PPP-ARISEN User Manual

An open-source PPP software with Ambiguity Resolution

for Interdisciplinary research of Seismology, Geodesy and Geodynamics

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❖ Overview

Abstract

As the exponential growth of Global Navigation Satellite System (GNSS) station worldwide, GNSS record of time-series becomes a very important information source for many areas of Earth science. Among the GNSS applications, Precise Point Positioning (PPP) approach plays an essential role because of the ability of high precise absolute positioning with standalone receiver when the ambiguity of carrier phase is recovered with its integer property. Although many general-purpose and self-sufficient toolboxes are available for users of GNSS algorithms, a user-friendly toolbox focusing on signal extraction and applications and supporting products of different IGS Analysis Centers (ACs) is helpful for obtaining accurate results of robustness and self-assessment. For the geoscience community, we present a cross-platform open source PPP toolbox PPP-ARISEN (Precise Point Positioning software with Ambiguity Resolution for Interdisciplinary research of Seismology/gEodesy/geodyNamics), which is compatible with both CODE and CNES products and realized ambiguity resolution based on Integer Phase Clock (IPC) method with Satellite-to-satellite Single Difference (SSD) strategy. The toolbox can achieve millimeter-level precision for static positioning compared with IGS weekly SINEX result and centimeter-level precision for kinematic mode, while the uniquely designed "Seismological" mode successfully captures clear dynamic signals induced by the earthquake with different products of IGS ACs. Moreover, we define and validate an effective index to judge the convergence status of PPP, which is called as Convergence Status Indicator based on ZWD Variances (CSI-ZWDV). The index is superior to previous experimental parameters of determining when to search for the integer ambiguities, along with its more explicit physical meaning.

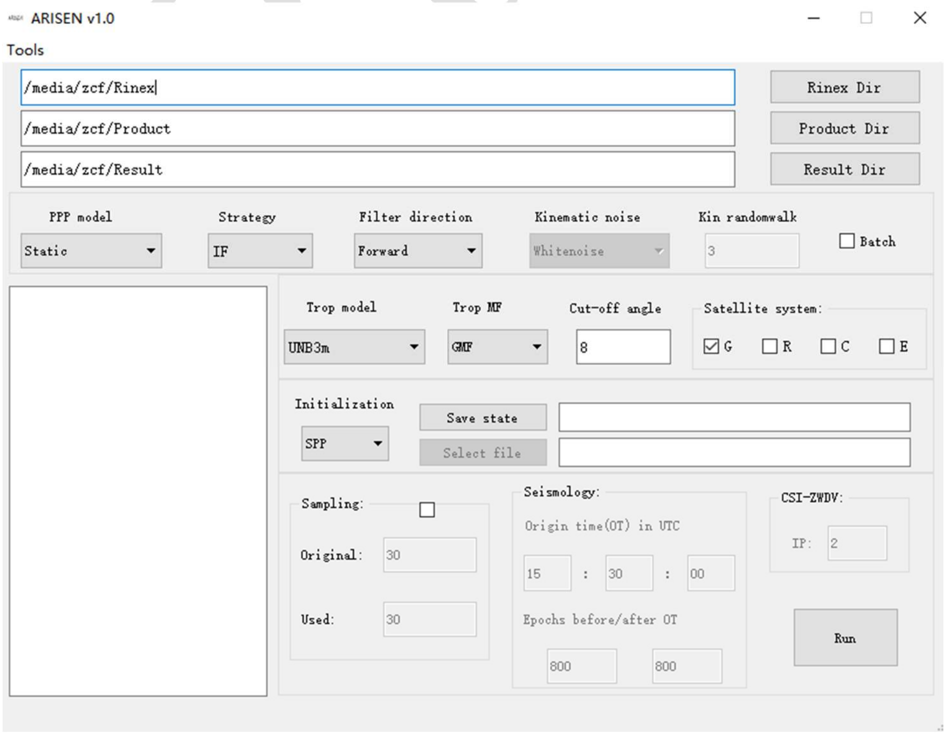
Key words

Cross-platform open-source software; Precise Point Positioning (PPP); PPP-ARISEN; IPC method; CSI-ZWDV

❖ Installation

Run PPP-ARISEN with executable program

You can directly run PPP-ARISEN with executable programs to process GNSS data, which are placed in "*PPP-ARISEN_v1.0\bin\windows10*" and "*PPP-ARISEN_v1.0\bin\ubuntu20*", and files shouldn't be deleted or changed in each executable program folder except the configuration file "*ARISEN.ini*". The configuration file "*ARISEN.ini*" is included in each executable program folder, and the "*annotation4ini.txt*" comment file is placed in "*PPP-ARISEN_v1.0\resources\user_manual*". The interface of PPP-ARISEN is as follows:



✧ **Windows users** (Windows10-x64, tested):

1. **Startup Programs via interface**: Double-click ***ARISEN.exe*** in "*...\bin\windows10*".

2. **Startup Programs via Command Line**:

   1) Configure "*ARISEN.ini*";

   2) Run PPP-ARISEN by command prompt in "*CMD*":

```
C:\Users\16094>cd /d G:\ARISEN\ARISEN_v1.0\bin\windows10

G:\ARISEN\ARISEN_v1.0\bin\windows10>ARISEN.exe

G:\ARISEN\ARISEN_v1.0\bin\windows10>
```

✧ **Linux users** (Ubuntu20.0-x64, tested):

1. **Configure library files**:

   1) Copy "*\…\bin\ubuntu20\lib-ARISEN*" to "**/lib/**":

```
cfz@cfz-ThinkStation-P330:~/data_23z/exe(ubu20)$ sudo cp -r lib-ARISEN /lib/
```

   2) Modify "*etc/ld.so.config*":

```
cfz@cfz-ThinkStation-P330:~/data_23z/exe(ubu20)$ sudo vim /etc/ld.so.conf
```

```
include /etc/ld.so.conf.d/*.conf
/lib/lib-ARISEN
~
~
:wq!
```

   3) Assign the binary program "*ARISEN*" the execution rights:

```
cfz@cfz-ThinkStation-P330:~/data_23z/exe(ubu20)$ sudo chmod +x ARISEN
```

2. **Startup Programs via interface**:

   1) Configure "*Startup_interface=true*" in "*ARISEN.ini*";

   2) Startup PPP-ARISEN by command prompt in "*Terminal*":

```
cfz@cfz-ThinkStation-P330:~/data_23z/exe(ubu20)$ ./ARISEN
```

3. **Startup Programs via Command Line**:

   1) Configure "*Startup_interface=false*" and other parameters according to your GNSS data in "*ARISEN.ini*";

   2) Run PPP-ARISEN by command prompt in "*Terminal*":

```
cfz@cfz-ThinkStation-P330:~/data_23z/exe(ubu20)$ ./ARISEN
```

Compile PPP-ARISEN from source code

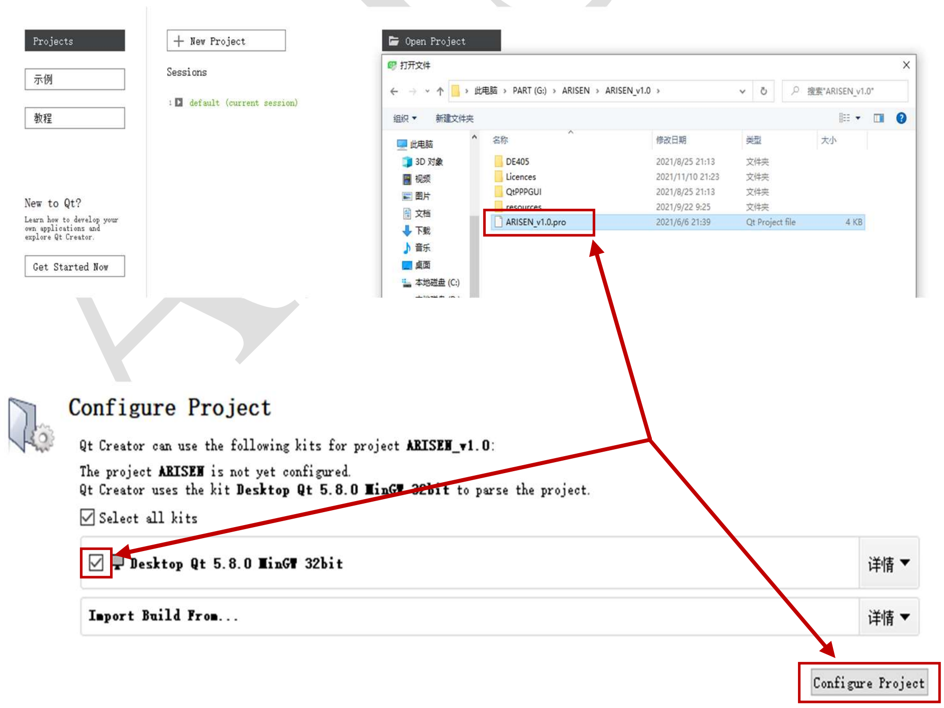
You can compile the source code of PPP-ARISEN with QT, as follows:

1. Preparation

You need to install QT (5.8.0) first. QT installation packages for different platforms are published on QT official website (www.qt.io). For Windows users, you need to download “**qt-opensource-windows-x86-mingw530-5.8.0.exe**”; for Linux users, you need to download “**qt-opensource-linux-x64-5.8.0.run**”; for Mac users, you need to download “**qt-opensource-mac-x64-clang-5.8.0.dmg**”. When installing QT, “**MinGW 5.3.0 32-bit**” should be checked.

