PRIDE PPP-AR II MANUAL

Multi-GNSS Precise Point Positioning with Ambiguity Resolution

by

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GNSS Research Center, Wuhan University

Dedicated to those

who are devoted to high-precision GNSS

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1 Introduction

1.1 Acknowledge

PRIDE PPP-AR (Precise Point Positioning with Ambiguity Resolution) originates in Dr. Maorong Ge's efforts on PPP-AR and later developed by Dr. Jianghui Geng's team. It is an open-source software package which is based on many GNSS professionals' collective work in GNSS Research Center, Wuhan University. We would like to thank them all for their brilliant contributions to this software. No proprietary modules are used anymore in the software. We make this package open source with the goal of benefiting those professionals in their early career, and also advocate the geodetic and geophysical applications of PPP-AR. Especially, we hope that this package can contribute to high-precision applications in geosciences such as crustal motion and troposphere sounding studies. The entire open-source project is funded by the National Natural Science Foundation of China (No. 42025401) and is under the auspices of IAG SC 4.4 "GNSS Integrity and Quality Control".

PRIDE PPP-AR can be downloaded at https://github.com/PrideLab/PRIDE-PPPAR. The precise products can be accessed at ftp://igs.gnsswhu.cn/pub/whu/phasebias/. Latest updates for Support, Training courses and FAQ can be found at https://pride.whu.edu.cn. The copyright of this package is protected by GNU General Public License (version 3). Relevant publications are

Geng J, Wen Q, Zhang Q, Li G, Zhang K (2022) GNSS observable-specific phase biases for all-frequency PPP ambiguity resolution. J. Geod. 96, 11. doi:10.1007/s00190-022-01602-3

Geng, J., Chen, X., Pan, Y. & Zhao, Q. (2019a). A modified phase clock/bias model to improve PPP ambiguity resolution at Wuhan University. Journal of Geodesy, 93(10), 2053-2067.

Geng, J., Chen, X., Pan, Y., Mao, S., Li, C., Zhou, J., Zhang, K. (2019b) PRIDE PPP-AR: an open-source software for GPS PPP ambiguity resolution. GPS Solutions 23:91 doi:10.1007/s10291-019-0888-1.

Geng J, Yang S, Guo J. Assessing IGS GPS/Galileo/BDS-2/BDS-3 phase bias products with PRIDE PPP-AR[J]. Satellite Navigation, 2021, 2(1): 1-15.

Geng J, Mao S. Massive GNSS network analysis without baselines: Undifferenced ambiguity resolution. J. Geophys. Res. 2021, 126(10), e2020JB021558. doi:10.1029/2020JB021558

1.2 Major Features

PRIDE PPP-AR aims at post-processing of multi-GNSS data for the science community including geodesy, seismology, photogrammetry, gravimetry, etc. The major features of PRIDE PPP-AR include:

1) GPS, GLONASS, Galileo, BDS-2/3 and QZSS capable;
2) High-rate GNSS data processing of up to 50 Hz;
3) Vienna Mapping Function 1/3 (VMF3) and GPT3 for troposphere modeling;

Note: Due to the author's limited level, excuse me for the errors or inappropriate in the manual

4) Second-order ionospheric correction;
5) High-dynamic mobile platforms applicable for aerial photogrammetry, ship-borne gravimetry, etc.;
6) Receiver clock jump mitigation;
7) Multi-day processing;
8) Satellite attitude quaternions;
9) A Windows and Mac OS GUI lite-version provided for very early career researchers;
10) Ambiguity-float PPP using data dating back to 1994 when SA was on;
11) GPS/Galileo/BDS-2/3 PPP-AR in the case of the bias-SINEX format phase biases (ftp://igs.gnsswhu.cn);
12) Adopt both rapid products (RAP) and real-time products (RTS) for more timeliness.

1.3 Contact Us

You can contact us for **bug reports** and **comments** by sending emails or leaving messages on our website.

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For Chinese users, we provide Tencent **QQ Group** service. Group Number: **971523302**. Leave your organization and name when applying for admission.

2 Version modifications

1. 2019-03-21 (v1.0)
   - Release of PRIDE-PPPAR v1.0
2. 2019-04-03 (v1.1)
   - Small bug fixing
   - RINEX-3 support
   - Fixed bug for high-rate computation
   - Support Linux-32 system (src/lib/shard/linux-32)
   - Support Mac OS system (src/lib/shard/mac)
3. 2019-05-01 (v1.2)
   - Support VMF1
4. 2019-05-23 (v1.3)
   - Auto-selection of IGS ATX
   - Change SP3 from COD to WHU since 2019
5. 2019-06-01 (v1.3)
   - Add src/utils/xyz2enu
6. 2019-07-12 (v1.3)
   - Support rapid phasebias product
7. 2019-07-16 (v1.4)
   - Add function: receiver clock jump check & recover
   - Print table valid time by pride_pppar
   - Compatibility fixing for pride_pppar.sh
   - If 'rnx2rtkp' doesn't work, please download the source code through 'https://github.com/tomojitakasu/RTKLIB/tree/rtklib_2.4.3' and compile it by yourself. The binary we provided is a 32-bit version.
8. 2019-09-05 (v1.4)
   - pride_pppar.sh: small bugs fixed
   - table: igs14.atx updated
9. 2019-12-15 (v1.4)
   - install.sh: add install tips for src/lib/libpridepppar.so
   - pride_pppar.sh: fix known bugs & add error replay for debug
   - table: jpleph_de405 updated (valid until 2040-007)
   - table: update IGS14.atx (igs14_2082.atx)
10. 2021-05-21 (v2.0)
    - Release of PRIDE PPP-AR v2.0
11. 2021-09-06 (v2.1)
    - Release of PRIDE PPP-AR v2.1
    - support quaternions
12. 2022-04-07 (v2.2)
    - Release of PRIDE PPP-AR v2.2
    - Batch script name changed from “pride_pppar” to “pdp3”, corresponding command

line input parameters also changed;

- Support multi-day processing;
- Support for quaternion products;
- No more DCB products required;
- The default products after 2020 changed to the multi-GNSS satellite orbit, clock, bias, quaternion and ERP products, which are computed and released by Wuhan University;
- The table file “leap.sec” needs to be downloaded now, and the “glonass_chn” table file is removed and replaced by the “sat_parameters” table file;
- GUI version of PRIDE PPP-AR with additional plotting functions;
- Fix known bugs.

3 Fundamentals

PPP (Precise Point Positioning) is a technology that uses external precise products (e.g., satellite orbit/clock), comprehensively considers and meticulously models various errors, processes single GNSS (Global Navigation Satellites System) receiver's observation by undifferenced calculation. It was put forward to reduce the huge computing burden of GNSS network solutions due to massive data, it has ushered in rapid development and application. Compared to the relative positioning, the popularity of PPP is that no nearby reference stations are required, the user can achieve high accuracy positioning with only a single receiver. Besides, compared to the SPP (Standard Point Positioning) based on broadcast ephemeris and pseudorange, PPP takes advantage of utilizing both pseudorange observations and carrier phase observations, and more precise satellite-related parameters.

PPP integrates the advantage of GNSS SPP and GNSS relative positioning and overcomes their disadvantages to some extent. However, PPP does not eliminate or weaken the influence of various observation errors by difference, so all error terms must be finely considered and corrected. And the number of parameters to be solved is so large that external files need to be introduced. Moreover, the phase bias caused by hardware delay from satellite ends and receiver ends will be absorbed in the ambiguity, the corresponding ambiguity will not be an integer. Therefore, the difficulty of PPP is to separate the phase bias from ambiguity to achieve ambiguity resolution (AR).

3.1 Mathematical model of PPP

For GNSS dual-frequency observations from station r to satellite s, the raw observation equation for original pseudorange and carrier-phase of the i-th frequency ($i=1,2$) in the unit of length is

$$\begin{cases} P_{r,i}^s = \rho_r^s + c(\delta t_r - \delta t^s) + \dfrac{A}{f_i^2} + d_{r,i} - d_i^s \\ L_{r,i}^s = \rho_r^s + c(\delta t_r - \delta t^s) - \dfrac{A}{f_i^2} + \lambda_i N_{r,i}^s + b_{r,i} - b_i^s \end{cases} \tag{3-1}$$

where, $P_{r,i}^s$ are pseudorange observations;$L_{r,i}^s$ are carrier-phase observations; ρ_r^s is the station-satellite geometric distance;c is the speed of light in vacuum; δt_r and δt^s are the receiver and satellite clock errors, respectively; $\dfrac{A}{f_i^2}$ denotes the impact of the first-order ionosphere delays; f_1 and f_2 are the frequencies of L_1 and L_2; λ_1 and λ_2 are the corresponding wavelength; N_1 and N_2 are integer ambiguities; $d_{r,i}$ and d_i^s denote the pseudorange bias of the i-th frequency, which is caused by the hardware delay of the receiver and the satellite; $b_{r,i}$ and b_i^s denote the phase bias of the i-th frequency, which is caused by the hardware delay of the receiver and the satellite; for simplicity, high-order ionospheric delay, tropospheric delay, multipath effect and random noise are omitted.

The geometric distance from the satellite to the receiver in equation (3-1) can be expressed as

$$\rho_r^s = |\boldsymbol{X}^s(t_s) - \boldsymbol{X}_r(t_r)| \tag{3-2}$$

where, t_s and t_r are signal transmission time and signal reception time respectively; $\boldsymbol{X}^s(t_s)$ and $\boldsymbol{X}_r(t_r)$ is the satellite coordinate vector at the signal transmitting time and the receiver coordinate vector at the signal receiving time respectively; $|\cdot|$ represents the vector module length.

For the first-order ionospheric delay in equation (3-1), it can be eliminated by the difference between the product of the dual-frequency observations and their frequency squares, while the difference between the two frequency squares is divided by the above equation to keep the geometric distance constant. The ionosphere-free observation equation is then formed

$$\begin{cases} P_{r,0}^s = \alpha P_{r,1}^s - \beta P_{r,2}^s = \rho_r^s + c(\delta t_r - \delta t^s) + d_{r,0} - d_0^s \\ L_{r,0}^s = \alpha L_{r,1}^s - \beta L_{r,2}^s = \rho_r^s + c(\delta t_r - \delta t^s) + \alpha\lambda_1 N_{r,1}^s - \beta\lambda_2 N_{r,2}^s + b_{r,0} - b_0^s \end{cases} \tag{3-3}$$

where

$$\begin{cases} \alpha = \dfrac{f_1^2}{f_1^2 - f_2^2} \\ \beta = \dfrac{f_2^2}{f_1^2 - f_2^2} \\ \alpha - \beta = 1 \end{cases}$$

and

$$\begin{cases} d_{r,0} = \alpha d_{r,1} - \beta d_{r,2} \\ d_0^s = \alpha d_1^s - \beta d_2^s \\ b_{r,0} = \alpha b_{r,1} - \beta b_{r,2} \\ b_0^s = \alpha b_1^s - \beta b_2^s \end{cases}$$

$P_{r,0}^S$ and $L_{r,0}^S$ are the ionosphere-free pseudorange observation and carrier-phase observation, respectively. Correspondingly, $d_{r,0}$ and d_0^s are the ionosphere-free pseudorange bias at the receiver end and the satellite end, $b_{r,0}$ and b_0^s are the ionosphere-free combination phase bias at the receiver end and the satellite end respectively. The ionosphere-free combination eliminates the first-order term of ionospheric delay and is the most commonly used observation model in PPP.

3.2 Error correction of PPP

As mentioned above, PPP uses undifferenced data processing and does not eliminate or weaken the impact of various observation errors through difference. Hence all error terms must be considered finely and corrected as much as possible. Usually, there are two types of error correction: (1) model correction is used for errors that can be finely modeled, such as the correction of satellite antenna PCO/PV (Phase Center Offset/Phase Variation); (2) for the errors that cannot be accurately modeled, they can be estimated as parameters or eliminated by using combined observations. For example the tropospheric delay after model correction still needs to be estimated by adding parameters, and the low-order term of ionospheric delay error can be eliminated by using dual-frequency combined observations.

In PPP, the main error sources can be divided into three categories: (1) errors related to satellites, (2) errors related to signal propagation paths, and (3) errors related to receivers and stations.

3.2.1 Errors related to satellites

(1) Satellite ephemeris error and clock error

Satellite ephemeris error refers to the discrepancy between the orbit represented by the satellite ephemeris and the real orbit. For the satellite coordinate vector $\boldsymbol{X}^s(t_s)$ in equation (3-2), the nominal accuracy of the post precise ephemeris product of IGS (International GNSS Service) is better than 2.5cm. The user can use Lagrange interpolation to calculate the satellite coordinates at the time of signal transmission. The calculation formula of signal transmission time is:

$$t_s = t_r + \delta t_r - \tau \tag{3-4}$$

where τ is the signal propagation time. It can be calculated by the geometric distance between the satellite and the observation station after correcting various errors, and the geometric distance is related to the satellite coordinates, so iterative calculation is required in this process.

Satellite clock error can be eliminated or weakened by utilizing precise satellite clock error products, that is, it can be substituted into the observation equation as a known value. At present, the precision of IGS legacy clock error products has reached 75ps, which can fully meet the needs of PPP.

(2) Earth rotation correction

Because the earth-fixed coordinate system is rotating with the rotation of the earth, the earth-fixed coordinate system corresponding to the satellite signal transmitting time and the receiver signal receiving time is different. Therefore, it is necessary to consider this correction to calculate the geometric distance from the satellite to the receiver in the earth-fixed coordinate. Set ω as the earth rotation angular velocity, and the resulting satellite coordinate change is

$$\boldsymbol{X}^{s\prime} = \boldsymbol{R} \cdot \boldsymbol{X}^s \tag{3-5}$$

where, $\boldsymbol{R}$ is the rotation matrix

$$\boldsymbol{R} = \begin{bmatrix} \cos w\tau & \sin\omega\tau & 0 \\ -\sin\omega\tau & \cos\omega\tau & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The correction of corresponding geometric distance is

$$\Delta\rho = \frac{\omega}{c}\left[Y^s(X_r - X^s) - X^s(Y_r - Y^s)\right] \tag{3-6}$$

(3) Relativistic effects

The relativistic effect is caused by the different states (motion speed and gravity potential) of the satellite clock and the receiver clock. The change of clock frequency caused by different velocities is called the special relativity effect, and the change of clock frequency caused by different gravity potentials is called the general relativity effect. Under the combined influence of the special relativity effect and the general relativity effect, the relative clock error occurs between the satellite clock and the receiver clock, and the satellite clock moves faster than the receiver clock. Its constant part can reduce its standard frequency when producing satellite clock. However, the frequency difference between the satellite clock and the receiver clock is related to the operating speed of the satellite and its distance from the earth center, so there are still residuals after the above correction, which can be corrected by the following formula:

$$\Delta\rho_{rel} = -\frac{2}{c}\boldsymbol{X}^s \cdot \dot{\boldsymbol{X}}^s \tag{3-7}$$

where $\boldsymbol{X}^s$ is the coordinate vector of the satellite and $\dot{\boldsymbol{X}}^s$ is the velocity vector of the satellite.

In addition to the frequency drift of satellite clock, the effect of general relativity also includes the delay of the geometric distance caused by the earth's gravitational field, which is called gravitational delay. The corresponding correction can refer to relevant paper.

(4) PCO/PV for satellite

PCO of satellite antenna refers to the deviation between satellite center of mass and satellite antenna phase center. The satellite orbit products used in PPP are based on the satellite center of mass and the signal observations are ranging from the phase center of the satellite antenna. For a satellite, PCO can be regarded as a fixed deviation vector.

Because the phase center changes with time during the actual transmission and reception of signals, there is a deviation compared with the average phase center, which is called PV. It is necessary to correct the change of phase center in high-precision applications.

(5) Phase wind-up

GNSS satellite signal adopts polarization wave. When the satellite antenna or receiver antenna rotates around its longitudinal axis, the carrier phase observation value will change, and its value can be up to one cycle. When the relative rotation occurs between the transmitting antenna and the receiver antenna, the carrier phase observation value will include error. In positioning, after the antenna pointing of the receiver changes, its error will be automatically absorbed into the receiver clock error, so there is no need to consider it. Since the solar panel on the satellite needs to be always aligned with the sun, the satellite antenna will rotate slowly. After entering the eclipse period, the satellite will accelerate the rotation, resulting in the error of carrier phase observation. The influence of phase wind-up on PPP is very obvious, and this error must be taken into account.

3.2.2 Errors related to signal propagation path

(1) Ionospheric delay

The ionosphere is a dispersive medium, mainly located in the atmospheric area about 70km to 1000km above the earth's surface. In this region, some neutral gas molecules are ionized, producing a large number of electrons and positive ions, thus forming an ionized region. In dispersive media, the propagation velocity of wave is a function of wave frequency. The phase velocity of electromagnetic wave propagation in the ionosphere (the phase velocity of electromagnetic wave with single frequency) will exceed the group velocity (the propagation velocity of a group of electromagnetic wave signals with different frequencies as a whole). Therefore, in the GNSS signal, the pseduorange code is delayed and the carrier phase is advanced.

As mentioned above, to eliminate and weaken the influence of ionospheric delay, ionospheric correction models and ionospheric grid models can be adopted. In addition, dual-frequency correction can be adopted to eliminate ionospheric delay error through linear combination of observations. After using the dual-frequency observations to eliminate the first-order ionospheric influence, the influence of the remaining high-order terms is very small and can be ignored.

(2) Tropospheric delay

The troposphere is the lower part of the atmosphere and is non-dispersive at frequencies above 15 GHz. Tropospheric delay can be divided into dry component and wet component. The common method of tropospheric delay correction in PPP is to correct the tropospheric delay by using the model as a priori value, estimate the residual tropospheric delay as piecewise constant or random walk noise, and map it to the direction of satellite signal propagation path through mapping function. Tropospheric delay can be expressed as:

$$\Delta\rho_{trop} = ZTD_{dry} \cdot M_{dry} + ZTD_{wet} \cdot M_{wet} \tag{3-8}$$

where, $ZTD_{dry/wet}$ is the zenith tropospheric dry/wet component delay and $M_{dry/wet}$ is the dry/wet component mapping function.

(3) Multi-path effect

The multi-path effect means that if the satellite signal (reflected wave) reflected by the reflector near the measured station enters the receiver antenna, it will interfere with the signal (direct wave) directly from the satellite, to make the observed value deviate from the true value. Multi-path errors vary greatly, depending on the receiver environment, satellite elevation angle, receiver signal processing method, antenna gain type, and signal characteristics.

At present, there is no more effective solution to the multipath effect. The main measures to weaken the multipath error are: selecting an appropriate station site, equipping the receiver with a diameter suppression plate or circle, appropriately prolonging the observation time, estimating additional parameters, etc. Because the satellite signal with low elevation is more likely to produce multi-path effect, the cut-off elevation can also be set during data preprocessing, and the impact of multi-path effect on precise point positioning can be weakened through long-time observation and smoothing.

3.2.3 Errors related to receivers and stations

(1) Receiver clock error

Because the receiver generally adopts quartz clock, its stability is worse than satellite clock, so the polynomial fitting method is generally not applicable. Instead, the receiver clock of each observation epoch is treated as an unknown parameter. In the process of processing, the receiver clock error is usually regarded as a group of white noise. It should be noted that unlike the calculation of satellite position, the receiver clock error in equation (3-1) of the original observation method needs to be closely estimated, because in the calculation of satellite position, the measurement error is multiplied by the satellite operating speed of 3.9km/s, and the influence of measurement error on geometric distance needs to be multiplied by the vacuum speed of light.

(2) Tidal correction

Under the gravitational action of the moon and the sun, the elastic earth surface will produce periodic changes, which is called solid tide. It lengthens the earth in the connecting direction between the earth's center and the celestial body, and tends to be flat in the vertical direction. The influence of earth tide on stations includes long-term migration related to latitude and short-term term mainly composed of daily period and sub-daily period. For the daily solution of PPP, although the periodic error can be basically eliminated, the residual effect can reach 5cm in the horizontal direction and 12cm in the vertical direction.

Ocean loading results from the load of the ocean tides on the underlying crust. The displacement due to the ocean loading is one order of magnitude smaller than the earth tide. In the daily solution of PPP, the impact is mm, when the station is more than 1000km away from the coastline, the impact is negligible. The influence on a single epoch can reach 5cm.

(3) PCO/PV for receiver

When GNSS receiver is used for measurement, the measured position of antenna phase center, and the antenna height is generally measured to the position of ARP (Antenna Reference Point). These two points generally do not coincide. This deviation is called receiver antenna PCO, and the PCO is also inconsistent for signals of different frequencies. It must be considered in PPP data processing.

The phase center of the receiver antenna is not fixed, and its instantaneous phase center changes with the elevation angle, azimuth angle and signal strength of the received signal. Similarly, the difference between the instantaneous phase center and the average phase center of the receiver antenna is called the antenna phase center change.

3.3 Undifferenced ambiguity resolution

The hardware delay term in equation (3-1) includes two parts which are the time-invariant part and the time-varying part, i.e.,

$$\begin{cases} d_{r,*} = \Delta d_{r,*} + \delta d_{r,*} \\ d_*^s = \Delta d_*^s + \delta d_*^s \\ b_{r,*} = \Delta b_{r,*} + \delta b_{r,*} \\ b_*^s = \Delta b_*^s + \delta b_*^s \end{cases} \tag{3-9}$$

where, $*$ is a wildcard character representing observations of different frequencies and their combination.

Another commonly used combined observation in PPP is Melbourne-Wübbena combination.

$$\begin{aligned} L_{r,m}^s &= \lambda_w\left(\frac{L_{r,1}^s}{\lambda_1} - \frac{L_{r,2}^s}{\lambda_2}\right) - \lambda_n\left(\frac{P_{r,1}^s}{\lambda_1} + \frac{P_{r,2}^s}{\lambda_2}\right) \\ &= \lambda_w\left(N_{r,w}^s + \frac{b_{r,1} - b_1^s}{\lambda_1} - \frac{b_{r,2} - b_2^s}{\lambda_2}\right) - \lambda_n\left(\frac{d_{r,1} - d_1^s}{\lambda_1} + \frac{d_{r,2} - d_2^s}{\lambda_2}\right) \end{aligned} \tag{3-10}$$

$\lambda_w = \dfrac{c}{f_1 - f_2}$ and $\lambda_n = \dfrac{c}{f_1 + f_2}$ are the wide-lane wavelength and narrow-lane wavelength respectively; $N_{r,w}^s = N_{r,1}^s - N_{r,2}^s$ is the ambiguity of wide-lane. M-W combination eliminates ionospheric delay, geometric distance from satellite to receiver, satellite clock and receiver clock. It is only affected by multipath effect, measurement noise and hardware delay. Because the wide-lane wavelength λ_w is up to 86cm, it is easy to determine its integer ambiguity, that is, the wide lane ambiguity is solved through M-W combination $L_{r,m}^s$. The corresponding receiver phase deviation and satellite phase deviation are

$$\begin{cases} b_{r,w} = \lambda_w\left(\dfrac{b_{r,1}}{\lambda_1} - \dfrac{b_{r,2}}{\lambda_2}\right) - \lambda_n\left(\dfrac{d_{r,1}}{\lambda_1} + \dfrac{d_{r,2}}{\lambda_2}\right) \\ b_w^s = \lambda_w\left(\dfrac{b_1^s}{\lambda_1} - \dfrac{b_2^s}{\lambda_2}\right) - \lambda_n\left(\dfrac{d_1^s}{\lambda_1} + \dfrac{d_2^s}{\lambda_2}\right) \end{cases} \tag{3-11}$$

After the ambiguity of wide-lane is resolved through M-W combination, we can substitute $N_{r,2}^{s}=N_{r,1}^{s}-\check{N}_{r,w}^{s}$ into ionosphere-free combination equation (3-3) which can then be transformed into

$$
\begin{cases} P_{r,0}^{s}=\alpha P_{r,1}^{s}-\beta P_{r,2}^{s}=\rho_r^s+c(\delta t_r-\delta t^s)+d_{r,0}-d_0^s \\ \overline{L}_{r,0}^{s}=L_{r,0}^{s}-\beta\lambda_2\check{N}_{r,w}^{s}=\rho_r^s+c(\delta t_r-\delta t^s)+\lambda_n N_{r,1}^{s}+b_{r,0}-b_0^s \end{cases} \tag{3-12}
$$

where, $\check{N}_{r,w}^{s}$ denotes the resolved wide-lane ambiguity; and the $N_{r,1}^{s}$ in this formula is also called narrow-lane ambiguity; $\overline{L}_{r,0}^{s}$ is the ionosphere-free combined carrier-phase observation after correcting the wide-lane ambiguity.

In the process of GNSS data, the ambiguity in the continuous arc is generally constrained as a constant, and the clock error is generally estimated as white noise. In this way, the constant part of the hardware delay is absorbed by the ambiguity parameter, and the time-varying part is absorbed by the clock parameter. Therefore, whether the hardware delay is constant or varies with time, the effect on the ambiguity is to introduce a constant deviation. The key to fixing the un- differenced ambiguity is to separate the constant bias from the integer ambiguity.

There are several methods to fix the undifferenced ambiguity: integer clock model, decoupled clock model, UPD (uncalibrated phase delay) model and phase clock/bias model.

(1) Integer clock model and decoupled clock model

The basic idea of the integer clock model is to assume that the wide-lane phase bias remains stable in a single day, estimate the wide-lane ambiguity through M-W combination, extract its fractional part from the wide-lane ambiguity estimation as the wide-lane phase bias, and the integer part is the wide-lane integer ambiguity. Then the fixed wide-lane ambiguity is brought into the ionosphere-free combination to solve the narrow-lane ambiguity. By rounding the resolved narrow-lane ambiguity, the corresponding narrow-lane phase bias is absorbed into the clock parameters. The decoupled clock model is similar to the integer clock model, except that the wide lane phase bias is estimated epoch by epoch. The positioning accuracy of integer clock model is high, but the satellite clock product is incompatible with IGS legacy clock product and DCB (Differential Code bias) product. The decoupled clock model needs to estimate two sets of clock products, which is rarely used by analysis centers and scientific research institutions.

(2) UPD model

In UPD model, the processing of wide-lane phase bias is the same as that of integer clock model, and the calculation process of narrow-lane phase deviation is consistent with that of wide-lane phase bias. The UPD model directly uses the IGS legacy clock product, but its narrow-lane phase bias is not stable, it needs to be estimated every ten minutes empirically, and the positioning accuracy is lower than the integer clock model.

It should be noted that the IGS legacy clock product is defined as dual-frequency ionosphere-free combined clock. Therefore, in its legacy products, in addition to the real satellite clock, it also includes the hardware bias part of ionosphere-free combination. Considering the weight difference between pseudorange observation and carrier-phase observation, the clock includes the time-invariant part of pseudorange bias and the time-varying part of phase bias. Its theoretical form is

$$\begin{cases}\delta t_{r,F} = \delta t_r + \dfrac{\Delta d_{r,0} + \delta b_{r,0}}{c} \\ \delta t_F^s = \delta t^s + \dfrac{\Delta d_0^s + \delta b_0^s}{c}\end{cases} \tag{3-13}$$

(3) Phase clock/bias model

The instability of narrow-lane phase bias in UPD model is considered to be due to the influence of satellite orbit/clock error and residual atmospheric error. Based on integer clock model and UPD model, phase bias/clock calculates the mean value of narrow lane ambiguity in UPD model in a single day and fixes it in subsequent data processing, then re-estimates the clock parameter, and absorbs the residual narrow-lane phase bias relative to the mean value of narrow-lane ambiguity into the clock error parameter. Therefore, the required integer ambiguity and its bias of narrow-lane are the integer part and fractional part of the mean value of narrow-lane ambiguity respectively. The re-estimated clock is the phase clock in the model. In the UPD model, the narrow-lane phase bias between the receiver and the satellite is

$$\begin{cases}b_{r,n} = \Delta b_{i,0} - \Delta d_{i,0} \\ b_n^s = \Delta b_0^s - \Delta d_0^s\end{cases} \tag{3-14}$$

After calculating the daily mean value of narrow-lane ambiguity and its phase bias based on UPD model, taking into account equation (3-13), the clock is re-estimated in the ionosphere-free combination (equation (3-12)), i.e.

$$\begin{cases}P_{r,0}^s = \rho_r^s + c(\delta t_{r,F} - \delta t_F^s) + (\delta d_{r,0} - \delta d_0^k - \delta b_{i,0} + \delta b_0^k) \\ \bar{L}_{r,0}^s - \lambda n \check{N}_{r,1}^s + \hat{b}_n^s = \rho_r^s + c(\delta t_{r,F} - \delta t_F^s) + b_{r,n}\end{cases} \tag{3-15}$$

where, $\delta t_{r,F}$ and δt_F^s are receiver clock error and satellite clock error to be estimated, respectively; $(\delta d_{r,0} - \delta d_0^k - \delta b_{i,0} + \delta b_0^k)$ is the residual term, which will be absorbed into the pseudorange residual and it can be ignored; the narrow lane phase bias at the receiver end $b_{r,n}$ will be absorbed by the receiver clock error $\delta t_{r,F}$.

Accordingly, the user's mathematical model for PPP-AR using phase bias/clock model is as follows:

$$\begin{cases}L_{r,m}^s + \hat{b}_w^r = \lambda_w N_{r,w}^s + b_{r,w} \\ P_{s,0}^r + c\hat{t}_F^s \approx \rho_r^s + ct_{r,F} \\ L_{r,0}^s + c\hat{t}_F^s - \beta\lambda_2 \check{N}_{r,w}^s + \hat{b}_n^s = \rho_r^s + ct_{r,F} + \lambda n N_{r,1}^s + b_{r,n}\end{cases} \tag{3-16}$$

where, $\hat{b}_w^r$ and $\hat{b}_n^r$ are the phase bias products of wide-lane and narrow-lane at the satellite end;

$\hat{t}_F^s$ is the satellite clock product; in equation (3-15), the $(\delta d_{r,0} - \delta d_0^k - \delta b_{i,0} + \delta b_0^k)$ in the

ionosphere-free combined pseudorange observations is ignored here. The narrow-lane phase bias $b_{r,n}$ at the receiver end will be absorbed by the receiver clock $\delta t_{r,F}$.

In the data processing, first fix the wide-lane ambiguity by M-W combination, and then wide-lane integer ambiguity, satellite clock and narrow-lane phase bias are brought into the ionosphere-free combination to fix the narrow-lane ambiguity.

