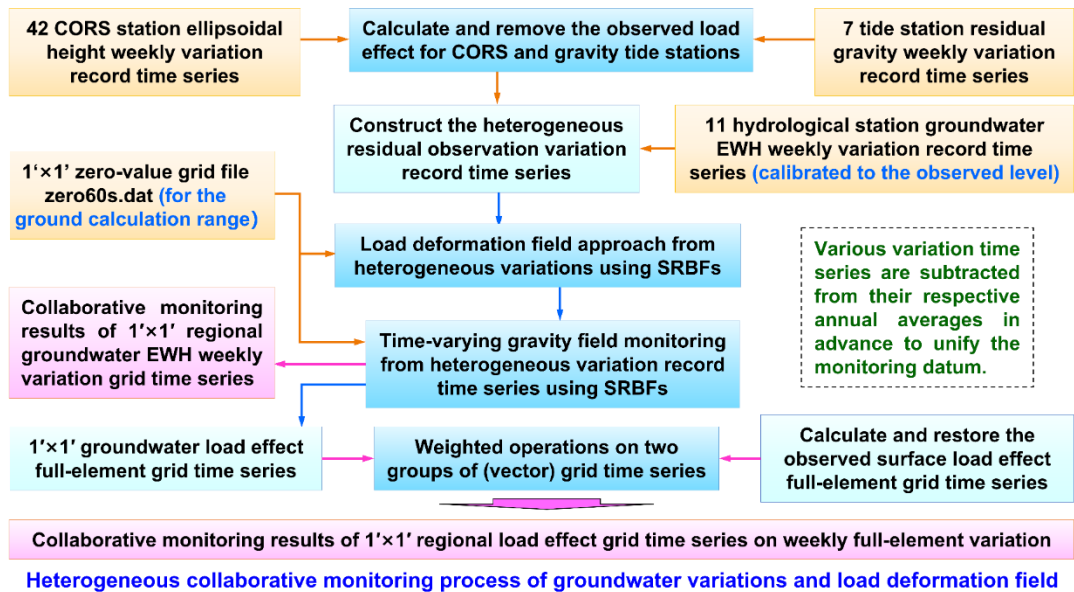


## Heterogeneous collaborative monitoring process of groundwater variations and load deformation field

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'.



**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.

**Step 2: Calculate and remove the observed load effect and construct the heterogeneous residual observation variation record time series according to the agreed format.**

Interpolation of irregular variation time series from grid time series | **Interpolation of given record time series from grid time series** | Interpolation at the given location and time from grid time series | Construction of record time series by space-time interpolation | Reconstruction of grid time series according to given spatiotemporal resolution

Open any variation grid time series file

Set the wildcard of the grid file names  
Ordinal Number of the first wildcard in the file name: 4  
Number of consecutive wildcards in file name: 10

Open the record time series file

Column ordinal number of first sampling epoch in header: 5  
Column ordinal number of first sampling variation in record: 7

Spatial interpolation mode: Gaussian function  
Temporal interpolation mode: Trigonometric function estimation

Program Process \*\* Operation Prompts

>> [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.  
>> Open any variation grid time series file C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/surfwatereff\_grav/Grdcg2019022712.dat.  
>> Open the record time series file C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/gravobs.txt.  
>> Enter the file format parameters according to the text box below. After giving the output file name, click the control button [Import setting parameters].  
>> Save the results as C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/gravsurfw.txt.  
>> The program also outputs the remnant variation record time series file C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/gravsurfw.mt 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.  
\*\* The grid time series files searched by wildcard instantiation:  
C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/surfwatereff\_grav/grdcg2019022712.dat  
C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/surfwatereff\_grav/grdcg2019032712.dat  
C:/ETideLoad4.5\_win64en/examples/Landwdfmonitordemo/surfwatereff\_grav/grdcg2019041712.dat