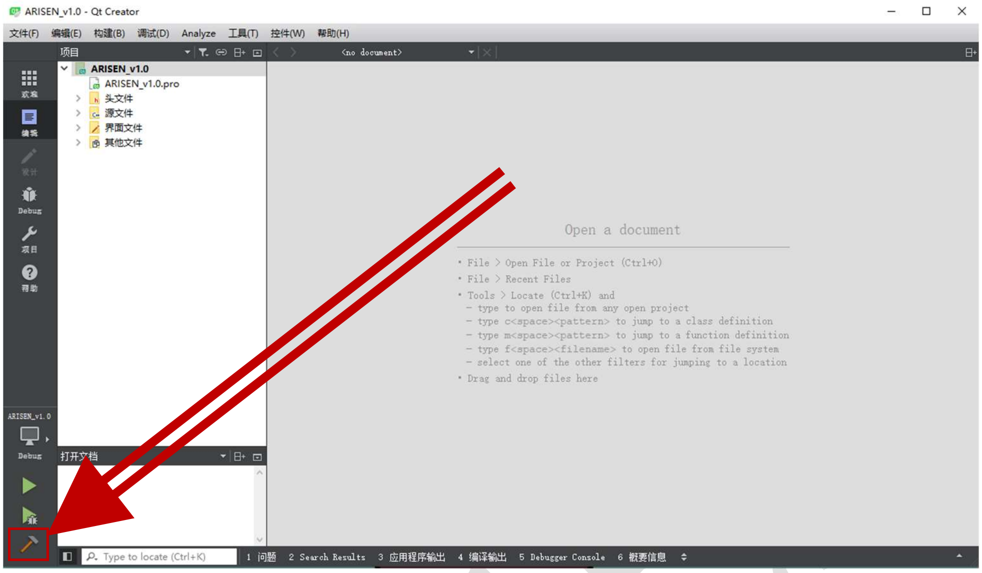
2. Open project

Open the “*ARISEN_v1.0.pro*” file with QT, and “*configure project*” (check “**MinGW 5.3.0 32-bit**”) as below:



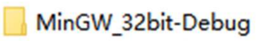
3. Build

Build ARISEN (*click the red box as below*):



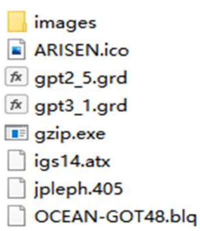
4. Copy source files

The files to be copied are placed in "*MinGW_32bit-Debug*" and "*MinGW_32bit-Debug(debug)*" under "*PPP-ARISEN_v1.0\resources\startup*", as follows:



:

:



✧ **Windows users** (Windows10-x64, tested)

1) Copy files in the "*MinGW_32bit-Debug*" to "*build-ARISEN_v1.0-Desktop_Qt_5_8_0_MinGW_32bit-Debug*";

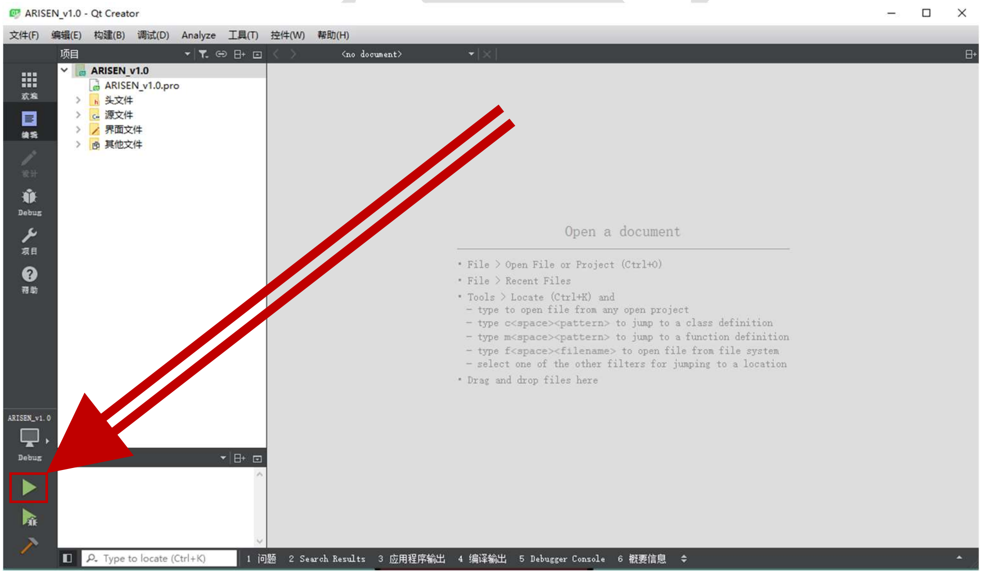
2) Copy files in the "*MinGW_32bit-Debug(debug)*" to "*build-ARISEN_v1.0-Desktop_Qt_5_8_0_MinGW_32bit-Debug\debug*";

✧ **Linux users** (Ubuntu20.0-x64, tested)

Copy files both in "*MinGW_32bit-Debug*" and "*MinGW_32bit-Debug(debug)*" to "*build-ARISEN_v1.0-Desktop_Qt_5_8_0_MinGW_32bit-Debug*" (You may be prompted that the "***ARISEN. ico***" file is duplicate. Replace it).

5. Run

Run PPP-ARISEN (*Click the red box as below*):



So far, PPP-ARISEN_v1.0 has been successfully Compiled!

Package executable program of PPP-ARISEN

Users can package the executable program of PPP-ARISEN with QT as follow:

✧ **Windows users** (Windows10-x64, tested)

1) **Run PPP-ARISEN in Release mode in QT creator to generate ARISEN.exe:**

When this process is done, the ARISEN.exe will be generated in the "*build-ARISEN_v1.0-Desktop_Qt_5_8_0_MinGW_32bit-Release*".

2) **Run "Qt 5.8 for Desktop (MinGW 5.3.0 32 bit)":**

ARISEN.exe should be moved to an "***example***" folder. Then 'cd' to the folder and 'windeployqt' ARISEN.exe in "Qt 5.8 for Desktop (MinGW 5.3.0 32 bit)" (It is one of QT's applications and you can find it in the Windows menu).

3) **Copy files both in "*MinGW_32bit-Debug*" and "*MinGW_32bitDebug(debug)*" under "*PPP-ARISEN_v1.0\resources\startup*" to your "*example*" folder.**

So far, the packaging is complete! ARISEN.exe in "*example*" folder can run like that in "**Run PPP-ARISEN with executable program**".

✧ **Linux users** (Ubuntu20.0-x64, tested)

1) **Run PPP-ARISEN in Release mode in QT creator to generate ARISEN:** This is consistent with that of Windows users.

2) **Copy library files:**

‘ARISEN’ program should be moved to an “***example***” folder. And there are many library files for ‘ARISEN’ program should be prepared like that in “*PPP-ARISEN_v1.0 \bin\ubuntu20 \lib-ARISEN*”. You can prepare those library files with a ‘.sh’ file as below:

```
#!/bin/sh

exe="/.../ARISEN" #filepath of executable program
des="/.../lib-ARISEN" #filepath to store library files

deplist=$(ldd $exe | awk  '{if (match($3,"/")){ printf("%s "),$3 } }')
cp $deplist $des
```

All the relevant library files must be included, otherwise the program cannot run successfully (Command ‘*ldd ARISEN*’ can list all the library files of ARISEN in “*Terminal*” for checking, and relevance of library files also need to be considered).

```
zcf@cfz:~/ARISEN/PPP-ARISEN-exe$ ldd ARISEN
        linux-vdso.so.1 (0x00007ffe39f95000)
        libQt5PrintSupport.so.5 => /home/zcf/MySoft/t5.14.0/5.14.0/gcc_64/lib/libQt5PrintSupport.so.5 (0x00007f6df882c000)
        libQt5Widgets.so.5 => /home/zcf/MySoft/t5.14.0/5.14.0/gcc_64/lib/libQt5Widgets.so.5 (0x00007f6df7fce000)
        libQt5Gui.so.5 => /home/zcf/MySoft/t5.14.0/5.14.0/gcc_64/lib/libQt5Gui.so.5 (0x00007f6df76bb000)
        libQt5Network.so.5 => /home/zcf/MySoft/t5.14.0/5.14.0/gcc_64/lib/libQt5Network.so.5 (0x00007f6df730f000)
        libQt5Core.so.5 => /home/zcf/MySoft/t5.14.0/5.14.0/gcc_64/lib/libQt5Core.so.5 (0x00007f6df6b38000)
        libstdc++.so.6 => /lib/x86_64-linux-gnu/libstdc++.so.6 (0x00007f6df6940000)
        libm.so.6 => /lib/x86_64-linux-gnu/libm.so.6 (0x00007f6df67f1000)
        libgcc_s.so.1 => /lib/x86_64-linux-gnu/libgcc_s.so.1 (0x00007f6df67d6000)
```

3) **Copy files both in “*MinGW_32bit-Debug*” and “*MinGW_32bitDebug(debug)*” under “*PPP-ARISEN_v1.0\resources\startup*” to your “*example*” folder.**

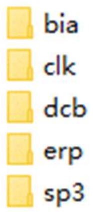
So far, the packaging is complete! ARISEN in “*example*” folder can run like that in “**Run PPP-ARISEN with executable program**”.

❖ PPP processing

Data preparation

- PPP: *observation*, *orbits*, *clocks* and *erp* files (*AR* products);

  There are three folders that need to be selected (“**Rinex Dir**”, “**Product Dir**” and “**Result Dir**”). For single station processing, a “***.*o**” file should be selected as “**Rinex Dir**”; for batch processing, a folder containing multiple “***.*o**” files should be selected as “**Rinex Dir**”. *Orbits*, *clocks*, *erp* files and *AR* products should be put in a “**Product Dir**” containing multiple subfolders as below:

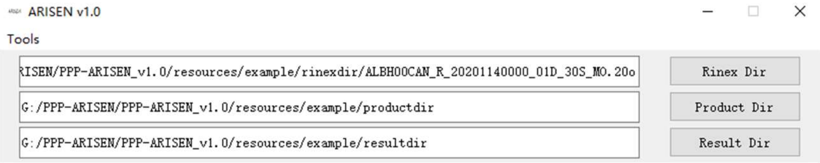
  Different products should be put in corresponding folders:

  - ✧ **Float PPP:** Three (that day, the day before and after) orbit files are put in the “**sp3**” folder; three clock files are put in the “**clk**” folder and the erp file is put in the “**erp**” folder.
  - ✧ **PPP-AR:**
    - ➢ **GRG products:** Except the files for **Float PPP**, a “**P1C1****.DCB**” file of GPS is put in the “**dcb**” folder. The wide lane bias files have been prepared when PPP-ARISEN is installed, but they need to be updated regularly (**Wide_lane_***_satellite_biais.wsb**: ftp://ftpsedr.cls.fr/pub/igsac/).
    - ➢ **COD products:** Except the files for **Float PPP**, a “*********.BIA**” file from CODE (ftp.aiub.unibe.ch) is put in the “**bia**” folder.

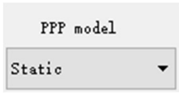
- A sample data set is provided in “*PPP-ARISEN_v1.0\resources\example*”, which is suggested to verify your installation by configuring the corresponding file paths in the example folder, and then verify your results with those results in “*\...resources\example\resultdir*”.

Static

1. Select observation file



2. Select "Static" model

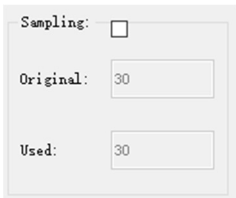


3. Configure Kalman filter

In the "**Initialization**" module:

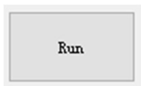
- ✧ When you need to save the filter state, click "**Save states**" to select a path;
- ✧ When the filter is completed, a "**.csv**" file will be generated under the path, in which the coordinate information and ZWD are saved;
- ✧ When you don't need to save the filter state, **just leave it blank**;
- ✧ When you select "**.snx**" or "**.csv**" to initialize, "**Select file**" will enable to select the corresponding "**.snx**" or "**.csv**" file.

