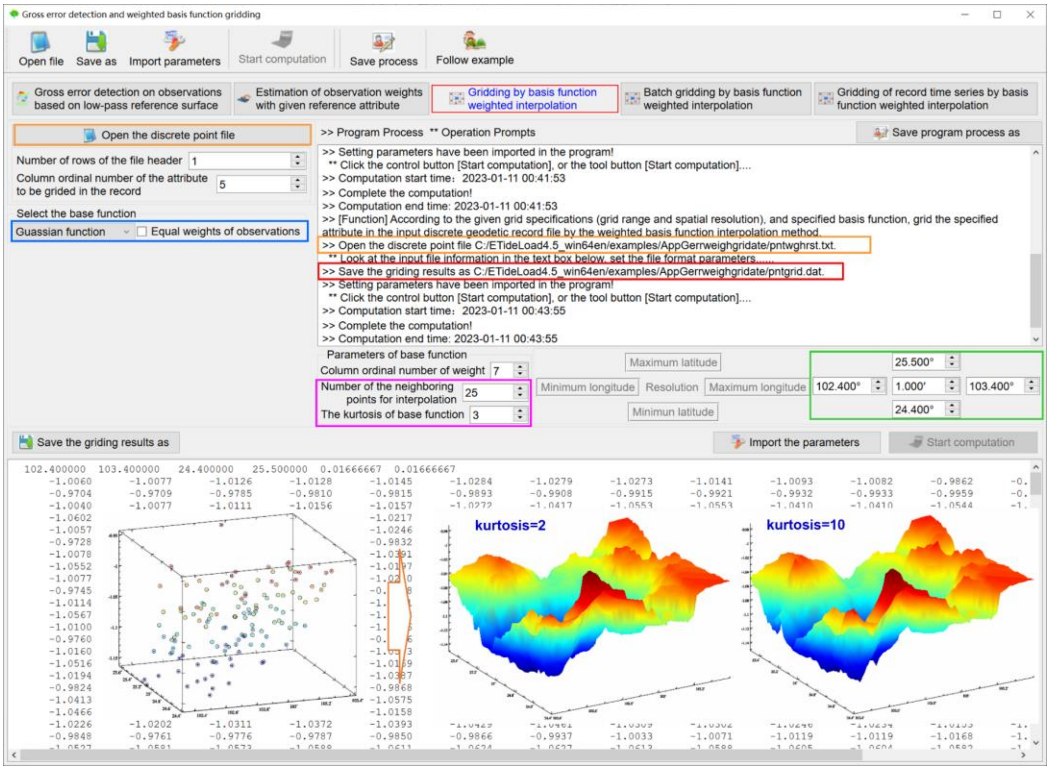
Weight function defined by ETideLoad4.5 $w(x,a) = 10\sigma\sqrt{\sigma^2 + (ax)^2}$, here x is the reference attribute, a is the given smoothing factor of the weight function, σ is the standard deviation of x calculated automatically by the program.

The larger the weight function smoothing factor a, the slower the weight function w decays with distance.

6.8.3 Gridding by basis function weighted interpolation

[Function] According to the given grid specifications (grid range and spatial resolution), and specified basis function, grid the specified attribute in the input discrete geodetic record file by the weighted basis function interpolation method.

[Input files] The discrete geodetic point file.



[Parameter settings] Enter number of rows of the discrete point file header, column ordinal number of the target attribute in the file record, and grid specifications parameters. And set the base function and its parameters.

The smaller the kurtosis is (the slower the basis function decays with distance), the larger the number of neighboring points in the interpolation, the smoother the interpolation, the weaker the edge effect, and the stronger the interpolation ability for sparse data.

The interpolation weight is equal to the product of the attribute weight and base function.

[Output file] The geodetic grid file.

The program of the gridding by basis function weighted interpolation is specially designed by ETideload based on the properties of general geophysical fields, and it is suitable for griding of single types of multi-source heterogeneous geophysical fields.

6.8.4 Batch gridding by basis function weighted interpolation

[Function] According to the given grid specifications, base function, and other parameters, respectively grid the specified attribute in each of the input discrete point files saved in a folder by the weighted basis function interpolation method.

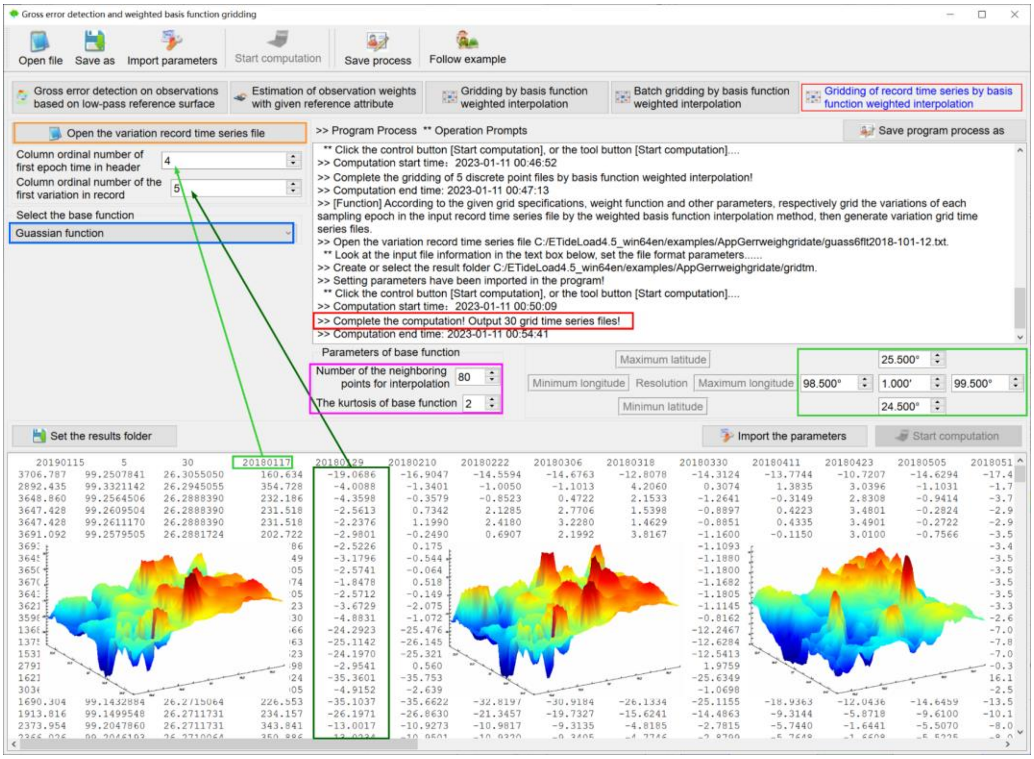
[Input files] Batch discrete geodetic point files with same format.

[Parameter settings] Set the wildcard parameters for batch discrete geodetic point files, Enter number of rows of the discrete point file header, column ordinal number of the target attribute in the file record, and grid specifications parameters. Select the base function, and set the number of the neighboring points and kurtosis of base function.

[Output files] A series of numerical grid files bsfgrd***.dat that correspond one-to-one with the input discrete point value files. Here, *** are the instance of the input discrete point file name wildcards.

6.8.5 Gridding of record time series by basis function weighted interpolation

[Function] According to the given grid specifications, weight function and other parameters, respectively grid the variations of each sampling epoch in the input record time series file by the weighted basis function interpolation method, then generate variation grid time series files.



6.9 Visualization plot tools for various geodetic data files

6.9.1 Visualization for multi-variation time series file

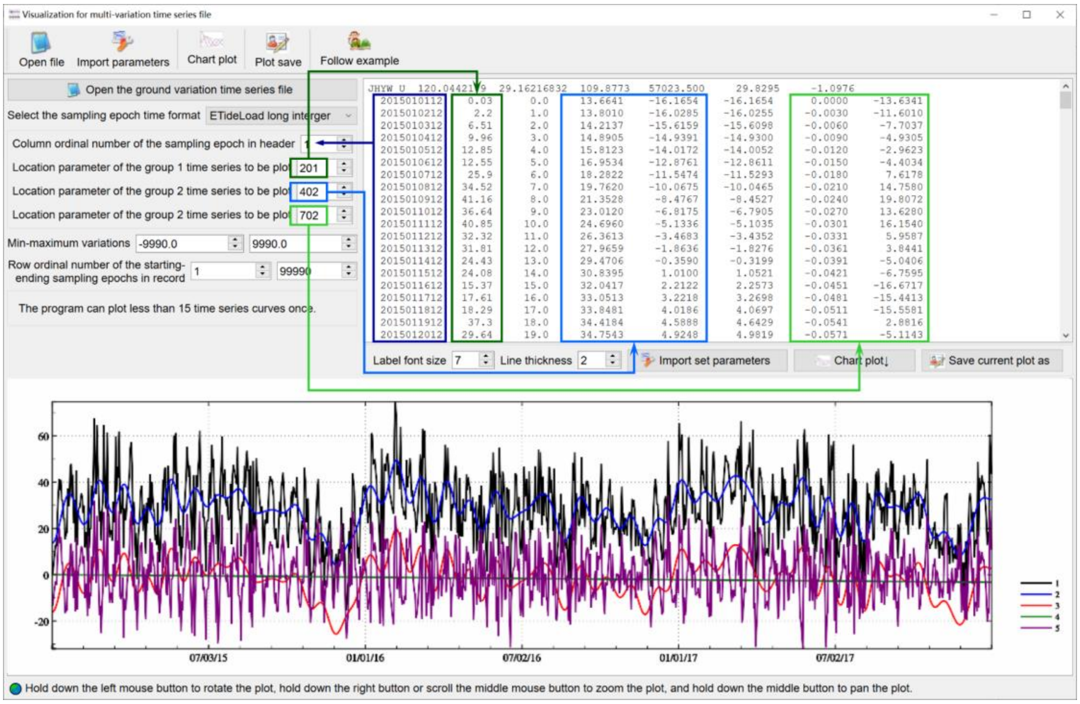
[Function] Plot multi-variation time series curves stored in a ground geodetic variation time series file.

The program can plot less than 15 time series curves once.

[Parameter settings] Select the sampling epoch time format, enter the column number of the sampling epoch time in the file record, set the location parameters of the time series plotted, and enter minimum-maximum of the plotted variations and row ordinal number of the starting-ending sampling epochs.

When the location parameter corresponding to the column ordinal number in the record is greater than the record maximum column number, the program automatically sets the location parameter as the serial number of the record maximum column.

When the column ordinal number of the end sampling variations is greater than the number of samples of the time series, the program automatically sets the number of samples of the time series as the column ordinal number of the end sampling variations.

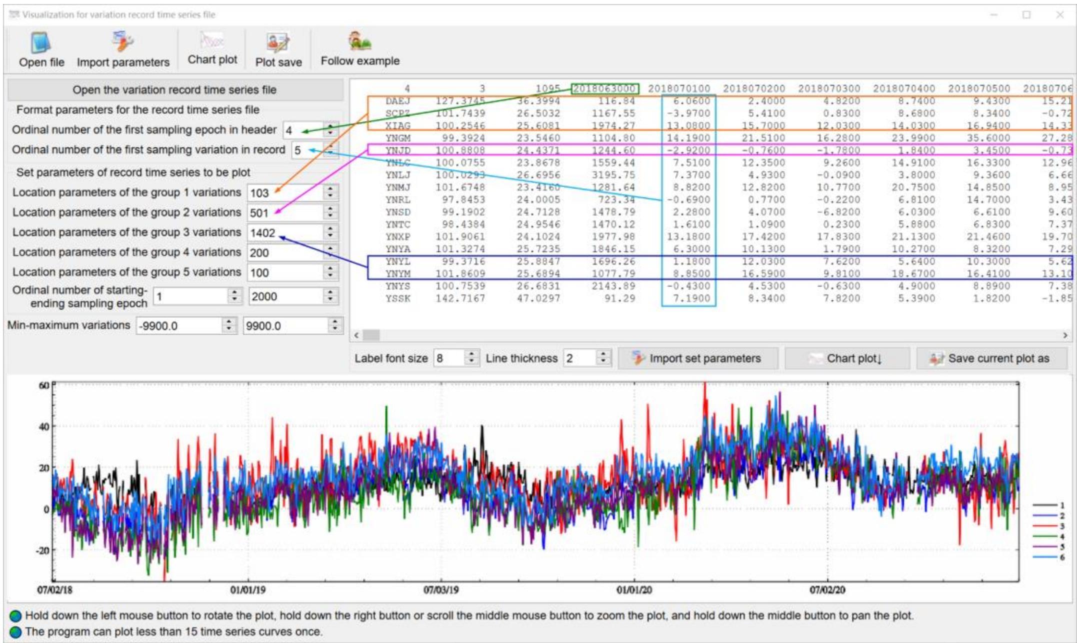


Hold down the left mouse button to rotate the plot, hold down the right button or scroll the middle mouse button to zoom the plot, and hold down the middle button to pan the plot.

6.9.2 Visualization for variation record time series file

[Function] Plot multi-variation time series curves stored in a variation record time series file.

[Parameter settings] Enter the ordinal number of the first sampling epoch in file header and the first sampling variation in record, set the location parameters of the time series plotted, and enter the ordinal number of starting-ending sampling epochs and minimum-maximum of the plotted variations.



When the location parameter corresponds to the row ordinal number of the record is greater than the number of rows of the file records, the program automatically sets number of rows of the file records as the row ordinal number of the last record.

The program can plot less than 15 time series curves once. When different groups of location parameters correspond to the same variation, the program is automatically merged, counted and plot according to one variation.

6.9.3 Visualization for specified attribute in discrete point file

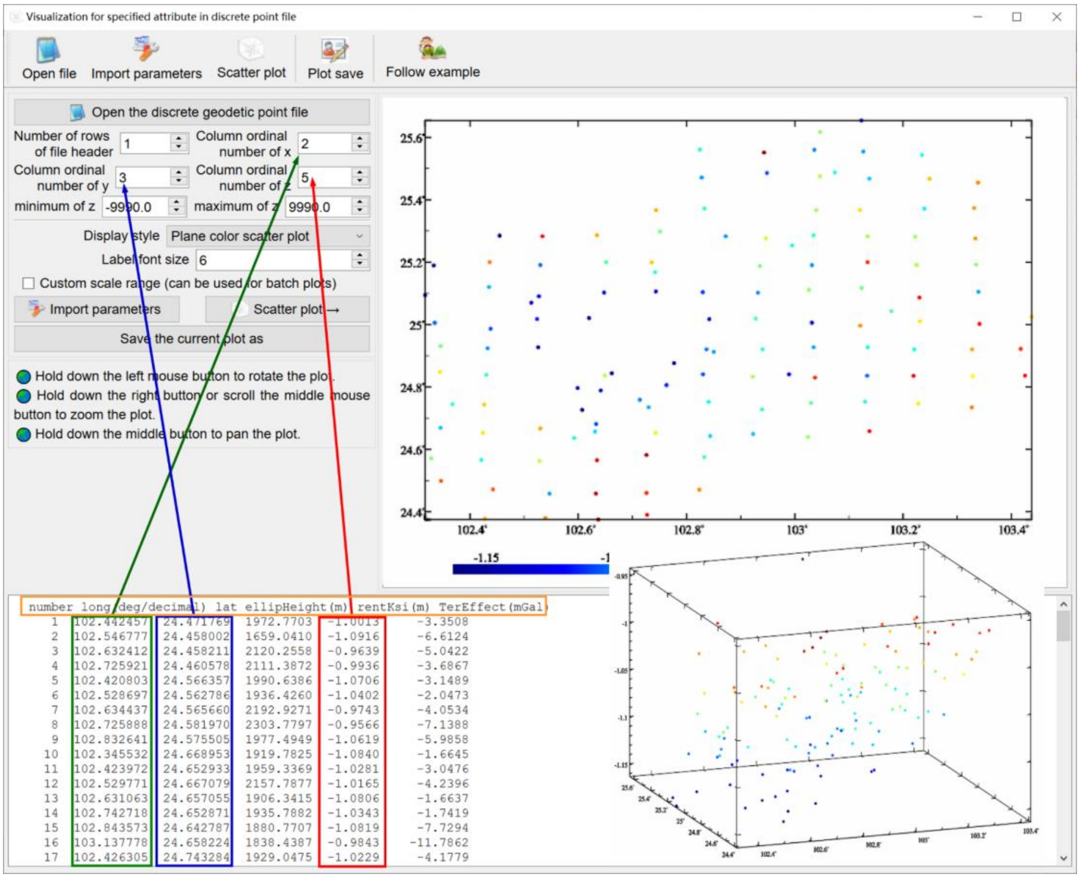
[Function] Displays the point locations and their specified attributes in a geodetic discrete point file.

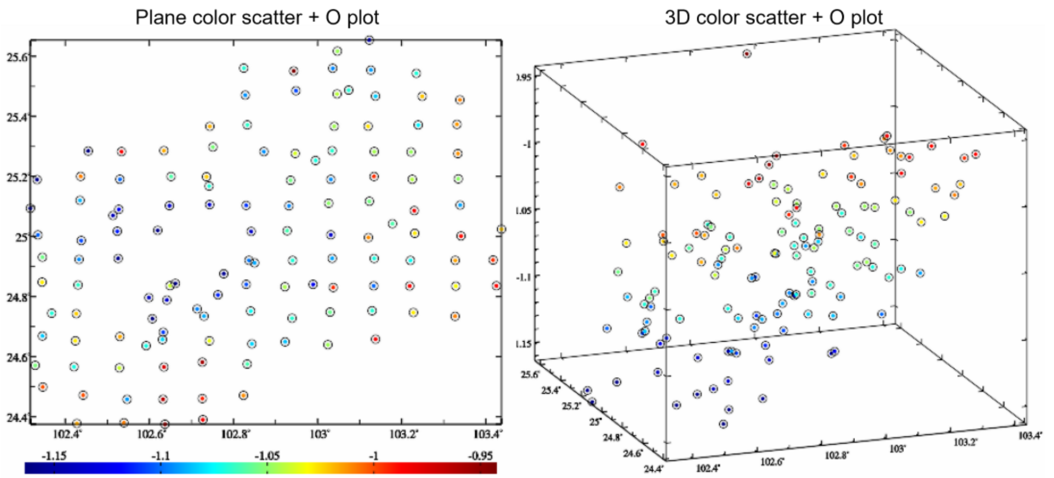
After changing the input data file, z attribute, or other parameters, you need to click the control button [Import setting parameters] again to update the graph.

If needing a larger scale plot, enlarge the graphics window on the right firstly, and then click the control button [Scatter plot].

Hold down the left mouse button to rotate the plot, hold down the right button or scroll the middle mouse button to zoom the plot, and hold down the middle button to pan the plot.

You can unify the scales by fixing the scale range for batch plots. Adjust the size of the plot window on the right and the plot requirements to an appropriate state before drawing batch plots. During plot period, the parameters and the size of the plot window are kept unchanged, and no mouse operation is performed on the plot.





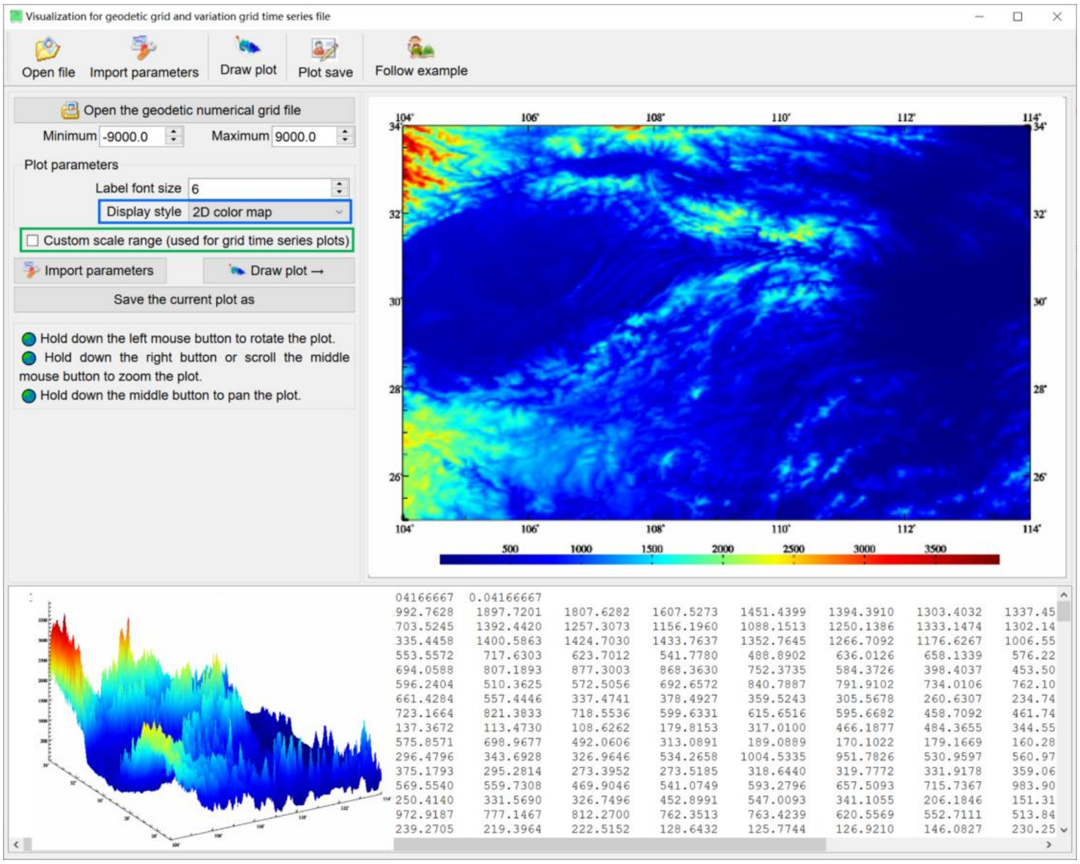
6.9.4 Visualization for geodetic grid and variation grid time series file

[Function] Plot for geodetic grid or grid time series files.

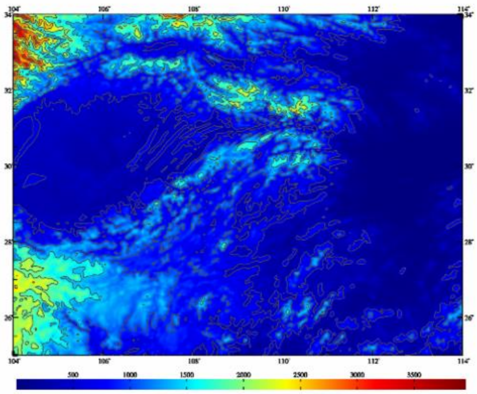
[Parameter settings] Select display style and set the checkbox [Custom scale range (used for grid time series plots)].

Allows the first component of a vector grid to be displayed as grid data.

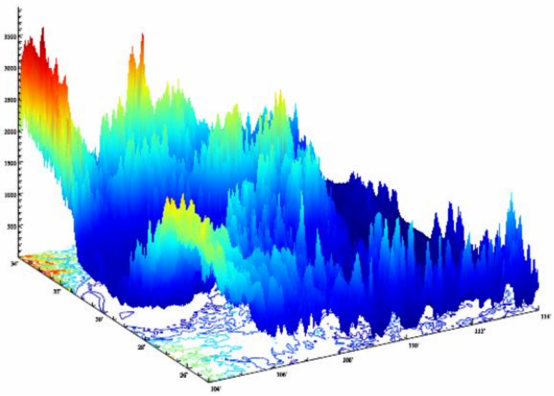
After setting the custom scale range, you can plot a series of figures for grid time series.