4 Program structure and algorithm

4.1 Program structure

PRIDE PPP-AR software runs according the structure shown in Figure 4-1, the process procedures are divided into three modules, least-squares estimator and integer ambiguity resolution in addition to a data preparation and pre-processing module. The first part, data preparation and pre-processing, prepare table file and precise products for following data process. The ***spp*** (standard point positioning) module will be used in this part to calculate the prior positions of station. The function of ***sp3orb*** (SP3 orbit) is to transform SP3 orbit into a self-defined binary format. Then, the software can efficiently access the precise orbit products. In least-squares estimator part, ***tedit*** (turboedit) is used to make data tentative pre-processing and generate "log-file" to record the RINEX (The Receiver Independent Exchange Format) health diagnosis information. Once got the "log-file", ***lsq*** (least-square adjustment) module can realize parameter estimation and output results. Then used ***redig*** (a posteriori residual diagnosis) module, the residuals can be processed and new "log-file" can be generated. By the iteration of ***lsq*** and ***redig***, data cleaning is completed. If ambiguity is not fixed, the ambiguity-float solution can be obtained. Otherwise, the module named **arsig** (ambiguity resolution at a single receiver) will be used to realize wide-lane and narrow-lane ambiguities resolution. In the next round **lsq** processing, these integer ambiguities will be introduced as hard constraints to achieve ambiguity-fixed solutions.

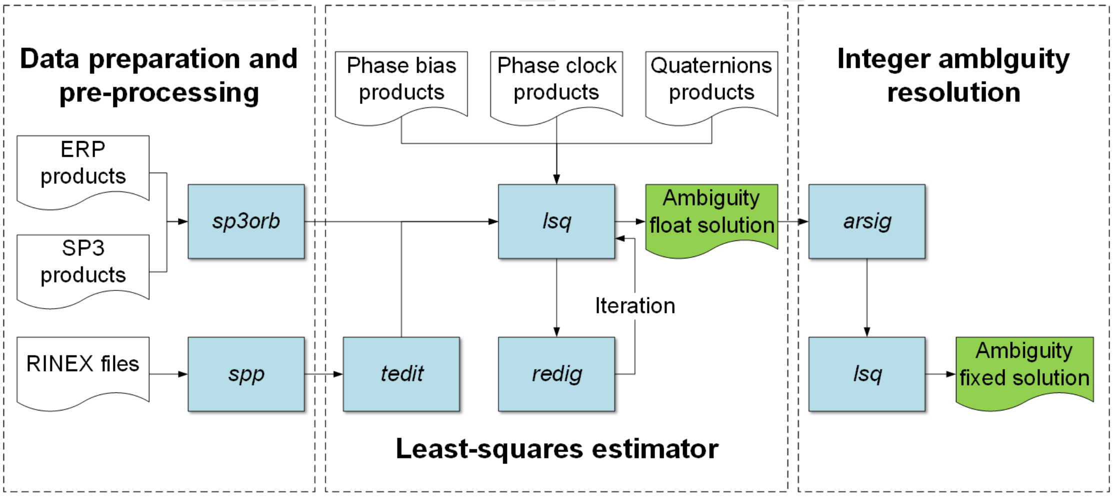

Figure 4-1. Program structure of PRIDE PPP-AR

4.2 Modules of PRIDE PPP-AR

The functions and usages of each module of PRIDE PPP-AR are shown below.

- ***spp*** is used to calculate initial positions of station, if the positioning mode is "S", the initial position will output to the "sit.xyz" file. Otherwise, if the positioning mode is "K", ***spp*** will also generate "kin-file" to record coordinates time series. Note: If the positioning mode is "F", the station coordinates will be fixed to the IGS daily solution.

S/F Mode:

spp -trop "saas" -ti ${interval} ${rinexobs} ${rinexnav}

K Mode:

spp -trop saas -ts $ts -te $te -ti ${interval} -o kin_${ydoy_s[0]}${ydoy_s[1]}_${site} ${rinexobs} ${rinexnav}

-trop	Tropsphere correction model. NON: Not correct; saas: saastamoinen model
-ti	Sampleing rate (Unit: s)
-o	Output file
${rinexobs}	RINEX observation file
${rinexnav}	Broadcast emphemeris file
[-?/-h]	Optional, output information for help
[-ts]	Optional, start time (format: year/month/day hour:minute:second)
[-te]	Optional, end date (format: year/month/day hour:minute:second)
[-elev]	Optional, Cut-off elevation (°)

- ***sp3orb*** transforms SP3 orbit files into a self-defined binary format. Then, the software can efficiently access the precise orbit products. In addition, the reference frame is changed from an earth-fixed system into an inertial system through the ERP file.

  sp3orb ${sp3} -cfg ${config} [-erp igserp]

${sp3}	SP3 file
-cfg ${config}	Configuration file
[-erp igserp]	Optional, ERP file

- ***tedit*** module is used to detect cycle jumps and receiver clock jumps, remove short piece of data and identify data gaps. This module can release the "log-file", which can reflect the health condition of RINEX file. It should be noted that we do not repair cycle slips but just mark and record them in the "log_" file, for further processing.

  S/F Mode:

  tedit ${rinexobs} -time ${ymd[*]} ${hms[*]} -len ${session} -int ${interval} -xyz ${xyz[*]} -short 1200 -lc_check only -rhd ${rhd_file} -pc_check 300 -elev ${cutoff_elev} -rnxn ${rinexnav}

  K Mode:

  tedit ${rinexobs} -time ${ymd[*]} ${hms[*]} -len ${session} -int ${interval} -xyz kin_${year}${doy}_${site} -short 120 -lc_check no -elev ${cutoff_elev} -rhd ${rhd_file} -rnxn ${rinexnav}

${rinexobs}	RINEX observation file
${rinexnav}	Broadcast emphemeris file
-time	Strat time (format:year/month/day/hour/minute/second)
-len	Session time of data processing (Unit:s)
-int	Data processing interval (Unit:s)
-xyz	S/F Mode:Initial coordinates K Mode:Initial "kin_*" file
-short	data piece shorter than this value will be removed
-elev	Cut-off elevation (Unit: °)
-lc_check	Combination of cycle slips detection methods
-pc_check	Checking the consistency of the receiver clock difference

- ***lsq*** is the estimator based on least-squares principle. In this module, we use the ionosphere-free combination to eliminate the first-order ionospheric delay. The module of lsq is used to process raw measurements and estimate unknown parameters such as positions, receiver clocks, tropospheric delays and ambiguities. It is the core part of PRIDE PPP-AR, after least-squares adjustment, we can obtain "pos-file" (or "kin-file"), "rck-file", "ztd-file", "htg-file" , "res-file" and “amb-file”.

lsq ${config} ${rinexobs}

${config}	Configuration file for current project

${rinexobs}	RINEX observation file

- Like ***tedit*** module, ***redig*** module can also make new ambiguities according to the jumps within epochs. Besides, it can remove the huge residuals and remove the short periods. ***redig*** module updates “log-file” by reading “res-file” from ***lsq*** module. To clean the observations, the ***lsq*** and ***redig*** need to be iterated continuously.

redig res_${year}${doy} [-jmp $jump -sht $short]

res_${year}${doy}	Residual file generated by lsq

-jmp $jump	Optional, If the difference of residuals between adjacent epochs is greater than $jump, it is marked as a new ambiguity

-sht $short	Optional, If the effective time of ambiguity is less than $short, the corresponding observation data will be deleted

- ***arsig*** module is used to realize wide-lane and narrow-lane ambiguity fixed. Firstly, the float wide-lane ambiguities generated from ***lsq*** module are fixed to the nearest integer using a bootstrapping method. Secondly, used ionosphere-free combination ambiguities and fixed wide-land ambiguities, float narrow-lane ambiguities can be fixed by LAMBDA (Leastsquares AMBiguity Decorrelation Adjustment) method in short observation sessions or be fixed directly to their nearest integers like wide-lane. Thirdly, with the fixed wide-lane and narrow-lane ambiguities (these constraint information is written in “cst-file”), users use ***lsq*** module to realize ambiguities fixed PPP solutions.

arsig ${config}

${conifg}	Configuration file for current project

4.3 pdp3 batch script

pdp3 is the batch script for PPP processing by PRIDE PPP-AR, which automatically processes GNSS data according to command line parameters. The user needs to ensure that the command line parameters are entered correctly and the configuration file is modified. ***pdp3*** contains the information of processing procedures, you can read the script for more details.

<u>The two parameters before the *main()* function in the script can be modified by users as needed</u>.

USECACHE=YES	# YES/NO (uppercase!)

Whether to use precision products and some table files under the local path

YES(Default):	If there are corresponding files in the product directory/table directory, copy them to the working directory, otherwise, the corresponding files will be downloaded

NO:	Download the corresponding file directly and do not match under the local path

DEBUG=NO

Whether to debug when program execution fails

YES:	Debug and keep the result files

NO(Default):	Delete the result file without debugging

The *main()* function is the entry of the script, and its flow is as follows:

1. Analyze command line parameters, check executable programs and required system tools
2. Output configuration information to the screen
3. Single-day processing or multi-day processing, as determined by the input time. If the number of days is one day, call ProcessSingleDay() for single-day processing; if the number of days is 2-5 days, call ProcessMultiDays() for multi-day processing.

The *ProcessSingleDay()* function flow is as follows:

1. Initialization, including variable definition and assignment, copying configuration files to the current directory, etc.

2. Call PrepareTables() function to prepare the required table files; call PrepareRinexNav() function to prepare the broadcast ephemeris; call PreParePoducts() to prepare the required precision products

3. The initial coordinates of the station are calculated by calling spp according to the positioning mode. The processing strategies for different positioning position modes are

S mode: outputting the calculated initial position to "sit.xyz" file;

K mode: outputting the calculated initial position to "sit.xyz" file and the calculated initial coordinate sequence to the "kin_" file

F mode: get the precise coordinates of the station in the ".ssc" solution file and write them into the "sit.xyz" file

4. According to the output of spp modify the processing time in the configuration file, that is, the starting time and processing time in the "Session time"

5. If the default product is "WUM0MGXRAP_", modify the configuration file "PCO on wide-lane" to YES; other products are NO. Users need to pay attention to this correction when using other products should be consistent with the product calculation strategies

6. Call sp3orb to convert the orbit product to binary; modify the station name and positioning mode in the configuration file; call ProcessSingleSite() for single station data processing

The *ProcessMultiDays()* function flow is as follows:

1. Initialization, including variable definition and assignment, copying configuration files to the current directory, etc.

2. Call the PrepareTables() function to prepare the required table files; match the observation files according to the observation file naming criteria, including long-named format and short-named format.

3. Call PrepareRinexNav() function to prepare the broadcast ephemeris; call PreParePoducts() to prepare the required precision products

4. The initial coordinates of the station are calculated by calling spp according to the positioning mode. The processing strategies for different positioning position modes are

S mode: outputting the calculated initial position to "sit.xyz" file;

K mode: outputting the calculated initial position to "sit.xyz" file and the calculated initial coordinate sequence to the "kin_" file

F mode: get the precise coordinates of the station in the ".ssc" solution file and write them into the "sit.xyz" file

5. According to the output of spp modify the processing time in the configuration file, that is, the starting time and processing time in the "Session time"

6. If the default product is "WUM0MGXRAP_", modify the configuration file "PCO on wide-lane" to YES; other products are NO. Users need to pay attention to this correction when using other products should be consistent with the product calculation strategies

7. Call sp3orb to convert the orbit product to binary; modify the station name and positioning mode in the configuration file; call ProcessSingleSite() for single station data processing

The process of *ProcessSingleSite()* function is as follows:

1. Initialization, including variable definition and assignment, getting configuration options, etc.; where the data editing mode is controlled by the "Strict editing" item in the configuration file, which should be modified to NO when the data quality is poor, meaning a more lenient editing threshold and fewer iterations

2. Invoke tedit for data pre-processing based on the positioning mode and related configuration information

3. Call lsq and redig iterations for residual editing to identify residual cycle slips until no new ambiguities and observations are censored

4. If the ambiguity resolution switch is Y/y, or the command line parameter does not specify whether to fix the ambiguity and there has code/phase bias product, call arsig to fix ambiguity, and then call lsq to adjust again; otherwise, end the calculation to get the ambiguity-float solution.

PrepareTables() for preparing table files:

1. Link the local files in the tale directory to the current directory

2. Prepare the leap seconds file “leap.sec”

(1) Checking whether the leap seconds file in the current directory accompanies the software (marked with * in the first line).

(2) Download the leap seconds file if it does not match or if the leap seconds file does not exist in the current directory.

(3) If the download is failed, copy the leap seconds file from the table directory to the current directory.

(4) If the download is successful and does not match the leap seconds file in the table directory, replace the leap seconds file in the table directory with the downloaded leap seconds file

3. Prepare satellite parameters file “sat_parameters”

(1) Check the time lag of the satellite parameter files in the current directory.

(2) Download satellite parameter files if it's lagging or does not exist in the current directory.

(3) If the download is failed, copy the satellite parameter file from the table directory to the current directory.

(4) If the download is successful and does not match the satellite parameter file in the table directory, replace the satellite parameter file in the table directory with the downloaded satellite parameter file.

PrepareRinexNav() for preparing broadcast ephemeris:

1. If processing today's data, download and merge the hourly GPS broadcast ephemeris and hourly GLONASS broadcast ephemeris.

2. If there is no broadcast ephemeris in short naming format in the data directory, match the broadcast ephemeris in long naming format starting with “BRDC00IGS_R_”, “BRDC00IGN_R_” and “BRDM00DLR_S_”.

3. If neither short-name format nor long-name format is available, then download the broadcast ephemeris

(1) Downloading the multi-system broadcast ephemeris if it is after 2016.

(2) Failure of multi-system broadcast ephemeris downloads or processing of pre-2016 data, downloading of GPS and GLONASS broadcast ephemeris and merging them.

4. Checking that the required satellite systems are available in the broadcast ephemeris.

PrepareProducts() for preparing products:

1. Determine the directory where the precise products are located according to the “Product directory” in the configuration file, if it is not modified, i.e. Default, create a “product” directory under the year directory, where the precise products are located in the “common” subdirectory, the VMF1/VMF3 required grid files are located in the “vmf” subdirectory, the ionosphere grid files are located in the “ion” subdirectory, and the SINEX files are located in the “ssc” subdirectory.

2. Prepare precise orbit, precise clock error and ERP products, and merge them into one file if there are multiple files

(1) Copy the corresponding product from the products directory to the current directory if it is not the default product.

(2) If it is the default product and there are corresponding files in the products directory, copy them to the current directory.

(3) If it is the default product and there are no corresponding files in the products directory, download the corresponding files; the default download of “WUM0MGXRAP_” product after 001 days in 2020; the default download of “COM” product from 001 days in 2014 to 365 days in 2019; the default download of “COD” product from 307 days in 2002 to 365 days in 2013.

(4) Download or copy the “WUM0MGXRTS_” product if the “WUM0MGXRAP_” product is not available.

3. Prepare quaternions products and code/phase bias products, and merge them into one file if there are multiple files

(1) Copy the corresponding product from the products directory to the current directory if it is not the default product.

(2) If it is the default product and there are corresponding files in the products directory, copy

them to the current directory.

(3) If it is the default product and there are no corresponding files in the products directory, download the corresponding files; no quaternion products before 2020; for bias products, the "WUM0MGXRAP_" product will be downloaded by default after 001 days in 2020 and the "COM" product will be downloaded by default from 182 days in 2018 to 365 days in 2019

4. Prepare ANTEX files

(1) Match the ANTEX file in the clock error file header; if no match or "igs14" is found in the clock error file header, the latest igs14 ANTEX file at the time of software release will be used by default.;

(2) Copy the ANTEX file in table directory to the current directory, if there is no corresponding ANTEX file in table directory, then download the corresponding file.

5. Copy or download the solution file if the positioning mode is F; copy or download the IONEX file if higher-order ionosphere correction is performed; download the corresponding grid file if the VMF1/VMF3 mapping function is used.

In addition, for users who can't solve online, you can refer to the *PrepareTables(), PrepareRinexNav()* and *PrepareProducts()*, which has the download address of those external files. You can pick out these three functions and modify them as scripts for downloading files. Users can download and place them in the corresponding directory. See Appendix A for a brief description of these required external files.

Files that need to be placed in the data directory:

- Broadcast emphasis
  Hourly: ftp://igs.gnsswhu.cn/pub/gps/data/hourly/
  Dailly: ftp://igs.gnsswhu.cn/pub/gps/data/daily/ or ftp://igs.ign.fr/pub/igs/data/

Files that need to be placed in the "common" subdirectory of the product directory:

- Software default "WUM0MGXRAP_" and "WUM0MGXRTS_" precise products:
  ftp://igs.gnsswhu.cn/pub/whu/phasebias/
- Software default "COD"/"COM" precise products:
  ftp://ftp.aiub.unibe.ch/CODE

Files that need to be placed in the "ion" subdirectory of the product directory:

- IONEX maps:
  ftp://ftp.aiub.unibe.ch/CODE

Files that need to be placed in the "vmf" subdirectory of the product directory:

- Tropospheric grid file
  VMF1: http://vmf.geo.tuwien.ac.at/trop_products/GRID/2.5x2/VMF1/VMF1_OP
  VMF3: http://vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_OP

Files that need to be placed in the "ssc" subdirectory of the product directory:

- SINEX file: ftp://igs.gnsswhu.cn/pub/gps/products/ or ftp://nfs.kasi.re.kr/gps/products/ or ftp://gssc.esa.int/cddis/gnss/products/

Files that need to be placed in the table directory:

- ANTEX file: https://files.igs.org/pub/station/general/pcv_archive/
- Leap second file: ftp://igs.gnsswhu.cn/pub/whu/phasebias/table/
- sat_parameters: ftp://igs.gnsswhu.cn/pub/whu/phasebias/table/

It should be noted that the default precise products start with "WUMMGXRAP_", in which the satellite clock products are located in the "${year}/clock" directory, the bias products are located in the "${year}/bias" directory, and the satellite ephemeris, attitude file and ERP file are located in the "${year}/orbit" directory; in case of high-order ionospheric correction, the IONEX file needs to be downloaded separately; if the mapping function is VM1/VM3, the tropospheric grid files of the current day and the hour before and after need to be downloaded for interpolation; the ANTEX file matched with the default precise product is recorded in the satellite clock product file header. If other products are used, the latest IGS14 ANTEX file at the time of software release is used by default. The SINEX file needs to be downloaded in F mode.

4.4 Algorithms for each module

4.4.1 tedit

As the data pre-processing module of PRIDE PPP-AR, *tedit* is mainly used to check the original observation file and detect the cycle slips and outliers. The main process can be divided into two parts: firstly, check the original observation file and construct the test volume, then identify the outliers in the test volume to determine whether the cycle slips occurs. Finally, the check information is output to the log-file. The data processing flow is shown in the figure below

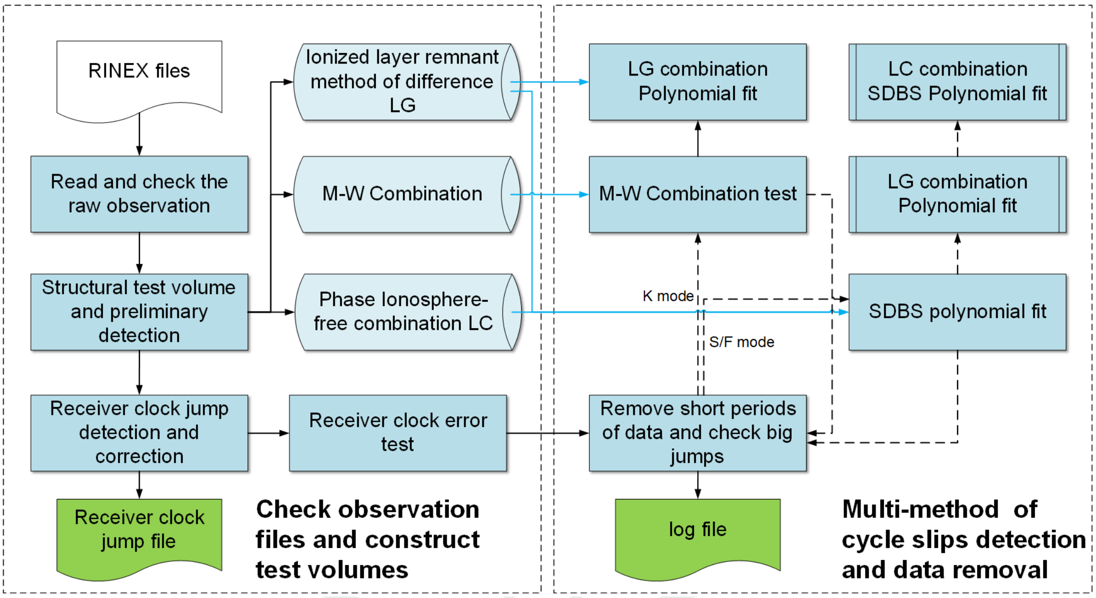

Figure 4-2. *tedit* algorithm flow. The light blue columns indicate the constructed test volume; the blue line indicates the input of each test volume; the black dashed line indicates the running process controlled by the pdp3 script and the process is performed only once; SDBS indicates the single difference between satellites

1. Check the observation file and construct the test volume

Read the original dual-frequency observations on an epoch-by-epoch basis. Calculate satellite elevation, distance between station and satellite, and satellite clock error based on the broadcast ephemeris. Then construct the geometry-free combination $L_G = \dfrac{L_1 - L_2}{\lambda_2 - \lambda_1}$. In this process, the L_G is initially checked for ionospheric anomalies and cycle slips are detected. Then remove data based on data availability and satellite elevation, etc.

Due to the instability of the receiver clock, the receiver clock error needs to be checked in advance, including the clock jump detection and gross error rejection. Construct the receiver clock jump test volume as follows:

$$R_{i,k} = (P_{i,k} - P_{i,k-1}) - (L_{i,k} - L_{i,k-1}) \tag{4-1}$$

where, $i=1,2$ denotes the frequency number; k and $k-1$ denotes the adjacent non-rejected current and previous epochs. The magnitude of the clock jump check for all satellites in the current epoch is used to determine whether a receiver clock jump occurs in that epoch, and if it exists, the receiver clock jump correction is calculated to the original observation and recorded for subsequent data processing.

The receiver clock error check is required in S/F mode. The receiver clock error test volume is constructed in the following form:

$$\overline{P}_{0,k}=P_{0,k}-(\rho-c\Delta T^{s}) \tag{4-2}$$

where, ρ and ΔT^{s} are the distance between station and satellite and the satellite clock error calculated based on the broadcast ephemeris, respectively. This test volume eliminates the geometric distance, satellite clock error, and ionospheric delay, and leaves only the receiver clock error and multi-path effects for pseudorange, and is therefore used to check for gross error in the receiver clock error. The weighted mean value of this test volume is obtained by median-based robust estimation and compared with a given threshold value to locate and reject the gross error in receiver clock error.

The M-W combination and the phase ionosphere-free combination are constructed, and the cycle slips are initially detected based on the change rate of the M-W combination of adjacent epoch. Based on the results of the above data rejection and cycle slips detection, short piece of data or big gap of adjacent non-rejected ephemerides are identified and marked for subsequent examination.

2. Cycle slips detection and data rejection according to the test volume

The *pdp3* script passes different control parameters to *tedit* according to the positioning mode, and different combinations of methods are used in *tedit* for data preprocessing, with only SDBS polynomial fit in S/F mode, and only M-W combination tests in K mode.

For the SDBS polynomial fit, the fitted values are chosen from the difference between the epoch results to facilitate better positioning of the cycle slips and gross error. The process is mainly divided into two parts: firstly, we fit each satellite LG combination, calculate its fitted residuals and RMS, mark the satellites that cannot be successfully fitted, count the number of available epoch for each satellite in the fitted arc, and take the satellite with the highest number of available epoch as the reference satellite. Next, the SDBS fitting term is constructed as follows:

$$L_{c,k}=(L_{0,k}^{si}-(\rho^{si}-c\Delta T^{si}))-(L_{0,k}^{sr}-(\rho^{sr}-c\Delta T^{sr})) \tag{4-3}$$

where, si and sr indicates the current satellite and the reference satellite, respectively. The test volume eliminates the effects of receiver clock error, satellite clock error and geometric distance, leaving only tropospheric delay, ambiguity, multi-path effect and observation noise, etc. The difference between the epoch can eliminate ambiguity and weaken tropospheric delay. The residuals and RMS are calculated by fitting the difference between the epoch results, and the residuals are used to determine whether the cycle slip occurs and mark it. Finally, the fitting results are statistically calculated: (1) to determine whether the current satellite has a cycle slip based on the LC combination SDBS fitting results; (2) to determine whether the reference satellite has a cycle slip based on the LG combination fitting results and the LC combination fitting results.

When testing the M-W combination, the mean and variance of the M-W combination are calculated recursively, and the M-W combination is marked according to the magnitude of the difference between the current epoch and the mean. *tedit* also has a polynomial fitting process for the LG combination to determine whether a cycle slip has occurred according to the fitting residuals and RMS, which is not used at present.

After running the above process, the short piece of data are checked again with the adjacent available epoch with larger intervals. Finally, the detection results and data rejection results are written to the log file, including the information related to the deleted observations and the newly added ambiguity.

4.4.2 lsq

lsq is based on the generalized least squares principle of the parameter elimination-recovery method for parameter estimation. As shown in the figure below, the data processing process can be divided into three parts: (1) initialization, obtaining configuration information, variable assignment, and the number of statistical parameters; (2) construction of the function model, constructing the parity mathematical model and filling the matrix by epoch, eliminating process parameters (such as receiver clock error) and state parameters (ambiguity parameters) in this process and compressing the normal equation matrix as needed; (3) adjustment, adjustment for the non-eliminated parameters, recovering the eliminated parameters and calculating the residuals, and inputting the results to different result files

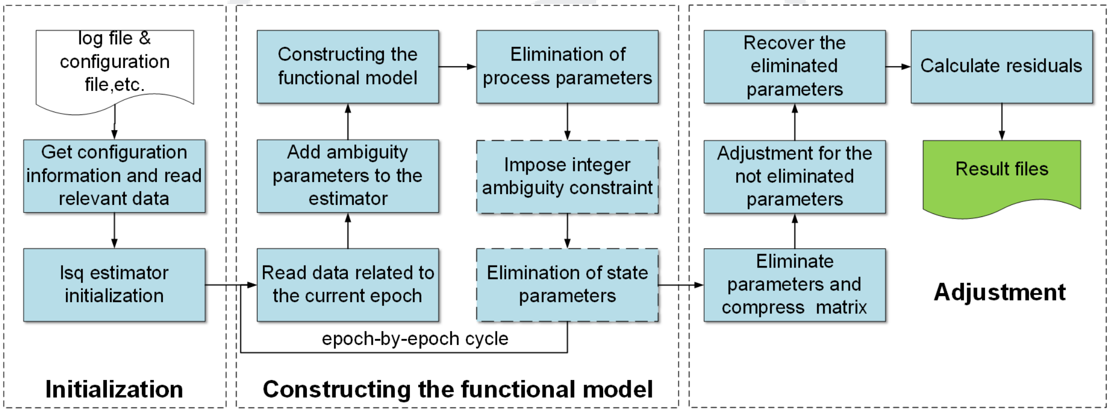

Figure 4-3. *lsq* algorithm flow. The dashed box part is executed only when the ambiguity parameters is eliminated

1. Initialization

First, get the configuration information required for *lsq* from the configuration file, such as satellite list, a priori constraints and process noise. S/F mode reads the initial coordinates of the station from the pos_ file or sit.xyz file; reads the data in the relevant files, such as the PCO/PV of the receiver and satellite, and the coordinates of the antenna reference point for the station.

Determine the information about the parameters and normal equation based on the positioning mode and relevant configuration information. The parameters are divided into three categories: constant parameters, process parameters and state parameters; the station coordinates are estimated as constant parameters in S/F mode, the process parameters include station position parameters in K mode, receiver clock error, zenith tropospheric delay parameters and horizontal tropospheric gradient parameters, and the state parameters are ambiguity parameters. If the integer ambiguity resolution method is rounding method, the ambiguity parameters need to be eliminated subsequently; otherwise, if the integer ambiguity resolution method is a search algorithm such as LAMBDA, the ambiguity parameters need to be retained before adjustment to obtain the variance-covariance matrix for integer ambiguity resolution. Thus, different matrix dimensions are assigned according to different integer ambiguity resolution strategies.

Initialize the parameter vector with the normal equation matrix. Based on the stochastic process, the state transfer matrix of STO or PWC is assigned to the unit array and the white noise state transfer matrix to the zero matrix. Based on the generalized least squares principle, the corresponding diagonal elements of the parameters in the normal equation are assigned a priori weights, i.e.

$$N_{bb} = \mathrm{diag}([P_x \ P_y \ P_z \ \cdots \ 0]) \tag{4-4}$$

where the ambiguity parameter part will be filled later.

2. Constructing the adjustment functional model

Based on the initialized least squares estimator, construct the function model epoch by epoch and fill the corresponding matrix, and some parameters are eliminated in the estimator in this process. First, read the observation data of the current epoch and the corresponding OSB; read the log file with the deleted satellite and new ambiguity information of the corresponding epoch; if the positioning mode is K mode, read the initial coordinates of the current epoch in the kin file; if there is a receiver clock jump in the current epoch, read the receiver clock jump file generated in *tedit* and correct it in the observation value of the current epoch. Same as constant parameters and process parameters, update the information related to the ambiguity parameters of the current epoch to the estimator.

The functional model corresponding to the original observation equation is established based on the satellite constellation selected in the configuration file and existing in the observation file, including the design matrix, OMC(Observed minus calculated) and the weights corresponding to the observations. In this process, the correction of each systematic error is carried out, and the calculated receiver clock error is used as the initial value of the receiver clock error parameter. The functional model of the ionosphere-free observation equation is constructed based on the functional model of the original observation equation, and the M-W combination is composed to calculate the initial value of the wide lane ambiguity, and then calculate the initial value of the ionosphere-free combination ambiguity. Calculate the elements of the normal equation matrix and fill them into the upper triangular matrix, and calculate the OMC weighted sum of squares in the functional model of the ionosphere-free combination for calculating the residual sum of squares.

The state equation in the PPP is extended with the virtual observation equation as in equation (3-5), where the state vector is the process parameter.

$$V = X_k - \Phi X_{k-1} + \omega_k, \ P_w \tag{4-5}$$

The process parameters of the previous epoch are eliminated, and the information related to the process parameters of the current epoch is added to the estimator according to the state equation. If the integer ambiguity resolution method is the rounding method, the ambiguity parameter needs to be eliminated. If the *lsq* is performed after *arsig*, the SDBS ambiguity "cst_" file generated in *arsig* is read and appended to the estimator as a strong constraint.

3. Adjustment

At the end of the epoch cycle, the remaining integer ambiguity constraint is attached, the process parameters are eliminated, and the remaining ambiguity parameters are also eliminated if the integer ambiguity resolution method is the rounding method, and the normal equation matrix is compressed. The non-eliminated parameters are solved, and the variance of unit weight and the posterior variance of the non-eliminated parameters are calculated.

Recover the eliminated parameters and calculate the residuals, and output the different results to the corresponding result files. S mode writes the position estimation and other information to the “pos_” file. Count the solvable ambiguity and write it to “amb_” file. if the integer ambiguity resolution method is LAMBDA method, write the information such as covariance matrix, residual sum of squares and degrees of freedom to “neq_” file for LAMBDA method to fix the narrow lane ambiguity.