Save the results as | Import setting parameters | Start computation

4	6	1	26	2019032712	2019030612	2019031312	2019032012	2019032712	2019040312	2019041012
Gravtd	98.0147	26.3549	0	1.0	3	-4.4577	-4.6250	-4.8507	-5.7569	
Gravtd	98.6582	26.0442	0	1.0	3	-7.7705	-7.8814	-8.1806	-8.7841	
Gravtd	100.7779	25.6125	0	1.0	3	-5.9367	-5.9056	-6.0923	-7.0614	
Gravtd	100.4539	26.2931	0	1.0	3	-4.4210	-4.5406	-4.7794	-5.7430	
Gravtd	99.5602	25.1185	0	1.0	3	-4.5239	-4.5828	-4.8460	-5.7905	
Gravtd	98.7893	24.9545	0	1.0	3	-5.3455	-5.5663	-5.7431	-6.3228	
Gravtd	100.6908	24.2371	0	1.0	3	-4.8397	-4.9158	-5.1177	-6.2023	

The observed surface loads here include the surface atmosphere, soil water, vegetation water, lake and river water, and sea level variation loads.

- The latitude and longitude of the site to be interpolated should not exceed the latitude and longitude range of the grid time series by too much.
- When there is large noise or more default values in the variation (vector) grid or their time series, Gaussian function method is recommended for time interpolation.

The observed surface loads in this example include surface atmosphere, soil water, vegetation water, lake and river water, and sea level variation loads.

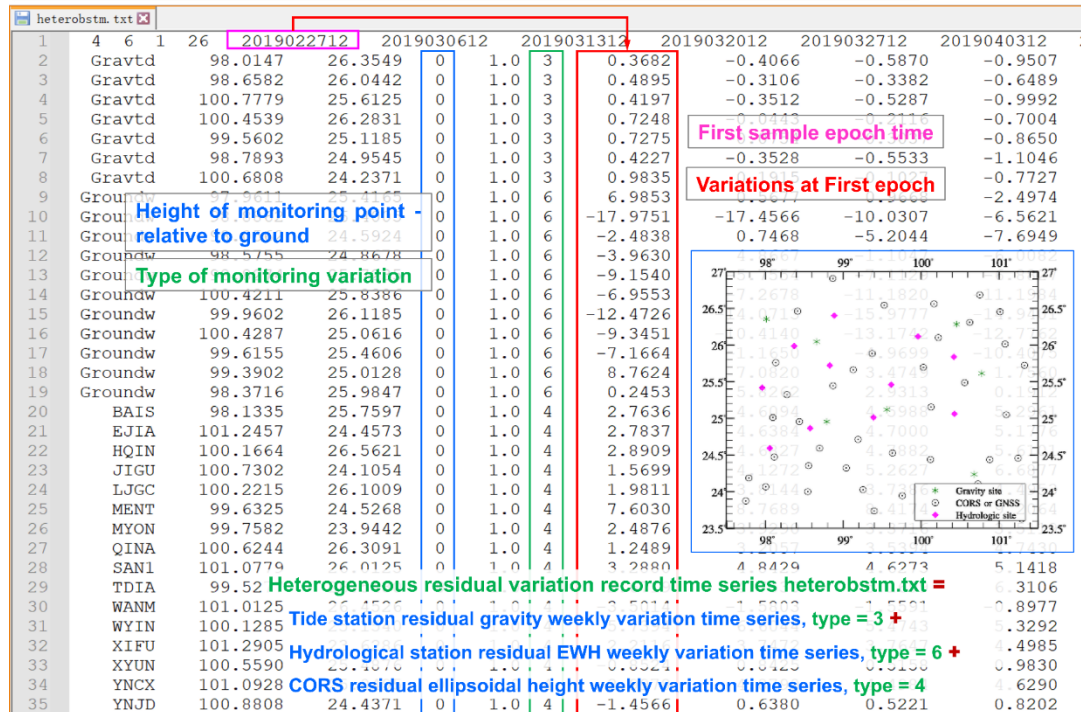
According to the agreed format in ETideLoad4.5, merge the 11 hydrological station groundwater EWH weekly variation, 7 tide station residual gravity weekly variation and 42 CORS residual ellipsoidal height weekly variation record time series to generate the heterogeneous residual observation variation 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 ( $\mu\text{Gal}$ ), = 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'x1' 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 3: Design the reasonable setting parameters for time series SRBF approach.**