In the "**Sampling**" module， the GNSS data can be resampled by filling in the original interval and down-sampled interval。



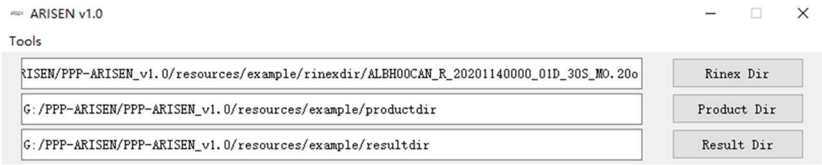
4. PPP processing

Click "**Run**" to start the solution.



Kinematic

1. Select observation file



2. Select "Kinematic" model

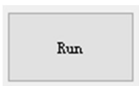
3. Configure Kalman filter

The configuration method here is basically the same as that of "**Static**" except the "**Kinematic noise**" module.

- ✧ With "**Whitenoise**" estimation strategy, PPP-ARISEN will process data with $10^6 m^2$ as the kinematic noise;
- ✧ With "**Randomwalk**" estimation strategy, PPP-ARISEN will process data with the parameter (unit: cm/s) filled in "**Kin randomwalk**" as the kinematic noise.

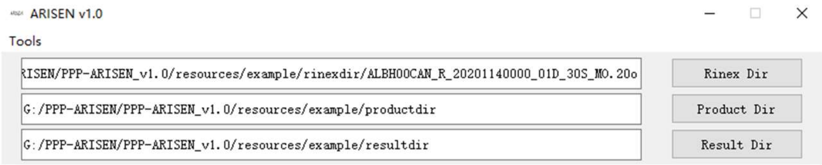
4. PPP processing

Click "**Run**" to start the solution.

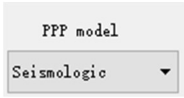


Seismological

1. Select observation file

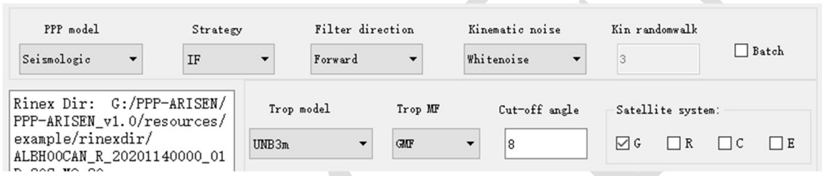


2. Select "Seismological" model

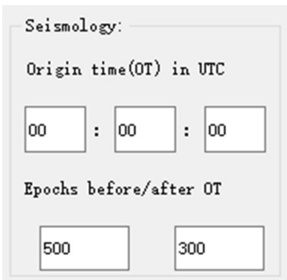


3. Configure Kalman filter

The configuration of Kalman parameters are the same as that of "**Kinematic**".

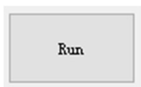


With "**Seismological**" model, the "**Seismology**" module is enabled. In this module, you need to fill in the origin time (UTC) of earthquake and the expanded epoch number before and after the origin time, in which the data piece with strong motion information should be included.



4. PPP processing

Click "**Run**" to start the solution.



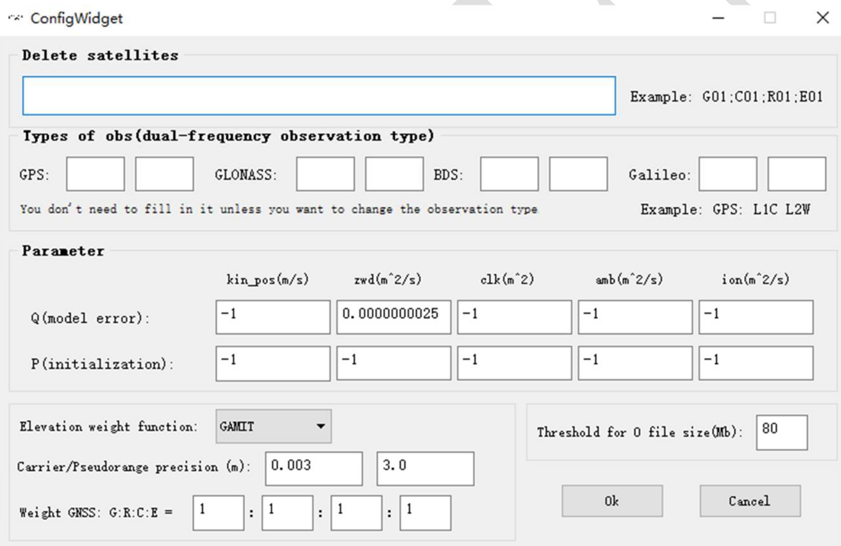
Advanced parameter configuration

1. CSI-ZWDV

When you use **PPP-AR** strategy for data processing, the "**CSI-ZWDV** (Convergence Status Indicator based on ZWD Variables)" module is enabled. The **2nd IP** in static model and the **3rd IP** in kinematic model are as default for robustness (**IP**: Infection Point).

2. Advanced configuration of PPP-ARISEN

Advanced configurations of PPP-ARISEN are in "**Tools/Configure**", as below:



- ✧ "**Delete satellites**": To delete some specific satellites;
- ✧ "**Type of obs**": To select some specific type of observations;
- ✧ "**Q(model error)**": To configure the model errors ("**- 1**": default);
- ✧ "**P(initialization)**": To initialize Kalman filter ("**- 1**": default);
- ✧ "**Elevation weight function**": To select an elevation weight function;
- ✧ "**Carrier/Pseudorange precision**": To configure Carrier/Pseudorange precision;
- ✧ "**Weight GNSS**": To weight between GNSSs;
- ✧ "**Threshold for O file size**" refers to the threshold of the observation file size. When the observation file is bigger than the threshold, PPP-ARISEN outputs the

solution results of each epoch in time to release the computer memory, while the "**Backsmooth**" method cannot be carried out. For processing a big observation file with "**Backsmooth**" method, it is recommended to use the Ubuntu system.

❖ Result and analysis

Output file format

1. Folder and file name

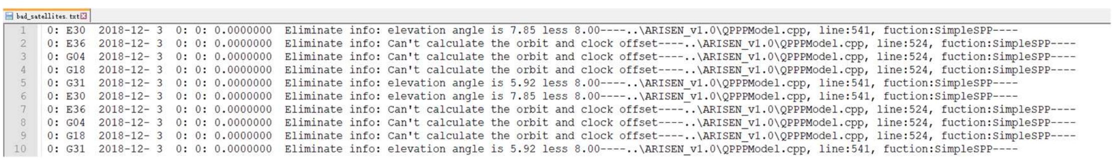
When the data processing is completed, the output file(s) will be placed in "**Result Dir**". The folder is named as follows:

"*Mark name(4c) + YearDOY(7c) _Analysis Center(3c) _(Backsmooth)_Kalman_Strategy_model_GNSS system*"

The folder contains four output files:

2. bad_satellites.txt

"***_bad_satellites**" file records the satellite which is deleted in PPP processing, including the epoch number, PRN, GPST and abnormal information.



```
bad_satellites.txt
0: E30  2018-12- 3  0: 0: 0.0000000  Eliminate info: elevation angle is 7.85 less 8.00----..\ARISEN_v1.0\QPPPModel.cpp, line:541, fuction:SimpleSPP----
0: E36  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G04  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G18  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G31  2018-12- 3  0: 0: 0.0000000  Eliminate info: elevation angle is 5.92 less 8.00----..\ARISEN_v1.0\QPPPModel.cpp, line:541, fuction:SimpleSPP----
0: E30  2018-12- 3  0: 0: 0.0000000  Eliminate info: elevation angle is 7.85 less 8.00----..\ARISEN_v1.0\QPPPModel.cpp, line:541, fuction:SimpleSPP----
0: E36  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G04  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G18  2018-12- 3  0: 0: 0.0000000  Eliminate info: Can't calculate the orbit and clock offset----..\ARISEN_v1.0\QPPPModel.cpp, line:524, fuction:SimpleSPP----
0: G31  2018-12- 3  0: 0: 0.0000000  Eliminate info: elevation angle is 5.92 less 8.00----..\ARISEN_v1.0\QPPPModel.cpp, line:541, fuction:SimpleSPP----
```

3. position.txt

"***_position**" file records the coordinate information, including epoch number, GPST, number of valid satellites, coordinate results of SPP, coordinate results and variance of PPP.

bad_satellites.txt | position.txt

epoch	Observation time	num_of_sats	spp_x(m)	spp_y(m)	spp_z(m)	ppp_x(m)	ppp_y(m)	ppp_z(m)	sigam_x(m)	sigam_y(m)	sigam_z(m)
0:	2018-12- 3 0: 0: 0.0000000	17	1942817.4807	-5804076.6373	-1796884.6103	1942817.7452	-5804077.6879	-1796885.0467	1.55422347	5.31300349	3.04788037
1:	2018-12- 3 0: 0:30.0000000	17	1942816.8260	-5804076.4082	-1796884.6194	1942817.3944	-5804076.8011	-1796884.4619	0.90833619	1.23205769	0.52000306
2:	2018-12- 3 0: 1: 0.0000000	16	1942816.9324	-5804076.6570	-1796884.7063	1942817.4676	-5804077.3246	-1796884.5140	0.70071199	0.78438939	0.26790979
3:	2018-12- 3 0: 1:30.0000000	15	1942816.9797	-5804076.8953	-1796884.4402	1942817.1381	-5804077.2409	-1796884.3632	0.58044688	0.56328048	0.18527799
4:	2018-12- 3 0: 2: 0.0000000	16	1942817.3033	-5804076.7234	-1796884.9245	1942817.2126	-5804077.4018	-1796884.4523	0.49383439	0.42477411	0.13940257
5:	2018-12- 3 0: 2:30.0000000	15	1942816.8945	-5804076.6087	-1796884.9982	1942817.5516	-5804077.4161	-1796884.5067	0.42447187	0.33376453	0.11012127
6:	2018-12- 3 0: 3: 0.0000000	16	1942816.8142	-5804076.5193	-1796884.5929	1942817.3571	-5804077.3983	-1796884.4663	0.36729377	0.27089175	0.08994812
7:	2018-12- 3 0: 3:30.0000000	16	1942817.1893	-5804077.0181	-1796884.5723	1942816.9856	-5804077.3732	-1796884.4674	0.31996210	0.22519741	0.07520953
8:	2018-12- 3 0: 4: 0.0000000	16	1942817.0728	-5804076.8117	-1796884.6661	1942816.8564	-5804077.2895	-1796884.4288	0.28075299	0.19074552	0.06400173
9:	2018-12- 3 0: 4:30.0000000	16	1942817.0890	-5804076.1969	-1796884.3160	1942816.9607	-5804077.2445	-1796884.4328	0.24818130	0.16405577	0.05525635
10:	2018-12- 3 0: 5: 0.0000000	16	1942817.0528	-5804076.8473	-1796884.6199	1942816.9705	-5804077.2037	-1796884.4418	0.22098450	0.14292242	0.04829429