4.4.3 redig

redig performs residual editing based on the “log_” file generated in *tedit* and the “res_” file generated in *lsq*, deletes the gross error and detects the residual small cycle slips, and its data processing flow is shown in Figure 4-4.

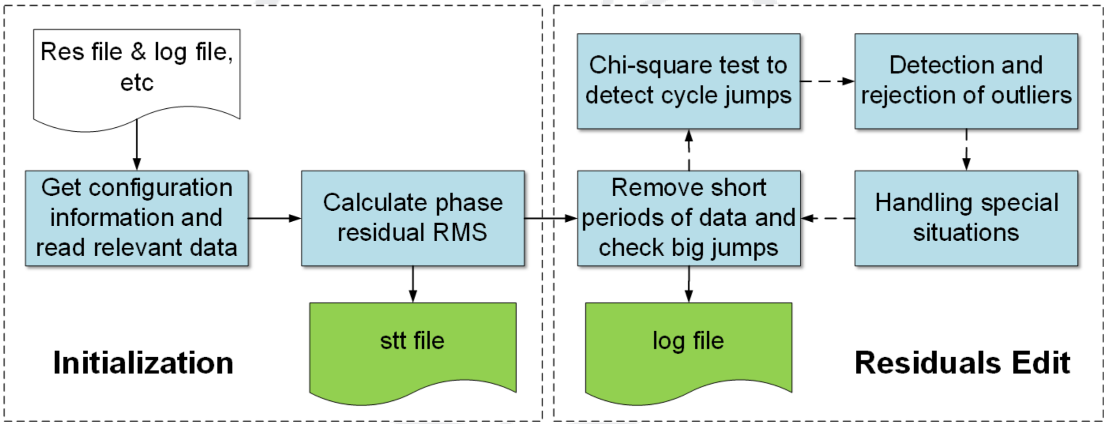

Figure 4-4. *redig* algorithm flow. The black dashed line indicates that the process is executed only once

The initialization section first obtains the configuration information required by *redig*, such as the number of ephemerides, the satellites included and the command line input parameters, etc. Next, the phase residuals in the “res_” file are read, and the status of existing observations is identified (whether the ambiguity has been established, the observations have been deleted, etc.). The RMS of each satellite phase residual is calculated separately and written to the header of the “stt_” file, as well as output to the screen, and the time series of each satellite phase residual is written to the “stt_” file.

After the initialization is finished, the residuals are edited satellite by satellite, firstly checking whether there are short pieces of data and removing them. Secondly, check whether there is residual cycle slip or gross error in the residual time series: (1) calculate the residual difference between adjacent available epochs and its mean and standard deviation, and also calculate the mean and standard deviation after removing the absolute value of the maximum residual difference to detect the jump based on the above calculated value of chi-square test. Repeat the above process until it passes the chi-square test and the maximum residual difference value does not exceed the threshold; (2) if the adjacent available epochs both detect the cycle slips, distinguish the cycle slips from the gross error according to the residual difference value; (3) deal with special cases, such as the last available epoch detects the cycle slip and delete it. Finally, remove the short piece of data after residual editing and update the "log_" file according to the residual editing result.

4.4.4 arsig

arsig uses SDBS to eliminate the hardware delay at the receiver and resolution integer ambiguity for the wide lane and narrow lane, where the wide lane ambiguity is fixed by rounding, and the narrow lane ambiguity can be fixed by the same rounding method when the data processing period is long, otherwise it should be fixed by the LAMBDA method. Its data processing flow is shown in Figure 4-5.

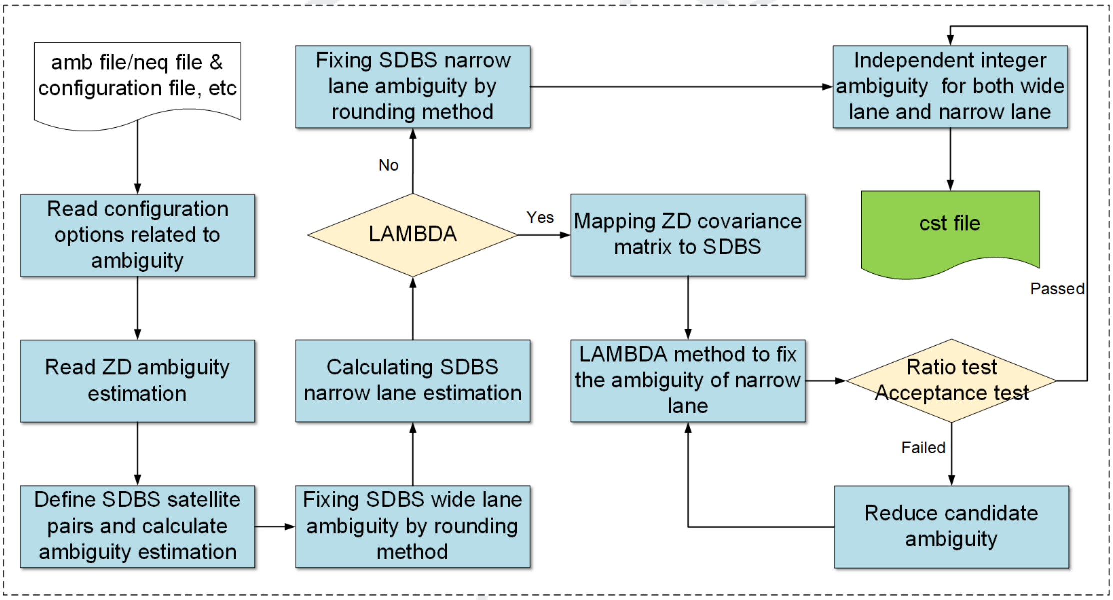

Figure 4-5. *arsig* algorithm flow. ZD indicates the zero difference

As can be seen from the figure, the key in *arsig* is the narrow-lane integer ambiguity resolution method, and all subsequent integer ambiguity resolution methods described refer to the narrow-aisle fuzziness fixation method. Firstly, initialization is performed and the parameters related to integer ambiguity resolution in the configuration file are read. If the integer ambiguity resolution method is rounding, the "amb_" file is read; if it is the LAMBDA method, the "neq_" file generated in lsq is read. Based on the available information, all satellite pairs are defined for SDBS, and the real values of SDBS ambiguity and its standard deviation are calculated. And calculate the standard deviation of iSDBS narrow lane ambiguity: LAMBDA method is calculated from the covariance matrix and unit weight variance, and the rounding method is empirical.

If the integer ambiguity resolution method is LAMBDA method, firstly the ZD covariance matrix is mapped to the corresponding SDBS covariance matrix. Secondly, narrow lane integer ambiguity resolution is performed according to LAMBDA algorithm, and acceptance test and ratio test are performed at the end of LAMBDA algorithm. If the test is failed, the number of candidate ambiguity is reduced and the ambiguity is fixed again until it can pass the test as well as meet a certain number of ambiguity. After the successful resolution, the information related to the narrow lane ambiguity is updated and the independent SDBS wide lane and narrow lane integer ambiguity are output to the "cst_" file.

5 Technical Aspects

5.1 User Requirements

5.1.1 System Requirements

PRIDE PPP-AR is composed of CUI APs. The executable binary CUI APs included in the package require Linux environment. All of the main codes were written in Fortran. A series of tests are conducted on different operating systems with several gfortran versions. The tests results are listed as below (Table 5-1). Note that you can also try other Linux distribution and Fortran compiler, and tell us if you have any problems.

Fortran compiler needs to be installed before installing PRIDE PPP-AR.

Table 5-1.PRIDE PPP-AR test results in different operating systems.

Platform version	gfortran version	Test result	Notes
Ubuntu14.04.4 (x64)	4.8.4	pass	1. Pre-install 'gfortran' before installation; 2. Test result is consistent with the reference
Ubuntu14.04.4 (x32)	4.8.4	pass	1. Pre-install 'gfortran' before installation; 2. Test result is consistent with the reference
Ubuntu16.04.11 (x64)	5.4.0	pass	Test result is consistent with the reference
Ubuntu16.04.11 (x32)	5.4.0	pass	Test result is consistent with the reference
Ubuntu18.04 (x64)	7.3.0	pass	1. Pre-install 'gfortran' before installation; 2. Test result is consistent with the reference
Ubuntu20.04.4 (x64)	4.8.4	pass	Test result is consistent with the reference
Ubuntu20.04.4 (x32)	4.8.4	pass	Test result is consistent with the reference
Arch Linux (x64)	8.2.1	pass	Test result is consistent with the reference
CentOS 6.5 (x64)	4.4.7	pass	Test result is consistent with the reference
CentOS 7 (x64)	4.8.5	pass	Test result is consistent with the reference

Debian 9.6 (x64)	6.3.0	pass	Test result is consistent with the reference
Debian 8.11 (x64)	4.9.2	pass	1. Pre-install ‘gfortran’ before installation; 2. Test result is consistent with the reference
MacOS 10.14	10.2.0	pass	1. Pre-install ‘gfortran’ before installation; 2. Test result is consistent with the reference

5.1.2 License

This program is open-source software: you can redistribute it and/or modify it under the terms of the GNU General Public License (version 3) as published by the Free Software Foundation.
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5.2 Installation Guide

5.2.1 Structures of PRIDE PPP-AR

The structure of PRIDE PPP-AR is as follows (Table 5-2). We provide a complete set of cases in the “example/” folder for users to execute. The program will be executed automatically, and users do not need to use the files in other folders alone. However, in order to give users a better understanding of the software content, further instructions are given below.

Table 5-2 PRIDE PPP-AR structures

		Instructions
\bin		**Executable program**
	arsig	Ambiguity resolution
	get_ctrl	Get configuration parameters
	lsq	Least squares adjustment
	pbopos	Convert "pos_" files to PBO position series
	redig	Residual editing
	sp3orb	Transform sp3 into self-defined binary file
	spp	Standard single point positioning
	tedit	Pre-processing RINEX files
	xyz2enu	Convert position of XYZ to ENU ("kin_file")
\scripts		**Scripts that facilitate data process**
	merge2brdm.py	Merge GPS and GLONASS broadcast ephemerides to brdm file
	pdp3.sh	Automatic processing Shell script (Linux)
	pdp3_Mac.sh	Automatic processing Shell script (Mac)
	plotkin.py	Python script for plotting Kinematic results
	plotkin.sh	GMT script for plotting Kinematic results
	plotres.py	Python script for plotting Residuals
	plotres.sh	GMT script for plotting Residuals
	plottrack.py	Python script for plotting track
	plotztd.py	Python script for plotting zenith troposphere delays
\src		**Source programs**
	arsig/	Ambiguity resolution
	header/	Header files
	lib/	Library functions
	lsq/	Least squares adjustment
	orbit/	Sp3orb
	redig	Residuals edit

	spp/	Standard point positioning
	tedit/	Pre-processing RINEX files
	utils/	Universal tools
	Makefile	Makefile
\table		**Dependent table files**
	config_template	Configuration file template
	file_name	File names definition
	gpt3_1.grd	External grid file of meteorological parameters file (1 degree×1 degree)
	leap.sec	Leap seconds
	oceanload	Ocean tide loading file
	orography_ell	Global terrain file for VMF1 (2.5 degree×2.5 degree)
	orography_ell_1x1	Global terrain file for VMF3 (1 degree×1 degree)
	sat_parameters	Satellite parameters
	ANTEX files	Provide antenna offset data in need
install.sh		Installation script
ChangeLog.txt		Change log of the software
README.md		Software related information
LICENSE.txt		GPL3 protocol
\doc		**Document flag**
	logo	The logo printed on screen when installing successfully
	Manual	Manual of the software
\example		**Examples**
	test.sh	Test script (Linux)
	test_Mac.sh	Test script (Mac)
	\data	Data of examples
	\results_ref	Reference results for examples

5.2.2 Installation and validation

Step 1: Make sure you have installed some essential programs in advance.

i.e., **bash, make, gfortran, wget**

Step 2: Run script ***./install.sh*** to install the program automatically. (This script executes Makefile to build CUI APs and add CUI APs to system PATH (~/**.PRIDE_PPPAR_BIN/***)).

If you see the prompt shown in the picture below, the installation is completed normally.

Figure 5-1. successfully installed interface

Step 3: Input y/Y to run the example.

The script ***test.sh*** (***test_Mac.sh***) in ***/example*** folder is used to validate the correctness and effectiveness of the installation and execution. The examples of PPP and PPP-AR will be are conducted after successfully running ***test.sh*** (***test_mac.sh***). The data processing procedure is conducted and some information is printed on the screen. After that, results files are created. Then compare the solution files between results and reference results to make sure the software installation is correct and valid.

Five examples are conducted by script ***test.sh***. '**static**' mode denotes that we regard the station as a static station, and estimate only one set of coordinates in the whole observation period. '**kinematic**' denotes that we regard the station as a kinematic station, and estimate one set of coordinates every epoch. '**high-rate**' denotes that we use high-frequency data, and estimate one set of coordinates every epoch. '**PPP-AR**' achieves ambiguity resolution by utilizing code/phase bias products. '**PPP-AR LAMBDA**' denotes the ambiguity resolution process is conducted by **LAMBDA** (Least-squares Ambiguity Decorrelation Adjustment) method.

Table 5-3. PRIDE PPP-AR test examples

Examples	**Content**
static-24h-fixed	Daily static solution, PPP-AR
kinematic-24h-fixed	Daily kinematic solution, PPP-AR
kinematic-1h-fixed-LAMBDA	Hourly kinematic solution, PPP-AR LAMBDA

highrate-1h-fixed-LAMBDA	High-rate solution, PPP-AR
tropo-24h-fixed	Daily tropospheric solution, PPP-AR

5.3 File Specifications

5.3.1 Solution Files

After successfully running the test script, the solution files will be moved to the "/example/result" directory, as shown in Table 5-3. The solution files of "static-24h-fixed" are shown in Figure 5-2. For the positioning results, the static solution stores it in the 'pos_' file, while the kinematic solution stores it in the 'kin_' file. Other kinematic solution files are consistent with static solution.

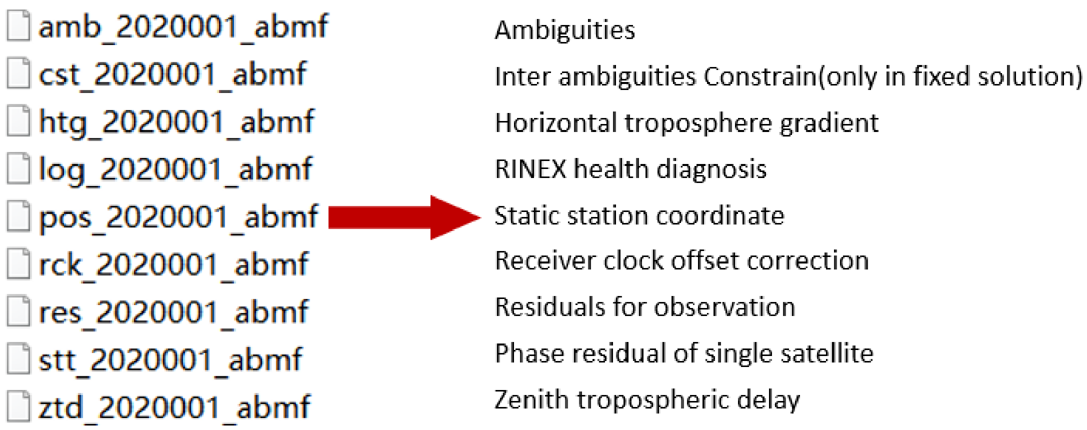


Figure 5-2. Solution files of "static-fixed-24h"

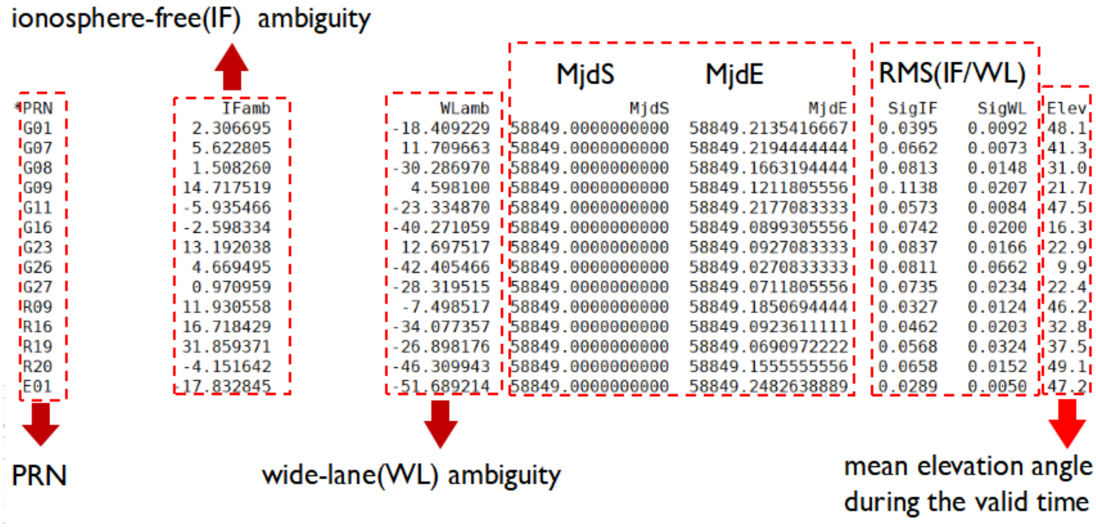
The solution files header recorded the basic configuration and corresponding file content description. Users can check the corresponding configuration information.

```
abmf                                                        STATION
Static       10.000000 10.000000 10.000000                  POS MODE/PRIORI (meter)
YES                                                         OBS STRICT EDITING
2020  1  1  0  0  0.00                                      OBS FIRST EPOCH
2020  1  1 23 59  0.00                                      OBS LAST EPOCH
   30.00                                                    OBS INTERVAL (sec)
    7.00                                                    OBS MASK ANGLE (deg)
    0.30                                                    MEASUREMENT NOISE PSEUDORANGE (1-SIGMA, meter)
    0.01                                                    MEASUREMENT NOISE CARRIER PHASE (1-SIGMA, cycle)
WUM0MGXRAP_20200010000_01D_01M_ORB.SP3                      SAT ORBIT
WUM0MGXRAP_20200010000_01D_30S_CLK.CLK                      SAT CLOCK
WUM0MGXRAP_20200010000_01D_01D_ERP.ERP                      SAT ERP
WUM0MGXRAP_20200010000_01D_30S_ATT.OBX                      SAT ATTITUDE
WUM0MGXRAP_20200010000_01D_01D_ABS.BIA                      SAT BIAS
SEPT POLARX5                                                SITE RECEIVER TYPE
TRM57971.00     NONE                                        SITE ANTENNA TYPE
        0.0000        0.0000        0.0000                  SITE ANTENNA E/N/H (meter)
IGS14_2136                                                  TABLE ANTEX
STO                                                         TROP ZENITH
PWC:720                                                     TROP GRADIENT
NO                                                          IONO 2ND
SOLID  POLE OCEAN                                           TIDES
YES  GPS    40  GAL    24  BDS2    2  BDS3   21  QZSS    0  AMB FIXING
  600.00                                                    AMB DURATION (sec)
   15.00                                                    AMB CUTOFF (deg)
    0.20    0.15 1000.00                                    AMB WIDELANE
    0.15    0.15 1000.00                                    AMB NARROWLANE
    2       4      1.80    3.00                             AMB SEARCH
Start Field Description                                     COMMENT
Name                                                        STATION NAME
Mjd                                                         MODIFIED JULIAN DAY
X                                                           X COORDINATE (meter)
Y                                                           Y COORDINATE (meter)
Z                                                           Z COORDINATE (meter)
Sx                                                          DIAGONAL COFACTOR OF X COORDINATE
Sy                                                          DIAGONAL COFACTOR OF Y COORDINATE
Sz                                                          DIAGONAL COFACTOR OF Z COORDINATE
Rxy                                                         OFF-DIAGONAL COFACTOR OF X AND Y COORDINATES
Rxz                                                         OFF-DIAGONAL COFACTOR OF X AND Z COORDINATES
Ryz                                                         OFF-DIAGONAL COFACTOR OF Y AND Z COORDINATES
Sig0                                                        SQUARE ROOT OF VARIANCE FACTOR (meter)
Nobs                                                        NUMBER OF OBSERVATIONS
End Field Description                                       COMMENT
                                                            END OF HEADER
```

Figure 5-3. Header of solution files

amb file

The values of float ambiguities are recorded in ‘amb’ file. Running ***arsig*** will call ‘amb’ file to obtain initial value of ambiguity. The parameters in the ‘amb’ file are: PRN, ionosphere-free(IF) ambiguity, wide-lane(WL) ambiguity, MjdS, MjdE, RMS(IF/WL), mean elevation angle during the valid time.

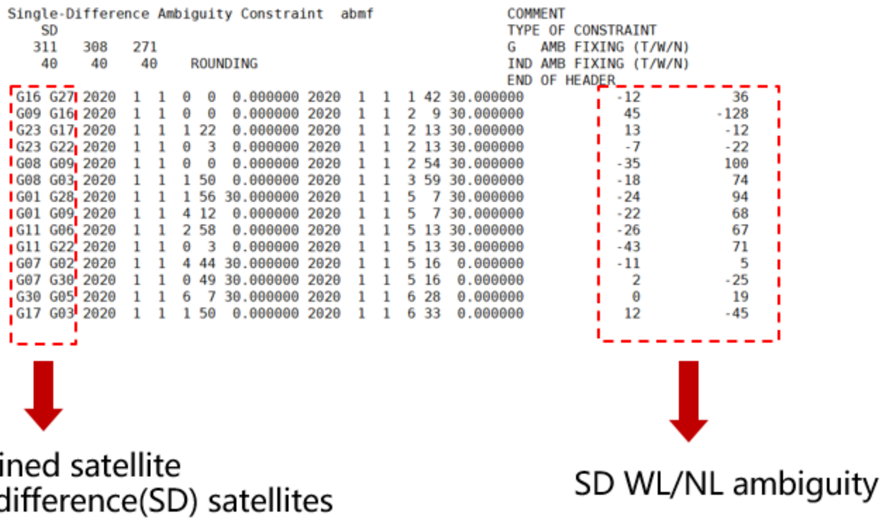


PRN	IFamb	WLamb	MjdS	MjdE	SigIF	SigWL	Elev
G01	2.306695	-18.409229	58849.0000000000	58849.2135416667	0.0395	0.0092	48.1
G07	5.622805	11.709663	58849.0000000000	58849.2194444444	0.0662	0.0073	41.3
G08	1.508260	-30.286970	58849.0000000000	58849.1663194444	0.0813	0.0148	31.0
G09	14.717519	4.598100	58849.0000000000	58849.1211805556	0.1138	0.0207	21.7
G11	-5.935466	-23.334870	58849.0000000000	58849.2177083333	0.0573	0.0084	47.5
G16	-2.598334	-40.271059	58849.0000000000	58849.0899305556	0.0742	0.0200	16.3
G23	13.192038	12.697517	58849.0000000000	58849.0927083333	0.0837	0.0166	22.9
G26	4.669495	-42.405466	58849.0000000000	58849.0270833333	0.0811	0.0662	9.9
G27	0.970959	-28.319515	58849.0000000000	58849.0711805556	0.0735	0.0234	22.4
R09	11.930558	-7.498517	58849.0000000000	58849.1850694444	0.0327	0.0124	46.2
R16	16.718429	-34.077357	58849.0000000000	58849.0923611111	0.0462	0.0203	32.8
R19	31.859371	-26.898176	58849.0000000000	58849.0690972222	0.0568	0.0324	37.5
R20	-4.151642	-46.309943	58849.0000000000	58849.1555555556	0.0658	0.0152	49.1
E01	17.832845	-51.689214	58849.0000000000	58849.2482638889	0.0289	0.0050	47.2

Figure 5-4. The ambiguities (‘amb_’) file

cst file

Run ***arsig***, 'cst' file will be produced. 'cst' file records the values of integer ambiguity. The parameters in the 'cst' file are: station name, single-difference(SD) satellites, time, SD WL/NL ambiguity.

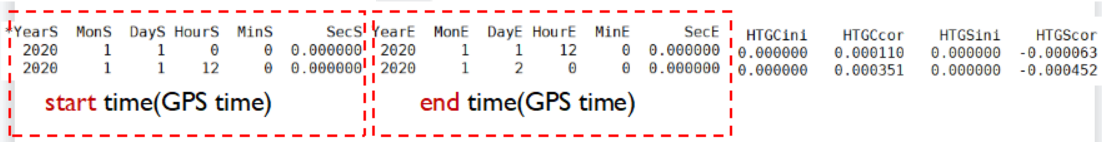


```
Single-Difference Ambiguity Constraint  abmf                 COMMENT
    SD                                                       TYPE OF CONSTRAINT
   311    308    271                                         G   AMB FIXING (T/W/N)
    40     40     40    ROUNDING                             IND AMB FIXING (T/W/N)
                                                             END OF HEADER
G16 G27 2020  1  1  0  0  0.000000 2020  1  1  1 42 30.000000        -12         36
G09 G16 2020  1  1  0  0  0.000000 2020  1  1  2  9 30.000000         45       -128
G23 G17 2020  1  1  1 22  0.000000 2020  1  1  2 13 30.000000         13        -12
G23 G22 2020  1  1  0  3  0.000000 2020  1  1  2 13 30.000000         -7        -22
G08 G09 2020  1  1  0  0  0.000000 2020  1  1  2 54 30.000000        -35        100
G08 G03 2020  1  1  1 50  0.000000 2020  1  1  3 59 30.000000        -18         74
G01 G28 2020  1  1  1 56 30.000000 2020  1  1  5  7 30.000000        -24         94
G01 G09 2020  1  1  4 12  0.000000 2020  1  1  5  7 30.000000        -22         68
G11 G06 2020  1  1  2 58  0.000000 2020  1  1  5 13 30.000000        -26         67
G11 G22 2020  1  1  0  3  0.000000 2020  1  1  5 13 30.000000        -43         71
G07 G02 2020  1  1  4 44 30.000000 2020  1  1  5 16  0.000000        -11          5
G07 G30 2020  1  1  0 49 30.000000 2020  1  1  5 16  0.000000          2        -25
G30 G05 2020  1  1  6  7 30.000000 2020  1  1  6 28  0.000000          0         19
G17 G03 2020  1  1  1 50  0.000000 2020  1  1  6 33  0.000000         12        -45
```


Figure 5-5. The integer ambiguities ('cst_') file

htg file

The parameters in the **horizontal troposphere gradient ('htg_') file** are: start time (GPS time), end time (GPS time), initial North-South troposphere gradient (m), North-South troposphere gradient correction (m), initial East-West troposphere gradient (m), East-West troposphere gradient correction (m).



```
*YearS  MonS  DayS HourS  MinS       SecS YearE  MonE  DayE HourE  MinE       SecE  HTGCini   HTGCcor   HTGSini   HTGScor
 2020     1     1     0     0  0.000000  2020     1     1    12     0  0.000000 0.000000  0.000110  0.000000 -0.000063
 2020     1     1    12     0  0.000000  2020     1     2     0     0  0.000000 0.000000  0.000351  0.000000 -0.000452
```


Figure 5-6. The horizontal troposphere gradient ('htg_') file

log file

The results of RINEX health diagnosis are recorded in 'log' file. In the part of the file header, the comment “INT AMB/DEL” denotes epoch interval. The comment “AMB MAX/TOT/NEW” denotes max numbers of ambiguity for epochs, total numbers of ambiguity and newly added ambiguity numbers after posterior residual diagnosis, respectively. The comment “EPO AVA/REM/NEW” denotes available numbers of epochs, deleted numbers of epochs and newly added epoch numbers after posterior residual diagnosis, respectively.

In the part of file body, the line started with “TIM” records the time of health diagnosis data. And then next lines record the health diagnosis data. The comment “AMB” denotes adding a new ambiguity parameter. The content includes satellite number and ending time. The start time is the time which has been given at the line with “TIM”. The comment “DEL” denotes the data of the satellite deleted as bad data.

```
Rinex Health Diagnose     ABMF                          COMMENT
     30.00     30.00                                    INT AMB/DEL
        35       151         0                          AMB MAX/TOT/NEW
     84016     15059         0                          EPO AVA/REM/NEW
                                                        END OF HEADER
TIM 2020  1  1  0  0  0.0000000
G01                           2020  1  1  5  7 30.0000000 AMB
G03                                                     DEL_LOWELEVATION
G07                           2020  1  1  5 16  0.0000000 AMB
G08                           2020  1  1  3 59 30.0000000 AMB
G09                           2020  1  1  2 54 30.0000000 AMB
G11                           2020  1  1  5 13 30.0000000 AMB
G16                           2020  1  1  2  9 30.0000000 AMB
```

Figure 5-7. the RINEX health diagnosis (‘log_’) file

pos file

Static position results are recorded in the 'pos' file, with only one set of coordinates. The parameters in the ‘pos’ file are: station name, reference time (mjd / sod), coordinates (m), variance of X/Y/Z, covariance of XY/XZ/YZ, unit weighted mean errors (m), the number of observations used. This file only appears in the results of static solution. Besides, the ***pbopos*** (Table 5-2) can be used convert “pos_” file to PBO format.

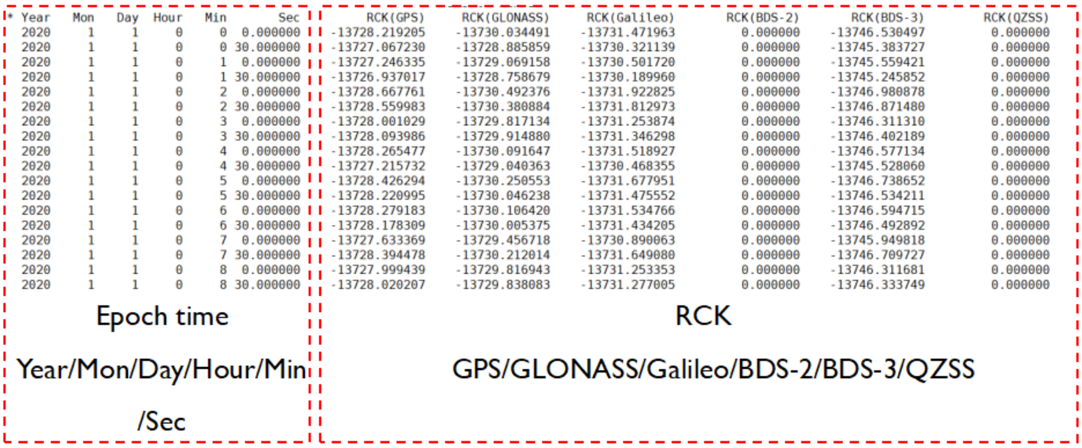
```
*Name        Mjd             X             Y             Z                  Sx                  Sy                  Sz
 abmf  58849.4997  2919785.7904 -5383744.9574  1774604.8600  0.45205365580695E-08  0.12554067299805E-07  0.19373651212222E-08

                   Rxy                   Rxz                   Ryz                  Sig0        Nobs
 -0.62544711497610E-08  0.19899133644847E-08 -0.37287323791219E-08  0.27449728760266E+01       84244
```

Figure 5-8. The static station coordinate (‘pos_’) file

rck file

The results of receiver clock are recorded in ‘rck’ file. In the file body, there are records of epoch time and receiver clock.

