

# **IonoMoni Users Manual**

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# Contents

|  |    |
|--|----|
| 1. Introduction .....                                    | 1  |
| 2. Mathematical models .....                             | 1  |
| 2.1 Basic Observation Equations .....                    | 1  |
| 2.2 Dual-frequency carrier-to-code leveling method ..... | 2  |
| 2.3 Uncombined Precise Point Positioning method .....    | 2  |
| 2.4 VTEC conversion from STEC and mapping function ..... | 3  |
| 2.4 ROTI Index .....                                     | 4  |
| 2.5 AATR Index .....                                     | 4  |
| 3. Environmental Requirements .....                      | 4  |
| 3.1 Environmental Requirements .....                     | 4  |
| 3.2 License .....  | 5  |
| 3.3 Python Environment .....                             | 5  |
| 4. Installation .....                                    | 5  |
| 5. Execution of the sample data .....                    | 6  |
| 5.1 Running Example for CCL_STEC Method .....            | 10 |
| 5.2 Running Example for PPP_STEC Method .....            | 11 |
| 5.3 Running Example for ROTI Index .....                 | 13 |
| 5.4 Running Example for AATR Index .....                 | 14 |
| 5.5 Execution and Results .....                          | 15 |
| 6. Visualization .....                                   | 16 |
| 6.1 CCL_STEC and PPP_STEC Results Plotting .....         | 16 |
| 6.2 VTEC Map Plotting .....                              | 17 |
| 6.3 ROTI and AATR Results Plotting .....                 | 17 |
| 6.4 Example of Plotting Results .....                    | 18 |
| 7. Batch Processing .....                                | 21 |
| 8. Data preparation .....                                | 23 |

## 1. Introduction

The ionosphere has a significant impact on Global Navigation Satellite System (GNSS) signals, introducing refraction and diffraction effects that can severely degrade positioning performance. With the current peak of Solar Cycle 25, increasingly prominent ionospheric space weather events and disturbances have further intensified adverse effects on GNSS applications. On the other hand, dual-frequency GNSS observations enable effective monitoring of ionospheric conditions, serving as a crucial foundation for the mitigation of ionospheric effects on GNSS positioning and the advancement of research into the physical mechanisms of ionospheric variability. The extraction and analysis of ionospheric parameters are essential for both scientific research and practical applications.

In this context, we developed the IonoMoni ionospheric parameter computation software, based on the secondary development of the GREAT-PVT software within the Visual Studio 2022 environment. The IonoMoni program offers multiple functionalities, including:

1. It supports STEC extraction using the dual-frequency Carrier-to-Code Leveling (CCL) method.
2. It supports STEC extraction based on the undifferenced and uncombined precise point positioning (UCPPP) method.
3. It supports VTEC conversion based on ionospheric mapping function and STEC.
4. It supports the calculation of the Rate of TEC Index (ROTI), which is a widely used indicator for detecting ionospheric irregularities of ionospheric diffractive effects.
5. It supports the estimation of the Along Arc TEC Rate (AATR), an effective metric for monitoring ionospheric disturbances, especially during geomagnetic storms or in equatorial and polar regions.

IonoMoni is able to process multi-GNSS observation data, including GPS, BDS, Galileo, and GLONASS constellations, and is compatible with both Rinex 2.x and Rinex 3.x file formats.

Furthermore, IonoMoni features batch processing and plotting capabilities, enabling efficient extraction and visualization of ionospheric parameters across multiple stations and multiple days.

## 2. Mathematical models

### 2.1 Basic Observation Equations

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

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

$$L_{r,n}^s = \rho_r^s + t_r - t^s - I_{r,n}^s + m_{r,w}^s Z_{r,w} + \lambda_n (N_{r,n}^s + B_{r,n} - B_n^s) + \phi_{r,n}^s + \varepsilon_{r,n}^s \quad (2)$$

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

n: frequency of observation (such as 1, 2);

$t_r$  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.

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

$N_{r,n}^s$ : 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 bias, in cycles, which can be divided into constant and time-varying parts. The constant part can be fully absorbed by the ambiguity parameter.

$\phi_{r,n}^s$ : wind-up effects of carrier phase.

$e_{r,n}^s$  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.

## 2.2 Dual-frequency carrier-to-code leveling method

The Geometry-Free (GF) combination of dual-frequency pseudorange and carrier phase measurements can be expressed as:

$$P_{r,4}^s = P_{r,1}^s - P_{r,2}^s = I_{r,1}^s - I_{r,2}^s + DCB^s - DCB_r + e_{r,1}^s - e_{r,2}^s \quad (3)$$

$$L_{r,4}^s = L_{r,1}^s - L_{r,2}^s = -I_{r,1}^s + I_{r,2}^s + \lambda_1(N_{r,1}^s + B_{r,1} - B_1^s) - \lambda_2(N_{r,2}^s + B_{r,2} - B_2^s) + \phi_{r,1}^s - \phi_{r,2}^s + \varepsilon_{r,1}^s - \varepsilon_{r,2}^s \quad (4)$$

where  $DCB^s = b_{r,1} - b_{r,2}$ , and  $DCB_r = b_1^s - b_2^s$ .

