FAST

User Manual

File Download and Signal Processing Toolkit for GNSS

Release 3.00.03

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Contents

1 Overview

1.1 User Notice

FAST (File Download and Signal Processing Toolkit for GNSS) is an open-source Python framework developed to enhance the efficiency of multi-GNSS data preprocessing. It integrates four core functionalities: data download, quality analysis, standard point positioning (SPP), and station selection. FAST offers both a graphical user interface (GUI) and command-line tools to meet diverse operational requirements.

The source code of FAST can be found on the Chang's Github at https://github.com/ChangChuntao/FAST. This package is copyrighted under the GPL-3.0 license.

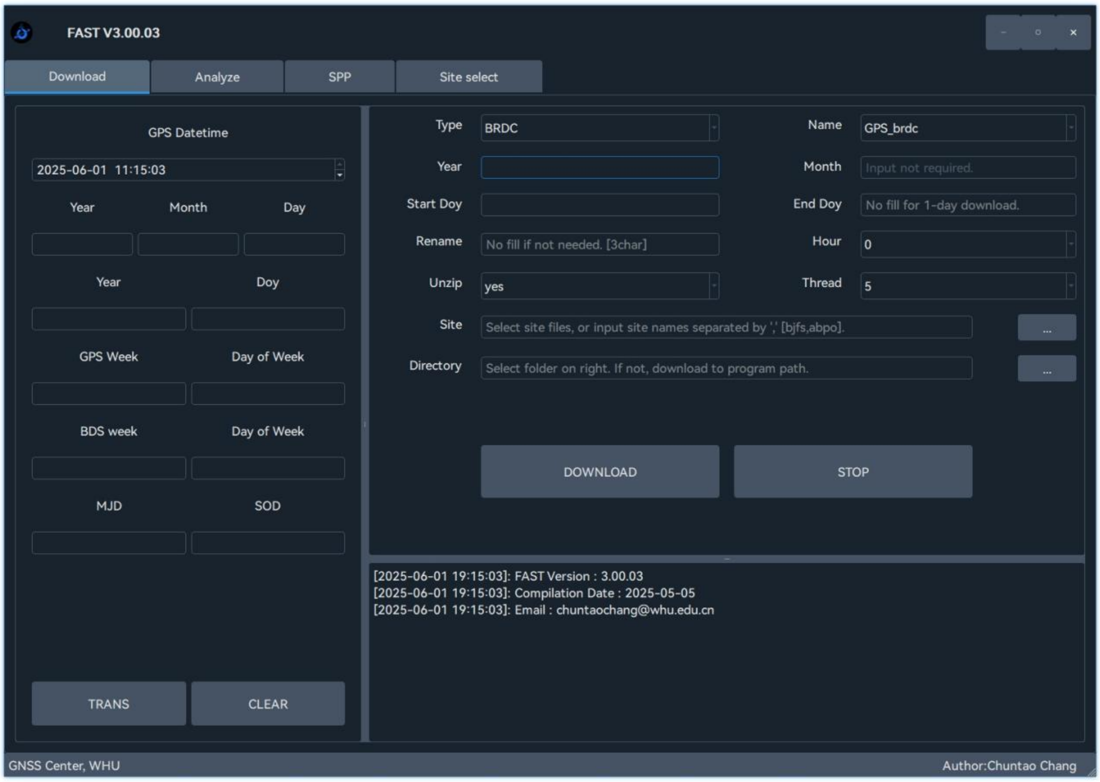


Fig 1 FAST Software Interface

1.2 Software Modules

The software comprises four core functional modules designed to streamline GNSS data processing workflows:

- **Data download module**: This module enables multi-threaded downloading of GNSS data, followed by automated processes such as decompression, format conversion, file concatenation, and renaming. The software efficiently checks for duplicate files locally, ensuring high efficiency and robustness.

- **Quality analysis module**: This module performs comprehensive quality analysis of GNSS data. By simply inputting RINEX files, users can analyze key metrics such as satellite observation counts, pseudorange and carrier phase noise, cycle slip ratios, and ionospheric delay variation rates.
- **SPP module**: Supporting dual-frequency ionosphere-free pseudorange positioning for GPS, BDS, and Galileo systems, this module offers a user-friendly interface with straightforward operations, making it ideal for beginners.
- **Station selection module**: This module allows users to select stations based on satellite system, antenna type, geographic range, and downsampling settings, providing an intuitive interface for efficient station selection.

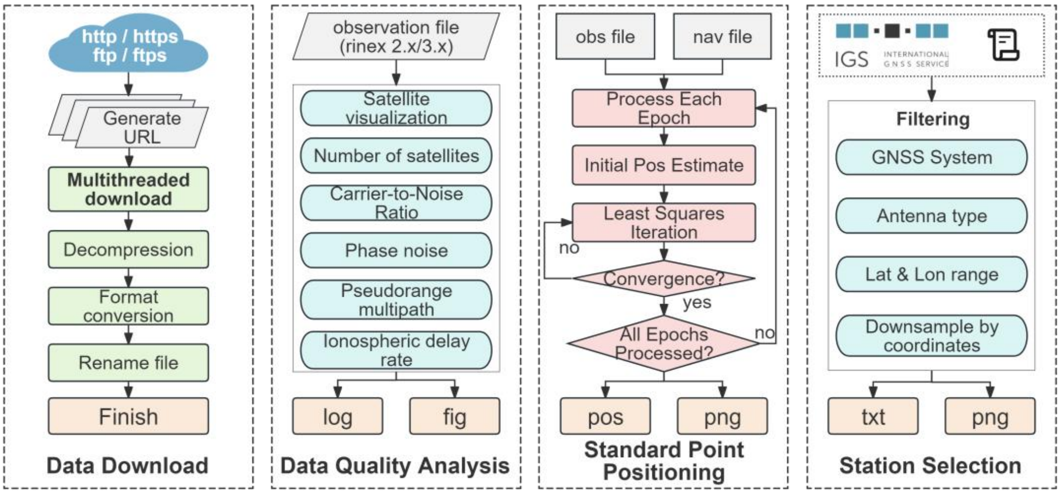


Fig 2 GNSS data processing procedure in FAST

1.3 Development Team

Key contributors and their respective roles are detailed below:

Table 1 Development Team Composition

Role	Contributor	Affiliation	Contributions
Project Lead	Dr. Chang Chuntao	GNSS Research Center, Wuhan University	Architecture, Core Development, Documentation
Algorithm Expert	Dr. Jiang Kecai	GNSS Research Center, Wuhan University	Parallel Computing Optimization

Role	Contributor	Affiliation	Contributions
Core Developer	Dr. Mu Renhai	GNSS Research Center, Wuhan University	Module Development, Testing
Quality Assurance	Dr. Li Bo	Liaoning Technical University	Testing, User Documentation
Quality Assurance	Dr. Wei Hengda	GNSS Research Center, Wuhan University	Testing, User Documentation

1.4 Contact Details

You can contact us by sending an email or leaving a message on our website to submit bugs and comments.

Github： https://github.com/ChangChuntao

Email： chuntaochang@whu.edu.cn

2 Installation

The FAST software is available for download on GitHub via its Releases page (Release FAST V3.00.03 · ChangChuntao/FAST), as shown in Table 2. Users can download the appropriate version based on their operating system.

Table 2 FAST Software Releases on GitHub

Platform	GUI Version	CLI Version
Windows	FastQt_Win_V3.00.03.zip	FAST_Win_V3.00.03.zip
macOS	FastQt_Mac_V3.00.03.zip	FAST_Mac_V3.00.03.zip
Ubuntu	-	FAST_Ubuntu_V3.00.03.zip
CentOS	-	FAST_CentOS_V3.00.03.zip

- **Windows:**

GUI Version: Download the corresponding zip file, extract it, and run the program by double-clicking FAST_QT.exe.

CLI Version: Download the corresponding zip file, extract it, and run the program by double-clicking FAST.exe.

- **macOS:**

GUI Version: Download the corresponding zip file and extract it. Grant execution permissions to the FAST_QT and the programs within the mac_bin folder through System Preferences. Run the program by double-clicking FAST_QT.

CLI Version: Download the corresponding zip file and extract it. Grant execution permissions to the FAST and the programs within the mac_bin folder through System Preferences. Run the program by double-clicking FAST.

- **Ubuntu and CentOS:**

CLI Version: Download the corresponding zip file and extract it. Run the following commands in the terminal within the extracted folder to grant execution permissions and run the program:

```
$ chmod +x FAST
$ chmod +x bin/*
$ ./FAST
```

3 GUI Usage

3.1 Setting

After downloading the GUI Version of the FAST software for Windows or macOS, you will find the corresponding **win_bin** or **mac_bin** folder, as shown in the Fig 3. The **_internal** folder contains various Python dependency libraries. The **win_bin** folder includes the complete CUI Version of FAST. The **ttf** folder stores font files, and the **shapefiles** folder contains the base map files for the Station Selection module.