4. modelling.txt

"***_modelling**" file records the detailed information of each epoch during PPP processing, including epoch number, GPST, ZHD, satellite coordinates, residuals of satellite observations, ambiguities, and model corrections.

bad_satellites.txt | position.txt | Satellite_info.ppp

```
>epoch_num: 1046     ( 16  )
Satellite Number: 16,(yyyy-mm-dd-hh-mm-ss):2018-12- 3  8:43: 0.0000000 ,ZHD: 1.7291 , BadFlag:   0, reference_sat:   7  3, diff_wl_refsats:    0    0, diff_nl_refsats:    0    0, sigam
prn        v_L_IF(m)        v_P_IF(m)     pos_sat_x(m)     pos_sat_y(m)     pos_sat_z(m)     wl_float(c)     wl_fixed(c)       times_wl      nl_float(c)     nl_fixed(c)       times_nl
G02:    -0.04638146,      1.21942025, -14364458.4988, -22363865.2152,   2819749.5476,       -2.24944,       -2.00000,     307.00000,      35.15356,      35.00000,      92.00000,
G05:    -0.06935634,     -1.28647168,  -7374215.8871, -16824774.0539, -19231525.6498,      -14.75907,      -15.00000,     128.00000,      30.58513,       0.00000,       0.00000,
G06:     0.01633771,     -1.75510705,  -3559672.8399, -22350561.6699,  13922175.5406,      -28.86875,      -29.00000,     508.00000,     -30.97830,     -31.00000,     178.00000,
G09:    -0.05471340,     -1.43506478,  23850578.5535,  -7968286.0435,  -8610870.1283,      -19.00345,      -19.00000,     117.00000,     -55.06968,     -55.00000,      21.00000,
G13:    -0.06739491,     -1.37540315, -16262623.1817, -12610655.3082, -16924251.5257,       -3.94113,       -4.00000,      41.00000,      24.11277,      24.00000,      21.00000,
G17:    -0.04410303,      0.80809664,  10567057.6619, -13748835.0330,  20490550.0028,       -2.33844,        0.00000,       1.00000,       0.00000,       0.00000,       0.00000,
G28:    -0.06110154,      0.39294217,  13376753.7902, -22988398.5410,    879516.5541,        5.72416,        0.00000,     117.00000,       0.00000,       0.00000,       0.00000,
G30:    -0.03422018,      0.36393462,   5350983.3939, -17780615.3825, -18911284.8522,      -15.24903,      -15.00000,     482.00000,     -25.96902,     -26.00000,      10.00000,
G07:     0.00000000,      0.00000000,  13401573.3682,  -7200474.1176, -21540760.8839,        0.00000,        0.00000,     621.00000,       0.00000,       0.00000,       0.00000,
E02:     0.02293483,      0.42900277,  15980651.7247,  -9049448.9143, -23209902.1765,       16.94631,       17.00000,     140.00000,      85.93678,      86.00000,     113.00000,
E07:    -0.03940180,      0.69682870,  -2966553.5851, -17338901.9909, -23805250.0843,       22.07592,       22.00000,     326.00000,      77.11262,      77.00000,      30.00000,
E08:    -0.04375729,      0.13651073,  17299882.0472, -19413866.0356, -14133969.7731,       10.91316,       11.00000,     732.00000,      72.02685,      72.00000,      27.00000,
E18:    -0.01972334,      0.11139374,  15428265.5043, -11894421.5710,  14780880.4712,      -25.34548,        0.00000,      89.00000,       0.00000,       0.00000,       0.00000,
E27:    -0.02081883,     -0.48274290,  -3180056.1571, -28294981.1181,   8105045.1516,       21.90991,       22.00000,     192.00000,     112.68016,       0.00000,       0.00000,
E30:     0.02074874,      0.18587580,   8976439.0619, -26263732.7491, -10301952.4925,       10.92276,       11.00000,     448.00000,      89.90848,      90.00000,     350.00000,
E03:     0.00000000,      0.00000000,  27575843.2541, -10020471.2269,   3855179.8301,        0.00000,        0.00000,     808.00000,       0.00000,       0.00000,       0.00000,
```

5. ZTD_Clock.txt

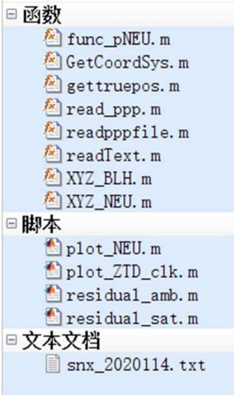
"***_ZTD_Clock**" file records epoch number, GPST, ZTD and receiver clock offsets.

bad_satellites.txt | position.txt | Satellite_info.ppp | ZTD_Clock.txt

epoch	Observation time	ZTD(m)	clk_G(m)	clk_C(m)	clk_R(m)	clk_E(m)
0:	2018-12- 3 0: 0: 0.0000000	1.4418	0.0000	0.0000	0.0000	0.0000
1:	2018-12- 3 0: 0:30.0000000	1.7503	0.0000	0.0000	0.0000	0.0000
2:	2018-12- 3 0: 1: 0.0000000	1.6777	0.0000	0.0000	0.0000	0.0000
3:	2018-12- 3 0: 1:30.0000000	1.6844	0.0000	0.0000	0.0000	0.0000
4:	2018-12- 3 0: 2: 0.0000000	1.6740	0.0000	0.0000	0.0000	0.0000
5:	2018-12- 3 0: 2:30.0000000	1.6812	0.0000	0.0000	0.0000	0.0000
6:	2018-12- 3 0: 3: 0.0000000	1.6967	0.0000	0.0000	0.0000	0.0000
7:	2018-12- 3 0: 3:30.0000000	1.6954	0.0000	0.0000	0.0000	0.0000
8:	2018-12- 3 0: 4: 0.0000000	1.7198	0.0000	0.0000	0.0000	0.0000

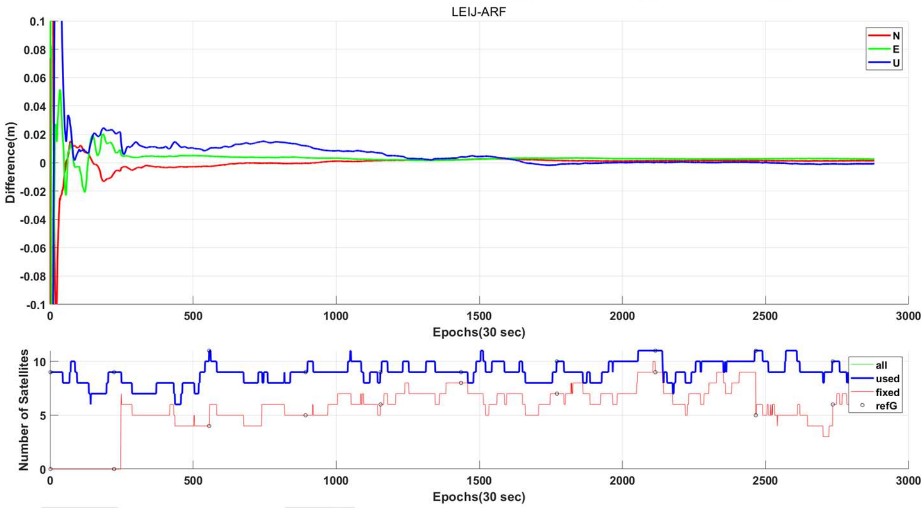
Plot and analysis

Some Matlab codes, which are used to plot and analyze the results, are put in "*...resources\plot_matlab*", as below:

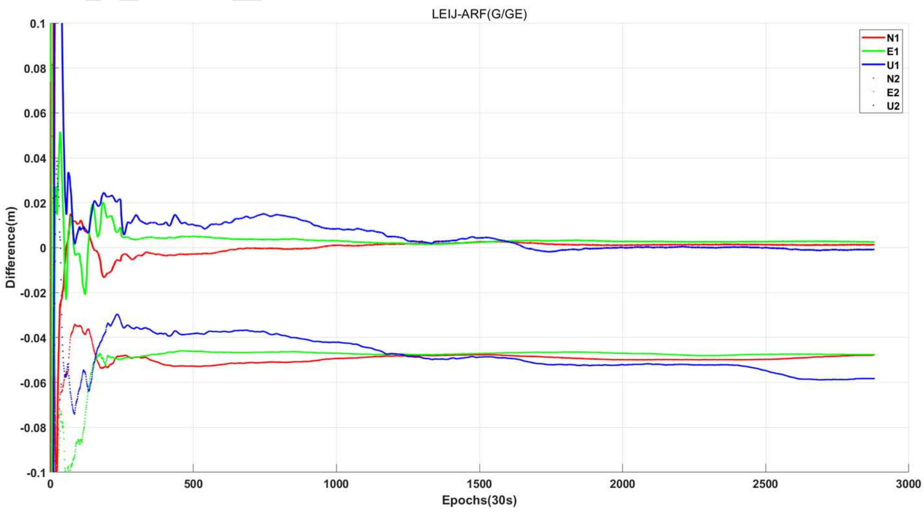


Examples:

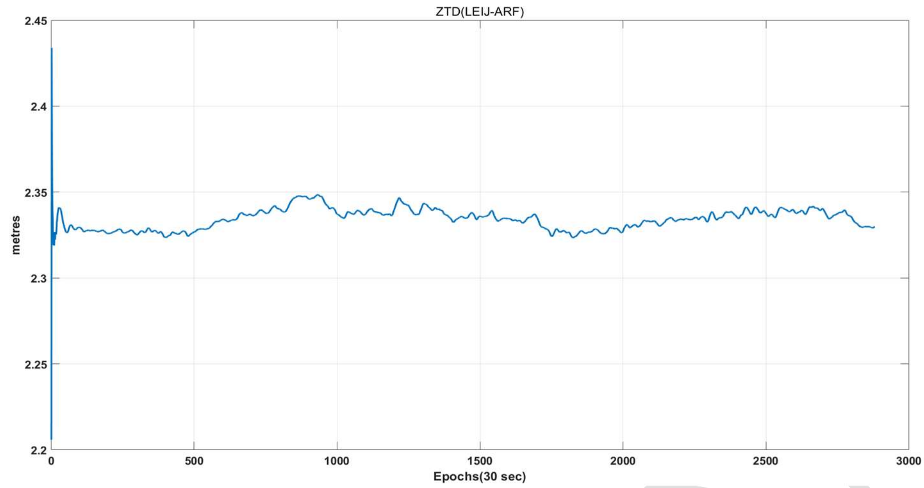
1. **Single station (plot_NEU.m)**



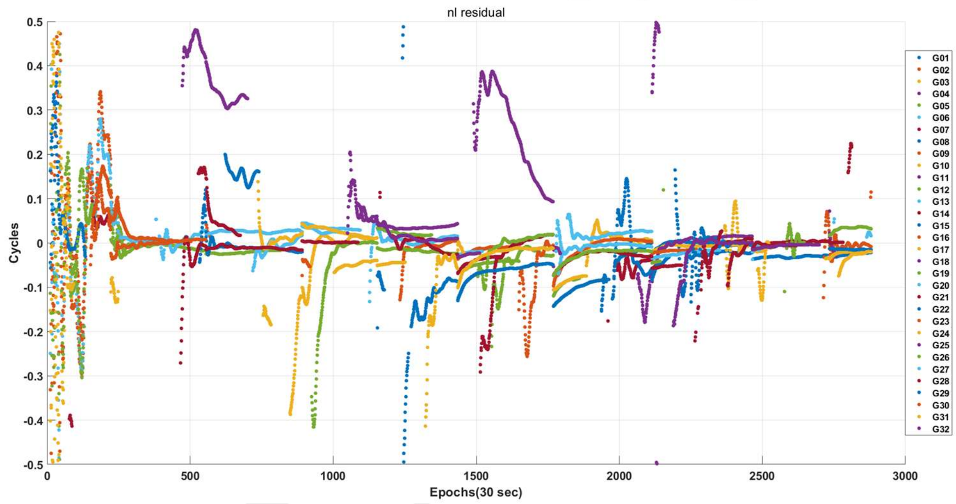
2. **Two stations (plot_NEU.m)**



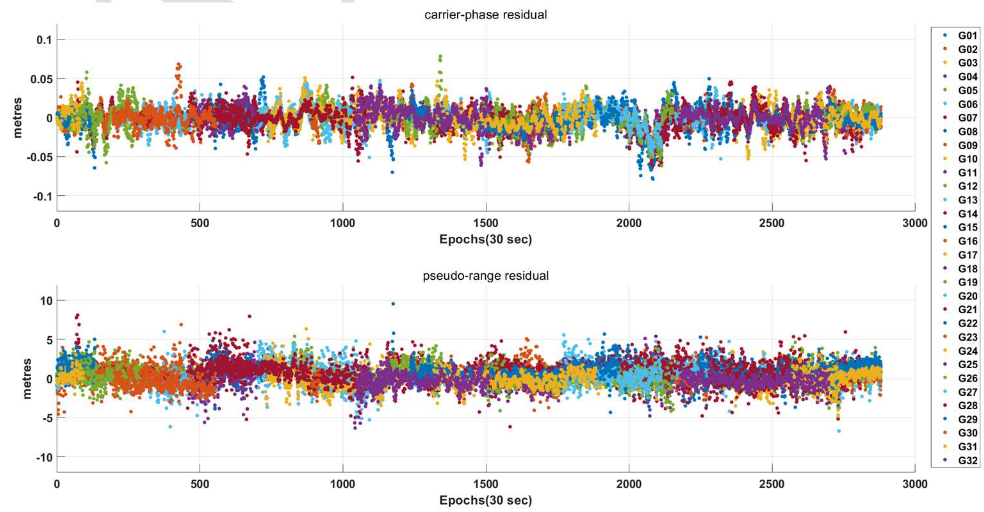
3. ZTD (plot_ZTD_clk.m)



4. Ambiguity residual (residual_amb.m)



5. Observation residual (residual_sat.m)



❖ Appendix

A. Strategies of PPP-ARISEN

Currently, PPP-ARISEN can use the Integer Phase Clock (IPC) products provided by CNES and CODE to fix the ambiguity of GPS and Galileo with dual-frequency GNSS observations (Laurichesse et al. 2009; Loyer et al. 2012; Katsigianni et al. 2019; Schaer et al. 2021).

The strategies and configuration parameter settings as well as the corresponding references of PPP-ARISEN are listed in Table 1. Except for the static and kinematic models, the "Seismological" model is designed, which provides some practical options and a user-friendly GUI for the high-rate GNSS.

Table 1 The main configuration parameters

Software	PPP-ARISEN
Model	Optional: Static, Kinematic, Seismological
Parameter estimator	Kalman filter
PPP strategy	Optional: IF, SSD(IF), ARI(SSD), ARF(SSD)
Precise products	PPP-AR: GRG/COD float PPP: IGS Final/Rapid products
GNSS relative weight	default: G:E = 1:1
GNSS measurement sigma	Adjustable (default: code: 3m, L: 3mm)
Elevation cut-off	Adjustable (default: 8°)
Elevation weight function	Optional (default: $\sigma^2 = a^2 + b^2 / \sin^2 E$)
Satellite and receiver antenna correction	igs14_2035.atx PCO: linear interpolation; PCV: bilinear interpolation
Tropospheric zenith hydrostatic delay	Optional: UNB3m, Hopfield (GPT2), Saastamoinen (GPT2, GPT3)
Tropospheric zenith wet delay	Random walk model (default: $3mm/\sqrt{h}$)
Tropospheric mapping function	Optional: GMF, NMF, VMF1, VMF3
Tide model	Solid Earth tide, ocean tide, pole tide (IERS conventions 2010)
Phase wind-up model	Wu et al. 1993

B. SSD observation model

Original GNSS observation equations are as equations (1) and (2):

$$p_{r,j}^{prn,s}=\rho_r^{prn,s}+c(dt_r-dt^{prn,s})+Mw_r^{prn,s}\cdot ZWD_r+\gamma_j^s\cdot I_{r,1}^s+c(CHD_{r,j}^{prn,s}-CHD_j^{prn,s})+\xi_{r,j}^{prn,s} \quad (1)$$

$$\begin{aligned}L_{r,j}^{prn,s}&=\lambda_j^{prn,s}\cdot\phi_{r,j}^{prn,s}\\&=\rho_r^{prn,s}+c(dt_r-dt^{prn,s})+Mw_r^{prn,s}\cdot ZWD_r-\gamma_j^s\cdot I_{r,1}^s+\lambda_j^{prn,s}N_{r,j}^{prn,s}+c(LHD_{r,j}^{prn,s}-LHD_j^{prn,s})+\zeta_{r,j}^{prn,s}\end{aligned} \quad (2)$$

where s indicates the GNSS index (G: GPS, R: GLONASS, C: BDS, E: Galileo); r and j are receiver number and frequency of navigation signal; $\rho_r^{prn,s}$ indicates the geometric distance between satellite antenna and receiver antenna (m); c is the speed of light (m/s); dt_r and $dt^{prn,s}$ indicate the clock offset of receiver and satellite (s); $Mw_r^{prn,s}$ and ZWD_r indicate the wet mapping function and the wet delay in the zenith direction of troposphere; γ_j^s is the frequency-dependent coefficient $(\gamma_j^s=(f_1^s)^2/(f_j^s)^2)$; $I_{r,1}^s$ is the ionospheric delay on frequency f_1^s (m); $\lambda_j^{prn,s}$ and $N_{r,j}^{prn,s}$ indicate the wavelength and ambiguity on frequency f_j^s; $CHD_{r,j}^{prn,s}$ and $CHD_j^{prn,s}$ are the frequency-dependent code hardware delay of receiver and satellite (s); $LHD_{r,j}^{prn,s}$ and $LHD_j^{prn,s}$ are the frequency-dependent phase hardware delays of receiver and satellite (s); $\xi_{r,j}^{prn,s}$ and $\zeta_{r,j}^{prn,s}$ indicate the observation noise of code and phase.

In order to eliminate the influence of ionosphere (first-order), the ionosphere free combination (IF) will be carried out. Take the dual-frequency GPS (L_1/L_2) signal as an example:

$$\alpha_{12}^G=\frac{f_1^2}{f_1^2-f_2^2} \quad (3) \qquad\qquad \beta_{12}^G=-\frac{f_2^2}{f_1^2-f_2^2} \quad (4)$$

$$p_{IF}^{prn,G}=\alpha_{12}^G p_1^{prn,G}+\beta_{12}^G p_2^{prn,G}=\rho_r^{prn,G}+c(dt_r-dt^{prn,G})+Mw_r^{prn,G}\cdot ZWD_r+c(CHD_{r,IF}^{prn,G}-CHD_{IF}^{prn,G})+\xi_{r,IF}^{prn,G} \quad (5)$$

$$\begin{aligned}L_{IF}^{prn,G}&=\alpha_{12}^G L_1^{prn,G}+\beta_{12}^G L_2^{prn,G}\\&=\rho_r^{prn,G}+c(dt_r-dt^{prn,G})+Mw_r^{prn,G}\cdot ZWD_r+\lambda_{IF}^{prn,G}N_{r,IF}^{prn,G}+c(LHD_{r,IF}^{prn,G}-LHD_{IF}^{prn,G})+\zeta_{r,IF}^{prn,G}\end{aligned} \quad (6)$$

For convenience, four types of clock offsets, that include hardware delays, are listed here: the pseudorange clock offset of receiver (7), the phase clock offset of receiver (8), the pseudorange clock offset of satellite (9), and the phase clock offset of satellite (10):

$$dt_{r,P_{IF}} = dt_r + CHD_{r,IF}^{prn,G} \quad (7) \qquad dt_{r,L_{IF}} = dt_r + LHD_{r,IF}^{prn,G} \quad (8)$$

$$dt_{P_{IF}} = dt^{prn,G} + CHD_{IF}^{prn,G} \quad (9) \qquad dt_{L_{IF}} = dt^{prn,G} + LHD_{IF}^{prn,G} \quad (10)$$

Generally speaking, the clock offset products provided by IGS are pseudorange based clock offset (9) products. When processing float PPP, the pseudorange based satellite clock offset products are directly applied to the pseudorange and carrier equations, while only the pseudorange clock offset of receiver (7) is estimated:

$$p_{IF}^{prn,G} = \alpha_{12}^{G} p_1^{prn,G} + \beta_{12}^{G} p_2^{prn,G} = \rho_r^{prn,G} + c(dt_{r,P_{IF}} - dt_{P_{IF}}^{prn,G}) + Mw_r^{prn,G} \cdot ZWD_r + \xi_{r,IF}^{prn,G} \quad (11)$$

$$\begin{aligned} L_{IF}^{prn,G} &= \alpha_{12}^{G} L_1^{prn,G} + \beta_{12}^{G} L_2^{prn,G} \\ &= \rho_r^{prn,G} + c(dt_{r,P_{IF}} - dt_{P_{IF}}^{prn,G}) + Mw_r^{prn,G} \cdot ZWD_r + \lambda_{IF}^{prn,G} N_{r,IF}^{prn,G} + c(LHD_{r,IF}^{prn,G} - CHD_{r,IF}^{prn,G}) - c(LHD_{IF}^{prn,G} - CHD_{IF}^{prn,G}) + \zeta_{r,IF}^{prn,G} \end{aligned} \quad (12)$$

Affected by $c(LHD_{r,IF}^{prn,G} - CHD_{r,IF}^{prn,G}) - c(LHD_{IF}^{prn,G} - CHD_{IF}^{prn,G})$, the phase ambiguity in IF combination is float and no longer integer.