2D color + Contour



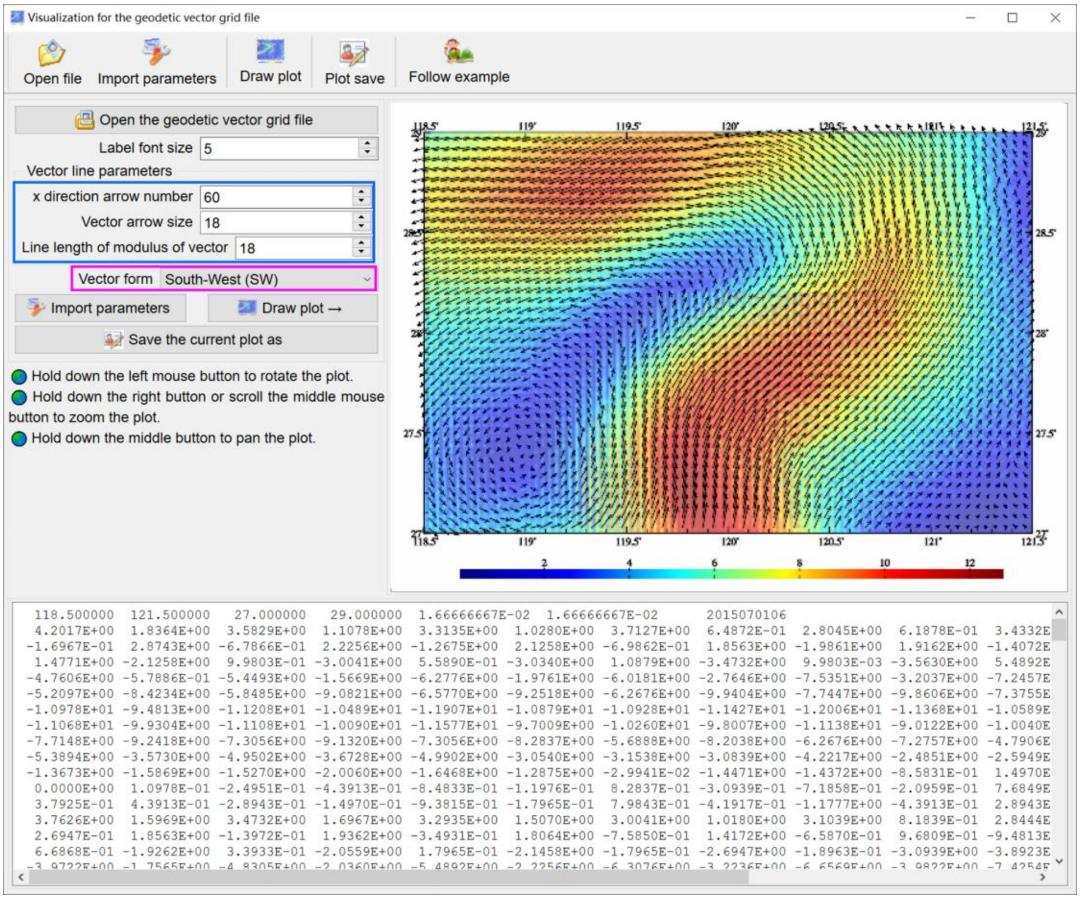
3D color + Contour



6.9.5 Visualization for the geodetic vector grid file

The X-axis and Y-axis of the plotting coordinate system respectively point east and north (EN), which is the same with horizontal displacement vector.

Vector form: East-North (EN, e.g., horizontal displacement vector), South-West (SW, e.g., vertical deflection vector), North - East (NE, e.g., Tangential gravity gradient vector).


Visualization for the geodetic vector grid file
Open file
Import parameters
Draw plot
Plot save
Follow example
Open the geodetic vector grid file
Label font size
Vector line parameters
x direction arrow number
Vector arrow size
Line length of modulus of vector
Vector form
South-West (SW)
Import parameters
Draw plot →
Save the current plot as
Hold down the left mouse button to rotate the plot.
Hold down the right button or scroll the middle mouse button to zoom the plot.
Hold down the middle button to pan the plot.
118.500000 121.500000 27.000000 29.000000 1.66666667E-02 1.66666667E-02 2015070106

7 Data file format, geophysical models and numerical standards

7.1 Geodetic Data Files in ETideLoad own Format

ETideLoad only recognizes the five kinds of geodetic stationary data and five kinds of geodetic variation time series data in ETideLoad own format. The geodetic stationary data files include the discrete geodetic record file, geodetic network observation record file, geodetic numerical grid file, geodetic vector grid file, and spherical harmonic coefficient (Stokes coefficient) model file. The variation time series files include the ground variation time series file, geodetic network site record time series file, geodetic network observation time series file, variation (vector) grid time series files, and spherical harmonic coefficient (Stokes coefficient) model time series files.

The program [Conversion of general ASCII record data into ETideLoad format], and the function [Normalized extraction of batch time series of geodetic monitoring network] are the important interfaces for ETideLoad to accept external text data. Using the function [Global prediction of solid earth tidal effects on various geodetic variations], or [Global prediction of surface atmosphere tidal load effects on various geodetic variations], you can construct a ground variation time series with the given location and sampling specifications. Using the program [Generating and constructing of regional geodetic grid], you can construct a numerical grid with the given grid specifications. The other programs or functions only accept the format data generated by ETideLoad own.

7.2 The file format of 5 kinds of stationary geodetic data

7.2.1 The discrete geodetic point record file

A discrete geodetic point record file can store multiple element attributes of massive discrete space points. The attributes of each point are represented by a row of record.

pntdata.txt

number	long(deg/decimal)	lat	ellipHeight(m)	rentKsi(m)	TerEffect(mGal)
1	102.442457	24.471769	1972.7703	-1.0013	-3.3508
2	102.546777	24.458002	1659.0410	-1.0916	-6.6124
3	102.632412	24.458211	2120.2558	-0.9639	-5.0422
4	102.725921	24.460578	2111.3872	-0.9936	-3.6867
5	102.420803	24.566357	1990.6386	-1.0706	-3.1489
6	102.528697	24.562786	1936.4260	-1.0402	-2.0473
7	102.634437	24.565660	2192.9271	-0.9743	-4.0534
8	102.725888	24.581970	2303.7797	-0.9566	-7.1388
9	102.832641	24.575505	1977.4949	-1.0619	-5.9858
10	102.345532	24.668953	1919.7825	-1.0840	-1.6645
11	102.423972	24.652933	1959.3369	-1.0281	-3.0476
12	102.529771	24.667079	2157.7877	-1.0165	-4.2396
13	102.631063	24.657055	1906.3415	-1.0806	-1.6637
14	102.742718	24.652871	1935.7882	-1.0343	-1.7419
15	102.843573	24.642787	1880.7707	-1.0819	-7.7294
16	103.137778	24.658224	1838.4387	-0.9843	-11.7862

(1) Multiple rows of the file headers are allowed, whose content and format are not restricted.

(2) One record represents the geodetic data of one site. The attributes of each record include site number (name), longitude (degree decimal), latitude (degree decimal), attribute 4, …, attribute n.

(3) The attribute convention is a numeric format, the number of the attributes (n) is not more than 80, and the attributes are separated by spaces.

(4) A record reading statement in Fortran language is:

```
read(fileno,*)(record(i),i=1,n)    ! real*8 record(n)
```

7.2.2 The geodetic network observation file

A geodetic network observation file can store the baseline component data for the CORS network, height differences for the levelling network, or gravity differences for the gravity network.

(1) The file header occupies a row and includes the number of characters of the baseline or route name, number of characters of the site name, ……

(2) The file record includes the baseline or route name, starting site (longitude, latitude, height), ending site (longitude, latitude, height), ……, observations (default value is 9999).

(3) The relations between the baselines (or routes) and the sites in the geodetic monitoring network are reflected with the composition of the characters of their name. A baseline or route name (B***A) is agreed to be composed of site names A and B at both ends, where the number of characters of all the sites names is required to be equal.

Therefore, the number of characters of the baseline or route name should not be less than twice the number of characters of the site name.

7.2.3 The geodetic numerical grid file

(1) There is a row of file header at the beginning of the file. The file header includes minimum longitude, maximum longitude, minimum latitude, maximum latitude, longitude interval of a cell grid, latitude interval of a cell grid. The units of all the attributes are decimal degrees.

(2) The grid elements are sequentially stored in an increasing manner of row latitude and column longitude until all data is stored. The elements are separated by spaces.

(3) The Fortran reading program for the entire grid data in a geodetic grid file:

```
open(unit=fileno,file=filename,status="old")
read(fileno,*)(hd(i),i=1,6)          ! hd(6) - the file header
nlon=nint((hd(2)-hd(1))/hd(5))     ! nlon - the number of grid columns along longitude direction
nlat=nint((hd(4)-hd(3))/hd(6))      ! nlat - the number of grid rows along latitude direction
do i=1,nlat
   read(fileno,*)(gr(i,j),j=1,nlon)    ! gr(nlat,nlon)- two dimension array used to store grid values
enddo
```

The grid value of grid cell represents the average value of the grid cell. In the numerical integral operation, the location of the center point of the grid cell is employed to calculate the integral distance from the grid cell to the calculation point.

dbmhgt150s.dat

```
104.000000  114.000000   25.000000   34.000000  0.04166667  0.04166667
    1880.6233     1872.6612     1910.7203     1931.7653     1992.7665     1897.7199
    1579.5158     1478.5360     1457.5736     1610.5877     1703.5435     1392.4407
    1127.0862     1141.1257     1156.1979     1181.3065     1335.4466     1400.5901
     530.3264      562.3283      484.3702      478.4546      553.5518      717.6379
     642.5849      575.7052      629.8202      654.9330      694.0609      807.1985
     726.9670      439.0212      598.0862      604.1542      596.2404      510.3528
     820.4032      667.4105      588.4110      585.4184      661.4350      557.4490
     494.4559      433.5850      353.7288      430.9312      723.1754      821.3956
     128.9223      219.0560      175.1799      152.2779      137.3618      113.4669
     456.2471      331.3871      360.5383      451.7036      575.8641      698.9905
     151.7805      150.9271      208.1027      343.2925      296.4793      343.6893
     220.4542      560.7228      752.9326      548.0788      375.1834      295.2821
     267.7073      300.9139      596.1386      576.3569      569.5556      559.7308
     466.1608      254.1723      224.2118      236.2868      250.4018      331.5582
     509.1123      504.2678      607.4595      873.6999      972.9491      777.1609
     129.8216      112.8806      145.9967      223.1369      239.2738      219.4003
    1868.6248     1859.6737     1903.7419     2051.7911     2088.7992     1910.7605
    1475.5124     1382.5200     1476.5441     1626.5437     1580.4903     1318.3843
    1155.2158     1193.2735     1209.3569     1255.4640     1365.5851     1386.7009
     603.2370      489.2430      499.3152      525.4287      630.5491      820.6481
     436.4368      493.5515      611.6602      584.7656      649.9001      678.0571
```

7.2.4 The geodetic vector grid file

A geodetic vector grid file is composed of the first components grid and the second components grid of the vector. The header file and the first component grid in the vector grid file are same as that in the geodetic grid file, and the second component grid follow the first component grid closely with the same way.

Vector grid such as vertical deviation and horizontal gradient vector grid in ETideLoad are stored in the form of vector grid file.

7.2.5 The spherical harmonic coefficient file

(1) The file header occupies a row and consists of two attributes for scaling parameters of the spherical harmonic coefficient model, namely the geocentric gravitational constant GM (×10^{14}m^2/s^2) and equatorial radius of the Earth a (m).

(2) The Earth's geopotential coefficient model and surface load spherical harmonic coefficient model in ETideLoad are stored in the form of spherical harmonic coefficient file.

(3) GM, a are the scale parameters of the model. Here, the surface harmonic functions in the spherical harmonic coefficient model are defined on the spherical surface whose radius is equal to the semi-major axis a of the Earth.

(4) The n-th degree m-th order spherical harmonic coefficient is expressed by a record with the format "degree n, order m, C_{nm}, S_{nm} (, C_{nm} error, S_{nm} error)".

ETideLoad does not require the degrees and orders of harmonic coefficients to be arranged and allows to exist insufficient orders. For the harmonic coefficient of insufficient order, ETideLoad automatically sets to zero.

7.3 The file format of 5 kinds of geodetic variation time series

The geodetic variation time series files adopt the ETideLoad own format, which includes the ground variation time series file, geodetic network site record time series file, geodetic network observation record time series file, variation (vector) grid time series files, and spherical harmonic coefficient (Stokes coefficient) model time series files.

7.3.1 The ground variation time series file

A ground variation time series file can store the time series data of several kinds of variations of a certain site, a certain baseline or route, and the sampling epochs (here, the epoch is an instantaneous time) of these variations are the same. Such as CORS station coordinate solution time series, solid tide station observation or analysis result time series, GNSS baseline solution time series, etc.

(1) The file header occupies a row and includes the site name, longitude (degree decimal), latitude (degree decimal), height (m) relative to the ellipsoidal surface (sea level, or the ground), the starting MJD (optional), ……

(2) Starting from the second row of the file, each row of records stores the sampling values of all the variations at one sampling epoch time. At least one column of attribute in the record is the sampling epoch time.

(3) Each attribute in the record (except the sampling epoch time) represents a type of variation time series, and the sampling epoch time of different types of variations is the same.

(4) The sum of the starting MJD0 in the header and the sampling epoch time (day) is equal to the sampling epoch time of MJD day in the record. When the sampling epoch time is the long integer agreed by ETideLoad, the starting MJD0 is not necessary in the file header.

tmsqurst.txt

NYB 101.230000	29.910000	47.218	58484.000000					
2019010100	0.000000	2.764	5.0173	1.5712	0.3849	10.3234	-5.2424	19.3396
2019010101	0.041667	2.778	57.5174	23.2452	10.8146	12.7102	-3.1452	23.8048
2019010102	0.083333	2.762	75.5361	30.5675	14.2375	13.9736	0.1439	26.1911
2019010103	0.125000	2.724	49.9989	19.8264	8.9137	13.8655	3.6134	26.0285
2019010104	0.166667	2.675	-14.8626	-7.1040	-4.1257	12.4479	6.1922	23.4162
2019010105	0.208333	2.626	-102.4140	-43.2138	-21.3751	10.0693	7.0460	18.9862
2019010106	0.250000	2.582	-187.9254	-78.2261	-37.8487	7.2674	5.8002	13.7343
2019010107	0.291667	2.546	-245.0339	-101.3204	-48.4404	4.6323	2.6332	8.7685
2019010108	0.333333	2.517	-252.6506	-103.9667	-49.2598	2.6643	-1.7744	5.0436
2019010109	0.375000	2.489	-200.5663	-82.1562	-38.6091	1.6655	-6.4133	3.1473
2019010110	0.416667	2.455	-92.4143	-37.5190	-17.4012	1.6833	-10.1887	3.1848
2019010111	0.458333	2.410	54.6679	22.8880	11.0186	2.5175	-12.1759	4.7817
2019010112	0.500000	2.354	213.5656	88.0350	41.5647	3.7816	-11.8314	7.1990
2019010113	0.541667	2.288	353.0904	145.2782	68.4536	5.0033	-9.1200	9.5289
2019010114	0.583333	2.223	444.9509	183.1245	86.4011	5.7439	-4.5343	10.9299
2019010115	0.625000	2.169	470.2372	193.8160	91.7570	5.7101	1.0003	10.8461
2019010116	0.666667	2.139	423.9270	175.1684	83.3590	4.8356	6.3198	9.1633
2019010117	0.708333	2.140	316.2909	131.2080	62.8992	3.3117	10.2823	6.2600
2019010118	0.750000	2.176	170.7224	71.3813	34.6611	1.5535	12.0396	2.9335
2019010119	0.791667	2.245	18.3457	8.4289	4.6113	0.1037	11.2554	0.2101
2019010120	0.833333	2.337	-109.4070	-44.6375	-20.9983	-0.5077	8.2071	-0.9215
2019010121	0.875000	2.439	-188.4457	-77.7247	-37.1906	0.0868	3.7328	0.2122
2019010122	0.916667	2.535	-207.9073	-86.1738	-41.5571	1.9732	-0.9763	3.7572
2019010123	0.958333	2.611	-172.6479	-71.8776	-34.8890	4.9074	-4.6886	9.2487
2019010124	1.000000	2.657	-101.5732	-42.6368	-20.9177	8.3545	-6.4671	15.6899
2019010201	1.041667	2.671	-22.1804	-9.8860	-5.2050	11.6122	-5.9287	21.7785
2019010202	1.083333	2.655	37.2344	14.5931	6.5038	13.9841	-3.3501	26.2240
2019010203	1.125000	2.617	55.5611	22.0431	9.9729	14.9570	0.4130	28.0700
2019010204	1.166667	2.568	24.8430	9.2293	3.7078	14.3301	4.1694	26.9320

7.3.2 The geodetic site variation record time series file

A geodetic site variation record time series file can store the time series data of one kind of variations for a group of geodetic sites. Such as the station coordinate time series for the CORS network, benchmark height time series for the levelling network, observation time series for the tide station network, and InSAR monitoring time series, etc.

(1) The file header occupies a row and includes all the sampling epochs arranged with time.

(2) The file record: the site name, longitude, latitude, height, ……, all the sampling

variations arranged with sampling time.

(3) ETideLoad stipulates that the number of sampling epochs in the file header is equal to the number of sampling variations in the record, and the sampling epochs are one-by-one correspondence with the sampling variations.

(4) When receiving the input record time series file from the program interface, it is generally required to specify the column ordinal number of the first sampling epoch in the file header and the column ordinal number of the first sampling variation in the record.

TsqavrRowU.txt TsqavrbslnU.txt

4	0	36			2015011612	2015021500	2015031612	2015041600	2015051612	2015061600
JINH	119.6426	29.2178	1191.60	1.0	-4.9145	9.3944	3.7319	0.4720	1.1566	2.7777
JINX	119.3792	29.0709	84.79	1.0	-4.3724	1.6001	6.6220	0.8372	2.9622	1.8461
JNJZ	119.6375	27.9764	286.78	1.0	-4.1680	3.2284	3.1467	-0.4777	2.3145	1.8212
JSAN	118.6086	28.7279	71.54	1.0	4.8394	10.8248	7.4036	2.4828	0.3532	-2.2769
LISH	119.9295	28.4613	71.54	1.0	4.8394	10.8248	7.4036	2.4828	0.3532	-2.2769
LONQ	119.1331	28.0807	233.28	1.0	-4.9987	3.4121	3.3682	-2.0458	-2.0137	-1.6199
QIYU	119.0793	27.6213	412.75	1.0	-2.9713	5.7773	7.2012	1.1874	-3.3157	-3.4728
QNYN	118.9638	27.6157	429.39	1.0	0.7446	7.2540	6.9323	0.2500	-1.3013	-1.8433
QUZH	118.8908	28.9937	90.79	1.0	-1.0815	5.9656	5.1221	-1.1572	0.5323	-1.6064
QZLY	119.1858	29.0336	73.91	1.0	-1.3703	6.4829	8.4987	1.9209	1.5578	0.7378
SHNQ	119.5028	27.4576	827.01	1.0	-6.5350	3.4134	3.8402	1.0473	3.2554	-2.4524
SNYN	119.5093	28.4546	182.77	1.0	-5.6627	3.1365	4.4180	0.4287	2.1431	2.2420
YAYA	120.0425	27.3930	555.71	1.0	-2.1462	5.1836	4.0938	3.6248	4.5640	1.2865
YONK	120.0168	28.9055	116.22	1.0	-1.6121	4.7569	7.1178	2.7207	0.1517	0.6173
ZJYH	119.6900	28.2660	130.05	1.0	-3.2802	4.5552	3.8968	-0.2975	0.4079	-0.3378

TsqavrRowU.txt TsqavrbslnU.txt InSARspdfmrst.txt

5	37			20141103	20141127	20141221	20150114	20150207	20150408	20150502	20150526
-9.310	117.3445416	39.0251902	-2.793	-0.3091	0.0866	0.0482	0.2194	0.2865	0.5720	0.3395	0.4760
-12.790	117.3457082	39.0251902	-2.304	-0.1796	0.2752	0.1906	0.2887	0.3340	0.5632	0.2861	0.2759
-7.482	117.3480415	39.0251902	-3.660	-0.3846	9999.0000	-0.0523	0.0135	0.1783	-0.0167	-0.5455	-0.1440
-6.699	117.3487081	39.0251902	-2.582	-0.2325	0.2301	0.0701	0.2610	0.4179	0.7154	0.4377	0.7507
-7.643	117.3488748	39.0251902	-2.882	-0.1876	0.3087	0.1757	0.3743	0.5347	0.9182	0.6967	0.9859
-9.001	117.3492081	39.0251902	-3.430	-0.2356	0.2486	0.2282	0.4480	0.5863	1.0390	0.8643	1.1080
-10.736	117.3495414	39.0251902	-4.123	-0.2211	0.1605	0.0977	0.4040	0.4816	1.0206	0.9163	1.0519
-10.264	117.3497081	39.0251902	-3.963	-0.2530	0.0627	0.0174	0.2817	0.3735	0.9470	0.9182	0.9979
-9.893	117.3498747	39.0251902	-3.843	-0.2733	0.0120	-0.0196	0.2078	0.3072	0.8895	0.8983	0.9588
-14.921	117.3503747	39.0251902	-3.558	-0.2906	0.0654	0.0359	0.2029	0.2907	0.8569	0.8558	0.8677
-13.835	117.3507080	39.0251902	-3.246	-0.1282	0.2632	0.1912	0.3657	0.4738	1.0386	1.0551	1.0863
-13.217	117.3508747	39.0251902	-3.191	-0.0641	0.3303	0.2465	0.4314	0.5473	1.1231	1.1658	1.2188
-12.657	117.3510413	39.0251902	-3.067	0.0039	0.3831	0.2929	0.4991	0.6149	1.2231	1.3072	1.3714
-12.424	117.3512080	39.0251902	-2.943	0.0099	0.3579	0.2776	0.4952	0.6110	1.2489	1.3458	1.3795
-12.475	117.3513747	39.0251902	-2.964	0.0053	0.3079	0.2478	0.4779	0.5912	1.2806	1.3846	1.3793
-12.682	117.3515413	39.0251902	-3.121	-0.0670	0.2179	0.1862	0.4278	0.5167	1.2285	1.3064	1.2891
-12.511	117.3517080	39.0251902	-3.357	-0.1241	0.1493	0.1503	0.3968	0.4565	1.1697	1.2314	1.2168
-11.102	117.3520413	39.0251902	-4.331	-0.1866	0.0288	0.1581	0.3671	0.4031	1.0231	1.0748	1.0342
-10.425	117.3522080	39.0251902	-4.557	-0.1592	0.0754	0.2553	0.4129	0.4636	1.0229	1.0912	1.0074
-7.999	117.3525413	39.0251902	-4.173	-0.0956	0.1919	0.4448	0.5395	0.5774	1.1620	1.2013	1.0798
-3.661	117.3528746	39.0251902	-3.783	-0.0689	9999.0000	0.4497	0.5472	0.5783	1.3511	1.2092	1.1608
-13.428	117.3543745	39.0251902	-3.938	0.1071	0.4859	0.6632	0.7978	0.9730	1.2854	1.6207	1.6274
-18.243	117.3545412	39.0251902	-3.980	0.1224	0.5127	0.6954	0.7888	0.9869	1.2956	1.6312	1.6339
-22.513	117.3547079	39.0251902	-3.825	0.1425	0.5367	0.7026	0.7356	0.9890	1.3448	1.6335	1.6239

7.3.3 The geodetic network observation record time series file

A geodetic network observation record time series file can store the variation record time series of the baseline component for the CORS network, the variation record time series of the height difference for the levelling network, or the variation record time series of the gravity difference for the gravity network.

