GREAT-PVT Users Guide

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1 Overview

GREAT (GNSS+ Research, Application, and Teaching) software, developed by the School of Geodesy and Geomatics at Wuhan University, is a comprehensive software platform designed for geodetic data processing, precise positioning, orbit determination, and multi-source integrated navigation. The core computational modules of the software are implemented in C++ (C++17), while auxiliary scripting modules utilize Python3 and C-Shell to automate data processing. All C++ modules adhere to the Google Open Source Project Style Guide and are managed using GIT for version control. The software employs CMake for build management, allowing users to flexibly choose mainstream C++ compilers such as GCC, Clang, and MSVC. Currently, GREAT provides command-line applications for both Windows and Linux platforms.

GREAT-PVT is a key module within the GREAT software, primarily dedicated to precise positioning solutions. It consists of two portable libraries: LibGREAT and LibGnut. The LibGREAT library focuses on PPP and RTK filtering solutions, including data decoding, storage, and the implementation of algorithms for PPP, PPP-AR, and RTK. The LibGnut library, derived from the open-source GNSS software G-nut, handles GNSS data decoding, storage, and basic parameter configuration. The main features of GREAT-PVT include:

(1) It supports GPS, GLONASS, Galileo, and BDS-2/3 systems.

(2) It supports multi-frequency PPP and PPP-AR.

(3) It supports ionosphere-free (IF) and uncombined (UC) PPP combination models.

(4) It supports dual-frequency and mixed-frequency RTK solutions.

In addition, the software package provides batch processing scripts and plotting tools for positioning results, facilitating the computation and analysis of multi-day data for users.

2 Environmental Requirements and License

2.1 Environmental Requirements

The executable CUI AP for Windows in the package was built by VS (Microsoft Visual Studio) 2022 on Windows 11 (64bit). All of the necessary dynamic link libraries are involved in the folder. Moreover, the CUI AP and shared libraries for Linux were built and tested on CentOS Linux release 7.7.1908 and x64 CPU.

Also, the users can use the open-source, cross-platform compilation tool CMake to build executable binary AP on their own operating systems.

2.2 License

GREAT-PVT is an open-source software, which is governed by the GNU General Public License (version 3) (https://www.gnu.org/licenses/gpl-3.0.html).

3 Compile and Installation

The software package can be accessed via the website (https://geodesy.noaa.gov/gps-toolbox). Extract the program package **GREAT-PVT_<ver>.zip** to appropriate directory **<install_dir>** (**<ver>** indicates the version number). The GREAT-PVT directory structure is as follows.

GREAT-PVT_<ver>	
./bin	The executable binary APs for Windows/Linux *
./src	Source programs of GREAT-PVT software *
./app	Main function of GREAT-PVT *
./LibGREAT	Source programs of PPP and RTK Processing *
./LibGnut	Source programs of the G-Nut library *
./third-party	Third-party libraries
./sample_data	Sample data for AP *
./PPPFLT_2023305	Sample data for PPP *
./RTKFLT_2020351	Sample data for RTK *
./util	Utilities *
./batch_process	Batch processing python scripts for PPP *
./ plot	Plotting scripts *
./ poleut1	Earth Orientation Parameters (EOP) Generation Program *
./doc	Document files *
./GREAT_PPP.xml	Sample XML files for PPP *
./GREAT_PPP.xml	Sample XML files for RTK *
GREAT-PVT_<ver>.pdf	User manual

3.1 Windows

You can use the existing programs in the folder **<install_dir>/GREAT-PVT_<ver>/bin/Windows**, or compile an executable program by yourself. The following instructions show how to build GREAT-PVT on Windows.

(1) Get CMake via the website (https://cmake.org/download/) and install it. Note that the minimum requirement of CMake version is 3.0.0.

(2) Execute the cmake-gui.

(3) Execute "Browse Source..." to select the folder **<install_dir>/GREAT-PVT_<ver>/src**, or you can drag CMakeList.txt in the directory **<install_dir>/GREAT-PVT_<ver>/src** to the interface of CMake-gui. Then modify attribute "Where to build the binaries" as **<install_dir>/GREAT-PVT_<ver>/src/build**.

(4) Execute "Configure" and choose the Integrated Development Environment (IDE) for the project (appears only the first time you click "Configure" button).

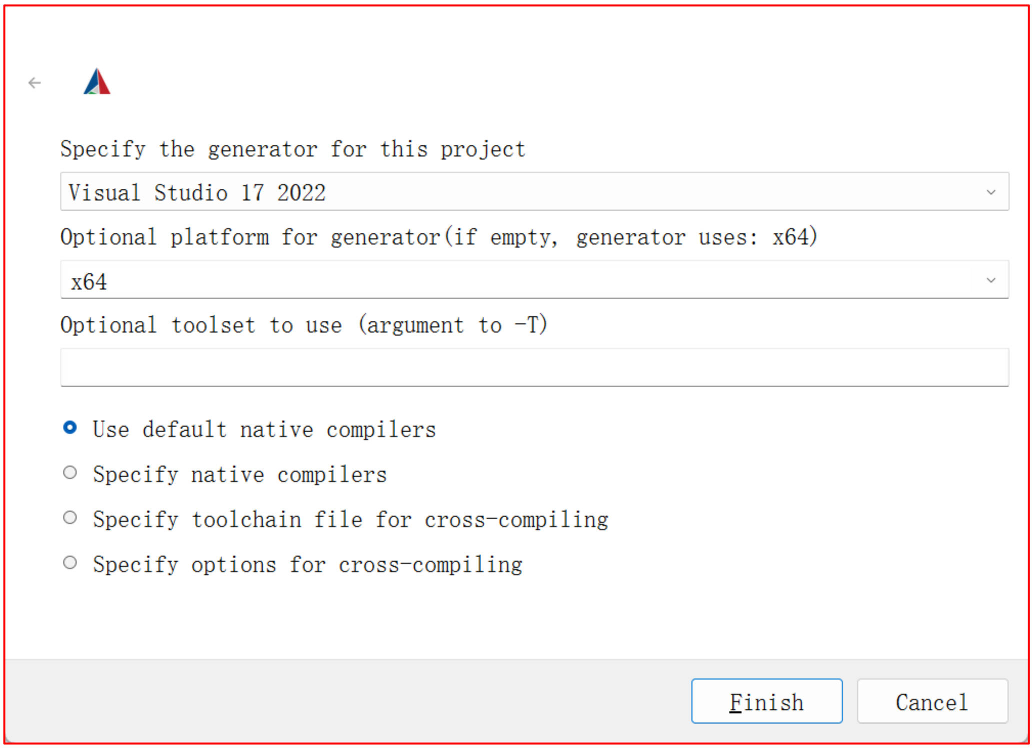

Figure 3.1.1 Example of IDE selection

(5) Configure third-party library paths.

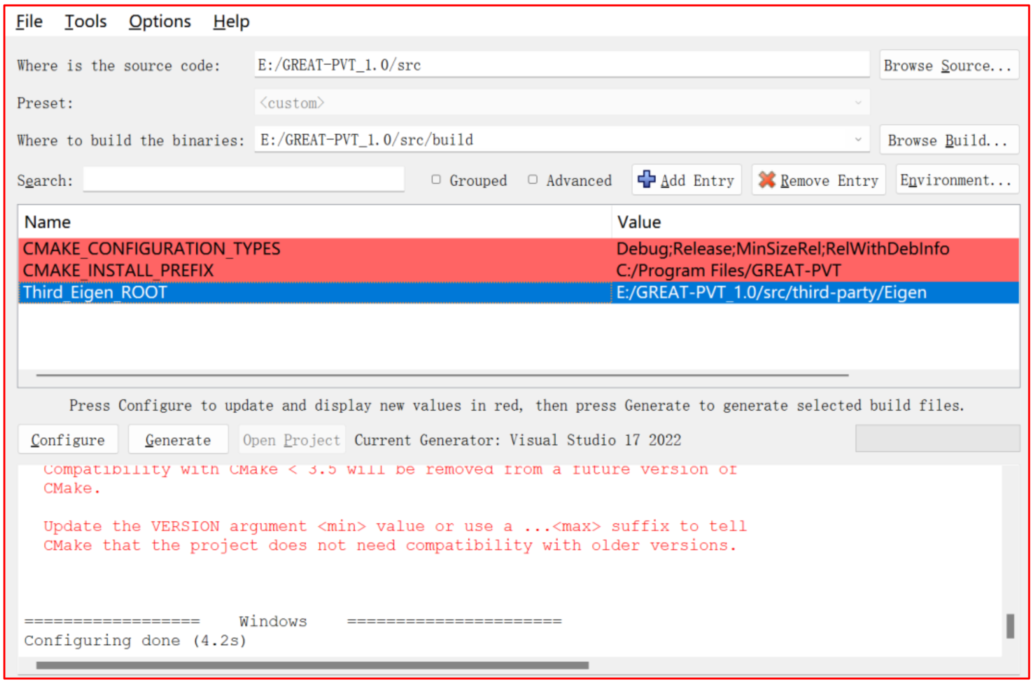

Figure 3.1.2 Configure third-party library paths

(6) Execute "Generate" to write the build files to **<install_dir>/GREAT-PVT_<ver>/src/build**.

(7) Execute "Open Project" and then compile source code in corresponding IDE.

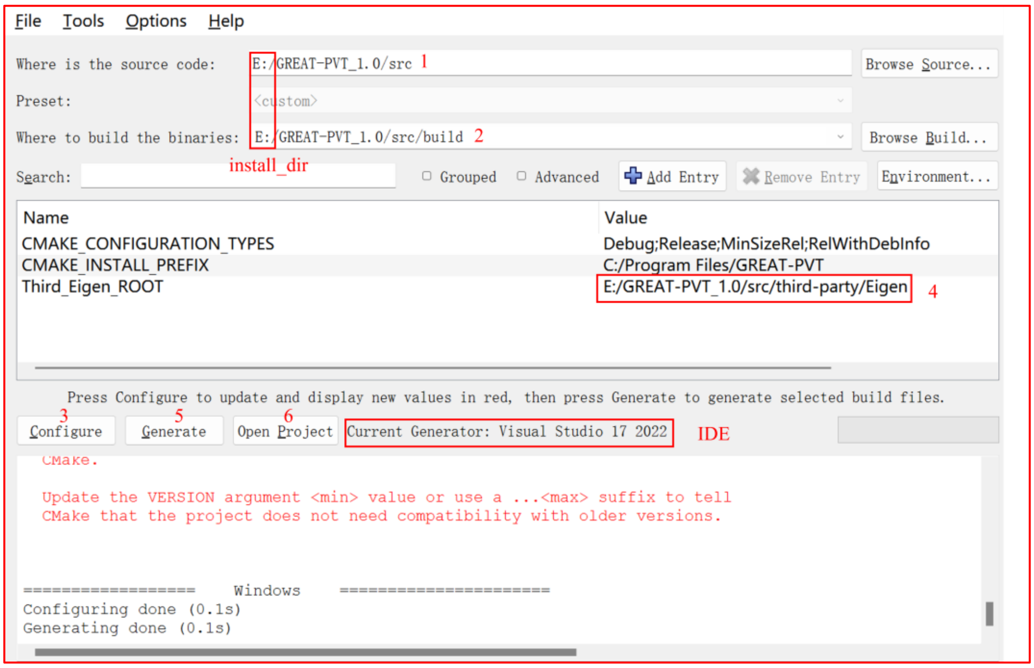

Figure 3.1.3 The compilation of GREAT-PVT in Windows

3.2 Linux

For Linux environment, you can use the existing program under the folder **<install_dir>/GREAT-PVT_<ver>/bin/Linux**. For Linux environment, before that, please enter
"**export LD_LIBRARY_PATH=<install_dir>/GREAT-PVT_<ver>/bin/Linux**"
to load the relevant shared libraries in the current terminal. You can also rebuild GREAT-PVT according to the following instructions.

(1) Get CMake via the website (https://cmake.org/download/) and install it. Note that the minimum requirement of CMake version is 3.0.0.

(2) Creat "build" directory in the directory **<install_dir>/GREAT-PVT_<ver>/src** and change the directory to "build".

```
>> mkdir build
>> cd build
```

(3) Execute "cmake3 ../" and then "make -j8" to compile the source code. The executable GREAT-PVT can be found in **<install_dir>/GREAT-PVT_<ver>/src/build_Linux/Bin**.

```
>> cmake3 ..
>> make -j8
```

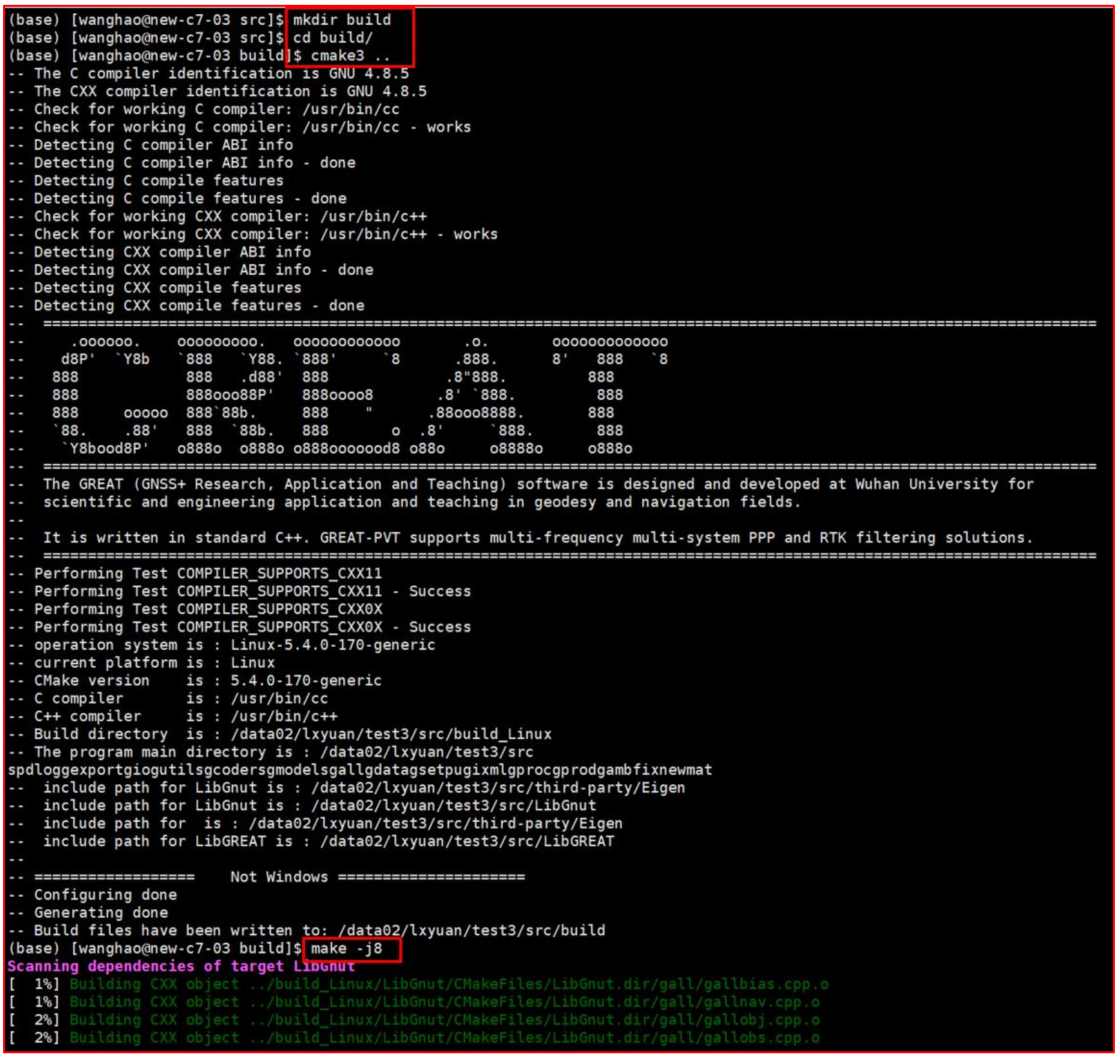

Figure 3.2.1 The compilation of GREAT-PVT in Linux

4 Data Processing Instructions

By convention, we have the following definitions firstly:

YYYY: 4-digit year; YY: 2-digit year; MM: 2-digit month; DD: 2-digit day;

DOY: 3-digit DOY (Day of Year);

hh: 2-digit hour; mm: 2-digit minute; ss: 2-digit second;

SITE: 4-digit site name.