The screenshot shows the software interface for Step 3. The main window is titled "Load deformation field monitoring from heterogeneous variations by spherical radial basis functions". It is divided into several sections:

- Left Panel:** Configuration options for the SRBF approach, including:
  - Open the geodetic variation record time series file: Column ordinal number of the first epoch time in header (5), Column ordinal number of the first variation in record (7), The column ordinal number of the variation type in record (6), The column ordinal number of the weights in record (5), The column ordinal number of the current variations in record (7).
  - Parameters of the first SRBF approach: Mean distance between geodetic sites (6.0 km), Select SRBF radial multipole kernel, minimum degree (0), maximum degree (900), burial depth of Bjerhammar sphere (1.00km), action distance of SRBF center (200km).
  - Parameters of cumulative SRBF approach: Select SRBF Poisson wavelet kernel, order m (0), minimum degree (720), maximum degree (1800), burial depth of Bjerhammar sphere (5.00km), action distance of SRBF center (60km).
- Center Panel:** A list of file paths and a box titled "Design the reasonable setting parameters in advance according to the principle below". The box contains a list of file paths:
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFewh2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFgeoid2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFgrav2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFgrndtilt2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFellipht2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFhorzdisp2019022712.dat
  - C:\ET1deLoad4\_5\_win64en\examples\Landdefmonitordemo\GroundSRBFestim\SRBFvertdef2019022712.dat
- Right Panel:** A graph titled "Algorithm of SRBF Approach" showing multiple time series plots of various parameters over time.
- Bottom Panel:** Four maps showing spatial distributions:
  - Spatial distribution of geodetic sites: A map showing the locations of geodetic sites.
  - Land water EWH variations (cm): A heatmap showing variations in equivalent water height.
  - Ground gravity variations (µGal): A heatmap showing variations in ground gravity.
  - Orthometric height variations (mm): A heatmap showing variations in orthometric height.

**Legend:**

- ① 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 geodetic height variations (mm) for CORS network or GNSS monitoring network, ⑤ normal or orthometric height variations (mm) from leveling monitoring network, and ⑥ equivalent water height variations (cm) from hydrological monitoring stations.
- ⑦ 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 average tends to zero.

**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  $1 \times 1'$  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.

- ① SRBFgeoid\*\*\*.dat is the residual load effect grid file on geoid or height anomaly (mm),
- ② SRBFterrgrav\*\*\*.dat is the residual load effect grid file on ground gravity (µGal),
- ③ SRBFgravdist\*\*\*.dat is the residual load effect grid file on gravity disturbance (µGal),
- ④ SRBFgrndtilt\*\*\*.dat is the residual load effect vector grid file on ground tilt (SW, to the south and to the west, mas),
- ⑤ SRBFvertdef\*\*\*.dat is the residual load effect vector grid file on vertical deflection (SW, to the south and to the west, mas),
- ⑥ SRBFhorzdisp\*\*\*.dat is the residual load effect vector grid file on horizontal displacement (EN, to the east and to the north, mm),
- ⑦ SRBFellipht\*\*\*.dat is the residual load effect grid file on ground radial displacement (mm),

⑧SRBForthogt\*\*\*.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).