And the Smoothed  $\widetilde{P}_{r,4}^s$  at epoch  $t$  can be expressed as follows:

$$\widetilde{P}_{r,4}^s(t) = w_t P_4^s(t) + (1 - w_t)(\widetilde{P}_4^s(t-1) + [L_4^s(t) - L_4^s(t-1)]) \quad (t > 1) \quad (5)$$

where  $t$  is the epoch,  $w_t$  is the weight factor. Cycle slips and gross errors in the carrier phase observations should be removed before using the carrier phase observations to smooth the pseudorange observations. Here, both dual-frequency pseudorange code observations and ionospheric residual observations are used to detect cycle slips and gross errors.

And the slant total electron content (STEC) can be extracted from GNSS dual-frequency observations as follow:

$$STEC(t) = -\frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)} (\widetilde{P}_{r,4}^s(t) - DCB^s(t) + DCB_r(t)) \quad (6)$$

## 2.3 Uncombined Precise Point Positioning method

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

$$\begin{cases} P_{r,n}^s = \mu_r^s \cdot x + t_r - \bar{t}_{IF}^s + \gamma_n \cdot I_{r,1}^s + m_{r,w}^s Z_{r,w} + b_{r,n} - b_n^s \\ + (\alpha_{ij} b_i^s + \beta_{ij} b_j^s) + e_{r,n}^s \\ L_{r,n}^s = \mu_r^s \cdot x + t_r - \bar{t}_{IF}^s - \gamma_n \cdot l_{r,1}^s + m_{r,w}^s Z_{r,w} + \lambda_n(B_{r,n} - B_n^s + N_{r,n}^s) \\ + (\alpha_{ij} b_i^s + \beta_{ij} b_j^s) + \varepsilon_{r,n}^s \end{cases} \quad (7)$$

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  $n = j$ ):

$$\begin{cases} P_{r,i}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s + \hat{t}_{r,i}^s + m_{r,w}^s Z_{r,w} + e_{r,i}^s \\ P_{r,j}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s + \gamma_{ij} \hat{t}_{r,i}^s + m_{r,w}^s Z_{r,w} + e_{r,j}^s \\ L_{r,i}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s - \hat{t}_{r,i}^s + m_{r,w}^s Z_{r,w} + \hat{N}_{r,i}^s + \varepsilon_{r,i}^s \\ L_{r,j}^s = \mu_r^s \cdot x + \hat{t}_r - \bar{t}_{IF}^s - \gamma_{ij} \cdot \hat{t}_{r,i}^s + m_{r,w}^s Z_{r,w} + \hat{N}_{r,j}^s + \varepsilon_{r,j}^s \end{cases} \quad (8)$$

where  $\hat{t}_r$  is the estimated receiver clock bias parameter,  $\hat{t}_{r,i}^s$ ,  $\hat{N}_{r,i}^s$  and  $\hat{N}_{r,j}^s$  are the estimated ionospheric parameter and ambiguity parameters for the two frequencies, respectively, expressed as:

$$\begin{cases} \hat{L}_{r,i}^s = I_{r,i}^s + \beta_{ij}(b_{r,i} - b_{r,j}) - \beta_{ij}(b_i^s - b_j^s) \\ \hat{N}_{r,i}^s = N_{r,i}^s + [(B_{r,i} - B_i^s) - (b_{r,i} - b_i^s)] + 2\beta_{ij}[(b_{r,i} - b_i^s) - (b_{r,j} - b_j^s)] \\ \hat{N}_{r,j}^s = N_{r,j}^s + [(B_{r,j} - B_j^s) - (b_{r,j} - b_j^s)] + 2\beta_{ij}[(b_{r,j} - b_j^s) - (b_{r,i} - b_i^s)] \end{cases} \quad (9)$$

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). The parameters to be estimated in the dual-frequency undifferenced and uncombined model include:

$$X = (x \quad \hat{t}_r \quad Z_{r,w} \quad \hat{I}_{r,i}^s \quad \hat{N}_{r,i}^s \quad \hat{N}_{r,j}^s)^T \quad (10)$$

Since the estimated quantity is the slant ionospheric delay on the first frequency, the corresponding STEC can be extracted as:

$$\text{STEC} = \frac{f_1^2 I_{r,1}^s}{40.3} \quad (11)$$

## 2.4 VTEC conversion from STEC and mapping function

The function for converting STEC to VTEC can be expressed as:

$$\text{VTEC} = \frac{\text{STEC}}{M(\varepsilon)} \quad (12)$$

where,  $M(\varepsilon)$  is the mapping function dependent on the satellite elevation angle  $\varepsilon$ .

The Single-Layer Model mapping function can be expressed as:

$$M(\varepsilon) = \left(1 - \left(\frac{R_E \cos \varepsilon}{R_E + h}\right)^2\right)^{-1/2} \quad (13)$$

where  $R_E$  is the mean radius of the Earth,  $h$  is the assumed ionospheric shell height.