Note that the python scripts mentioned in this session require Python 3.* environment.

4.1 Data Preparation

The input files required for the GREAT-PVT software include observation data, broadcast ephemeris, precise orbit data, precise clock products, Differential Code Bias (DCB), Inter-frequency Clock Bias (IFCB), Uncalibrated Phase Delay (UPD), IGS antenna files, planetary ephemeris files, ocean tide files, and Earth Orientation Parameters (EOP) files. Among these, GREAT-UPD and GREAT-IFCB have been open-sourced and are available at https://github.com/GREAT-WHU. Tables 4.1.1 provides the format descriptions and acquisition methods for the input files required by the GREAT-PVT software.

Table 4.1.1 Format description and acquisition methods of input files

Input files	File Description	Format Description and Acquisition Methods
RINEXO	GNSS Observations	https://files.igs.org/pub/data/format/rinex304.pdf https://cddis.nasa.gov/archive/gnss/data/daily/
RINEXN	Broadcast Ephemeris	https://files.igs.org/pub/data/format/rinex304.pdf https://cddis.nasa.gov/archive/gnss/data/daily/2024/brdc/
SP3	Precise Orbit	https://files.igs.org/pub/data/format/sp3d.pdf https://cddis.nasa.gov/archive/gnss/products/
RINEXC	Precise Clock Products	https://files.igs.org/pub/data/format/rinex_clock304.txt https://cddis.nasa.gov/archive/gnss/products/
DCB	Differential Code Bias	https://files.igs.org/pub/data/format/sinex_bias_100.pdf https://cddis.nasa.gov/archive/gnss/products/bias/
IFCB	Inter-frequency Clock Bias	https://github.com/GREAT-WHU/GREAT-IFCB/blob/main/doc/GREAT-IFCB_1.0.pdf https://github.com/GREAT-WHU/GREAT-IFCB
UPD	Uncalibrated Phase Delay	https://github.com/GREAT-WHU/GREAT-UPD/blob/main/doc/GREAT-UPD_1.0.pdf https://github.com/GREAT-WHU/GREAT-UPD

Input files	File Description	Format Description and Acquisition Methods
jpleph_de405	Planetary Ephemeris	https://ssd.jpl.nasa.gov/planets/eph_export.html https://ssd.jpl.nasa.gov/ftp/eph/planets/Linux/
oceanload	Ocean Tide	http://holt.oso.chalmers.se/loading/example_blq.html http://holt.oso.chalmers.se/loading
poleut1	Earth Orientation Parameters	Refer to Appendix A.4
atx	Antenna	https://files.igs.org/pub/station/general/antex14.txt https://files.igs.org/pub/station/general/pcv_archive/

4.2 Data Processing

Before performing GREAT-PVT software, users need to generate configuration files in XML (Extensible Markup Language) format. For detailed settings of the configuration files for PPP and RTK, please refer to Appendices A.1 and A.2. For ease of reference and modification, template configuration files named "GREAT_PPP.xml" and "GREAT_RTK.xml" are provided for PPP and RTK calculations, respectively. These files are located in the **<install_dir>/GREAT-PVT_<ver>/doc** folder.

To run the example "PPPFLT_2023305" using the executable program in a Windows environment, users only need to type the command lines:

```
>>  cd <install_dir>\GREAT-PVT_<ver>\sample_data\PPPFLT_2023305
>> <install_dir>\GREAT-PVT_<ver>\bin\Windows\GREAT_PVT.exe -x xml\GREAT_PPPFLT_static_DF_Fixed.xml > ppp.log
```

It is important to note that the XML files provided in the example are for Windows. When running the executable program in a Linux environment, the path separators in the XML files need to be changed to "/". The formats of the result files for PPP and RTK calculations can be found in Appendix A.3.

Meanwhile, the software package provides a Python script for PPP batch processing, located in the folder **<install_dir>/GREAT-PVT_<ver>/util/batch_process**. The file directory structure is as follows:

Table 4.2.1 Description of the PPP batch processing file directory

Directory	Description
./data	Example data for batch processing
./ini	Configuration files
./project	Output folder for batch processing results
./PythonScripts	Python script files
./sitelist	Station list
./xml	Template XML files for batch processing

The scripts in the PythonScripts folder are described as follows:

Table 4.2.2 Description of PPP Batch Processing Script Files

Python Script	Description
run_cmd_pppflt_multi.py	Main script for PPP batch processing
gnss_sitelist_io.py	Provides a general interface for reading GNSS station files
gnss_ini_tool.py	Manages the data pool and reads input data
gnss_print_tool.py	Outputs key information to the terminal
gnss_run_tool.py	Provides command-line operation and execution functions
gnss_timestran_tool.py	Handles time format conversion and calculation in processing
gnss_xml_tool.py	Parses and generates XML configuration files

The run_pppflt.ini configuration file located in the `./ini` folder is described as follows:

Table 4.2.3 Description of the PPP batch processing configuration file

Configuration Node	Description
beg_time	Start time <YYYY DOY>
end_time	End time <YYYY DOY>
int_time	Calculation interval (in days)
site_path	Path to the station list file
project_path	Path to the output result files
great_pppflt	Path to the GREAT-PVT executable program
great_pppflt_xml	Path to the batch processing template XML file
rinexo_name	Observation file name, e.g., <SITE><DOY>0.<YY>o
rinexc_name	Precise clock offset file name, e.g., COD0MGXFIN_<YYYY><DOY>0000_01D_30S_CLK.CLK
rinexn_name	Broadcast ephemeris file name, e.g., brdc <DOY>0.<YY>p
bia_name	DCB file name, e.g., CAS0MGXRAP_<YYYY><DOY>0000_01D_01D_DCB.BSX
sp3_name	Precise ephemeris file name, e.g., COD0MGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3
ifcb_name	IFCB file name, e.g., ifcb_<YYYY><DOY>
upd_name	UPD file name, e.g., upd_wl_<YYYY><DOY>_GREC upd_nl_<YYYY><DOY>_GREC
systerm_de	Planetary ephemeris file, e.g., jpleph_de405_great

Configuration Node	Description
systerm_atx	Antenna file, e.g., igs20_2290.atx
systerm_blq	Ocean tide loading file, e.g., oceanload
systerm_eop	Earth orientation parameters file, e.g., poleut1
systerm_path	Path to system files
rinexo_path	Path to observation files
rinexc_path	Path to precise clock offset files
rinexn_path	Path to broadcast ephemeris files
bia_path	Path to differential code bias files
sp3_path	Path to precise ephemeris files
ifcb_path	Path to inter-frequency clock bias files
upd_path	Path to uncalibrated phase delay files

After preparing the data in the `./data` folder, configure the "`run_pppflt.ini`" file as shown in Figure 4.2.1. To perform multi-day PPP calculations, users need to enter the command:

```
>> python3 <install_dir>/GREAT-PVT_<ver>/util/batch_process/PythonScripts/run_cmd_pppflt_multi.py -year <YYYY> -beg <DOY> -end <DOY> -ini <install_dir>/GREAT-PVT_<ver>/util/batch_process/ini/run_pppflt.ini
```

After the process is completed, a batch result folder in the format <YYYY>_<DOY> will be generated in the "`project`" folder. This folder contains the daily XML configuration files and FLT result files.

```
[great_pppflt]
# begin time
beg_time = 2023 305
# end time
end_time = 2023 306
# interval (day)
int_time = 1
# site list
site_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/sitelist/site_list_ppp.txt
# output path
project_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/project
# program path
great_pppflt = /mnt/e/GREAT-PVT_1.0/bin/Linux/GREAT_PVT
# template xml
great_pppflt_xml = /mnt/e/GREAT-PVT_1.0/util/batch_process/xml/GREAT_PPP.xml

[data_pool]
# input files and path
systerm_de = jpleph_de405_great
systerm_atx = igs20_2290.atx
systerm_blq = oceanload
systerm_eop = poleut1
systerm_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/sys
rinexo_name = <SITE><DOY>0.<YY>o
rinexc_name = COD0MGXFIN_<YYYY><DOY>0000_01D_30S_CLK.CLK
rinexn_name = brdc<DOY>0.<YY>p
bia_name = CAS0MGXRAP_<YYYY><DOY>0000_01D_01D_DCB.BSX
sp3_name = COD0MGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3
ifcb_name = ifcb_<YYYY><DOY>
upd_name = upd_wl_<YYYY><DOY>_GREC~upd_nl_<YYYY><DOY>_GREC
rinexo_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/obs/<YYYY>/<DOY>
rinexc_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/clk
rinexn_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/rinexn
bia_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/bia
sp3_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/sp3
ifcb_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/ifcb
upd_path = /mnt/e/GREAT-PVT_1.0/util/batch_process/data/upd
```

Figure 4.2.1 The compilation of GREAT-PVT in Linux

4.3 Sample data processing instructions

4.3.1 Example for PPP

The PPP example data is located in the folder **`<install_dir>/GREAT-PVT_<ver>/sample_data/PPPFLT_2023305`**. Data from the GODN and HARB stations on November 1, 2023, are selected for PPP processing. The file directory structure is as follows:

Table 4.3.1 PPP example file directory structure

Directory	Description
./gnss	GNSS data folder
./model	System folder
./obs	Observation data folder
./upd	UPD folder
./xml	XML configuration folder
./result	Output folder for results

GREAT-PVT supports IF and UC PPP processing. The IF combination supports dual-frequency processing, while the UC method supports both dual-frequency and multi-frequency processing. The **`./xml`** folder provides XML configuration files for dual-frequency, multi-frequency, float solutions, fixed solutions, static and kinematic PPP processing. For detailed XML settings, refer to Appendix A.1.

In addition to using the executable programs provided in the software package to run the examples (refer to Section 4.1), users can also compile the source code (refer to Section 3.1) and follow the steps below to run the examples on Microsoft Visual Studio (MSVS).

Open the app folder in the Visual Studio Solution Explorer, right-click on GREAT_PVT, and set GREAT_PVT as the startup project.

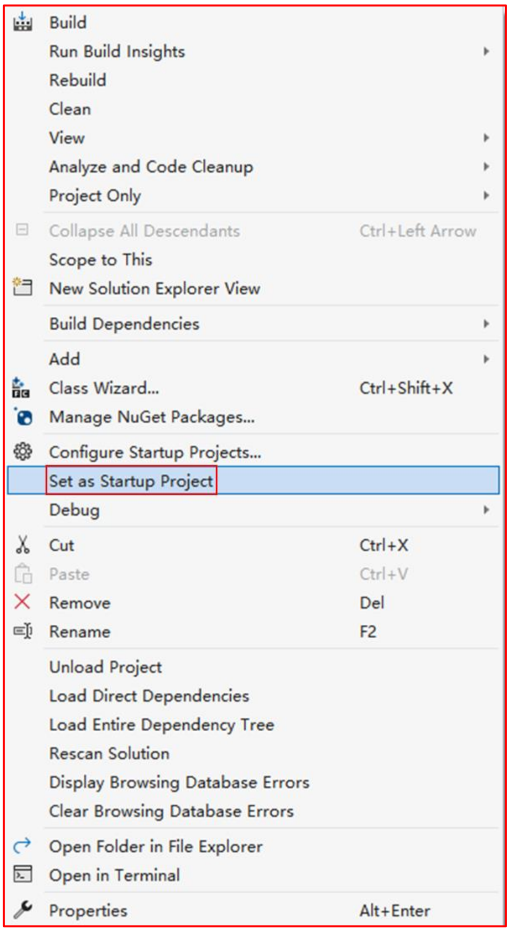

Figure 4.3.1 Setting GREAT_PVT as the startup project

Right-click on GREAT_PVT, select Properties, set the working directory to the example directory, and configure the command parameters.