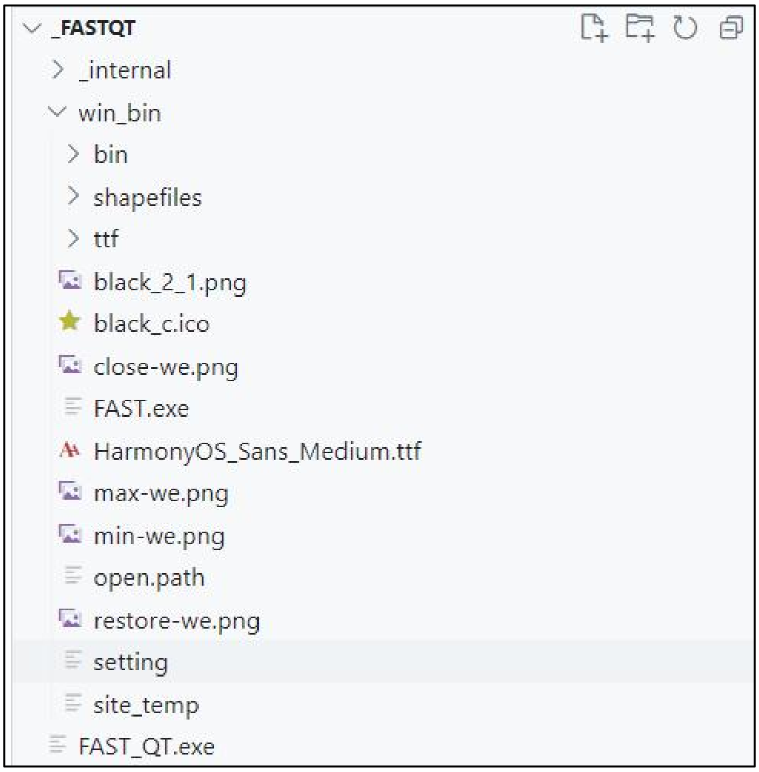


Fig 3 Software File Structure

You can configure the software through the setting file in the folder, which allows you to customize the following options:

- **plotBackgroundColor**: Set the background color for plotted images. Two options are available: **white** and **dark**.
- **language**: Set the interface language. Two languages are supported: CHN (Chinese) and ENG (English).
- **savePngDPI**: Set the DPI for saved images. The default value is 800.

- **ttf**: Configure system fonts. Users can download .ttf files to the **win_bin/ttf** folder and set them up through the setting file.

```
win_bin > setting
1   plotBackgroundColor    = white     # white / dark
2   language               = ENG      # CHN / ENG
3   savePngDPI             = 800      # int
4   ttf                    = HarmonyOS_Sans_Medium.ttf
```

Fig 4 setting

3.2 Data download module

As shown in Table 1, the Data Download module supports 13 types of data, encompassing a wide range of research applications such as GNSS positioning, GNSS and LEO orbit determination, and reference frame establishment. To optimize efficiency, the module employs multi-threaded technology for concurrent data downloading, with the number of concurrent threads fully adjustable by the user.

Table 3 Supported Data Types

Data Type	Organization/Analysis Center
GPS/GNSS Precise Orbits	IGS/WHU/COD/GFZ/IAC/SHAO/GRG
GPS/GNSS Precise Clocks	IGS/WHU/COD/GFZ/IAC/SHAO/GRG
Broadcast Ephemeris	IGS/DLR
Observation Files	IGS(MGEX)/ CORS: HK/EU/USA/AUS
OSB/DCB	WHU/COD/GFZ/CAS/GRG
Sinex	IGS/IVS/IDS/ILS
LEO Data	GRACE/SWARM/CHAMP
Table Files	PANDA/GAMIT
SLR	Haiyang/Beidou/GRACE
Time Series	Nevada Geodetic Laboratory
Troposphere	IGS/COD/JPL
Ionosphere	IGS/WHU/COD/JPL/CAS/ESA
ERP	IGS/WHU/COD/GFZ

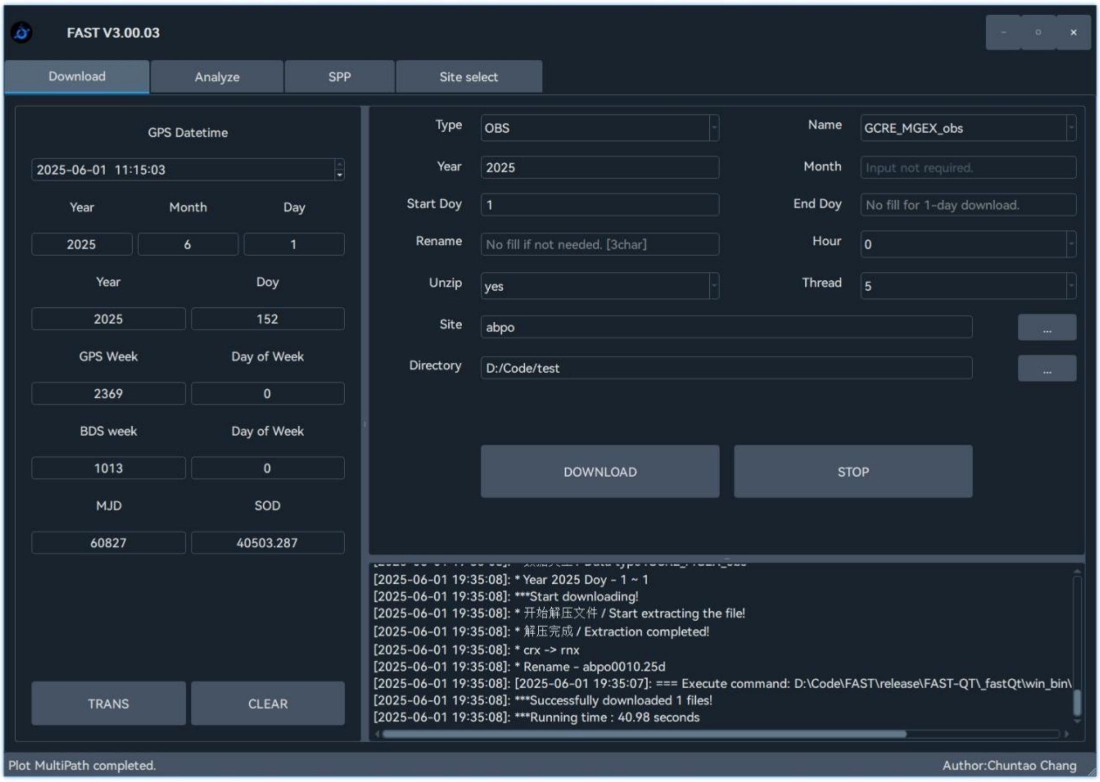


Fig 5 Data download module

As shown in the Fig 5, the upper right side of the module contains the input fields. After selecting the required product type, time, and file operation type, click the **DOWNLOAD** button to trigger the download process. If any issues arise during the download, you can click the **STOP** button to halt the process. The input fields are explained as follows：

- **Type**: Select the Data Type to be downloaded (required).
- **Name**: Select the name of the product type to be downloaded (required).
- **Year**: Enter the year of the data to be downloaded (optional; for example, this option may not be required for Table Files).
- **Start Doy**: Enter the start DOY (Day of Year) of the data to be downloaded (optional; for example, this option may not be required for Table Files).
- **End Doy**: Enter the end DOY of the data to be downloaded (optional; if downloading data for a single day, this field is not required).
- **Month**: Enter the month of the data to be downloaded (optional; only applicable for certain data types).

- **Rename**: When the data type is 'SP3', 'CLK', 'BIA', 'DCB', 'ERP', or 'SNX', enter a three-character string to rename the files to shorter names (optional; only applicable for certain data types).
- **Hour**: Select the hour of the data to be downloaded (optional; only required for certain ultra-rapid products).
- **Unzip**: Choose whether to unzip the downloaded files.
- **Thread**: Select the number of concurrent downloads.
- **Site**: Select site files using the button on the right, or input site names separated by commas (e.g., [bjfs, abpo]) (optional).
- **Directory**: Choose the download directory (optional; if left blank, the files will be downloaded to the software directory).

After the download process is completed, FAST automatically detects and decompresses files based on their compression format and the operating system in use. It supports automatic decompression of common formats such as .gz, .z, .zip, and .tgz. For crx-format observation files, the software seamlessly integrates with the crx2rnx tool to convert files into standard receiver independent exchange format (RINEX) format. Additionally, users can optionally rename precision orbit and other products to short filenames, ensuring compatibility with legacy software systems.

3.3 Quality analysis module

The Quality Analysis module is a valuable tool for assessing the reliability and accuracy of GNSS data. This module enables users to input observations and customize the analysis by selecting specific GNSS systems, satellites, frequencies, and the start and end times of the data to be analyzed. The results of the quality analysis are presented in two formats: graphical visualizations and result files. The graphical outputs are displayed directly on the user interface, providing an intuitive way to interpret complex data patterns, and can also be saved as files. Additionally, the result files offer detailed numerical summaries for further offline analysis or documentation purposes.