The idea of IPC method is to distinguish between the pseudorange clock offset and the phase clock offset of receiver, so as to recover the ambiguity to integer (Laurichesse et al. 2009):

$$p_{IF}^{prn,G} = \alpha_{12}^{G} p_1^{prn,G} + \beta_{12}^{G} p_2^{prn,G} = \rho_r^{prn,G} + c(dt_{r,P_{IF}} - dt_{P_{IF}}^{prn,G}) + Mw_r^{prn,G} \cdot ZWD_r + \xi_{r,IF}^{prn,G} \quad (13)$$

$$L_{IF}^{prn,G} = \alpha_{12}^{G} L_1^{prn,G} + \beta_{12}^{G} L_2^{prn,G} = \rho_r^{prn,G} + c(dt_{r,L_{IF}} - dt_{L_{IF}}^{prn,G}) + Mw_r^{prn,G} \cdot ZWD_r + \lambda_{IF}^{prn,G} N_{r,IF}^{prn,G} + \zeta_{r,IF}^{prn,G} \quad (14)$$

Although this process can recover the ambiguity to integer, but it is necessary to estimate the clock offsets of (7) and (8) at the same time. Satellite-to-satellite Single Difference (SSD) method can eliminate the clock offsets of receiver (Liu et al. 2016), thereby simplifying the observation model. The SSD equations (15) and (16) can be obtained by subtracting (13) and (14) between satellites, and equations (17) and (18) can be sorted out:

$$p_{IF}^{nm,G} = p_{IF}^{m,G} - p_{IF}^{n,G} = \rho_r^{m,G} - \rho_r^{n,G} - c(dt_{P_{IF}}^{m,G} - dt_{P_{IF}}^{n,G}) + Mw_r^{m,G} \cdot ZWD_r - Mw_r^{n,G} \cdot ZWD_r + \xi_{r,IF}^{m,G} - \xi_{r,IF}^{n,G} \quad (15)$$

$$\begin{aligned} L_{IF}^{nm,G} &= L_{IF}^{m,G} - L_{IF}^{n,G} \\ &= \rho_r^{m,G} - \rho_r^{n,G} - c(dt_{L_{IF}}^{m,G} - dt_{L_{IF}}^{n,G}) + Mw_r^{m,G} \cdot ZWD_r - Mw_r^{n,G} \cdot ZWD_r + \lambda_{IF}^{m,G} N_{r,IF}^{m,G} - \lambda_{IF}^{n,G} N_{r,IF}^{n,G} + \xi_{r,IF}^{m,G} - \xi_{r,IF}^{n,G} \end{aligned} \quad (16)$$

$$p_{IF}^{nm,G} = p_{IF}^{m,G} - p_{IF}^{n,G} = \rho_r^{nm,G} - cdt_{P_{IF}}^{nm,G} + Mw_r^{nm,G} \cdot ZWD_r + \xi_{r,IF}^{nm,G} \quad (17)$$

$$L_{IF}^{nm,G} = L_{IF}^{m,G} - L_{IF}^{n,G} = \rho_r^{nm,G} - cdt_{L_{IF}}^{nm,G} + Mw_r^{nm,G} \cdot ZWD_r + \lambda_{IF}^{nm,G} N_{r,IF}^{nm,G} + \xi_{r,IF}^{nm,G} \quad (18)$$

SSD observation model could be obtained from IF observation model. Taking GPS-only as an example, the observation equation of IF is shown in (19) (the receiver clock offset will be eliminated, so it is not listed here), and the variance of the observation value is shown in (20):

$$\underbrace{\begin{pmatrix} e_x^1 & e_y^1 & e_z^1 & Mw^1 & 1 & 0 & 0 & 0 \\ e_x^2 & e_y^2 & e_z^2 & Mw^2 & 0 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_x^n & e_y^n & e_z^n & Mw^n & 0 & 0 & 0 & 1 \\ e_x^1 & e_y^1 & e_z^1 & Mw^1 & 0 & 0 & 0 & 0 \\ e_x^2 & e_y^2 & e_z^2 & Mw^2 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_x^n & e_y^n & e_z^n & Mw^n & 0 & 0 & 0 & 0 \end{pmatrix}_{2n\times(4+n)}}_{B'_{IF}}, \underbrace{\begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ T_w \\ N_{IF}^1 \\ N_{IF}^2 \\ \vdots \\ N_{IF}^n \end{pmatrix}_{(4+n)\times 1}}_{X_{IF}}, \underbrace{\begin{pmatrix} \rho_0^1 - L_{IF}^1 \\ \rho_0^2 - L_{IF}^2 \\ \vdots \\ \rho_0^n - L_{IF}^n \\ \rho_0^1 - P_{IF}^1 \\ \rho_0^2 - P_{IF}^2 \\ \vdots \\ \rho_0^n - P_{IF}^n \end{pmatrix}_{2n\times 1}}_{L_{IF}} \quad (19)$$

$$Q_{IF} = \begin{pmatrix} q_{L^1} & & & & & & & \\ & q_{L^2} & & & & & & \\ & & \ddots & & & & & \\ & & & q_{L^n} & & & & \\ & & & & q_{P^1} & & & \\ & & & & & q_{P^2} & & \\ & & & & & & \ddots & \\ & & & & & & & q_{P^n} \end{pmatrix}_{2n\times 2n} \quad (20)$$

Take the first satellite as the reference satellite as an example: the SSD observation model (21) can be obtained by the rule (23); the variance of the SSD (22) can be obtained by the rule (24); in particular, the form of the SSD ambiguity is shown in (25):

$$\underbrace{\begin{pmatrix} e_x^{12} & e_y^{12} & e_z^{12} & Mw^{12} & 1 & 0 & 0 & 0 \\ e_x^{13} & e_y^{13} & e_z^{13} & Mw^{13} & 0 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_x^{1n} & e_y^{1n} & e_z^{1n} & Mw^{1n} & 0 & 0 & 0 & 1 \\ e_x^{12} & e_y^{12} & e_z^{12} & Mw^{1} & 0 & 0 & 0 & 0 \\ e_x^{13} & e_y^{13} & e_z^{13} & Mw^{2} & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ e_x^{1n} & e_y^{1n} & e_z^{1n} & Mw^{1n} & 0 & 0 & 0 & 0 \end{pmatrix}_{2(n-1)\times(4+n-1)}}_{B_{SSD}}, \underbrace{\begin{pmatrix} \delta x \\ \delta y \\ \delta z \\ T_w \\ N_{IF}^{12} \\ N_{IF}^{13} \\ \vdots \\ N_{IF}^{1n} \end{pmatrix}_{(4+n-1)\times 1}}_{X_{SSD}}, \underbrace{\begin{pmatrix} (\rho_0 - L_{IF})^{12} \\ (\rho_0 - L_{IF})^{13} \\ \vdots \\ (\rho_0 - L_{IF})^{1n} \\ (\rho_0 - P_{IF})^{12} \\ (\rho_0 - P_{IF})^{13} \\ \vdots \\ (\rho_0 - P_{IF})^{1n} \end{pmatrix}_{2(n-1)\times 1}}_{L_{SSD}} \quad (21)$$

$$Q_{SSD}=\begin{pmatrix} q_{L^{12}} & & & & & & & \\ & q_{L^{13}} & & & & & & \\ & & \ddots & & & & & \\ & & & q_{L^{1n}} & & & & \\ & & & & q_{P^{12}} & & & \\ & & & & & q_{P^{13}} & & \\ & & & & & & \ddots & \\ & & & & & & & q_{P^{1n}} \end{pmatrix}_{2(n-1)\times 2(n-1)} \quad (22)$$

$$E^{nm}=E^{m}-E^{n} \quad (23)$$

$$E^{nm}=E^{m}+E^{n} \quad (24)$$

$$N_{IF}^{nm}=N_{IF}^{m}-N_{IF}^{n}=\alpha_{12}^{G}\lambda_{1}^{G}N_{1}^{nm}+\beta_{12}^{G}\lambda_{2}^{G}N_{2}^{nm}=\lambda_{NL}^{G}N_{1}^{nm}+cf_{2}/(f_{1}^{2}-f_{2}^{2})\cdot N_{WL}^{nm} \quad (25)$$

C. PPP-AR with IPC method

With dual-frequency GNSS observations, the strategy of PPP-AR is shown in Fig. 1. According to formula (25), SSD ambiguity is decomposed into N_{WL}^{nm} and N_{NL}^{nm}.

First, calculating integer WL Ambiguities of SSD (WLA-SSD) by rounding the smoothed float WLA-SSDs, which are obtained from Hatch–Melbourne–Wübbena (HMW) combination, to the nearest integer value under the help of PPP-AR products of CNES or CODE.

The float WL ambiguity N_{WL} shown in (27) is decomposed by the Hatch–Melbourne–Wübbena (HMW) combination in (26) ($B_{r,HMW}$ and B_{HMW} are the WL biases of receiver and satellite respectively. $B_{r,HMW}$ is eliminated by SSD; B_{HMW} is corrected by bias products); Because the pseudorange observation noise is large, in order to obtain a more reliable N_{WL}, it needs to be smoothed by arc, as shown in (28) to obtain $\bar{N}_{WL}$; then in the SSD observation model, the single difference between $\bar{N}_{WL}$ is required to obtain $\bar{N}_{WL}^{nm}$, which is rounded to the nearest integer value.