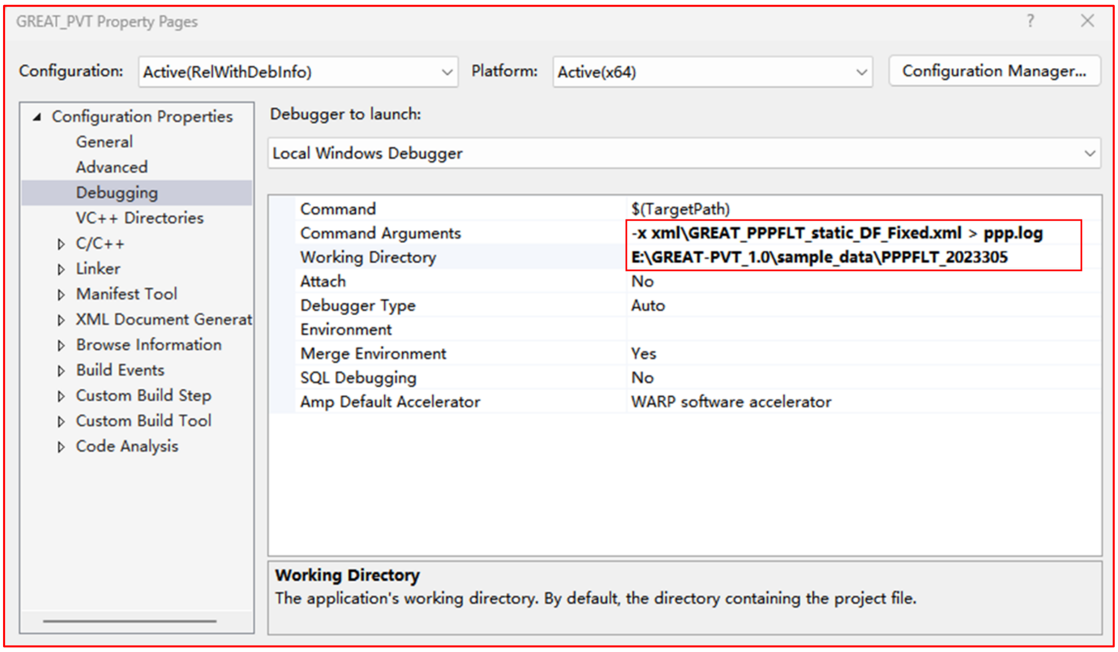

Figure 4.3.2 Setting PPP processing command parameters and working directory

Run the program.

Figure 4.3.3 Running GREAT-PVT

4.3.2 Example for RTK

The RTK example data is located in the folder **<install_dir>/GREAT-PVT_<ver>/sample_data/RTKFLT_2020351**. This dataset consists of GNSS observation data collected by a Septentrio receiver in an urban vehicular environment. The rover station is WUDA, and the reference truth values are derived from the tightly coupled RTK/INS results generated by IE software. The file directory structure is as follows:

Table 4.3.2 RTK example file directory structure

Directory	Description
./gnss	GNSS data folder
./model	System folder
./obs	Observation data folder
./reference	Reference truth data folder
./xml	XML configuration folder
./result	Output folder for results

GREAT-PVT supports mixed-frequency RTK processing. An example RTK configuration file, GREAT_RTKFLT.xml, is provided in the **./xml** folder. For detailed XML settings, please refer to

Appendix A.2.

Similar to PPP data processing, the RTK data processing involves the following steps: Open the app folder in the Visual Studio Solution Explorer, right-click on GREAT_PVT, and set GREAT_PVT as the startup project. Right-click on GREAT_PVT, select Properties, set the working directory to the example directory, and configure the command parameters. Run the program.

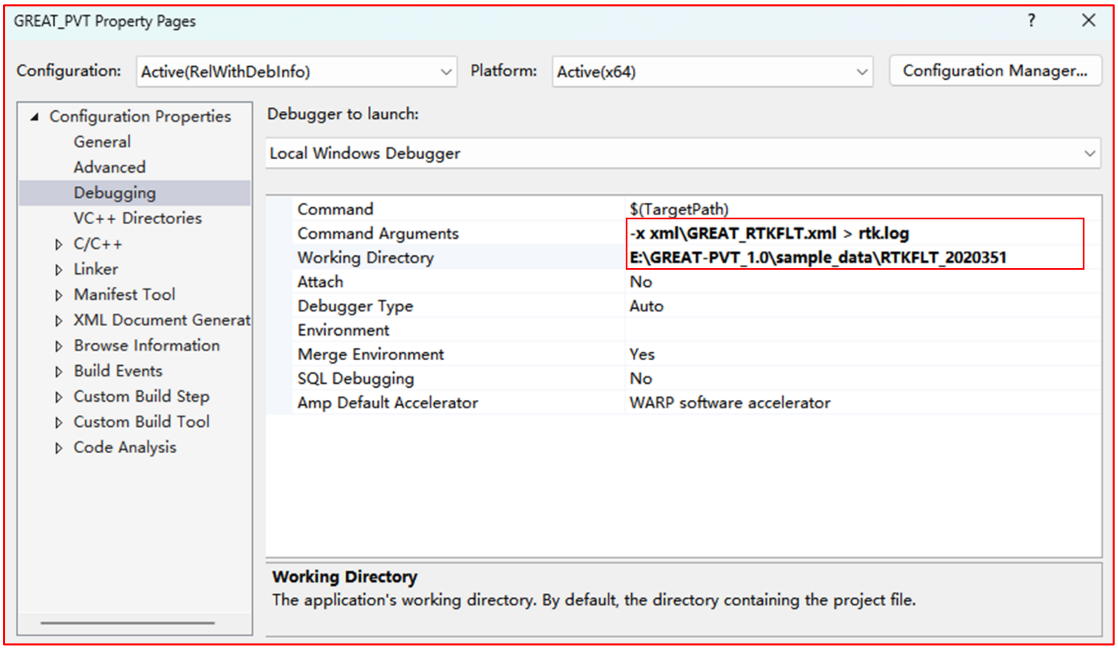

Figure 4.3.4 Setting RTK processing command parameters and working directory

4.4 Results Plotting and Analysis Tools

GREAT-PVT provides Python scripts for plotting and analyzing PPP and RTK solution results. These scripts are located in the folder **<install_dir>/GREAT-PVT_<ver>/util/plot.** The file directory structure is as follows:

Table 4.4.1 Description of plotting tools file

Directory	Description
./data_ppp	PPP result files
./data_rtk	RTK result files
./ PythonScripts	Plotting scripts
./output	Output folder for plotting results

4.4.1 PPP Results Plotting

Users need to prepare the following two types of files:

- SINEX files: Place them in the **`./data_ppp/snx/`** folder.
- GREAT-PVT solution files: Place float solution files in the **`./data_ppp/sta_float/`** folder. Place fixed solution files in the **`./data_ppp/sta_fix/`** folder.

After preparing the data files, use the "**snx_to_crd.py**" script to convert SINEX files into coordinate (CRD) files. Open the "**snx_to_crd.py**" script and modify the time and file paths in the main function. Figure 4.4.1 provides an example configuration. After running, CRD files will be output in the **`./data_PPP/crd`** folder.

```
# year
year = 2023
# DOY
day = 305
# snx Folder path
sinex_path = rf".\data_ppp\snx"
# crd Folder path (output directory)
crd_path = rf".\data_ppp\crd"
```

Figure 4.4.1 Example configuration for "snx_to_crd.py"

Open the "**ppp_plot.py**" script and modify the site list, time, and file paths. Figure 4.4.2 provides an example configuration. After running, result files will be generated in the **`./output`** folder. The PNG files are error sequence plots for the corresponding stations, and the SUM files contain statistical data.

```
siteList = [
    "HARB","GODN"
]

# Year of data
year = 2023
# DOY the data
day = 305
# Set data type: floating point solution (ppp-float) or fixed solution (ppp-fixed)
type1 = "PPP-float"
type2 = "PPP-fixed"

# Station data corresponding to type1
fltPath1 = rf".\data_ppp\kin_float"
# Station data corresponding to type2
fltPath2 = rf".\data_ppp\kin_fix"
# Saved results directory
savePath = rf".\output"
# gnss_crd_io.py crd file path output by the script
crdPath = rf".\data_ppp\crd\snx_igs_2023_305.crd"
```

Figure 4.4.2 Example configuration for "ppp_plot.py"

Figure 4.4.3 and 4.4.4 are the dual-frequency static PPP results of the four systems of GODN station and HARB station, respectively; Figure 4.4.5 and 4.4.6 are the dual-frequency copying dynamic PPP results of the four systems of GODN station and HARB station, respectively.

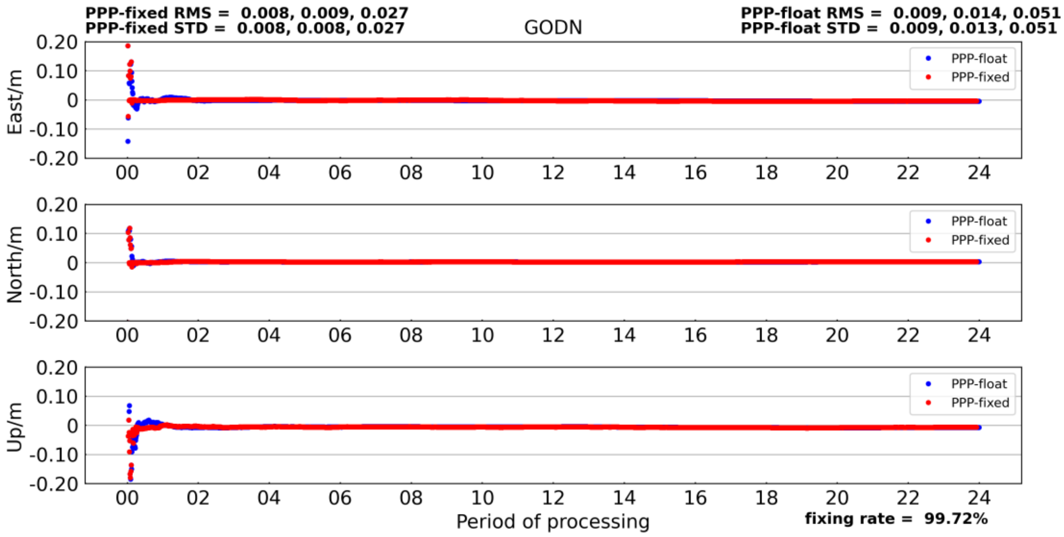

Figure 4.4.3 Error comparison of static PPP float and fixed solutions for the GODN station

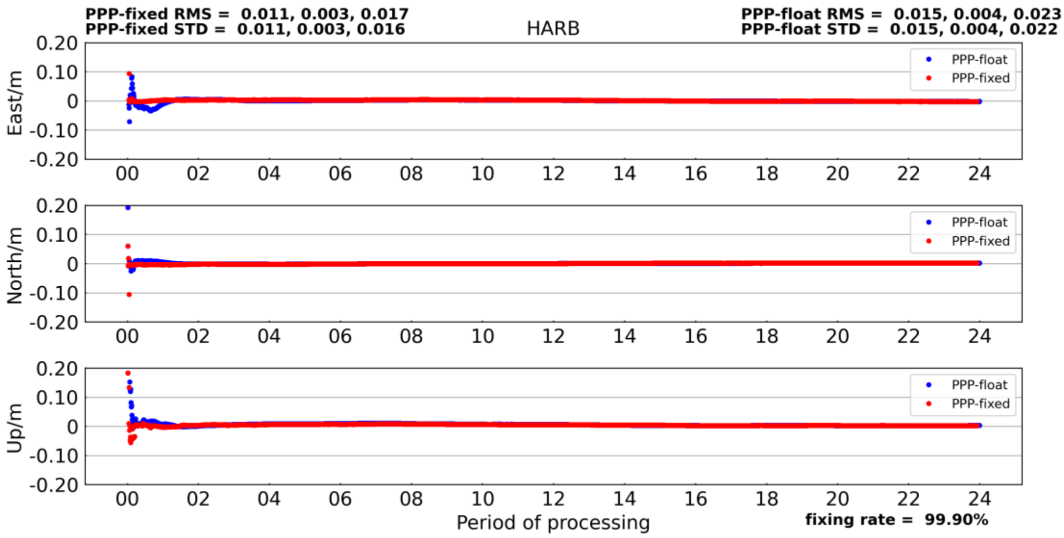

Figure 4.4.4 Error comparison of static PPP float and fixed solutions for the HARB station

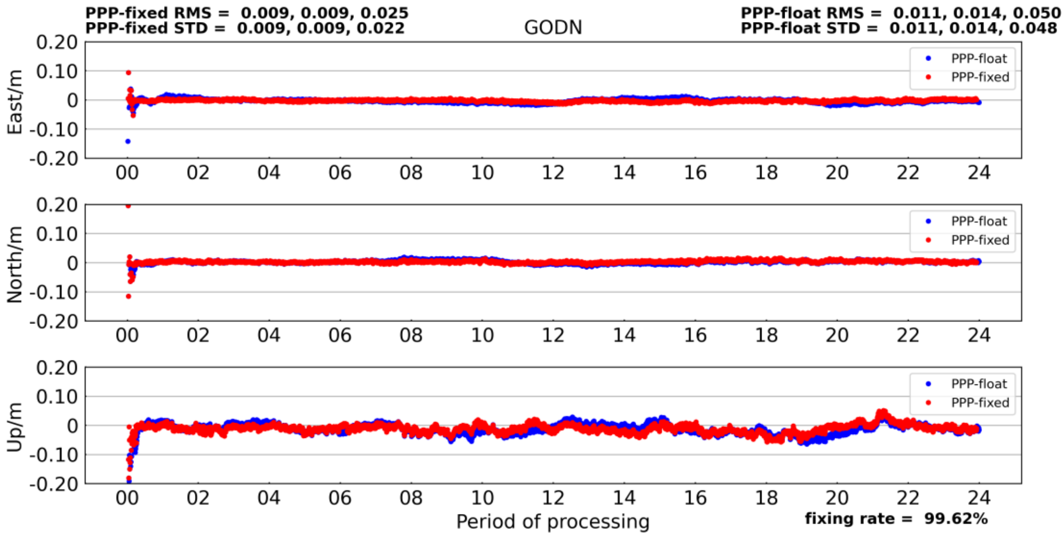

Figure 4.4.5 Error comparison of kinematic PPP float and fixed solutions for the GODN station

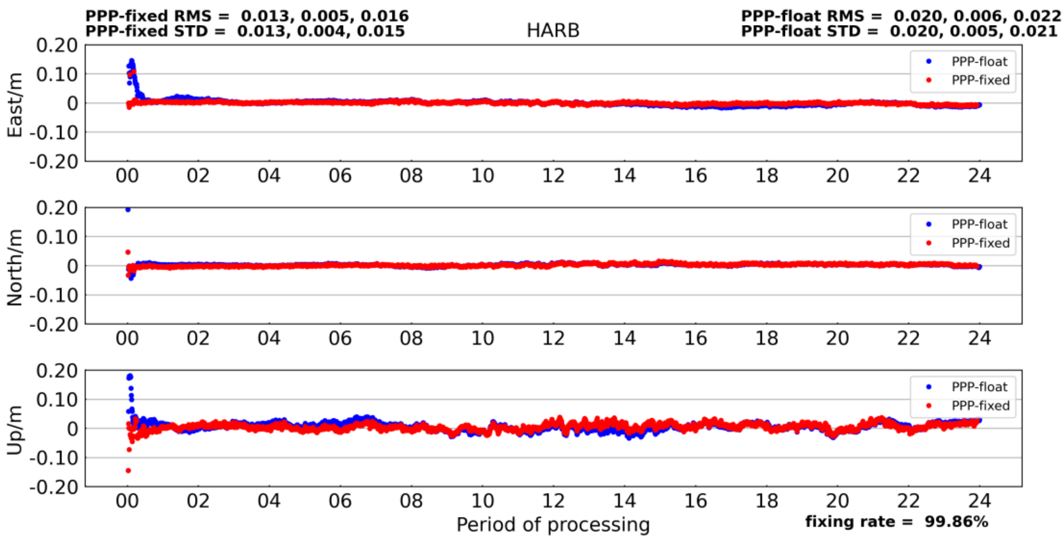

Figure 4.4.6 Error comparison of kinematic PPP float and fixed solutions for the HARB station

4.4.2 RTK Results Plotting

Place the RTK result files and reference truth files in the `./data_rtk` folder. Open the "**rtk_plot.py**" script and modify the paths to the RTK result files and reference coordinate files. Figure 4.4.7 provides an example configuration. Run "**rtk_plot.py**" to obtain the error sequence plot, which is generated in the `./output` folder.

```
# File path
calc_result_file = rf'.\data_rtk\SEPT-RTK.flt'
true_value_file = rf'.\data_rtk\TC_CombinedtoGNSS.txt'
```

Figure 4.4.7 Example configuration for "rtk_plot.py"

Figure 4.4.8 shows the ENU error sequence calculated by the RTK sample data. The results show that under the condition of good observation environment, the errors in the three directions remain within 1 decimeter, and the statistical results of the RMS in the ENU direction are (0.12, 0.30, 0.51) m.