Fig 6 Quality analysis module

As shown in the Fig 6, the left side contains the input panel, with fields and buttons arranged from top to bottom as follows: OBS file selection, analysis options, system selection, PRN selection, frequency point selection, start time, end time, PLOT button, SAVE button, and Batch Analyze and Save button. The typical operation process is as follows:

1. Click the "**OBS**" button to select the RINEX observation data file.
2. Choose the analysis options, system, PRN, frequency points, and set the start and end times.
3. Click the **PLOT** button to initiate the calculation and plotting process. The resulting plot will be displayed on the right side of the software.
4. If needed, click the **SAVE** button to save the plot image and the text file containing detailed analysis results. The plot image corresponds to the one shown on the right side of the software, while the text file includes comprehensive analysis outcomes.

For an operation involving analysis of all satellites and frequency, the process is as follows:

1. Click the "**OBS**" button to select the RINEX observation data file.

2. Click the "**Batch Analyze and Save**" button and choose the location to save the analysis results.

3. The software will automatically perform the analysis and save the results.

The **Sat Vis** option is designed to analyze and plot the observation status of each satellite and frequency. As depicted in Fig 7, the x-axis represents time, while the y-axis denotes satellite PRN. Different colored points in the plot signify various frequency points, as indicated in the legend. For instance, "G_L1C" stands for the L1C of GPS satellites.

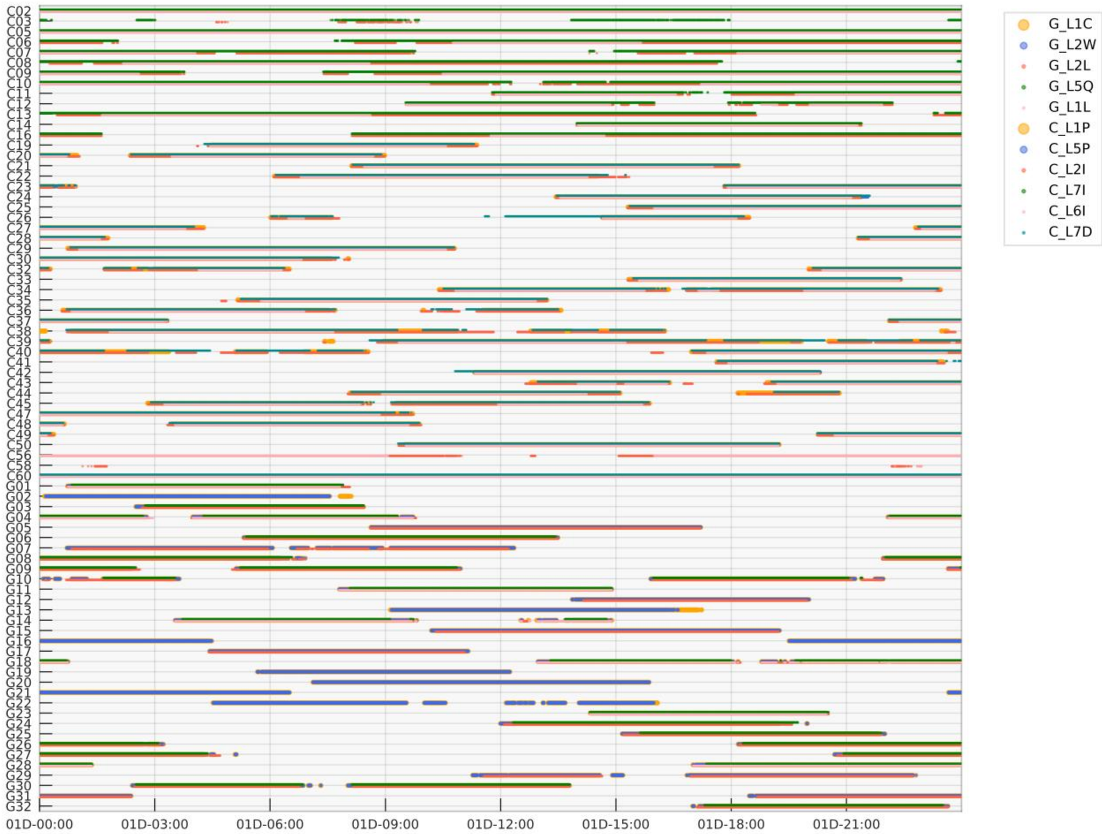


Fig 7 Sat Vis option

The **Sat Num** option performs a statistical analysis of the number of satellites per epoch for each system. Here, the x-axis represents time and the y-axis represents the number of satellites. Different colored lines in the plot correspond to different systems, as explained in the legend. For example, "C AVE:29 MIN:18 MAX:28" means that the average number of observed BDS satellites per epoch is 29, with a minimum of 18 and a maximum of 28.

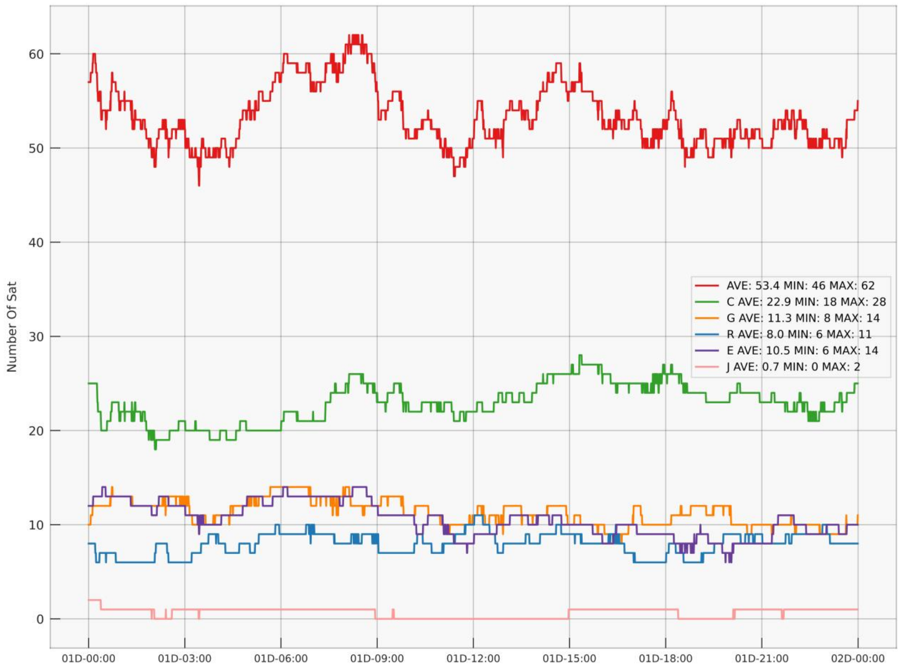


Fig 8 Sat Num option

The **CSR** (Cycle Slip Ratio) option calculates the ratio of cycle slips to the total number of observations. The FAST software employs GF+MW to detect cycle slips, and the results are presented in the output file as O/slips values, which represent the ratio of observations to cycle slips. As shown in Fig 9, the x-axis represents satellite PRN and the y-axis represents the Cycle Slip Ratio. A smaller O/slips value indicates more severe cycle slips.

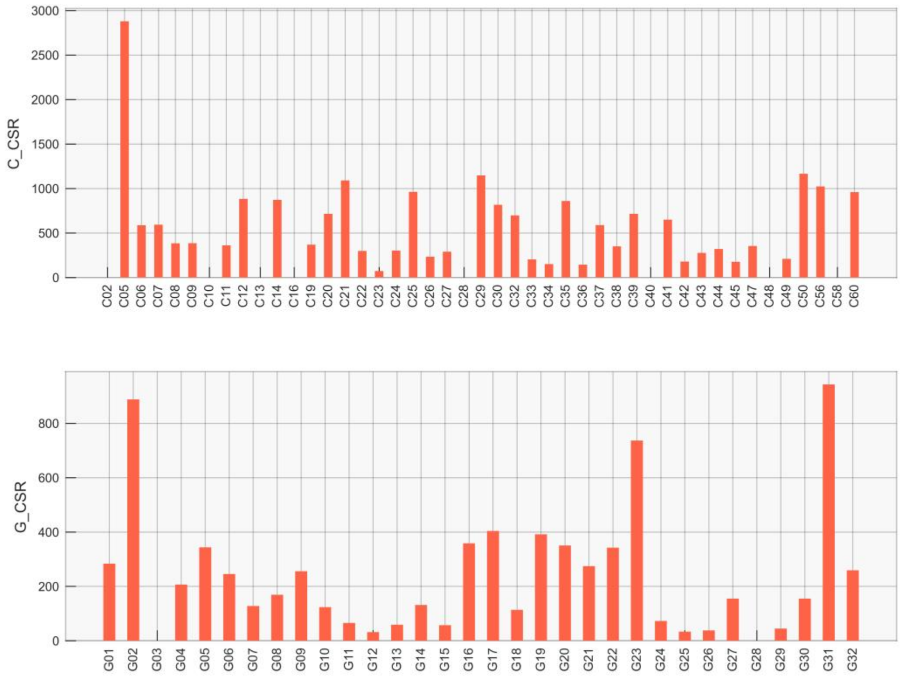


Fig 9 CSR option

The **CNR** (Carrier-to-Noise Ratio) is defined as the ratio of signal strength to noise strength and is used to measure the quality of the ranging signal. A higher CNR value suggests better observation signal quality. As illustrated in Fig 10, CNR is plotted as a boxplot within the software.