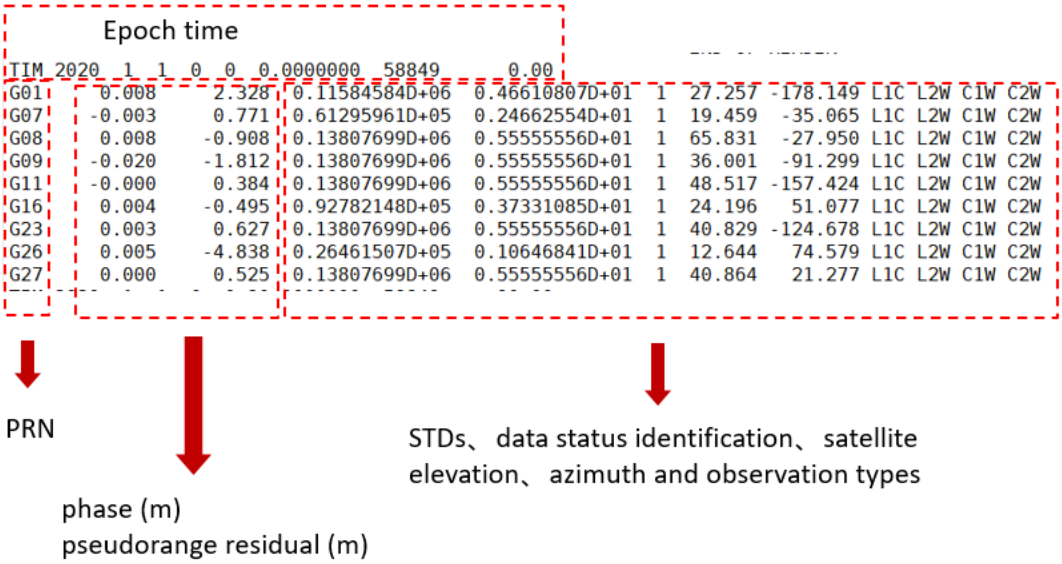


* Year	Mon	Day	Hour	Min	Sec	RCK(GPS)	RCK(GLONASS)	RCK(Galileo)	RCK(BDS-2)	RCK(BDS-3)	RCK(QZSS)
2020	1	1	0	0	0.000000	-13728.219205	-13730.034491	-13731.471963	0.000000	-13746.530497	0.000000
2020	1	1	0	0	30.000000	-13727.067230	-13728.885859	-13730.321139	0.000000	-13745.383727	0.000000
2020	1	1	0	1	0.000000	-13727.246335	-13729.069158	-13730.501720	0.000000	-13745.559421	0.000000
2020	1	1	0	1	30.000000	-13726.937017	-13728.758679	-13730.189960	0.000000	-13745.245852	0.000000
2020	1	1	0	2	0.000000	-13728.667761	-13730.492376	-13731.922825	0.000000	-13746.980878	0.000000
2020	1	1	0	2	30.000000	-13728.559983	-13730.380884	-13731.812973	0.000000	-13746.871480	0.000000
2020	1	1	0	3	0.000000	-13728.001029	-13729.817134	-13731.253874	0.000000	-13746.311310	0.000000
2020	1	1	0	3	30.000000	-13728.093986	-13729.914880	-13731.346298	0.000000	-13746.402189	0.000000
2020	1	1	0	4	0.000000	-13728.265477	-13730.091647	-13731.518927	0.000000	-13746.577134	0.000000
2020	1	1	0	4	30.000000	-13727.215732	-13729.040363	-13730.468355	0.000000	-13745.528060	0.000000
2020	1	1	0	5	0.000000	-13728.426294	-13730.250553	-13731.677951	0.000000	-13746.738652	0.000000
2020	1	1	0	5	30.000000	-13728.220995	-13730.046238	-13731.475552	0.000000	-13746.534211	0.000000
2020	1	1	0	6	0.000000	-13728.279183	-13730.106420	-13731.534766	0.000000	-13746.594715	0.000000
2020	1	1	0	6	30.000000	-13728.178309	-13730.005375	-13731.434205	0.000000	-13746.492892	0.000000
2020	1	1	0	7	0.000000	-13727.633369	-13729.456718	-13730.890063	0.000000	-13745.949818	0.000000
2020	1	1	0	7	30.000000	-13728.394478	-13730.212014	-13731.649080	0.000000	-13746.709727	0.000000
2020	1	1	0	8	0.000000	-13727.999439	-13729.816943	-13731.253353	0.000000	-13746.311681	0.000000
2020	1	1	0	8	30.000000	-13728.020207	-13729.838083	-13731.277005	0.000000	-13746.333749	0.000000

Figure 5-9. The receiver clock offset correction ('rck_') file

res file

The values of residuals for observation are recorded in 'res' file, as an output of ***lsq***. The parameters in 'res' file are: PRN, phase residual (m), pseudorange residual (m), STDs, data status identification, satellite elevation, azimuth, observation types.



```
TIM 2020  1  1  0  0  0.0000000  58849       0.00
G01    0.008     2.328  0.11584584D+06  0.46610807D+01  1  27.257 -178.149 L1C L2W C1W C2W
G07   -0.003     0.771  0.61295961D+05  0.24662554D+01  1  19.459  -35.065 L1C L2W C1W C2W
G08    0.008    -0.908  0.13807699D+06  0.55555556D+01  1  65.831  -27.950 L1C L2W C1W C2W
G09   -0.020    -1.812  0.13807699D+06  0.55555556D+01  1  36.001  -91.299 L1C L2W C1W C2W
G11   -0.000     0.384  0.13807699D+06  0.55555556D+01  1  48.517 -157.424 L1C L2W C1W C2W
G16    0.004    -0.495  0.92782148D+05  0.37331085D+01  1  24.196   51.077 L1C L2W C1W C2W
G23    0.003     0.627  0.13807699D+06  0.55555556D+01  1  40.829 -124.678 L1C L2W C1W C2W
G26    0.005    -4.838  0.26461507D+05  0.10646841D+01  1  12.644   74.579 L1C L2W C1W C2W
G27    0.000     0.525  0.13807699D+06  0.55555556D+01  1  40.864   21.277 L1C L2W C1W C2W
```


Figure 5-10. the residuals for observation ('res_') file

stt file

The statistic value of phase residuals are recorded in ‘stt’ file and you can check this file to obtain the quality of PPP result. The parameters in the ‘stt’ file are: RMS of phase residuals (mm), time series of residuals (mm).

```
+RMS OF RESIDUALS---PHASE(MM)
NAME SUMM G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 G32 R01 R02 R03 R05 R07 R08 R09 R1
1 R12 R13 R14 R15 R16 R17 R18 R19 R20 R21 R22 R23 E01 E02 E03 E04 E05 E07 E08 E09 E11 E12 E13 E14 E15 E21 E24 E25 E26 E27 E30 E31 E33 E36 C01 C02 C03 C04 C05 C06 C07 C0
8 C09 C10 C12 C13 C14 C16 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30 C32 C33 C34 C35 C36 C37
ABMF   16  10  10  25   0  11  15  14  16  18  17  13  17  13  15  14   9  11   0  17  22  15  19  14  14  16  13  14  12  14  20  16  21  11  19  14  16  15  16  11  2
5  15  16  16  15  13  21  18  19  13  10  14  14   6   7  20  13  10  26  12  12  19  12  26   0  31  11  26  18  12  15  16  12   8  14   0   0   0   0   0   0   0
0   0   0  14   0   8   0  18  49  16  13  13  12  20  17  13   8  20   8  22  12  21  13  19  11
NAME SUMM G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 G32 R01 R02 R03 R05 R07 R08 R09 R1
1 R12 R13 R14 R15 R16 R17 R18 R19 R20 R21 R22 R23 E01 E02 E03 E04 E05 E07 E08 E09 E11 E12 E13 E14 E15 E21 E24 E25 E26 E27 E30 E31 E33 E36 C01 C02 C03 C04 C05 C06 C07 C0
8 C09 C10 C12 C13 C14 C16 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30 C32 C33 C34 C35 C36 C37
-RMS OF RESIDUALS---PHASE(MM)
+TIME SERIES OF RESIDUALS---PHASE(MM)
  ABMF G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 G32 R01 R02 R03 R05 R07 R08 R09 R11 R
12 R13 R14 R15 R16 R17 R18 R19 R20 R21 R22 R23 E01 E02 E03 E04 E05 E07 E08 E09 E11 E12 E13 E14 E15 E21 E24 E25 E26 E27 E30 E31 E33 E36 C01 C02 C03 C04 C05 C06 C07 C08 C
09 C10 C12 C13 C14 C16 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30 C32 C33 C34 C35 C36 C37
     1   2                      -8  11 -13      -3                   3                           4           1   1                                              -2
               -16          12   5               0           9                         -11          -1           5              -3
                                         4              11   0      -3   6                 -14
     2   7                      -9   8 -13       0                   2                          -2          13   2                                              -2
                -9           6   4               0           6                         -13           3           6              -3
                                         0               7   3       1   5                 -11
     3  10                     -10  10 -13      -2                   0                           0          11   0                                              -3
               -11           3  10              -2           7                          -6          -4           7              -1
                                         1               8   2       2  -3                 -10
     4   6                     -12  12 -13       1                  -1                           0          16  -1                                              -3
                -9           3   9               0          11                         -14           2           3              -2
                                         4               9   0      -1  -5                 -13
     5   8                      -2  10 -13       0                   2                          -3           6  -2                                              -1
               -10           3   8               3          14                         -14          -1           2              -3
                                         3              10   0      -4 -13                 -10
     6   5                      -4  14 -10       1                  -1                          -5           1  -1                                              -4
                -9           9   3               1          11                         -12           2           3              -5
                                         1               9   0      -1 -11                  -8
     7   3                     -14  15  -8       2                   5                 -29  -3         -17   0                                              -2
                -6           7   1               1           9                         -20           3           5              -2
                                         4               9  -2      -1 -13                  -9
     8   5                     -14  14  -8       3                   0                 -22  -5         -22   3                                              -3
                -4           3   3               5           8                         -17           3           0              -3
                                         3               8   1      -2  -2                 -11
     9  -2                      -5  12  -3       4                   1                 -15  -5         -25   1                                              -3
                -7           6   3               2           5                         -15           2           3              -1
                                         5               6  -2       3 -11                  -9
```

Figure 5-11. the phase residual of single satellite (‘stt_’) file

ztd file

The value of zenith tropospheric delay are record in ‘ztd’ file. The parameters in the ‘ztd’ file are: epoch time, initial value of dry tropospheric delay, initial value of wet tropospheric delay, wet tropospheric delay correction.

* Year	Mon	Day	Hour	Min	Sec	ZDD	ZWDini	ZWDcor
2020	1	1	0	0	0.000000	2.311437	0.194235	0.040568
2020	1	1	0	0	30.000000	2.311463	0.193990	0.040568
2020	1	1	0	1	0.000000	2.311463	0.193990	0.040568
2020	1	1	0	1	30.000000	2.311463	0.193990	0.040568
2020	1	1	0	2	0.000000	2.311463	0.193989	0.040568
2020	1	1	0	2	30.000000	2.311463	0.193989	0.040568
2020	1	1	0	3	0.000000	2.311463	0.193989	0.040568
2020	1	1	0	3	30.000000	2.311463	0.193988	0.040568
2020	1	1	0	4	0.000000	2.311463	0.193988	0.040568
2020	1	1	0	4	30.000000	2.311463	0.193988	0.040568
2020	1	1	0	5	0.000000	2.311463	0.193987	0.040568
2020	1	1	0	5	30.000000	2.311463	0.193987	0.040568
2020	1	1	0	6	0.000000	2.311463	0.193987	0.040568
2020	1	1	0	6	30.000000	2.311463	0.193986	0.040568
2020	1	1	0	7	0.000000	2.311463	0.193986	0.040568
2020	1	1	0	7	30.000000	2.311463	0.193986	0.040568

epoch time

initial value of dry / wet tropospheric delay、
wet tropospheric delay correction

Figure 5-12. the zenith tropospheric delay (‘ztd_’) file

kin file

The results of position are recorded in ‘kin’ file when using the **K** model (kinematic). The coordinates in this file are recorded epoch by epoch. The parameters in the ‘kin’ file are: reference time, position coordinates(X, Y, Z), position coordinates(B, L, H), number of satellites, PDOP. This file only appears in the results of kinematic solution. Besides, You can run ***xyz2enu*** to get the corresponding topocentric coordinate.

* Mjd	Sod	X	Y	Z	Latitude	Longitude	Height	Nsat/GREC2C3J	PDOP
59215	0.00	4097216.569	4429119.272	-2065771.196	-19.0183042469	47.2292140325	1553.034	6 06 00 00 00 00 00	2.66
59215	30.00	4097216.567	4429119.268	-2065771.190	-19.0183042159	47.2292140201	1553.028	7 07 00 00 00 00 00	2.47
59215	60.00	4097216.562	4429119.268	-2065771.190	-19.0183042226	47.2292140572	1553.025	7 07 00 00 00 00 00	2.47
59215	90.00	4097216.563	4429119.270	-2065771.192	-19.0183042350	47.2292140608	1553.027	7 07 00 00 00 00 00	2.46
59215	120.00	4097216.562	4429119.263	-2065771.190	-19.0183042327	47.2292140270	1553.021	7 07 00 00 00 00 00	2.45
59215	150.00	4097216.567	4429119.268	-2065771.192	-19.0183042318	47.2292140212	1553.029	7 07 00 00 00 00 00	2.44
59215	180.00	4097216.556	4429119.261	-2065771.184	-19.0183041975	47.2292140558	1553.014	7 07 00 00 00 00 00	2.44
59215	210.00	4097216.558	4429119.260	-2065771.187	-19.0183042240	47.2292140363	1553.016	7 07 00 00 00 00 00	2.43
59215	240.00	4097216.551	4429119.262	-2065771.186	-19.0183042242	47.2292140927	1553.012	7 07 00 00 00 00 00	2.42
59215	270.00	4097216.556	4429119.267	-2065771.194	-19.0183042744	47.2292140885	1553.022	7 07 00 00 00 00 00	2.41
59215	300.00	4097216.544	4429119.258	-2065771.190	-19.0183042816	47.2292141187	1553.006	7 07 00 00 00 00 00	2.41
59215	330.00	4097216.547	4429119.263	-2065771.194	-19.0183042984	47.2292141317	1553.013	7 07 00 00 00 00 00	2.40
59215	360.00	4097216.549	4429119.265	-2065771.187	-19.0183042293	47.2292141282	1553.013	7 07 00 00 00 00 00	2.39
59215	390.00	4097216.551	4429119.263	-2065771.191	-19.0183042680	47.2292141006	1553.014	7 07 00 00 00 00 00	2.38
59215	420.00	4097216.553	4429119.268	-2065771.189	-19.0183042350	47.2292141155	1553.018	7 07 00 00 00 00 00	2.38
59215	450.00	4097216.546	4429119.256	-2065771.184	-19.0183042286	47.2292140859	1553.004	7 07 00 00 00 00 00	2.37
59215	480.00	4097216.550	4429119.263	-2065771.184	-19.0183042089	47.2292141103	1553.011	7 07 00 00 00 00 00	2.36
59215	510.00	4097216.552	4429119.268	-2065771.189	-19.0183042353	47.2292141268	1553.018	7 07 00 00 00 00 00	2.35

X(m) Y (m) Z (m)

B(°) L (°) H(m)

Number of satellites(All/GPS/GLONASS
/Galieo/BDS2/BDS3/QZSS) / PDOP

Figure 5-13. the kinematic station coordinate (‘kin_’) file

5.3.2 Usage of result data processing scripts/programs

As shown in Table 5-2, there are some useful scripts under the “scripts/” directory that facilitate users to process results. Note that if your Python 3 path is not ‘/usr/bin/python3’, you can use the ***which*** command to find the path of python3 in your computer.

```
which python3
/usr/local/bin/python3
```

Then, modify these python program header to the corresponding path.

```
#!/usr/bin/python3
#!/usr/local/bin/python3
```

Copy the modified python scripts to the system path (~/.PRIDE_PPPAR_BIN/). Then you can use these python scripts directly in any directory.

```
cp plotkin.py ~/.PRIDE_PPPAR_BIN/
```

Moreover, the python scripts require some modules of python, i.e., NumPy and Matplotlib.

Usage of pbopos

pbopos is used to convert PRIDE-PPPAR pos files to PBO position series. The usage of ***pbopos*** is as follows:

```
pbopos site path [x_ref y_ref z_ref]
```

- “site” is the station name
- “path” is the “pos_” file with path
- “[x_ref y_ref z_ref]” is optional parameter, represent the reference coordinates.

All “pos_” files with standard naming in directory will be recognized and found automatically, depends on which kind of path you input:

- './' stop until no successive “pos_” file exists
- './yyyy/ddd/ stop untill no successive year folder exists

Usage of xyz2enu

xyz2enu is used to convert the geocentric coordinate to the topocentric coordinate (unit: m). The usage of ***xyz2enu*** is as follows:

```
xyz2enu kin_fl enu_fl [x_ref y_ref z_ref]
```

- “kin_fl” is the “kin_” file
- “enu_fl” is user-defined output file name
- “[x_ref y_ref z_ref]” is optional parameter, represent the reference coordinates. If there is no input, the coordinates mean value of “kin_” file will be used.

Plots of position time series

The ***plotkin.py*** script and the ***plotkin.sh*** script are used to plot position time series of **K** mode.

```
plotkin.py kin_filename png_filename [x_ref y_ref z_ref]
```

```
plotkin.sh kin_filename png_filename [x_ref y_ref z_ref]
```

- "kin_filename" is the 'kin' file
- "png_filename" is the PNG format picture name to be saved
- "[x_ref y_ref z_ref]" is optional parameter, represent the reference coordinates. If there is no input, the coordinates mean value of "kin_" file will be used.

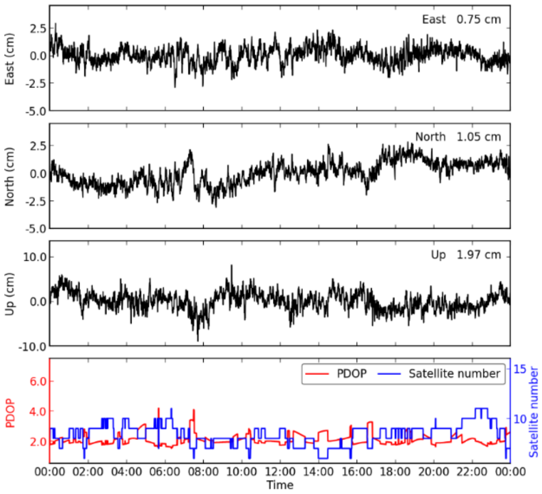


Figure 5-14. Example of *plotkin.py*

Plots of residuals

There is a python script and a GMT script for plotting residuals in the 'scripts' folder named ***plotres.py*** and ***plotres.sh***.

```
plotres.py res_filename PRN
plotres.sh res_filename png_filename
```

- "res_filename" denotes the 'res' file
- "PRN" denotes the satellite will be plotted in ***plotres.py***, and the picture will be saved as "PRN.png"
- "png_filename" denotes the PNG format picture will be saved in ***plotres.sh***, and the ***plotres.sh*** will plot all satellites contained in the 'res' file

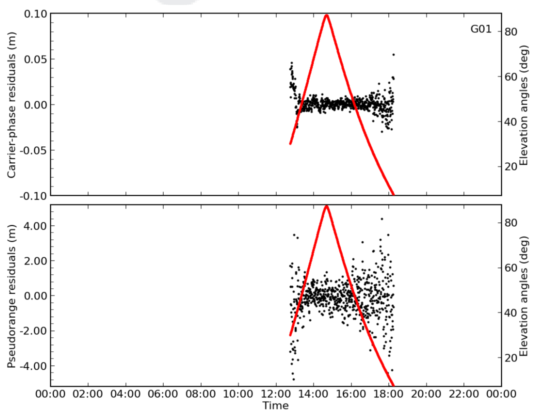


Figure 5-15. Example of *plotres.py*

Plots of track

Trajectory can also be plotted via 'kin' file, i.e., through ***plottrack.py*** we can obtain the required picture.

```
plottrack.py kin_filename png_filename
```

- "kin_filename" is the 'kin' file
- "png_filename" is the PNG format picture name to be saved

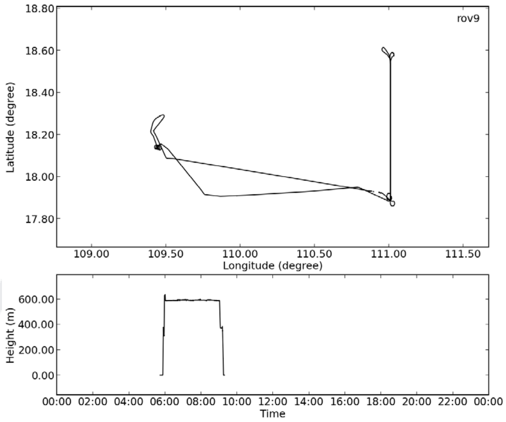


Figure 5-16. Example of plottrack.py

Plots of ZTD

Another plotting script is ***plotztd.py***, the usage of ***plotztd.py*** is as follows.

```
plotztd.py ztd_filename png_filename
```

- "ztd_filename" is the 'ztd' file
- "png_filename" is the PNG format picture name to be saved

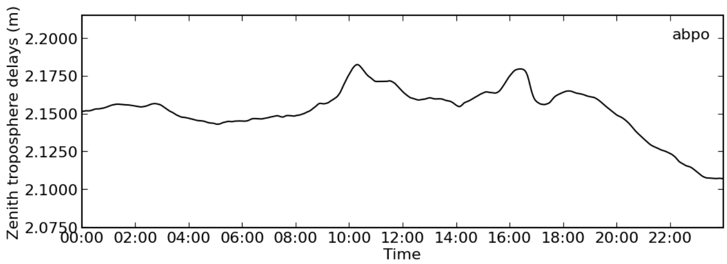


Figure 5-17. Example of plotztd.py

5.3.3 Table Files

Ocean Tide Loading File (oceanload)

In order to obtain ocean tide loading information, you can submit station coordinates to the website (http://holt.oso.chalmers.se/loading/) as required. Then copy the oceanload information to your ocean tide loading file oceanload. The station coordinates in sit.xyz can be used to calculate ocean tide loading information. The parameters and format of these files are described at the website.

File Name Definition File (file_name)

File names of PRIDE PPP-AR are defined in file 'file_name'. The first column records keyword of output file and following it is the format of file name. In the format, YYYY denotes the year of processing and DDD denotes the day of year. SNAM denotes the station name. For example, "res_2020001_abmf" denotes the residual of station abmf in 1st, 2020. The format of 'file_name' is as below (Figure 5-18):

```
amb       amb_-YYYY--DDD-
cst       cst_-YYYY--DDD-
fcb       fcb_-YYYY--DDD-
htg       htg_-YYYY--DDD-
kin       kin_-YYYY--DDD-_-SNAM-
neq       neq_-YYYY--DDD-
orb       orb_-YYYY--DDD-
pos       pos_-YYYY--DDD-_-SNAM-
rck       rck_-YYYY--DDD-
res       res_-YYYY--DDD-
log       log_-YYYY--DDD-_-SNAM-
rnxo      -SNAM--DDD-0.-YY-o
rnxm      -SNAM--DDD-0.-YY-m
rnxn      auto-DDD-0.-YY-n
sck       sck_-YYYY--DDD-
stt       stt_-YYYY--DDD-
ztd       ztd_-YYYY--DDD-
vmf       vmf_-YYYY--DDD-
tec       tec_-YYYY--DDD-
rck       rck_-YYYY--DDD-
att       att_-YYYY--DDD-
```

Figure 5-18. Format of file_name

Global Terrain File (orography_ell)

In order to correct the effect of terrain on the results, the global terrain correction file orography_ell which contains coefficients for terrain correction is used, and the grid accuracy is 2.5 degree * 2.5 degree.

Global Terrain File (orography_ell _1x1)

The content of another file named orography_ell_1x1 is similar to orography_ell, but the grid precision is 1 degree * 1 degree.

External Grid File (gpt3_1.grd)

GPT3_1 is based on a 1 degree * 1 degree external grid file ('gpt3_1.grd') with mean values as well as sine and cosine amplitudes for the annual and semiannual variation of the coefficients.

Configuration File Template (config_template)

Records the data processing strategy that is the basis for the operation of the software.

5.4 Quick Start and Program Execution

After the software installation is completed, the corresponding executable programs and data processing scripts will be stored in the system path ~/.PRIDE_PPPAR_BIN/*. Considering the previous command line form of ***pdp3*** and configuration file is more complex, some adjustments have been made to facilitate users to use PRIDE PPP-AR , <u>but the software is still running based on the configuration file</u>. Before you start, you need to know some considerations:

1) <u>Change the way the *pdp3* script runs,</u> so that users can enter command line parameters according to their needs;
2) As described in section 5.2.2 Drawing Lines, the three configuration file templates under the software installation directory (*~/.PRIDE_PPPAR_BIN* /config_template) are used by default. <u>If the users needs to modify the rest of the options in the configuration file, the configuration file template from the “table” directory can be used as the basis.</u>

In this section: the package directory is path-to-software; the working directory is path-to-project; the path to the directory where the RINEX observation files and broadcast ephemeris are located is path-to-data; the path to the configuration file is path-to-config; the observation files, broadcast ephemeris and configuration files are: RINEXo, RINEXn and config respectively.

5.4.1 Usage of *pdp3*

The usage of ***pdp3*** is shown in Figure 5-19.

```
Usage: pdp3 [options] <obs-file>

  All char type arguments could be either upper-case or lower-case

Start up:

  -V, --version                        display version of this script

  -H, --help                           print this help

Common options:

  -cfg <file>, --config <file>         configuration file for PRIDE PPP-AR 2

  -sys <char>, --system <char>         GNSS to be processed, select one or more from "GREC23J":
                                       -----+----------------------+-----+-----------------------
                                         G  |  GPS                 |  R  |  GLONASS
                                         E  |  Galileo             |  C  |  BeiDou-2 and BeiDou-3
                                         2  |  BeiDou-2 only       |  3  |  BeiDou-3 only
                                         J  |  QZSS                |     |
                                       -----+----------------------+-----+-----------------------
                                         * default: all GNSS

  -m <char>, --mode <char>             positioning mode, select one from "K/S/F":
                                       -----+------------+-----+------------+-----+-----------
                                         S  |  static    |  K  | kinematic  |  F  |  fixed
                                       -----+------------+-----+------------+-----+-----------

  -s <date [time]>, --start <date [time]>   start date (and time) for processing, format:
                                       --------+---------------------+--------+---------------
                                         date  |  yyyy/mm/dd or yyyy/doy  |  time  |  hh:mm:ss
                                       --------+---------------------+--------+---------------
                                         * default: the first observation epoch in obs-file

  -e <date [time]>, --end <date [time]>     end date (and time) for processing, format:
                                       --------+---------------------+--------+---------------
                                         date  |  yyyy/mm/dd or yyyy/doy  |  time  |  hh:mm:ss
                                       --------+---------------------+--------+---------------
                                         * default: the last observation epoch in obs-file

  -n <char>, --site <char>             site name for processing, format: NNNN
                                         * default: the MARKER NAME in obs-file, or the first four
                                             characters of the filename in RINEX naming convention

  -i <num>,  --interval <num>          processing interval in seconds, 0.02 <= interval <= 30
                                         * default: the minimal observation interval in obs-file
```

Figure 5-19. *pdp3* script partial help information

Except for "**obs-file**", all other options are optional, and the order of priority is: Command Line Parameters > Configuration File > Default Value. The option name must be entered correctly, and the input parameters can be entered in both upper and lower case, where **< >** indicates that the input parameter is required and **[ ]** indicates that the input parameter is optional. The meaning of each option is as follows:

- **obs-file**: RINEX observation file with path, either relative path or absolute path. Note that the broadcast ephemeris needs to be in the same directory as the RINEX observation file. For multi-day processing, all observation files are stored in the same directory, and then the observation file names for the first day are entered. Multi-day processing observation file matching methods include: (1) search for observation files in standard naming format; (2) support for observation files that are directly merged for multiple days.
- **-V, --version**: output software version.
- **-H, --help**: output ***pdp3*** script help information.

Common options:

- **-cfg, --config**: configuration file with path, either relative path or absolute path. If this item is not specified, the default matches the configuration file in the installation directory (~/.PRIDE_PPPAR_BIN/config_template).
- **-sys <char>, --system <char>:** Select the GNSS systems involved in data processing by entering one or more of "GREC23J", which means "GPS/GLONASS/Galileo/BDS/BDS-2/BDS-3/QZSS" respectively. When this option is not entered, all five systems are used by default.
- **-m <char>, --mode <char>**: positioning mode. S for the static solution,K for the kinematic solution and F for the station-fixed solution. If this item is not specified and the configuration file is specified, the positioning mode in the configuration file will be read, otherwise the K mode is used by default. The order of priority is: command line > configuration file > default.

- **-s <date [time]>**, **--start <date [time]>**: start time for processing, format: “yyyy/mm/dd hh:mm:ss”, indicates the year, month, day and hour, minute and second, where “hh:mm:ss” is optional. And can take the form of a yyyy/doy (year and day of year). If this item is not specified, use the first epoch of the observation file as the start time.
- **-e <date [time]>**, **--end <date [time]>**: end time for processing, format: “yyyy/mm/dd hh:mm:ss”, indicates the year, month, day and hour, minute and second, where “hh:mm:ss” is optional. And can take the form of a yyyy/doy (year and day of year). If this item is not specified, the default is to use the last epoch of the observation file as the end time.
- **-n <char>, --site <char>**: four digit and letter combinations for station name. If this item is not specified, Read the station name corresponding to “MARKER NAME” in the observation file header; If the station name is not read, take the first four characters of the observation file name (subject to the standard naming format)
- **-i <num>, --interval <num>**:processing interval. The values range from 0.02s to 30s. If this item is not specified and the configuration file is specified, the processing interval in the configuration file will be read, otherwise, the sampling rate of the observation file is used by default..