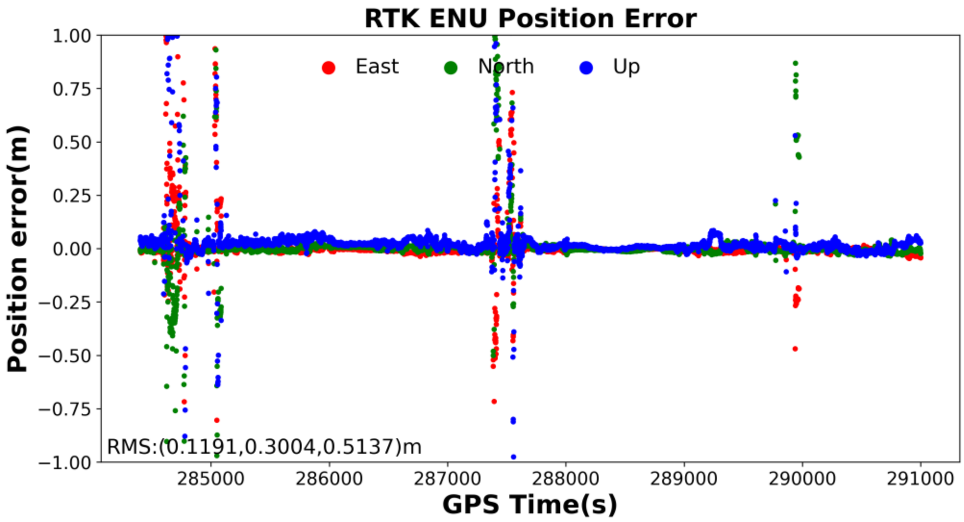

Figure 4.4.8 ENU errors of RTK results for example data

5 Support

Any suggestions, corrections, and comments about GREAT-PVT are sincerely welcomed and could be sent to:

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It is recommended to acknowledge GREAT-PVT when you find it useful!

Appendix A File Formats

By convention, we have the following definitions firstly:

YYYY: 4-digit year; YY: 2-digit year; MM: 2-digit month; DD: 2-digit day;

DOY: 3-digit DOY (Day of Year);

hh: 2-digit hour; mm: 2-digit minute; ss: 2-digit second

A.1 PPP Configure XML for GREAT-PVT

A configuration file containing processing options, solution options and file options. It is expressed in XML format, which contains the "Keyword = Value" form records indicating the various options. The texts starting with "<!--" and ending with "-->" in a line are treated as comments. The following table shows the format of the XML file.

Item	Descriptions	Element in XML File
General Settings (First Level Element)		**<gen>**
Begin Time	Set begin time in form of GPS time. The format is, "YYYY-MM-DD hh:mm:ss".	<beg>
End Time	Set end time in form of GPS time. The format is, "YYYY-MM-DD hh:mm:ss".	<end>
Station List	Set the list of stations participating in the solution (4-character string).	<rec>
Satellite System	Set the satellite systems to be used in the solution.	<sys>
Sampling Interval	Set the sampling frequency of the observations.	<int>
Estimation Method	Default is filtering.	<est>
Input File Settings for GREAT_PPPFLT (First Level Element)		**<inputs>**
RINEX OBS File	RINEX observation file for processing. Note that it supports RINEX 2.10, 2.11, 2.12, 3.00, 3.01, 3.02, 3.03, 3.04, 3.05 OBS.	<rinexo>
RINEX NAV File	RINEX navigation file for processing. Note that it supports RINEX 2.10, 2.11, 2.12, 3.00, 3.01, 3.02, 3.03, 3.04, 3.05 NAV.	<rinexn>
Precise Clock File	Precise clock file for processing.	<rinexc>
Precise Orbit File	Precise orbit file for processing.	<sp3>
DCB File	DCB file for differential code bias correction.	<bias>
Antenna File	Satellite antenna information file for phase center correction	<atx>
Ocean Tide File	Ocean tide file for tide correction.	<blq>
Planetary Ephemeris File	Planetary ephemeris file for calculating planetary parameters.	<de>
EOP Parameter File	Earth Orientation Parameters file for rotation matrix calculation.	<eop>
IFCB File	Inter-frequency clock bias file.	<ifcb>

Item	Descriptions	Element in XML File
UPD File	Uncalibrated phase delay file for ambiguity resolution.	<upd>
Output File Settings for GREAT_PPPFLT (First Level Element)		**<outputs>**
Log File	Log file for recording output information.	<log>
Results	Output file for PPP calculation results.	<flt>
Processing Settings for GREAT_PPPFLT (First Level Element)		**<process>**
Phase Observations	Whether to use carrier phase observations: - true: yes - false: no	<phase>
Tropospheric Parameters	Whether to estimate tropospheric parameters: - true: yes - false: no	<tropo>
Ionospheric Parameters	Whether to estimate ionospheric parameters: - true: yes - false: no	<iono>
Doppler Observations	Whether to use Doppler observations: - true: yes - false: no	<doppler>
Tropospheric Model	Tropospheric model to be used.	<tropo_model>
A Priori Sigma of Estimated Parameters	A priori sigma for station coordinates.	<sig_init_crd>
	A priori sigma for station velocity.	<sig_init_vel>
	A priori sigma for tropospheric parameters.	<sig_init_ztd>
	A priori sigma for ambiguities.	<sig_init_amb>
	A priori sigma for Galileo inter-system and inter-frequency biases.	<sig_init_gal>
	A priori sigma for GLONASS inter-system and inter-frequency biases.	<sig_init_glo>
	A priori sigma for BDS inter-system and inter-frequency biases.	<sig_init_bds>
	A priori sigma for ionospheric parameters.	<sig_init_vion>
Cutoff Elevation Angle	Minimum elevation angle for satellite observations.	<minimum_elev>
Observation Combination	Observation combination method for processing: - IONO_FREE : IF, supports dual-frequency - RAW_ALL: UC, supports dual-frequency and multi-frequency	<obs_combination>
Maximum Posterior Residual	Threshold for posterior residual editing.	<max_res_norm>
Coordinate Constraint	Coordinate constraint method: - est: estimated constraint - fix: fixed constraint - kin: kinematic constraint	<crd_constr>

Item	Descriptions	Element in XML File
Kinematic Mode	Whether to enable kinematic mode: - true: yes - false: no	<pos_kin>
Minimum Number of Satellites	Minimum threshold for the number of satellites in the solution.	<min_sat>
Observation Weighting	Method for determining observation weights.	<obs_weight>
BDS Code Bias Correction	Whether to correct BDS satellite code biases: - true: yes - false: no	<bds_code_bias_corr>
Cycle Slip Detection	Cycle slip detection model: - default: default model	<slip_model>
Observation Frequency	Number of observation frequencies used in the solution.	<frequency>
Filter Settings for GREAT_PPPFLT (First Level Element)		**<filter>**
Filter Algorithm	Filter algorithm to be used: - srcf: square-root filter - kalman: Kalman filter	method_flt
A Priori Noise of Estimated Parameters	White noise for station coordinates.	noise_crd
	White noise for station velocity.	noise_vel
	White noise for receiver clock drift.	noise_dclk
	White noise for receiver clock offset.	noise_clk
	White noise for ionospheric parameters.	noise_vion
	Random walk noise for tropospheric parameters.	rndwk_ztd
	Random walk noise for ambiguities.	rndwk_amb
	Random walk noise for GLONASS ISB/IFB.	rndwk_glo
	Random walk noise for Galileo ISB/IFB.	rndwk_gal
	Random walk noise for BDS ISB/IFB.	rndwk_bds
	Random walk noise for GPS IFB.	rndwk_gps
Ambiguity Resolution Settings for GREAT_PPPFLT (First Level Element)		**<ambiguity>**
Fixing Mode	Whether to perform ambiguity resolution: - NO: float - SEARCH: fix	<fix_mode>
UPD Mode	Use UPD products for ambiguity resolution.	<upd_mode>
Partial Ambiguity Fixing	Whether to perform partial ambiguity fixing: - YES: yes - NO: no	<part_fix>
Minimum Number of Fixed Ambiguities	Minimum number of fixed ambiguities in partial ambiguity fixing mode.	<part_fix_num>
Ratio Value	Ratio test value for ambiguity resolution using the LAMBDA method.	<ratio>

Item	Descriptions	Element in XML File
Reference Satellite	Whether to set a reference satellite: - YES: yes - NO: no	<set_refsat>
Minimum Common Time	Minimum common observation time for ambiguity resolution.	<min_common_time>
Extra Wide-Lane Observations	Settings for ambiguity resolution with different observation combinations: - alpha&maxdev: confidence interval parameters - maxsig: maximum sigma value	<extra_widelane_decision>
Wide-Lane Observations		<widelane_decision>
Narrow-Lane Observations		<narrowlane_decision>
Satellite Settings for GREAT_PPPFLT (First Level Element)		**<gps>/ <bds>/ <gal>/ <glo>**
A Priori Sigma of Observations	Sigma for pseudorange observations.	sigma_C
	Sigma for carrier phase observations.	sigma_L
Frequency	Satellite frequency, corresponding to the frequency band (options: 1/2/3/4/5).	<freq>
Satellite	Satellite PRN number.	<sat>
Frequency Band	Observation frequency bands for different satellite systems: - GPS: 1->L1，2->L2，5->L5 - GAL: 1->E1，5->E5a，7->E5b，8->E5，6->E6 - BDS: 2->B1I，7->B2I，6->B3I，1->B1C，5->B2a，9->B2b，8->B2a+b - GLO: 1->G1，2->G2	<band>

EXAMPLE

```
<config>
    <gen>
        <beg> 2023-11-01 00:00:00 </beg>    <!--> begin time <!-->
        <end> 2023-11-01 23:59:30 </end>    <!--> end time <!-->
        <int> 30                  </int>    <!--> sampling interval <!-->
        <sys> GPS GAL BDS GLO     </sys>    <!--> system ex: GPS GAL GLO QZS BDS SBS <!-->
        <rec> HARB GODN           </rec>    <!--> site (4-char upper) <!-->
        <est> FLT                 </est>    <!--> Estimator : FLT <!-->
    </gen>

    <inputs>
        <rinexo>  <!--> rinex obs file <!-->
            obs\harb3050.23o
            obs\godn3050.23o
        </rinexo>
        <rinexn> gnss\brdc3050.23p </rinexn>  <!--> rinex nav file <!-->
        <rinexc> gnss\COD0MGXFIN_20233050000_01D_30S_CLK.CLK </rinexc>  <!--> precise satellite clock offset file <!-->
        <sp3> gnss\COD0MGXFIN_20233050000_01D_05M_ORB.SP3 </sp3>  <!--> precise orbit file <!-->
        <de> model\jpleph_de405_great </de>  <!--> Planetary ephemeris file <!-->
        <atx> model\igs20_2290.atx </atx>  <!--> Antenna correction file <!-->
        <blq> model\oceanload </blq>  <!--> oceanload file <!-->
        <eop> model\poleut1 </eop>  <!--> ERP file <!-->
        <bias> gnss\CAS0MGXRAP_20233050000_01D_01D_DCB.BSX </bias>  <!--> DCB file <!-->
        <!--><ifcb> gnss\ifcb_2023305 </ifcb><!-->  <!--> IFCB file, for GPS 3 frequency <!-->
        <upd> upd\upd_wl_2023305_G upd\upd_wl_2023305_E upd\upd_wl_2023305_C upd\upd_nl_2023305_G upd\upd_nl_2023305_E upd\upd_nl_2023305_C </upd>
    </inputs>

    <outputs append="false" verb="0">  <!--> output file: whether append & verb: the larger the value, the more detailed the output log. <!-->
        <log type="CONSOLE" name="ppp" level="INFO"/>  <!--> log file <!-->
        <ppp> .\result\$(rec)-PPP </ppp>  <!--> ppp log file <!-->
        <flt> .\result\$(rec)-PPP_sta_DF_Fixed.flt </flt>  <!--> result file <!-->
    </outputs>
```