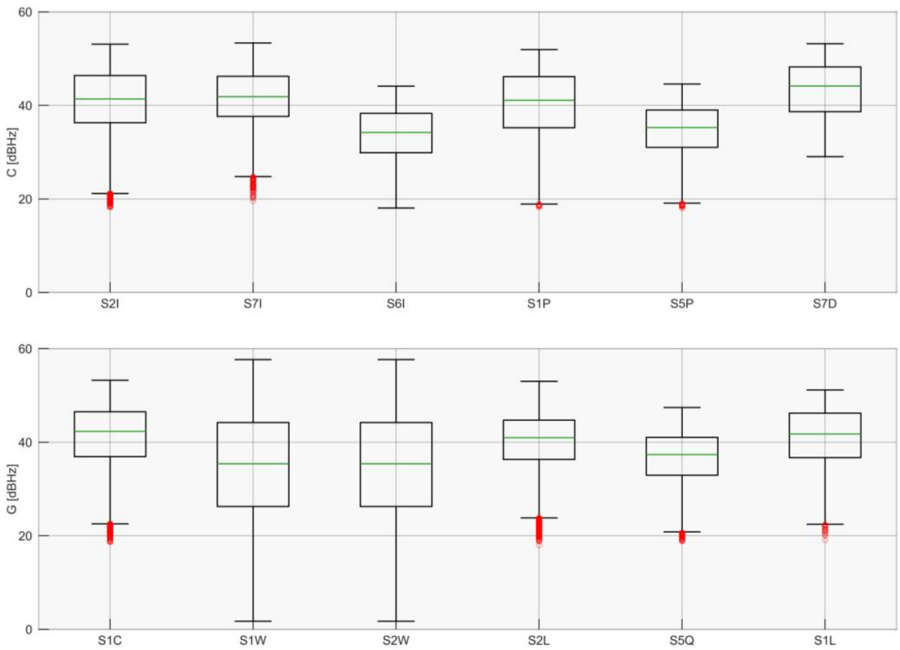


Fig 10 CNR option

The software uses the third-order difference of the GF phase combination to analyze **phase noise**. As shown in Fig 11, the x-axis represents time and the y-axis represents the magnitude of noise.

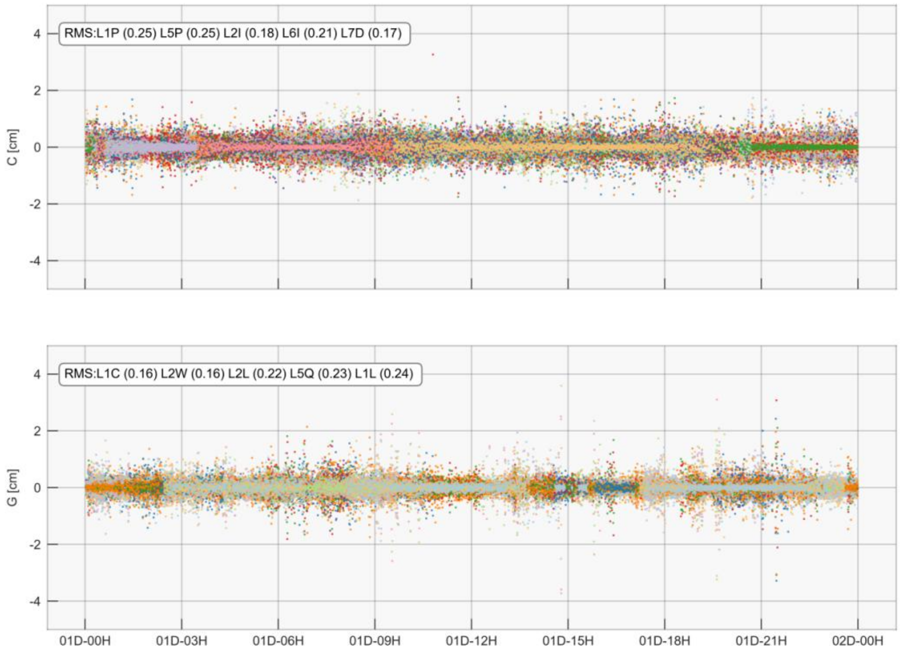


Fig 11 phase noise option

Multipath (**MP**) refers to the phenomenon where GNSS signals are reflected and refracted by objects around the station before entering the receiver antenna, causing deviations in the observed values. As depicted in Fig 12, multipath effects are extracted using MP combinations.

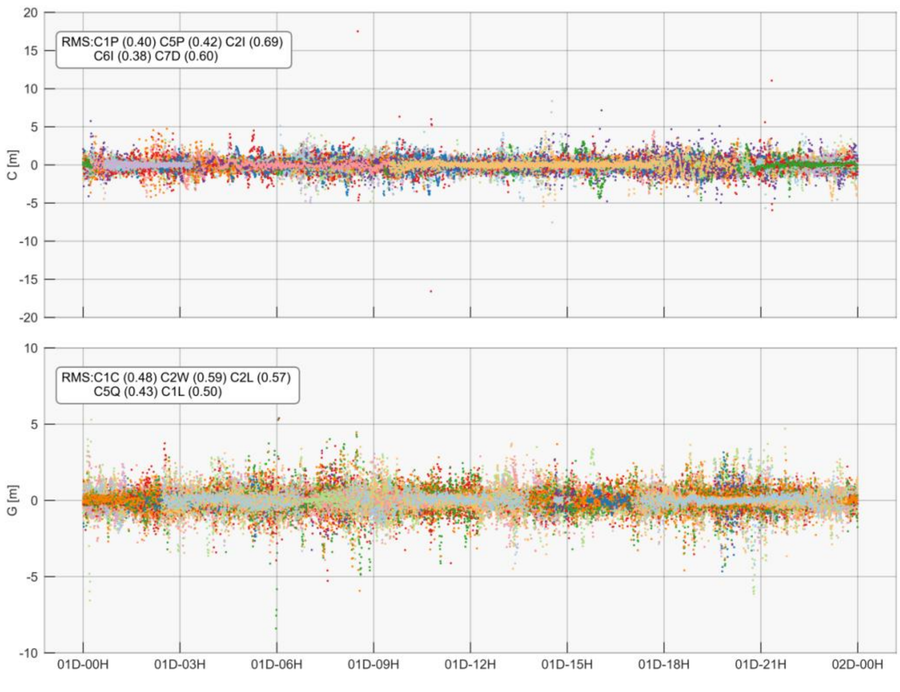


Fig 12 MP option

The **IOD** (Ionospheric Delay Rate) represents the rate of change of ionospheric delay, indicating the variation in the ionosphere over a unit of time. As shown in Fig 13, the IOD is calculated using dual-frequency observations. The x-axis represents time and the y-axis represents the IOD in units of m/s.

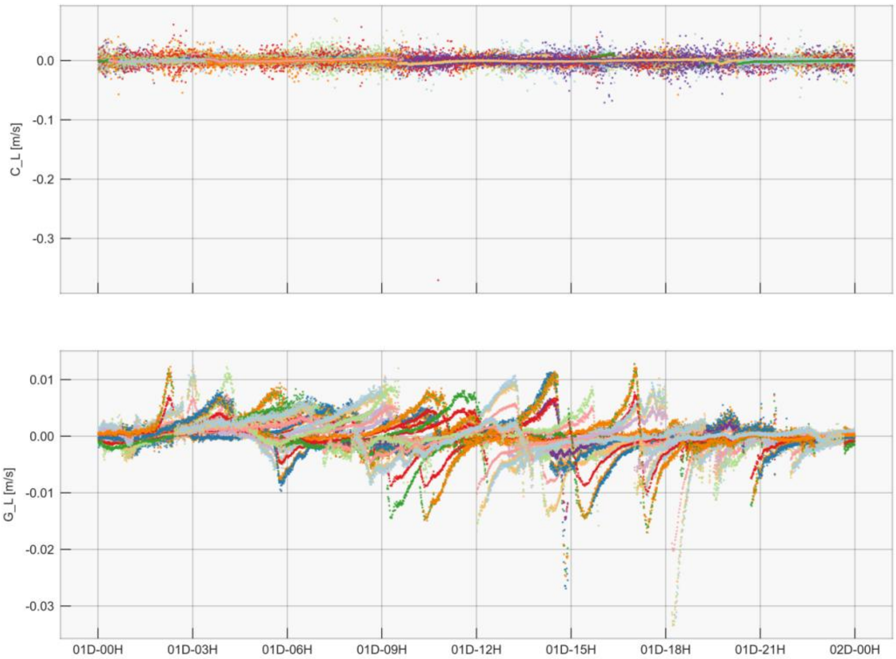


Fig 13 IOD option

3.4 SPP module

The SPP module supports dual-frequency, ionosphere-free pseudorange measurements for GPS, BeiDou, and Galileo systems. The SPP module employs a least-squares algorithm to estimate the receiver's position, accounting for systematic errors such as satellite and receiver clock biases, tropospheric delays. The position solution is iteratively refined to minimize residuals, ensuring high-accuracy results. The SPP module provides a user-friendly interface that simplifies the positioning process. Users can easily input observation data, configure processing parameters, and visualize the results. The module supports multi-system GNSS data, making it versatile for various applications.