  Advanced options:
- **-aoff**, **--wapc-off**: disable APC correction on the Melbourne-Wübbena combination. If this option is not entered, APC correction will be applied. Note that this correction should be consistent with the calculation strategy of the corresponding products. When using products other than “WUMMGX0RAP_*”, try entering this parameter on the command line if you do not know the calculation strategy of the corresponding products and the fixed rate of the wide lane is low.
- **-c <num>**, **--cutoff-elev <num>:** The cutoff elevation angle, in the range of 0° to 60°. If this option is not entered, the default is 7°.
- **-f**, **--float:** No ambiguity resolution is performed and the float solution is calculated. If this option is not entered and there are code/phase bias products the fixed solution is calculated
- **-hion**, **--high-ion:** use 2nd ionospheric delay model with CODE's GIM product. When this option is not entered, no higher-order ionospheric correction is performed.
- **-hoff**, **--htg-off:** disable horizontal tropospheric gradient (HTG) estimation. The K mode does not estimate the horizontal tropospheric gradient when this option is not entered, and the S/F mode is PWC:720 (Estimated every 12 hours).
- **-l, --loose-edit:** Disable strict editing mode, which should be used when high dynamic data quality is poor. If this option is not entered, strict editing is performed by default. Arcs shorter than ten minutes in strict edit mode will be excluded, otherwise two minutes.
- **-p <char>**, **--mapping-func <char>:** ZTD mapping function. Options include (1) G: GMF mapping function; (2) N: NMF mapping function; (3) V1: VMF1 mapping function; and (4) V3: VMF3 mapping function. GMF mapping function is used by default if this option is not entered.
- **-toff <char>**, **--tide-off <char>:** Disable tide correction, enter one or more of “SOP” for solid, ocean, and polar tides. If this option is not entered, apply all tide corrections.
- **-x <num>, --fix-method <num>:** Ambiguity resolution method. Options include: (1) rounding method; (2) LAMBDA method. The default Ambiguity resolution method is LAMBDA method when the processing time is less than 6 hours, otherwise it is the rounding method. The LAMBDA method should be used when the processing time is short, otherwise the rounding method should be used.
- **-z <char[length] [num]>**, **--ztd <char[length] [num]>:** The zenith tropospheric delay model and the corresponding process noise parameters (optional). The zenith tropospheric delay model options include: (1) p60/P60: PWC:60, estimated every 1h, where the estimated duration (60) is customizable (needs to be greater than or equal to 60); (2) s/S: STO, stochastic walk noise. This option defaults to sto when not entered, The corresponding process noise parameters are in units of m/sqrt(s) and 0.02m/sqrt(h), the range is 0~10. STO corresponds to the default value of 0.0004 when the process noise parameter is not entered, and PWC corresponds to the default value of 0.02m/sqrt(h).

Note: For multi-day processing, use **-s** (**--start**) and **-e** (**--end**) to specify the data processing session time, use the observation files that have not been merged for multiple days to put them in the same directory, and **obs-file** to specify the observation files for the first day. In addition, when processing highly dynamic data, due to the large amount of data, pdp3 will be relatively time-consuming to match the relevant information at the beginning, so please be patient.

5.4.2 Configuration file

As mentioned above, there is a configuration file template in the "path-to-software/table" directory, which is used to record the data processing policy of PRIDE PPP-AR. The command-line parameters described in section 4.4.1 are equivalent to specifying the configuration options in the configuration file, and the users can modify the configuration information through the configuration file. If no command-line parameters are entered and a configuration file is specified, the corresponding configuration options in the configuration file will be matched. The configuration file uses the "**Keyword=Value**" format to record the various options. For enumerated values, the optional value is an enumerated label (NO, YES, etc.). The text after "!" in a line is considered a comment. The configuration file is divided into the following parts: observation session configuration and satellite product, data processing strategies, ambiguity fixing options, satellite list and station list.

Observation session configuration and satellite product

The command line options corresponding to each configuration option in this section include:

- Interval = Default
  The sampling rate corresponds to the command line option **-i** or **--interval**. "Default" means that the default value, i.e. the corresponding sample rate in the observation file, is used.
- Session time = -YYYY- -MM- -DD- -HH- -MI- -SS- -SE-
  The data processing start time and processing duration, in order, are the year, month, day, hour, minute and second and the processing duration in seconds. Note that the modification does not take effect when using the ***pdp3*** script. If the user wants to specify the processing time period, enter the corresponding command line parameters, which correspond to -s (--start) and -e (--end).
- Table directory = /home/username/path-to-table/table/
  Specify the directory where the table files are located. Note that after the software is successfully installed, the "Table directory" will be changed to the "table/" directory in the package directory, and the user does not need to modify it.
  Table directory = /home/username/path-to-software/table/
- Product directory = /home/username/path-to-product/products/
  Specify the catalog where the precision products are located. For the "Product directory" directory, if the user does not modify it, i.e. "Default", the "product" directory will be created in the "path-to-project/year" directory, for example, when processing the data in 2022
  Product directory = /home/username/path-to-project/2022/product/

The required precise product categories are stored in subdirectories of the "products" directory, including "common", "ssc", "vmf" and "ion". "vmf" and "ion" subdirectories. These directories are the most error-prone areas and are usually left at their default values.

Note that the Rinex directory in the previous version of the configuration file is replaced by the first option of ***pdp3***, which stores the observation files and broadcast ephemeris, so the user needs to make sure to enter the correct path and observation file name (you can use the Tab key to complete the path when entering to prevent input errors).

After that is the product name section, which are Satellite orbit. Satellite Clock, ERP, Quaternions and Code/phase bias, "Default" means use the default product, related information can refer to the end of section 4.3 and Appendix A. If you want to use other products, you need to decompress them and place them in the " Product directory/common" directory. Then change the corresponding product name in the configuration file from "Default" to the actual file name. If there is no quaternions product, you can change Quaternions to "none"; if you don't need ambiguity resolution, you don't need the code/phase bias product, and you can change Code/phase bias to "none". Note that multi-day processing should include all days of product filenames, separated by spaces

data processing strategies

There are five configuration options in this section:

- Strict editing = YES
  data editing mode. The corresponding command line option is **-l** or **--loose-edit**. Which should be modified to "NO" when the data quality is poor, meaning a more lenient editing threshold and fewer iterations.
- ZTD model = STO
  Zenith troposphere delay process noise model (PWC/STO). PWC:60 means piece-wise constant for 60 minutes; STO means stochastic walk noise. The corresponding command line option is **-z** or –**ztd**. "Default" means the default value, i.e. STO.
- HTG model = PWC:720
  Horizontal troposphere gradient process noise model (PWC/NON). NON means no estimates. "Default" means the default value, i.e. PWC:720 for S/F mode and NON for K mode.

ZTD model and HTG model modification suggestions: (1) S/F model: PWC: 60 and PWC: 720; (2) K model: STO and NON.

- Iono 2nd = NO
  Changed to YES if correcting 2-order ionospheric delays. The corresponding command line option is **-hion** or **--hgh-ion**. "Default" means NO. The residual higher-order ionospheric delay in the ionosphere-free observations has a negligible effect on the PPP and is not normally corrected. The corresponding GIM product will be stored in the "Product directory/ion" directory when this correction is performed..
- Tides = SOLID/OCEAN/POLE
  Remove any of them to shut it down, or changed to NON if not correcting tidal errors. The corresponding command line option is **-toff** or**--tide-off** . Among them, the ocean tide correction needs to be interpolated according to the oceanload file under the Table directory. If "*##warning (oceanload_coef): no ocean load coefficients* for" is prompted in the output ***lsq*** part of the screen or the head of the result file shows that the ocean tide correction is not carried out, update the oceanload file according to **step 3** of section 5.4.3 and solve again

ambiguity fixing options

There are two main configuration options to note in this section, the others can be left at their default values

- Ambiguity co-var = Default
  Ambiguity resolution method, the corresponding command line option is **-x** or **--fix-method**. "Default" means the default value, YES when the instant length is less than 6h, use LAMBDA method for ambiguity resolution, otherwise use rounding method.
- Ambiguity duration =600
  Single-difference satellite pair co-viewing time length required for ambiguity resolution.
- Cutoff elevation =15
  Cut-off elevation angle required for ambiguity resolution.
- PCO on wide-lane = Default
  PCO corrections on Melbourne-Wübbena or not， the corresponding command line option is **-aoff** or **--apc-off**.
- Widelane decision = 0.20 0.15 1000.
  Bias, standard deviation, and threshold in cycle for judging wide-lane ambiguity resolution.
- Narrowlane decision = 0.15 0.15 1000.
  Bias, standard deviation, and threshold in cycle for judging narrow-lane ambiguity resolution.
- Critical search = 2 4 1.8 3.0
  The four parameters are, the maximum number of ambiguities removed, the minimum number of ambiguities retained, the minimum value of ratio for ambiguity search and the threshold value in the LAMBDA algorithm in order. When the ambiguity of the narrow lane cannot be fixed using the LAMBDA method, i.e. "*no more can be fixed*" is output in the LAMBDA fixed rate section of ***arsig***, the first value (the maximum amount of ambiguity is eliminated) can be adjusted upward gradually and solve again.

satellite list and station list.

The satellite list consists of the satellite PRN and the corresponding weighting factor, the larger the weighting factor, the lower the weighting. Users can disable the satellite by inserting "#" at the beginning of a single GNSS PRN, corresponding to the command line parameter **-sys** or **--system** (note that these two command line parameters indicate that all satellites of the corresponding input system are selected, and satellites of other systems will be disabled). Since the orbit accuracy of BDS-2 GEO satellites (C01-C05) is low, you can disable them if the positioning result is poor.

Leave the default values in the station list except for the configuration options corresponding to the command line parameters. Note: (1) only one line can be kept in the station list; (2) x/X in this part is a wildcard, indicating the corresponding default value; (3) if you want to make changes, pay attention to keep the same indentation as the original one. They indicate the station name, positioning mode, tropospheric mapping function, priori constraint of receiver clock, cut-off elevation angle, priori constraint of ZTD and process noise, priori constraint of HTG and process noise, priori constraint of pseudorange and phase, and priori constraint of 3D coordinates (also process noise parameter in K mode). Where the last character m means in meters and c means in cycles.

NAME TP MAP CLKm EV ZTDm PoDm HTGm PoDm RAGm PHSc PoXEm PoYNm PoZHm xxxx X XXX 9000 xx 0.20 xxxxx .005 xxxx 0.30 0.01 10.00 10.00 10.00

- NAME
  The name of the station, a combination of four letters and numbers. The corresponding command line option is **-n** or **--site**.
- TP
  Positioning mode, the corresponding command line parameter is **-m** or **--mode**, the corresponding SINEX file will be stored in the "Product directory/ssc" directory if the positioning mode is F.
- MAP
  The mapping function for the ZTD, with the command line parameter **-z** or **--ztd**. If the mapping function is VMF1/VMF3, the corresponding tropospheric grid file will be stored in the "Product directory/vmf" directory.
- EV
  The cutoff elevation angle, corresponding to the command line parameter **-c** or **--cutoff-elev**.
- ZTDm PoDm
  Priori constraint of ZTD with process noise, where the process noise parameter corresponds to the second parameter of **-z** or **--ztd.**

5.4.3 General operation steps

After installation and verification, let's start the PPP data processing! The general steps when using PRIDE PPP-AR for data processing are:

Step 1: Make sure you have the software installed. For the method of installing software, see section 5.2.2.

Step 2: Refer to section 5.4.1 and section 5.4.2, if you want to modify other configuration options in addition to the command line options, modify the configuration file based on the configuration file template in the "example" directory in the software package.

Step 3: In case of non-networked solving, it is necessary to prepare in advance the external files to be downloaded and place them in the corresponding directories. This includes precision products, partial table files and broadcast ephemeris, refer to the last part of Section 4.3 and Appendix A.

Step 4: [Optional choice for stations offshore] Get Ocean tide loading parameters using the coordinates in ***sit.xyz*** according to the website (http://holt.oso.chalmers.se/loading/), or you can calculate the station coordinates by ***spp***, such as

```
spp    -trop saas path-to-data/RINEXo path-to-data/RINEXn
```

Choose the model ***FES2004*** (Figure 5-20), and leave the rest of the options as default.

Figure 5-20. Ocean tide model

Then submit a task by add station coordinates as below at the website. When you get the oceanload coefficients through your email, append them to oceanload in "Table directory" as the original format (Figure 5-21).

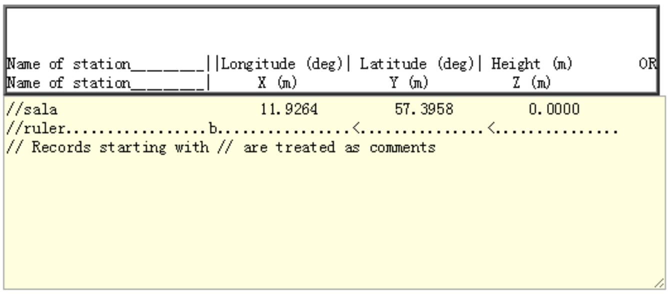


Figure 5-21. Submitting the task

Step 5: Calling ***pdp3*** for data processing.

```
pdp3 [-cfg path-to-config/config ……] path-to-data/RINEXo
```

Step 6: After processing, check the solution files in ***path-to-project/year/doy*** directory.

5.4.4 Processing Examples

If you already know how to process data with pdp3, you can start processing your data. Otherwise, you can practice with the data in the “path-to-software/example” directory. Create “Practice” folder under the “example” directory for program execution (If you are familiar with Linux, you can change the directory as needed). This section illustrates the parameter selection and input for common data processing scenarios, which can be used as a reference for users to adjust the relevant processing strategies as needed when processing data. Note that a corresponding complete configuration file will be generated under the result directory (year/day-of-year directory), which can be viewed by users to check the configuration information.

Example 1: Static single-day solution

For static single-day solution, enter **-m** or **--mode** option to specify the positioning mode as S mode, enter **-z** or **--ztd** option to specify the ZTD model as PWC:60, and keep the rest of the default configuration.

1) Create ‘Practice1’ directory under ‘Practice’ directory;
2) Open terminal, run ***pdp3*** script to start data processing under ‘Practice/Practice1’ directory;

```
pdp3 -m s -z p60 ../../data/2020/001/abmf0010.20o
```

3) The result files will be output in the “2020/001” directory, change directory to the “2020/001” directory;
4) For static solution, users can use ***pbopos*** to convert “pos_” file to PBO format

```
pbopos abmf pos_2020001_abmf
```

5) Plot residuals to analyze the solution;

```
plotres.py res_2020001_abmf G01
```

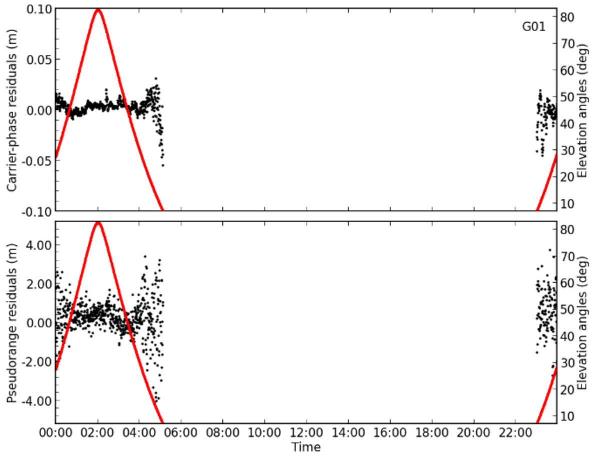


Figure 5-22. Resdiuals of abmf, 001 day in 2020

Example 2: Kinematic solutions

It is sufficient to keep the default configuration parameters when processing kinematic solutions. You can enter the **-l** or **--lose-edit** parameter if the data quality is poor.

1) Back to the 'Practice' directory and create 'Practice2' directory;
2) Open the terminal and run the ***pdp3*** script to start data processing under the 'Practice/Practice2' directory;

```
pdp3 ../../data/2021/210/ccj22100.21o
```

1) The result files will be output in the "2021/001" directory, change directory to the "2021/210" directory;
2) For kinematic solution, users can use ***xyz2enu*** to transform XYZ to ENU, If reference coordinates are empty, the coordinates mean value of "kin_" file will be used;

```
xyz2enu kin_2021210_ccj2 enu_2021210_ccj2
```

3) Plot displacement of station.

```
plotkin.py kin_2021210_ccj2 enuts_ccj2
```

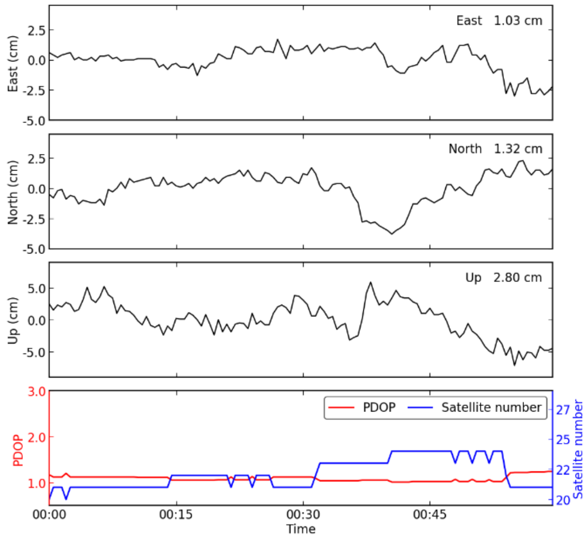


Figure 5-23. Position time series of ccj2, 210 day in 2021

Example 3: Seismic Data

The seismic data is the same as the dynamic solution, and each configuration parameter can be kept as default.

1) Back to the ‘Practice’ directory and create ‘Practice3’ directory;
2) In this example, using data during the Alaska M8.1 earthquake, data from UNAVCO (https://www.unavco.org).
3) Open terminal, run ***pdp3*** script to start data processing under ‘Practice/Practice3’ directory;

```
pdp3 ../../data/2021/210/ac122100.21o
```

4) The result files will be output in the “2021/001” directory, change directory to the “2021/210” directory;
5) Plot displacement of station.

```
plotkin.py kin_2021210_ac12 enuts_ac12
```

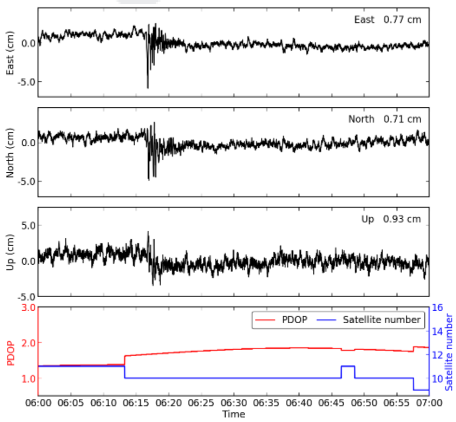


Figure 5-24. Position time series of ac12, 210 day in 2021

Example 4: Using other products

When using other products, you should pay attention to whether to add PCO correction in the M-W observation. If you are not sure, you can compare the parameters with and without **-aoff** or **--wapc-apc**, and then choose the solution with a higher fixed rate of wide-lane. In order not to modify the original configuration file template, copy "path-to-software/example/config_template" to the directory of this example.

1) Back to the 'Practice' directory and create 'Practice4' directory;
2) In this example, we will use the precise product released by CODE, the corresponding GPS week and days of week are 21684, the download link is Index of /CODE_MGEX/CODE/2021/ (unibe.ch);
3) Create the directory "2021/product/common" after the download is completed, and unzip the downloaded precise products and store them in this directory.
4) Switch to the 'Practice4' directory, copy the configuration file template from the "Table directory" directory to the current directory, and modify the product name in the configuration file.

   Satellite orbit = *COM21684.EPH*
   Satellite clock = *COM21684.CLK*
   ERP = *COM21684.ERP*
   Quaternions = *COM21684.OBX*
   Code/phase bias = *COM21684.BIA*

   Note: In multi-day processing you need to write all product file names with spaces as separators; or write individual merged product file names after merging them yourself, e.g.

   Satellite orbit = *COM21684.EPH COM21685.EPH*
5) Open terminal and run the script to start data processing under the 'Practice/Practice4' directory;

```
pdp3 -cfg config_template -aoff ../../data/2021/210/ccj22100.21o
```

6) The result files will be output in the "2021/210" directory, change directory to the "2021/210" directory;
7) Plot displacement of station.

```
plotkin.py kin_2021210_ccj2 enuts_ccj2
```

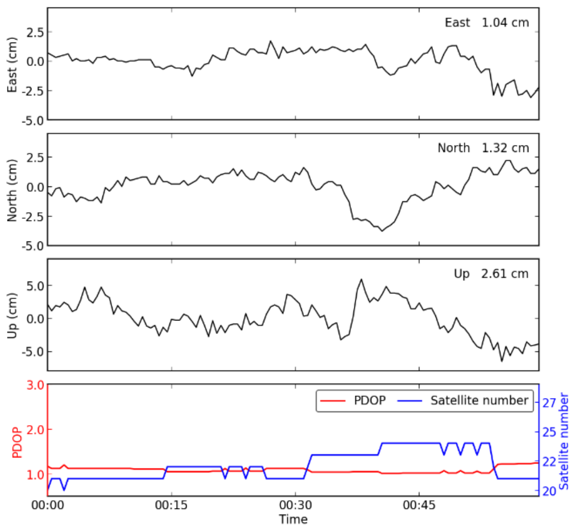


Figure 5-25. Position time series of ccj2, 210 day in 2021

Example 5: Preparing external files while offline

Processing data in offline mode requires prior preparation of external files, download links refer to the end of section 4.3. As in Example 4, the downloaded precision products need to be sorted into the respective subdirectories.

Required external files:

- Precise products: Downloaded and stored in the "Product directory/common" directory.
- Broadcast ephemeris: downloaded and stored in the directory where the observation files are located.
- leap.sec file: Since the time interval between two leaps is long, update this file after the leap occurs, download it and store it in the "Table directory" directory.
- satparameters file: This file is mainly used to read GLONASS satellite channel number, when processing data containing GLONASS satellite, you need to update this file, download it and store it in "Table directory" directory.
- ANTEX file: the default "WUM0MGXRAP_* clock difference product recorded the corresponding antenna file, if the "Table directory" directory does not have the file, you need to download and store in the "Table directory" directory.

Optional external files:

- IGS SINEX file: required when the positioning mode is F mode, it indicates the fixed station coordinates to improve the accuracy of ZTD estimation, download and store it in "Product directory/ssc" directory.
- Tropospheric grid file: required when the mapping function is VMF1 or VMF3, downloaded and stored them in the "Product directory/vmf" directory.
- The GIM products: needed for higher-order ionospheric corrections, download and store it in the "Product directory/ion" directory.

This example takes F mode as an example and downloads the corresponding precise products, broadcast ephemeris and solution files.

1) Back to the 'Practice' directory and create 'Practice5' directory, Download the external files required for the F model in 2021 day 220;

   Precise products: ftp://igs.gnsswhu.cn/pub/whu/phasebias/2021

Broadcast ephemeris:
ftp://igs.gnsswhu.cn/pub/gps/data/daily/2021/220/21p/BRDC00IGS_R_20212200000_01D_MN.rnx.gz
ANTEX file: The antenna file recorded in the header of the clock difference file in this example is "igs14_2148.atx",
https://files.igs.org/pub/station/general/pcv_archive/igs14_2148.atx
Satellite parameter file: ftp://igs.gnsswhu.cn/pub/whu/phasebias/table/sat_parameters
Solution file: ftp://igs.gnsswhu.cn/pub/gps/products/2170/igs21P21700.ssc.Z

2) Store the corresponding external files in the corresponding directories.
3) Open terminal and run the script to start data processing under the 'Practice/Practice5' directory.

```
pdp3 -m f ../../data/2021/220/BAKO00IDN_R_20212200000_01D_30S_MO.rnx
```

4) The result files will be output in the "2021/220" directory, change directory to the "2021/220" directory;
5) Plot the ZTD time series.

```
plotztd.py ztd_2021220_bako ztdts_2021220_bako
```

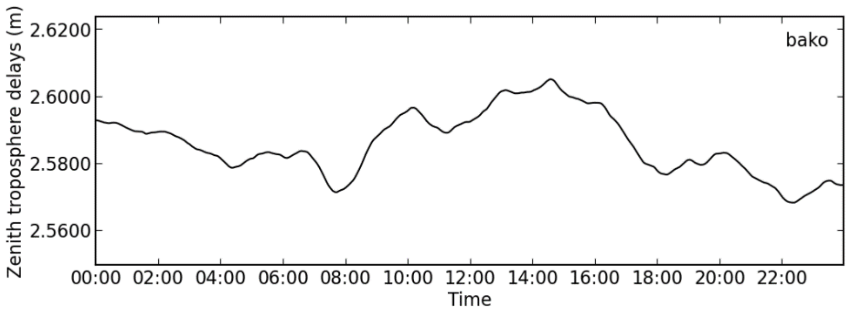


Figure 5-26. ZTD time series of bako, 220 day in 2021

6 PRIDE PPP-AR for GUI

6.1 Overview

6.1.1 The difference between the GUI version and the CUI version

1) The GUI version cannot handle high-frequency data above 1Hz;
2) GUI version will not download RTS products, GLONASS broadcast ephemeris and hourly broadcast ephemeris;
3) The GUI version cannot download COD/COM products before 2020, users can download and modify the corresponding configuration by themselves, see section 6.3.2;
4) Only support for single-day processing;
5) Same as section 5.4.3 **step3**, some stations near the coast need ocean tidal correction. Table directory of the GUI version is in the installation directory.

6.1.2 Software Introduction

This GUI version of PRIDE PPP-AR software is based on the Linux version. The executable files used in the software are the same as the Linux version, and the products preparation process and data processing steps are also the same as the Linux version. The software can help users to use PRIDE PPP-AR on Mac system and Windows system in a friendly way.

This software can achieve most of the functions of the Linux version, and it can process the observation data of a single station in a single day at a time. However, due to the memory limitation of Windows system, you still need to use Linux version if you need to process high frequency dynamic data with sampling frequency higher than 1Hz, continuous multi-day data processing, or large batch of observation data solving.

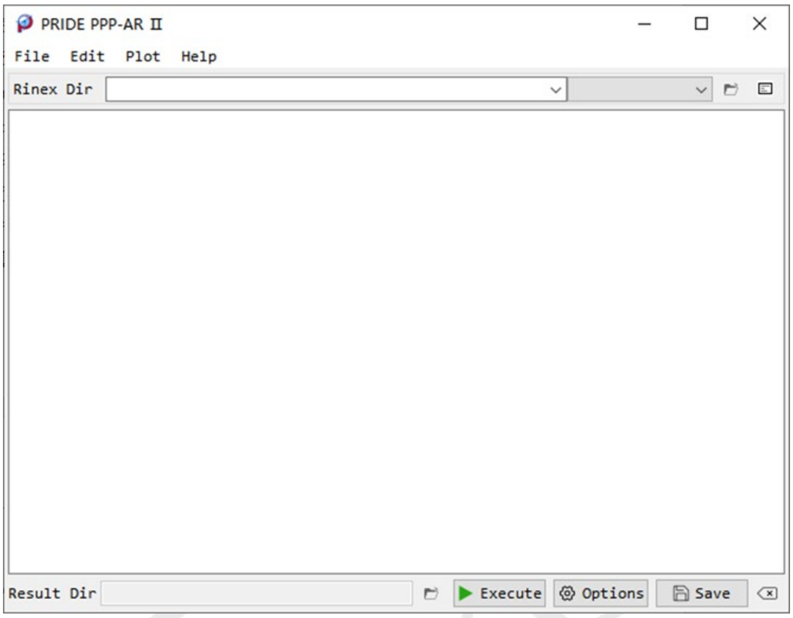


Figure 6-1. Main interface of the software PRIDE PPP-AR

6.1.3 Software features

PRIDE PPP-AR GUI version has the following features:

(1) User-friendly interface for users who are not good at operating Linux systems;

(2) Support a variety of result files' plotting, and support zoom, cursor and other auxiliary functions;

(3) The calculation results are consistent with the Linux version, and compatible with the Linux version, such as the configuration file (config) and the result files (kin, res, etc.) can be interoperable;

(4) Inherited most of the data processing functions of Linux version, such as hourly kinematic data processing with sampling interval greater then 1s, kinematic/static solution of 30s observation data in a single day, etc.

(5) Maintain the same solution options as Linux version, such as support for the solutions of the five systems of GRECJ, LAMBDA algorithm, a variety of tropospheric delay estimation models, a variety of AC GNSS products.

6.1.4 Software main interface

As shown in the figure, the main interface of the software has the following main sections.

(1) Menu bar: In the first menu bar, the "File" bar allows you to select the directory of the RINEX file where the calculation is performed, save the execution steps in the output message area, load the config file, etc.; the "Options" in the Edit bar can be used to set the parameters of the solution; the "Plot Figure" option in the "Plot" can be used for plotting after the solution; the

"Help" option in "Help" can be used to go to the official website of this software.

(2) Workspace: mainly buttons for viewing config file in item 2, controls related to directory setting in item 3 workspace, message output area in item 4, controls related to result files' directory in item 5, buttons for parameter setting and calculation in item 6, and buttons for saving or clearing output messages in item 7.

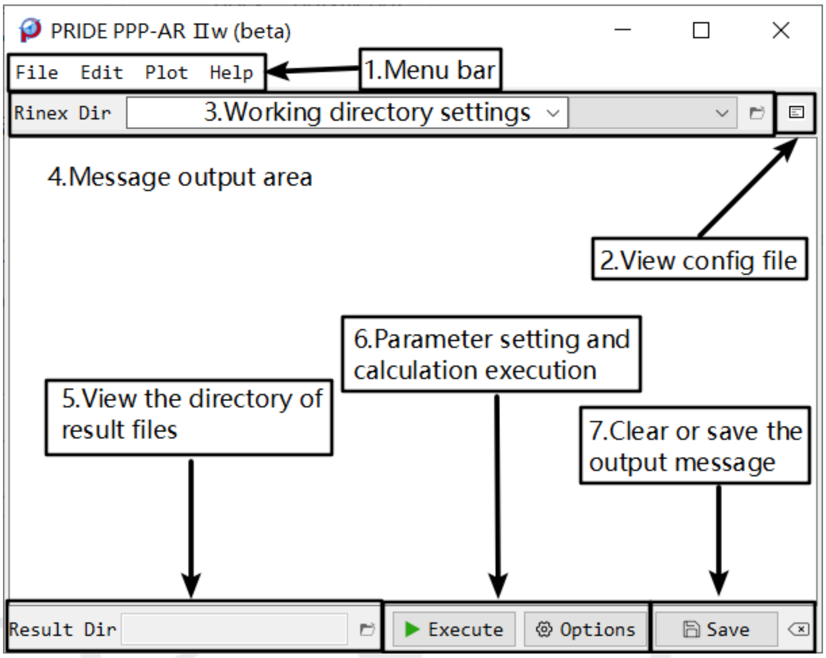


Figure 6-2. Main components of the main software interface

6.2 Software Operation Steps

(1) **Select the observation file to be processed**: first click on the folder icon in the main interface and select the path where the observation file to be processed is located in the file path option dialog that pops up; then the combo box on the left side of the folder icon will have the observation file name to choose from, and select the observation file to be processed from the combo box according to the file name, or select "ALL" to process all the observation files in the working directory.