The Modified Single-Layer Model mapping function can be expressed as:

$$M_{MSLM}(\varepsilon) = \left[1 - \left(\frac{R_E \sin(\alpha z)}{R_E + h}\right)^2\right]^{-1/2} \quad (14)$$

where  $z$  is the zenith angle, and  $\alpha$  is an empirical correction factor.

The F&K mapping function can be expressed as:

$$M_{F\&K}(\varepsilon) = \frac{1 + \frac{R_E + h}{R_E}}{\sin \varepsilon + \sqrt{\left(\frac{R_E + h}{R_E}\right)^2 - \cos^2 \varepsilon}} \quad (15)$$

The Ou mapping function can be expressed as:

$$mf_{temp} = \frac{1}{\cos \left[ \arcsin \left( \frac{R_E \cos \varepsilon}{R_E + h} \right) \right]} \quad (16)$$

where  $mf_{temp}$  is an intermediate variable representing the obliquity factor.

$$M_{Ou}(\varepsilon) = \begin{cases} \sin(\varepsilon + 50^\circ) \cdot mf_{temp}, & \varepsilon < 40^\circ \\ mf_{temp}, & \varepsilon \geq 40^\circ \end{cases} \quad (17)$$

The Fanselow mapping function can be expressed as:

$$M_{Fanselow}(\varepsilon) = \frac{\sqrt{(R_E \sin \varepsilon)^2 + 2R_E h_2 + h_2^2} - \sqrt{(R_E \sin \varepsilon)^2 + 2R_E h_1 + h_1^2}}{h_2 - h_1} \quad (18)$$

where  $h_1 = h - 35000$ ,  $h_2 = h + 70000$  are the lower and upper boundaries of the ionospheric layer, respectively.

## 2.4 ROTI Index

ROTI is defined as the standard deviation of the ROT (Rate Of TEC) over some time interval. It is calculated as follows, where  $L_n$ ,  $\lambda_n$ , and  $f_n$  are the phase measurement, wavelength, and frequency for the nth frequency.

$L_4^S(i)$  is the geometry-free phase combination at time i:

$$L_4^S(i) = L_{r,1}^S(i) - L_{r,2}^S(i) \quad (19)$$

ROT (in TECU/minute) is calculated as:

$$\text{ROT}(i) = \frac{L_4^S(i) - L_4^S(i-1)}{\Delta t \times 10^{16} \times 40.3 \times \left( \frac{1}{f_1^2} - \frac{1}{f_2^2} \right)} \quad (20)$$

TECU (TEC Unit) is defined as  $10^{16}$  electrons per m<sup>2</sup>.  $\Delta t$  is the time difference between the epochs, in minutes. Finally, ROTI, calculated over N epochs, is

$$\text{ROTI}(i) = \sqrt{\frac{1}{N} \sum_{j=i-N}^i (\text{ROT}(j) - \overline{\text{ROT}})^2} \quad (21)$$

## 2.5 AATR Index

The variation of the STEC between two consecutive observations can be computed for a given epoch, i, as:

$$\Delta \text{STEC}_r^s(i) = L_{4,r}^s(i) - L_{4,r}^s(i-1) \quad (22)$$

where r denotes the receiver and s the satellite.

For a given transmitter-receiver pair, the variation over time of the STEC (Along Arc STEC Rate, AASR<sub>r</sub><sup>s</sup>) can be computed as:

$$\text{AASR}_r^s(i) = \frac{\Delta \text{STEC}_r^s(i)}{\Delta T} \quad (23)$$

where i indicates the observation epoch,  $\Delta \text{STEC}_r^s(i)$  corresponds to the difference of STECs between two consecutive observations in the same satellite-receiver arc and  $\Delta T$  is the elapsed time between these consecutive observations (typically 30 or 60 seconds). We apply this mapping squared in order to mitigate the effect of low elevation rays (instead of applying a cut-off angle). Then

$$\text{AATR}_r^s(i) = \frac{1}{M(\varepsilon)} \cdot \frac{\text{AASR}_r^s(i)}{M(\varepsilon)} = \frac{\Delta \text{STEC}_r^s(i)}{(M(\varepsilon))^2 \cdot \Delta T} \quad (24)$$

Finally, based on the previous equation (20), the AATR indicator is defined as the hourly weighted RMS of the instantaneous AATR values, computed over a predefined period for all satellites in view from a particular station, resulting in the AATR index for a given receiver.

$$\text{RMS}_{\text{AATR},r}(I) = \sqrt{\frac{1}{N} \sum_{i=I}^{I+\Delta I} \sum_{s=1}^{n_{\text{sat}}(i)} (\text{AATR}_r^s(i))^2} \quad (25)$$

where N is total number of observations during the selected interval  $\Delta I$  (typically one hour), after having summed all satellites in view,  $n_{\text{sat}}(i)$ , at every epoch i.