Figure A.1.1 Example of XML for PPP (a)

```xml
<gps sigma_C="0.6" sigma_L="0.01">  <!--> GPS pseudorange sigma & phase sigma <!-->
    <sat>  <!--> satellite prn <!-->
        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
    </sat>
    <band> 1 2 </band>  <!--> the satellite frequency, for example, C5X, is represented as 5 <!-->
    <freq> 1 2 </freq>  <!--> satellite frequency, corresponding to band, optional value 1/2/3/4/5 <!-->
</gps>
<glo sigma_C="0.6" sigma_L="0.01">  <!--> GLO pseudorange sigma & phase sigma <!-->
    <sat>
        R01 R02 R03 R04 R05 R06 R07 R08 R09 R10
        R11 R12 R13 R14 R15 R16 R17 R18 R19 R20
        R21 R22 R23 R24 <!-- R25 R26  -->
    </sat>
    <band> 1 2 </band>
    <freq> 1 2 </freq>
</glo>
<gal sigma_C="0.6" sigma_L="0.01">  <!--> GAL pseudorange sigma & phase sigma <!-->
    <sat>
        E01 E02 E03 E04 E05 E06 E07 E08 E09 E10
        E11 E12 E13 E14 E15 E16 E17 E18 E19 E20
        E21 E22 E23 E24 E25 E26 E27 E28 E29 E30
        E31 E32 E33 E34 E35 E36
    </sat>
    <band> 1 5 </band>
    <freq> 1 2 </freq>
</gal>
```

Figure A.1.2 Example of XML for PPP (b)

```xml
<bds sigma_C="0.6" sigma_L="0.01">  <!--> BDS pseudorange sigma & phase sigma <!-->
    <sat>
        <!-- C01 C02 C03 C04 C05 --> C06 C07 C08 C09 C10
        C11 C12 C13 C14 C15 C16 C17 C18 C19 C20
        C21 C22 C23 C24 C25 C26 C27 C28 C29 C30
        C31 C32 C33 C34 C35 C36 C37 C38 C39
        C41 C42 C43 C44 C45 C46 <!-- C47 C48 C49 C50
        C51 C52 C53 C54 C55 C56 C57 C58 C59 C60 -->
    </sat>
    <band> 2 6 </band>
    <freq> 1 2 </freq>
</bds>
<qzs sigma_C="0.6" sigma_L="0.01">  <!--> QZS pseudorange sigma & phase sigma <!-->
    <sat>
        J01 J02 J03 J04
    </sat>
    <band> 1 2 </band>
    <freq> 1 2 </freq>
</qzs>
```

Figure A.1.3 Example of XML for PPP (c)

```xml
<process>
    <phase>              true          </phase>  <!--> use phase obs (true/false) <!-->
    <tropo>              true          </tropo>  <!--> estimate trop param (true/false) <!-->
    <iono>               true          </iono>  <!--> estimate iono param (true/false) <!-->
    <doppler>            false         </doppler>  <!--> use doppler obs (true/false) <!-->
    <tropo_model>        saastamoinen  </tropo_model>  <!--> trop model <!-->
    <sig_init_crd>       30            </sig_init_crd>  <!--> initial sigma of coordinate <!-->
    <sig_init_vel>       10            </sig_init_vel>  <!--> initial sigma of velocity <!-->
    <sig_init_ztd>       10            </sig_init_ztd>  <!--> initial sigma of ztd <!-->
    <sig_init_amb>       30            </sig_init_amb>  <!--> initial sigma of ambiguity <!-->
    <sig_init_gal>       10            </sig_init_gal>  <!--> initial sigma of Galileo isb/ifb <!-->
    <sig_init_glo>       10            </sig_init_glo>  <!--> initial sigma of GLONASS isb/ifb <!-->
    <sig_init_bds>       10            </sig_init_bds>  <!--> initial sigma of BDS isb/ifb <!-->
    <sig_init_vion>      100           </sig_init_vion>  <!--> initial sigma of slant iono <!-->
    <minimum_elev>       7             </minimum_elev>  <!--> cut-off satellite elevation(deg) <!-->
    <obs_combination>    RAW_ALL       </obs_combination>  <!--> obs comb type (IONO_FREE/RAW_ALL) <!-->
    <max_res_norm>       3             </max_res_norm>  <!--> posterior residual threshold <!-->
    <crd_constr>         est           </crd_constr>  <!--> coordinate constraint method (EST/FIX/KIN/SIMU_KIN) <!-->
    <pos_kin>            false         </pos_kin>  <!--> kinematic mode (true/false) <!-->
    <min_sat>            5             </min_sat>  <!--> min satellite number <!-->
    <obs_weight>         SINEL         </obs_weight>  <!--> weigh model of obs <!-->
    <bds_code_bias_corr> true          </bds_code_bias_corr>  <!--> whether to correct BDS codeBias (true/false) <!-->
    <slip_model>         default       </slip_model>  <!--> cycle slip detect method <!-->
    <frequency>          2             </frequency>  <!--> frequency number <!-->
</process>
```

Figure A.1.4 Example of XML for PPP (d)

```xml
<filter
    method_flt="srcf"
    noise_crd="0"
    noise_vel="1"
    noise_clk = "1000"
    noise_dclk="100"
    noise_vion="100"
    rndwk_ztd="6"
    rndwk_amb="0"
    rndwk_glo = "20"
    rndwk_gal = "20"
    rndwk_bds = "20"
    rndwk_gps = "20"
/>

<ambiguity>
    <fix_mode> SEARCH </fix_mode>  <!--> ambiguity fixed mode (NO/SEARCH) <!-->
    <upd_mode> UPD </upd_mode>  <!--> upd mode <!-->
    <part_fix> YES </part_fix>  <!--> part_fix (YES/NO) <!-->
    <part_fix_num> 4 </part_fix_num>  <!--> threshold in partial ambiguity fixing <!-->
    <ratio> 2.0 </ratio>  <!--> threshold in LAMBDA method <!-->
    <set_refsat> YES </set_refsat>  <!--> set_refsat (YES/NO) <!-->
    <min_common_time> 1 </min_common_time>  <!--> minimum common time/seconds <!-->
    <extra_widelane_decision maxdev = "0.07" maxsig = "0.10" alpha = "1000" />  <!--> ex
    <widelane_decision maxdev = "0.25" maxsig = "0.12" alpha = "1000" />  <!--> widelane
    <narrowlane_decision maxdev = "0.35" maxsig = "0.12" alpha = "1000" />  <!--> narrow
</ambiguity>
```

Figure A.1.5 Example of XML for PPP (e)

A.2 RTK Configure XML for GREAT-PVT

A configuration file containing processing options, solution options and file options. It is expressed in XML format, which contains the "Keyword = Value" form records indicating the various options. The texts starting with "<!--" and ending with "-->" in a line are treated as comments. The following table shows the format of the XML file.

Item	Descriptions	Element in XML File
General Settings (First Level Element)		**<gen>**
Begin Time	Set begin time in form of GPS time. The format is, "YYYY-MM-DD hh:mm:ss".	<beg>

Item	Descriptions	Element in XML File
End Time	Set end time in form of GPS time. The format is, "YYYY-MM-DD hh:mm:ss".	<end>
Station List	Set the list of stations participating in the solution (4-character string).	<rec>
Satellite System	Set the satellite systems to be used in the solution.	<sys>
Sampling Interval	Set the sampling frequency of the observations.	<int>
Base Station	Set the base station (4-character string).	<base>
Rover Station	Set the base station (4-character string).	<rover>
Base Station Coordinate Settings for GREAT_RTKFLT (First Level Element)		**<receiver>**
Base Station Coordinates	Set the coordinates of the RTK base station. - id: Base station name. - X, Y, Z: Base station coordinates.	<rec>
Input File Settings for GREAT_RTKFLT (First Level Element)		**<inputs>**
RINEX OBS File	RINEX observation file for processing. Note that it supports RINEX 2.10, 2.11, 2.12, 3.00, 3.01, 3.02, 3.03, 3.04, 3.05 OBS.	<rinexo>
RINEX NAV File	RINEX navigation file for processing. Note that it supports RINEX 2.10, 2.11, 2.12, 3.00, 3.01, 3.02, 3.03, 3.04, 3.05 NAV.	<rinexn>
Antenna File	Satellite antenna information file for phase center correction	<atx>
Ocean Tide File	Ocean tide file for tide correction.	<blq>
Planetary Ephemeris File	Planetary ephemeris file for calculating planetary parameters.	<de>
EOP Parameter File	Earth Orientation Parameters file for rotation matrix calculation.	<eop>
Output File Settings for GREAT_RTKFLT (First Level Element)		**<outputs>**
Log File	Log file for recording output information.	<log>
Results	Output file for RTK calculation results.	<flt>
Processing Settings for GREAT_RTKFLT (First Level Element)		**<process>**
Phase Observations	Whether to use carrier phase observations: - true: yes - false: no	<phase>
Tropospheric Parameters	Whether to estimate tropospheric parameters: - true: yes - false: no	<tropo>
Ionospheric Parameters	Whether to estimate ionospheric parameters: - true: yes - false: no	<iono>
Doppler Observations	Whether to use Doppler observations: - true: yes - false: no	<doppler>

Item	Descriptions	Element in XML File
Tropospheric Model	Tropospheric model to be used.	<tropo_model>
A Priori Sigma of Estimated Parameters	A priori sigma for station coordinates.	<sig_init_crd>
	A priori sigma for station velocity.	<sig_init_vel>
	A priori sigma for tropospheric parameters.	<sig_init_ztd>
	A priori sigma for ambiguities.	<sig_init_amb>
	A priori sigma for Galileo inter-system and inter-frequency biases.	<sig_init_gal>
	A priori sigma for GLONASS inter-system and inter-frequency biases.	<sig_init_glo>
	A priori sigma for BDS inter-system and inter-frequency biases.	<sig_init_bds>
	A priori sigma for ionospheric parameters.	<sig_init_vion>
Cutoff Elevation Angle	Minimum elevation angle for satellite observations.	<minimum_elev>
Observation Combination	Observation combination method for processing: - RAW_ALL: supports dual-frequency and multi-frequency - RAW_MIX : mixed-frequency	<obs_combination>
Maximum Posterior Residual	Threshold for posterior residual editing.	<max_res_norm>
Kinematic Mode	Whether to enable kinematic mode: - true: yes - false: no	<pos_kin>
Minimum Number of Satellites	Minimum threshold for the number of satellites in the solution.	<min_sat>
Observation Weighting	Method for determining observation weights.	<obs_weight>
Base Station Coordinate Determination	Method for determining base station coordinates: - CFILE: read from configuration file - spp: single-point positioning	<basepos>
BDS Code Bias Correction	Whether to correct BDS satellite code biases: - true: yes - false: no	<bds_code_bias_corr>
Cycle Slip Detection	Cycle slip detection model: - default: default model	<slip_model>
Observation Frequency	Number of observation frequencies used in the solution.	<frequency>
Filter Settings for GREAT_RTKFLT (First Level Element)		**<filter>**
Filter Algorithm	Filter algorithm to be used: - srcf: square-root filter - kalman: Kalman filter	method_flt

Item	Descriptions	Element in XML File
A Priori Noise of Estimated Parameters	White noise for station coordinates.	noise_crd
	White noise for station velocity.	noise_vel
	White noise for receiver clock offset.	noise_clk
	Random walk noise for tropospheric parameters.	rndwk_ztd
Ambiguity Reset	Time interval for resetting ambiguity parameters.	reset_amb
Ambiguity Resolution Settings for GREAT_RTKFLT (First Level Element)		**<ambiguity>**
Fixing Mode	Whether to perform ambiguity resolution: - NO: float - SEARCH: fix	<fix_mode>
Partial Ambiguity Fixing	Whether to perform partial ambiguity fixing: - YES: yes - NO: no	<part_fix>
Minimum Number of Fixed Ambiguities	Minimum number of fixed ambiguities in partial ambiguity fixing mode.	<part_fix_num>
Ratio Value	Ratio test value for ambiguity resolution using the LAMBDA method.	<ratio>
Minimum Common Time	Minimum common observation time for ambiguity resolution.	<min_common_time>
Extra Wide-Lane Observations	Settings for ambiguity resolution with different observation combinations: - alpha&maxdev: confidence interval parameters - maxsig: maximum sigma value	<extra_widelane_decision>
Wide-Lane Observations		<widelane_decision>
Narrow-Lane Observations		<narrowlane_decision>
Satellite Settings for GREAT_RTKFLT (First Level Element)		**<gps>/ <bds>/ <gal>/ <glo>**
A Priori Sigma of Observations	Sigma for pseudorange observations.	sigma_C
	Sigma for carrier phase observations.	sigma_L
Frequency	Satellite frequency, corresponding to the frequency band (options: 1/2/3/4/5).	<freq>
Satellite	Satellite PRN number.	<sat>
Frequency Band	Observation frequency bands for different satellite systems: - GPS: 1->L1，2->L2，5->L5 - GAL: 1->E1，5->E5a，7->E5b，8->E5，6->E6 - BDS: 2->B1I，7->B2I，6->B3I，1->B1C，5->B2a，9->B2b，8->B2a+b - GLO: 1->G1，2->G2	<band>

EXAMPLE

```xml
<gen>
   <beg> "2020-12-16 07:00:00" </beg>  <!--> begin time <!-->
   <end> "2020-12-16 08:50:00" </end>  <!--> end time <!-->
  <sys > GPS  GAL  BDS </sys>  <!--> system ex: GAL GLO QZS BDS SBS <!-->
  <rec>  SEPT WUDA </rec>  <!--> site (4-char upper) <!-->
  <base> WUDA </base>  <!--> base site (4-char upper) <!-->
  <rover> SEPT </rover>  <!--> rover site (4-char upper) <!-->
  <int> 1 </int>  <!--> sampling interval <!-->
</gen>

<receiver>
   <rec id="WUDA" X="-2267761.0442"  Y="5009370.8908"  Z="3220970.5961"/>  <!--> base site coordinate <!-->
</receiver>

<inputs>
  <rinexo> obs\SEPT3510.20O  obs\WUDA3510.20O </rinexo>  <!--> rinex obs file <!-->
  <rinexn> gnss\brdm3510.20p </rinexn>  <!--> rinex nav file <!-->
  <atx>    model\igs20_2290.atx </atx>  <!--> Antenna correction file <!-->
  <blq> model\oceanload </blq>  <!--> oceanload file <!-->
  <de>  model\jpleph_de405_great </de>  <!--> Planetary ephemeris file <!-->
  <eop> model\poleut1 </eop>  <!--> ERP file <!-->
</inputs>


<outputs>
  <log  type="BASIC"  level="INFO" />  <!--> log file <!-->
  <ppp> result/$(rec)-RTK </ppp> <!--> RTK log file <!-->
  <flt> result/$(rec)-RTK.flt </flt>  <!--> result file <!-->
</outputs>
```