(2) **Select the desired solution parameters**: click on the Options button and set exactly the parameters such as sampling interval, dynamic or static, ambiguity fixing strategy and satellites list involved in the solution in the Options dialog, plus other options such as tropospheric estimation parameters and product options can be modified as needed. This step generates a config file equivalent to the Linux version, which can be viewed by clicking on the icon to the right of the folder icon.

(3) **Start solving**: Click the Execute button to perform PPP solving on the observation file selected in the first step and according to the solving parameters selected in the second step; during the solving process, this GUI version of PRIDE PPP-AR program will execute programs such as

spp, sp3orb, redig, tedit, lsq and arsig in the same order as the Linux version to perform a series of PPP or PPP-AR operations. The solving process takes about tens of seconds, and during this process the middle whiteboard text box will display the solving steps simultaneously, in addition you can save the contents of the text box to a text file by using the Save button in the bottom right corner of the main interface, the button to the right of the Save button is to clear all the contents of the text box.

(4) **To access the results file**: you can access the results folder by clicking on the folder icon directly below the main interface, or you can click on the Plot Figure option under Plot in the menu bar at the top of the main interface to plot from the results file; in addition, you can also choose to save and clear the existing contents of the text box before solving for another observation file.

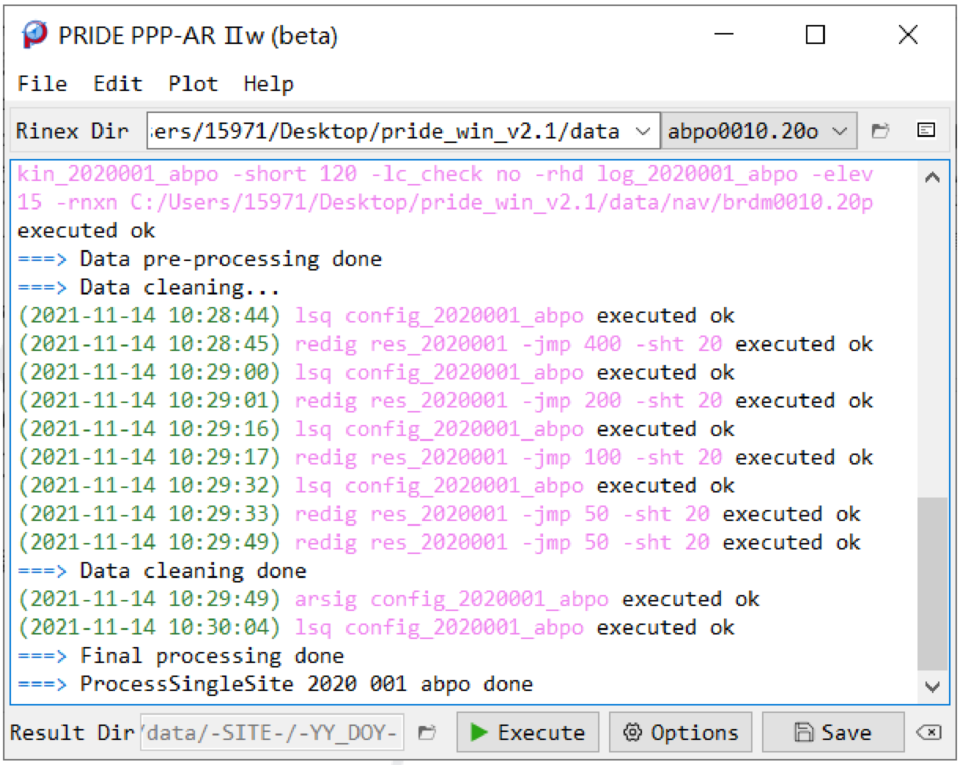


Figure 6-3. Output message of the solution results

6.3 Options

The parameters in the Options dialog all correspond to the command line parameters and the config file parameters in the Linux version. The template config in the example in the Linux version of the software can also be used directly in this version of the software. When the software starts, the “.PRIDE_PPPAR_config” folder will be created under the system user folder by default, and the template config file “config_template” will be further created under it, according to which the options parameters of Options are derived.

6.3.1 General Options

(1) Interval: Sampling interval, 30s, 1s, 5s, 15s, etc. can be selected as the sampling interval of the observation data, and the user needs to select it according the actual observation file to be calculated.

(2) Strict Editing: refined editing options, optional YES and NO.

(3) Positioning mode: divided into Kinematic, Static and Fixed, that is, the kinematic mode calculates the position of each ephemeris station, which will be recorded in the kin file at the end; the static mode calculates the average position of each ephemeris and gives the variance, which will be recorded in the pos file at the end; the fixed position mode refers to the SNX file reference coordinates of the IGS to solve, and the final The calculation gives the mean position and variance, which is recorded in the pos file; it should be noted that only stations with IGS can be solved by the method of fixed position mode.

(4) Satellite system: the satellite system involved in the solution.

(5) Excluded satellites: satellites that are excluded from the list of satellites involved in the solution.

(6) Downweighted satellites: some satellites with reduced weights in position resolution (e.g., GEO satellites).

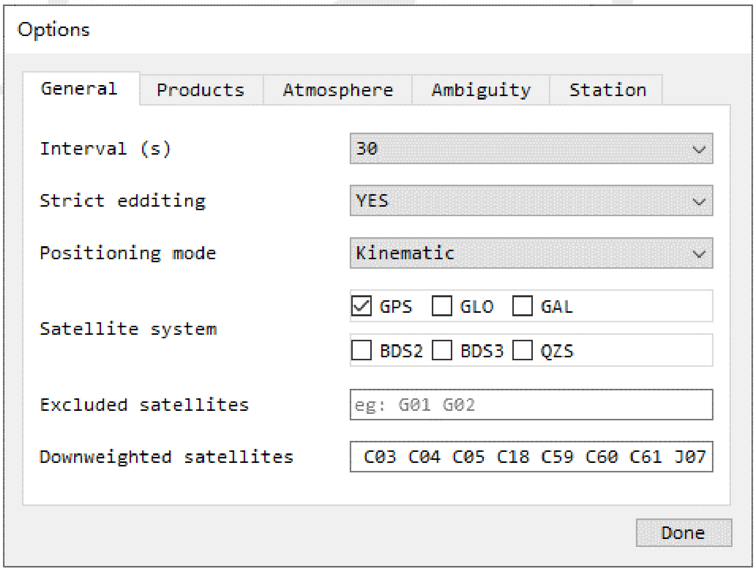


Figure 6-4. General Options

6.3.2 Products options

Product dir is the directory where the product is stored in Figure 6-5. By default, it is automatically specified as the next level of the product directory after the observation file directory is selected; you can also customize the path by mouse-clicking the folder icon on its right side.

Product options: There are satellite orbit product, satellite clock product, ERP product, quaternion product (optional) and phase deviation product, etc. If the products are missing, the software will automatically download and decompress the relevant product to the product directory under the directory where the observation file is located.

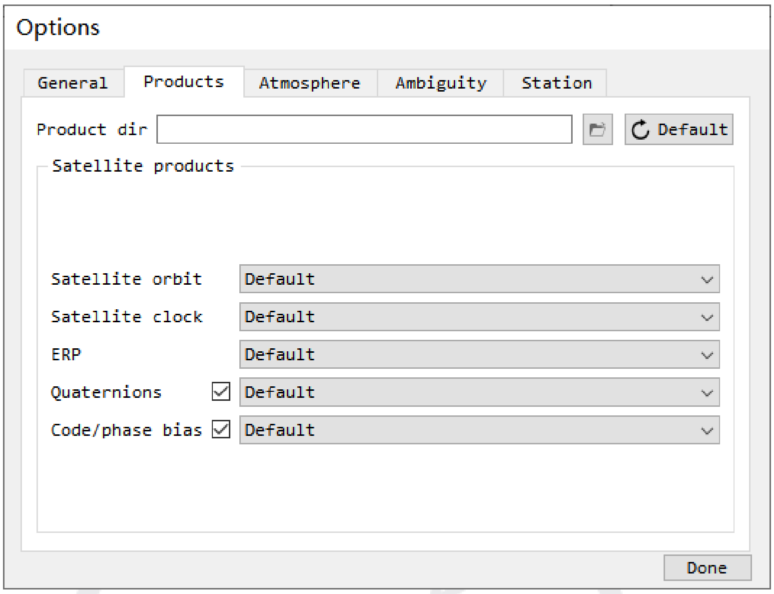


Figure 6-5. Product Options

If you want to choose another Analysis Center product, you can also customize it by changing Default to the file name, for example in Figure 6-6. Besides, the options of quaternions and bias can be set as “None” if there are no such products corresponding to orbit product and clock product.

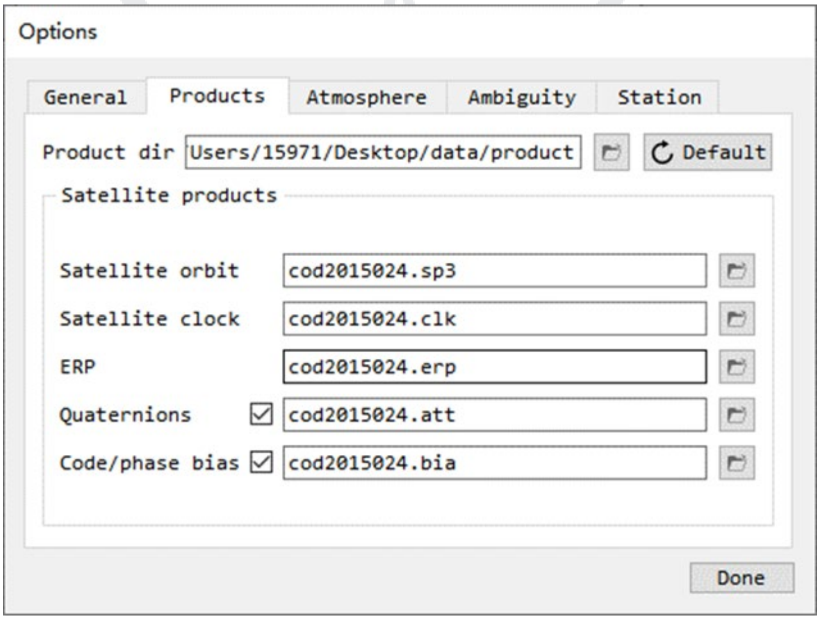


Figure 6-6. Using products of other AC

The broadcast ephemeris file will be automatically downloaded and extracted to the automatically created nav directory without user’s operation. If the broadcast ephemeris brdm-file is missing while online, the software will download it automatically; if it is not online, the user should download the required broadcast ephemeris brdm-file for the day in advance, create a new nav folder and put the brdm-file into it. Since the multi-system broadcast ephemeris “brdm” file did not exist in the early pre-2015 period, the software selects the “brdc” file of the GPS system for the calculation.

Software working directory: in Figure 6-7 the RINEX observation file directory selected in the main interface of the software must contain the observation files to be processed; then other directories will be created automatically while processing: the nav directory which holds the broadcast ephemeris, the product directory which holds the satellite product files. After processing the observation file, the result files are generated in a multi-level directory such as “2020/001/abpo” under the working directory.

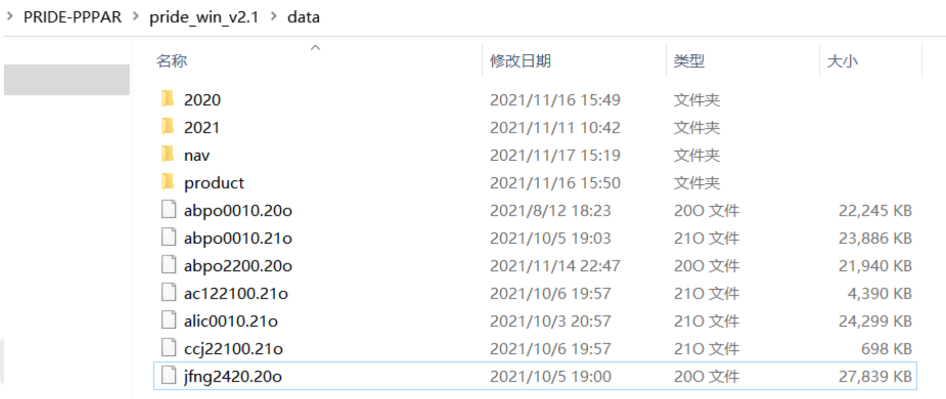


Figure 6-7. Software Working Directory

6.3.3 Atmosphere options

(1) 2nd-order ionosphere correction: whether to correct the second order ionosphere delay.
(2) Troposphere mapping function: there are four options: GMF, NIE (NMF), VM1 (VMF1), VM3 (VMF3).
(3) ZTD model: zenith troposphere estimation methods are mainly PWC (piece-wise constant, often estimated in 60 min), STO (random walk).
(4) HTG model: horizontal tropospheric gradient estimation methods, the 3 main ones are PWC (piece-wise constant, often estimated in 720 minutes), STO (random walk), and NON.

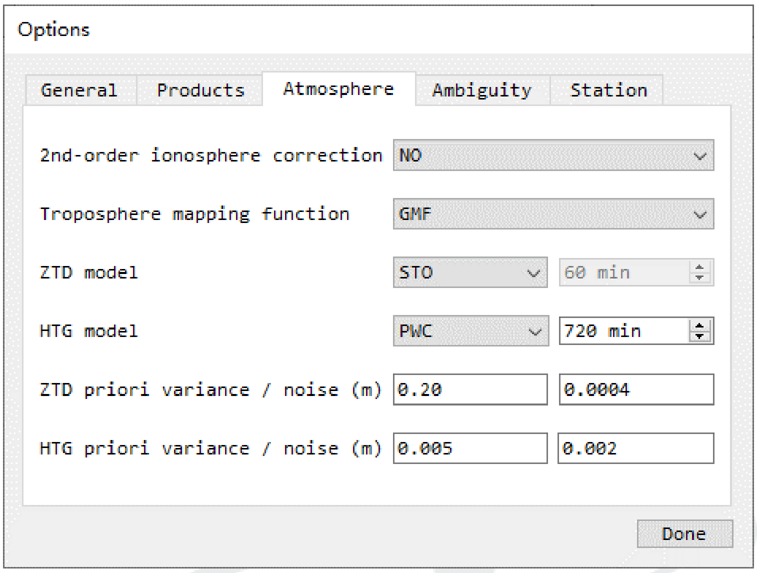


Figure 6-8. Atmospheric Delay Options

6.3.4 Ambiguity options

(1) AR mode/Ambiguity co-var: The former is whether the ambiguity is fixed or not, i.e., the calculation is done by fixed solution or float solution; the latter is “YES”, i.e., the ambiguity is fixed by LAMBDA algorithm, and “NO”, i.e., the ambiguity is fixed by Rounding method is used to fix the fuzziness.

(2) Ambiguity cut-off: the cutoff mean elevation angle used to determine if the fixed ambiguity is valid.

(3) Ambiguity duration: the valid time duration of ambiguity fixation in seconds.

(4) PCO on wide-lane: whether to perform PCO corrections on MW combinations.

(5) Widelane round-off: bias, standard deviation, and threshold in cycle for judging wide-lane ambiguity resolution.

(6) Narrowlane round-off: bias, standard deviation, and threshold for determining narrow-lane ambiguity fixation, in cycle.

(7) Critical search: the four parameters are, the maximum number of ambiguities removed, the minimum number of ambiguities retained, the minimum value of ratio for ambiguity search and the threshold value in the LAMBDA algorithm in order.

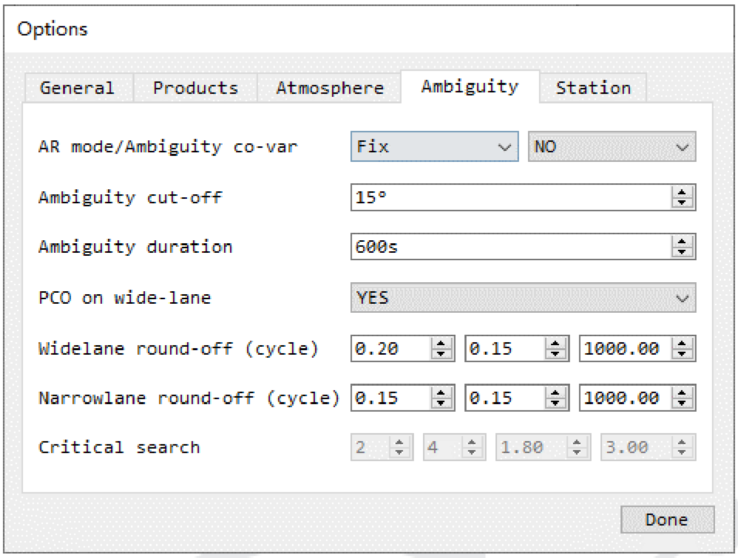


Figure 6-9. Ambiguity Options

6.3.5 Station options

(1) Pseudorange noise: pseudorange observation noise in the unit of m.

(2) Phase noise: phase observation noise, in the unit of cycle.

(3) Tides: earth tide correction, tidal load and earth pole shift correction.

(4) Observation cut-off: the cutoff height angle for data preprocessing as a tedit parameter.

(5) A priori coordinate constraint: a priori three-dimensional sit constraint.

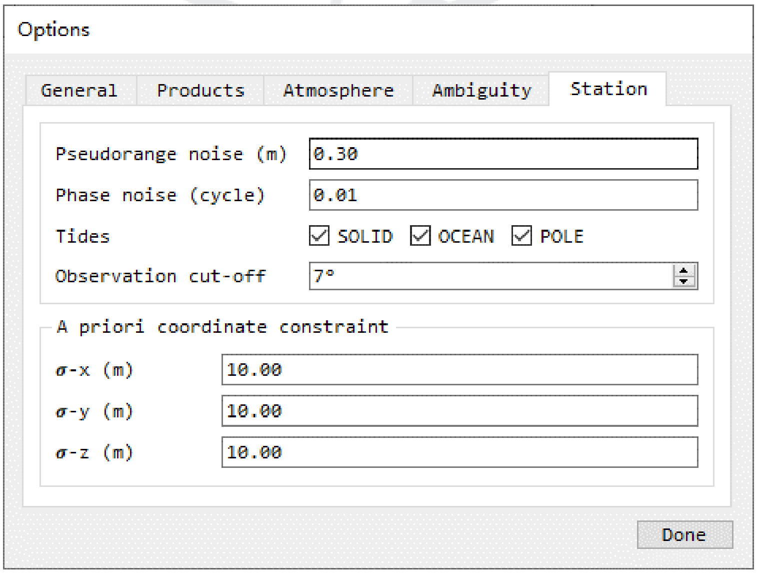


Figure 6-10. Station parameter options

6.3.6 Other functions

By clicking on the Load config file option under the File menu bar, the config file is redirected and the settings parameters in the software Options are updated simultaneously, and subsequent solving will follow the config file selected in this step as a template. The RINEX file directory, the broadcast ephemeris file directory and the product catalog in the config file will be reset according to the directory set in the main interface.

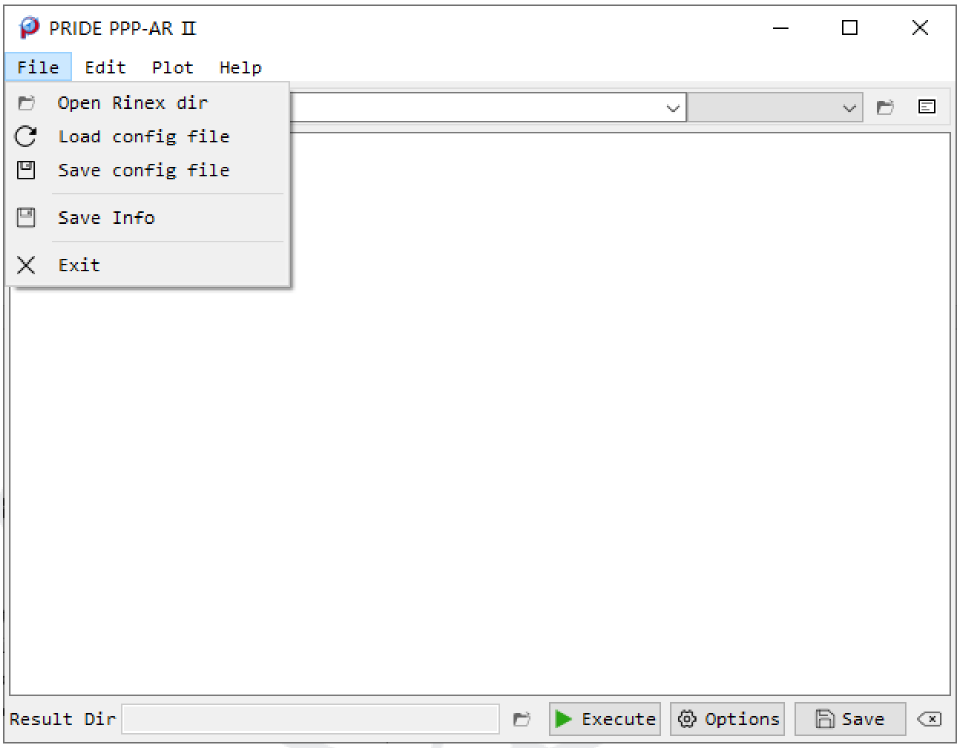


Figure 6-11. Menu bar File bar

6.4 Plotting

6.4.1 Main plotting window

1) Menu bar: At the top of the main interface is the menu bar, through the options in the File bar you can import the result file, or save the plot.
2) Toolbar: Below the menu bar is the toolbar, through these icons you can adjust the style of plotting, the time interval of data display, and you can open the cursor function, etc.
3) File import area: below the toolbar is the function area about file import, by clicking the button kin, res, ztd, and other result files you can plot ENU, res, elev, track, DOP, Nsats, Skyview, ztd and other plots.
4) Plotting area: below the functional area of file import is the plotting area, which is composed of several tabs such as ENU, res, elev, track, DOP, Nsats, Skyview, ztd, etc. By

clicking the tabs you can switch the displayed plots.

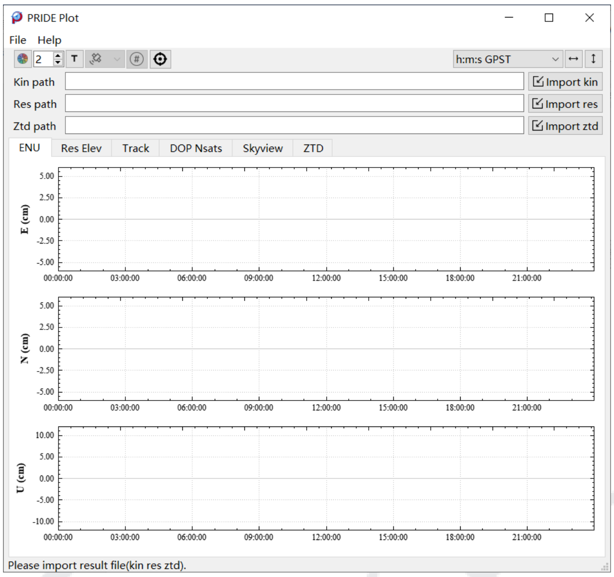


Figure 6-12. Plotting Interface

6.4.2 Plotting methods

6.4.2.1 Plotting ENU, Track, DOP, Nsats

After importing the kin file, the software will automatically generate charts such as ENU-t, Track, DOP-t, Nsats-t. If you want to view the various types of maps, you only need to select the corresponding tab page. Kin file contains the station coordinates of positioning, the DOP value of each epoch, the number of satellites in each constellation.

The ENU-t plot shows the ENU directional deviation compared to the average coordinates of the dynamic positioning results in the kin file.

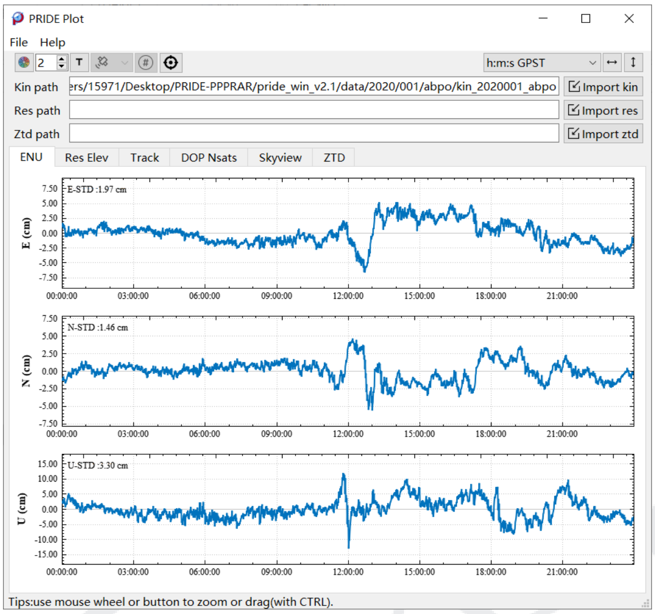


Figure 6-13. ENU-t chart

The planar trajectory map shows the planar trajectory of the dynamic positioning result, i.e. the trajectory map formed by converting the dynamic positioning coordinate points to the station-centered coordinate system and connecting them by ephemeral moments.

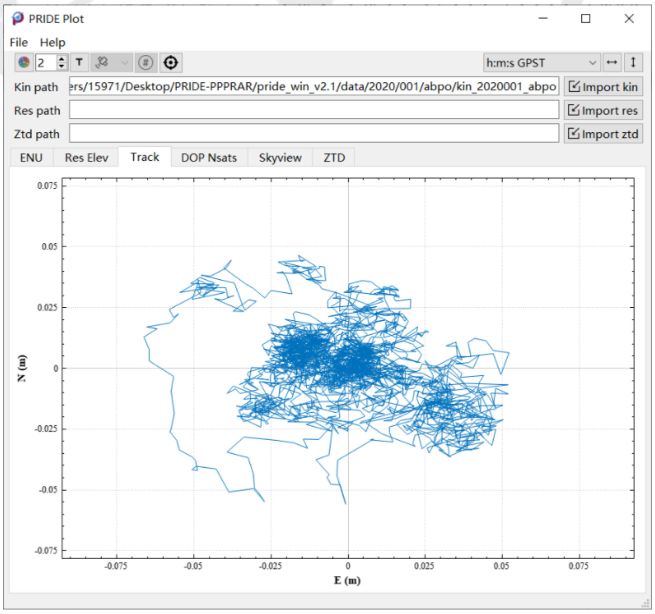


Figure 6-14. Position plane trajectory chart

At the top of Figure 6-15 is the DOP-t plot, which indicates the PDOP values for the observation period, and at the bottom of Figure 6-15 is the Nsats-t plot, which indicates the number of satellites involved in the solution during the observation period.

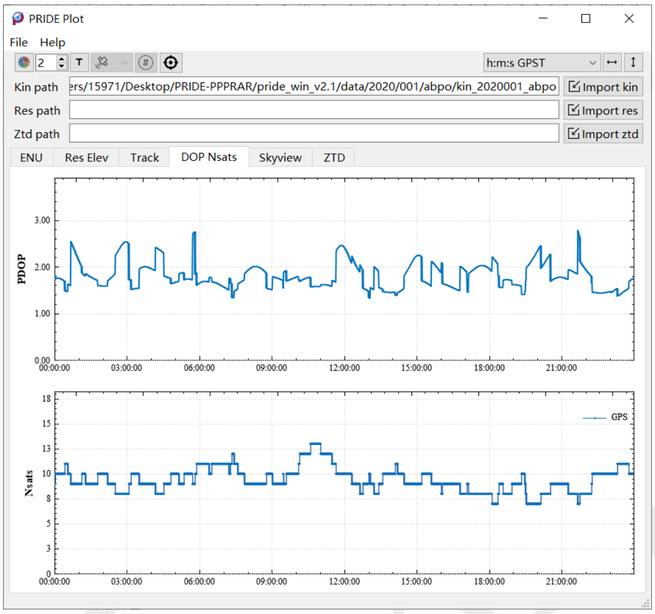


Figure 6-15. DOP and Nsats-t charts

6.4.2.2 Plotting residuals, satellite elevation angles

After importing the res file, click on the combo box of the satellite icon in the toolbar and select the corresponding satellite system or PRN to view the overall residual chart of a satellite system or the residual chart of a single satellite, and the corresponding satellite elevation angle will also be displayed below.

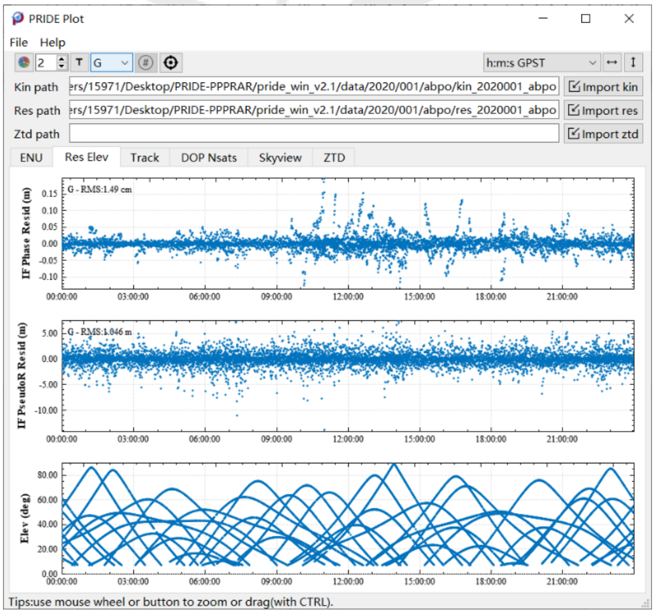


Figure 6-16. Res and elev-t charts

6.4.2.3 Plot the satellite sky view

After importing the res file, select the tab page of Skyview, click the combo box of the satellite icon in the toolbar, select the corresponding satellite system or PRN to view the satellite sky view, in addition, you can click the "#" icon in the toolbar to show or hide the satellite prn.

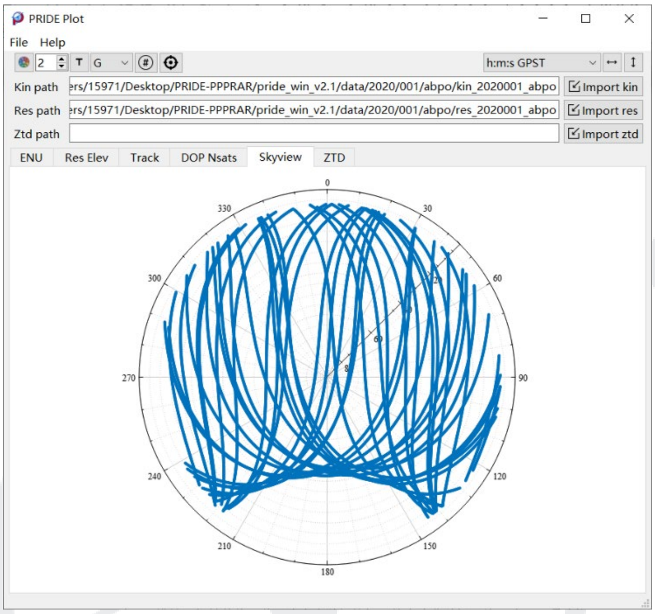


Figure 6-17. Satellite sky view

6.4.2.4 Plotting the ztd chart

Import the ztd file and the software will automatically generate a ZTD plot, which contains a plot of ZDD, ZWD and the sum of the two ZTD over time in the ztd file.