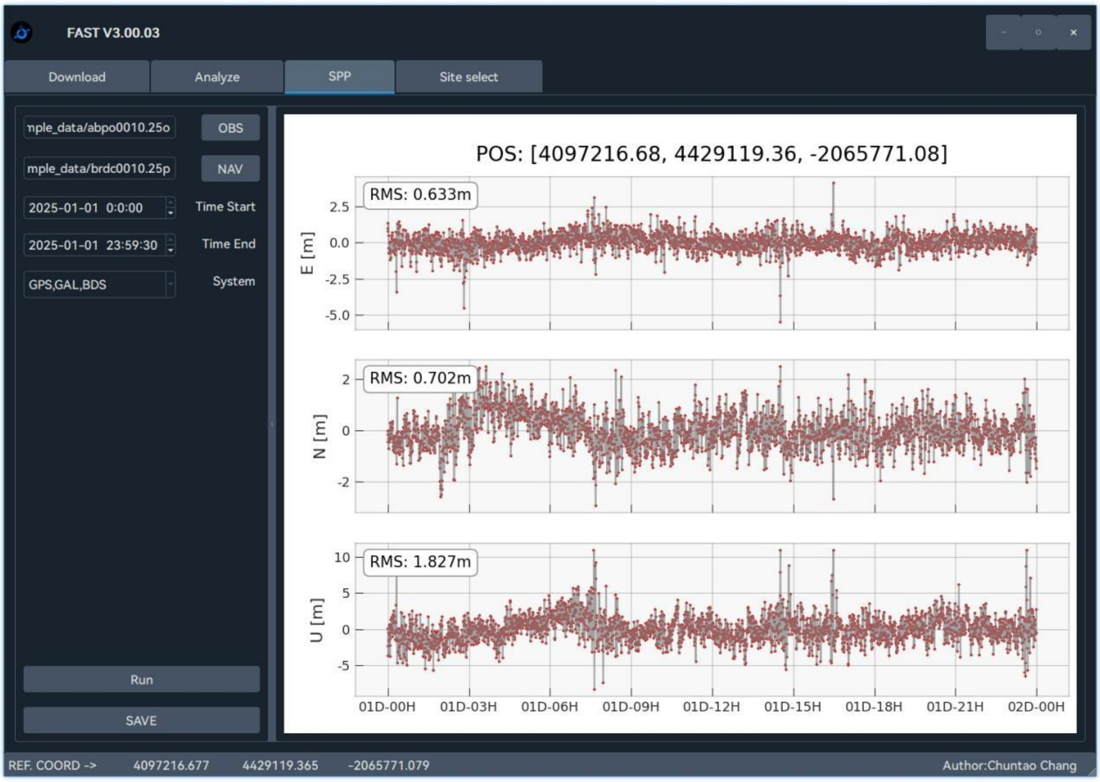


Fig 14 SPP module

The interface of the SPP module is shown in the Fig 14. The typical operation process of this module is as follows: Click the **OBS** button to select the RINEX observation file. After selection, the software will automatically display the start and end times of the observation in the "**Time Start**" and "**Time End**" fields. Users can also manually enter the times if needed. Click the **NAV** button to select the broadcast ephemeris corresponding to the time period. In the system section, multiple GNSS systems for computation can be selected from the drop-down menu. Click **RUN** to perform the calculation. After the calculation, the results will be displayed on the right side of the software. Finally, based on the requirements, the **SAVE** button can be clicked to save the positioning image and result files.

3.5 Station selection module

The Station Selection module in FAST is designed to simplify the procedure of filtering and selecting reference stations based on various criteria, including satellite system, antenna type, geographic coverage, and downsampling requirements. This module comes equipped with information on IGS stations, yet it also permits users to input custom station data for enhanced flexibility. Given the significant impact of reference station selection on the quality of results in applications such as GNSS orbit determination and CORS site selection, this module plays a pivotal role. Furthermore, similar to the Quality Analysis module, the Station Selection module allows for direct visualization of results on the interface, which can be saved as images or station list files for further analysis.

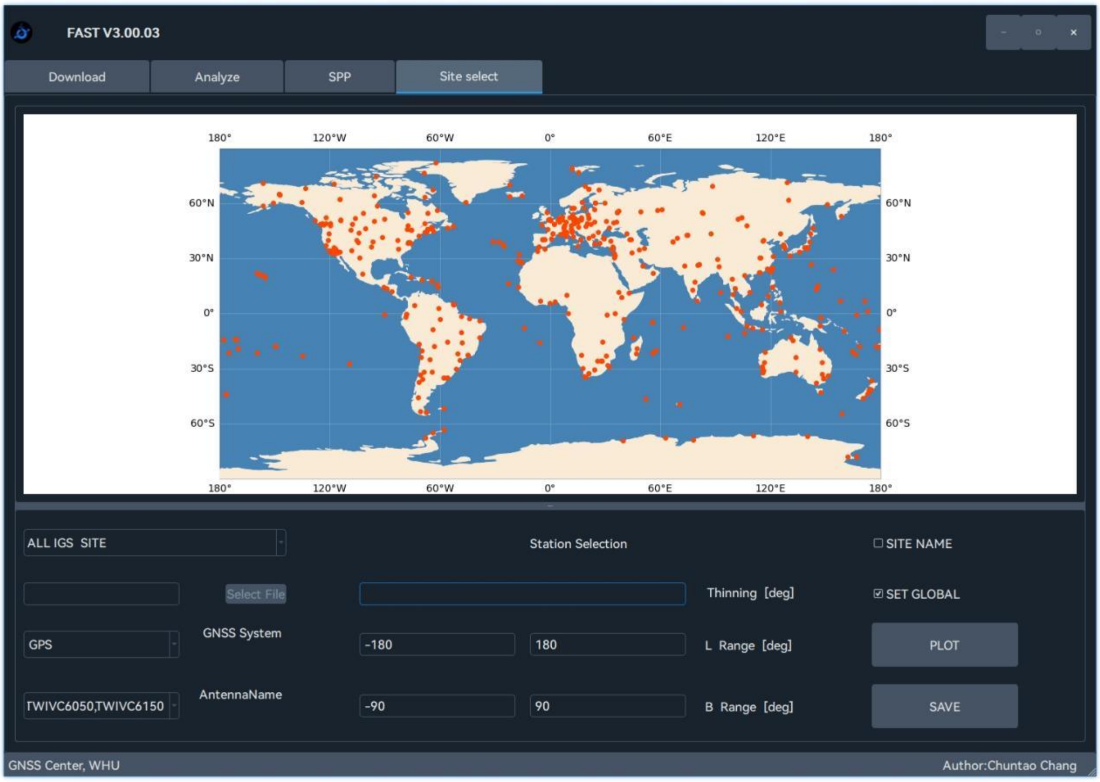


Fig 15 Station selection module

The FAST software includes information on IGS stations, which is located in the file win_bin\bin\IGSNetwork.csv. Users can update this file by downloading the latest version from the IGS website. The software offers three input modes for station information:

1. **ALL IGS SITE**: This mode inputs all the station information from the IGSNetwork.csv file.

2. **IGS LIST FILE**: This mode allows users to input a list of IGS station names. The file should contain the station names separated by spaces.

3. **SITE FILE**: This mode enables users to input a custom list of stations. As shown in the Fig 16, the file should be formatted with "L B SITE" for each station entry.

thin_15deg_site.txt_sitInf.txt U ×

sample_data > site > thin_15deg_site.txt_sitInf.txt

1	-69.91100000	18.46100000	abmf
2	46.79300000	-21.90600000	abpo
3	-156.61500000	71.32300000	ac23
4	-156.65300000	58.68200000	ac24
5	-5.24000000	6.87100000	acrg
6	-77.06600000	38.92100000	acso
7	37.32900000	11.56900000	adis
8	-51.12000000	-30.07400000	aggo
9	127.00100000	37.54100000	aira
10	1.48500000	43.55000000	ajac

Fig 16 site file

After inputting the station information, users can perform downsampling by entering a specified degree in the "Thinning" field and filter stations based on geographic coverage by entering the range of longitudes and latitudes in the "**L Range**" and "**B Range**" fields, respectively. If the input mode is set to "**ALL IGS SITE**" or "**IGS LIST FILE**", users can further filter stations by selecting specific GNSS systems from the "**GNSS System**" drop-down menu and by choosing specific antenna types from the "AntennaName" drop-down menu. Once the settings are complete, clicking the **PLOT** button will initiate the calculation process. After the calculation is finished, the filtered stations will be displayed on the map. Users have the option to show or hide station names by setting the "**SITE NAME**" option and can set the plotting range to be global by selecting the "**SET GLOBAL**" option. Finally, users can click the **SAVE** button to save the station selection results according to their needs.

4 CLI Usage

The current version of the CLI only provides data download and time conversion functions. The FAST program offers two ways to download data: Interactive Mode and Command-line Mode.