Figure A.2.1 Example of XML for RTK (a)

```xml
<process>
 <phase>               true           </phase>  <!--> use phase obs (true/false) <!-->
 <tropo>               false          </tropo>  <!--> estimate trop param (true/false) <!-->
 <iono>                false          </iono>  <!--> estimate iono param (true/false) <!-->
 <doppler>             false          </doppler>   <!--> use doppler obs (true/false) <!-->
 <tropo_model>         saastamoinen   </tropo_model>  <!--> trop model <!-->
 <sig_init_crd>        30             </sig_init_crd>  <!--> initial sigma of coordinate <!-->
 <sig_init_vel>        10             </sig_init_vel>  <!--> initial sigma of velocity <!-->
 <sig_init_ztd>        10             </sig_init_ztd>  <!--> initial sigma of ztd <!-->
 <sig_init_amb>        30             </sig_init_amb>  <!--> initial sigma of ambiguity <!-->
 <sig_init_gal>        10             </sig_init_gal>  <!--> initial sigma of Galileo isb/ifb <!-->
 <sig_init_glo>        10             </sig_init_glo>  <!--> initial sigma of GLONASS isb/ifb <!-->
 <sig_init_bds>        10             </sig_init_bds>  <!--> initial sigma of BDS isb/ifb <!-->
 <sig_init_vion>       100            </sig_init_vion>  <!--> initial sigma of slant iono <!-->
 <minimum_elev>        7              </minimum_elev>  <!--> cut-off satellite elevation(deg) <!-->
 <obs_combination>     RAW_MIX        </obs_combination>  <!--> obs comb type <!-->
 <max_res_norm>        3              </max_res_norm>   <!--> posterior residual threshold <!-->
 <pos_kin>             true           </pos_kin>  <!--> kinematic mode (true/false) <!-->
 <min_sat>             5              </min_sat>  <!--> min satellite number <!-->
 <obs_weight>          SINEL          </obs_weight>  <!--> weigh model of obs <!-->
 <basepos>             CFILE          </basepos>   <!--> Base station coordinate acquisition method(CFILE/spp) <!-->
 <bds_code_bias_corr>  true           </bds_code_bias_corr>  <!--> whether to correct BDS codeBias (true/false) <!-->
 <slip_model>          default        </slip_model>  <!--> cycle slip detect method <!-->
 <frequency>           2              </frequency>  <!--> frequency number <!-->
</process>
```

Figure A.2.2 Example of XML for RTK (b)

```xml
<filter
  method_flt="kalman"
  noise_crd="30"
  noise_vel="1"
  noise_dclk="100"
  rndwk_ztd="6"
  reset_amb="0"
/>
<!--filter
        method_flt   filter method(srcf, kalman)
        noise_crd    noise of rec coordinate
        noise_vel    noise of rec velocity
        noise_dclk   noise of rec dclk
        rndwk_ztd    random walk of ztd
        reset_amb    time interval of ambiguity reset
/-->

<ambiguity>
   <fix_mode> SEARCH </fix_mode>  <!--> ambiguity fixed mode (NO/SEARCH) <!-->
   <part_fix>  YES  </part_fix>  <!--> part_fix (YES/NO) <!-->
   <part_fix_num>  3  </part_fix_num>  <!--> threshold in partial ambiguity fixing <!-->
   <ratio>  2.5  </ratio>  <!--> threshold in LAMBDA method <!-->
   <min_common_time>  0  </min_common_time>  <!--> minimum common time/seconds <!-->
   <extra_widelane_decision  maxdev = "0.1" maxsig = "0.10" alpha = "1000" />  <!--> extra widelane setting, alpha&maxdev(C
   <widelane_decision      maxdev = "0.275" maxsig = "0.10" alpha = "1000" />  <!--> widelane setting, option: alpha&maxdev(
   <narrowlane_decision    maxdev = "0.375" maxsig = "0.10" alpha = "1000" />  <!--> narrowlane setting, option: alpha&maxde
</ambiguity>
```

Figure A.2.3 Example of XML for RTK (c)

```xml
<bds sigma_C="3" sigma_L="0.03" >  <!--> BDS pseudorange sigma & phase sigma <!-->
<freq> 1 2 </freq>  <!--> the satellite frequency, for example, C5X, is represented as 5 <!-->
<band> 2 6 </band>  <!--> satellite frequency, corresponding to band, optional value 1/2/3/4/5 <!-->
</bds>

<gps sigma_C="2" sigma_L="0.02" >
 <freq> 1 2 </freq>
 <band> 1 2 </band>
</gps>

<gal sigma_C="3" sigma_L="0.03" >
 <freq> 1 2 </freq>
 <band> 1 5 </band>
</gal>

<glo sigma_C="4" sigma_L="0.04" >
 <freq> 1 2 </freq>
 <band> 1 2 </band>
</glo>
```

Figure A.2.4 Example of XML for RTK (d)

A.3 FLT Result File

The FLT file records the positioning results and accuracy metrics for PPP or RTK solutions. The details are as follows:

Column Number	Column Name (Columns 1-19)	Data Section Description	Format
1	Seconds of Week	GPS seconds of the week.	F10.4
2	X-ECEF	X-axis coordinate in ECEF (Earth-Centered, Earth-Fixed) frame.	F12.4
3	Y-ECEF	Y-axis coordinate in ECEF frame.	F12.4
4	Z-ECEF	Z-axis coordinate in ECEF frame.	F12.4
5	Vx-ECEF	X-axis velocity in ECEF frame.	F7.4
6	Vy-ECEF	Y-axis velocity in ECEF frame.	F7.4
7	Vz-ECEF	Z-axis velocity in ECEF frame.	F7.4
8	X-RMS	RMS of X-axis coordinate in ECEF frame.	F6.4
9	Y-RMS	RMS of Y-axis coordinate in ECEF frame.	F6.4
10	Z-RMS	RMS of Z-axis coordinate in ECEF frame.	F6.4
11	Vx-RMS	RMS of X-axis velocity in ECEF frame	F6.4
12	Vy-RMS	RMS of Y-axis velocity in ECEF frame	F6.4
13	Vz-ECEF	RMS of Z-axis velocity in ECEF frame	F6.4
14	NSat	Number of visible satellites	I2
15	PDOP	Position Dilution of Precision (PDOP) value	F3.2
16	sigma0	Unit weight standard deviation	F5.2
17	AmbStatus	Ambiguity resolution status (e.g., Float or Fix)	A5
18	Ratio	Ratio value for ambiguity resolution	F4.2
19	Quality	Data quality indicator	I1

EXAMPLE

#Seconds of Week	X-ECEF	Y-ECEF	Z-ECEF	Vx-ECEF	Vy-ECEF	Vz-ECEF	X-RMS	Y-RMS	Z-RMS	Vx-RMS	Vy-RMS	Vz-RMS	NSat	PDOP	sigma0	AmbStatus	Ratio	Quality
# (s)	(m)	(m)	(m)	(m/s)	(m/s)	(m/s)	(m)	(m)	(m)	(m/s)	(m/s)	(m/s)	(#)	(#)	(m)			
259260.0000	1130760.6201	-4831297.5510	3994154.7241	0.0000	0.0000	0.0000	0.6276	1.8155	1.4432	0.0000	0.0000	0.0000	30	0.89	1.03	Float	0.00	6
259290.0000	1130760.4998	-4831298.2487	3994154.8923	0.0000	0.0000	0.0000	0.0332	0.1301	0.1156	0.0000	0.0000	0.0000	29	0.94	0.49	Fixed	3.43	2
259320.0000	1130760.9377	-4831299.3549	3994155.5148	0.0000	0.0000	0.0000	0.3544	0.8252	0.6264	0.0000	0.0000	0.0000	29	0.94	0.90	Float	0.00	5
259350.0000	1130760.9385	-4831298.6322	3994155.2549	0.0000	0.0000	0.0000	0.0083	0.0525	0.0557	0.0000	0.0000	0.0000	28	0.96	1.12	Fixed	2.52	1
259380.0000	1130760.7413	-4831298.6283	3994155.3184	0.0000	0.0000	0.0000	0.2109	0.3677	0.2529	0.0000	0.0000	0.0000	29	0.93	1.09	Float	0.00	4
259410.0000	1130760.7440	-4831298.6474	3994155.3270	0.0000	0.0000	0.0000	0.1706	0.2727	0.1819	0.0000	0.0000	0.0000	29	0.93	1.15	Float	0.00	4
259440.0000	1130760.7860	-4831298.5354	3994155.2582	0.0000	0.0000	0.0000	0.1423	0.2121	0.1380	0.0000	0.0000	0.0000	29	0.91	0.87	Float	0.00	4
259470.0000	1130760.7474	-4831298.4749	3994155.1607	0.0000	0.0000	0.0000	0.1220	0.1738	0.1113	0.0000	0.0000	0.0000	30	0.89	1.51	Float	0.00	3
259500.0000	1130760.7249	-4831298.4856	3994155.1333	0.0000	0.0000	0.0000	0.1060	0.1470	0.0936	0.0000	0.0000	0.0000	30	0.89	1.61	Float	0.00	3
259530.0000	1130760.7569	-4831298.4493	3994155.1111	0.0000	0.0000	0.0000	0.0714	0.0628	0.0307	0.0000	0.0000	0.0000	30	0.89	0.89	Fixed	4.55	1
259560.0000	1130760.6777	-4831298.6190	3994155.1469	0.0000	0.0000	0.0000	0.0033	0.0190	0.0204	0.0000	0.0000	0.0000	30	0.89	1.63	Fixed	2.18	1
259590.0000	1130760.7895	-4831298.5126	3994155.1523	0.0000	0.0000	0.0000	0.0748	0.1026	0.0673	0.0000	0.0000	0.0000	30	0.88	1.38	Float	0.00	3
259620.0000	1130760.6789	-4831298.6169	3994155.1447	0.0000	0.0000	0.0000	0.0061	0.0244	0.0243	0.0000	0.0000	0.0000	30	0.88	0.91	Fixed	2.24	1
259650.0000	1130760.7365	-4831298.5791	3994155.1596	0.0000	0.0000	0.0000	0.0612	0.0842	0.0562	0.0000	0.0000	0.0000	30	0.88	1.52	Float	0.00	2
259680.0000	1130760.6771	-4831298.6125	3994155.1402	0.0000	0.0000	0.0000	0.0027	0.0122	0.0118	0.0000	0.0000	0.0000	29	0.93	1.20	Fixed	6.28	1
259710.0000	1130760.6771	-4831298.6123	3994155.1394	0.0000	0.0000	0.0000	0.0026	0.0116	0.0112	0.0000	0.0000	0.0000	29	0.91	1.05	Fixed	10.15	1
259740.0000	1130760.6782	-4831298.6195	3994155.1455	0.0000	0.0000	0.0000	0.0026	0.0143	0.0133	0.0000	0.0000	0.0000	29	0.91	0.86	Fixed	13.63	1
259770.0000	1130760.6777	-4831298.6138	3994155.1396	0.0000	0.0000	0.0000	0.0024	0.0106	0.0102	0.0000	0.0000	0.0000	30	0.90	1.30	Fixed	15.02	1
259800.0000	1130760.6777	-4831298.6122	3994155.1373	0.0000	0.0000	0.0000	0.0022	0.0100	0.0097	0.0000	0.0000	0.0000	30	0.90	1.15	Fixed	8.90	1
259830.0000	1130760.6738	-4831298.5924	3994155.1179	0.0000	0.0000	0.0000	0.0015	0.0057	0.0055	0.0000	0.0000	0.0000	30	0.90	0.91	Fixed	2.16	1
259860.0000	1130760.6774	-4831298.6106	3994155.1358	0.0000	0.0000	0.0000	0.0021	0.0091	0.0089	0.0000	0.0000	0.0000	30	0.90	0.91	Fixed	20.83	1

Figure A.3.1 Example of FLT file format

A.4 poleut1 File

To generate the poleut1 product, the executable program "**conveop**" is required. The command line to be used is as follows:

>> ./conveop $filename -inp $filename_old -out $filename_new -year <YYYY>

$filename: The finals2000A.data file to be downloaded. The specific download paths are:
https://cddis.nasa.gov/archive/products/iers
https://datacenter.iers.org/data/10/finals2000A.data
-inp: Specifies the input poleut1 product, which is used to read the header information and file format. The parameter $filename_old refers to the old poleut1 product.
-out: Specifies the output poleut1 product, which does not include information from the old product. The parameter $filename_new refers to the newly generated poleut1 product.
-year: Controls the time period for generating the poleut1 product.

Additionally, leap_seconds must be provided in the working directory. A specific command example is:

>> ./conveop finals2000A.data -inp poleut1 -out poleut1_new -year 2024

Figure A.4.1 illustrates a sample of the poleut1 product. The start date is set 30 days prior to January 1st of the year indicated by the 'year' command-line argument. The end date is determined by the earlier of two dates: 30 days after January 1st of the subsequent year or the last updatable date as per the finals2000A.data file. If the 'year' parameter is omitted, the start and end dates will align with those of the input poleut1 product. The temporal resolution of this product is one day.