**Step 4: Estimate the residual EWH and 10 kinds of residual load effect weekly variation grid time series**

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

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

Algorithm of SRBF Approach

Open the geoidetic variation record time series file

Open the calculation surface height grid file

Create or select the results folder

Save program process as

Column ordinal number of the first epoch time in header: 5

Column ordinal number of the first variation in record: 7

The column ordinal number of the variation type in record: 6

The column ordinal number of the weights in record: 5

Mean distance between geoidetic sites: 6.0 km

Parameters of the first SRBF approach

Select SRBF: radial multipole kernel

order m: 0

minimum degree: 9

maximum degree: 900

burial depth of Bjerhammar sphere: 1.00km

action distance of SBRF center: 200km

Parameters of cumulative SRBF approach

Select SRBF: radial multipole kernel

order m: 0

minimum degree: 720

maximum degree: 1800

burial depth of Bjerhammar sphere: 5.00km

action distance of SBRF center: 60km

Type of adjustable variations: gravity disturbance var

Solution of normal equation: LU triangular decomp

Contribution rate x of adjustable variations: 1.00

Cumulative SRBF approach times: 1

Import setting parameters

Start Computation

using the setting parameters Just designed

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFterograv2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFgravdist2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFgrndt11c2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFvestdisp2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFhorzdis2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFfullipht2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBForthogt2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFgradient2019082112.dat

C:\ETideLoad4\_5\_win64en/examples/Landwdfmonitordemo/GrondwSRBFestim\SRBFhorzgrad2019082112.dat

Extract the effects to be plot

Plot

The monitoring epoch time 2019082112

Spatial distribution of geoidetic sites

Land water EWH variations (cm)

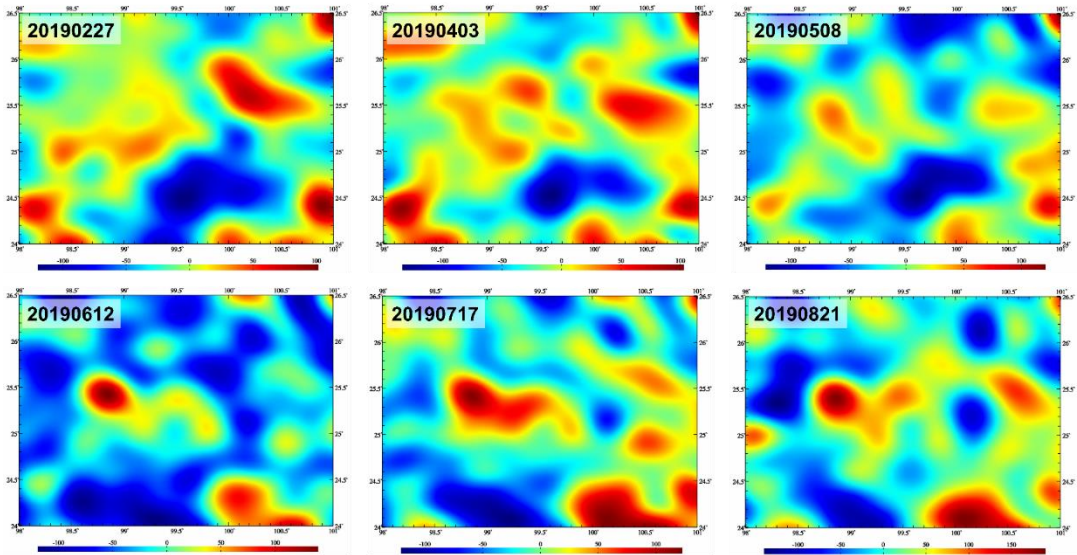
Ground gravity variations (µGal)

Orthometric height variations (mm)

The geoidetic 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 geoidetic height variations (mm) from CORS network or GNSS monitoring network, ⑤ normal or orthometric height variations (mm) from leveling monitoring network, and ⑥ equivalent water height variations (cm) from hydrological monitoring stations.

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 average tends to zero.