## 3. Environmental Requirements

### 3.1 Environmental Requirements

The executable CUI AP for Windows in the package was built using Microsoft Visual Studio 2022 on Windows 11 (64-bit), with the ReleaseWithXml configuration. All required dynamic link libraries are included in

the directory.

### 3.2 License

IonoMoni is released as open-source software under the GNU General Public License, version 3 (GPLv3). This license permits anyone to use, modify, and redistribute the software, provided that the same license terms are preserved and the source code remains accessible.

For detailed information, please refer to the full license text at: <https://www.gnu.org/licenses/gpl-3.0.html>.

### 3.3 Python Environment

IonoMoni includes several auxiliary Python scripts that require a Python environment and a set of dependencies listed in the requirements.txt file. For optimal compatibility, Python version 3.13 is recommended. It is further advised to use a virtual environment manager, such as Conda or venv, to ensure reproducibility and isolate dependencies.

## 4. Installation

Extract the software package **IonoMoni.zip** to a suitable directory <install\_dir>. The directory structure of IonoMoni is as follows:

Table 4.1 IonoMoni Directory Structure

| IonoMoni                  |   |
|---------------------------|---|
| <b>/src</b>               | IonoMoni Source Code                            |
| <b>/include</b>           | IonoMoni Header Files                           |
| <b>/lib</b>               | Static Libraries and Export Files               |
| <b>/build_resources</b>   | Dynamic Link Libraries and Sample data          |
| <b>/batch_process</b>     | Python Batch Processing Script                  |
| <b>/plot</b>              | Python Plotting Script                          |
| <b>/poleut1</b>           | Earth Orientation Parameters Generation Program |
| <b>/doc</b>               | User manual and Sample XML                      |
| <b>/CMakeLists.txt</b>    | CMake Build Configuration File                  |
| <b>/CMakePresets.json</b> | CMake Build Preset Settings                     |

The following instructions show how to build IonoMoni on Windows.

- (1) Using Visual Studio 2022, open the IonoMoni root folder as a CMake project. In the configuration menu, select “Release with XML”, and wait for CMake to configure and generate the build system automatically, as shown in Figures 4.1 and 4.2.

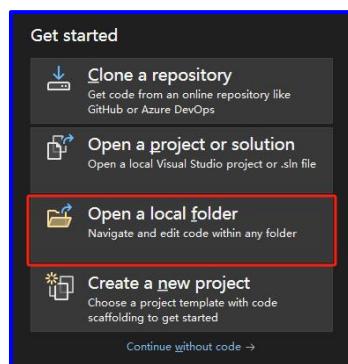


Figure 4.1 open the IonoMoni root folder



Figure 4.2 select “Release with XML”

- (2) Copy all contents from the `./build_resources` directory to `./out/build/release-with-xml/`.
- (3) In Visual Studio 2022, click Build → Build All (or press Ctrl + Shift + B) to compile and generate the IonoMoni.exe executable in the `./out/build/release-with-xml/` directory, as shown in Figures 4.3.

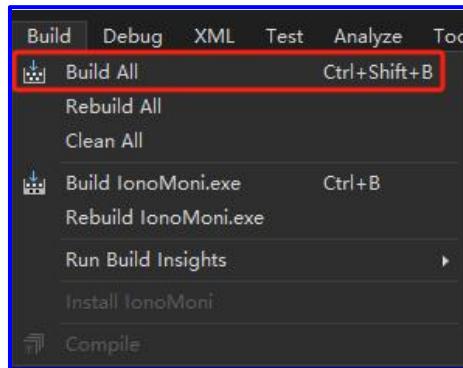


Figure 4.3 generate the IonoMoni.exe executable

## 5. Execution of the sample data

The input files for the sample case are located in the `build_resources` folder and should be copied to `./out/build/release-with-xml/` during the installation process. (Different modes of IonoMoni require different input files. Details about data preparation can be found in section **8.Data Acquisition.**) The folder structure is shown as follows:

Table 5.1 Sample Data Folder Structure

| Sample data          |                          |
|----------------------|--------------------------|
| <code>./gnss</code>  | GNSS data folder         |
| <code>./obs</code>   | Observation data folder  |
| <code>./model</code> | System folder            |
| <code>./upd</code>   | UPD folder               |
| <code>./xml</code>   | XML configuration folder |

We selected GNSS observation data from stations HKWS and ABPO on November 30, 2023, as the sample dataset. IonoMoni is configured and executed through XML files that define both the processing mode and associated parameters. In the following sections, we provide a detailed explanation of XML configuration usage. By making minor adjustments to the provided example XML templates, users can quickly and effectively begin using IonoMoni. The configuration elements are as follows:

Table 5.2 XML Configuration Elements and Corresponding Descriptions

| Item  | Descriptions   | Element in XML File |
|---|--|---------------------|
| <b>General Settings (First Level Element)</b> |  | <gen>               |
| Function                                      | Set the operation mode: CCL_STEC, PPP_STEC, ROTI, and AATR.              | <function>          |
| 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. (Currently, only 30-second intervals are supported.)                         | <int>               |
| Estimation Method                                 | Default is filtering.  | <est>               |
| <b>Input File Settings (First Level Element)</b>  |  | <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.      | <rinexn>            |
| Precise Clock File                                | Precise clock file for PPP_STEC processing.  | <rinexc>            |
| 3Days Precise Clock File                          | Precise clock file for CCL_STEC ROTI AATR processing.  | <THREE_SP3>         |
| 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>               |
| UPD File  | Uncalibrated phase delay file for ambiguity resolution.  | <upd>               |
| <b>Output File Settings (First Level Element)</b> |  | <outputs>           |
| Log File  | Log file for recording output information.   | <log>               |
| Results   | Output file for PPP calculation results.   | <flt>               |
| <b>Processing Settings (First Level Element)</b>  |  | <process>           |
| Sliding window for ROTI                           | Sliding window size used in ROTI computation (in epochs).  | <roti_window>       |
| Unit of ROT                                       | Unit of ROT, used for AATR and ROTI processing:<br>-sec:TECU/sec -min:TECU/min   | <rot_unit>          |
| Computation interval for AATR                     | Generate one AATR every specified number of epochs.  | <aatr_interval>     |
| Minimum arc length                                | Minimum arc length threshold (in epochs).  | <arc_min_length>    |
| Ionospheric Height                                | Height of the ionospheric layer (in meters)  | <ion_height>        |
| Mapping Function                                  | Type of mapping function used for VTEC conversion (0=SLM, 1=MSLM, 2=F_K, 3=Ou, 4=Fanbelow)                                   | <mapping_function>  |
| Cutoff Elevation Angle                            | Minimum elevation angle for satellite observations.  | <minimum_elevation> |

| Item   | Descriptions   | Element in XML File   |
|--|--|-----------------------|
| Phase Observations                           | Whether to use carrier phase observations:<br>- true: yes - false: no  | <phase>               |
| Tropospheric Parameters                      | Whether to estimate tropospheric parameters:<br>- true: yes - false: no  | <tropo>               |
| Ionospheric Parameters                       | Whether to estimate ionospheric parameters:<br>- true: yes - false: no   | <iono>                |
| Doppler Observations                         | Whether to use Doppler observations:<br>- 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_iono>       |
| Observation Combination                      | Observation combination method for processing:<br>- IONO_FREE : IF, supports dual-frequency<br>- RAW_ALL : UC, supports dual-frequency and multi-frequency | <obs_combinati on>    |
| Maximum Posterior Residual                   | Threshold for posterior residual editing.  | <max_res_norm >       |
| Coordinate Constraint                        | Coordinate constraint method:<br>- est: estimated constraint<br>- fix: fixed constraint<br>- kin: kinematic constraint                                     | <crd_constr>          |
| Kinematic Mode                               | Whether to enable kinematic mode:<br>- 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:<br>- true: yes - false: no   | <bds_code_bias _corr> |
| Cycle Slip Detection                         | Cycle slip detection model:<br>- default: default model  | <slip_model>          |
| Observation Frequency                        | Number of observation frequencies used in the solution.  | <frequency>           |
| <b>Filter Settings (First Level Element)</b> |  | <filter>              |

| Item   | Descriptions  | Element in XML File          |
|--|---|------------------------------|
| Filter Algorithm   | Filter algorithm to be used:<br>- srkf: square-root filter - kalman: Kalman filter  | method_flg                   |
| 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_delk                   |
|  | 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                    |
| <b>Ambiguity Resolution Settings (First Level Element)</b> |   | <ambiguity>                  |
| Fixing Mode  | Whether to perform ambiguity resolution:<br>- 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:<br>- 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>                      |
| Reference Satellite  | Whether to set a reference satellite:<br>- 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:<br>- alpha&maxdev: confidence interval parameters<br>- maxsig: maximum sigma value | <extra_widelane_decision>    |
| Wide-Lane Observations                                     |   | <widelane_decision>          |
| Narrow-Lane Observations                                   |   | <narrowlane_decision>        |
| <b>Satellite Settings (First Level Element)</b>            |   | <gps>/<bds>/<br><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>                        |

| Item           | Descriptions  | Element in XML File       |
|----------------|---|---------------------------|
| Frequency Band | <p>Observation frequency bands for different satellite systems:</p> <ul style="list-style-type: none"> <li>- GPS: 1-&gt;L1, 2-&gt;L2, 5-&gt;L5 (Currently, only L1 and L2 frequencies are supported.)</li> <li>- GAL: 1-&gt;E1, 5-&gt;E5a, 7-&gt;E5b, 8-&gt;E5, 6-&gt;E6 (Currently, only E1 and E5a frequencies are supported.)</li> <li>- BDS: 2-&gt;B1I, 7-&gt;B2I, 6-&gt;B3I, 1-&gt;B1C, 5-&gt;B2a, 9-&gt;B2b, 8-&gt;B2a+b (Currently, only B1I B2I and B3I frequencies are supported.)</li> <li>- GLO: 1-&gt;G1, 2-&gt;G2</li> </ul> | <code>&lt;band&gt;</code> |