Figure 6-18. zdd, zwd and ztd-t charts

6.4.3 Auxiliary functions

(1) Cursor: Click the toolbar cursor switch button, then when the mouse moves into the plotting area, the cursor will follow the mouse and show both the horizontal and vertical axis values. If the cursor button is clicked again, the cursor will be hidden. In particular, this feature is not available for the satellite sky view.

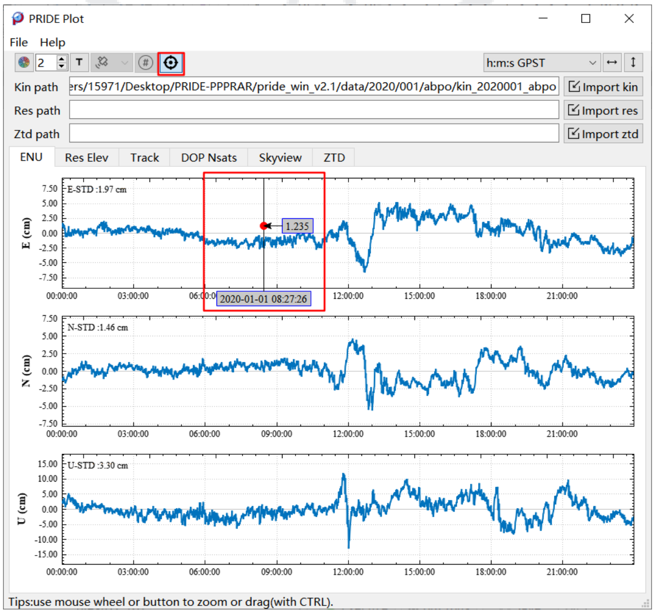


Figure 6-19. Cursor function demonstration

(2) Frame or move data interval: Use the left mouse button to frame part of the data interval in the chart to achieve local zoom, and use the mouse wheel to zoom in locally with the mouse pointer position as the center; such as holding down the keyboard ctrl key at the same time, and hold down the left mouse button to move the chart where the mouse pointer is located left and right. In addition, the rightmost part of the toolbar has a button to restore the data display interval in the horizontal and vertical directions, click to reset the data display interval in the view respectively, while hitting the keyboard spacebar is equivalent to restore the horizontal and vertical directions at the same time.

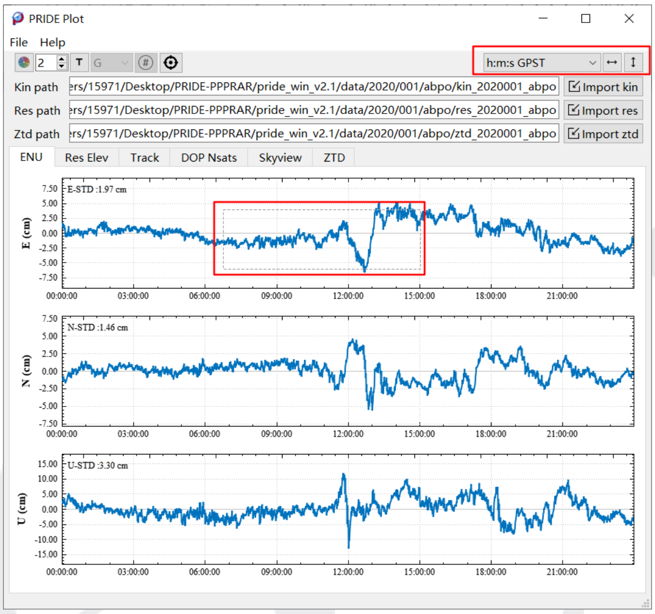


Figure 6-20. Local zoom function display

(3) Change the style of the graph: the three leftmost controls of the toolbar serve to change the plotting line color, line width and scale text font, etc. In addition, you can also select the time format such as “h:m:s” according to the first combo box on the right in Figure 6-20.

Appendix A. Required external files

This section briefly introduces the external files that need to be downloaded. For more information on the relevant files, please refer to the official website of IGS (https://igs.org/), the official website of IERS (IERS), etc.

A.1 Precise products

Satellite orbit

The precise ephemeris product gives the orbit information of GNSS satellites at certain time intervals, including satellite coordinates, satellite clock errors and optionally motion velocity, coordinate standard deviation and satellite clock errors standard deviation. The current standard format is SP3 (Standard Product 3), including SP3-a, SP3-c and SP3-d. A brief description of the corresponding format is given below, and the specific file format can be found at sp3d.pdf (igs.org).

1. File header
   - The first line starts with "#a", "#b" or "#d", indicating the SP3 file type; the third character is "P" or "V", marking the position or speed; the penultimate data is the reference frame;
   - The second line, beginning with "##", records the GPS week for the corresponding day, the seconds of week, the sampling interval, the integer part and the fractional part of the MJD.
2. Data blocks
   - The line starting with "*" marks the beginning of the epoch, followed by the corresponding epoch time;
   - The first character of the data line is always "P", followed by the PRN of the satellite; the subsequent three-dimensional coordinates of the satellite and the satellite clock errors are recorded; in the precise ephemeris, which records the three-dimensional velocity and other information of the satellite, the next line is the corresponding velocity and other information;
   - The end-of-file marker is "EOF"

```
#dP2021  1  1  0  0  0.00000000     1440   u+U IGS14 FIT  WHU
## 2138 432000.00000000    60.00000000 59215 0.0000000000000
+  108   G01G02G03G04G05G06G07G08G09G10G12G13G14G15G16G17G18
+        G19G20G21G22G23G24G25G26G27G28G29G30G31G32R01R02R03
+        R04R05R07R08R09R12R13R14R15R16R17R18R19R20R21R22R24
+        E01E02E03E04E05E07E08E09E11E12E13E14E15E18E19E21E24
+        E25E26E27E30E31E33E36C01C02C03C04C05C06C07C08C09C10
+        C11C12C13C14C16C19C20C21C22C23C24C25C26C27C28C29C30
+        C32C33C34C35C36C37  0  0  0  0  0  0  0  0  0  0  0
++         6  5  4  4  4  5  6  5  5  5  4  3  6  6  3  6  4
++         5  5  6  5  4  5  4  4  4  6  5  6  6  5  5  5  3
++         4  6  6  6  5  6  7  6  4  6  5  6  7  7  5  6  6
++         6  5  6  6  6  4  5  5  6  5  6  5  6  6  6  4  6
++         5  6  5  5  5  6  7 10 11  9 10 11 10  9  7  9  9
++         7  6  7  8  9  5  7  6  7  5  7  6  5  6  6  6  7
++         6  7  6  6  6  7  0  0  0  0  0  0  0  0  0  0  0
%c M  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i    0    0    0    0      0      0      0      0         0
%i    0    0    0    0      0      0      0      0         0
/* PCV:igs14_2148 OL/AL:FES2014b NONE     YY ORB:CoN CLK:CoN
*  2021  1  1  0  0  0.00000000
PG01  13686.913718 -22099.331874  -4728.984961    787.523386
PG02 -19186.667008   9880.628187 -14824.322870   -560.896820
PG03   8561.424035 -13533.185254 -21253.783348    -44.532118
PG04   3793.780406 -21261.175099 -15424.276996   -169.081492
PG05 -24778.487941   3662.578471   8958.153908    -29.803304
PG06 -14414.317272  -5075.976878 -21665.436236     -4.584436
PG07    629.888463 -20311.343883  17168.828037      4.206769
PG08   9102.972867 -14406.457916  20306.648164     -4.949926
PG09  -6401.404378 -25206.795027  -5400.234870   -307.809463
PG10  20297.979374  11772.607043  12796.745618    -28.940789
```

Figure A-1. Example of a SP3d file

Clock error

The satellite clock error product records the correction of the satellite time relative to the standard time. The latest file format is currently clock RINEX 3.04. A brief description of the corresponding format is given below, and the specific file format can be found at https://files.igs.org/pub/data/format/rinex_clock304.txt.

1. File header
   - The line where the "TIME SYSTEM ID" is located records the time system used;
   - The line where "SYS / DCBS APPLIED" is located records the input bias-SINEX file;
   - The line where "SYS / PCVS APPLIED" is located records the input ANTEX file;
   - The line where "LEAP SECONDS" is located records the value of the leap seconds;
   - The line "SOLN STA NAME / NUM" records the station/receiver name, station/receiver identifier number and geocentric XYZ station coordinates.
2. Data blocks
   - The first column: "AS" indicates satellite clock errors;
   - Second column: Satellite PRN;
   - Last column: satellite clock error in unit of seconds.

```
Clock information consistent with                           COMMENT
     WUM0MGXRAP_20210010000_01D_60S_ORB.SP3                 COMMENT
     WUM0MGXRAP_20210010000_01D_01D_ERP.ERP                 COMMENT
Satellite clock values at intervals of 30 sec               COMMENT
Contact pride@whu.edu.cn                                    COMMENT
Website pride.whu.edu.cn                                    COMMENT
   GPS                                                      TIME SYSTEM ID
    18                                                      LEAP SECONDS
G    PANDA          WUM0MGXRAP_20210010000_01D_01D_OSB.BIA  SYS / DCBS APPLIED
R    PANDA          WUM0MGXRAP_20210010000_01D_01D_OSB.BIA  SYS / DCBS APPLIED
E    PANDA          WUM0MGXRAP_20210010000_01D_01D_OSB.BIA  SYS / DCBS APPLIED
C    PANDA          WUM0MGXRAP_20210010000_01D_01D_OSB.BIA  SYS / DCBS APPLIED
G    PANDA          IGS14_2148.ATX                          SYS / PCVS APPLIED
R    PANDA          IGS14_2148.ATX                          SYS / PCVS APPLIED
E    PANDA          IGS14_2148.ATX                          SYS / PCVS APPLIED
C    PANDA          IGS14_2148.ATX                          SYS / PCVS APPLIED
     1    AS                                                # / TYPES OF DATA
WHU  GNSS RESEARCH CENTER, WUHAN UNIVERSITY, P.R.CHINA      ANALYSIS CENTER
     1                                                      # OF CLK REF
CEDU 50138M001                                              ANALYSIS CLK REF
   159    IGS14                                             # OF SOLN STA / TRF
ABPO 33302M001           4097216530  4429119220 -2065771165SOLN STA NAME / NUM
......
......
ZIMM 14001M004           4331296843   567556166  4633134123SOLN STA NAME / NUM
   108                                                      # OF SOLN SATS
G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G12 G13 G14 G15 G16 PRN LIST
G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 PRN LIST
G32 R01 R02 R03 R04 R05 R07 R08 R09 R12 R13 R14 R15 R16 R17 PRN LIST
R18 R19 R20 R21 R22 R24 E01 E02 E03 E04 E05 E07 E08 E09 E11 PRN LIST
E12 E13 E14 E15 E18 E19 E21 E24 E25 E26 E27 E30 E31 E33 E36 PRN LIST
C01 C02 C03 C04 C05 C06 C07 C08 C09 C10 C11 C12 C13 C14 C16 PRN LIST
C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30 C32 C33 C34 PRN LIST
C35 C36 C37                                                 PRN LIST
                                                            END OF HEADER
AS G01  2021  1  1  0  0  0.000000  1    0.787523386303E-03
AS G02  2021  1  1  0  0  0.000000  1   -0.560896819699E-03
AS G03  2021  1  1  0  0  0.000000  1   -0.445321176114E-04
AS G04  2021  1  1  0  0  0.000000  1   -0.169081492236E-03
AS G05  2021  1  1  0  0  0.000000  1   -0.298033041277E-04
AS G06  2021  1  1  0  0  0.000000  1   -0.458443554921E-05
AS G07  2021  1  1  0  0  0.000000  1    0.420676890748E-05
AS G08  2021  1  1  0  0  0.000000  1   -0.494992603914E-05
```

Figure A-2. Example of a clock RINEX 3.04 file

ERP

When fixing the satellite orbit, ERP parameters need to be considered for data processing under the inertial reference frames. ERP files record the Earth rotation parameters, including polar position and UT1-UTC, etc. The current version is version 2. A brief description of the corresponding format is given below, and the specific file format can be found at [IGSMAIL-1943] New IGS ERP Format (version 2).

- MJD: modified Julian day
- Xpole and Ypole: pole coordinates
- UT1-UTC: Difference between UT (Universal Time) and UTC (Coordinated Universal Time)
- LOD: Length of day

```
version 2
DAY   1, YEAR 2021
----------------------------------------------------------------------------------------------
  MJD      Xpole   Ypole  UT1-UTC    LOD  Xsig  Ysig   UTsig  LODsig    Nr Nf Nt    Xrt    Yrt  Xrtsig  Yrtsig
             (10**-6")       (0.1 usec)   (10**-6")     (0.1 usec)                 (10**-6"/d)    (10**-6"/d)
59215.50   68274  304714 -1750491  -5274     8     9       7       5  159 159  77  -766   1633    10      13
```

Figure A-3. Example of an ERP file

Code/phase bias

The current version of the bias file is Bias-SINEX V1.00. The absolute bias OSB (Observable-specific Signal Bias) of the original code/phase observations is recorded in the PRIDE PPP-AR default product. A brief description of the corresponding format is given below, and the specific file format can be found at sinex_bias_100.dvi (igs.org).

1. File header
   - The penultimate parameter in the first row is the bias model, with "A" denoting absolute bias and "R" denoting relative bias;
   - The line where "OBSERVATION_SAMPLING" is located indicates the sampling interval;
   - The row where "PARAMETER_SPACING" is located indicates the effective time span of the bias;
   - The line "TIME_SYSTEM" indicates the time system used;

```
%=BIA 1.00 WHU 2021:232:39318 WHU 2021:001:00000 2021:001:86400 A 00001063
*-------------------------------------------------------------------------------
* Bias Solution INdependent EXchange Format(Bias-SINEX)
*-------------------------------------------------------------------------------
+FILE/REFERENCE
*INFO_TYPE_________INFO________________________________________________________
 DESCRIPTION         PRIDE Lab, GNSS Research Center, Wuhan University
 INPUT               IGS14_2148.ATX
 OUTPUT              WHU 1-day rapid bias products in Bias-SINEX format
 CONTACT             pride@whu.edu.cn
 SOFTWARE            PANDA
 HARDWARE            Centos: Linux, x86_64
-FILE/REFERENCE
*-------------------------------------------------------------------------------
+FILE/COMMENT
*PRODUCT_REFERENCE______________________________________________________________
 GPS phase biases and phase clocks are estimated with the same stations
 Published by PRIDE Lab, GNSS Research Center, Wuhan University
 URL: ftp://igs.gnsswhu.cn/pub/whu/phasebias
 URL: pride.whu.edu.cn
 Overview of the satellite biases included in the file
 GPS     C1C, C1W
 GPS     C2C, C2W, C2L, C2S, C2X
 GPS     C5Q, C5X
 GLONASS C1C, C1P
 GLONASS C2C, C2P
 GALILEO C1C, C1X
 GALILEO C5Q, C5X
 GALILEO C6C
 GALILEO C7Q, C7X
 GALILEO C8Q, C8X
 BDS-2   C2I
 BDS-2   C7I
 BDS-2   C6I
 BDS-3   C1X, C1P
 BDS-3   C2I
 BDS-3   C5X, C5P
 BDS-3   C6I
 BDS-3   C7Z
 BDS-3   C8X
 QZSS    C1C, C1X
 QZSS    C2L, C2X
 QZSS    C5Q, C5X
-FILE/COMMENT
*-------------------------------------------------------------------------------
+BIAS/DESCRIPTION
*KEYWORD_________________________________VALUE (S) ____________________________
 OBSERVATION_SAMPLING                                30
 PARAMETER_SPACING                                86400
 DETERMINATION_METHOD                    CO-ESTIMATED
 BIAS_MODE                               ABSOLUTE
 TIME_SYSTEM                             G
 RECEIVER_CLOCK_REFERENCE_GNSS           G
 SATELLITE_CLOCK_REFERENCE_OBSERVABLES   G  C1W  C2W
 SATELLITE_CLOCK_REFERENCE_OBSERVABLES   R  C1P  C2P
 SATELLITE_CLOCK_REFERENCE_OBSERVABLES   E  C1X  C5X  C1C  C5Q
 SATELLITE_CLOCK_REFERENCE_OBSERVABLES   C  C2I  C6I
 SATELLITE_CLOCK_REFERENCE_OBSERVABLES   J  C1X  C2X
```

Figure A-4. Example of a code/bias file header

2. Data blocks
   - The bias type, satellite SVN number, satellite PRN number, code designator, start and end time, unit, bias value and STDs
   - The end-of-file marker is "%=ENBIA"

```
+BIAS/SOLUTION
*BIAS SVN_ PRN STATION__ OBS1 OBS2 BIAS_START____ BIAS_END______ UNIT __ESTIMATED_VALUE____ _STD_DEV___ _ESTIMATED_SLOPE____ _STD_DEV___
 OSB  G063 G01           C1C       2021:001:00000 2021:001:86400 ns   0.956390000000000E+01 .172000E-01
 OSB  G063 G01           C1W       2021:001:00000 2021:001:86400 ns   0.107335000000000E+02 .500000E-03
 OSB  G063 G01           C2L       2021:001:00000 2021:001:86400 ns   0.162136000000000E+02 .416000E-01
 OSB  G063 G01           C2S       2021:001:00000 2021:001:86400 ns   0.162185000000000E+02 .496000E-01
 OSB  G063 G01           C2W       2021:001:00000 2021:001:86400 ns   0.176775000000000E+02 .700000E-03
 OSB  G063 G01           C2X       2021:001:00000 2021:001:86400 ns   0.164655000000000E+02 .619800E+00
 OSB  G063 G01           C5Q       2021:001:00000 2021:001:86400 ns   0.707190000000000E+01 .525000E-01
 OSB  G063 G01           C5X       2021:001:00000 2021:001:86400 ns   0.672590000000000E+01 .763000E-01
 OSB  G063 G01           L1C       2021:001:00000 2021:001:86400 ns   -.124695039306045E+01 .116424E-01
 OSB  G063 G01           L1W       2021:001:00000 2021:001:86400 ns   -.124695039306045E+01 .116424E-01
 OSB  G063 G01           L2W       2021:001:00000 2021:001:86400 ns   -.193179422306557E+01 .188925E-01
 OSB  G063 G01           L2S       2021:001:00000 2021:001:86400 ns   -.193179422306557E+01 .188925E-01
 OSB  G063 G01           L2L       2021:001:00000 2021:001:86400 ns   -.193179422306557E+01 .188925E-01
 OSB  G061 G02           C1C       2021:001:00000 2021:001:86400 ns   -.111071000000000E+02 .732000E-01
 OSB  G061 G02           C1W       2021:001:00000 2021:001:86400 ns   -.127445000000000E+02 .150000E-02
 OSB  G061 G02           C2L       2021:001:00000 2021:001:86400 ns   -.210021000000000E+02 .155670E+01
 OSB  G061 G02           C2W       2021:001:00000 2021:001:86400 ns   -.209895000000000E+02 .220000E-02
 OSB  G061 G02           L1C       2021:001:00000 2021:001:86400 ns   0.426851625747606E+00 .113622E-01
 OSB  G061 G02           L1W       2021:001:00000 2021:001:86400 ns   0.426851625747606E+00 .113622E-01
 OSB  G061 G02           L2W       2021:001:00000 2021:001:86400 ns   0.643915435186783E+00 .186094E-01
 OSB  G061 G02           L2S       2021:001:00000 2021:001:86400 ns   0.643915435186783E+00 .186094E-01
 OSB  G061 G02           L2L       2021:001:00000 2021:001:86400 ns   0.643915435186783E+00 .186094E-01
 OSB  G069 G03           C1C       2021:001:00000 2021:001:86400 ns   0.647950000000000E+01 .113800E+00
```

Figure A-5. Example of a code/phase bias file data blocks

Quaternions

The quaternions file records the quaternions associated with the satellite attitude, which can be converted into a rotation matrix for the transformed of the earth-fixed system to the satellite-fixed system. The current file version is ORBXEX 0.09 (ORBit EXchange format) and the corresponding brief format is described below.

1. File header
    - "TIME_SYSTEM" indicates the corresponding time system, in line with the corresponding satellite orbit/clock file;
    - "EPOCH_INTERVAL" indicates the sampling interval;
    - "COORD_SYSTEM" indicates the ECEF (Earth Center Earth Fixed) frame involved in the transformation

```
%=ORBEX  0.09
%%
+FILE/DESCRIPTION
 DESCRIPTION         Satellite attitude quaternions of WHU GNSS rapid solution
 CREATED_BY          PRIDE Lab, GNSS Research Center, Wuhan University
 CREATION_DATE       2021 09 01 15 03 00
 INPUT_DATA          u+U
 CONTACT             pride@whu.edu.cn
 TIME_SYSTEM         GPS
 START_TIME          2021  1  1  0  0  0.000000000000
 END_TIME            2021  1  2  0  0  0.000000000000
 EPOCH_INTERVAL         30.000
 COORD_SYSTEM        IGS14
 FRAME_TYPE          ECEF
 LIST_OF_REC_TYPES   ATT
-FILE/DESCRIPTION
+SATELLITE/ID_AND_DESCRIPTION
 G01
 G02
 G03
 G04
 G05
 G06
 G07
 G08
 G09
 G10
 G12
 G13
```

Figure A-6. Example of a quaternions file header

2. Data blocks

The data blocks are marked by "+EPHEMERIS/DATA" and "-EPHEMERIS/DATA".

- The row where the current epoch is located is identified by "##", followed by the corresponding epoch time and the number of satellites of that epoch;

- The data row is identified by “ATT”, followed by the satellite PRN, the number of data and the corresponding quaternions.

```
+EPHEMERIS/DATA
*ATT RECORDS: TRANSFORMATION FROM TERRESTRIAL FRAME COORDINATES (T) TO SAT. BODY FRAME ONES (B) SUCH AS
*                                  (0,B) = q.(0,T).trans(q)
*REC ID_                N ___q0_(scalar)_____ ____q1__x_________ ____q2__y_________ ____q3__z_________
## 2021 01 01 00 00  0.000000000000 108
 ATT G01                4  0.0073517832149779 -0.3321223384064447  0.5479071307935610  0.7677489691563009
 ATT G02                4  0.3402538341753952  0.3002354837408475 -0.3560351632772442  0.8168995930602414
 ATT G03                4  0.0484591928309526  0.1831033504492600 -0.2591092501550277 -0.9470941168482292
 ATT G04                4  0.1069203119576232  0.1339736365491190 -0.4375600468391984 -0.8827005817437573
 ATT G05                4  0.5662958751712760  0.0292807960652229 -0.8170189033867401  0.1045549054540916
 ATT G06                4  0.0949382755672016 -0.2737637514495153 -0.1283321265132913 -0.9484571669449235
 ATT G07                4  0.0575120861592225  0.1516730144530112 -0.8942494247512676 -0.4171398122504945
 ATT G08                4  0.1188266213933063 -0.1947180209761077  0.9192863497307452  0.3207455900774349
 ATT G09                4  0.2321295003625461  0.0348372110365338 -0.6301839128939313 -0.7401151935464672
 ATT G10                4  0.2750776156997116  0.3941410640233388  0.7642288529814175 -0.4300457967033500
 ATT G12                4  0.2035175787414587  0.2000545881893258 -0.2767905821578833  0.9175760080322030
 ATT G13                4  0.2856794158925113 -0.0015783940180094 -0.9548189452364981  0.0818874949250409
 ATT G14                4  0.3883506231434809  0.0018203162087713 -0.8747153061776299 -0.2899200115403300
 ATT G15                4  0.1768128795176963 -0.0632962859235457 -0.9278902991090358  0.3221030559375204
 ATT G16                4  0.0682758023991445 -0.8082866220576663  0.0972907666636814  0.5766677189953965
 ATT G17                4  0.3271520070861443 -0.1198626323065541 -0.5312153727546062 -0.7722789271922652
```

Figure A- 7. Example of a quaternions data blocks

IONEX maps

IONEX-Format (IONosphere map Exchange format) is a global ionospheric product calculated daily by the IGS using observations from GNSS stations. It mainly provides a generic interface to IGS ionospheric products that supports the exchange of 2- or 3-dimensional TEC maps given in a geographic grid. A brief description of the corresponding format is given below, and the specific file format can be found at ionex1.pdf (igs.org).

1. File header
   - The lines with the label “DESCRIPTION” give a brief description of the technique, model, etc.;
   - “INTERVAL” indicates the interval between the TEC maps, in seconds (integer);
   - “# OF MAPS IN FILE” indicates the total number of TEC/RMS/HGT maps;
   - “ELEVATION CUTOFF” indicates the minimum elevation angle in degrees;
   - “BASE RADIUS” indicates the mean earth radius or bottom of height grid (in km);
   - “HGT1 / HGT2 / DHGT” defines an equidistant grid in height;
   - “LAT1 / LAT2 / DLAT” defines an equidistant grid in latitude;
   - “LON1 / LON2 / DLON” defines an equidistant grid in longitude;
2. Data blocks

   The data block of a single epoch is enclosed by “START OF TEC MPA” and “END OF TEC MAP”, “START OF RMS MAP” and “END OF RMS MAP”.
   - “EPOCH OF CURRENT MAP” indicates the epoch of current MAP (UT);
   - “LAT/LON1/LON2/DLON/H” record initializing a new TEC/RMS/HGT data block for latitude “LAT” (and height ‘H(GT)’), from “LON1” to “LON2”;

```
     1                                                      START OF TEC MAP
  2021     1     1     0     0     0                        EPOCH OF CURRENT MAP
    87.5-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
   13   13   14   14   15   15   15   15   16   16   16   16   16   15   15   15
   14   14   13   13   12   11   11   10    9    8    8    7    6    6    5    5
    4    4    3    3    3    2    2    2    2    2    2    2    2    2    2    2
    2    3    3    3    3    4    4    4    5    5    5    6    6    7    7    8
    8    9    9   10   10   11   12   12   13
    85.0-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
   15   16   17   19   20   21   21   22   23   23   23   23   23   23   22   21
   20   19   18   16   15   13   12   10    8    7    5    4    3    2    1    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    1    1    1    2    2    3    3    4    4    5    5    6
    7    8    9   10   11   12   13   14   15
    82.5-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
   16   17   19   21   23   24   25   27   28   28   29   29   29   28   27   26
   25   23   21   19   16   14   11    9    7    4    2    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    1    1    1    1    1    2    2    3    3    4    4
    5    6    7    8   10   11   13   14   16
    80.0-180.0 180.0   5.0 450.0                            LAT/LON1/LON2/DLON/H
   16   18   20   22   24   26   28   29   30   31   32   32   32   31   30   29
   27   25   22   19   16   13   10    7    4    2    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    1    1
    1    2    2    2    2    2    2    2    2    2    2    2    3    3    3    4
    5    5    6    8    9   10   12   14   16
```

Figure A-8. Example of an IONEX maps file

Grid-wise VMF1/VMF3

VMF1 and VMF3 are tropospheric mapping models developed by the Vienna University of Technology, Austria. VMF1/VMF3 value for arbitrary sites can be determined through interpolation from the grid-wise VMF1/VMF3 data. A brief description of the corresponding format is given below, and the specific file format can be found at [VMF Data Server - Products (tuwien.ac.at)](https://vmf.geo.tuwien.ac.at).

1. File header
   - The line where "! Epoch:" is located records the epoch corresponding to the file;
   - "! Range/resolution" indicates the latitude and longitude ranges and their respective increments;
2. Data blocks
   - latitude [°]
   - longitude [°]
   - hydrostatic "a" coefficient
   - wet "a" coefficient
   - hydrostatic zenith delay [m]
   - wet zenith delay [m]

```
! Version:            1.0
! Source:             J. Boehm, TU Vienna (created: 2021-03-22)
! Data_types:         VMF1 (lat lon ah aw zhd zwd)
! Epoch:              2021 01 01 00 00  0.0
! Scale_factor:       1.e+00
! Range/resolution:   -90 90 0 360 2 2.5
! Comment:            http://vmf.geo.tuwien.ac.at/trop_products/GRID/2.5x2/VMF1/VMF1_OP/
 90.0   0.0 0.00118018  0.00051471  2.3070  0.0296
 90.0   2.5 0.00118018  0.00051471  2.3070  0.0296
 90.0   5.0 0.00118018  0.00051471  2.3070  0.0296
 90.0   7.5 0.00118018  0.00051471  2.3070  0.0296
 90.0  10.0 0.00118018  0.00051471  2.3070  0.0296
 90.0  12.5 0.00118018  0.00051471  2.3070  0.0296
 90.0  15.0 0.00118018  0.00051471  2.3070  0.0296
 90.0  17.5 0.00118018  0.00051471  2.3070  0.0296
 90.0  20.0 0.00118018  0.00051471  2.3070  0.0296
 90.0  22.5 0.00118018  0.00051471  2.3070  0.0296
 90.0  25.0 0.00118018  0.00051471  2.3070  0.0296
```

Figure A-9. Example of a grid-wise VMF1 file

```
! Version:            1.0
! Source:             D. Landskron, TU Vienna (created: 2021-01-02)
! Data_types:         VMF3 (lat lon ah aw zhd zwd)
! Epoch:              2021 01 01 00 00  0.0
! Scale_factor:       1.e+00
! Range/resolution:   -89.5 89.5 0.5 359.5 1 1
! Comment:            vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_OP/2021/
 89.5    0.5  0.00117105  0.00066185  2.3072  0.0338
 89.5    1.5  0.00117107  0.00066421  2.3073  0.0338
 89.5    2.5  0.00117108  0.00066495  2.3073  0.0337
 89.5    3.5  0.00117110  0.00066328  2.3074  0.0337
 89.5    4.5  0.00117113  0.00065998  2.3074  0.0336
 89.5    5.5  0.00117115  0.00065458  2.3075  0.0336
 89.5    6.5  0.00117116  0.00064727  2.3075  0.0335
 89.5    7.5  0.00117118  0.00063827  2.3075  0.0334
 89.5    8.5  0.00117120  0.00062723  2.3076  0.0333
 89.5    9.5  0.00117123  0.00061520  2.3076  0.0331
 89.5   10.5  0.00117125  0.00060236  2.3077  0.0330
 89.5   11.5  0.00117127  0.00058876  2.3077  0.0329
 89.5   12.5  0.00117131  0.00057491  2.3078  0.0327
 89.5   13.5  0.00117133  0.00056083  2.3078  0.0326
 89.5   14.5  0.00117135  0.00054727  2.3079  0.0324
 89.5   15.5  0.00117138  0.00053527  2.3079  0.0323
```

Figure A-10. Example of a grid-wise VMF3 file

SINEX

The SINEX (Solution Independent Exchange format) file records the station positions and velocity. The SINEX file with ".snx" suffix records the station position/velocity, and the SINEX file with ".ssc" suffix records the station coordinates. What we need is the SOLUTION/ESTIMATE Block, enclosed by the "+SOLUTION/ESTIMATE Block" and the "-SOLUTION/ESTIMATE Block". The brief format of this section is presented below, and the specific file format can be found at [Microsoft Word - sinex_v202.doc (iers.org)].