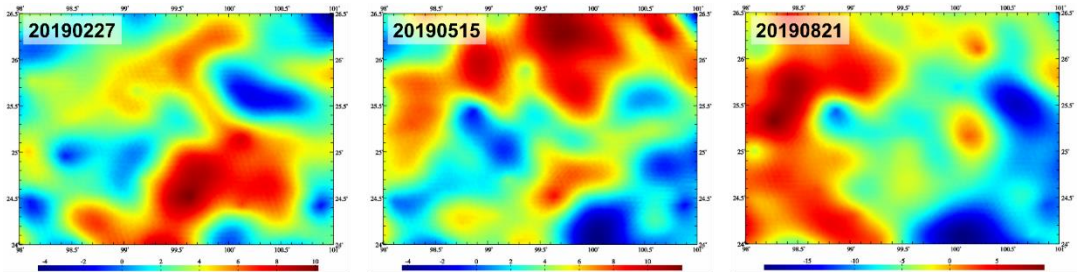
Heterogeneous collaborative monitoring: 42 CORS stations, 7 gravity tide stations and 11 hydrological stations



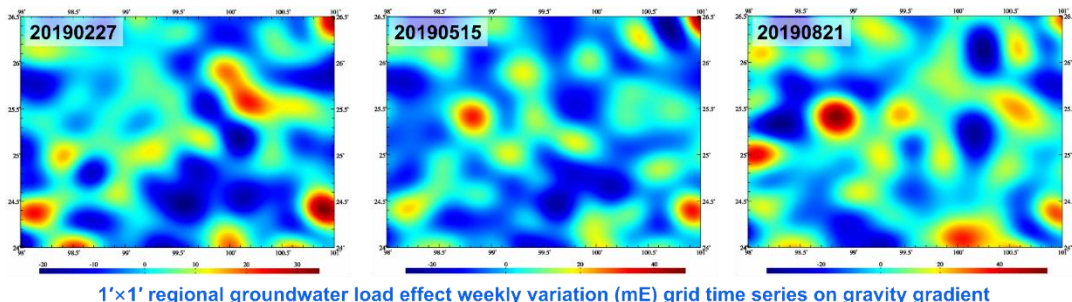
Collaborative monitoring results of 1'x1' regional groundwater EWH weekly variation grid time series

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'x1' regional groundwater load effect weekly variation (mm) grid time series on ground orthometric height



**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.

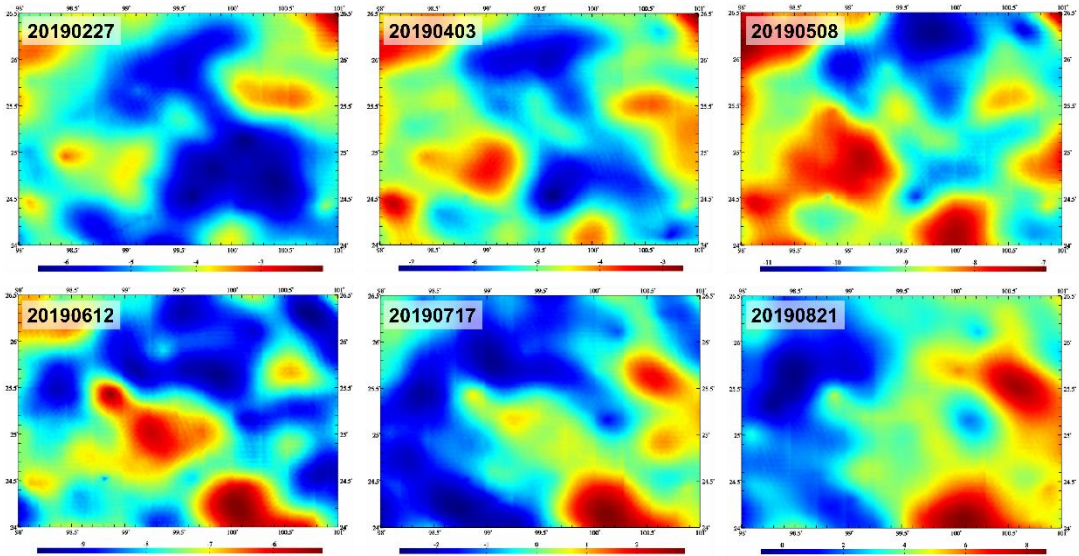
Call the function [Weighted operations on two groups of grid time series], directly add the full element weekly variation grid time series of the observed surface load effects to the full element weekly variation grid time series of the residual (groundwater) load effects, respectively, to generate the regional 1'x'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.