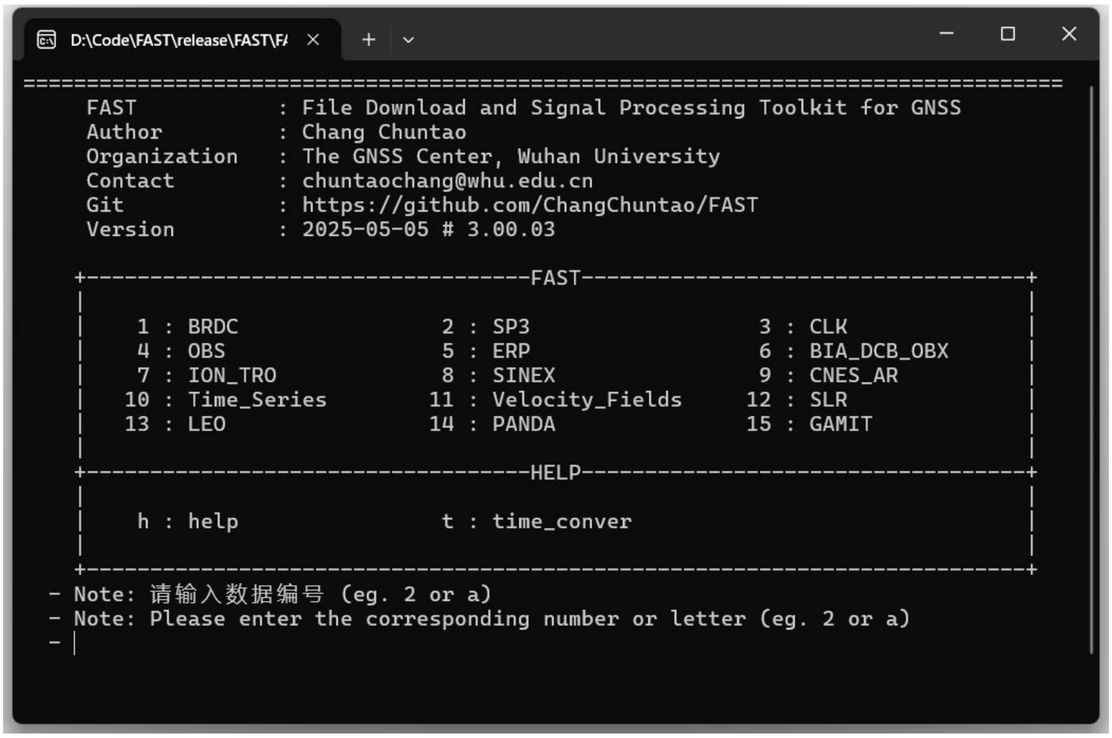


Fig 17 CLI version

4.1 Interactive Mode

For example, to download the final precise ephemeris product from Wuhan University, the operation process is as follows:

1. Enter the number **2** corresponding to the precise ephemeris and press Enter.

2. Enter the number **5** corresponding to the final precise ephemeris from Wuhan University and press Enter.

3. Follow the prompt to input the data you need to download. If you only need to download data for a single day, enter **<year doy>**. If you need to download data for multiple days, enter **<year start_doy end_doy>**. For example, to download data from DOY 1 to DOY 2 of 2025, you would enter **2025 1 2**.

```
   +---------------------------------FAST---------------------------------+
   |                                                                      |
   |    1 : BRDC                2 : SP3                3 : CLK            |
   |    4 : OBS                 5 : ERP                6 : BIA_DCB_OBX    |
   |    7 : ION_TRO             8 : SINEX              9 : CNES_AR        |
   |   10 : Time_Series        11 : Velocity_Fields   12 : SLR            |
   |   13 : LEO                14 : PANDA             15 : GAMIT          |
   |                                                                      |
   +---------------------------------HELP---------------------------------+
   |                                                                      |
   |    h : help                t : time_conver                           |
   |                                                                      |
   +----------------------------------------------------------------------+
 - Note: 请输入数据编号 (eg. 2 or a)
 - Note: Please enter the corresponding number or letter (eg. 2 or a)
 - 2

   +----------------------------------SP3---------------------------------+
   |                                                                      |
   +----------------------------------GPS---------------------------------+
   |                                                                      |
   |   1 : GPS_IGS_sp3          2 : GPS_IGR_sp3          3 : GPS_IGU_sp3  |
   |   4 : GPS_GRG_sp3                                                    |
   |                                                                      |
   +---------------------------------GCRE---------------------------------+
   |                                                                      |
   |   5 : GCRE_WHU_F_sp3       6 : GCRE_WHU_R_sp3       7 : GCRE_WHU_U_sp3  |
   |   8 : GCRE_WHU_H_sp3       9 : GCRE_WHU_RTS_sp3    10 : GCRE_SHA_F_sp3  |
   |  11 : GCRE_COD_F_sp3      12 : GCRE_GRG_F_sp3      13 : GCRE_GFZ_R_sp3  |
   |  14 : GCRE_IAC_F_sp3                                                 |
   |  15 : GRE_GFZ_F_sp3       16 : GRE_COD_R_sp3       17 : GLO_IGL_F_sp3   |
   |  18 : GRE_JAX_U_sp3       19 : CEG_GRG_U_sp3                         |
   |                                                                      |
   +----------------------------------------------------------------------+
 - Note: 请输入数据编号 / Please enter the data number (eg. 2)
 - Note: 返回上级目录,输入'y' / To go back to the parent directory, enter 'y'
   5
 * The data type is GCRE_WHU_F_sp3

 - 若需下载多天数据,请输入 <年 起始年积日 截止年积日> / Enter <year start_doy end_doy>
 - 若需下载单天数据,请输入 <年 年积日> / or enter <year doy>
 - Note: 如需返回上级目录,请输入y / In need of returning parent menu, plear enter <y>
   2025 1 2
 * Year - 2025 Doy - 1 ~ 2
```

Fig 18 Interactive Mode

4. After the download is complete, follow the prompt to input whether you need to unzip the files.

5. If you need to rename the files to shorter names after unzipping, enter a three-character string. For example, you could enter "**whu**".

```
 - 是否解压文件? 如需解压直接回车,若无需解压输入任意字符回车! / Unzip: Enter. Skip unzip: Any+Enter!

 * 开始解压文件 / Start extracting the file!
 * 解压完成 / Extraction completed!
 - 如无需更名直接回车,若需更名请输入三位字符! / Rename: <3char> + Enter. Skip: Enter!
   whf
 - 运行结束,是否重新引导? (y)
 - Execution completed. Would you like to restart? (y)
```

Fig 19 File Decompression

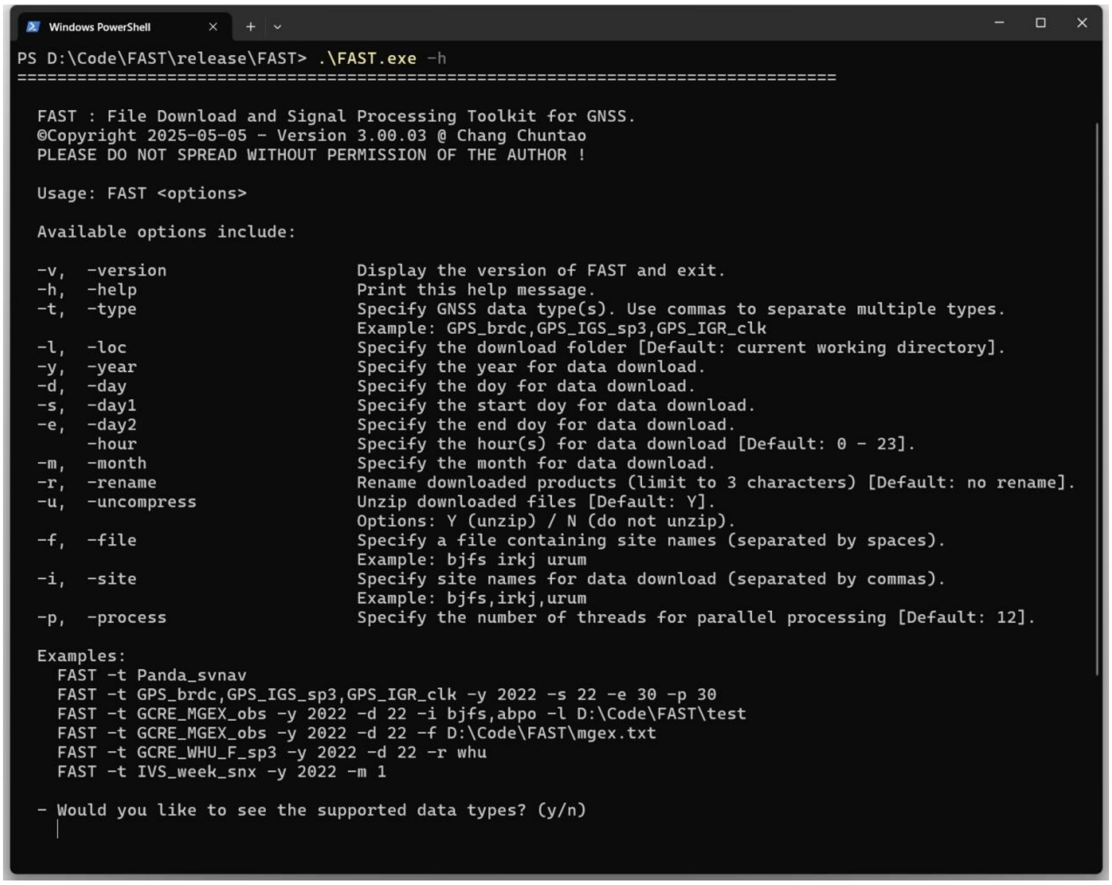
whf23473.sp3	2025/6/3 3:08	SP3 文件	2,722 KB
whf23474.sp3	2025/6/3 3:08	SP3 文件	2,722 KB