(1) The file header occupies a row and includes the number of characters of the baseline or route name, number of characters of the site name, sampling length, ……, all the sampling epochs arranged with time.

(2) The file record includes the baseline or route name, starting site (longitude, latitude, height), ending site (longitude, latitude, height), ……, all the observed variations arranged with sampling time (default value is 9999).

(3) The relations between the baselines (or routes) and the sites in the geodetic monitoring network are reflected with the composition of the characters of their name. A baseline or route name (B***A) is agreed to be composed of site names A and B at both

ends, where the number of characters of all the sites names (such as A and B) is required to be equal.

Therefore, the number of characters of the baseline or route name should not be less than twice the number of characters of the site name.

TsqavrRowU.txt TsqavrbslnU.txt

9	0	36					2015011612	2015021500	2015031612	2015041600	2015051612	2015061600
CANN_DONT	120.4247	27.5226	0.00	121.1503	27.8346	0.00	6.4092	3.5311	-0.6494	3.4802	1.9057	-0.3761
CANN_FDIQ	120.4247	27.5226	0.00	120.2073	27.3353	0.00	7.5566	9999.0000	9.8866	4.9806	-3.7116	0.3579
CANN_JHYW	120.4247	27.5226	0.00	120.0784	29.2727	0.00	3.3886	1.7941	-0.5867	-0.4076	0.7054	-0.2796
CANN_JINH	120.4247	27.5226	0.00	119.6426	29.2178	0.00	2.8530	-0.7712	-1.3292	1.3058	-1.2947	-2.4476
CANN_JINX	120.4247	27.5226	0.00	119.3792	29.0709	0.00	4.3333	1.6376	2.9746	3.5908	1.9899	-1.6367
CANN_JNJZ	120.4247	27.5226	0.00	119.6375	27.9764	0.00	4.9006	3.1138	1.0930	0.3909	0.8296	-1.6116
CANN_JSAN	120.4247	27.5226	0.00	118.6086	28.7279	0.00	2.5860	0.7616	-0.7290	-0.5568	-4.1410	-5.3632
CANN_LHAI	120.4247	27.5226	0.00	121.1895	28.9059	0.00	1.0756	-1.6069	-1.8127	-0.4355	-0.0362	-0.7623
CANN_LISH	120.4247	27.5226	0.00	119.9295	28.4613	0.00	13.8711	10.5885	3.5993	4.5791	-0.7531	-6.0081
CANN_LONQ	120.4247	27.5226	0.00	119.1331	28.0807	0.00	7.3816	6.1923	2.8486	1.8460	-1.9823	-3.9091
CANN_LUOY	120.4247	27.5226	0.00	119.7051	27.5525	0.00	8.8132	9.4984	3.5027	4.0624	0.1673	-1.3212
CANN_PANA	120.4247	27.5226	0.00	120.4367	29.0542	0.00	0.2485	-2.0512	-4.4740	-2.9385	-0.0623	-0.7816
CANN_PCHQ	120.4247	27.5226	0.00	118.5422	27.9232	0.00	5.5253	5.7473	3.2665	1.6373	-1.4516	-6.3300
CANN_PCJM	120.4247	27.5226	0.00	118.4454	28.1680	0.00	14.2248	12.7588	7.9740	8.5291	3.1970	1.6813
CANN_QINT	120.4247	27.5226	0.00	120.2900	28.1394	0.00	7.1517	4.5782	2.4621	4.4460	-0.4966	-3.3975
CANN_QIYU	120.4247	27.5226	0.00	119.0793	27.6213	0.00	7.1481	6.6956	4.4206	1.9230	-5.9045	-7.7402
CANN_QNYN	120.4247	27.5226	0.00	118.9638	27.6157	0.00	10.9311	7.9043	4.5820	1.4154	-3.5702	-5.8564
CANN_QUZH	120.4247	27.5226	0.00	118.8908	28.9937	0.00	8.1029	5.9283	1.7235	1.2962	-0.8214	-5.2339
CANN_QZLY	120.4247	27.5226	0.00	119.1858	29.0336	0.00	7.1312	6.3296	4.8051	4.9249	0.4817	-2.6667
CANN_RUIA	120.4247	27.5226	0.00	120.6490	27.7833	0.00	8.9624	7.8483	0.2735	0.8812	-0.2184	-3.3412
CANN_SHNQ	120.4247	27.5226	0.00	119.5028	27.4576	0.00	4.8563	4.6628	0.3999	3.4718	0.5071	-6.6786
CANN_SNYN	120.4247	27.5226	0.00	119.5093	28.4546	0.00	3.3183	3.1267	1.3992	1.8621	1.0732	-1.1970
CANN_SUIC	120.4247	27.5226	0.00	119.2693	28.5951	0.00	14.7246	7.6386	10.1070	4.5706	6.3427	0.2411
CANN_TAIZ	120.4247	27.5226	0.00	121.4164	28.6183	0.00	4.0291	3.2741	0.3639	1.5962	-0.2033	-1.0270

7.3.4 The variation grid time series files for geodetic field

A group of variation grid time series files are composed of a series of numerical grid model files of a certain kind of variation (vector), and the seventh attribute of the header in each grid file is agreed to be the sampling epoch time. Such as the grid time series of land water equivalent height, sea level variation, and grid time series of various regional load deformation field or temporal gravity field, etc.

zwdx20150331.dat zwdx20150531.dat zwdx20150831.dat

118.500000	121.500000	27.000000	29.000000	1.66666667E-02	1.66666667E-02	2015033118			
-0.3746	-0.5686	-0.6666	-0.9356	-1.0686	-1.0836	-1.0606	-1.0586	-1.0586	-1.0566
-0.5445	-0.4746	-0.4986	-0.6746	-0.8176	-0.8646	-0.9356	-0.9356	-0.9575	-0.9565
-0.9326	-0.9128	-0.9132	-0.8647	-0.7606	-0.7255	-0.6170	-0.5403	-0.4534	-0.4873
-0.5622	-0.5214	-0.4842	-0.4644	-0.4832	-0.4767	-0.5045	-0.4994	-0.4972	-0.4458
-0.1776	-0.0795	0.0535	0.0904	0.1088	0.0885	-0.0087	-0.1460	-0.2341	-0.2686
-0.0685	0.1893	0.3498	0.4787	0.5169	0.4660	0.2675	0.1964	0.1144	0.0974
0.1248	-0.0175	-0.1520	-0.2620	-0.3917	-0.4810	-0.5751	-0.6501	-0.7137	-0.7640
-0.2918	-0.1304	0.0015	0.1363	0.2607	0.3785	0.4382	0.4686	0.4562	0.3953
-0.4998	-0.6231	-0.7580	-0.8453	-0.9315	-0.9857	-1.0331	-1.0529	-1.0680	-1.0697
-1.0796	-1.0936	-1.0966	-1.0966	-1.0996	-1.1006	-1.1006	-1.0996	-1.0997	-1.0978
-1.0184	-0.9872	-0.9330	-0.8807	-0.8047	-0.7382	-0.6460	-0.5719	-0.4788	-0.3955
-0.2513	-0.3094	-0.3723	-0.4617	-0.5417	-0.6397	-0.7159	-0.7967	-0.8500	-0.8985
-0.4647	-0.6176	-0.7077	-0.9746	-1.0456	-1.0596	-1.0546	-1.0526	-1.0576	-1.0416
-0.4536	-0.3635	-0.4356	-0.6346	-0.7596	-0.8306	-0.9016	-0.9016	-0.9385	-0.9385
-0.9086	-0.9138	-0.9142	-0.8636	-0.7696	-0.7325	-0.6810	-0.6283	-0.5264	-0.5533
-0.5762	-0.5344	-0.5152	-0.4914	-0.5093	-0.5217	-0.5505	-0.5446	-0.5243	-0.4589
-0.1982	-0.1410	-0.0271	0.0068	0.0242	0.0178	-0.0763	-0.1896	-0.2368	-0.2702
-0.0970	0.1349	0.3035	0.4214	0.4327	0.4208	0.2203	0.1393	0.0803	0.0864
0.0868	-0.0434	-0.1649	-0.2578	-0.4047	-0.5100	-0.5791	-0.6770	-0.7527	-0.7781

7.3.5 The spherical harmonic coefficient model time series files

A group of spherical harmonic coefficient model time series files can store the time series of the spherical harmonic coefficient (Stokes' coefficient) models of global surface load variation, global load deformation field, or temporal global gravity field.

(1) The header file occupies one row and consists of three attributes, namely the geocentric gravitational constant GM ($\times10^{14}m^2/s^2$), equatorial radius of the Earth a (m), and sampling epoch (in ETideLoad format).

(2) GM, a are the scale parameters of the model. Here, the surface harmonic functions in the spherical harmonic coefficient model are defined on the spherical surface whose radius is equal to the semi-major axis a of the Earth.

(3) The n-th degree m-th order spherical harmonic coefficient is expressed by a record with the format: degree n, order m, C_{nm}, S_{nm} (, C_{nm} error, S_{nm} error). At different sampling epochs, n of the model files can be not the same.

(4) ETideLoad does not require the degrees and orders of harmonic coefficients to be arranged and allows to exist insufficient orders. For the harmonic coefficient of insufficient order, ETideLoad automatically sets to zero.

7.4 Geophysical models and numerical standards in ETideLoad4.5

ETideLoad4.5 is mainly based on the geophysical models and numerical standards recommended by IERS Conventions (2010). You can update them from the program [geophysical models and numerical standards settings]. These geophysical models and numerical standards are stored in file form.

7.4.1 The surface atmosphere tidal load spherical harmonic coefficient model file

The 360-degree surface atmosphere tidal load spherical harmonic coefficient model file ECMWF2006.dat is stored in the folder C:\ETideLoad4.5_win64en\iers in FES2004 format, which were constructed by the spherical harmonic analysis programs of ETideLoad4.5 using 0.5°× 0.5° global harmonic parameter grids of four atmospheric tidal constituents, to meet the basic needs of centimeter-level geodesy. The four tidal constituents are respectively the diurnal, semi-diurnal, semi-annual and annual periodic tidal constituents (S_1, S_2, Ss_a, Sa) whose harmonic parameter grids come from ECMWF-DCDA2006 of European Centre for Medium-Range Weather Forecasts.

ECMWF2006.dat

```
Atmospheric tide model: ECMWF-DCDA2006 normalized model up to (360,360) in hPa
半日/周日/半年/年周期
Doodson   Darw   n    m      Csin+        Ccos+        Csin-        Ccos-        C+          eps+        C-          eps-
 164.556   S1    1    0   -0.01055351   0.00555959  -0.01055351   0.00555959  0.01192835  297.7803  0.01192835  297.7803
 164.556   S1    2    0   -0.00898730   0.02713172  -0.00898730   0.02713172  0.02858149  341.6727  0.02858149  341.6727
 164.556   S1    3    0    0.02416514   0.01232573   0.02416514   0.01232573  0.02712707   62.9756  0.02712707   62.9756
 164.556   S1    4    0    0.01971779  -0.01808456   0.01971779  -0.01808456  0.02675523  132.5261  0.02675523  132.5261
 164.556   S1    5    0    0.00538826  -0.01556217   0.00538826  -0.01556217  0.01646859  160.9021  0.01646859  160.9021
 164.556   S1    6    0   -0.01896560  -0.00055330  -0.01896560  -0.00055330  0.01897366  268.3289  0.01897366  268.3289
 164.556   S1    7    0    0.00163224   0.00711629   0.00163224   0.00711629  0.00730108   12.9183  0.00730108   12.9183
 164.556   S1    8    0    0.00341644   0.00607435   0.00341644   0.00607435  0.00696920   29.3550  0.00696920   29.3550
 164.556   S1    9    0   -0.00469730  -0.00311697  -0.00469730  -0.00311697  0.00563739  236.4331  0.00563739  236.4331
 164.556   S1   10    0    0.00442735  -0.01563001   0.00442735  -0.01563001  0.01624496  164.1847  0.01624496  164.1847
 164.556   S1   11    0    0.00941838  -0.00082619   0.00941838  -0.00082619  0.00945455   95.0132  0.00945455   95.0132
 164.556   S1   12    0   -0.00454013   0.00688423  -0.00454013   0.00688423  0.00824654  326.5953  0.00824654  326.5953
 164.556   S1   13    0   -0.01227672   0.00310149  -0.01227672   0.00310149  0.01266243  284.1781  0.01266243  284.1781
 164.556   S1   14    0    0.00203678   0.00166923   0.00203678   0.00166923  0.00263340   50.6638  0.00263340   50.6638
 164.556   S1   15    0    0.00253994   0.00381849   0.00253994   0.00381849  0.00458608   33.6306  0.00458608   33.6306
 164.556   S1   16    0    0.00613602  -0.00041704   0.00613602  -0.00041704  0.00615017   93.8882  0.00615017   93.8882
 164.556   S1   17    0   -0.00113104  -0.00413462  -0.00113104  -0.00413462  0.00428652  195.2992  0.00428652  195.2992
 164.556   S1   18    0   -0.00311700   0.00136741  -0.00311700   0.00136741  0.00340375  293.6868  0.00340375  293.6868
 164.556   S1   19    0   -0.00217138   0.00053937  -0.00217138   0.00053937  0.00223737  283.9498  0.00223737  283.9498
 164.556   S1   20    0   -0.00017645   0.00369644  -0.00017645   0.00369644  0.00370065  357.2671  0.00370065  357.2671
 164.556   S1   21    0    0.00068441  -0.00165216   0.00068441  -0.00165216  0.00178831  157.4980  0.00178831  157.4980
 164.556   S1   22    0    0.00100221  -0.00214635   0.00100221  -0.00214635  0.00236881  154.9703  0.00236881  154.9703
 164.556   S1   23    0    0.00461395  -0.00179653   0.00461395  -0.00179653  0.00495136  111.2744  0.00495136  111.2744
 164.556   S1   24    0   -0.00143873   0.00014453  -0.00143873   0.00014453  0.00144597  275.7366  0.00144597  275.7366
 164.556   S1   25    0   -0.00083151  -0.00001238  -0.00083151  -0.00001238  0.00083160  269.1470  0.00083160  269.1470
 164.556   S1   26    0   -0.00272792  -0.00095240  -0.00272792  -0.00095240  0.00288940  250.7543  0.00288940  250.7543
 164.556   S1   27    0   -0.00183890   0.00217563  -0.00183890   0.00217563  0.00284868  319.7946  0.00284868  319.7946
```

In ECMWF-DCDA2006 model, the diurnal and semidiurnal constituents (S_1, S_2) of atmospheric pressure can constitute RP03 model.

The surface atmosphere tides, their tidal constituent harmonic parameters and tidal load spherical harmonic coefficients are all in hPa or mbar as unit.

7.4.2 The ocean tidal load spherical harmonic coefficient model file

The 100-degree ocean tidal load spherical harmonic coefficient model file FES2004S1.dat is stored in the folder C:\ETideLoad4.5_win64en\iers in FES2004 format. The relationship between the ocean tidal load normalized spherical harmonic coefficients and the geopotential coefficients is as the formula (6.15) in the IERS Conventions (2010).

ECMWF2006.dat FES2004S1.dat

```
Ocean tide model: FES2004 normalized model (fev. 2004) up to (100,100) in cm
(long period from FES2002 up to (50,50) + equilibrium Om1/Om2, atmospheric tide NOT included)
Doodson Darw   n   m    Csin+     Ccos+      Csin-     Ccos-      C+    eps+    C-     eps-
  55.565 Om1   2   0 -0.540594  0.000000   0.000000  0.000000  0.5406 270.000 0.0000  0.000
  55.575 Om2   2   0 -0.005218  0.000000   0.000000  0.000000  0.0052 270.000 0.0000  0.000
  56.554 Sa    1   0  0.017233  0.000013   0.000000  0.000000  0.0172  89.957 0.0000  0.000
  56.554 Sa    2   0 -0.046604 -0.000903   0.000000  0.000000  0.0466 268.890 0.0000  0.000
  56.554 Sa    3   0 -0.000889  0.000049   0.000000  0.000000  0.0009 273.155 0.0000  0.000
  56.554 Sa    4   0  0.012069 -0.000413   0.000000  0.000000  0.0121  91.960 0.0000  0.000
  56.554 Sa    5   0 -0.009780 -0.000421   0.000000  0.000000  0.0098 267.535 0.0000  0.000
  56.554 Sa    6   0  0.006895  0.000043   0.000000  0.000000  0.0069  89.643 0.0000  0.000
  56.554 Sa    7   0 -0.010515 -0.000287   0.000000  0.000000  0.0105 268.437 0.0000  0.000
  56.554 Sa    8   0  0.002067 -0.000011   0.000000  0.000000  0.0021  90.305 0.0000  0.000
  56.554 Sa    9   0 -0.004236 -0.000110   0.000000  0.000000  0.0042 268.512 0.0000  0.000
  56.554 Sa   10   0 -0.001781 -0.000085   0.000000  0.000000  0.0018 267.268 0.0000  0.000
  56.554 Sa   11   0 -0.001372 -0.000068   0.000000  0.000000  0.0014 267.163 0.0000  0.000
  56.554 Sa   12   0 -0.004081 -0.000048   0.000000  0.000000  0.0041 269.326 0.0000  0.000
  56.554 Sa   13   0 -0.000116 -0.000041   0.000000  0.000000  0.0001 250.534 0.0000  0.000
  56.554 Sa   14   0 -0.003043 -0.000007   0.000000  0.000000  0.0030 269.868 0.0000  0.000
  56.554 Sa   15   0  0.001109 -0.000028   0.000000  0.000000  0.0011  91.446 0.0000  0.000
  56.554 Sa   16   0 -0.002596 -0.000034   0.000000  0.000000  0.0026 269.250 0.0000  0.000
  56.554 Sa   17   0 -0.000674  0.000022   0.000000  0.000000  0.0007 271.870 0.0000  0.000
  56.554 Sa   18   0  0.000546  0.000006   0.000000  0.000000  0.0005  89.370 0.0000  0.000
  56.554 Sa   19   0 -0.000024  0.000023   0.000000  0.000000  0.0000 313.781 0.0000  0.000
  56.554 Sa   20   0  0.000867  0.000014   0.000000  0.000000  0.0009  89.075 0.0000  0.000
```

In order to meet the basic needs of satellite, coastal zone and ocean gravity gradient data processing, we adopted AVISO+'s FES2014b global tidal height harmonic parameters grid models to construct the 360-degree ocean tidal height spherical harmonic coefficient model file FES2014cs.dat in FES2004 format by the spherical harmonic analysis programs of ETideLoad4.5.

FES2014cs.dat includes spherical harmonic coefficients of the 36 tidal constituents (Ω1, Ω2; 2N2, Eps2, J1, K1, K2, L2, La2, M2, M3, M4, M6, M8, Mf, MKS2, Mm, MN4, MS4, MSf, MSqm, Mtm, Mu2, N2, N4, Nu2, O1, P1, Q1, R2, S1, S2, S4, Sa, Ssa, T2), in which the spherical harmonic coefficients of the two balance tidal constituents (Ω1, Ω2) come from FES2004S1.dat.

The ocean tidal height, harmonic parameters of the tidal constituent and tidal load spherical harmonic coefficients are all in cm as unit.

7.4.3 The Earth's Load Love number file

The Earth's load Love numbers also called the load deformation coefficients (LDC) can be calculated using the spherically symmetric non-rotating elastic earth model REF6371. The Load Love numbers in ETideLoad4.5 come from a Regional ElAstic Rebound calculator (REAR1.0, 2015.11), using the file Love_load_cm.dat stored in the folder C:\ETideLoad4.5_win64en\iers. The file includes the load Love numbers of the radial displacement, horizontal displacement and geopotential $(h'_n, l'_n, k'_n), n = 1, \cdots, 32768$ from 1 to 32768 degree, as shown in the figure.