### 5.1 Running Example for CCL\_STEC Method

```

<gen>
  <function>CCL_STEC      </function>
  <beg> 2023-11-26 00:00:00 </beg>    <!-- begin time <!-->
  <end> 2023-11-26 23:59:30 </end>    <!-- end time <!-->
  <int> 30                  </int>     <!-- sampling interval <!-->
  <sys> GPS BDS GLO GAL   </sys>     <!-- system ex: GPS GAL GLO BDS <!-->
  <rec> ABPO HKWS          </rec>     <!-- site (4-char upper) <!-->
  <est> FLT                </est>     <!-- Estimator : FLT <!-->
</gen>

```

Figure 5.1.1 XML configuration example for the CCL\_STEC mode

```

<inputs>
  <rinexo> <!-- rinex obs file <!-->
    obs\hkws3300.23o
    obs\abpo3300.23o
  </rinexo>
  <rinex> gnss\BRDC00IGS_R_20233300000_01D_MN.rnx </rinex> <!-- rinex nav file <!-->
  <rinexc> gnss\CODOMGXFIN_20233300000_01D_30S_CLK.CLK </rinexc> <!-- precise satellite clock offset file <!-->
  <sp3> gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3 </sp3> <!-- precise orbit file <!-->

  <THREE_SP3> <!-- CCL ROTI AATR precise orbit file <!-->
    gnss\CODOMGXFIN_20233290000_01D_05M_ORB.SP3
    gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3
    gnss\CODOMGXFIN_20233310000_01D_05M_ORB.SP3
  </THREE_SP3>
  <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\CA50MGXRAP_20233300000_01D_01D_DCB.BSX </bias> <!-- DCB file <!-->
  <upd> upd\upd_nl_2023330_GREC upd\upd_wl_2023330_GREC </upd> <!-- uncalibrated phase delay, for fixing ambiguity <!-->
</inputs>

```

Figure 5.1.2 XML configuration example for the CCL\_STEC mode

```

<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, currently only 1 and 2 frequencies are supported. <!-->
<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"> <!--> GL0 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
</sat>
<band> 1 2 </band>
<freq> 1 2 </freq>

```

Figure 5.1.3 XML configuration example for the CCL\_STEC mode

```

<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> <!--> the satellite frequency, currently only 1 and 5 frequencies are supported. <!-->
<freq> 1 2 </freq>
</gal>
<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 C40
    C41 C42 C43 C44 C45 C46
</sat>
<band> 2 7 </band> <!--> the satellite frequency, currently only 2 and 6, 7 frequencies are supported. <!-->
<freq> 1 2 </freq>
</bds>

```

Figure 5.1.4 XML configuration example for the CCL\_STEC mode

```

<process>
    <roti_window> 10 <!--> roti_window <!--> sliding window size (in epochs) <!-->
    <rot_unit> min <!--> rot_unit <!--> unit of ROT (sec/min) <!-->
    <aatr_interval> 60 <!--> aatr_interval <!--> AATR calculation interval (in epochs) <!-->
    <arc_min_length> 10 <!--> arc_min_length <!--> minimum arc length threshold (in epochs) <!-->
    <ion_height> 350000 <!--> ion_height <!--> height of the ionospheric layer (in meters) <!-->
    <mapping_function> 0 <!--> mapping_function <!--> type of mapping function used for VTEC conve
    <minimum_elev> 7 <!--> minimum_elev <!--> cut-off satellite elevation(deg) <!-->

```

Figure 5.1.5 XML configuration example for the CCL\_STEC mode

## 5.2 Running Example for PPP\_STEC Method

The settings for each satellite system are specified in Figures 5.1.3 and 5.1.4.

```

<gen>
    <function>PPP_STEC </function><!--> function: CCL_STEC PPP_STEC ROTI AATR <!-->
    <beg> 2023-11-26 00:00:00 </beg> <!--> begin time <!-->
    <end> 2023-11-26 23:59:30 </end> <!--> end time <!-->
    <int> 30 </int> <!--> sampling interval <!-->
    <sys> GPS BDS GLO GAL </sys> <!--> system ex: GPS GAL GLO BDS <!-->
    <rec> ABPO HKWS </rec> <!--> site (4-char upper) <!-->
    <est> FLT </est> <!--> Estimator : FLT <!-->
</gen>

```

Figure 5.2.1 XML configuration example for the PPP\_STEC mode

```

<inputs>
    <rinexo>    <!--> rinex obs file <!-->
        obs\hkws3300.23o
        obs\abpo3300.23o
    </rinexo>
    <rinexn> gnss\BRDC00IGS_R_20233300000_01D.MN.rnx </rinexn>  <!--> rinex nav file <!-->
    <rinexc> gnss\CODOMGXFIN_20233300000_01D_3OS_CLK.CLK </rinexc>  <!--> precise satellite clock offset file <!-->
    <sp3> gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3 </sp3>  <!--> precise orbit file <!-->

    <THREE_SP3>  <!--> CCL ROTI AATTR precise orbit file <!-->
        gnss\CODOMGXFIN_20233290000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233310000_01D_05M_ORB.SP3
    </THREE_SP3>
    <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\poleuti </eop>  <!--> EOP file <!-->
    <bias> gnss\CASOMGXRAP_20233300000_01D_01D_DCB.BSX </bias>  <!--> DCB file <!-->
    <upd> upd\upd_nl_2023330_GREC upd\upd_wl_2023330_GREC </upd>  <!--> uncalibrated phase delay, for fixing ambiguity <!-->
</inputs>