- Index: Index of estimated parameters. Values from 1 to the number of parameters.
- _TYPE_: Identification of the type of parameter.
- CODE: Site code for which the parameter is estimated.
- PT: Point Code for which the parameter is estimated.
- SOLN: Solution ID at a Site/Point code for which the parameter is estimated.
- _REF_EPOCH__: Epoch at which the estimated parameter is valid.
- UNIT: Units used for the estimates add sigmas.
- S: Constraint applied to the parameter.
- ___ESTIMATED_VALUE___: Estimated value of the parameter.

- __STD_DEV__: Estimated standard deviation for the parameter.

```
+SOLUTION/ESTIMATE
*INDEX _TYPE_ CODE PT SOLN _REF_EPOCH__ UNIT S ___ESTIMATED_VALUE___ __STD_DEV__
     1 STAX   AB01  A    1 21:335:43200 m    2 -3.89656321430101e+06 2.19449e-03
     2 STAY   AB01  A    1 21:335:43200 m    2 -3.95471543079333e+05 9.29684e-04
     3 STAZ   AB01  A    1 21:335:43200 m    2  5.01714162850610e+06 2.54759e-03
     4 STAX   AB07  A    3 21:335:43200 m    2 -3.42575038202844e+06 1.81464e-03
     5 STAY   AB07  A    3 21:335:43200 m    2 -1.21468607197146e+06 1.03099e-03
     6 STAZ   AB07  A    3 21:335:43200 m    2  5.22366245316521e+06 2.47390e-03
     7 STAX   AB09  A    1 21:335:43200 m    2 -2.58361493551525e+06 1.33789e-03
     8 STAY   AB09  A    1 21:335:43200 m    2 -5.46237009535480e+05 8.93759e-04
     9 STAZ   AB09  A    1 21:335:43200 m    2  5.78650166876350e+06 2.61165e-03
    10 STAX   AB51  A    1 21:335:43200 m    2 -2.38374983293552e+06 1.28158e-03
```

Figure A- 11. Example of a SINEX file

A.2 Table files

leap.sec

The time difference between UTC and UT1 needs to be kept within 0.9s as specified, otherwise the adjustment will take the form of leap seconds. The leap seconds file required by the software can be downloaded at ftp://igs.gnsswhu.cn/pub/whu/phasebias/table/leap.sec. It records the MJD and its leap second value. Note that the first line of the leap seconds file ends with a "*" sign to distinguish it from other files with the same naming format. In case of no internet access computing, the user needs to download the file beforehand and place it in the table directory specified in the configuration file.

```
+leap sec *
 45151  21
 45516  22
 46247  23
 47161  24
 47892  25
 48257  26
 48804  27
 49169  28
 49534  29
 50083  30
 50630  31
 51179  32
 53736  33
 54832  34
 56109  35
 57204  36
 57754  37
 59761  38
-leap sec
```

Figure A-12. Example of a leap.sec file

sat_parameters

The "sat_parameters" file is used to record the satellite parameters. A brief description of the corresponding file format is as follows.

- PRN: PRN of the satellite;
- SVN: SVN of the satellite;
- LAUNCHED: Launch time of the satellite in the format of YYYYDDD:SSSSS;
- DECOMMISSIONED: Decommission time of the satellite in the format of YYYYDDD:SSSSS;
- COSPAR-ID: Committee on Space Research-ID;
- MASS: Mass of the satellite in the unit of kg;
- MAX_YAW: Maximum speed of satellite rotation at the beginning of design
- FID: The frequency ID of the satellite;
- BLOCK-TYPE: Block type of the satellite;

```
#           LAUNCHED      DECOMMISSIONED             MASS     MAX_YAW
#PRN  SVN   YYYYDDD:SSSSS YYYYDDD:SSSSS COSPAR-ID   [KG]       [DEG] FID BLOCK-TYPE
#--------------------------------------------------------------------------------
+prn_indexed
 G01  G032  1992327:00000 2008290:86399 1992-079A   930.00   0.000   0 BLOCK IIA
 G01  G037  2008297:00000 2009006:86399 1993-032A   930.00   0.000   0 BLOCK IIA
 G01  G049  2009083:00000 2011126:86399 2009-014A  1080.00   0.000   0 BLOCK IIR-M
 G01  G035  2011153:00000 2011193:86399 1993-054A   930.00   0.000   0 BLOCK IIA
 G01  G063  2011197:00000 0000000:00000 2011-036A  1633.00   0.000   0 BLOCK IIF
 G02  G013  1989161:00000 2004133:86399 1989-044A   843.00   0.000   0 BLOCK II
 G02  G061  2004311:00000 0000000:00000 2004-045A  1080.00   0.000   0 BLOCK IIR-B
 G03  G011  1985282:00000 1994107:86399 1985-093A   455.00   0.000   0 BLOCK I
 G03  G033  1996088:00000 2014230:86399 1996-019A   930.00   0.000   0 BLOCK IIA
 G03  G035  2014248:00000 2014293:86399 1993-054A   930.00   0.000   0 BLOCK IIA
 G03  G069  2014302:00000 0000000:00000 2014-068A  1633.00   0.000   0 BLOCK IIF
 G04  G001  1978053:00000 1985198:86399 1978-020A   455.00   0.000   0 BLOCK I
 G04  G034  1993299:00000 2015313:86399 1993-068A   930.00   0.000   0 BLOCK IIA
 G04  G049  2016033:00000 2016257:86399 2009-014A  1080.00   0.000   0 BLOCK IIR-M
 G04  G032  2016259:00000 2016340:86399 1992-079A   930.00   0.000   0 BLOCK IIA
 G04  G034  2016344:00000 2017003:86399 1993-068A   930.00   0.000   0 BLOCK IIA
 G04  G049  2017006:00000 2017132:86399 2009-014A  1080.00   0.000   0 BLOCK IIR-M
 G04  G038  2017139:00000 2017195:86399 1997-067A   930.00   0.000   0 BLOCK IIA
```

Figure A- 13 Example of the sat_parameters file

ANTEX

The ANTEX (The Antenna Exchange Format) file is used to record the PCO/PV at the satellite and station ends, which is stored in the "igsXX.atx" file, consistent with the current igsXX reference frame. The current version of the ANTEX file is Version 1.4. The brief description of the corresponding file format is as follows, and the specific format of the file can be viewed https://files.igs.org/pub/data/format/antex14.txt.

1. File header
   - "ANTEX VERSION /SYST" denotes file version and satellite systems included in the file
   - "PCV TYPE / REFANT" denotes the phase center variation type, 'A': absolute values, 'R': relative values;

2. Data blocks

The data block contains satellite antennas and receiver antennas, all organized in a hierarchical sorting way, single data block enclosed by “START OF ANTENNA” and “END OF ANTENNA”. Satellite antenna part: first sorted according to the satellite system, then sorted according to satellite code “sNN”, and finally sorted according to “VALID FROM”.

- “TYPE / SERIAL NO” denotes the antenna type, satellite PRN number, satellite SVN number and cospar id;
- “DAZI” denotes increment of the azimuth, “0.0” denotes non-azimuth-dependent phase center variations
- “ZEN1 / ZEN2 / DZEN” denotes the zenith distance “ZEN1” to “ZEN2” with increment “DZEN”
- “VALID FROM” and “VALID FROM” represents the start of validity period and end of validity period in GPS time, respectively;
- “START OF FREQUENCY” and “END OF FREQUENCY” indicate the start and end of a new frequency section, respectively;
- “NORTH / EAST / UP” denotes the mean antenna phase center relative to the center of mass of the satellite in X-, Y- and Z-direction (in millimeters);
- The flag “NOAZI” denotes the non-azimuth-dependent PV values, the PV values from “ZEN1” to “ZEN2” were subsequently recorded;

```
                                                            START OF ANTENNA
BLOCK IIA           G01                 G032      1992-079A TYPE / SERIAL NO
                                             0    29-JAN-17 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  17.0   1.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
  1992    11    22     0     0    0.0000000                 VALID FROM
  2008    10    16    23    59   59.9999999                 VALID UNTIL
IGS14_2163                                                  SINEX CODE
   G01                                                      START OF FREQUENCY
    279.00      0.00   2319.50                              NORTH / EAST / UP
   NOAZI   -0.80   -0.90   -0.90   -0.80   -0.40    0.20    0.80    1.30    1.40    1.20    0.70    0.00   -0.40   -0.70   -0.90   -0.90   -0.90   -0.90
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
    279.00      0.00   2319.50                              NORTH / EAST / UP
   NOAZI   -0.80   -0.90   -0.90   -0.80   -0.40    0.20    0.80    1.30    1.40    1.20    0.70    0.00   -0.40   -0.70   -0.90   -0.90   -0.90   -0.90
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
```

Figure A-14. Example of the satellite section of an ANTEX file

Receiver antennas part: first sorted according to antenna type, then sorted according to receiver radome code, and finally sorted according to the “SERIAL NO”.

- “TYPE / SERIAL NO” denotes the antenna type and serial number;
- “NORTH / EAST / UP” denotes the mean antenna phase center relative to the antenna reference point (ARP). North, east and up component (in millimeters);
- IF “DAZI” > 0.0, the PV value corresponding to the azimuth angle in increments of “DAZI” is recorded after the line where “NOAZI” is located.

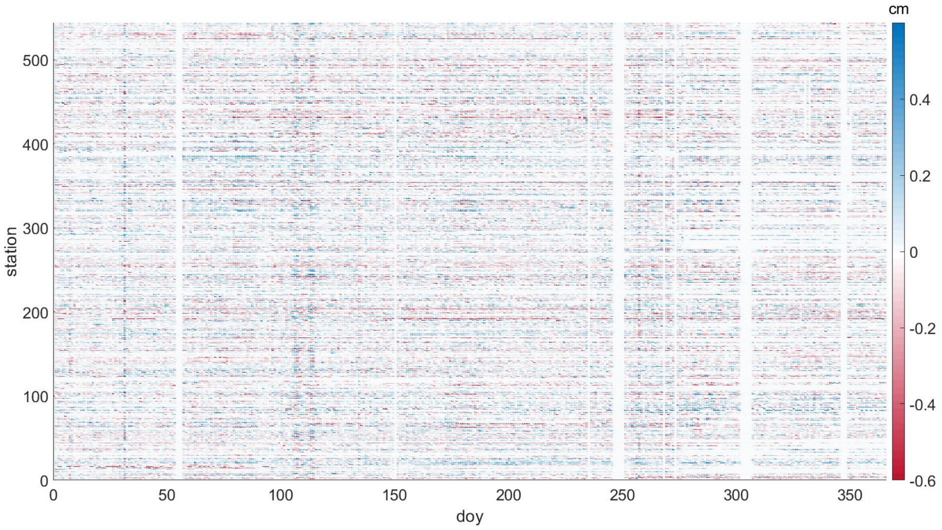
```
                                                            START OF ANTENNA
TWIVSP6037L     NONE                                        TYPE / SERIAL NO
ROBOT               Geo++ GmbH               5    12-NOV-20 METH / BY / # / DATE
     5.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
    21                                                      # OF FREQUENCIES
IGS14_2163                                                  SINEX CODE
  ________________________________________                  COMMENT
  | Freq.[MHz] | Freq. Codes              |                 COMMENT
  |---------------------------------------|                 COMMENT
  |   1602.000 | R01 R04                  |                 COMMENT
  |   1575.420 | G01 E01 J01 S01 C01      |                 COMMENT
  |   1561.098 | C02                      |                 COMMENT
  |   1278.750 | E06 J06                  |                 COMMENT
  |   1268.520 | C06                      |                 COMMENT
  |   1246.000 | R02 R06                  |                 COMMENT
  |   1227.600 | G02 J02                  |                 COMMENT
  |   1207.140 | E07 C07                  |                 COMMENT
  |   1202.025 | R03                      |                 COMMENT
  |   1191.795 | E08 C08                  |                 COMMENT
  |   1176.450 | G05 E05 J05 C05 S05 I05  |                 COMMENT
  |_______________________________________|                 COMMENT
   G01                                                      START OF FREQUENCY
      0.35      -0.70      48.82                            NORTH / EAST / UP
   NOAZI    0.00   -0.10   -0.35   -0.64   -0.85   -0.88   -0.73   -0.50   -0.32   -0.34   -0.63   -1.08   -1.48   -1.57   -1.14   -0.19    1.00    1.93    2.02
     0.0    0.00   -0.02   -0.25   -0.61   -0.99   -1.27   -1.35   -1.23   -1.00   -0.76   -0.62   -0.61   -0.61   -0.47   -0.01    0.77    1.66    2.28    2.17
     5.0    0.00   -0.01   -0.23   -0.57   -0.94   -1.20   -1.28   -1.17   -0.96   -0.76   -0.68   -0.72   -0.76   -0.63   -0.15    0.66    1.57    2.15    1.91
    10.0    0.00    0.00   -0.21   -0.54   -0.89   -1.13   -1.20   -1.10   -0.91   -0.77   -0.76   -0.86   -0.94   -0.81   -0.29    0.59    1.55    2.10    1.72
    15.0    0.00    0.00   -0.19   -0.50   -0.83   -1.05   -1.10   -1.01   -0.86   -0.78   -0.84   -1.02   -1.15   -1.01   -0.44    0.52    1.57    2.13    1.64
    20.0    0.00    0.01   -0.17   -0.47   -0.77   -0.97   -1.00   -0.91   -0.80   -0.78   -0.92   -1.19   -1.37   -1.24   -0.62    0.45    1.61    2.22    1.66
    25.0    0.00    0.02   -0.15   -0.43   -0.71   -0.88   -0.89   -0.80   -0.71   -0.76   -0.99   -1.35   -1.61   -1.50   -0.83    0.34    1.63    2.35    1.78
    30.0    0.00    0.02   -0.14   -0.40   -0.65   -0.79   -0.78   -0.68   -0.61   -0.72   -1.04   -1.50   -1.85   -1.79   -1.09    0.18    1.60    2.46    1.96
    35.0    0.00    0.03   -0.12   -0.37   -0.60   -0.70   -0.66   -0.55   -0.50   -0.65   -1.06   -1.62   -2.07   -2.08   -1.39   -0.06    1.50    2.52    2.16
    40.0    0.00    0.03   -0.11   -0.35   -0.55   -0.62   -0.55   -0.41   -0.36   -0.55   -1.04   -1.71   -2.27   -2.36   -1.72   -0.36    1.30    2.49    2.34
    45.0    0.00    0.03   -0.11   -0.32   -0.50   -0.54   -0.44   -0.28   -0.22   -0.44   -0.98   -1.74   -2.42   -2.63   -2.07   -0.73    0.99    2.35    2.43
    50.0    0.00    0.03   -0.10   -0.31   -0.46   -0.48   -0.34   -0.15   -0.08   -0.30   -0.89   -1.73   -2.51   -2.85   -2.41   -1.15    0.59    2.08    2.41
```

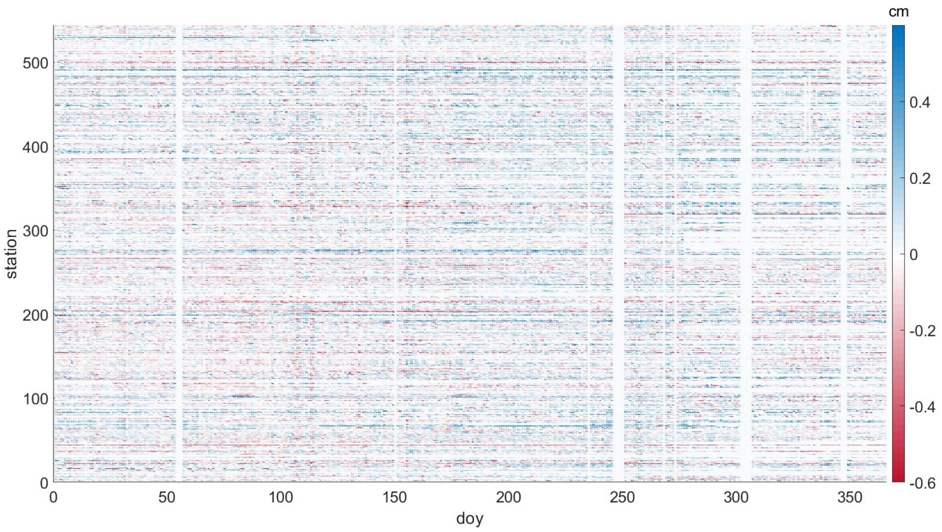
Figure A-15. Example of the receiver section of an ANTEX file

Appendix B. Typical examples

B.1 Daily solutions

We test a series of IGS static stations in 2020. Then we compare the static PPP-AR results with IGS SINEX solutions. The figures listed below (Figure B-1) record the difference between our solutions and IGS SINEX solutions in east/north/up directions, respectively. The X axis, which denotes day of year, ranges from 1 to 366. The Y axis denotes different stations. The color map, which ranges from blue to red, represents the difference value in the unit of centimeter.





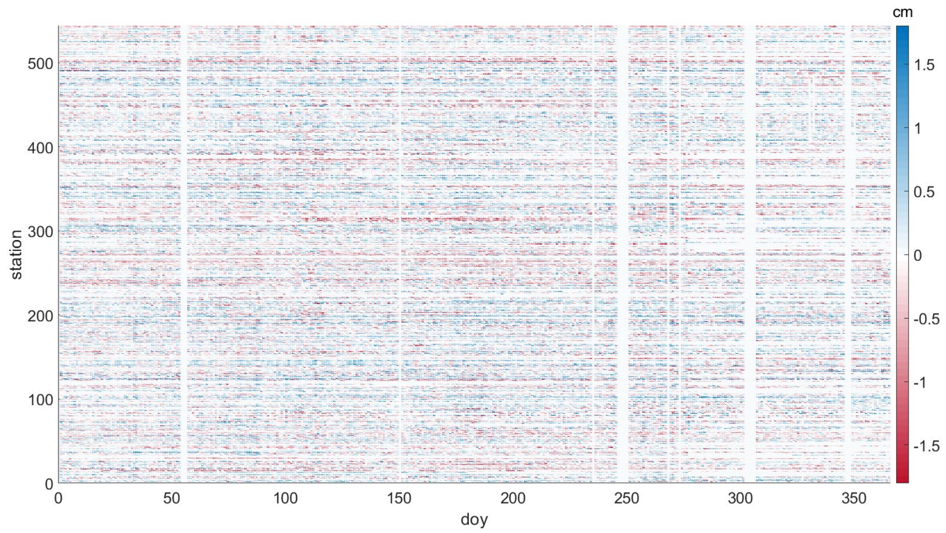


Figure B-1. Difference between PRIDE PPP-AR II solution and IGS SINEX solution of various stations.

B.2 Super-high-rate (50 Hz) data

PRIDE PPP-AR II can still process super-high-rate data, up to 50 Hz. Then we test HLFY station (1300 kilometers away from epicenter), to presenting the 2011 earthquake of the Pacific coast of Tōhoku occurred in Japan at 05:46:24 (UTC) on March 11, 2011 with a magnitude of MW 9.0. As shown in Figure B-2, the evident horizontal vibration is reach about 10 centimeters.

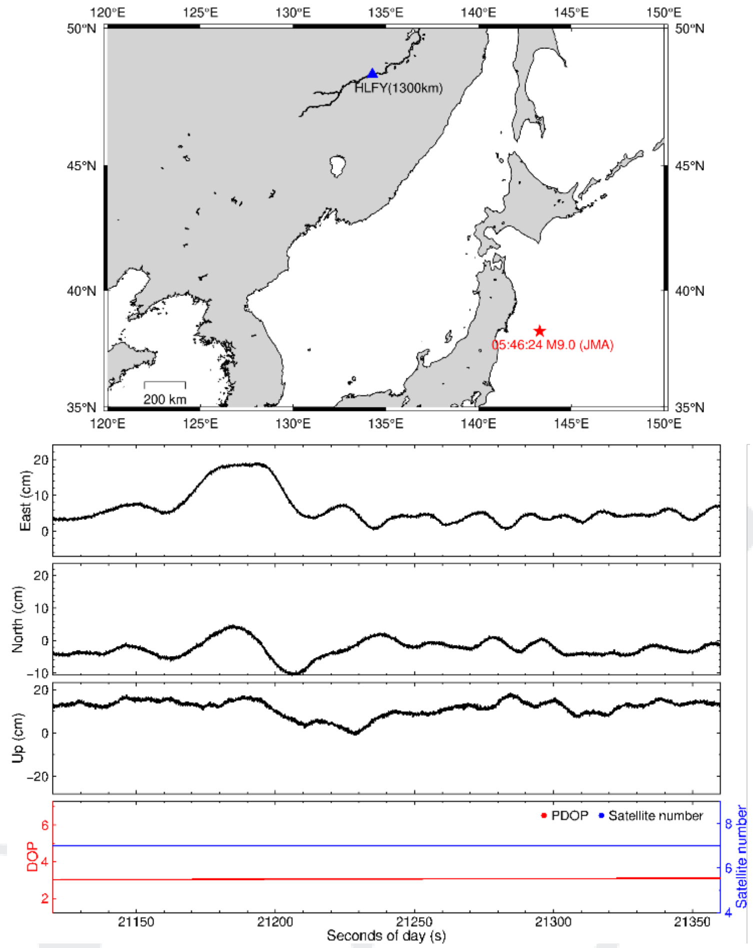


Figure B-2. Time series of super-high-rate kinematic solutions (cm) in east, north, and up components at station HLFY on March 11, 2011

B.3 High-dynamic mobile platforms

In an aerial photogrammetry experiment, high-dynamic PPP has been realized. The observation period is on November 27, 2017 and lasting about 5 hours. The sampling rate is 0.5 seconds. The trajectory of the aircraft is shown in Figure B-3. And we use relative positioning solutions of WayPoint software (a commercial positioning software) as the reference solutions, whose maximum baseline length is up to 170 kilometers. As shown in Figure B-4, In the airborne experiment with less shielding, the positioning accuracy is basically the same with that of commercial software. Besides, fixed ambiguity can also significantly improve the positioning accuracy in high-dynamic data solutions.

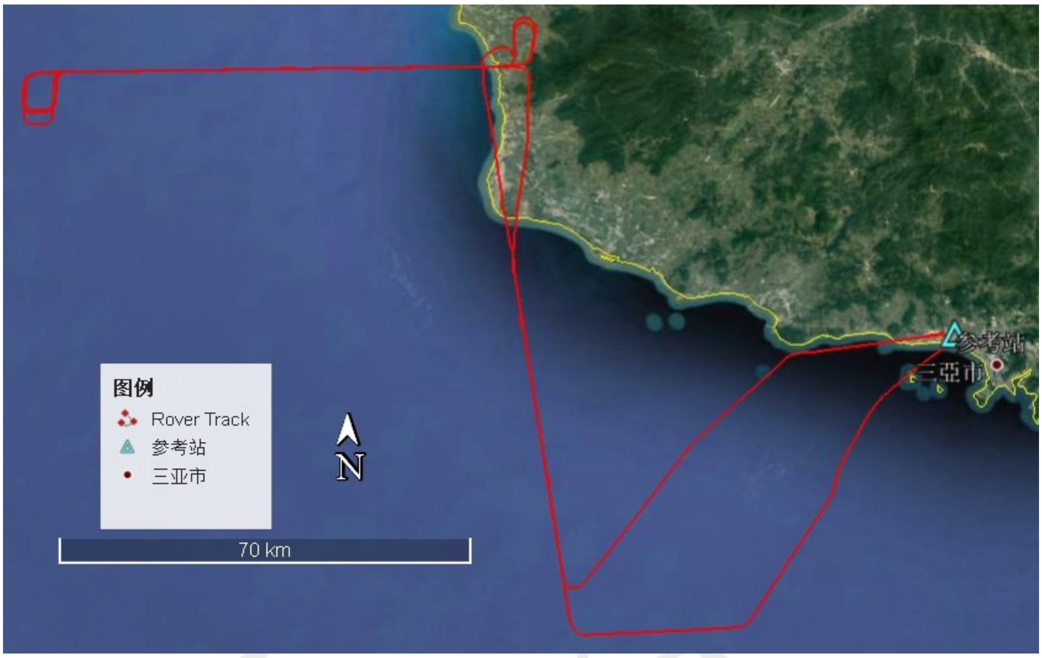


Figure B-3. Trajectory of the aircraft in high-dynamic aerial photogrammetry experiment

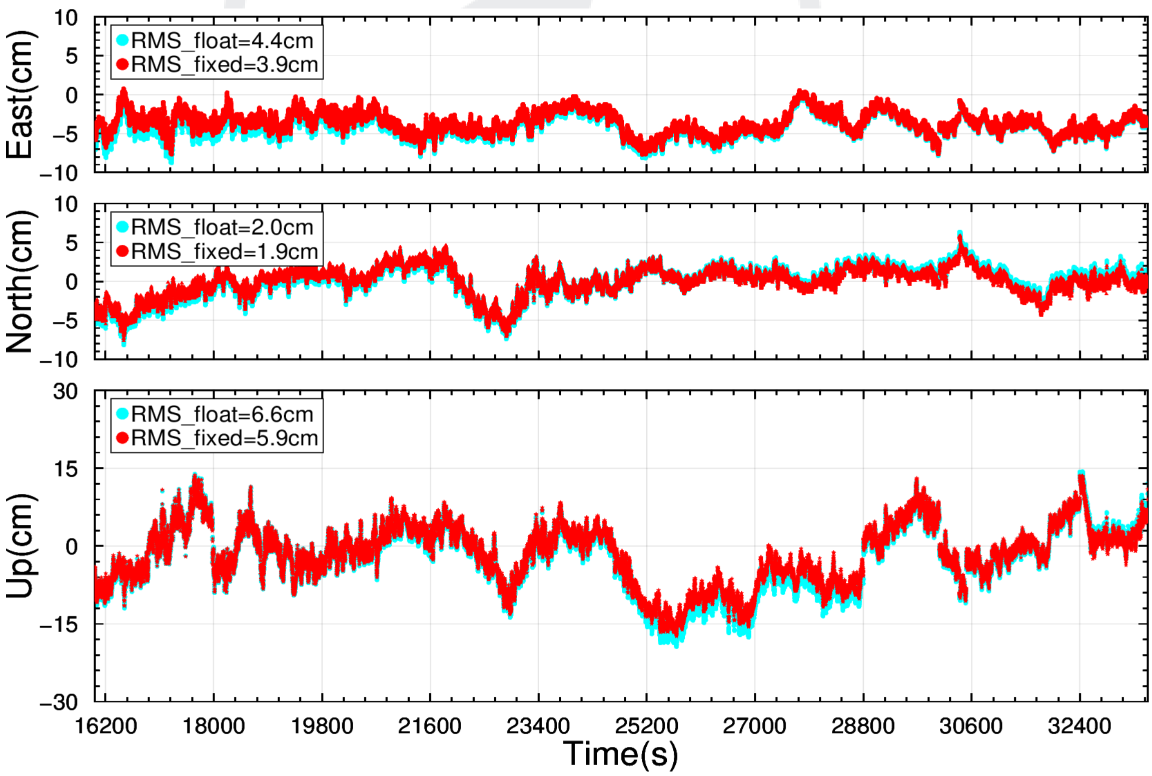


Figure B-4. Location differences between PRIDE PPP-AR and WayPoint software

Appendix C. GPS data processing when SA is on

GPS data when SA is on have low-precision broadcast ephemeris, so the usage of broadcast ephemeris in these periods should be cautious. To process these GPS data for users easily, we have set some configurations in ***"tedit"*** module to avoid obtaining satellite clock corrections from broadcast ephemeris. Besides, users should change the **"Strict editing"** mode from **"YES"** to **"NO"** in configuration file. And change the products name in the configuration file.

As an example, we select precise satellite clock/orbit/ERP repro2 products of JPL to process GPS data when SA is on. We test an IGS station (ALBH) in 1995. The figure listed below (Figure C-1) records the position time series in east/north/up directions, respectively. The X axis, which denotes day of year, ranges from 1 to 365. The Y axis denotes changes of positions.

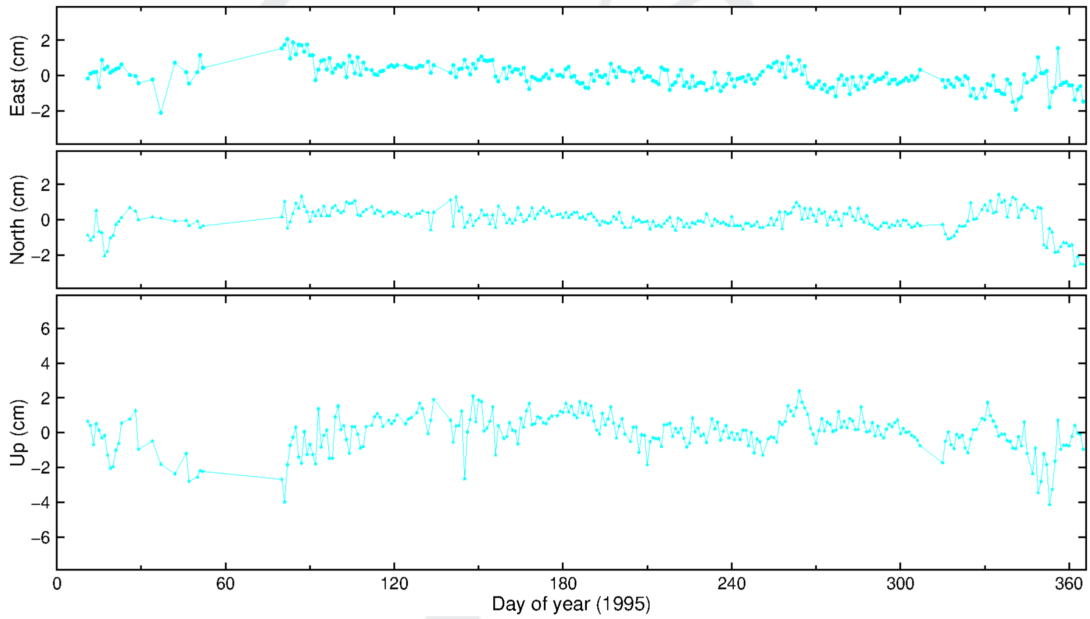


Figure C-1. Position time series at station ALBH in 1995