In order to suppress the high-degree oscillations of the load Green's function, the load

Green's function is calculated to 54000 degrees in ETideLoad, and the load Love numbers exceeding 32768 degrees (n>32768) are calculated with the following asymptotic formula

h_n' =-6.209114， l_n' =1.890061/n， k_n' =-2.682697/n.

```
The load Love numbers from the REAR package are attached. There are no
more of these oscillations at high degree, and they go up to degree 32768.
November 20, 2015, Jean-Paul
CM: center of mass reference frame
     n      h' (vert)           l' (horiz)           k' (potent)
     0    0.0000000000D+00   0.0000000000D+00   -1.0000000000D+00
     1   -0.0287112988D+01   0.1045044062D+00   -1.0000000000D+00
     2   -0.9945870591D+00   0.2411251588D-01   -0.3057703360D+00
     3   -0.1054653021D+01   0.7085493677D-01   -0.1962722363D+00
     4   -0.1057783895D+01   0.5958723183D-01   -0.1337905897D+00
     5   -0.1091185915D+01   0.4702627503D-01   -0.1047617976D+00
     6   -0.1149253656D+01   0.3940811757D-01   -0.9034958051D-01
     7   -0.1218363201D+01   0.3499400649D-01   -0.8205733906D-01
     8   -0.1290473661D+01   0.3225123202D-01   -0.7652348967D-01
     9   -0.1361847865D+01   0.3038562458D-01   -0.7239287690D-01
    10   -0.1430981761D+01   0.2902258995D-01   -0.6907768441D-01
    11   -0.1497377458D+01   0.2798156018D-01   -0.6629382122D-01
    12   -0.1560934855D+01   0.2716367080D-01   -0.6388475059D-01
    13   -0.1621715593D+01   0.2650554043D-01   -0.6175536119D-01
    14   -0.1679770379D+01   0.2596800569D-01   -0.5983856019D-01
    15   -0.1735198310D+01   0.2551661917D-01   -0.5808965155D-01
    16   -0.1788088250D+01   0.2512667367D-01   -0.5647488828D-01
    17   -0.1838448069D+01   0.2478452380D-01   -0.5496610314D-01
    18   -0.1886440474D+01   0.2447083426D-01   -0.5354901315D-01
    19   -0.1932084480D+01   0.2417919471D-01   -0.5220607051D-01
    20   -0.1975465902D+01   0.2389862142D-01   -0.5092726303D-01
    21   -0.2016677975D+01   0.2362510597D-01   -0.4970406011D-01
    22   -0.2055800328D+01   0.2335504487D-01   -0.4853059813D-01
```

7.4.4 The IERS Earth orientation parameter time series file

The IERS Earth orientation parameters (EOP) time series file IERSeopc04.dat (ITRF2008) were stored in the folder C:\ETideLoad4.5_win64en\iers. You can update the EOP time series from the IERS website. For future epochs, the forecast EOP products can be employed. Considering the non-tidal nature of the polar motion, the forecast time should be controlled within half a year.

```


                    INTERNATIONAL EARTH ROTATION AND REFERENCE SYSTEMS SERVICE
                         EARTH ORIENTATION PARAMETERS
                           EOP (IERS) 14 C04


              FORMAT(3(I4),I7,2(F11.6),2(F12.7),2(F11.6),2(F11.6),2(F11.7),2(F12.6))
##################################################################################

      Date      MJD        x          y        UT1-UTC       LOD         dX        dY        x Err      y Err    UT1-UTC Err  LOD Err      dX Err      dY Err
                           "          "           s           s          "         "          "          "          s           s          "           "
     (0h UTC)

2001   1   1  51910  -0.073506   0.398095   0.0931626   0.0006630   0.000150  -0.000109   0.000061   0.000048  0.0000107  0.0000131    0.000028    0.000030
2001   1   2  51911  -0.072651   0.399806   0.0924546   0.0007596   0.000141  -0.000092   0.000061   0.000048  0.0000070  0.0000131    0.000028    0.000031
2001   1   3  51912  -0.071557   0.401864   0.0916573   0.0008515   0.000132  -0.000074   0.000061   0.000047  0.0000034  0.0000131    0.000028    0.000031
2001   1   4  51913  -0.071024   0.403840   0.0907195   0.0008969   0.000149  -0.000084   0.000061   0.000047  0.0000084  0.0000132    0.000029    0.000031
2001   1   5  51914  -0.070723   0.405333   0.0897667   0.0008872   0.000174  -0.000103   0.000060   0.000047  0.0000163  0.0000132    0.000029    0.000031
2001   1   6  51915  -0.070378   0.406725   0.0889292   0.0008068   0.000199  -0.000122   0.000060   0.000047  0.0000221  0.0000132    0.000029    0.000031
2001   1   7  51916  -0.070068   0.408041   0.0882375   0.0006463   0.000224  -0.000141   0.000060   0.000047  0.0000163  0.0000132    0.000029    0.000031
2001   1   8  51917  -0.070205   0.409479   0.0876861   0.0004933   0.000250  -0.000160   0.000060   0.000047  0.0000104  0.0000132    0.000029    0.000031
2001   1   9  51918  -0.070220   0.410814   0.0872445   0.0004441   0.000275  -0.000179   0.000060   0.000046  0.0000046  0.0000132    0.000029    0.000032
2001   1  10  51919  -0.069861   0.412336   0.0868199   0.0004186   0.000270  -0.000158   0.000060   0.000046  0.0000043  0.0000133    0.000029    0.000031
2001   1  11  51920  -0.069330   0.414004   0.0864003   0.0004447   0.000155  -0.000180   0.000059   0.000046  0.0000039  0.0000133    0.000029    0.000031
2001   1  12  51921  -0.068456   0.416120   0.0858451   0.0005855   0.000106  -0.000203   0.000059   0.000046  0.0000088  0.0000133    0.000028    0.000030
2001   1  13  51922  -0.067463   0.418251   0.0851161   0.0007422   0.000095  -0.000222   0.000059   0.000046  0.0000138  0.0000133    0.000028    0.000030
2001   1  14  51923  -0.066479   0.420226   0.0842390   0.0008823   0.000084  -0.000241   0.000059   0.000046  0.0000112  0.0000134    0.000028    0.000029
2001   1  15  51924  -0.065406   0.422044   0.0833100   0.0009404   0.000072  -0.000259   0.000059   0.000046  0.0000086  0.0000134    0.000027    0.000028
2001   1  16  51925  -0.063999   0.423541   0.0824180   0.0009155   0.000061  -0.000278   0.000059   0.000046  0.0000060  0.0000134    0.000027    0.000028
2001   1  17  51926  -0.062602   0.425076   0.0816384   0.0007815   0.000050  -0.000297   0.000059   0.000046  0.0000034  0.0000135    0.000027    0.000027
2001   1  18  51927  -0.061434   0.426438   0.0809369   0.0005717   0.000307  -0.000078   0.000060   0.000046  0.0000060  0.0000135    0.000026    0.000026
2001   1  19  51928  -0.060301   0.428009   0.0803992   0.0004021   0.000387  -0.000005   0.000060   0.000046  0.0000114  0.0000135    0.000026    0.000025
2001   1  20  51929  -0.059175   0.429380   0.0801026   0.0002618   0.000335  -0.000045   0.000060   0.000046  0.0000197  0.0000136    0.000025    0.000025
2001   1  21  51930  -0.058122   0.430418   0.0799970   0.0000786   0.000284  -0.000085   0.000060   0.000046  0.0000198  0.0000136    0.000025    0.000024
2001   1  22  51931  -0.056745   0.431190   0.0799904  -0.0000387   0.000232  -0.000124   0.000060   0.000047  0.0000199  0.0000136    0.000024    0.000023
2001   1  23  51932  -0.055378   0.432515   0.0800354  -0.0000794   0.000180  -0.000164   0.000061   0.000047  0.0000200  0.0000137    0.000024    0.000022
2001   1  24  51933  -0.054038   0.434299   0.0801054  -0.0000531   0.000189  -0.000183   0.000061   0.000047  0.0000090  0.0000137    0.000024    0.000022
2001   1  25  51934  -0.052227   0.436048   0.0801105   0.0000481   0.000130  -0.000240   0.000061   0.000047  0.0000025  0.0000137    0.000023    0.000021
2001   1  26  51935  -0.050435   0.438026   0.0799589   0.0001715   0.000101  -0.000252   0.000062   0.000048  0.0000160  0.0000137    0.000023    0.000021
2001   1  27  51936  -0.049130   0.439812   0.0796787   0.0002940   0.000094  -0.000242   0.000062   0.000048  0.0000312  0.0000137    0.000022    0.000020
2001   1  28  51937  -0.047602   0.441607   0.0792944   0.0004503   0.000086  -0.000232   0.000062   0.000048  0.0000276  0.0000137    0.000022    0.000019
2001   1  29  51938  -0.045537   0.443509   0.0788172   0.0005621   0.000079  -0.000221   0.000063   0.000048  0.0000239  0.0000138    0.000021    0.000019
2001   1  30  51939  -0.043660   0.444974   0.0782782   0.0006019   0.000072  -0.000211   0.000063   0.000048  0.0000203  0.0000138    0.000021    0.000018
2001   1  31  51940  -0.042067   0.446396   0.0777060   0.0005437   0.000254  -0.000159   0.000063   0.000049  0.0000063  0.0000138    0.000021    0.000019
2001   2   1  51941  -0.040683   0.447325   0.0772066   0.0004689   0.000298  -0.000141   0.000064   0.000049  0.0000064  0.0000138    0.000022    0.000020
2001   2   2  51942  -0.039012   0.448060   0.0767917   0.0003692   0.000290  -0.000134   0.000064   0.000049  0.0000143  0.0000138    0.000022    0.000020
2001   2   3  51943  -0.037722   0.448868   0.0764837   0.0002097   0.000283  -0.000128   0.000064   0.000049  0.0000284  0.0000138    0.000023    0.000021
2001   2   4  51944  -0.036102   0.449525   0.0763497   0.0000712   0.000275  -0.000122   0.000064   0.000049  0.0000205  0.0000138    0.000023    0.000022
2001   2   5  51945  -0.034057   0.450440   0.0763128  -0.0000019   0.000268  -0.000115   0.000064   0.000050  0.0000125  0.0000138    0.000024    0.000022
```

7.4.5 The geocentric motion parameter time series file

The geocentric motion parameter time series file GCN_L1_L2_30d_CF-CM.txt (ITRF2005) were stored in the folder C:\ETideLoad4.5_win64en\iers, which are monthly variation time series products of geocentric motion parameters measured by 5 satellite laser ranging (SLR) provided by UT/CSR. For future epochs, the forecast products can be employed, but the forecast time should be controlled within three months.

ECMWF2006.dat | FES2004S1.dat | IERSeopc04.dat | GCN_L1_L2_30d_CF-CM.txt

Year	X	Y	Z	X_sig	Y_sig	Z_sig
2001.0402	2.50	2.00	5.40	1.78	1.48	4.24
2001.1248	0.65	-1.35	10.75	1.61	1.34	3.68
2001.2128	-0.10	-3.40	3.05	1.61	1.41	3.51
2001.2932	-0.85	-3.55	-4.10	2.82	2.15	3.79
2001.3784	0.40	-2.50	-7.00	1.70	2.30	3.05
2001.4646	-1.65	-1.60	-6.60	1.62	3.30	3.11
2001.5456	-1.55	-2.45	-3.35	1.27	1.85	3.00
2001.6278	-4.45	-0.40	-2.80	1.44	1.90	3.22
2001.7120	-2.05	0.85	-4.05	1.44	1.95	3.34
2001.7911	-1.20	2.05	0.25	1.27	2.05	3.28
2001.8708	0.05	2.05	-2.60	1.44	1.55	3.11
2001.9569	0.05	3.70	-4.60	1.53	1.41	3.39
2002.0399	3.85	4.05	-6.05	1.70	1.75	3.39
2002.1250	1.10	0.25	1.75	1.36	1.27	3.17
2002.2103	0.40	-1.45	3.30	1.44	1.20	2.94
2002.2899	0.50	-2.20	3.10	1.53	1.27	3.34
2002.3769	0.95	-3.45	-0.80	1.44	1.55	5.36
2002.4625	-1.15	-4.50	-5.75	1.62	1.27	2.94
2002.5412	-3.30	-4.90	-4.80	2.16	1.48	2.94
2002.6263	-1.85	0.15	-5.55	1.78	2.35	3.17
2002.7114	-1.85	0.05	0.70	1.53	2.05	3.90
2002.7952	-2.80	-0.30	0.55	1.44	1.90	3.73
2002.8744	-2.75	1.70	0.15	1.44	3.10	3.62
2002.9543	1.75	3.45	9.15	1.95	1.56	5.72
2003.0438	1.40	-0.35	2.40	1.61	1.95	4.19
2003.1279	0.70	0.75	2.30	1.44	1.25	3.28
2003.2108	1.90	-0.05	4.10	1.36	1.55	2.77
2003.2952	1.60	-1.70	2.35	1.78	1.48	3.28
2003.3796	0.50	-3.75	1.35	1.53	1.27	3.16

7.4.6 Ocean tidal constituent harmonic parameters grid model files

(1) The ocean tidal height model is composed of multiple grid models of all tidal constituent harmonic parameters. Each tidal constituent harmonic parameters are stored as a vector grid file.

(2) All the tidal constituent grid files from an ocean tidal height model should be in a folder with the same grid specifications.

(3) The 10 vector grid files in the folder C:\ ETideLoad4.5_win64en\OceanTide represent the ocean tide model GOT4.8 with 10 global grid models of 10 tidal constituent harmonic parameters.

(4) The type of the tidal constituent is identified by the seventh attribute (Doodson constant) in its grid file header. These files can be named at will.

M2_got4.8.dat

0.000000	360.000000	-90.000000	90.000000	0.50000000	0.50000000	255555						
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(5) The ocean tidal height model can be global or regional. The ocean tidal height and the harmonic parameters are all in cm as unit.

7.4.7 The JPL Planetary Ephemeris DE405 file

The JPL Planetary Ephemeris DE405 file JEPH.405 was stored in the folder C:\ETideLoad4.5_win64en\iers. The ephemeris starts at 0:00 on 9 December 1599 (JD2305424. 5) and ends at 0: 00 on 20 February 2201 (JD2525008. 5).

7.4.8 The correction file of frequency dependence for Love numbers

The correction file IERS2010T65.dat of frequency dependence was generated from Table 6.5a、6.5b and 6.5c in IERS Conventions (2010), to calculate the corrections of frequency dependence of geopotential Love numbers to obtain the high-accuracy solid tidal effect on the Earth's external geopotential.

7.4.9 The Desai ocean pole tide coefficient file

The ocean pole tide is generated by the centrifugal effect of polar motion on the oceans. Desai (2002) presents a self-consistent equilibrium model of the ocean pole tide. This model accounts for continental boundaries, mass conservation over the oceans, self-gravitation, and load of the ocean floor. Using this model, the ocean pole tide produces the following perturbations to the normalized geopotential coefficients, as a function of the pole shift parameters (m_1, m_2).

ECMWF2006.dat | FES2004S1.dat | IERSeopc04.dat | GCN_L1_L2_30d_CF-CM.txt | desaiscopolecoef.txt

n	m	Anm(Real)	Bnm(Real)	Anm(Imaginary)	Bnm(Imaginary)
1	0	1.8736759805448e-02	0.0000000000000e+00	2.9688884960424e-02	0.0000000000000e+00
1	1	2.8258913146935e-02	2.1774643075236e-02	2.3898264393684e-02	5.6771602236635e-02
2	0	-3.9555099024374e-03	0.0000000000000e+00	6.8390464271953e-04	0.0000000000000e+00
2	1	-2.4325330521304e-01	5.4680741193318e-03	5.4680741193318e-03	-1.9252111185300e-01
2	2	1.9102047023374e-02	1.1158297399424e-02	-1.5123770169928e-02	-2.4857839911518e-04
3	0	-2.0869478248378e-02	0.0000000000000e+00	-1.0775272844125e-02	0.0000000000000e+00
3	1	3.0809252024501e-02	7.4552838003486e-03	5.5937937407386e-03	6.6496877724041e-02
3	2	2.3295703062692e-02	3.7984356463618e-02	-2.1678456242839e-03	1.1232359168959e-02
3	3	7.9776020803848e-03	1.2502542787182e-02	-2.2341399966187e-02	-2.2979590161975e-02
4	0	-1.0612668622736e-02	0.0000000000000e+00	-1.5569196271270e-02	0.0000000000000e+00
4	1	1.3606306893006e-04	2.2051992576636e-03	2.0130037501025e-03	1.6323514549038e-02
4	2	1.1139374002795e-02	1.7031544962514e-02	-7.9621127289889e-03	-8.4440848505132e-04
4	3	-1.6100794768731e-02	1.4681986705593e-02	9.5178410813713e-03	-2.1017136590507e-02
4	4	4.3132021252707e-03	-4.6836271624465e-03	-2.9309550249205e-03	1.3175690530653e-02
5	0	7.0731357453056e-03	0.0000000000000e+00	-1.8023029843730e-03	0.0000000000000e+00
5	1	2.5644907587134e-03	-1.0076857169607e-02	-9.6273922883022e-03	-1.1684145258283e-02
5	2	-7.9615162895536e-03	2.0820461332209e-03	-3.0274671879191e-03	-1.0475800274156e-02
5	3	-1.1818705609675e-02	1.2063416189422e-02	-1.6584597520384e-02	-2.8253596831795e-02
5	4	9.2731253376468e-03	1.8353138561674e-02	-1.0870088052722e-02	4.7120935900411e-03
5	5	1.4460712839068e-02	-8.5510747244577e-03	8.9167437380844e-04	1.6048852898081e-02
6	0	7.4439256593180e-03	0.0000000000000e+00	-1.0670986469176e-03	0.0000000000000e+00
6	1	1.8261459881891e-02	-3.7775168887123e-03	-3.6768761254667e-03	-1.4329108864964e-03
6	2	-8.4568708595335e-03	2.5640802224787e-03	8.0976103423504e-03	-6.3983905389798e-03
6	3	-1.5355186088842e-02	1.8642889355748e-03	-9.6956523287846e-03	-2.2353328754893e-02
6	4	1.4142224508565e-03	-2.2076728030274e-03	-6.1060835758971e-03	1.4301205310949e-02
6	5	3.7744391579465e-03	1.6205935938625e-02	-7.4210466275681e-03	-2.8879881476777e-03
6	6	3.2420227193323e-03	-1.0204123402364e-03	6.5738366845630e-03	-6.6744309720085e-03
7	0	-1.3403793397592e-03	0.0000000000000e+00	-8.9119937331666e-04	0.0000000000000e+00
7	1	-1.1987665799148e-02	3.7952628984046e-03	3.0548620901213e-03	-2.4656687484472e-02
7	2	1.3964996790643e-03	1.7659797083036e-03	-9.6345882913594e-04	5.1931284495957e-04
7	3	-1.7567622661385e-02	6.8385783341764e-04	9.3943264784830e-03	4.5672879067042e-03
7	4	2.8083751020130e-03	4.6098055178789e-04	-9.4429840592558e-03	2.6160014372180e-03
7	5	1.3438573148260e-02	-4.9709663788905e-03	5.4401137615611e-03	1.2610209142217e-02
7	6	2.3574978727809e-03	-1.8507773876743e-03	-8.8485482473243e-03	-1.7275571315203e-03
7	7	1.7687501823906e-03	-3.8588288830715e-03	5.1311168222451e-03	-3.4729764622333e-03
8	0	2.4179833053297e-03	0.0000000000000e+00	6.3989330948214e-04	0.0000000000000e+00
8	1	5.4747795444986e-03	-4.1645492784766e-03	-3.5505342447356e-03	9.2109717009068e-03
8	2	-3.5541696851032e-03	-1.0507455458039e-02	-2.8591215118039e-03	-5.7895937048006e-05
8	3	-3.6234392832446e-03	5.2650936441460e-03	2.0052526194323e-03	5.9074589159813e-03

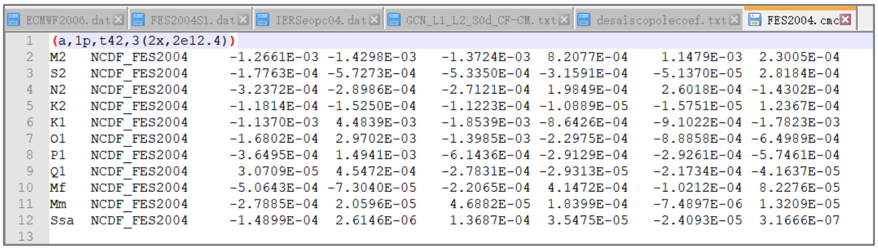
The Desai calculating formula of the ocean pole tide adopts the formula (6.23) in the IERS Conventions (2010), and the 360-degree ocean pole tide coefficient file desaiscopolecoef.txt is stored in the folder C:\ETideLoad4.5_win64en\iers.

7.4.10 The center of mass correction coefficient file for the ocean tide

(1) The center of mass correction formula of ocean tide adopts the formula (1.17) in the IERS Conventions (2010). The object of correction is the three-dimensional coordinates of the ground site in the terrestrial reference frame。

(2) When different tidal models are used to calculate the tidal load effect on the ground site displacement, the corresponding correction coefficients of ocean tide should be used to calculate the center of mass correction.

(3) There are some center of mass correction coefficient files for common ocean tide models stored in the folder C:\ETideLoad4.5_ win64en\ CmcOtide. In which, the center of mass correction coefficients for the ocean tide model FES2004:




```
(a,1p,t42,3(2x,2e12.4))
M2   NCDF_FES2004     -1.2661E-03 -1.4298E-03   -1.3724E-03  8.2077E-04    1.1479E-03  2.3005E-04
S2   NCDF_FES2004     -1.7763E-04 -5.7273E-04   -5.3350E-04 -3.1591E-04   -5.1370E-05  2.8184E-04
N2   NCDF_FES2004     -3.2372E-04 -2.8986E-04   -2.7121E-04  1.9849E-04    2.6018E-04 -1.4302E-04
K2   NCDF_FES2004     -1.1814E-04 -1.5250E-04   -1.1223E-04 -1.0889E-05   -1.5751E-05  1.2367E-04
K1   NCDF_FES2004     -1.1370E-03  4.4839E-03   -1.8539E-03 -8.6426E-04   -9.1022E-04 -1.7823E-03
O1   NCDF_FES2004     -1.6802E-04  2.9702E-03   -1.3985E-03 -2.2975E-04   -8.8858E-04 -6.4989E-04
P1   NCDF_FES2004     -3.6495E-04  1.4941E-03   -6.1436E-04 -2.9129E-04   -2.9261E-04 -5.7461E-04
Q1   NCDF_FES2004      3.0709E-05  4.5472E-04   -2.7831E-04 -2.9313E-05   -2.1734E-04 -4.1637E-05
Mf   NCDF_FES2004     -5.0643E-04 -7.3040E-05   -2.2065E-04  4.1472E-04   -1.0212E-04  8.2276E-05
Mm   NCDF_FES2004     -2.7885E-04  2.0596E-05    4.6882E-05  1.8399E-04   -7.4897E-06  1.3209E-05
Ssa  NCDF_FES2004     -1.4899E-04  2.6146E-06    1.3687E-04  3.5475E-05   -2.4093E-05  3.1666E-07
```

8 Main Algorithms and Formulas used in ETideLoad4.5

8.1 Solid tidal effects on various geodetic variations outside solid Earth

8.1.1 The tidal generating potentials of celestial bodies

The celestial bodies' tidal direct effects on the Earth's external geopotential can be expressed by the variations of geopotential coefficients in the Earth-fixed coordinate system

$$\Delta\bar{C}_{nm} - i\Delta\bar{S}_{nm} = \frac{1}{2n+1}\sum_{j=2}^{10}\frac{GM_j}{GM}\left(\frac{a}{r_j}\right)^{n+1}\bar{P}_{nm}(sin\varphi_j)e^{im\lambda_j}, \quad (1.1)$$

where $j = 2{\sim}10$ represent the moon, sun, Mercury, Venus, Mars, Jupiter, Saturn, Uranus and Neptune. $\Delta\bar{C}_{nm} - i\Delta\bar{S}_{nm}$ are the variations of the normalize geopotential coefficients with degree n and order m (with $\Delta\bar{S}_{n0} = 0$), $\bar{P}_{nm}$ are the normalized associated Legendre functions, $n = 2,3$ for the moon, and $n = 2$ for the other celestial bodies. $GM_j, r_j, \varphi_j, \lambda_j$ are respectively the gravitational parameter, distance from geocenter, geocentric latitude, and longitude (from Greenwich) of the celestial body j. GM, a are respectively the geocentric gravitational constant and Equatorial radius of the Earth.

8.1.2 Nominal values of solid Earth tide external geopotentials

The tidal generating potentials cause the deformation of the solid Earth, leading to the re-adjustment of the Earth's mass, resulting in additional external geopotentials, known as the indirect effects of the external geopotential, whose can be quantitatively represented by the geopotential Love numbers.

The solid earth tidal effects on geopotential coefficients are equal to the sum of the direct effects and indirect effects of the tidal generating potentials.

For the elastic earth, the Love numbers are independent of the frequency, and such a Love number is called the nominal Love number, as shown in Table 1.

Table 1 Nominal values of solid Earth tidal external potential Love numbers

n	m	periods of tidal constituents	k_{nm}	h_{nm}	l_{nm}
2	0	long period	0.29525	0.6078	0.0847
2	1	diurnal	0.29470	0.6078	0.0847
2	2	semi-diurnal	0.29801	0.6078	0.0847
3	0	long period	0.093	0.2920	0.0150
3	1	diurnal	0.093	0.2920	0.0150
3	2	semi-diurnal	0.093	0.2920	0.0150
3	3	1/3-diurnal	0.094	0.2920	0.0150

(1) Nominal solid tidal effects on geopotential coefficients

$$\Delta\bar{C}_{nm} - i\Delta\bar{S}_{nm} = \frac{1+k_{nm}}{2n+1}\sum_{j=2}^{10}\frac{GM_j}{GM}\left(\frac{a}{r_j}\right)^{n+1}\bar{P}_{nm}(sin\varphi_j)e^{im\lambda_j}, \quad (1.2)$$

where k_{nm} are the nominal geopotential love numbers with degree n and order m.