```

Figure 5.2.2 XML configuration example for the PPP\_STEC mode

```

<minimum_elev> 7 </minimum_elev><!--> cut-off satellite elevation(deg) <!<!-->

<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 <!-->
<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 <!-->

```

Figure 5.2.3 XML configuration example for the PPP\_STEC mode

```

<process>
    <roti_window> 10 </roti_window><!--> sliding window size (in epochs)<!-->
    <rot_unit> min </rot_unit><!--> unit of ROT (sec/min)<!-->
    <aatr_interval> 60 </aatr_interval><!--> AATTR calculation interval (in epochs) <!-->
    <arc_min_length> 10 </arc_min_length><!--> minimum arc length threshold (in epochs)<!-->
    <ion_height> 350000 </ion_height><!--> height of the ionospheric layer (in meters) <!-->
    <mapping_function> 0 </mapping_function><!--> type of mapping function used for VTEC conve
    <minimum_elev> 7 </minimum_elev><!--> cut-off satellite elevation(deg) <!<!-->

```

Figure 5.2.4 XML configuration example for the PPP\_STEC mode

```

<filter
    method_flt="kalman"
    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> NO </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/amb1onds <!-->
    <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 5.2.5 XML configuration example for the PPP\_STEC mode

### 5.3 Running Example for ROTI Index

The settings for each satellite system are specified in Figures 5.1.3 and 5.1.4.

```

<gen>
    <function>ROTI </function><!--> function: CCL_STEC PPP_STEC ROTI AATR <!-->
    <beg> 2023-11-26 00:00:00 </beg> <!--> begin time <!-->
    <end> 2023-11-26 23:59:30 </end> <!--> end time <!-->
    <int> 30 </int> <!--> sampling interval <!-->
    <sys> GPS BDS GLO GAL </sys> <!--> system ex: GPS GAL GLO BDS <!-->
    <rec> ABPO HKWS </rec> <!--> site (4-char upper) <!-->
    <est> FLT </est> <!--> Estimator : FLT <!-->
</gen>

```

Figure 5.3.1 XML configuration example for the ROTI mode

```

<inputs>
    <rinexo> <!--> rinex obs file <!-->
        obs\hkws3300.23o
        obs\abpo3300.23o
    </rinexo>
    <rinexn> gnss\BRDC00IGS_R_20233300000_01D_MN.rnx </rinexn> <!--> rinex nav file <!-->
    <rinexc> gnss\CODOMGXFIN_20233300000_01D_30S_CLK.CLK </rinexc> <!--> precise satellite clock offset file <!-->
    <sp3> gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3 </sp3> <!--> precise orbit file <!-->

    <THREE_SP3> <!--> CCL ROTI AATTR precise orbit file <!-->
        gnss\CODOMGXFIN_20233290000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233310000_01D_05M_ORB.SP3
    </THREE_SP3>
    <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\poleutl </eop> <!--> ERP file <!-->
    <bias> gnss\CAS0MGXRAP_20233300000_01D_01D_DCB.BSX </bias> <!--> DCB file <!-->
    <upd> upd\upd_nl_2023330_GREC upd\upd_wl_2023330_GREC </upd> <!--> uncalibrated phase delay, for fixing ambiguity <!-->
</inputs>

```

Figure 5.3.2 XML configuration example for the ROTI mode

```

<process>
    <roti_window> 10 </roti_window> <!--> sliding window size (in epochs) <!-->
    <rot_unit> min </rot_unit> <!--> unit of ROT (sec/min) <!-->
    <aatr_interval> 60 </aatr_interval> <!--> AATTR calculation interval (in epochs) <!-->
    <arc_min_length> 10 </arc_min_length> <!--> minimum arc length threshold (in epochs) <!-->
    <ion_height> 350000 </ion_height> <!--> height of the ionospheric layer (in meters) <!-->
    <mapping_function> 0 </mapping_function> <!--> type of mapping function used for VTEC conve
    <minimum_elev> 7 </minimum_elev> <!--> cut-off satellite elevation(deg) <!<!-->

```

Figure 5.3.3. XML configuration example for the ROTI mode

#### 5.4 Running Example for AATR Index

The settings for each satellite system are specified in Figures 5.1.3 and 5.1.4.