**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**

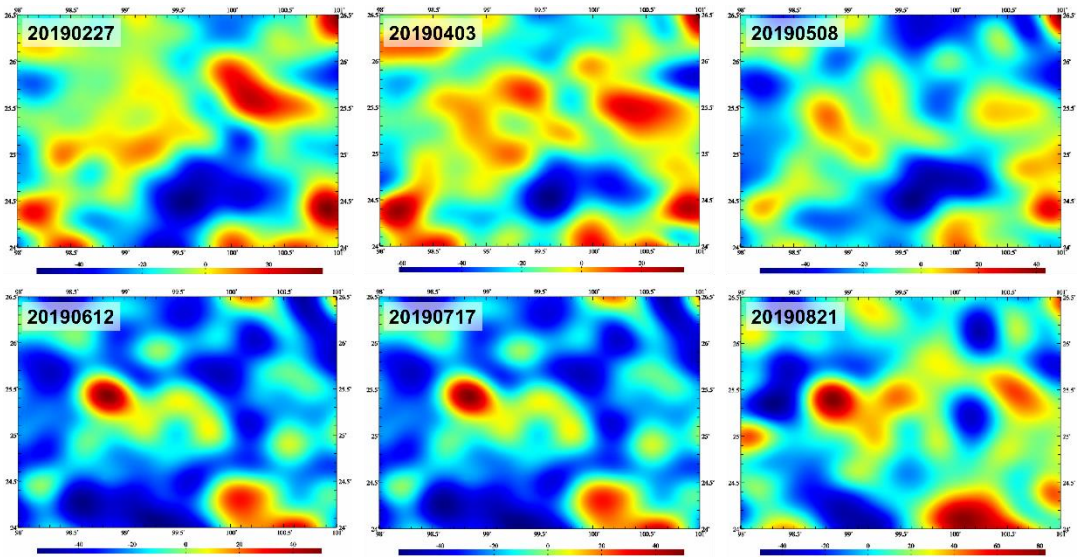
**Weighted operations on two groups of (vector) grid time series**

The software interface shows the following configuration and results:

- Operation Mode:** Plus +
- Weights:** The first weight: 1.00, The second weight: 1.00
- File Paths:** A list of 26 file paths starting with 'C:/ETideload4\_5\_win64en/examples/Landwdfmonitordemo/surflod\_nogroundwks/sub/20190500.dat' through '20190821.dat'.
- Operation Prompts:**
  - >> Program Process \*\* Operation Prompts
  - >> Setting parameters have been imported in the program!
  - \*\* Click the control button [Start computation], or the tool button [Start computation]...
  - >> Computation start time: 2023-05-18 15:23:19
  - >> Complete the weighted operations of two groups of grid time series files! There are 26 pairs of grid time series files operated.
  - >> Computation end time: 2023-05-18 15:23:20
- Results:** A 3D surface plot showing the weighted sum of two input surfaces, with a corresponding data grid below. The grid contains numerical values such as 98.000000, 101.000000, 24.000000, etc., arranged in a grid format.



Collaborative monitoring results of 1'x1' surface load effect weekly variation (mm) grid time series on geoid



Collaborative monitoring results of 1'x1' load effect weekly variation ( $\mu\text{Gal}$ ) grid time series on ground gravity

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.