(2) Nominal solid tidal effect on height anomaly/geoid height

$$\zeta = \frac{GM}{\gamma r}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm})(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (1.3)$$

(3) Nominal solid tidal effect on ground gravity⦿

$$g_t = \frac{GM}{r^2}\sum_{n=2}^{3}(n+1)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}\left(1+\frac{2}{n}h_{nm} - \frac{n+1}{n}k_{nm}\right)(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}, \quad (1.4)$$

(4) Nominal solid tidal effect on gravity disturbance

$$\delta g = \frac{GM}{r^2}\sum_{n=2}^{3}(n+1)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm})(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (1.5)$$

(5) Nominal solid tidal effects on ground tilt⦿

South: $$\xi^s = \frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm}-h_{nm})(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (1.6)$$

West: $$\eta^s = \frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=1}^{n}(1+k_{nm}-h_{nm})m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (1.7)$$

(6) Nominal solid tidal effects on vertical deflection

South: $$\xi = \frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm})(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (1.8)$$

West: $$\eta = \frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=1}^{n}(1+k_{nm})m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (1.9)$$

(7) Nominal solid tidal effects on ground site displacement⦿

East: $$e = -\frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n} l_{nm}m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (1.10)$$

North: $$n = -\frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n} l_{nm}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (1.11)$$

Radial: $$r = \frac{GM}{\gamma r}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n} h_{nm}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (1.12)$$

(8) Nominal solid tidal effect on disturbing gravity gradient (radial)

$$T_{rr} = \frac{GM}{r^3}\sum_{n=2}^{3}(n+1)(n+2)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm})(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (1.13)$$

(9) Nominal solid tidal effect on horizontal gravity gradient

North: $$T_{NN} = -\frac{GM}{r^3}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(1+k_{nm}) (\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial^2}{\partial\theta^2}\bar{P}_{nm} \quad (1.14)$$

West: $$T_{WW} = \frac{GM}{r^3 cos^2\varphi}\sum_{n=2}^{3}\left(\frac{a}{r}\right)^n \sum_{m=1}^{n}(1+k_{nm})m^2 (\Delta\bar{C}_{nm}sinm\lambda + \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm} \quad (1.15)$$

The geodetic variations above marked with ⦿ are valid only when the sites are fixed to the solid Earth. The other geodetic variations can be on ground or outside the solid Earth.

8.1.3 The frequency dependent corrections to geopotential coefficients

In order to represent the variations of geopotential coefficients caused by the external geopotentials of the anelastic Earth, three forms of the geopotential Love numbers are needed, namely $k_{nm}^{(0)}, k_{nm}^{(\pm)}(n>2)$, and here $k_{2m}^{(-)}=0$ due to the mass conservation of the deformation Earth, as shown in Table 2.

Table 2 The frequency dependent of external potential Love numbers

nm		periods of tidal constituents	Elastic Earth		Anelastic Earth		
n	m		k_{nm}	$k_{nm}^{(+)}$	Re(k_{nm})	Im(k_{nm})	$k_{nm}^{(+)}$
2	0	long period	0.29525	-0.00087	0.30190	-0.00000	-0.00089
2	1	diurnal	0.29470	-0.00079	0.29830	-0.00144	-0.00080
2	2	semi-diurnal	0.29801	-0.00057	0.30102	-0.00130	-0.00057
3	0	long period	0.093	···			
3	1	diurnal	0.093	···			
3	2	semi-diurnal	0.093	···			
3	3	1/3-diurnal	0.094	···			

The viscous nature of the mantle causes a delay in the response of the Earth's external potential, so that the Love number k varies with frequency, and $k_{nm}^{(0)}$ and $k_{2m}^{(+)}$ have small imaginary parts. The following two steps are usually used to deal with the variations of geopotential coefficients caused by additional external geopotentials.

(1) Using of the geopotential Love numbers $k_{2m}^{(+)},(m=0,1,2)$ with the frequency dependent, compute the variations of degree 4 geopotential coefficients from the degree 2 geopotential

$$\Delta\bar{C}_{4m}-i\Delta\bar{S}_{4m}=\frac{k_{2m}^{(+)}}{5}\sum_{j=2}^{10}\frac{GM_j}{GM}\left(\frac{a}{r_j}\right)^3\bar{P}_{2m}(sin\varphi_j)e^{im\lambda_j}. \quad (1.16)$$

(2) Using the frequency dependent corrections $\delta k_{2m}^{(0)}=k_{2m}^{(0)}-k_{2m}$ for degree 2 Love numbers, compute the corrections of degree 2 geopotential coefficients. The corrections involve the contributions of 71 tidal constituents including the long period, diurnal and semi-diurnal tidal constituents to the imaginary parts of the geopotential Love numbers.

8.1.4 The solid Earth tidal effects on ground site displacement

The tidal generating potentials' indirect effects on the site displacement can be quantitatively represented by the displacement Love numbers. For the viscoelastic Earth, the displacement Love numbers depend on both station latitude and tidal frequency. The solid Earth tidal effects on ground site displacement are usually computed in two steps.

(1) Using the Nominal displacement Love numbers $h_{2m}^{(0)},l_{2m}^{(0)}(m=0,1,2)$, compute the indirect effects of the degree 2 and 3 tidal generating potentials on site displacement by formula (1.10) ~ (1.12).

(2) Considering the deviation between the frequency-dependent degree 2 displacement Love numbers and their nominal value, compute the corrections to results of step 1. The

corrections involve the contributions of all tidal constituents to the imaginary parts of the displacement Love numbers.

8.2 Earth pole shift effects on various geodetic variations outside solid Earth

The Earth pole shift parameters (m_1, m_2) can be accurately measured by the space geodetic method. In modern geodesy, the pole shift parameters are expressed by the non-tidal variations of geopotential coefficient $(\Delta\bar{C}_{21}, \Delta\bar{S}_{21})$ after removing the effects of the solid Earth tide and load tide.

8.2.1 The pole shift effect on the external geopotential

The pole shift effect on the external geopotential is caused by the centrifugal effect of the pole shift, the pole shift effect is non-tidal. The direct effect ΔV of the pole shift on the external geopotential can be expressed as

$$\Delta V = -\frac{\omega^2 r^2}{2} sin2\theta Re[(m_1 - im_2)(cos\lambda + isin\lambda)], \tag{2.1}$$

where r, θ, λ are respectively the distance from geocenter, geocentric co-latitude, and longitude of the calculated point, ω is the angular velocity of the Earth's rotation.

The pole shift causes the solid earth to deform, resulting in the additional geopotential, that is, the indirect effect V^a of the pole shift on the external geopotential, which can be quantitatively represented by the degree 2 Love number k_2

$$V^a = k_2 \Delta V = -\frac{\omega^2 r^2}{2} sin2\theta Re[k_2(m_1 - im_2)(cos\lambda + isin\lambda)]. \tag{2.2}$$

The total effect V_t of the pole shift on the external geopotential is equal to the sum of its direct and indirect effects

$$V_t = (1 + k_2)\Delta V = -\frac{\omega^2 r^2}{2} sin2\theta Re[(1 + k_2)(m_1 - im_2)(cos\lambda + isin\lambda)]$$
$$= -\frac{\omega^2 r^2}{2} sin2\theta Re\{(1 + k_2)[(m_1 cos\lambda + m_2 sin\lambda) + i(m_1 sin\lambda - m_2 cos\lambda)]\}. \tag{2.3}$$

8.2.2 The pole shift effects on height anomaly/geoid

Given the degree 2 Love numbers, $k_2 = 0.3077 + 0.0036i, \quad h_2 = 0.6207, \quad l_2 = 0.0836$, the pole shift effects on various physical and geometric geodetic variations on the ground and outside the solid Earth can be calculated.

$$\zeta_t = \frac{1+k_2}{\gamma}\Delta V = -\frac{\omega^2 r^2}{2\gamma} sin2\theta Re[(1 + k_2)(m_1 cos\lambda + m_2 sin\lambda) + i(m_1 sin\lambda - m_2 cos\lambda)]$$
$$= -\frac{\omega^2 r^2}{2\gamma} sin2\theta Re\{(1.3077 + 0.0036i)[(m_1 cos\lambda + m_2 sin\lambda) + i(m_1 sin\lambda - m_2 cos\lambda)]\}$$
$$= -\frac{\omega^2 r^2}{2\gamma} sin2\theta[(1.3077m_1 + 0.0036m_2)cos\lambda + (1.3077m_2 - 0.0036m_1)sin\lambda] \tag{2.4}$$

where γ is the normal gravity on the calculated point.

8.2.3 The pole shift effect on ground gravity⦿

$$g_t = -\frac{\left(1+h_2-\frac{3}{2}k_2\right)\partial\Delta V}{\partial r} = \omega^2 r sin2\theta Re\left[\left(1 + h_2 - \frac{3}{2}k_2\right)(m_1 - im_2)(cos\lambda + isin\lambda)\right]$$
$$= \omega^2 r sin2\theta Re\{(1.15915 - 0.0054i)[(m_1 cos\lambda + m_2 sin\lambda) + i(m_1 sin\lambda - m_2 cos\lambda)]\}$$
$$= \omega^2 r sin2\theta[(1.15915m_1 - 0.0054m_2)cos\lambda + (1.15915m_2 + 0.0054m_1)sin\lambda]. \tag{2.5}$$

8.2.4 The pole shift effect on gravity disturbance

$$\delta g_t = -(1+k_2)\frac{\partial\Delta V}{\partial r} = \omega^2 r sin2\theta Re[(1+k_2)(m_1 - im_2)(cos\lambda + isin\lambda)] = -\frac{2\gamma}{r}\zeta_t$$
$$= \omega^2 r sin2\theta[(1.3077m_1 + 0.0036m_2)cos\lambda + (1.3077m_2 - 0.0036m_1)sin\lambda]. \quad (2.6)$$

8.2.5 The pole shift effects on ground tilt⦿

South: $\xi_t^s = (1+k_2-h_2)\frac{\partial\Delta V}{\gamma r\partial\theta} = -\frac{\omega^2 r}{\gamma}cos2\theta Re[(1+k_2-h_2)(m_1 - im_2)(cos\lambda + isin\lambda)]$
$$= -\frac{\omega^2 r}{\gamma}cos2\theta[(0.687m_1 + 0.0036m_2)cos\lambda + (0.687m_2 - 0.0036m_1)sin\lambda]. \quad (2.7)$$
West: $\eta_t^s = (1+k_2-h_2)\frac{\partial\Delta V}{\gamma rsin\theta\partial\lambda} = \frac{\omega^2 r}{\gamma}cos\theta Re[(1+k_2-h_2)(m_1 - im_2)(sin\lambda - icos\lambda)]$
$$= \frac{\omega^2 r}{\gamma}cos\theta Re\{(0.687 + 0.0036i)[(m_1 sin\lambda + m_2 cos\lambda) - i(m_1 cos\lambda + m_2 sin\lambda)]\}$$
$$= \frac{\omega^2 r}{\gamma}cos\theta[(0.687m_1 + 0.0036m_2)sin\lambda + (0.0036m_1 + 0.687m_2)cos\lambda]. \quad (2.8)$$

8.2.6 The pole shift effects on vertical deflection

South: $\xi_t = \frac{(1+k_2)\partial\Delta V}{\gamma r\partial\theta} = \frac{-\omega^2 r}{\gamma}cos2\theta[(1+k_2)(m_1 - im_2)(cos\lambda + isin\lambda)] = \frac{2\zeta_t}{r}ctg2\theta$. (2.9)

West: $\eta_t = (1+k_2)\frac{\partial\Delta V}{\gamma rsin\theta\partial\lambda} = \frac{\omega^2 r}{\gamma}cos\theta Re[(1+k_2)(m_1 - im_2)(sin\lambda - icos\lambda)]$
$$= \frac{\omega^2 r}{\gamma}cos\theta[(1.3077m_1 + 0.0036m_2)sin\lambda + (0.0036m_1 + 1.3077m_2)cos\lambda]. \quad (2.10)$$

8.2.7 The pole shift effects on ground site displacement⦿

East: $e = \frac{l_2\partial\Delta V}{\gamma sin\theta\partial\lambda} = l_2\frac{\omega^2 r^2}{\gamma}cos\theta Re[(m_1 - im_2)(sin\lambda - icos\lambda)]$
$$= 0.0836\frac{\omega^2 r^2}{\gamma}cos\theta(m_1 sin\lambda - m_2 cos\lambda). \quad (2.11)$$
North: $n = -\frac{l_2\partial\Delta V}{\gamma\partial\theta} = -l_2\frac{\omega^2 r^2}{\gamma}cos2\theta Re[(m_1 - im_2)(cos\lambda + isin\lambda)]$
$$= -0.0836\frac{\omega^2 r^2}{\gamma}cos2\theta(m_1 cos\lambda + m_2 sin\lambda). \quad (2.12)$$
Radial: $r = \frac{h_2\Delta V}{\gamma} = -0.6207\frac{\omega^2 r^2}{2\gamma}sin2\theta(m_1 cos\lambda + m_2 sin\lambda)$. (2.13)

8.2.8 The pole shift effect on disturbing gravity gradient (radial)

$$T_{rr} = \frac{(1+k_2)\partial^2\Delta V}{\partial r^2} = -\omega^2 sin2\theta Re[(1+k_2)(m_1 - im_2)(cos\lambda + isin\lambda)] = \frac{\delta g_t}{r}$$
$$= -\omega^2 sin2\theta[(1.3077m_1 + 0.0036m_2)cos\lambda + (1.3077m_2 - 0.0036m_1)sin\lambda]. \quad (2.14)$$

8.2.9 The pole shift effects on horizontal gravity gradient

North: $T_{NN} = T_{\varphi\varphi} = -(1+k_2)\omega^2 sin2\theta[(m_1 - im_2)(cos\lambda + isin\lambda)]$
$$= -\omega^2 sin2\theta[(1.3077m_1 + 0.0036m_2)cos\lambda + (1.3077m_2 - 0.0036m_1)sin\lambda]. \quad (2.15)$$
West: $T_{WW} = -\frac{(1+k_2)\partial^2\Delta V}{r^2 sin^2\theta\partial\lambda^2} = -(1+k_2)\omega^2 ctg\theta[(m_1 - im_2)(cos\lambda + isin\lambda)]$
$$= 2T_{rr}cos^2\theta = 2T_{\varphi\varphi}cos^2\theta = -2\frac{\delta g_t}{r}cos^2\theta. \quad (2.16)$$

The geodetic variations above marked with ⦿ are valid only when the sites are fixed to the solid Earth. The other geodetic variations can be on the ground or outside the solid Earth.

The pole shift is the polar location shift of the instantaneous relative to a certain reference epoch (such as the epoch J2000.0) after removing all the solid Earth tidal and load tidal effects. Both the pole shift and geocentric movement do not include various tidal effects.

Non-tidal effects are difficult to be modeled and are generally measured using geodetic techniques. In most fast or real-time geodetic applications, short-time forecast estimations can be adopted.

The Earth orientation parameters product EOP_C04 recommended by the IERS Conventions (2010), has not removed the annual and semi-annual tidal effects of the atmospheric load. Therefore, the Earth pole shift parameters (m_1, m_2) calculated by the product EOP_C04 obviously contain annual and semi-annual components.

8.3 Spherical harmonic synthesis on load deformation field

8.3.1 The surface loads and the effects on geopotential coefficients

In the Earth surface system, surface non-tidal load variations such as soil and vegetation water, lake water, glacier and snow, groundwater, atmosphere, and sea level variations can be uniformly expressed by variations of the surface equivalent water height (EWH). The equivalent water height variation h_w at the surface point (R, θ, λ) can be expressed as a load normalized spherical harmonic series

$$h_w(R,\theta,\lambda) = R\sum_{n=1}^{\infty}\sum_{m=0}^{n}[\Delta C_{nm}^{w} cosm\lambda + \Delta S_{nm}^{w} sinm\lambda]\,\bar{P}_{nm}(cos\theta), \tag{3.1}$$

where R is the mean radius of the Earth, $\Delta C_{nm}^{w}, \Delta S_{nm}^{w}$ are the load normalized spherical harmonic coefficients with degree n and order m, $\bar{P}_{nm}(t = cos\theta) = \bar{P}_{nm}$ are the normalized associated Legendre functions with degree n and order m.

The variations of global surface equivalent water height directly cause the variations of the surface geopotential

$$\Phi^{d}(R,\theta,\lambda) = \sum_{n=1}^{\infty}\frac{4\pi G\rho_w R^2}{2n+1}\sum_{m=0}^{n}[\Delta C_{nm}^{w} cosm\lambda + \Delta S_{nm}^{w} sinm\lambda]\,\bar{P}_{nm}, \tag{3.2}$$

where G is the Newtonian gravitational constant, ρ_w is the density of the water.

According to the theory of the earth's gravity field, the variations of the surface geopotential Φ^d can also be expressed by the variations of the geopotential coefficients $(\Delta\bar{C}_{nm}, \Delta\bar{S}_{nm})$ as

$$\Phi^{d} = \frac{GM}{R}\sum_{n=1}^{\infty}\sum_{m=0}^{\infty}(\Delta\bar{C}_{nm} cosm\lambda + \Delta\bar{S}_{nm} sinm\lambda)\bar{P}_{nm}\,(cos\theta). \tag{3.3}$$

Comparing the formulas (3.2) and (3.3), we have

$$\Delta\bar{C}_{nm} = \frac{4\pi R^3}{M}\frac{\rho_w}{2n+1}\,\Delta C_{nm}^{w} = \frac{4\pi R^3}{\rho_e V}\frac{\rho_w}{2n+1}\,\Delta C_{nm}^{w} = \frac{4\pi R^3}{4\pi R^3\rho_e/3}\frac{\rho_w}{2n+1}\,\Delta C_{nm}^{w} = \frac{3}{2n+1}\frac{\rho_w}{\rho_e}\Delta C_{nm}^{w},$$

similarly, we have $\Delta\bar{S}_{nm} = \frac{3}{2n+1}\frac{\rho_w}{\rho_e}\Delta S_{nm}^{w}$. (3.4)

Where ρ_e, M, V are the mean density, total mass and total volume of the Earth, respectively.

The surface load effects on various geodetic variations on the ground or outside the solid Earth can also be expressed by the variations of the geopotential coefficients $(\Delta\bar{C}_{nm}, \Delta\bar{S}_{nm})$.

8.3.2 The surface load effect on height anomaly/geoid

$$\zeta = \frac{GM}{\gamma r}\sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^{n}(1 + k_n')\sum_{m=0}^{n}(\Delta\bar{C}_{nm} cosm\lambda + \Delta\bar{S}_{nm} sinm\lambda)\bar{P}_{nm}. \tag{3.5}$$

8.3.3 The surface load effect on ground gravity⦿

$$g_t = \frac{GM}{r^2}\sum_{n=2}^{\infty}(n+1)\left(1+\frac{2}{n}h_n' - \frac{n+1}{n}k_n'\right)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (3.6)$$

8.3.4 The surface load effect on gravity disturbance

$$\delta g = \frac{GM}{r^2}\sum_{n=2}^{\infty}(n+1)(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (3.7)$$

8.3.5 The surface load effects on ground tilt⦿

South: $$\xi^s = \frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{\infty}(1+k_n'-h_n')\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (3.8)$$

West: $$\eta^s = \frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{\infty}(1+k_n'-h_n')\left(\frac{a}{r}\right)^n \sum_{m=1}^{n} m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (3.9)$$

8.3.6 The surface load effects on vertical deflection

South: $$\xi = \frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{\infty}(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (3.10)$$

West: $$\eta = \frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{\infty}(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=1}^{n} m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (3.11)$$

8.3.7 The surface load effects on ground site displacement⦿

East: $$e = -\frac{GM}{\gamma r^2 \sin\theta}\sum_{n=2}^{\infty} l_n'\left(\frac{a}{r}\right)^n \sum_{m=1}^{n} m(\Delta\bar{C}_{nm}sinm\lambda - \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (3.12)$$

North: $$n = -\frac{GM}{\gamma r^2}\sin\theta\sum_{n=2}^{\infty} l_n'\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial}{\partial\theta}\bar{P}_{nm}. \quad (3.13)$$

Radial: $$r = \frac{GM}{\gamma r}\sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^n h_n' \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (3.14)$$

8.3.8 The surface load effect on disturbing gravity gradient (radial)

$$T_{rr} = \frac{GM}{r^3}\sum_{n=2}^{\infty}(n+1)(n+2)(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\bar{P}_{nm}. \quad (3.15)$$

8.3.9 The surface load effects on horizontal gravity gradient

$$\sum_{m=1}^{n}(1+k_{nm})m^2(\Delta\bar{C}_{nm}sinm\lambda + \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm}. \quad (3.17)$$

North: $$T_{NN} = -\frac{GM}{r^3}\sum_{n=2}^{\infty}(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}(\Delta\bar{C}_{nm}cosm\lambda + \Delta\bar{S}_{nm}sinm\lambda)\frac{\partial^2}{\partial\theta^2}\bar{P}_{nm} \quad (3.16)$$

West: $$T_{WW} = -\frac{GM}{r^3 cos^2\varphi}\sum_{n=2}^{\infty}(1+k_n')\left(\frac{a}{r}\right)^n \sum_{m=1}^{n}(1+k_n')m^2(\Delta\bar{C}_{nm}sinm\lambda + \Delta\bar{S}_{nm}cosm\lambda)\bar{P}_{nm} \quad (3.17)$$

The geodetic variations above marked with ⦿ are valid only when the sites are fixed to the solid Earth. The other geodetic variations can be on the ground or outside the solid Earth.

In the Formulas (3.5) ~ (3.17), h_n', l_n', k_n' are the radial displacement, horizontal displacement and geopotential load Love numbers, respectively.