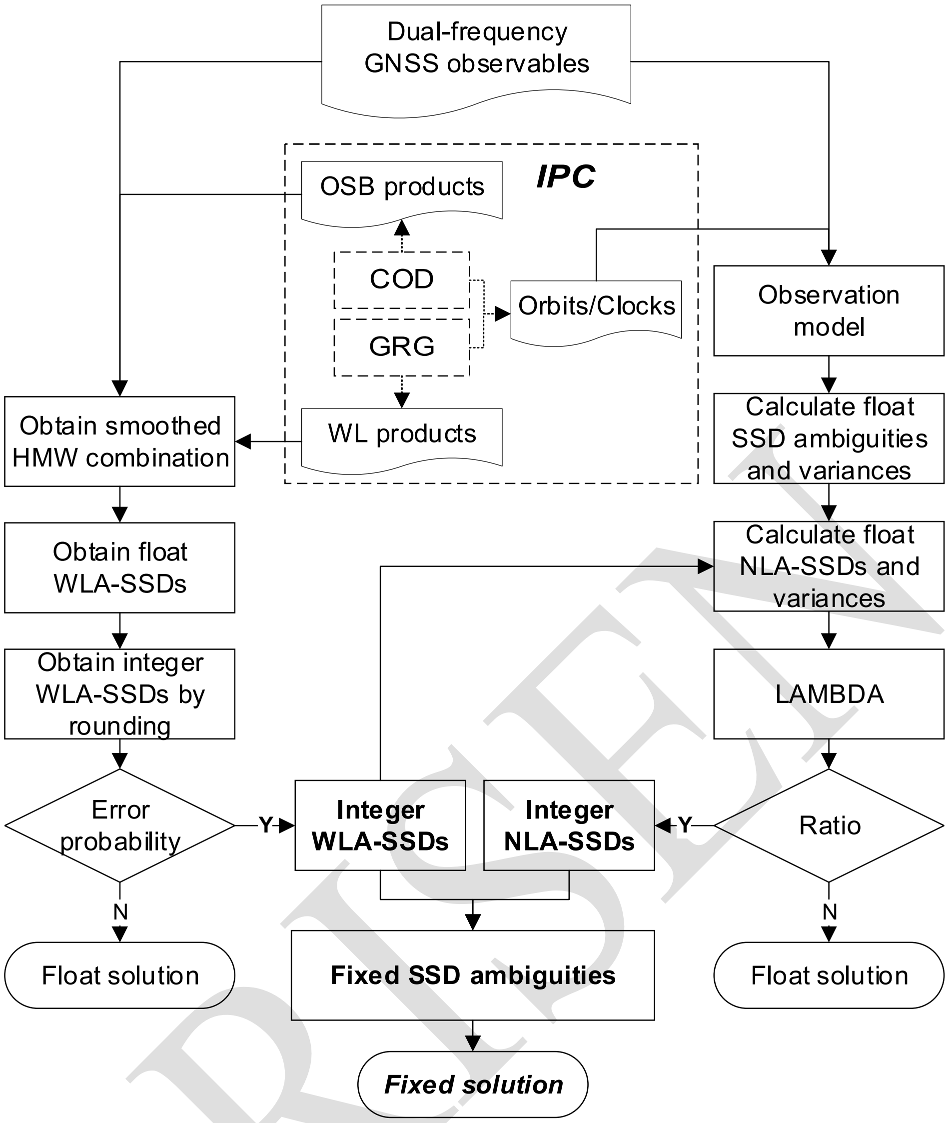


Fig.1 PPP-AR flowchart of PPP-ARISEN.

$$
\begin{aligned}
L_{HMW} &= \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} - \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} \\
&= \frac{c}{f_1 - f_2}(N_1 - N_2) + B_{r,HMW} - B_{HMW} + \varepsilon_{HMW} = \lambda_{WL} N_{WL} + B_{r,HMW} - B_{HMW} + \varepsilon_{HMW}
\end{aligned} \tag{26}
$$

$$N_{WL} = L_{HMW} / \lambda_{WL} + B_{r,HMW} / \lambda_{WL} - B_{HMW} / \lambda_{NL} + \varepsilon_{HMW} / \lambda_{WL} \quad (27)$$

$$\bar{N}_{WL}(i) = \bar{N}_{WL}(i-1) + \frac{1}{i}[N_{WL} - \bar{N}_{WL}(i-1)] \quad (28)$$

$$\bar{N}_{WL}^{nm} = \bar{N}_{WL}^{m} - \bar{N}_{WL}^{n} \quad (29)$$

Second, getting integer NL Ambiguities of SSD (NLA-SSD) with LAMBDA method from float NLA-SSDs, which can be decomposed form float SSD ambiguities and integer WLA-SSDs in (30) and (31).

$$N_1^{nm} = (\lambda_{IF} N_{IF}^{nm} - \frac{cf_2}{f_1^2 - f_2^2} \hat{N}_{WL}^{nm}) / \lambda_{NL} \quad (30)$$

$$Q_{N_1^{nm}} = (\lambda_{IF} / \lambda_{NL})^2 Q_{N_{IF}^{nm}} \quad (31)$$

Third, obtaining fixed SSD ambiguities according to the relationship between SSD ambiguities and WLA-/NLA-SSDs in (25). Then, the fixed SSD ambiguities are put into the estimator as high-precise observations to constrain the parameter estimation process with higher weighting.

However, in some cases, such as large observation noises or bad Geometric Dilution Of Precision (GDOP), it is difficult to achieve Full Ambiguity Resolution in PPP-AR. With ideas similar to the Partial Ambiguity Resolution in double-difference ambiguity resolution processing of Wang and Feng (2013), PPP-ARISEN makes full use of the covariance information decorrelated form variance matrix. And the following NLA-SSDs search method has been designed in PPP-ARISEN:

(1) Decorrelating the variances of float NLA-SSDs and obtaining an ascending sequence of decorrelated variances;

(2) Adjusting the float NLA-SSDs and their corresponding variances according to the sequence in step (1) to get the reassembled float NLA-SSDs queue and their variance matrix;

(3) Obtaining integer NLA-SSDs from reassembled float NLA-SSDs queue and their variance matrix in step (2) with LAMBDA method.

Compared with the original method, the modifications occur at the third step. As shown in Fig.2, an iterative search method is performed to obtain as many integer NLA-SSDs as possible. First of all, we try to identify all the integer candidates of NLA-SSDs with the LAMBDA method. Then, if the Ratio test fails, the component in the tail of the ascending sequence, which is the float NLA-SSD candidate with the largest variance, is deleted as well as its variance. Finally, the iteration renews until the ratio test succeeds or the iteration fails when the number of float NLA-SSDs is less than 2.

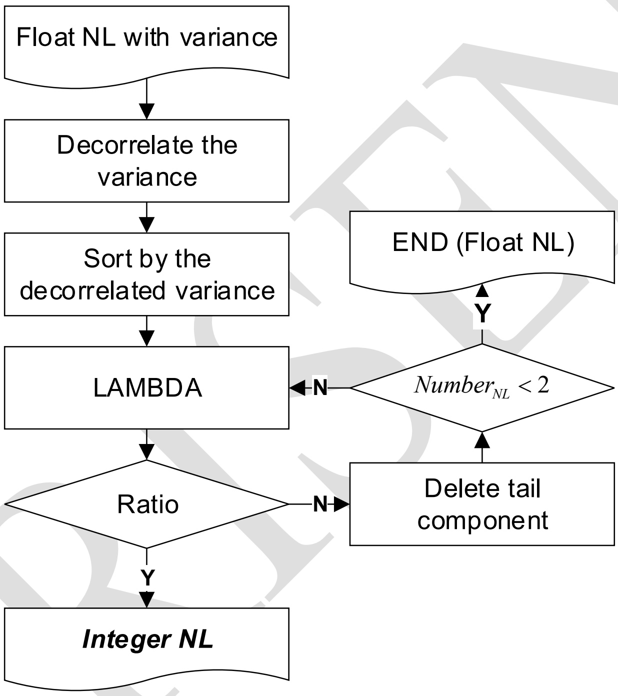


Fig.2 Process of partial ambiguity resolution in PPP-ARISEN.

D. CSI-ZWDV

In the process of PPP-AR, LAMBDA method is widely used for obtaining integer NL ambiguity, but its potential larger priori error and poor precision of float ambiguity solution could lead to failure of the NL fixing (Loyer et al. 2012; Verhagen et al. 2012). Therefore, it is crucial for PPP-AR when to implement the LAMBDA method to search for the correct integer solution (Fig.3).

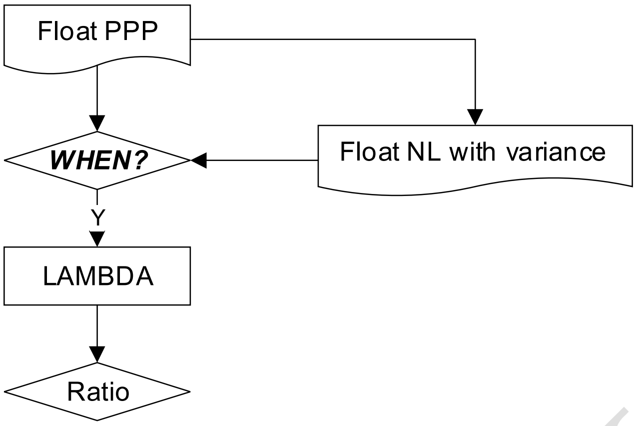


Fig.3 When to search integer NL ambiguity with LAMBDA method?

As shown in Fig.4, variance matrix of estimated parameters can be divided into 3 parts according to the characteristics in SSD strategy, i.e., the coordinates (POS, 3×3), the zenith wet delay of troposphere (ZWD, 1×1) and the ambiguities (AMB, (n-m)×(n-m)), where *n* denotes the satellite number used for positioning, and *m* is the reference satellites number in SSD strategy. In PPP-ARISEN, one reference satellite is selected for each system).

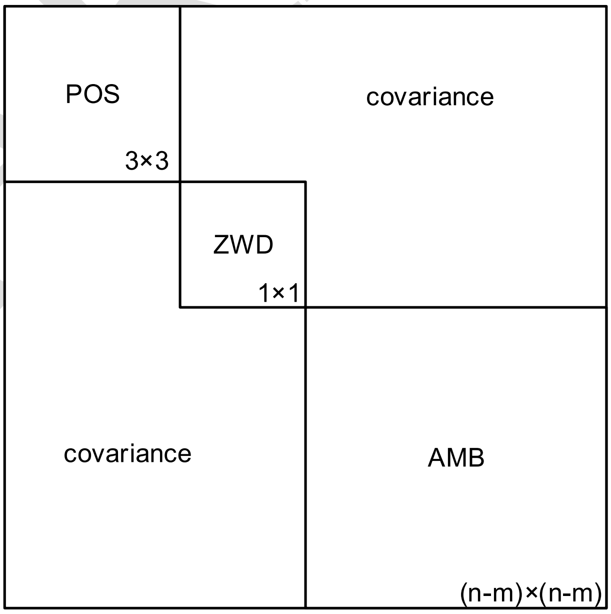


Fig.4 Variance matrix of estimated parameters in SSD PPP.