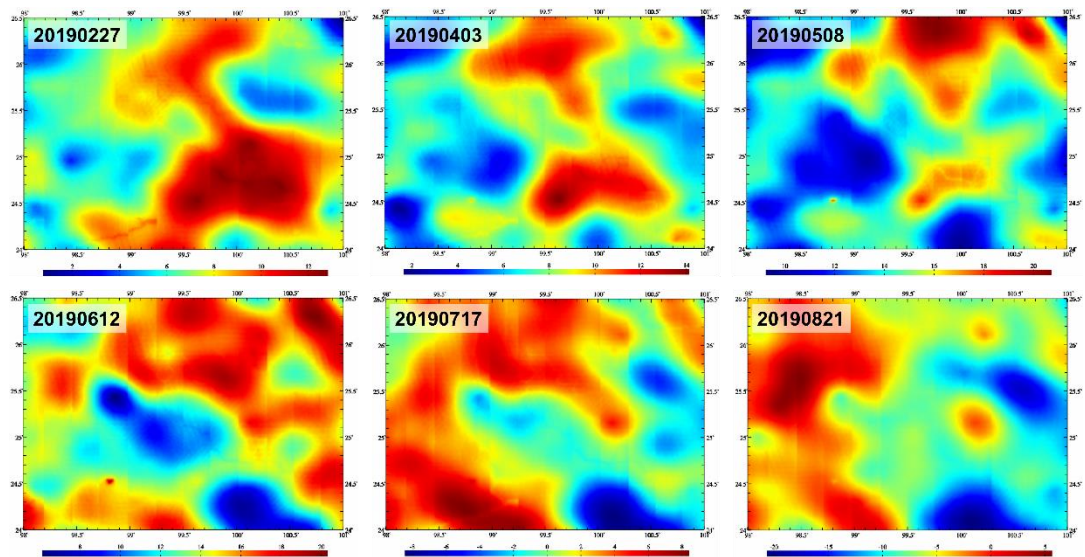
(1) The algorithm can effectively solve the problems of high-degree oscillation and poor convergence of Green's function and spectrum leakage and singularity of Green's integral in the near area around the calculation point, and then realize the collaborative monitoring of GNSS, gravity, leveling, ground 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

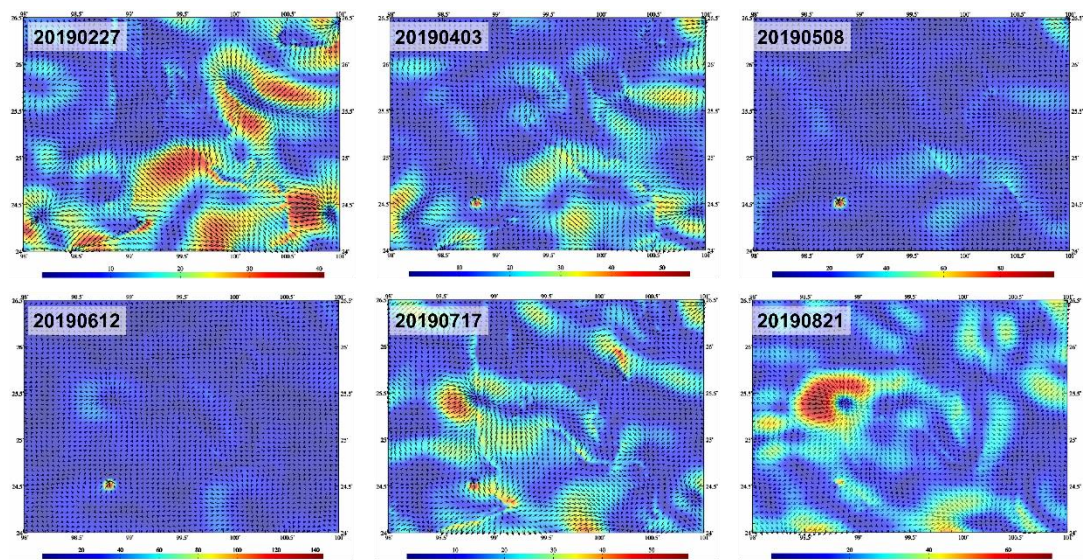


standard deviation of cofactor matrix to avoid the load deformation field affected by the observation errors. The algorithm has high stability and universality, which is suitable for massive computation of multiple time series collaborative monitoring.

(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'x1' load effect weekly variation (mm) grid time series on ground ellipsoidal height



Collaborative monitoring results of 1'x1' load effect weekly variation (mas) vector grid time series on ground tilt