8.3.10 Fast recursion algorithm for $\bar{P}_{mn}(t)$ and their derivatives to θ

Let $t = cos\theta, u = sin\theta$. (3.18)

(1) Standard forward column recursion algorithm for $\bar{\boldsymbol{P}}_{\boldsymbol{nm}}(\boldsymbol{t})$ $(\boldsymbol{n}<\mathbf{1900})$

$$\begin{cases}\bar{P}_{nm}(t)=a_{nm}t\bar{P}_{n-1,m}(t)-b_{nm}\bar{P}_{n-2,m}(t) \quad \forall n>1, m<n \\ \bar{P}_{nn}(t)=\sqrt{\frac{2n+1}{2n}}\bar{P}_{n-1,n-1}\end{cases} \tag{3.19}$$

$$a_{nm}=\sqrt{\frac{(2n-1)(2n+1)}{(n+m)(n-m)}}, \quad b_{nm}=\sqrt{\frac{(2n+1)(n+m-1)(n-m-1)}{(2n-3)(n+m)(n-m)}}$$

$$\bar{P}_{00}(t)=1, \quad \bar{P}_{10}(t)=\sqrt{3}t, \quad \bar{P}_{11}(t)=\sqrt{3}u \tag{3.20}$$

(2) Improved Belikov recursion algorithm for $\bar{\boldsymbol{P}}_{\boldsymbol{nm}}(\boldsymbol{t})$ $(\boldsymbol{n}<\mathbf{64800})$

When n=0,1, use formula (3.20) to calculate $\bar{P}_{nm}(t)$. When $n\geq 2$:

$$\bar{P}_{n0}(t)=a_n t\bar{P}_{n-1,0}(t)-b_n\frac{u}{2}\bar{P}_{n-1,1}(t), \quad m=0 \tag{3.21}$$

$$\bar{P}_{nm}(t)=c_{nm}t\bar{P}_{n-1,m}(t)-d_{nm}u\bar{P}_{n-1,m+1}(t)+e_{nm}u\bar{P}_{n-1,m-1}(t), \ m>0 \tag{3.22}$$

$$a_n=\sqrt{\frac{2n+1}{2n-1}}, \quad b_n=\sqrt{\frac{2(n-1)(2n+1)}{n(2n-1)}} \tag{3.23}$$

$$c_{nm}=\frac{1}{n}\sqrt{\frac{(n+m)(n-m)(2n+1)}{2n-1}}, \quad d_{nm}=\frac{1}{2n}\sqrt{\frac{(n-m)(n-m-1)(2n+1)}{2n-1}} \tag{3.24}$$

When $m>0$:

$$e_{nm}=\frac{1}{2n}\sqrt{\frac{2}{2-\delta_0^{m-1}}}\sqrt{\frac{(n+m)(n+m-1)(2n+1)}{2n-1}} \tag{3.25}$$

ETideLoad4.5 adopts mainly the improved Belikov recursion algorithm to calculate the normalized associated Legendre functions $\bar{P}_{nm}(t)$。

(3) Cross-degree recursive algorithm for $\bar{\boldsymbol{P}}_{\boldsymbol{nm}}(\boldsymbol{t})$ $(\boldsymbol{n}<\mathbf{20000})$

When n=0,1, use formula (3.20) to calculate $\bar{P}_{nm}(t)$. When $n\geq 2$:

$$\bar{P}_{nm}(t)=\alpha_{nm}\bar{P}_{n-2,m}(t)+\beta_{nm}\bar{P}_{n-2,m-2}(t)-\gamma_{nm}\bar{P}_{n,m-2}(t) \tag{3.26}$$

$$\alpha_{nm}=\sqrt{\frac{(2n+1)(n-m)(n-m-1)}{(2n-3)(n+m)(n+m-1)}}$$
$$\beta_{nm}=\sqrt{1+\delta_0^{m-2}}\sqrt{\frac{(2n+1)(n+m-2)(n+m-3)}{(2n-3)(n+m)(n+m-1)}} \tag{3.27}$$
$$\gamma_{nm}=\sqrt{1+\delta_0^{m-2}}\sqrt{\frac{(n-m+1)(n+m-3)}{(n+m)(n+m-1)}}$$

(4) Non-singular recursive algorithm for $\frac{\partial}{\partial\theta}\bar{\boldsymbol{P}}_{\boldsymbol{nm}}(\boldsymbol{\cos\theta})$

$$\frac{\partial}{\partial\theta}\bar{P}_{nm}(\cos\theta)=-\sin\theta\frac{\partial}{\partial t}\bar{P}_{nm}(t) \tag{3.28}$$

$$\begin{cases}\frac{\partial}{\partial\theta}\bar{P}_{n0}=-\sqrt{\frac{n(n+1)}{2}}\bar{P}_{n1}, \quad \frac{\partial}{\partial\theta}\bar{P}_{n1}=\sqrt{\frac{n(n+1)}{2}}\bar{P}_{n0}-\frac{\sqrt{(n-1)(n+2)}}{2}\bar{P}_{n2} \\ \frac{\partial}{\partial\theta}\bar{P}_{nm}=\frac{\sqrt{(n+m)(n-m+1)}}{2}\bar{P}_{n,m-1}-\frac{\sqrt{(n-m)(n+m+1)}}{2}\bar{P}_{n,m+1}, \quad m>2\end{cases} \tag{3.29}$$

$$\frac{\partial}{\partial\theta}\bar{P}_{00}(t)=0, \quad \frac{\partial}{\partial\theta}\bar{P}_{10}(t)=-\sqrt{3}u, \quad \frac{\partial}{\partial\theta}\bar{P}_{11}(t)=\sqrt{3}t \tag{3.30}$$

(5) Non-singular recursive algorithm for $\frac{\partial^2}{\partial\theta^2}\bar{\boldsymbol{P}}_{\boldsymbol{nm}}$

$$\begin{cases}\frac{\partial^2}{\partial\theta^2}\bar{P}_{n0}=-\frac{n(n+1)}{2}\bar{P}_{n0}+\sqrt{\frac{n(n-1)(n+1)(n+2)}{8}}\bar{P}_{n2} \\ \frac{\partial^2}{\partial\theta^2}\bar{P}_{n1}=-\frac{2n(n+1)+(n-1)(n+2)}{4}\bar{P}_{n1}+\frac{\sqrt{(n-2)(n-1)(n+2)(n+3)}}{4}\bar{P}_{n3}\end{cases} \tag{3.31}$$

$$\frac{\partial^2}{\partial\theta^2}\bar{P}_{nm}=\frac{\sqrt{(n-m+1)(n-m+2)(n+m-1)(n+m)}}{4}\bar{P}_{n,m-2}-\frac{(n+m)(n-m+1)+(n-m)(n+m+1)}{4}\bar{P}_{nm}$$
$$+\frac{\sqrt{(n-m-1)(n-m)(n+m+1)(n+m+2)}}{4}\bar{P}_{n,m+2},\quad m>2 \tag{3.32}$$
$$\frac{\partial^2}{\partial\theta^2}\bar{P}_{00}(t)=0,\quad \frac{\partial^2}{\partial\theta^2}\bar{P}_{10}(t)=-\sqrt{3}t,\quad \frac{\partial^2}{\partial\theta^2}\bar{P}_{11}(t)=-\sqrt{3}u \tag{3.33}$$

8.4 Surface load effects on various geodetic variations by Green's Integral

8.4.1 The Integral formulas of the direct effects of surface loads

(1) The integral formula of the direct effect on geopotential of surface loads

Given the surface load equivalent water height (EWH) h_w, whose direct effect V_w on the geopotential near Earth space directly given by the universal gravitation formula

$$V_w=G\rho_w\int_S\frac{h_w}{L}dS,\quad L=\sqrt{r^2+r'^2-2rr'cos\psi}, \tag{4.1}$$

where L is the spatial distance between the calculation point (r,θ,λ) near Earth space and the center (r',θ',λ') of integral area element on the surface, r,θ,λ are the spherical geocentric coordinates of the calculated point, namely distance from geocenter, co-latitude and longitude, respectively. G is Newton's gravitational constant, $\rho_w=1000kg/m^3$ is the water density. ψ is the spherical angle between the calculation point (r,θ,λ) and the center (r',θ',λ') of the area element.

$$cos\psi=cos\theta cos\theta'+sin\theta sin\theta' cos(\lambda'-\lambda),\quad sin\psi=sin\theta cos\theta'+cos\theta sin\theta' cos(\lambda'-\lambda), \tag{4.2}$$
$$sin\psi cos\alpha=sin\theta cos\theta'-cos\theta sin\theta' cos(\lambda'-\lambda),\quad sin\psi sin\alpha=sin\theta' sin(\lambda'-\lambda), \tag{4.3}$$
$$\frac{\partial\psi}{\partial\theta}=-\frac{\partial\psi}{\partial\varphi}=cos\alpha,\quad \frac{\partial\psi}{\partial\lambda}=-sin\alpha sin\theta. \tag{4.4}$$

When the calculation point is located on the surface and overlaps with the center of integral area element, we have

$$L=r\psi,\quad r-r'cos\psi=r\psi^2/2, \tag{4.5}$$
$$A=dS=r^2\int_{\alpha=0}^{2\pi}\int_0^{\psi_0}\psi d\psi d\alpha=\pi r^2\psi_0^2\rightarrow\psi_0=\frac{1}{r}\sqrt{\frac{A}{\pi}}, \tag{4.6}$$

here $A=dS$ is the area of integral area element. In this case, the formula (4.1) on the calculation point is an integral singularity

$$V_0=G\rho_w r^2\int_{\alpha=0}^{2\pi}\int_0^{\psi_0}\frac{h_w}{r\psi}\psi d\psi d\alpha=2\pi G\rho_w h_w r\psi_0. \tag{4.7}$$

(2) The integral formula of the direct effect on gravity disturbance of surface loads

According to the definition of gravity disturbance, we have

$$\delta g=-\frac{\partial V_w}{\partial r}=-G\rho_w\int_S h_w\frac{\partial}{\partial r}\left(\frac{1}{L}\right)dS=G\rho_w\int_S h_w\frac{r-r'cos\psi}{L^3}dS. \tag{4.8}$$

When the calculation point is located on the surface and overlaps with the center of integral area element, the formula (4.8) on the calculation point is an integral singularity

$$\delta g_0=2\pi G\rho_w h_w\int_0^{\psi_0}\frac{\psi^2/2}{\psi^3}\psi d\psi=\pi G\rho_w h_w\psi_0. \tag{4.9}$$

(3) The integral formula of the direct effect on vertical deflection of surface loads

$$\Theta=\frac{1}{\gamma r}\frac{\partial V_w}{\partial\psi}=\frac{G\rho_w}{\gamma r}\int_S h_w\frac{\partial}{\partial\psi}\left(\frac{1}{L}\right)dS=-\frac{G\rho_w}{\gamma}\int_S h_w r'\frac{sin\psi}{L^3}dS, \tag{4.10}$$

$$\xi = \Theta\frac{\partial\psi}{\partial\theta} = -\frac{G\rho_w}{\gamma}\int_S h_w r'\frac{sin\psi}{L^3}cos\alpha dS,\ \eta = -\Theta\frac{\partial\psi}{\partial\lambda} = -\frac{G\rho_w}{\gamma}sin\theta\int_S h_w r'\frac{sin\psi}{L^3}sin\alpha dS. \quad (4.11)$$

Where γ is the normal gravity on the calculated point.

(4) The integral formula of the direct effect on disturbing gravity gradient of surface loads

According to the definition of disturbing gravity gradient, we have

$$T_{rr} = \frac{\partial^2 V_w}{\partial r^2} = G\rho_w\int_S h_w\frac{\partial}{\partial r}\left(\frac{r-r'cos\psi}{L^3}\right)dS = G\rho_w\int_S h_w\left[\frac{1}{L^3}-\frac{3(r-r'cos\psi)^2}{L^5}\right]dS \quad (4.12)$$

$$\frac{\partial}{\partial r}\left(\frac{r-r'cos\psi}{L^3}\right) = \frac{1}{L^3}-\frac{3(r-r'cos\psi)}{L^4}\frac{\partial}{\partial r}L = \frac{1}{L^3}-\frac{3(r-r'cos\psi)^2}{L^5},\quad \frac{\partial}{\partial r}L = \frac{r-r'cos\psi}{L}$$

When the calculation point is located on the surface and overlaps with the center of integral area element, the formula (12) on the calculation point is an integral singularity

$$T_{rr}^0 = -2\pi G\rho_w h_w r^2\int_0^{\psi_0}\left(\frac{1}{r^3\psi^3}-\frac{3\psi^4}{4r^3\psi^5}\right)\psi d\psi = -\frac{2\pi G\rho_w h_w}{r}\int_0^{\psi_0}\left(\frac{1}{\psi^2}-\frac{3}{4}\right)d\psi \approx \frac{\pi G\rho_w h_w}{r\psi_0^2} \quad (4.13)$$

(5) The integral formula of the direct effect on horizontal gravity gradient of surface loads

$$\Gamma\Gamma = \frac{\partial^2 V_w}{r^2\partial\psi^2} = -\frac{G\rho_w}{r}\int_S h_w r'\frac{\partial}{\partial\psi}\left(\frac{sin\psi}{L^3}\right)dS = -\frac{G\rho_w}{r}\int_S h_w r'\left(\frac{cos\psi}{L^3}-\frac{3rr'sin^2\psi}{L^5}\right)dS, \quad (4.14)$$

$$T_{NN} = \Gamma\frac{\partial^2\psi}{\partial\theta^2} = \frac{G\rho_w}{r}\int_S h_w r'\left(\frac{cos\psi}{L^3}-\frac{3rr'sin^2\psi}{L^5}\right)ctg\psi(1-cos\alpha)dS \quad (4.15)$$

$$T_{WW} = -\Gamma\frac{\partial^2\psi}{\partial\lambda^2} = \frac{G\rho_w}{r}\int_S h_w r'\left(\frac{cos\psi}{L^3}-\frac{3rr'sin^2\psi}{L^5}\right)$$

$$\left[ctg\psi - ctg\psi(sin\theta sin\alpha)^2 - \frac{cos\theta cos\theta'}{sin\psi}\right]dS \quad (4.16)$$

$$\frac{\partial^2\psi}{\partial\theta^2} = \frac{\partial}{\partial\theta}cos\alpha = \frac{\partial}{\partial\theta}\frac{sin\theta cos\theta' - cos\theta sin\theta' cos(\lambda'-\lambda)}{sin\psi} = ctg\psi(1-cos^2\alpha) \quad (4.17)$$

$$\frac{\partial^2\psi}{\partial\lambda^2} = -sin\theta\frac{\partial}{\partial\lambda}sin\alpha = -sin\theta sin\theta'\frac{\partial}{\partial\lambda}\frac{sin(\lambda'-\lambda)}{sin\psi} = sin\theta sin\theta'\left[\frac{cos(\lambda'-\lambda)}{sin\psi}-\frac{sin(\lambda'-\lambda)cos\psi}{sin^2\psi}sin\alpha sin\theta\right]$$

$$= \frac{cos\psi - cos\theta cos\theta'}{sin\psi} - \frac{cos\psi}{sin\psi}(sin\theta sin\alpha)^2 = (1-sin^2\theta sin^2\alpha)ctg\psi - \frac{cos\theta cos\theta'}{sin\psi} \quad (4.18)$$

8.4.2 Green's functions formula of the indirect effects of surface loads

The effects of unit point-mass load $q_w = \rho_w h_w$ (kg/m^2) on various ground geodetic variations can be expressed by load Green's function. Let $t = cos\psi$, k_n', h_n', l_n' represent the load love numbers of geopotential, ground radial displacement, and horizontal displacement, respectively. The Green's functions algorithm formula of the load indirect effects on various ground geodetic variations are given in following.

(1) Green's function of the indirect effect on ground geopotential / height anomaly (G_i^V/G_i^ζ)

$$G_i^V(\psi) = \gamma G_i^\zeta(\psi) = \frac{a\gamma}{M}\frac{k_\infty'}{2sin\frac{\psi}{2}} + \frac{a\gamma}{M}\sum_{n=0}^{\infty}(k_n'-k_\infty')P_n(t), \quad (4.19)$$

where M is the total mass of the Earth, a is the Equatorial radius of the Earth, and $P_n(t)$ is n degree Legendre function with t as its independent variable.

(2) Green's function of the indirect effect on ground gravity

$$G_i^g(\psi) = -\frac{\gamma}{M}\frac{k_\infty'-2h_\infty'}{2sin\frac{\psi}{2}} - \frac{\gamma}{M}\sum_{n=0}^{\infty}[(n+1)k_n' - k_\infty' - 2(h_n'-h_\infty')]P_n(t). \quad (4.20)$$

(3) Green's function of the indirect effect on gravity disturbance

$$G_i^{\delta g}(\psi) = -\frac{\gamma}{M}\frac{k'_\infty}{2sin\frac{\psi}{2}} - \frac{\gamma}{M}\sum_{n=0}^{\infty}[(n+1)k'_n - k'_\infty]P_n(t). \tag{4.21}$$

(4) Green's function of the indirect effect on ground tilt

$$G_i^t(\psi) = -\frac{1}{M}\frac{h'_\infty cos\frac{\psi}{2}}{4sin^2\frac{\psi}{2}} + \frac{1}{M}\frac{k'_\infty cos\frac{\psi}{2}\left(1+2sin\frac{\psi}{2}\right)}{2sin\frac{\psi}{2}\left(1+sin\frac{\psi}{2}\right)} - \frac{1}{M}\sum_{n=1}^{\infty}\left(k'_n - \frac{k'_\infty}{n} - h'_n + h'_\infty\right)\frac{\partial P_n(t)}{\partial\psi}. \tag{4.22}$$

(5) Green's function of the indirect effect on vertical deflection

$$G_i^{\Theta}(\psi) = \frac{1}{M}\frac{k'_\infty cos\frac{\psi}{2}\left(1+2sin\frac{\psi}{2}\right)}{2sin\frac{\psi}{2}\left(1+sin\frac{\psi}{2}\right)} - \frac{1}{M}\sum_{n=1}^{\infty}\left(k'_n - \frac{k'_\infty}{n}\right)\frac{\partial P_n(t)}{\partial\psi}. \tag{4.23}$$

(6) Green's function of the indirect effect on ground horizontal displacement

$$G^l(\psi) = -\frac{a}{M}\frac{l'_\infty cos\frac{\psi}{2}\left(1+2sin\frac{\psi}{2}\right)}{2sin\frac{\psi}{2}\left(1+sin\frac{\psi}{2}\right)} + \frac{a}{M}\sum_{n=1}^{\infty}\left(l'_n - \frac{l'_\infty}{n}\right)\frac{\partial P_n(t)}{\partial\psi}. \tag{4.24}$$

(7) Green's function of the indirect effect on ground radial displacement

$$G^r(\psi) = \frac{a}{M}\frac{h'_\infty}{2sin\frac{\psi}{2}} + \frac{a}{M}\sum_{n=0}^{\infty}(h'_n - h'_\infty)P_n(t). \tag{4.25}$$

(8) Green's function of the indirect effect on disturbing gravity gradient (radial)

$$G^{T_{rr}}(\psi) = \frac{\gamma}{aM}\sum_{n=0}^{\infty}(n+1)(n+2)k'_nP_n(t) \tag{4.26}$$

(9) Green's function of the indirect effect on horizontal gravity gradient

$$G_i^{T_{ss}}(\psi) = \frac{\gamma}{aM}\sum_{n=0}^{\infty}k'_n\frac{\partial^2 P_n(t)}{\partial\psi^2}. \tag{4.27}$$

Let $\mathcal{G}_i(l) = 2asin\frac{\psi}{2}G_i(\psi) = lG_i(\psi)$, then after substituting the load Love numbers into the formula (4.19) ~ (4.27), obtain the Green's function values, such as table 3.

Table 3 Green's function values of the indirect effects of surface loads

l(km)	$\mathcal{G}_i^{\zeta}\times10^{-13}$	$\mathcal{G}_i^{g}\times10^{-17}$	$\mathcal{G}_i^{\delta g}\times10^{-18}$	$\mathcal{G}_i^{t}\times10^{-14}$	$\mathcal{G}_i^{\Theta}\times10^{-19}$	$\mathcal{G}^{l}\times10^{-12}$	$\mathcal{G}^{r}\times10^{-11}$	$\mathcal{G}_i^{nn}\times10^{-15}$	$\mathcal{G}_i^{ss}\times10^{-15}$
0.1	-0.0249	-11.3315	15.8795	42.2955	-2.1192	-0.8369	-42.1264	40.7525	20.0337
0.2	-0.0439	-9.8972	29.6981	21.1510	-8.0632	-3.1842	-41.9553	73.6102	34.1831
0.3	-0.0625	-8.8334	39.7946	14.1058	-16.6878	-6.5901	-41.7788	92.3770	37.9744
0.4	-0.0804	-8.2348	45.2182	10.5853	-26.3601	-10.4097	-41.5956	93.8712	29.4189
0.5	-0.0975	-8.1095	45.8894	8.4739	-35.3064	-13.9425	-41.4057	78.5612	9.4993
0.6	-0.1139	-8.3807	42.5773	7.0657	-41.9834	-16.5790	-41.2101	50.3867	-18.0490
0.7	-0.1294	-8.9073	36.7009	6.0583	-45.3905	-17.9241	-41.0109	15.8142	-47.6055
0.8	-0.1444	-9.5157	30.0034	5.3006	-45.2558	-17.8704	-40.8109	-17.6468	-72.9744
1.0	-0.1727	-10.3454	20.4992	4.2343	-36.8762	-14.5596	-40.4173	-55.8494	-91.9157
1.2	-0.1998	-10.1321	21.4749	3.5210	-26.2416	-10.3574	-40.0402	-39.6641	-61.0517
1.4	-0.2261	-9.1669	30.0077	3.0153	-22.8895	-9.0304	-39.6752	8.4433	-7.5471
1.6	-0.2518	-8.3519	37.0350	2.6419	-28.6871	-11.3158	-39.3091	42.4515	24.9158
2.0	-0.3003	-8.9633	28.5858	2.1198	-40.5309	-15.9830	-38.5476	-4.3817	-24.2022

2.5	-0.3570	-9.1242	24.1119	1.6843	-25.9871	-10.2232	-37.6133	-17.0612	-27.2278
3.0	-0.4112	-7.9718	32.8632	1.4080	-35.2424	-13.8576	-36.7093	28.7167	17.2271
3.5	-0.4621	-8.9437	20.3140	1.2022	-32.5321	-12.7629	-35.7866	-31.1746	-40.2655
4.0	-0.5112	-7.7218	29.8481	1.0465	-28.2814	-11.0562	-34.9109	22.8507	15.9355
5.0	-0.6036	-7.8959	22.7679	0.8291	-26.3578	-10.2305	-33.1702	-5.9459	-11.1019
6.0	-0.6903	-7.8527	18.1028	0.6858	-29.9324	-11.5649	-31.5082	-23.6048	-28.4842
7.0	-0.7725	-7.2943	18.8748	0.5827	-33.7803	-12.9988	-29.9389	-13.5281	-18.2480
8.0	-0.8510	-6.5206	22.0921	0.5013	-33.1161	-12.6452	-28.4652	9.3638	5.3150
10.0	-0.9991	-6.0125	18.9937	0.3784	-24.7530	-9.1540	-25.7982	5.3162	2.8950
12.0	-1.1387	-5.9045	13.1167	0.2999	-27.9718	-10.2454	-23.5296	-16.1892	-18.4692
14.0	-1.2726	-4.9048	17.3988	0.2398	-26.5722	-9.5373	-21.6664	13.0654	11.2087
16.0	-1.4019	-4.8896	12.8941	0.1911	-21.0009	-7.2164	-20.1480	-4.3047	-5.5888
20.0	-1.6520	-4.0437	14.8205	0.1306	-20.9145	-7.0582	-18.0179	12.2601	11.2369
25.0	-1.9534	-3.6904	13.7959	0.0872	-19.8016	-6.6584	-16.5317	10.0949	9.3198
30.0	-2.2455	-3.5544	12.9067	0.0638	-18.9897	-6.5141	-15.7982	5.5325	4.9129
35.0	-2.5296	-3.5250	12.0811	0.0505	-18.1729	-6.4230	-15.4331	0.0753	-0.4331
40.0	-2.8059	-3.5272	11.4345	0.0423	-17.1945	-6.2698	-15.2297	-4.7358	-5.1568
50.0	-3.3365	-3.4643	11.2395	0.0322	-14.9772	-5.7725	-14.9607	-8.1685	-8.4622
60.0	-3.8395	-3.2518	12.5464	0.0262	-13.6029	-5.4612	-14.6941	-2.7549	-2.9775
70.0	-4.3177	-3.0073	14.0654	0.0229	-13.9783	-5.7205	-14.3923	4.6469	4.4506
80.0	-4.7741	-2.8804	14.3310	0.0210	-15.3999	-6.3101	-14.0649	6.2127	6.0235
100.0	-5.6311	-2.9117	11.9306	0.0171	-15.7804	-6.3810	-13.3843	-4.6763	-4.8316
120.0	-6.4270	-2.6545	12.4755	0.0129	-14.0249	-5.5346	-12.7235	0.1761	0.0607
140.0	-7.1738	-2.4359	12.7461	0.0120	-15.5946	-5.9880	-12.0989	3.7448	3.6348
160.0	-7.8804	-2.4586	10.7233	0.0100	-14.9953	-5.5941	-11.5133	-4.4893	-4.5820
180.0	-8.5536	-2.2087	11.5710	0.0080	-13.8312	-4.9933	-10.9748	1.9062	1.8299
200.0	-9.1986	-2.0952	11.1758	0.0080	-15.1075	-5.3733	-10.4758	1.7439	1.6689
250.0	-10.7136	-1.8097	10.7082	0.0058	-14.0435	-4.7072	-9.3924	3.2869	3.2307
300.0	-12.1238	-1.5962	10.1419	0.0042	-12.9077	-4.0819	-8.5118	3.2916	3.2481
350.0	-13.4587	-1.4397	9.5227	0.0030	-11.9089	-3.5581	-7.7994	2.1184	2.0836