Item	Descriptions	Unit
MJD	Modified Julian Date	days
XPOLE	X-component of polar motion	arcsec
YPOLE	Y-component of polar motion	arcsec
UT1-TAI	Length of day variation	seconds

Additionally, DPSI and DEPSI are nutation-related parameters, where PRED_ID represents the tag value, 'I' stands for IERS (International Earth Rotation and Reference Systems Service), and 'P' denotes a predicted value.

```
+pole&ut1
% UT1 type = UT1R
% Start&End%Interval =    60280   60625   1.00
% Num. of Vars&Units =     5  0.1D+01  0.1D+01  0.1D+01  0.1D+01  0.1D+01
% Format = (f9.2,1x,2f10.6,f15.7,2f10.3,6(1x,a1))
%% MJD         XPOLE      YPOLE       UT1-TAI        DPSI      DEPSI    PRED_ID
 60280.00   0.224305  0.223935    -36.9884799     0.000     0.000 I I I - - -
 60281.00   0.222071  0.222430    -36.9884607     0.000     0.000 I I I - - -
 60282.00   0.219794  0.220875    -36.9884422     0.000     0.000 I I I - - -
 60283.00   0.217420  0.219115    -36.9884091     0.000     0.000 I I I - - -
 60284.00   0.214571  0.217536    -36.9883969     0.000     0.000 I I I - - -
 60285.00   0.211936  0.215746    -36.9884039     0.000     0.000 I I I - - -
 60286.00   0.208772  0.214113    -36.9884002     0.000     0.000 I I I - - -
 60287.00   0.205670  0.212065    -36.9883599     0.000     0.000 I I I - - -
 60288.00   0.203013  0.210473    -36.9883052     0.000     0.000 I I I - - -
 60289.00   0.199952  0.209451    -36.9882879     0.000     0.000 I I I - - -
 60290.00   0.196871  0.208244    -36.9883071     0.000     0.000 I I I - - -
 60291.00   0.193357  0.207726    -36.9883613     0.000     0.000 I I I - - -
 60292.00   0.189583  0.206787    -36.9884319     0.000     0.000 I I I - - -
 60293.00   0.185845  0.205745    -36.9884815     0.000     0.000 I I I - - -
 60294.00   0.181994  0.204722    -36.9885548     0.000     0.000 I I I - - -
 60295.00   0.178144  0.203403    -36.9886599     0.000     0.000 I I I - - -
 60296.00   0.174426  0.202336    -36.9887453     0.000     0.000 I I I - - -
 60297.00   0.170661  0.201214    -36.9888360     0.000     0.000 I I I - - -
 60298.00   0.167464  0.200619    -36.9889686     0.000     0.000 I I I - - -
 60299.00   0.164895  0.200433    -36.9891348     0.000     0.000 I I I - - -
 60300.00   0.162559  0.200456    -36.9893678     0.000     0.000 I I I - - -
 60301.00   0.160059  0.200780    -36.9896609     0.000     0.000 I I I - - -
 60302.00   0.157580  0.201308    -36.9899867     0.000     0.000 I I I - - -
 60303.00   0.155062  0.201492    -36.9903172     0.000     0.000 I I I - - -
```

Figure A.4.1 Example of poleut1 file format

Appendix B PPP Principles

B.1 Basic Observation Equations

The original GNSS pseudorange ($P_{r,n}^{s}$) and phase ($L_{r,n}^{s}$) observations can be expressed as:

$$P_{r,n}^{s} = \rho_r^s + t_r - t^s + \gamma_n \cdot I_{r,1}^{s} + m_{r,w}^{s} Z_{r,w} + b_{r,n} - b_n^s + e_{r,n}^{s} \tag{1}$$

$$L_{r,n}^{s} = \rho_r^s + t_r - t^s - \gamma_n \cdot I_{r,1}^{s} + m_{r,w}^{s} Z_{r,w} + \lambda_n \left(N_{r,n}^{s} + B_{r,n} - B_n^s\right) + \varepsilon_{r,n}^{s} \tag{2}$$

Where,

ρ_r^s: Geometric distance from the satellite antenna phase center (s) to the receiver antenna phase center (r), in meters;

t_r and t^s: Receiver and satellite clock biases, in meters.

$Z_{r,w}$: Zenith wet delay of the troposphere, in meters.

$m_{r,w}^{s}$: Mapping function for the zenith wet delay.

$I_{r,1}^{s}$: Ionospheric delay at the first frequency, in meters.

γ_n: Ionospheric mapping factor, $\gamma_n = \lambda_n^2/\lambda_1^2$

$N_{r,n}^{s}$: Integer carrier phase ambiguity, in cycles.

$b_{r,n}$ and b_n^s: Receiver and satellite pseudorange hardware delays, in meters, typically stable over a day or a continuous arc.

$B_{r,n}$ and B_n^s: Receiver and satellite phase delays, in cycles, which can be divided into constant and time-varying parts. The constant part can be fully absorbed by the ambiguity parameter.

$e_{r,n}^{s}$ and $\varepsilon_{r,n}^{s}$: Sum of observation noise and multipath effects for pseudorange and phase observations, respectively.

It is worth noting that the tropospheric delay, whether wet or dry, can be expressed as the product of the zenith tropospheric delay and the corresponding mapping function. The dry component is usually corrected using a priori models (e.g., the Saastamoinen model), while the wet component, due to its high uncertainty, is typically estimated as a parameter. Other errors, such as satellite and receiver antenna phase center offsets (PCO) and variations (PCV), relativistic effects, solid and ocean tides, and phase wind-up, can be corrected using existing error models.

B.2 Dual-Frequency PPP Model

Based on the basic GNSS observation equations, different PPP functional models can be constructed. Depending on the observation combination method, commonly used PPP models include the ionosphere-free combination model and the undifferenced and uncombined model.

The ionosphere-free combination model uses dual-frequency observations to construct ionosphere-free (IF) observations, eliminating the first-order ionospheric delay. For dual-frequency observations, assuming the two frequencies are i and j, the ionosphere-free pseudorange and phase observations $P_{r,IF}^{s}$ and $L_{r,IF}^{s}$ can be expressed as:

$$P_{r,IF}^{s} = \frac{f_i^2}{f_i^2 - f_j^2} P_{r,i}^{s} - \frac{f_j^2}{f_i^2 - f_j^2} P_{r,j}^{s}$$

$$L_{r,IF}^{s} = \frac{f_i^2}{f_i^2 - f_j^2} L_{r,i}^{s} - \frac{f_j^2}{f_i^2 - f_j^2} L_{r,j}^{s} \tag{3}$$

Defining the ionosphere-free combination coefficients α_{ij} and β_{ij}:

$$\alpha_{ij} = \frac{f_i^2}{f_i^2 - f_j^2} \quad \beta_{ij} = -\frac{f_j^2}{f_i^2 - f_j^2} \tag{4}$$

The dual-frequency ionosphere-free observations can be expressed as:

$$\begin{cases} P_{r,IF}^{s} = \rho_r^s + t_r - t^s + m_{r,w}^s Z_{r,w} + b_{r,IF} - b_{IF}^s + e_{r,IF}^{s} \\ L_{r,n}^{s} = \rho_r^s + t_r - t^s + m_{r,w}^s Z_{r,w} + \lambda_{IF}\left(N_{r,IF}^{s} + B_{r,IF} - B_{IF}^s\right) + \varepsilon_{r,IF}^{s} \end{cases} \tag{5}$$

$$\begin{cases} b_{r,IF} = \alpha_{ij} b_{r,i} + \beta_{ij} b_{r,j} \\ b_{IF}^s = \alpha_{ij} b_i^s + \beta_{ij} b_j^s \\ B_{r,IF} = \left(\alpha_{ij}\lambda_i B_{r,i} + \beta_{ij}\lambda_j B_{r,j}\right)/\lambda_{IF} \\ B_{IF}^s = \left(\alpha_{ij}\lambda_i B_i^s + \beta_{ij}\lambda_j B_j^s\right)/\lambda_{IF} \\ N_{r,IF}^{s} = \left(\alpha_{ij}\lambda_i N_{r,i}^{s} + \beta_{ij}\lambda_j N_{r,j}^{s}\right)/\lambda_{IF} \end{cases} \tag{6}$$

Here, $b_{r,IF}$ and b_{IF}^s are the receiver and satellite pseudorange hardware delays for the ionosphere-free combination, respectively. $B_{r,IF}$, B_{IF}^s and $N_{r,HF}^{s}$ are the receiver and satellite phase delays and the combined ambiguity for the ionosphere-free combination, respectively. $e_{r,IF}^{s}$ and $\varepsilon_{r,IF}^{s}$ are the observation noise and multipath effects for the ionosphere-free pseudorange and phase observations, respectively.

In the PPP model, the satellite clock bias t_r is corrected using precise products. It is important to note that the precise satellite clock products provided by analysis centers are estimated using the ionosphere-free combination, and the generated clock corrections absorb the pseudorange hardware delays of the dual-frequency ionosphere-free combination. Therefore, the relationship between the precise clock product $\bar{t}_F^s$ and the "true" satellite clock bias t^s can be expressed as:

$$\bar{t}_{IF}^s = t^s + \left(\alpha_{ij} b_i^s + \beta_{ij} b_j^s\right) \tag{7}$$

Combining equations (5) to (7), the linearized pseudorange and phase ionosphere-free observation equations can be expressed as:

$$\begin{cases} p_{r,IF}^s = \mu_r^s \cdot x + \hat{t}_{r,IF} - \bar{t}_{IF}^s + m_{r,w}^s Z_{r,w} + e_{r,IF}^{s} \\ l_{r,IF}^s = \mu_r^s \cdot x + \hat{t}_{r,IF} - \bar{t}_{IF}^s + m_{r,w}^s Z_{r,w} + \widehat{N}_{r,IF}^s + \varepsilon_{r,IF}^{s} \end{cases} \tag{8}$$

Where $p_{r,IF}^s$ and $l_{r,IF}^s$ are the observed minus computed (OMC) ionosphere-free pseudorange and phase observations, respectively; μ_r^s is the unit vector from the receiver to the satellite; x is the coordinate correction to be estimated; $\hat{t}_{r,IF}$ is the estimated receiver clock bias parameter:

$$\hat{t}_{r,IF} = t_r + \left(\alpha_{ij} b_{r,i} + \beta_{ij} b_{r,j}\right) \tag{9}$$

The receiver clock bias parameter absorbs the receiver pseudorange hardware delay. Since the phase observations are corrected using precise clock products and share the same receiver clock bias parameter as the pseudorange observations, the phase observation equation will introduce the pseudorange hardware delay, which will be absorbed by the ambiguity parameter $\widehat{N}_{r,IF}^{s}$:

$$\widehat{N}_{r,IF}^{s} = N_{r,IF}^{s} + \left[\alpha_{ij}\left(B_{r,i} - B_i^s + b_i^s - b_{r,i}\right) + \beta_{ij}\left(B_{r,j} - B_j^s + b_j^s - b_{r,j}\right)\right] \tag{10}$$

It is important to note that in dual-frequency ionosphere-free PPP, if the same frequencies as the precise clock products are used, the satellite pseudorange hardware delay can be completely eliminated by the clock products. If different frequencies are used, additional pseudorange hardware delay corrections (e.g., using differential code bias products from CODE, DLR, or IGG) are required.

The parameters to be estimated in the dual-frequency ionosphere-free PPP model include station coordinates, tropospheric delay, receiver clock bias, and ambiguity:

$$X = \begin{pmatrix} \mathbf{x} & \hat{t}_{r,IF} & Z_{r,w} & \widehat{N}_{r,IF}^{s} \end{pmatrix}^T \tag{11}$$

The ionosphere-free combination model eliminates the ionospheric delay by combining observations, while the undifferenced and uncombined model directly uses the original observations for PPP processing. In addition to estimating station coordinates, tropospheric delay, receiver clock bias, and phase ambiguity, the undifferenced and uncombined model also estimates ionospheric parameters.

The basic functional model for pseudorange and phase in the undifferenced and uncombined model is as follows:

$$\begin{cases} p_{r,n}^s = \mu_r^s \cdot x + t_r - \bar{t}_{IF}^s + \gamma_n \cdot I_{r,1}^s + m_{r,w}^s Z_{r,w} + b_{r,n} - b_n^s \\ \qquad + \left(\alpha_{ij} b_i^s + \beta_{ij} b_j^s\right) + e_{r,n}^s \\ l_{r,n}^s = \mu_r^s \cdot x + t_r - \bar{t}_{IF}^s - \gamma_n \cdot I_{r,1}^s + m_{r,w}^s Z_{r,w} + \lambda_n\left(B_{r,n} - B_n^s + N_{r,n}^s\right) \\ \qquad + \left(\alpha_{ij} b_i^s + \beta_{ij} b_j^s\right) + \varepsilon_{r,n}^s \end{cases} \tag{12}$$

It is important to note that the hardware delay terms depend on the frequencies used. Specifically, when using the frequencies corresponding to the ionosphere-free clock products ($n = i$ or $n = j$):

$$\begin{cases} p_{r,i}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s + \hat{I}_{r,i}^s + m_{r,w}^s Z_{r,w} + e_{r,i}^s \\ p_{r,j}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s + \gamma_{ij} \hat{I}_{r,i}^s + m_{r,w}^s Z_{r,w} + e_{r,j}^s \\ l_{r,i}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s - \hat{I}_{r,i}^s + m_{r,w}^s Z_{r,w} + \widehat{N}_{r,i}^s + \varepsilon_{r,i}^s \\ l_{r,j}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s - \gamma_{ij} \cdot \hat{I}_{r,i}^s + m_{r,w}^s Z_{r,w} + \widehat{N}_{r,j}^s + \varepsilon_{r,j}^s \end{cases} \tag{13}$$

Where $\hat{t}_r$ is the estimated receiver clock bias parameter, with the same form as the ionosphere-free combination receiver clock bias. $\hat{I}_{r,i}$, $\widehat{N}_{r,i}$ and $\widehat{N}_{r,j}$ are the estimated ionospheric parameter and ambiguity parameters for the two frequencies, respectively, expressed as:

$$
\begin{cases}
\hat{I}_{r,i}^{s} = I_{r,i}^{s} + \beta_{ij}\left(b_{r,i} - b_{r,j}\right) - \beta_{ij}\left(b_{i}^{s} - b_{j}^{s}\right) \\
\widehat{N}_{r,i}^{s} = N_{r,i}^{s} + \left[\left(B_{r,i} - B_{i}^{s}\right) - \left(b_{r,i} - b_{i}^{s}\right)\right] + 2\beta_{ij}\left[\left(b_{r,i} - b_{i}^{s}\right) - \left(b_{r,j} - b_{j}^{s}\right)\right] \\
\widehat{N}_{r,j}^{s} = N_{r,j}^{s} + \left[\left(B_{r,j} - B_{j}^{s}\right) - \left(b_{r,j} - b_{j}^{s}\right)\right] + 2\beta_{ij}\left[\left(b_{r,j} - b_{j}^{s}\right) - \left(b_{r,i} - b_{i}^{s}\right)\right]
\end{cases} \tag{14}
$$

It is important to note that when using the same frequencies as the ionosphere-free clock products, the satellite pseudorange hardware delay （$b_i^s - b_j^s$） can be absorbed by the ionospheric parameter. If different frequencies are used, the satellite pseudorange hardware delay must be corrected using corresponding pseudorange bias products (e.g., differential code bias). This will be discussed in detail in the multi-frequency undifferenced and uncombined PPP functional model. The parameters to be estimated in the dual-frequency undifferenced and uncombined model include:

$$
X = \left(\boldsymbol{x} \quad \hat{t}_r \quad Z_{r,w} \quad \hat{I}_{r,i}^{s} \quad \widehat{N}_{r,i}^{s} \quad \widehat{N}_{r,j}^{s}\right)^{T} \tag{15}
$$