Fig 20 File renaming

4.2 Command-line Mode

To view the usage help for Command-line Mode, enter the following command in the terminal:

```
$ FAST -h
```



```
PS D:\Code\FAST\release\FAST> .\FAST.exe -h
==================================================================================

  FAST : File Download and Signal Processing Toolkit for GNSS.
  ©Copyright 2025-05-05 - Version 3.00.03 @ Chang Chuntao
  PLEASE DO NOT SPREAD WITHOUT PERMISSION OF THE AUTHOR !

  Usage: FAST <options>

  Available options include:

  -v,  -version                  Display the version of FAST and exit.
  -h,  -help                     Print this help message.
  -t,  -type                     Specify GNSS data type(s). Use commas to separate multiple types.
                                 Example: GPS_brdc,GPS_IGS_sp3,GPS_IGR_clk
  -l,  -loc                      Specify the download folder [Default: current working directory].
  -y,  -year                     Specify the year for data download.
  -d,  -day                      Specify the doy for data download.
  -s,  -day1                     Specify the start doy for data download.
  -e,  -day2                     Specify the end doy for data download.
       -hour                     Specify the hour(s) for data download [Default: 0 - 23].
  -m,  -month                    Specify the month for data download.
  -r,  -rename                   Rename downloaded products (limit to 3 characters) [Default: no rename].
  -u,  -uncompress               Unzip downloaded files [Default: Y].
                                 Options: Y (unzip) / N (do not unzip).
  -f,  -file                     Specify a file containing site names (separated by spaces).
                                 Example: bjfs irkj urum
  -i,  -site                     Specify site names for data download (separated by commas).
                                 Example: bjfs,irkj,urum
  -p,  -process                  Specify the number of threads for parallel processing [Default: 12].

  Examples:
    FAST -t Panda_svnav
    FAST -t GPS_brdc,GPS_IGS_sp3,GPS_IGR_clk -y 2022 -s 22 -e 30 -p 30
    FAST -t GCRE_MGEX_obs -y 2022 -d 22 -i bjfs,abpo -l D:\Code\FAST\test
    FAST -t GCRE_MGEX_obs -y 2022 -d 22 -f D:\Code\FAST\mgex.txt
    FAST -t GCRE_WHU_F_sp3 -y 2022 -d 22 -r whu
    FAST -t IVS_week_snx -y 2022 -m 1

  - Would you like to see the supported data types? (y/n)
```

Fig 21 Command-line Mode

4.3 GNSS Time Conversion Tool

In Interactive Mode, enter the '**t**' to use the GNSS Time Conversion Tool. As shown in the Fig 22, input the time format you need to convert. For example, if you want to convert the time to Year-DOY format and you need to convert DOY 1 of 2025, you would enter 2025 1 and press Enter to perform the conversion. The software will then output the result as shown in the figure.

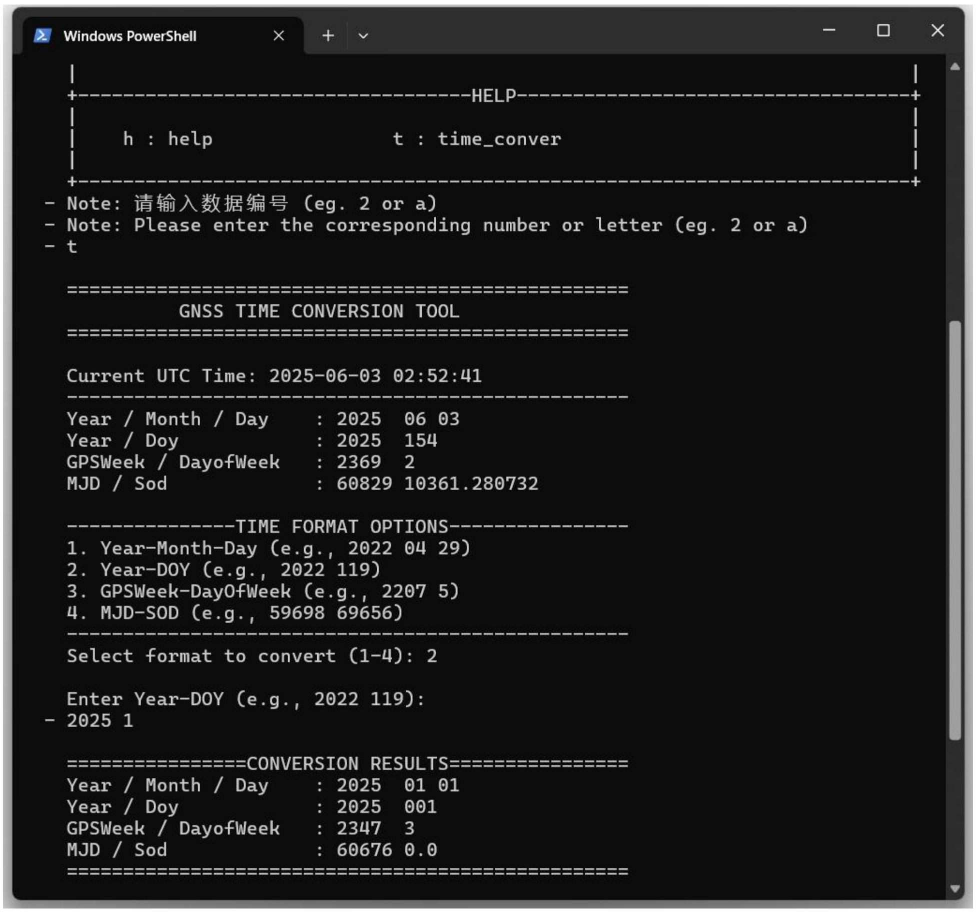


Fig 22 GNSS Time Conversion Tool

5 Mathematical Model

5.1 Cycle slip detection

This option identifies cycle slips using Melbourne-Wübbena (MW)(Bezmenov et al., 2019) and Geometry-Free (GF)(Zhang et al., 2023) combinations and calculates the ratio of cycle slips. The observation model for the Melbourne-Wübbena (MW) combination is as follows:

$$L_{\mathrm{MW}} = \frac{f_1\lambda_1\varphi_1 - f_2\lambda_2\varphi_2}{f_1 - f_2} - \frac{f_1P_1 + f_2P_2}{f_1 + f_2} = N_{\mathrm{WL}}\lambda_{\mathrm{WL}} \tag{1}$$

where: φ_1, φ_2 represent the carrier phase observations in cycles; P_1, P_2 represent the pseudorange observations in meters; f_1 、 f_2 represent the frequencies of the respective bands; λ_{WL} , N_{WL} represent the wide-lane wavelength and wide-lane ambiguity, respectively. The cycle slip detection statistic is constructed as follows:

$$N_{\mathrm{WL}} = \frac{L_{\mathrm{WL}}}{\lambda_{\mathrm{WL}}} = \varphi_1 - \varphi_2 - \frac{f_1 \bullet P_1 + f_2 \bullet P_2}{\lambda_{\mathrm{WL}}\left(f_1 + f_2\right)} \tag{2}$$

The recursive formula is used to calculate the average wide-lane ambiguity and root mean square for each epoch i:

$$\bar{N}_{WL}(i) = \bar{N}_{WL}(i-1) + \frac{1}{i}\left[N_{WL}(i) - \bar{N}_{WL}(i-1)\right] \tag{3}$$

$$\sigma^2(i) = \sigma^2(i-1) + \frac{1}{i}\left[\left(N_{WL}(i) - \bar{N}_{WL}(i-1)\right)^2 - \sigma^2(i-1)\right] \tag{4}$$

Where: $\bar{N}_{WL}(i)$ is the average wide-lane ambiguity for the previous i epochs; $\sigma^2(i)$ is the variance for the previous i epoch. If the condition in equation (5) is satisfied, it is considered that there is a cycle slip in the current epoch:

$$|N_{\mathrm{WL}}(i) - \bar{N}_{\mathrm{WL}}(i-1)| \geqslant 4\sigma(i-1) \tag{5}$$

The MW combination cannot detect cycle slips of equal magnitude on two frequencies, so a set of dual-frequency combinations different from the wide-lane combination is needed. The GF combination is usually used, expressed as:

$$L_{GF} = \lambda_1\varphi_1 - \lambda_2\varphi_2 = \frac{I}{f_1^2} - \frac{I}{f_2^2} + \lambda_1 N_1 - \lambda_2 N_2 + \varepsilon_{L_{GF}} \tag{6}$$

Where: $\varepsilon_{L_{GF}}$ is the combination observation noise of the carrier phase.