400.0	-14.7375	-1.3210	8.9521	0.0023	-11.1503	-3.1625	-7.2265	0.4258	0.3969
500.0	-17.1749	-1.1331	8.3207	0.0016	-10.3019	-2.7029	-6.4078	-2.1612	-2.1831
600.0	-19.4980	-0.9603	8.5053	0.0014	-9.8691	-2.4641	-5.9044	-2.3040	-2.3219
800.0	-23.8986	-0.6720	9.9646	0.0010	-9.0007	-2.0628	-5.4405	0.1041	0.0908

8.4.3 Legendre function and its first and second derivatives to ψ

Let $t = cos\,\psi, \quad u = sin\,\psi,$ (4.28)

$$P_n(t) = \frac{2n-1}{n} tP_{n-1}(t) - \frac{n-1}{n} P_{n-2}(t), \tag{4.29}$$

$$P_1 = t, \quad P_2 = \frac{1}{2}(3t^2 - 1). \tag{4.30}$$

$$\frac{\partial}{\partial\psi} P_n(t) = \frac{2n-1}{n} t \frac{\partial}{\partial\psi} P_{n-1}(t) - \frac{2n-1}{n} uP_{n-1}(t) - \frac{n-1}{n}\frac{\partial}{\partial\psi} P_{n-2}(t). \tag{4.31}$$

$$\frac{\partial}{\partial\psi} P_1(t) = -u, \quad \frac{\partial}{\partial\psi} P_2(t) = -3ut. \tag{4.32}$$

$$\frac{\partial^2}{\partial\psi^2} P_n(t) = \frac{2n-1}{n}\left(t\frac{\partial^2}{\partial\psi^2} P_{n-1} - 2u\frac{\partial}{\partial\psi} P_{n-1} - tP_{n-1}\right) - \frac{n-1}{n}\frac{\partial^2}{\partial\psi^2} P_{n-2}, \tag{4.33}$$

$$\frac{\partial^2}{\partial\psi^2} P_1(t) = -t, \quad \frac{\partial^2}{\partial\psi^2} P_2(t) = 3(1 - 2t^2). \tag{4.34}$$

8.5 Algorithms for global tidal load spherical harmonic coefficient model

8.5.1 Construction of tidal load spherical harmonic coefficient model

General procedure of construction of the global ocean tidal load normalized spherical harmonic coefficient model (in FES2004 format) from global ocean tidal height harmonic parameters grids are:

(1) From the global ocean tidal harmonic parameters grid model of each tidal constituent, generate the normalized spherical harmonic coefficient model of each tidal constituent by spherical harmonic analysis method.

(2) According to the astronomical tide height algorithm, convert the normalized spherical harmonic coefficients based on the harmonic parameters of the tidal constituent into the normalized spherical harmonic coefficient based on the tidal load of the tidal constituent.

(3) Merging the global tidal load normalized spherical harmonic coefficients of all tidal constituents, generate the global ocean tide load normalized spherical harmonic coefficient model in FES2004 format.

Astronomical tidal height $T(t)$, expressed as the height of the astronomical tidal level relative to the local long-term mean sea surface, is equal to the sum of M tidal constituent heights

$$T(\varphi,\lambda,t) = \sum_{i=1}^{M} T_i(\varphi,\lambda,t) = \sum_{i=1}^{M} H_i(\varphi,\lambda)cos[\theta_i(t) - g_i(\varphi,\lambda)], \tag{5.1}$$

where M is the number of the ocean tidal constituents, θ_i, H_i, g_i are respectively the astronomical argument, the amplitude and the phase of the tidal constituent i.

The astronomical tide height T_i of the tidal constituent i can be expanded as

$$T_i(\varphi,\lambda,t) = H_i(\varphi,\lambda)cosg_i(\varphi,\lambda)cos\theta_i(t) + H_i(\varphi,\lambda)sing_i(\varphi,\lambda)sin\theta_i(t)$$

$$= H_i^+(\varphi,\lambda)cos\theta_i(t) + H_i^-(\varphi,\lambda)sin\theta_i(t) = H_i^+cos\theta_i + H_i^-sin\theta_i. \quad (5.2)$$

Through the spherical harmonic analysis, the tidal height T_i of the tidal constituent i can be also expressed as the normalized spherical harmonic series

$$T_i(\varphi,\lambda,t) = \sum_{n=1}^{N}\sum_{m=0}^{n}\bar{P}_{nm}(sin\varphi)\left[T_{i,nm}^+(\lambda,t) + T_{i,nm}^-(\lambda,t)\right], \quad (5.3)$$

where $T_{i,nm}^+(\lambda,t) = \bar{C}_{i,nm}^+cos(\theta_i + m\lambda) + \bar{S}_{i,nm}^+sin(\theta_i + m\lambda)$, (5.4)

$$T_{i,nm}^-(\lambda,t) = \bar{C}_{i,nm}^-cos(\theta_i - m\lambda) + \bar{S}_{i,nm}^-sin(\theta_i - m\lambda). \quad (5.5)$$

Expand the trigonometric functions in the formulas (5.4) and (5.5), we have

$$T_{i,nm}^+(\lambda,t) = \bar{C}^+[cos\theta_i cosm\lambda - sin\theta_i sinm\lambda] + \bar{S}^+[sin\theta_i cosm\lambda + cos\theta_i sinm\lambda]$$

$$= [\bar{C}^+cosm\lambda + \bar{S}^+sinm\lambda]cos\theta_i + [-\bar{C}^+sinm\lambda + \bar{S}^+cosm\lambda]sin\theta_i, \quad (5.6)$$

$$T_{i,nm}^-(\lambda,t) = \bar{C}^-[cos\theta_i cosm\lambda + sin\theta_i sinm\lambda] + \bar{S}^-[sin\theta_i cosm\lambda - cos\theta_i sinm\lambda]$$

$$= [\bar{C}^-cosm\lambda - \bar{S}^-sinm\lambda]cos\theta_i + [\bar{C}^-sinm\lambda + \bar{S}^-cosm\lambda]sin\theta_i. \quad (5.7)$$

Comparing the formula (5.2) and formula (5.3), for the tidal constituent i, (any tidal constituent number i is omitted below), we have

$$H^+ = \sum_{n=1}^{N}\sum_{m=0}^{n}\bar{P}_{nm}\,(\bar{C}^+cosm\lambda + \bar{S}^+sinm\lambda + \bar{C}^-cosm\lambda + \bar{S}^-sinm\lambda), \quad (5.8)$$

$$H^- = \sum_{n=1}^{N}\sum_{m=0}^{n}\bar{P}_{nm}\,(-\bar{C}^+sinm\lambda + \bar{S}^+cosm\lambda + \bar{C}^-sinm\lambda + \bar{S}^-cosm\lambda), \quad (5.9)$$

$$H^+ = \sum_{n=1}^{N}\sum_{m=0}^{n}\bar{P}_{nm}\,[(\bar{C}^+ + \bar{C}^-)cosm\lambda + (\bar{S}^+ - \bar{S}^-)sinm\lambda], \quad (5.10)$$

$$H^- = \sum_{n=1}^{N}\sum_{m=0}^{n}\bar{P}_{nm}\,[(\bar{S}^+ + \bar{S}^-)cosm\lambda + (-\bar{C}^+ + \bar{C}^-)sinm\lambda], \quad (5.11)$$

$$\bar{C}^+ = \hat{C}^+sin\varepsilon^+, \quad \bar{C}^- = \hat{C}^-sin\varepsilon^-, \quad \bar{S}^+ = \hat{C}^+cos\varepsilon^+, \bar{S}^- = \hat{C}^-cos\varepsilon^- . \quad (5.12)$$

Similarly, from the global surface atmosphere tidal harmonic parameter grid models, can construct the surface atmosphere tidal load spherical harmonic coefficient model by the spherical harmonic analysis. The 360-degree surface atmosphere tidal load spherical harmonic coefficient model ECMWF2006.dat in ETideLoad4.5 were constructed according to the process above from the 0.5˚× 0.5˚ global harmonic parameter grids of the four atmospheric pressure tidal constituents (S_1, S_2, Ss_a, Sa).

8.5.2 Ocean tidal load effects on geopotential coefficients

According to Farrell's (1972) theory, the external geopotential of ocean tidal load V^{ot} can be be expressed by Green's function integral

$$V^{ot}(\varphi,\lambda,t) = G\rho_w\iint_S\, H(\varphi',\lambda',t)G^V(\psi)dS, \quad (5.13)$$

where H is the ocean tidal height, S means the whole sea, ψ is the spherical angular between the calculation point (φ,λ) and the sea surface moving point (φ',λ'), $G^V(\psi)$ is the load Green's function of the external geopotential.

The load Green's function $G^V(\psi)$ can be expressed in the form of a spherical harmonic series with the load love numbers k_n':

$$G^V(\psi) = \sum_{n=1}^{\infty}(1 + k_n')P_n(cos\psi). \quad (5.14)$$

Substituting (5.14) into (5.13), the integral relationship between the global ocean tidal height H and the variations of the geopotential coefficient $(\Delta\bar{C}_{nm}, \Delta\bar{S}_{nm})$ can be obtained:

$$\begin{bmatrix}\Delta\bar{C}_{nm}\\ \Delta\bar{S}_{nm}\end{bmatrix} = \frac{G\rho_w(1+k_n')}{g_0(2n+1)}\int_0^{2\pi}\int_0^{\pi} H\bar{P}_{nm}(sin\varphi)\begin{bmatrix}cosm\lambda\\ sinm\lambda\end{bmatrix}cos\varphi d\varphi d\lambda, \tag{5.15}$$

here $g_0 = \frac{GM}{a^2}$ is the average gravity of the sea surface.

Given an ocean tidal height model expressed by the harmonic constants (amplitudes and phases) grids of all the tidal constituent (angular frequency σ), on the sea surface(φ, λ) at epoch time t, the instantaneous ocean tidal height:

$$H(t, \varphi, \lambda) = H_t(\varphi, \lambda) = \sum_\sigma H_\sigma(\varphi, \lambda)cos[\theta_\sigma(t, \varphi, \lambda) - g_\sigma], \tag{5.16}$$

here H_σ is the amplitude of the tidal constituent σ, $\theta_\sigma(\varphi, \lambda, t)$ is the astronomical argument of the tidal constituent σ on the sea surface(φ, λ) at epoch time t, g_σ is the phase at Greenwich of the tidal constituent σ.

The in-phase amplitude $H_\sigma cosg_\sigma$ and the cross-phase amplitude $H_\sigma sing_\sigma$ are represent by spherical harmonic series, and they are brought into formula (5.16) to obtain

$$H_t(\varphi, \lambda) = \sum_\sigma \sum_{n=1}^{N} \sum_{m=0}^{n} \bar{P}_{nm}(cos\varphi) \sum_{+}^{-} H_{\sigma,nm}^{\pm}(\lambda, t) \tag{5.17}$$

$$H_{\sigma,nm}^{\pm}(t, \lambda) = \bar{C}_{\sigma,nm}^{\pm}cos(g_\sigma + \varepsilon_\sigma \pm m\lambda) + \bar{S}_{\sigma,nm}^{\pm}sin(g_\sigma + \varepsilon_\sigma \pm m\lambda) \tag{5.18}$$

Here $(\bar{C}_{\sigma,nm}^{\pm}, \bar{S}_{\sigma,nm}^{\pm})$ are called as the prograde and retrograde normalized spherical harmonic coefficients of the tidal constituent σ with degree n and order m, which can be expressed in terms of harmonic amplitude $\hat{C}_{\sigma,nm}^{\pm}$ and phase $\varepsilon_{\sigma,nm}^{\pm}$ as:

$$\bar{C}_{\sigma,nm}^{\pm} = \hat{C}_{\sigma,nm}^{\pm}sin\varepsilon_{\sigma,nm}^{\pm}, \quad \bar{S}_{\sigma,nm}^{\pm} = \hat{C}_{\sigma,nm}^{\pm}cos\varepsilon_{\sigma,nm}^{\pm} \tag{5.19}$$

In formula (5.18), ε_σ is called as the phase bias of the tidal constituent σ, which can be defined according to the sign of H_σ (Cartwright & Eden, 1973) as Table 4.

Table 4 Values of the phase bias ε_σ according to the sign of H_σ

The phase bias ε_σ		$H_\sigma > 0$	$H_\sigma < 0$
$m = 0$	long period	π	0
$m = 1$	diurnal	$\pi/2$	$-\pi/2$
$m = 2$	semi-diurnal	0	π

Substituting (5.17) into (5.15), taking into account (5.18) and (5.19), the external geopotential coefficient variations can be expressed as:

$$\Delta\bar{C}_{nm} - i\Delta\bar{S}_{nm} = \sum_\sigma (C_{\sigma,nm}^{\pm}, \mp iS_{\sigma,nm}^{\pm})e^{\pm i\theta_\sigma} \tag{5.20}$$

Comparing equations (5.20) and (5.16), we have:

$$C_{\sigma,nm}^{\pm} = \frac{4\pi G\rho_w(1+k_n')}{g_0(2n+1)}\hat{C}_{\sigma,nm}^{\pm}sin(\varepsilon_{\sigma,nm}^{\pm} + \varepsilon_\sigma) \tag{5.21}$$

$$S_{\sigma,nm}^{\pm} = \frac{4\pi G\rho_w(1+k_n')}{g_0(2n+1)}\hat{C}_{\sigma,nm}^{\pm}cos(\varepsilon_{\sigma,nm}^{\pm} + \varepsilon_\sigma) \tag{5.22}$$

Using formulas (5.21) and (5.22), the ocean tidal harmonic constants grid model represented can be converted into the harmonic amplitude, and then the geopotential coefficient variations can be calculated according to the formula (5.20).

8.6 Load deformation field approach from heterogeneous variations using SRBFs

When the object variable of load effect is the geopotential differential or its linear combination, such as the load effect on gravity disturbance, vertical deflection, horizontal displacement or gravity gradient, the load Green 's function has serious high-degree oscillation and non-convergence problems, and the load Green 's integral has spectrum leakage and singularity problems, as shown in Fig.1.

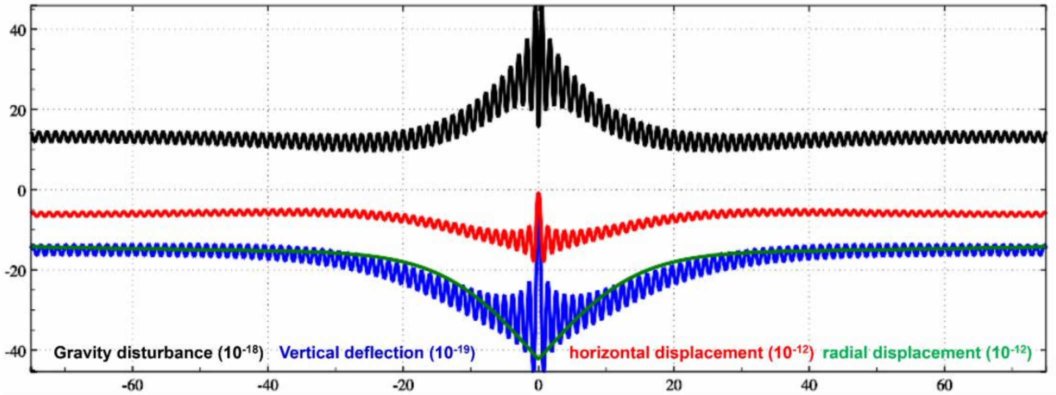


Fig.1 Near-region properties of Green's function of load effect on geopotential differential variable

It is not difficult to find that when the Green′s integral is used to calculate the load effect on the object variable which is not dominant in the geopotential differential, such as calculating the load effect on height anomaly, ground radial displacement and orthometric height, or load effect on ground gravity or tilt whose site has not obvious vertical deformation , an acceptable integral result can be obtained. However, when calculating the load effect on gravity disturbance, vertical deflection or horizontal displacement, the integral result is very unstable, and its reliability is poor.

Similarly, for the monitoring to the land water and surface load deformation field, when the monitoring variable is GNSS ellipsoidal height variation, the regional land water variation and load effect can be estimated by using Green's integral constraint. However, if the geopotential differential in the monitoring variable is dominant, such as the monitoring variable is gravity disturbance, vertical deflection, horizontal displacement, or gravity gradient variations it is difficult to obtain a stable solution by using the Green′s integral method.

ETideLoad4.5 has fully derived and completely implemented the algorithm of the SRBF approach of surface load and the SRBF synthesis of load effect to effectively solve the problems of high-degree oscillation and poor convergence of Green′s function and spectrum leakage and singularity of Green′s integral, and then proposes a solid geophysical analytical constraint scheme based on the SRBF representation in the spectral domain to solve the deep fusion problem of multi-source heterogeneous monitoring variations such as GNSS, gravity, leveling, ground tilt and groundwater, and strictly realizes the collaborative monitoring of multiple heterogeneous geodetic and surface environmental loads in the geodynamic framework.

8.6.1 Spherical radial basis function representation of Load EWH

The surface load equivalent water height (EWH) $h_w(x)$ at the surface point x can be expressed as a linear combination of normalized surface harmonic basis functions:

$$h_w(x) = r\sum_{n=2}^{N}\left(\frac{a}{r}\right)^n \sum_{m=-n}^{n} \bar{F}_{nm}\bar{Y}_{nm}(e) \qquad (6.1)$$

where $x = r \cdot e = r(sin\theta cos\lambda, sin\theta sin\lambda, cos\theta)$, r, λ, θ are the geocentric distance, longitude and colatitude of the surface point x respectively, $\bar{F}_{nm}$ are the fully normalized spherical harmonic coefficients, $\bar{Y}_{nm}$ is the normalized surface harmonic basis function, and a is the equatorial radius of the Earth, which means that $\bar{Y}_{nm}$ are defined on a sphere with the radius of a.

$$\bar{Y}_{nm}(e) = \bar{P}_{nm}(cos\theta)cosm\lambda, \quad \bar{F}_{nm} = \delta\bar{C}_{nm}, \quad m \geq 0$$
$$\bar{Y}_{nm}(e) = \bar{P}_{n|m|}(cos\theta)sin|m|\lambda, \quad \bar{F}_{nm} = \bar{S}_{n|m|}, \quad m < 0 \qquad (6.2)$$

where $\bar{P}_{nm}(cos\theta)$ is the fully normalized associative Legendre function, n is called as the degree of the harmonic coefficient, and m is called as the order of harmonic l coefficients.

If the domain of the surface spherical functions are transformed from the sphere with radius a to the Bjerhammar sphere with radius $\mathcal{R}$, then the spherical harmonic coefficients $\bar{F}_{nm}$ should be converted into $\bar{E}_{nm}$, we have $a^n\bar{F}_{nm} = \mathcal{R}^n\bar{E}_{nm}$, and the formula (10.1) becomes:

$$h_w(x) = r\sum_{n=2}^{N}\left(\frac{\mathcal{R}}{r}\right)^n \sum_{m=-n}^{n} \bar{E}_{nm}\bar{Y}_{nm}(e) \qquad (6.3)$$

The surface load EWH $h_w(x)$ at any surface point x can also be expressed as a linear combination of K spherical radial basis functions (SRBF):

$$h_w(x) = a\sum_{k=1}^{K} d_k\Phi_k(x, x_k) \qquad (6.4)$$

where $x_k = \mathcal{R} \cdot e_k$ is the SRBF node defined on the Bjerhammar sphere, also known as the SRBF center or SRBF pole, d_k is the SRBF coefficient, K is the number of the SRBF nodes and equal to the number of SRBF coefficients, $\Phi_k(x, x_k)$ is the spherical radial basis function of the EWH can be abbreviated as $\Phi_k(x) = \Phi_k(x, x_k)$.

The spherical radial basis function $\Phi_k(x, x_k)$ can be furtherly expanded into the Legendre series:

$$\Phi_k(x, x_k) = \sum_{n=2}^{N}\phi_n P_n(\psi_k) = \sum_{n=2}^{N}\frac{2n+1}{4\pi}B_n\left(\frac{\mathcal{R}}{r}\right)^n P_n(\psi_k) \qquad (6.5)$$

where ϕ_n is the degree n Legendre coefficient of SRBF, which characterizes the shape of SRBF and basically determines the spatial and spectral figures of SRBF, also known as the shape factor. When the spectral domain degree n need be not emphasized, B_n is also called as the Legendre coefficient of SRBF. $\mu = R/r$ is also called as the bandwidth parameter since it is related to the spectral domain bandwidth of the radial basis function $\Phi_k(x)$.

Substitute the formula (10.5) into (10.4) to get:

$$h_w(x) = \frac{r}{4\pi}\sum_{n=2}^{N}(2n+1)B_n\left(\frac{\mathcal{R}}{r}\right)^n \sum_{k=1}^{K} d_k P_n(\psi_k)$$
$$= \frac{r}{4\pi}\sum_{k=1}^{K} d_k \sum_{n=2}^{N}(2n+1)B_n\left(\frac{\mathcal{R}}{r}\right)^n P_n(\psi_k) \qquad (6.6)$$

Considering the addition theorem of spherical harmonics:

$$P_n(\psi_k) = P_n(e, e_k) = \frac{4\pi}{2n+1}\sum_{m=-n}^{n} \bar{Y}_{nm}(e)\bar{Y}_{nm}(e_k) \quad (6.7)$$

then the formula (10.5) can be written as

$$h_w(x) = r\sum_{n=2}^{N} B_n \left(\frac{\mathcal{R}}{r}\right)^n \sum_{m=-n}^{n} \sum_{k=1}^{K} d_k \bar{Y}_{nm}(e)\bar{Y}_{nm}(e_k) \quad (6.8)$$

Comparing formulas (10.1), (10.3) and (10.8), we have:

$$\bar{F}_{nm} = \left(\frac{\mathcal{R}}{a}\right)^n \bar{E}_{nm} = B_n \left(\frac{\mathcal{R}}{a}\right)^n \sum_{k=1}^{K} d_k \bar{Y}_{nm}(e_k) \quad (6.9)$$

Using formula (10.9), the spherical harmonic coefficient $\bar{F}_{nm}$ can be calculated from the spherical radial basis function coefficient d_k. After that, the spherical harmonic coefficient can be employed to calculate various load effects outside the solid Earth.