B.3 Multi-Frequency and Multi-GNSS PPP Model

For multi-frequency undifferenced and uncombined PPP, the pseudorange and phase observations at the k-th frequency （$k \neq i$ and $k \neq j$） can be expressed as:

$$
\begin{cases}
p_{r,k}^{s} = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^{s} + \gamma_{ik}\hat{I}_{r,j}^{s} + m_{r,w}^{s} Z_{r,w} + IFB + e_{r,k}^{s} \\
l_{r,k}^{s} = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^{s} - \gamma_{ik} \cdot \hat{I}_{r,i}^{s} + m_{r,w}^{s} Z_{r,w} + \widehat{N}_{r,k}^{s} + \varepsilon_{r,k}^{s}
\end{cases} \tag{16}
$$

Where:

$$
\begin{cases}
IFB = \left[\left(b_{r,k} - b_{k}^{s}\right) - \left(b_{r,i} - b_{i}^{s}\right)\right] + \dfrac{\beta_{ij}}{\beta_{ik}}\left[\left(b_{r,i} - b_{i}^{s}\right) - \left(b_{r,j} - b_{j}^{s}\right)\right] \\
\widehat{N}_{r,k}^{s} = N_{r,k}^{s} + \left[\left(B_{r,k} - B_{k}^{s}\right) - \left(b_{r,i} - b_{i}^{s}\right)\right] \\
\qquad + \beta_{ij}\left(1 + \gamma_{i,k}\right)\left[\left(b_{r,i} - b_{i}^{s}\right) - \left(b_{r,j} - b_{j}^{s}\right)\right]
\end{cases} \tag{17}
$$

The receiver clock bias and ionospheric parameters are expressed as before, and $\widehat{N}^{s}{}_{r,k}$ is the ambiguity parameter at frequency k. In the dual-frequency undifferenced and uncombined model, when using the same frequencies as the ionosphere-free clock products （i and j）, the ionospheric parameter and pseudorange hardware delay are highly correlated, and the ionospheric parameter can fully absorb the pseudorange hardware delay. However, for the k-th frequency, since the hardware delay is significantly different from the first two frequencies, the ionospheric parameter cannot fully absorb the hardware delay, and an IFB (Inter-Frequency Bias) parameter must be introduced.

This section considers the functional model for multi-GNSS PPP under the observation conditions of GPS, GLONASS, Galileo, and BDS (where BDS-2 and BDS-3 use common signals and are not distinguished). The pseudorange and phase observation equations for the four systems are as follows:

$$
\begin{cases}
p_{r,n}^{s,G} = \mu_r^{s,G} \cdot x + t_r - t^{s,G} + \gamma_n^{G} \cdot I_{r,1}^{s,G} + m_{r,w}^{s,G} \cdot Z_{r,w} + \left(b_{r,n}^{G} - b_{n}^{s,G}\right) + e_{r,n}^{s,G} \\
p_{r,n}^{s,R} = \mu_r^{s,R} \cdot x + t_r - t^{s,R} + \gamma_n^{R_k} \cdot I_{r,1}^{s,R} + m_{r,w}^{s,R} \cdot Z_{r,w} + \left(b_{r,n}^{R_k} - b_{n}^{s,R}\right) + e_{r,n}^{s,R} \\
p_{r,n}^{s,E} = \mu_r^{s,E} \cdot x + t_r - t^{s,E} + \gamma_n^{E} \cdot I_{r,1}^{s,E} + m_{r,w}^{s,E} \cdot Z_{r,w} + \left(b_{r,n}^{E} - b_{n}^{s,E}\right) + e_{r,n}^{s,E} \\
p_{r,n}^{s,C} = \mu_r^{s,C} \cdot x + t_r - t^{s,C} + \gamma_n^{C} \cdot I_{r,1}^{s,C} + m_{r,w}^{s,C} \cdot Z_{r,w} + \left(b_{r,n}^{C} - b_{n}^{s,C}\right) + e_{r,n}^{s,C}
\end{cases} \tag{18}
$$

$$\begin{cases} l_{r,n}^{s,G} = \mu_r^{s,G} \cdot x + t_r - t^{s,G} - \gamma_n^G \cdot I_{r,1}^{s,G} + m_{r,w}^{s,G} \cdot Z_{r,w} + N_{r,n}^{s,G} + \left(B_{r,n}^G - B_n^{s,G}\right) + \varepsilon_{r,n}^{s,G} \\ l_{r,n}^{s,R} = \mu_r^{s,R} \cdot x + t_r - t^{s,R} - \gamma_n^{R_k} \cdot I_{r,1}^{s,R} + m_{r,w}^{s,R} \cdot Z_{r,w} + N_{r,n}^{s,R} + \left(B_{r,n}^{R_k} - B_n^{s,R}\right) + \varepsilon_{r,n}^{s,R} \\ l_{r,n}^{s,E} = \mu_r^{s,E} \cdot x + t_r - t^{s,E} - \gamma_n^E \cdot I_{r,1}^{s,E} + m_{r,w}^{s,E} \cdot Z_{r,w} + N_{r,n}^{s,E} + \left(B_{r,n}^E - B_n^{s,E}\right) + \varepsilon_{r,n}^{s,E} \\ l_{r,n}^{s,C} = \mu_r^{s,C} \cdot x + t_r - t^{s,C} - \gamma_n^C \cdot I_{r,1}^{s,C} + m_{r,w}^{s,C} \cdot Z_{r,w} + N_{r,n}^{s,C} + \left(B_{r,n}^C - B_n^{s,C}\right) + \varepsilon_{r,n}^{s,C} \end{cases} \tag{19}$$

Where the superscripts G, E and C represent GPS, Galileo, and BDS satellites, respectively. For GLONASS, due to its frequency division multiple access (FDMA) technology, R_k represents the satellite, where k is its frequency factor. The hardware delays for pseudorange observations differ between systems. Since the pseudorange hardware delay is strongly coupled with the receiver clock bias, the pseudorange hardware delays of different systems are absorbed into the receiver clock bias, leading to inconsistencies in receiver clock biases between systems in multi-GNSS PPP. Therefore, an Inter-System Bias (ISB) parameter must be introduced. Typically, the GPS receiver clock bias is used as the reference, and the differences between the receiver clock biases of other systems and the GPS receiver clock bias are estimated. For GLONASS, due to its FDMA characteristics, the hardware delays for satellites at different frequencies are also different, requiring the introduction of an Inter-Frequency Bias (IFB) parameter.

After defining the functional model for Multi-GNSS PPP, the stochastic model must also be determined. This includes the selection of weight ratios for various GNSS observations, the a priori accuracy of estimated parameters, and the determination of process noise. The observation stochastic model includes the a priori accuracy of pseudorange and phase observations and the weighting method for observations. Assuming that the a priori accuracy of pseudorange and phase observations for different systems and frequencies are equal, denoted as σ_P and σ_L (common empirical values are σ_p= 0.3m and σ_L = 3mm), the variance-covariance matrix $\boldsymbol{\Sigma}_{UC}$ based on the original observations can be expressed as:

$$\boldsymbol{\Sigma}_{UC} = \mathrm{diag}(\sigma_p^2, \sigma_L^2) \tag{20}$$

Common weighting methods include elevation-dependent weighting and signal-to-noise ratio (SNR) weighting. Elevation-dependent weighting is the most commonly used method, where the observation accuracy (standard deviation) σ is expressed as a function of the elevation angle e:

$$\sigma^2 = f(e) \tag{21}$$

Different elevation-dependent stochastic models have been developed based on various functions. The widely used models include those based on exponential functions and trigonometric functions. For example:

$$\begin{aligned} &\text{Bernese: } \sigma^2 = a^2 + b^2 \cos^2 e \\ &\text{GAMIT: } \sigma^2 = a^2 + b^2/\sin^2 e \end{aligned} \tag{22}$$

Where e is the satellite elevation angle in radians; a and b are coefficients determined empirically or through fitting. The stochastic model used in GREAT-PVT is a common model in PANDA software:

$$\sigma^2 = \sigma_0^2 a_0 \tag{23}$$

Where σ_0 is the a priori accuracy of the observations (0.3 m for pseudorange and 3 mm for phase);

a_0 is a function of the elevation angle e:

$$a_0 = \begin{cases} 1 & e \geq 30 \quad \text{deg} \\ \dfrac{1}{2\sin e} & e < 30 \quad \text{deg} \end{cases} \tag{24}$$

This means that observations are down-weighted when the satellite elevation angle is below 30 degrees and equally weighted when the elevation angle is above 30 degrees. Unless otherwise specified, observations from different systems or satellites are generally equally weighted.

In PPP, the parameters to be estimated include station coordinates, receiver clock bias, tropospheric delay, and phase ambiguity. In the undifferenced and uncombined model, ionospheric delay is also estimated. In multi-frequency and multi-GNSS scenarios, additional parameters such as inter-frequency bias (IFB) and inter-system bias (ISB) must be estimated. The stochastic models for these parameters are selected based on their characteristics: The station coordinates are typically estimated as constants in static mode, whereas in kinematic mode, they can be considered as random walk or white noise processes; The receiver clock bias is commonly estimated as white noise at each epoch; The tropospheric delay parameters can be estimated as piecewise constant, piecewise linear, or random walk processes; Ambiguity parameters are estimated as constants over continuous arcs, with new ambiguity parameters introduced if cycle slips occur; The ionospheric delay is generally also considered a random walk process; Various bias parameters require specific analysis of their variational characteristics to select the appropriate stochastic model.

Appendix C RTK Principles

C.1 Single-Differenced Observation Equations

In GNSS differential positioning, single-difference observations are obtained by differencing observations from two receivers for the same satellite at the same epoch. For two receivers observing the same satellite, multiple observation equations can be listed, and one equation is chosen as the reference. The other equations are differenced with the reference equation to obtain the single-difference linear observation equations:

$$\begin{aligned} \Delta\rho_{12}^{j} &= \Delta R_{12}^{j0} + l_1^j dX_1 - l_2^j dX_2 + m_1^j dY_1 - m_2^j dY_2 + n_1^j dZ_1 - n_2^j dZ_2 \\ &\quad + \Delta\delta t_{12} + \Delta d_{ion12}^{j} + \Delta d_{trop12}^{j} + \Delta\varepsilon_{\rho} \\ \lambda\Delta\varphi_{12}^{j} &= -\lambda\Delta N_{12}^{j} + \Delta R_{12}^{j0} + l_1^j dX_1 - l_2^j dX_2 + m_1^j dY_1 - m_2^j dY_2 + n_1^j dZ_1 - n_2^j dZ_2 \\ &\quad + \Delta\delta t_{12} - \Delta d_{ion12}^{j} + \Delta d_{trop12}^{j} + \Delta\varepsilon_{\varphi} \end{aligned} \tag{25}$$

Where:

Δ: Single-difference operator.

ΔR_{12}^{j0}: Difference in approximate geometric distances between stations and satellites, in meters.

$\Delta\delta t_{12}$: Difference in receiver clock biases, in meters.

Δd_{ion12}^{j}: Difference in ionospheric errors, in meters.

Δd_{trop12}^{j}: Difference in tropospheric errors, in meters.

ΔN_{12}^{j}: Difference in integer ambiguities, in cycles.

$\Delta\varepsilon_{\rho}$: Difference in pseudorange noise, in meters.

$\Delta\varepsilon_{\varphi}$: Difference in phase noise, in meters.

For short baselines (within 15 km), the single-difference atmospheric errors (ionospheric and tropospheric delays) can be assumed to be approximately zero due to their strong spatial correlation. If only one static base station and one rover station are considered, the coordinate corrections for the base station are zero.

C.2 Double-Differenced Observation Equations

Based on the single-difference equations, double-difference equations are obtained by differencing observations from two satellites. For two satellites observed simultaneously, the double-difference positioning equations are:

$$
\begin{aligned}
&\Delta\nabla\rho_{12}^{ij} = \Delta\nabla R_{12}^{ij0} + \nabla l^{ij}dX + \nabla m^{ij}dY + \nabla n^{ij}dZ + \Delta\nabla\varepsilon_{\rho} \\
&\lambda\Delta\nabla\varphi_{12}^{ij} = -\lambda\Delta\nabla N_{12}^{ij} + \Delta\nabla R_{12}^{ij0} + \nabla l^{ij}dX + \nabla m^{ij}dY + \nabla n^{ij}dZ + \Delta\nabla\varepsilon_{\varphi}
\end{aligned} \tag{26}
$$

Where ∇ is single-differenced operator between satellites; $\Delta\nabla$ is double-difference operator between stations and satellites. The double-difference eliminates the receiver clock bias difference and reduces the number of observations by one. In the carrier phase observation equation, the initial phase ambiguity is reduced to an integer, providing favorable conditions for ambiguity resolution.

C.3 Ionosphere-Free Double-Differenced Observation Equations

For medium-long baselines (15–20 km or longer), atmospheric errors (ionospheric and tropospheric delays) become significant factors affecting RTK positioning accuracy and convergence. The ionosphere-free combination can be applied to eliminate the residual double-difference ionospheric delay errors. The double-differenced tropospheric delay can be estimated at the receiver end. The model is as follows:

$$
\begin{cases}
\Delta\nabla\rho_{12.IF}^{ij} = \Delta\nabla R_{12}^{ij0} + \nabla l^{ij}dX + \nabla m^{ij}dY + \nabla n^{ij}dZ + \Delta\nabla d_{\pi op12}^{ij} + \Delta\nabla\varepsilon_{\rho_{ij}} \\
\lambda\Delta\nabla\varphi_{12.IF}^{ij} = -\lambda\Delta\nabla N_{12.IF}^{ij} + \Delta\nabla R_{12}^{ij0} + \nabla l^{ij}dX + \nabla m^{ij}dY + \nabla n^{ij}dZ \\
\qquad\qquad\qquad + \Delta\nabla d_{trop12}^{ij} + \Delta\nabla\varepsilon_{\varphi_{IF}}
\end{cases} \tag{27}
$$

C.4 Multi-GNSS RTK

When real-time kinematic positioning involves multi-GNSS signals, differences in time and space reference systems can adversely affect positioning results if not properly accounted for. For unified time and space references, coordinate and time transformations can be used to align all systems to the GPS reference frame.

It is important to note that each satellite system has its own receiver clock bias. If aligned to GPS, the double-difference observations for other systems must account for the Inter-System Bias (ISB). However, for reliability, this software adopts intra-system double-differences, where double-differences are performed only within the same satellite system, eliminating the receiver clock bias within the system.