The GF combination eliminates the effects of receiver clock error, satellite clock error, and tropospheric delay, and only includes ionospheric error and frequency-related measurement noise. If the condition in equation (7) is satisfied, it is considered that there is a cycle slip in the i epoch:

$$\left|L_{GF}(i)-L_{GF}(i-1)\right|>0.15 \tag{7}$$

5.2 Phase Noise

The GF combination eliminates the effects of geometric distance and clock errors, retaining the ionospheric delay and noise, By taking the third difference(Zhao et al., 2016), the ionospheric trend term is eliminated, and the phase noise is extracted:

$$\begin{cases} \Delta^1 GF(t_i)=GF(t_i)-GF(t_{i-1}) \\ \Delta^2 GF(t_i)=\Delta^1 GF(t_i)-\Delta^1 GF(t_{i-1}) \\ \Delta^3 GF(t_i)=\Delta^2 GF(t_i)-\Delta^2 GF(t_{i-1}) \end{cases} \tag{8}$$

$$\Delta^3 GF(t_i)=GF(t_i)-3GF(t_{i-1})+3GF(t_{i-2})-GF(t_{i-3}) \tag{9}$$

The result of the third difference is approximately the phase noise combination:

$$\Delta^3 GF(t_i)\approx \varepsilon_{GF}(t_i)-3\varepsilon_{GF}(t_{i-1})+3\varepsilon_{GF}(t_{i-2})-\varepsilon_{GF}(t_{i-3}) \tag{10}$$

5.3 Pseudorange multipath

The pseudorange and carrier phase observation equations are combined to eliminate the effects of tropospheric and ionospheric delays, calculated according to formula (11). When using multi-frequency observation data, the two navigation signal frequencies with the largest difference are used for the dual-frequency combination calculation.

$$\begin{cases} MP_{k_1}=\rho_{k_1}-\dfrac{f_{k_1}^2+f_{k_2}^2}{f_{k_1}^2-f_{k_2}^2}\varphi_{k_1}+\dfrac{2f_{k_2}^2}{f_{k_1}^2-f_{k_2}^2}\varphi_{k_2} \\ MP_{k_2}=\rho_{k_2}-\dfrac{2f_{k_1}^2}{f_{k_1}^2-f_{k_2}^2}\varphi_{k_1}+\dfrac{f_{k_1}^2+f_{k_2}^2}{f_{k_1}^2-f_{k_2}^2}\varphi_{k_2} \end{cases} \tag{11}$$

Where: MP_{k_1} and MP_{k_2} are the quantities calculated on frequencies k_1 and k_2, respectively, which include multipath error and integer ambiguity information;

ρ_{k_1} and ρ_{k_2} are the pseudorange observations on frequencies k_1 and k_2 in meters; φ_{k_1} and φ_{k_2} are the carrier phase observations on frequencies k_1 and k_2 in meters.

For the same satellite observed continuously without cycle slips, the combination of ambiguity parameters will not change. The multipath error is calculated over multiple epochs without cycle slips according to formula (12).

$$\overline{MP_k} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N_{sw}}\left(MP_k(t_i) - \frac{\sum_{i=1}^{N_{sw}} MP_k(t_i)}{N_{sw}}\right)^2} \tag{12}$$

Where: $\overline{MP_k}$ represents the evaluation value of the multipath error observed by the receiver for the satellite at frequency k; N is the number of epochs; $MP_k(t_i)$ is the calculated value containing multipath error and integer ambiguity information observed by the receiver for the satellite at frequency k in epoch t.

5.4 Ionospheric delay rate

The ionospheric delay and the ionospheric delay rate are calculated according to formulas (13) and (14), respectively.

$$\begin{cases} I_{k_1} = \dfrac{f_{k_2}^2}{f_{k_1}^2 - f_{k_2}^2}(\varphi - \varphi_{k_1}) \\ I_{k_2} = \dfrac{f_{k_1}^2}{f_{k_1}^2 - f_{k_2}^2}(\varphi_{k_2} - \varphi) \end{cases} \tag{13}$$

Where: I_{k1} and I_{k2} represent the calculated values observed by the receiver for the satellite at frequencies k_1 and k_2, respectively, which include ionospheric delay, multipath, and integer ambiguity information.

$$\begin{cases} IOD_{k_1} = \dfrac{I_{k_1}(t_i) - I_{k_1}(t_{i-1})}{t_i - t_{i-1}} \\ IOD_{k_2} = \dfrac{I_{k_2}(t_i) - I_{k_2}(t_{i-1})}{t_i - t_{i-1}} \end{cases} \tag{14}$$

IOD_{k1} and IOD_{k2} represent the ionospheric delay rate for the satellite at frequencies k_1 and k_2, respectively, in units of meters per second (m/s). When the ionospheric delay rate of change is greater than 0.07 m/s, it indicates that a jump in ionospheric delay has occurred.

5.5 Standard point positioning

SPP is a fundamental technique in GNSS data processing(Chang et al., 2025). It determines the user's position by solving the pseudorange observation equations using broadcast ephemeris(Renfro et al., 2018). FAST implements SPP using a dual-frequency, ionosphere-free combination approach across GPS, BDS-3, and Galileo systems. The main processing strategy is summarized below.

Table 4 SPP Processing Strategy and Frequency Settings

Item	Setting
Observation Types	GPS (G): L1 & L2 Galileo (E): E1 & E5a BDS-3 (C): B1I & B3I
GNSS Orbit & Clock	Broadcast ephemeris
Tropospheric Delay	Collins(Collins, 1999)
Ionospheric Delay	First-order eliminated with Ionosphere-free combination
Elevation Cutoff	5°
Stochastic Model	Elevation-dependent weighting
Parameter Estimation	Least squares

At a given epoch, the pseudorange observation model is:

$$\rho_j = \sqrt{(x^j - x)^2 + (y^j - y)^2 + (z^j - z)^2} + ct_r - ct^j + ct_{ion} + ct_{tro} + ct_{mp} \tag{15}$$

Where ρ_j is the observed pseudorange; (x^j, y^j, z^j) and (x, y, z) are the coordinates of the satellite and the receiver in the Earth-Centered Earth-Fixed (ECEF) coordinate system, respectively; $c(t_r - t^j + t_{ion} + t_{tro} + t_{mp})$ represent receiver and satellite clock biases, ionospheric delay, tropospheric delay, and other error such as multipath effects. After moving all known quantities to the left-hand side, the observation equation for SPP becomes:

$$\rho'_j = \sqrt{(x_{sj} - x)^2 + (y_{sj} - y)^2 + (z_{sj} - z)^2} + ct_r \tag{16}$$

Equation (16) is a nonlinear system of equations. To solve it, the equation is linearized using a Taylor series expansion around an approximate receiver position:

$$\Delta\rho_j = i_{xj}\Delta x + i_{yj}\Delta y + i_{zj}\Delta z - ct_r \tag{17}$$

Where i_{xj}, i_{yj}, i_{zj} are the direction cosines from the receiver to the jth satellite, derived from the line-of-sight unit vector. The linearized equations for multiple satellites can be written in matrix form as:

$$P = H\Delta X \tag{18}$$

$$P = \begin{bmatrix} \Delta\rho_1 \\ \Delta\rho_2 \\ \vdots \\ \Delta\rho_N \end{bmatrix}, \quad H = \begin{bmatrix} i_{x1} & i_{y1} & i_{z1} & 1 \\ i_{x2} & i_{y2} & i_{z2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ i_{xN} & i_{yN} & i_{zN} & 1 \end{bmatrix}, \quad \Delta X = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ -ct_r \end{bmatrix} \tag{19}$$

The solution is obtained using the least squares method:

$$\Delta X = (H^T H)^{-1} H^T D \tag{20}$$

After each iteration, the computed corrections are applied to update the approximate receiver position. The design matrix and residuals are then recalculated using the updated position, and the process is repeated until convergence is achieved. The final solution yields the estimated coordinates of the GNSS receiver.

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7 References

Bezmenov, I. V., Blinov, I. Y., Naumov, A. V., & Pasynok, S. L. (2019). An algorithm for cycle-slip detection in a Melbourne–Wübbena combination formed of code and carrier phase GNSS measurements. *MEASUREMENT TECHNIQUES*, 62, 415-421.

Chang, C., Zhao, Q., Li, M., & Li, W. (2025). Augmentation message design for LEO-enhanced precise positioning: In-orbit performance assessment. *MEASUREMENT*, 243, 116314.

Collins, J. P. (1999). Assessment and development of a tropospheric delay model for aircraft users of the global positioning system. *M. Sc. E. thesis, Department of Geodesy and Geomatics Engineering Technical Report*(203)

Renfro, B. A., Stein, M., Boeker, N., & Terry, A. (2018). An analysis of global positioning system (GPS) standard positioning service (SPS) performance for 2017. *See https://www. gps. gov/systems/gps/performance/2014-GPS-SPS-performance-analysis. pdf*

Zhang, Z., Zeng, J., Li, B., & He, X. (2023). Principles, methods and applications of cycle slip detection and repair under complex observation conditions. *JOURNAL OF GEODESY*, 97(5), 50.

Zhao, Q., Wang, G., Liu, Z., Hu, Z., Dai, Z., & Liu, J. (2016). Analysis of BeiDou satellite measurements with code multipath and geometry-free ionosphere-free combinations. *SENSORS*, 16(1), 123.