The position, distribution and amount of the SRBF nodes (centers) $\{x_k\}$ on the Bjerhammar sphere are the key indicators for load deformation field approach using spherical radial basis functions, which determine the spatial degrees of freedom (spatial resolution) and spatial feature of regional load deformation field, similar to the degree of the global surface load spherical harmonic coefficient model.

8.6.2 Spherical radial basis functions suitable for load deformation field

Some spherical radial basis kernel function such as the point mass kernel function, Poisson kernel function, radial multipole kernel function and Poisson wavelet kernel function are all harmonic, which are suitable for load deformation field approach.

Let x be the surface calculation point and x_k be the SRBF center on the Bjerhammar sphere $\Omega_{\mathcal{R}}$.

(1) The point mass kernel function

The point mass kernel function is an inverse multiquadric function (IMQ) proposed by Hardy (1971), which is the kernel function of the gravitational potential integral formula $V = G\iiint \frac{dm}{L}$, and its analytical expression is:

$$\Phi_{IMQ}(x, x_k) = \frac{1}{L} = \frac{1}{|x - x_k|} \quad (6.10)$$

where L is the space distance between x and x_k. Since $\Delta(1/L) = 0$, the point mass kernel function $\Phi_{IMQ}(x, x_k)$ satisfies the Laplace equation.

(2) The Poisson kernel function

The Poisson kernel function is derived from the Poisson integral, and its analytical expression is:

$$\Phi_P(x, x_k) = -2r\frac{\partial}{\partial r}\left(\frac{1}{L}\right) - \frac{1}{L} = \frac{r^2 - r_k^2}{L^3} \quad (6.11)$$

(3) The radial multipole kernel function

The analytical expression of the radial multipole kernel function is:

$$\Phi_{RM}^m(x, x_k) = \frac{1}{m!}\left(\frac{\partial}{\partial r_k}\right)^m \frac{1}{L} \quad (6.12)$$

where m can be called as the order of the radial multipole kernel function, and the zero-order radial multipole kernel function is the point mass kernel function $\Phi_{IMQ}(x, x_k) = \Phi_{RM}^0(x, x_k)$.

(4) The Poisson wavelet kernel function

The analytical expression of the Poisson wavelet kernel function is:

$$\Phi_{PW}^{m}(x,x_k)=2(\chi_{m+1}-\chi_m),\quad \chi_m=\left(r_k\frac{\partial}{\partial r_k}\right)^m\frac{1}{L} \tag{6.13}$$

The zero-order Poisson wavelet kernel function is the Poisson kernel function $\Phi_P(x,x_k)=\Phi_{PW}^{0}(x,x_k)$.

(5) Calculation of spherical radial basis functions

The spherical radial basis function analytical expressions (6.10) ~ (6.13) are usually expressed in the Legendre series (10.5), and then calculated according to the Legendre expansion to highlight the spectral domain figures of the load deformation field.

ETideLoad4.5 normalizes the Legendre expansion of the spherical radial basis function $\Phi_k(x,x_k)$, and then calculates the spherical radial basis functions (SRBF) using the normalized Legendre expansion. When dealing with different types of observed geodetic variations, the SRBF of various variations are uniformly divided by the normalization coefficients of EWH SRBF to maintain the analytical relationship between different types of geodetic variations.

Let the spherical angular distance $\psi_k=0$ from x_k to x, then $cos\psi_k=1$, $P_n(cos\psi_k)=P_n(1)=1$, substitute these into formula (10.5), we have the general expression of the normalization coefficient of EWH SRBF:

$$\Phi^0=\sum_{n=2}^{N}\frac{2n+1}{4\pi}B_n\mu^n \tag{6.14}$$

The Legendre expansion of the normalized EWH spherical radial basis function is:

$$\Phi_k(x,x_k)=\frac{1}{\Phi^0}\sum_{n=2}^{N}\phi_nP_n(\psi_k)=\frac{1}{\Phi^0}\sum_{n=2}^{N}\frac{2n+1}{4\pi}B_n\mu^nP_n(\psi_k) \tag{6.15}$$

The above four forms of EWH SRBF and their corresponding Legendre coefficients are shown in Table 5.

SRBF	$\Phi_k(x,x_k)$	ϕ_n	B_n
Point mass kernel	$\frac{1}{L}=\frac{1}{\vert x-x_k\vert}$	μ^n	$\frac{4\pi}{2n+1}$
Poisson kernel function	$\frac{r^2-r_k^2}{L^3}$	$(2n+1)\mu^n$	4π
radial multipole kernel	$\frac{1}{m!}\left(\frac{\partial}{\partial r_k}\right)^m\frac{1}{L}$	$C_n^m\mu^{n-m}\ \ (n\geq m)$	$\frac{4\pi C_n^m}{2n+1}\mu^{-m}$
Poisson wavelet kernel	$2(\chi_{m+1}-\chi_m)$ $\chi_m=\left(r_k\frac{\partial}{\partial r_k}\right)^m\frac{1}{L}$	$(-nln\mu)^m(2n+1)\mu^n$	$4\pi(-nln\mu)^m$

8.6.3 Unit spherical Reuter grid construction algorithm

(1) Unit spherical Reuter grid construction algorithm

Given the Reuter grid level Q (even number), the geocentric latitude interval $d\varphi$ of the unit spherical Reuter grid in the spherical coordinate system and the geocentric latitude φ_i of the center of the cell grid i are respectively

$$d\varphi=\frac{\pi}{Q},\quad \varphi_i=-\frac{\pi}{2}+\left(i-\frac{1}{2}\right)d\varphi,\quad 1\leq i<Q \tag{6.16}$$

The grid number J_i in the prime vertical circle direction at latitude φ_i, the longitude interval $d\lambda_i$ and the side length dl_i are respectively

$$J_i=\left[\frac{2\pi cos\varphi_i}{d\varphi}\right],\quad d\lambda_i=\frac{2\pi}{J_i},\quad dl_i=d\lambda_i cos\varphi_i \tag{6.17}$$

It is not difficult to find that $dl_i\approx d\varphi$. Let

$$\varepsilon_i=\frac{ds_i-ds}{ds}=\frac{dl_i-d\varphi}{d\varphi}=\frac{d\lambda_i}{d\varphi}cos\varphi_i-1 \tag{6.18}$$

where ds is the cell grid area near the equator, ds_i is the cell grid area at the prime vertical circle φ_i, and ε_i is the relative deviation of the parallel circle cell grid area relative to the cell grid area near the equator.

ε_i is generally small, about a few ten-thousandth, and the value is related to the Reuter grid level Q. Near the equator, we have $ds=d\varphi\cdot d\varphi$, $\varepsilon_{Q/2}=0$.

Given the range of longitude and latitude of the local area, you can directly determine the minimum and maximum value of i according to the formula (10.22), and then calculate the maximum J_i at each prime vertical circle according to the formula (10.23), to determine the regional Reuter grid whose level is Q without calculating the global grid.

8.6.4 SRBF representation for surface load EWH and geodetic variations

According to the spherical harmonic expansions of load effects (3.5) ~ (3.17), the parameterized representations of geodetic variations can be derived from the SRBF representation (6.6) of Load EWH.

$$h_w(x)=r\sum_{k=1}^{K}d_k\sum_{n=2}^{N}(2n+1)B_n\left(\frac{\mathcal{R}}{r}\right)^n P_n(\psi_k) \tag{6.19}$$

$$\zeta=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma}\sum_{k=1}^{K}d_k\sum_{n=2}^{N}B_n(1+k_n')\left(\frac{\mathcal{R}}{r}\right)^n P_n(\psi_k) \tag{6.20}$$

$$\delta g=\frac{3\rho_w}{\rho_e}\frac{GM}{r}\sum_{k=1}^{K}d_k\sum_n(n+1)(1+k_n')B_n\left(\frac{\mathcal{R}}{r}\right)^{n-1} P_n(\psi_k) \tag{6.21}$$

$$g_t=\frac{3\rho_w}{\rho_e}\frac{GM}{r}\sum_{k=1}^{K}d_k\sum_n(n+1)\left(1+\frac{2}{n}h_n'-\frac{n+1}{n}k_n'\right)B_n\left(\frac{\mathcal{R}}{r}\right)^{n-1} P_n(\psi_k) \tag{6.22}$$

$$\xi^s=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r}\sum_{k=1}^{K}d_k\,cos\alpha_k\sum_n(1+k_n'-h_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.23}$$

$$\eta^s=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r}\sum_{k=1}^{K}d_k\,sin\alpha_k\sum_n(1+k_n'-h_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.24}$$

$$\xi=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r}\sum_{k=1}^{K}d_k\,cos\alpha_k\sum_n(1+k_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.25}$$

$$\eta=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r}\sum_{k=1}^{K}d_k\,sin\alpha_k\sum_n(1+k_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.26}$$

$$e=-\frac{3\rho_w}{\rho_e}\frac{GM}{r\gamma}\sum_{k=1}^{K}d_k\,cos\alpha_k\sum_n l_n'B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.27}$$

$$n=-\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r}\sum_{k=1}^{K}d_k\,sin\alpha_k\sum_n l_n'B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial P_n(\psi_k)}{\partial\psi_k} \tag{6.28}$$

$$r=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma}\sum_{k=1}^{K}d_k\sum_{n=2}^{N}B_nh_n'\left(\frac{\mathcal{R}}{r}\right)^n P_n(\psi_k) \tag{6.29}$$

$$\hbar=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma}\sum_{k=1}^{K}d_k\sum_{n=2}^{N}B_nh_n'\left(\frac{R}{r}\right)^n P_n(\psi_k) \tag{6.30}$$

$$T_{rr}=\frac{3\rho_w}{\rho_e}\frac{GM}{r^2}\sum_{k=1}^{K}d_k\sum_n(n+1)(n+2)B_n\left(\frac{\mathcal{R}}{r}\right)^{n-1} P_n(\psi_k) \tag{6.31}$$

$$T_{NN}=\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r^2}\sum_{k=1}^{K}d_k\frac{\partial^2\psi_k}{\partial\varphi_k^2}\sum_n(1+k_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial^2 P_n(\psi_k)}{\partial\psi_k^2} \tag{6.32}$$

$$T_{WW}=-\frac{3\rho_w}{\rho_e}\frac{GM}{\gamma r^2cos^2\varphi}\sum_{k=1}^{K}d_k\frac{\partial^2\psi_k}{\partial\lambda_k^2}\sum_n(1+k_n')B_n\left(\frac{\mathcal{R}}{r}\right)^n \frac{\partial^2 P_n(\psi_k)}{\partial\psi_k^2} \tag{6.33}$$

where α_k is the geodetic azimuth of ψ_k.

Similar to the spatial load Green's function integration method, if the regional surface load equivalent water height h_w is known, the SRBF spectral domain analysis of the load equivalent water height h_w can be performed according to Equation (6.19) to estimate the SRBF coefficients. ETideLoad4.5 calls this process as the load SRBF approach. Then, the regional full-element load deformation field is calculated from SRBF coefficients according to Equations (6.20) to (6.33). ETideLoad4.5 calls this process as load effect SRBF synthesis.

Here, the point mass kernel function is selected as SRBF, and the minimum degree and the maximum degree are set to be 90 and 1800 respectively. The buried depth of the Bjerhammar sphere is set to be 5 km, and the maximum act distance of SRBF center is 150 km. The SRBF spatial curves of the load effect on gravity disturbance, vertical deflection, horizontal displacement, and radial displacement are calculated, as shown in Fig.2.

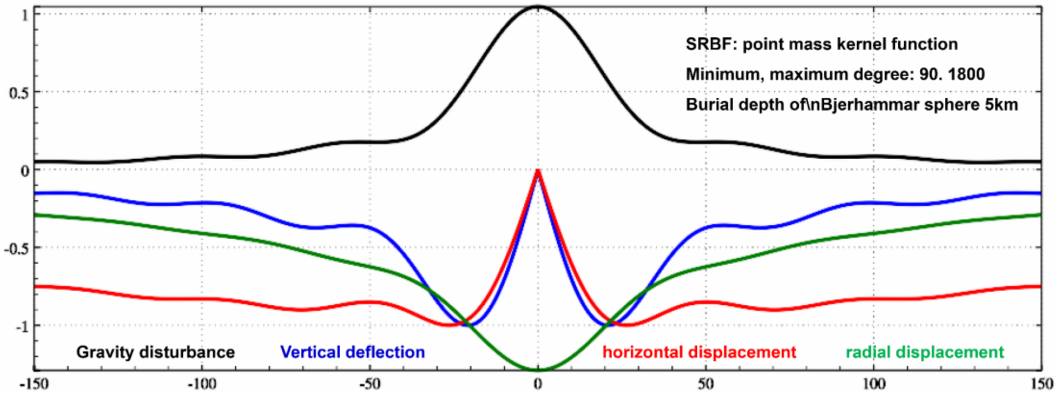


Fig.2 Near-region properties of SRBF spatial curve of load effect on geopotential differential variable

Comparing Fig.1 and Fig.2, it can be seen that the convergence property of SRBF near the calculation point is obviously better than that of load Green's function even for the load effect on radial displacement. The SRBFs of load effects on gravity disturbance, vertical deflection and horizontal displacement are monotonically convergent within 20 km near the calculation point. It can be seen that the high-degree oscillation and non-convergence problems of load Green 's function can be effectively solved by using SRBF instead.

8.6.5 First and second order horizontal partial derivatives of ψ

$$\frac{\partial\psi}{\partial\varphi}=-cos\alpha,\quad \frac{\partial\psi}{\partial\lambda}=-cos\varphi sin\alpha \tag{6.34}$$

where, α is the geodetic azimuth of ψ, which can be obtained from the spherical trigonometric formula:

$$sin\psi cos\alpha=cos\varphi sin\varphi'-sin\varphi cos\varphi' cos(\lambda'-\lambda) \tag{6.35}$$

$$sin\psi sin\alpha=cos\varphi' sin(\lambda'-\lambda) \tag{6.36}$$

Taking the partial derivative with respect to φ on both sides of equation (6.35), considering (6.34), we have:

$$sin\psi\frac{\partial^2\psi}{\partial\varphi^2}=-\sin\varphi sin\varphi'-cos\varphi cos\varphi' cos(\lambda'-\lambda)+cos\psi cos^2\alpha \tag{6.37}$$

In the same way, taking the partial derivatives of both sides of equation (6.36) with respect to λ, we have:

$$-cos\psi cos\varphi sin^2\alpha+sin\psi\frac{\partial^2\psi}{\partial\lambda^2}=-cos\varphi' sin(\lambda'-\lambda), \tag{6.38}$$

so that we can get:

$$sin\psi \frac{\partial^2\psi}{\partial\lambda^2} = -cos\varphi' sin(\lambda' - \lambda) + cos\psi cos\varphi sin^2\alpha \quad (6.39)$$

8.6.6 SRBF coefficients estimation with edge effect suppression

Substituting the Legendre coefficient B_n in Table 5 into the equations (6.20)~(6.33), we can obtain the basic observation equations for regional load deformation field approach with the (residual) geodetic variations $F(x_i)$ as the observations and the SRBF coefficients $\{d_k\}$ as the unknowns.

$$L = \{F(x_i)\}^T = A\{d_k\}^T + e \quad (i = 1, \cdots, M; k = 1, \cdots, K) \quad (6.40)$$

where A is the $M \times K$ design matrix, e is the $M \times 1$ observation error vector, M is the number of observations, K is the number of RBF centers, that is, the number of unknowns $\{d_k\}$, and x_i is the position of the observations.

ETideLoad proposes an algorithm that can improve the performance of parameter estimation by suppressing edge effect. When the SRBF center v is located at the margin of the calculation area, its corresponding SRBF coefficient is set to zero, that is, $d_v = 0$ as the observation equation to suppress the edge effect. The normal equation with the additional suppression of edge effect constructed by ETideLoad is:

$$[A^T PA + \epsilon\Xi]\{d_k\}^T = A^T PL \quad (6.41)$$

where Ξ is a diagonal matrix, whose element is equal to 1 only when the SRBF center corresponding to its subscript is in the margin of the area, and the others are zero. ϵ is equal to the diagonal standard deviation of the cofactor matrix $A^T PA$.

The action distance dr of SRBF centers is required to be equal to maintain the spatial consistency of the approach performance of load deformation field. Where dr corresponds to the domain of the SRBF argument, so any observation variation is a linear combination of the spherical radial basis functions of the SRBF centers only within the radius dr.

ETideLoad improves the ill-conditioned or singularity of $A^T PA$ by adding some observation equations that can suppresses edge effect to improve the stability and reliability of parameter estimation without the regularization of the normal equation.

8.6.7 SRBF approach from heterogeneous geodetic variations

ETideLoad proposes a SRBF load deformation filed approach method that can suppress edge effect and adjust the contribution of the given type of observation variations at the same time. The normal equation is:

$$\sum_i^{i\neq j}\left(\frac{1}{\varepsilon_i}A_i^T P_i A_i\right) + \frac{\kappa^2}{\varepsilon_j}A_j^T P_j A_j + \epsilon\Xi\{d_k\}^T = \sum_i^{i\neq j}\left(\frac{1}{\varepsilon_i}A_i^T P_i L_i\right) + \frac{\kappa^2}{\varepsilon_j}A_j^T P_j L_j \quad (6.42)$$

where ε_j is the cofactor matrix combination parameter of the given type of adjustable variations, ε_i is the cofactor matrix combination parameter of the i $(i \neq j)$ variation, and κ is the contribution rate of the adjustable variation j.

ETideLoad multiplies the normal equation coefficient matrix $A_j^T P_j A_j$ and constant matrix $A_j^T P_j L_j$ of the adjustable variation$j$ by κ respectively, to increase ($\kappa > 1$) or decrease ($\kappa < 1$) the contribution of the adjustable variation.

(2) Parameter estimation method with different types of heterogeneous variations

The parameter estimation with several types of variations usually employs the variance component estimation method. In this case, the normal equation need be solved by an iterative solution. The initial variance is the variance of the source variations, and the residual variation variance of the previous iteration result is employed in the iterative process.

Variance component estimation method affected by observation variation errors, not only has the risk of no stable solution, but also interferes with the analytical nature of the load deformation field approach algorithm. ETideLoad proposes a cofactor matrix diagonal standard deviation method to combinate different types of heterogeneous variations for estimation of the SRBF coefficients, to instead of the common variance component estimation method. Which takes ε_i and ε_j as the cofactor matrix diagonal standard deviation of the variation i and cofactor matrix diagonal standard deviation of the adjustable variation j, respectively.

Using the cofactor matrix diagonal standard deviation method, the properties of the parameter estimation solution are only related to the space distribution of the observation variations without influence of observation errors, so the normal equation does not need be iteratively solved. Which is conducive to combination of various types of observation variations with extreme differences in space distribution and improve the analytical nature of the SRBF approach algorithm.

(3) The cumulative SRBF approach method to achieve the best approach of the load deformation field

The target field elements are equal to the convolution of the observation variations and the filter SRBF. When the target field elements and the variations are of different types, it is difficult for one SRBF to effectively match the spectral center and bandwidth of the variations and the target field element at the same time, which would make the spectral leakage of the target field element. In addition, the SRBF type, the minimum and maximum degree of Legendre expansion and the SRBF centers distribution also affect the approach performance. Therefore, only the optimal estimation of SRBF coefficient with the burial depth as parameter is not enough to ensure the best approach of load deformation field.

To solve this key problem, according to the linear additivity of load deformation field, ETideLoad proposes a cumulative SRBF approach scheme. Using the multiple cumulative SRBF approach scheme, it is not necessary to determine the optimal burial depth.

When each SRBF approach adopts SRBF with different spectral figure, the cumulative SRBF approach can fully resolve the spectral domain signal of target field element from multiple SRBF spectral centers and bandwidths, and then optimally restore the target field element in space domain.

Every cumulative approach can be considered that the current load deformation field is refined by the remove-restore scheme with the previous load deformation field as the reference field. Generally cumulative 1 ~ 3 times can obtain a stable solution.

ETideLoad gives the effectiveness principle of the parameter optimization and cumulative approach: ① The estimated load EWH and its deformation field in space is continuous and differentiable, and ② the residual standard deviation of the variations is obviously reduced, and the residual statistical average tends to zero.

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2	Spherical harmonic synthesis on ocean tidal load effects outside solid Earth	OTideloadharmsynth
3	Spherical harmonic synthesis on atmosphere tidal load effects outside solid Earth	ATideloadharmsynth
4	Computation of Earth pole shift and ocean pole tide effects outside solid Earth	Poleshifteffectscalc
5	Computation of permanent tidal effects and	Permanentdgeocenter

	correction of Earth's mass center	
6	Computation of solid Earth and load tidal effects on geodetic networks	Controlnetworktidef
7	The regional approach of load tidal effects by load Green's Integral	Tdloadgreenintegral
8	Numerical forecast of various tidal effects on surface all-element geodetic variations	SolidLoadtidecalctl
9	Separation and processing of gross errors in geodetic variation time series	TmsrsErrorseppreproc
10	Low-pass filtering and signal reconstructing for irregular time series	Tmsrslowpfltrconstr
11	Weighted operation, difference, integral and interpolation on time series	TmsrsAddifferinterp
12	Normalized extraction from batch time series of geodetic monitoring network	Tmsrsbatchnormalize
13	Processing and analysis on batch time series of geodetic monitoring network	Tmsrsnetwkanalyspro
14	Construction and analysis on record time series from geodetic network	Tmrecordanalysproc
15	Processing and analysis on variation (vector) grid time series	Tmgridanalysisproc
16	Multi-form spatiotemporal interpolation from grid time series	Tmgrdinterpolation
17	Spherical harmonic analysis on global surface load time series	Loadspharmonanalys
18	Spherical analysis on tide parameters and construction of tidal load model	Loadtidespharmsynth
19	Computation of the load model value by spherical harmonic synthesis	Loadspharmsynthesis
20	Computation of load deformation field by spherical harmonic synthesis	Loadeformharmsynth
21	Regional approach of load deformation field by Green's Integral	Loadfmrntgreenintg
22	Regional approach of load deformation field using SRBFs	LoadfmtewhSRBF
23	Load deformation field monitoring from heterogeneous variations with Green's integral constraints	LoadestimateGreen
24	Load deformation field monitoring from heterogeneous variations by spherical radial basis functions	LoadestimateSRBF
25	Geodynamic calculation on geodetic field grid time series	Loadfmgridtmdyncalc
26	Complete computation processes of high-resolution regional load deformation field time series	Loadfmfdcalcdemo
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28	Pseudo-stable adjustment of record time series for geodetic network variations	Tmrecordnetwkadjust
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