When the variance of POS or AMB is used as an indicator to implement the LAMBDA method, the covariance matrix usually is ignored. The POS is often affected by the motion state of the receiver as well as the data quality, and the AMB often is influenced by the changes of satellites in view, especially the rising and re-locked satellites. They are both multiple parameter subsets, and are potentially coupled with each other or among components in the subset itself. Meanwhile, as a single parameter with definite physical meaning, ZWD is a relatively “independent” of slow changing parameter, which is often modeled by a random walk stochastic process in the entire filtering process. If the AMB or POS deviate the true values in the initial or re-initial process, the other parameter subsets are destined to be disturbed. So, they can't remain steady and the estimated parameters should fluctuate. Conversely, if the AMB and the POS are estimated accurately with tolerable biases or without biases, the estimated ZWD should have decoupled with the other parameters to a great extent and shows its slow changing nature. Therefore, based on the theoretical and logical deduction above, ZWD variances can be chosen as a reference to determine when to start the LAMBDA algorithm to search for integer NL-SSDs.

In order to verify the assumption above, the records from 191 IGS stations are processed with GRG products in SSD float PPP (tagged SSD), in which ZWDs and corresponding variances of each station are extracted. To analyze their characteristics, the GNSS data are processed in batches with four modes, i.e., static and kinematic with GPS-only record (S-G/K-G) as well as double-system GPS/Galileo record (S-GE/K-GE).

As shown in the Fig.5, all the variances curves are nearly the same except slightly larger amplitude of the vibration in the kinematic cases and shorter convergence time for case with GPS/Galileo (GE) record. But for each of the ZWD variance curve, there must be an Inflection Point (IP) appeared after a distinct reduction of monotony at the beginning piece (e.g. points in red circles shown in Fig.6), after which the change-rate of ZWD variances becomes moderate and the ZWD variance curve shows random state with millimeter-level vibrations in the range of power density of stochastic process used to model the ZWD (experimentally set to $3mm/\sqrt{\mathrm{h}}$). Therefore, if the IPs could be adopted as a time indicator of starting to search the NL ambiguity with LAMBDA method, compared with experiential criteria or hard threshold, the criterion based on IPs is not only physically meaningful, but also more flexible to deal with the data of various qualities and observation environments.

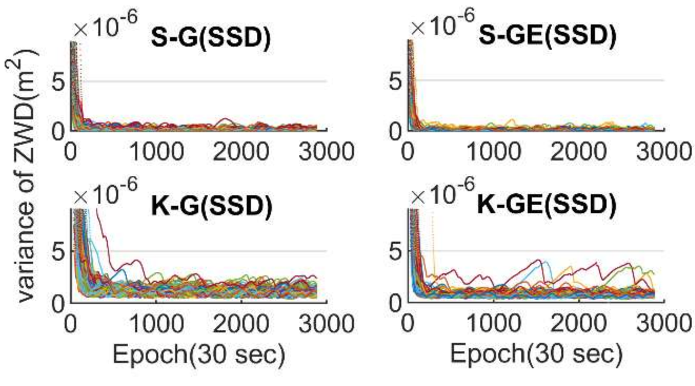


Fig.5 Variances of ZWD of SSD float PPP in 4 modes with 191 IGS stations (DOY: 114/2020).

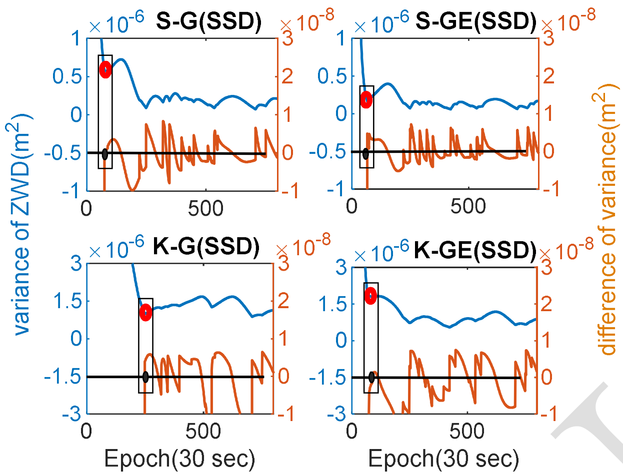


Fig.6 Variance (blue) and its epoch-difference curves (red) of ZWD in 4 modes of SSD float PPP at CCJ2 (DOY: 114/2020). The left y-axis is the variance curve of ZWD, and the right y-axis is the epoch-differenced variance.

Table 2 3D error (m) and FD (minute) at IPs in SSD float PPP

		1-δ		3-δ	
		3D error (STD)	**FD (STD)**	**3D error (STD)**	**FD (STD)**
S-G	**1st IP**	0.050 (0.025)	55.928 (25.951)	0.079 (0.056)	102.720 (48.563)
	2nd IP	0.037 (0.017)	70.874 (28.142)	0.059 (0.043)	129.783 (56.324)
	3rd IP	0.030 (0.014)	94.920 (34.182)	0.047 (0.031)	175.245 (71.482)
S-GE	**1st IP**	0.039 (0.016)	45.221 (19.079)	0.064 (0.051)	84.572 (35.303)
	2nd IP	0.033 (0.016)	53.027 (21.043)	0.056 (0.049)	98.995 (38.822)
	3rd IP	0.027 (0.011)	73.786 (27.554)	0.044 (0.038)	137.622 (51.016)
K-G	**1st IP**	0.052 (0.036)	105.294 (30.394)	0.067 (0.047)	204.481 (61.642)
	2nd IP	0.045 (0.030)	124.821 (36.392)	0.063 (0.051)	243.887 (73.993)
	3rd IP	0.033 (0.015)	147.729 (36.204)	0.050 (0.034)	295.544 (73.943)
K-GE	**1st IP**	0.031 (0.019)	82.557 (26.479)	0.040 (0.026)	165.273 (53.077)
	2nd IP	0.028 (0.014)	97.557 (32.355)	0.038 (0.026)	195.723 (65.349)
	3rd IP	0.024 (0.010)	120.412 (34.417)	0.037 (0.028)	237.738 (70.894)

Besides, 1δ/3δ-value coordinate 3D errors (refer to IGS weekly SINEX results) and the Filtering Duration (FD) at different IPs are listed in Table 2. As shown in the statistical results, both of the static and kinematic cases, 3D errors with GE record are smaller than that in GPS-only at the same IP, and the FD is also shorter. And the 3D errors at first IP are smaller than 8 centimeters with few centimeter standard deviation in all the test, which means that the accuracy at most stations reaches centimeter-level at the first IP. To investigate the performance of IPs without SSD, the same records are also processed in the IF float PPP (tagged IF) with GRG products, and the results (Fig.7 and Table 3) show the similar characteristics to case of the PPP with SSD strategy, which means that the estimation of receiver clock offset with other parameters simultaneously has no significant influence on the performance of IPs. Hence indicators based on IPs also could be suggested as a general and useful reference index to flexibly represent the convergence status and reasonably quantify the convergence time, especially for the station without any apriori information, kinematic positioning or re-initialization.

In PPP-ARISEN, the epoch-differenced series of ZWD variances (e.g. red lines in Fig.6) are used to detect the corresponding IPs, where the sign of values is opposite with respect to the adjacent previous one (e.g. the first IP of CCJ2 station shown as black points in Fig.6). In practice, large amount of the IPs could be obtained but only the ones in the front are useful for our research. Here we name the IPs as the PPP Convergence Status Indicator based on ZWD Variances (CSI-ZWDV) under the processing strategy that the ZWD is estimated as a random walk unknown in a filtering estimator. The proposed index CSI-ZWDV is successfully applied to the PPP-ARISEN toolbox with the **second** IP in static mode and the **third** IP in kinematic mode as default for robust instead of rapid integer ambiguity resolution.

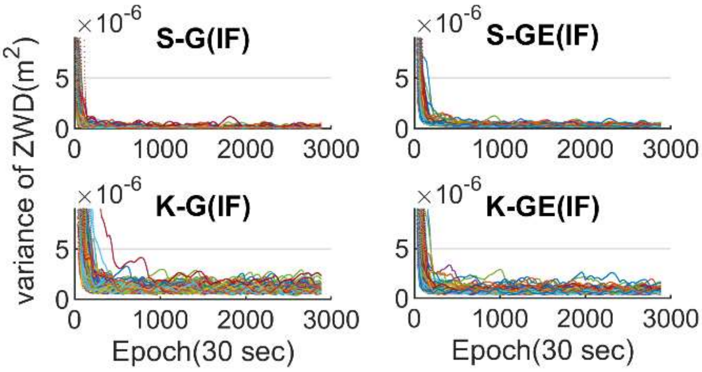


Fig.7 Variances of ZWD of float PPP without SSD in 4 modes with 191 IGS stations (DOY: 114/2020).

Table 3 3D error (m) and FD (minute) at IPs in float PPP without SSD

		1-δ		3-δ	
		3D error (STD)	**FD (STD)**	**3D error (STD)**	**FD (STD)**
S-G	**1st IP**	0.046 (0.023)	55.645 (26.611)	0.076 (0.057)	102.581 (48.671)
	2nd IP	0.035 (0.016)	70.187 (29.005)	0.057 (0.042)	129.973 (56.418)
	3rd IP	0.029 (0.014)	96.309 (37.092)	0.045 (0.030)	176.039 (71.461)
S-GE	**1st IP**	0.018 (0.007)	80.611 (22.733)	0.025 (0.014)	159.536 (47.623)
	2nd IP	0.016 (0.006)	90.695 (24.177)	0.023 (0.013)	177.238 (49.888)
	3rd IP	0.015 (0.006)	115.290 (28.877)	0.022 (0.013)	227.462 (59.546)
K-G	**1st IP**	0.040 (0.019)	109.637 (30.215)	0.064 (0.047)	206.685 (62.130)
	2nd IP	0.036 (0.016)	130.122 (36.476)	0.062 (0.053)	247.107 (73.097)
	3rd IP	0.031 (0.013)	156.122 (35.645)	0.048 (0.038)	304.763 (72.109)
K-GE	**1st IP**	0.026 (0.012)	85.458 (27.280)	0.039 (0.025)	170.294 (54.466)
	2nd IP	0.025 (0.010)	99.989 (29.668)	0.035 (0.020)	199.473 (67.340)
	3rd IP	0.024 (0.009)	125.645 (37.196)	0.034 (0.018)	243.059 (73.619)

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❖ Contact us

We sincerely hope that all users can put forward opinions and suggestions to improve the software, and even some specific requirements for your research. You are welcome to contact us and discuss on any technical details.

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