```

<gen>
    <function>AATTR </function> <!--> function: CCL_STEC PPP_STEC ROTI AATTR <!-->
    <beg> 2023-11-26 00:00:00 </beg> <!--> begin time <!-->
    <end> 2023-11-26 23:59:30 </end> <!--> end time <!-->
    <int> 30 </int> <!--> sampling interval <!-->
    <sys> GPS BDS GLO GAL </sys> <!--> system ex: GPS GAL GLO BDS <!-->
    <rec> ABPO HKWS </rec> <!--> site (4-char upper) <!-->
    <est> FLT </est> <!--> Estimator : FLT <!-->
</gen>

```

Figure 5.4.1 XML configuration example for the AATR mode

```

<inputs>
    <rinexo> <!--> rinex obs file <!-->
        obs\hkws3300.23o
        obs\abpo3300.23o
    </rinexo>
    <rinexn> gnss\BRDC00IGS_R_20233300000_01D_MN.rnx </rinexn> <!--> rinex nav file <!-->
    <rinexc> gnss\CODOMGXFIN_20233300000_01D_30S_CLK.CLK </rinexc> <!--> precise satellite clock offset file <!-->
    <sp3> gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3 </sp3> <!--> precise orbit file <!-->

    <THREE_SP3> <!--> CCL ROTI AATTR precise orbit file <!-->
        gnss\CODOMGXFIN_20233290000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233300000_01D_05M_ORB.SP3
        gnss\CODOMGXFIN_20233310000_01D_05M_ORB.SP3
    </THREE_SP3>
    <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\poleutl </eop> <!--> ERP file <!-->
    <bias> gnss\CAS0MGXRAP_20233300000_01D_01D_DCB.BSX </bias> <!--> DCB file <!-->
    <upd> upd\upd_nl_2023330_GREC upd\upd_wl_2023330_GREC </upd> <!--> uncalibrated phase delay, for fixing ambiguity <!-->
</inputs>

```

Figure 5.4.2 XML configuration example for the AATR mode

```

<process>
  <roti_window>      10          </roti_window><!-- sliding window size (in epochs)<!-->
  <roti_unit>        min         </roti_unit><!-- unit of ROT (sec/min)<!-->
  <aatr_interval>    60          </aatr_interval><!-- AATR calculation interval (in epochs) <!-->
  <arc_min_length>   10          </arc_min_length><!-- minimum arc length threshold (in epochs)<!-->
  <ion_height>       350000     </ion_height><!-- height of the ionospheric layer (in meters) <!-->
  <mapping_function> 0           </mapping_function><!-- type of mapping function used for VTEC conve
  <minimum_elev>     7           </minimum_elev><!-- cut-off satellite elevation(deg) <!-->

```

Figure 5.4.3 XML configuration example for the AATR mode

## 5.5 Execution and Results

After configuring the input files and XML, set **IonoMoni.cpp** as the startup item and run the program, as shown in Figures 5.5.1 and 5.5.2. The output files will be automatically saved in the result folder, which will be created under the **./out/build/release-with-xml/** directory.

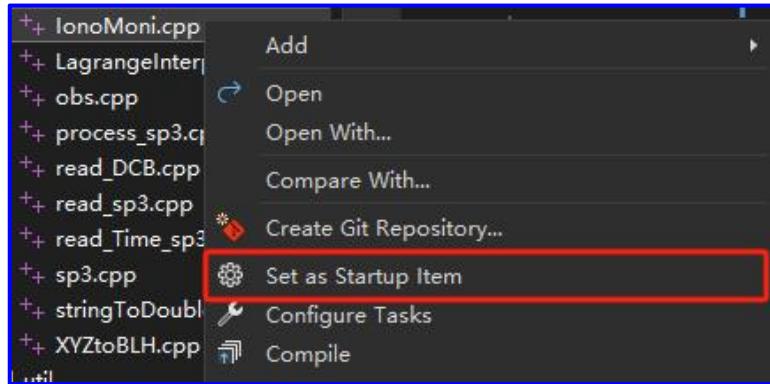


Figure 5.5.1 Set IonoMoni.cpp as the start



Figure 5.5.2 Run the IonoMoni program

The ROT, ROTI, and STEC results are saved in a matrix format to text files named after the corresponding station and satellite system. Each row represents one epoch, and each column corresponds to one satellite. Figure 5.5.3 shows an example of the ROT, ROTI, and STEC results.

| Epoch \ PRN | G01     | G02       | G03     | G04     | G05     | G06     | G07      | G08      | G09      | G10     | G11     |
|-------------|---------|-----------|---------|---------|---------|---------|----------|----------|----------|---------|---------|
| Epoch 0001: | 0.00000 | 0.00000   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000  | 0.00000  | 0.00000  | 0.00000 | 0.00000 |
| Epoch 0002: | 0.00000 | 0.00000   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000  | 0.00000  | 0.00000  | 0.00000 | 0.00000 |
| Epoch 0003: | 0.00000 | 0.00000   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000  | 0.00000  | 0.00000  | 0.00000 | 0.00000 |
| Epoch 0004: | 0.00000 | 0.00000   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000  | 0.00000  | 0.00000  | 0.00000 | 0.00000 |
| Epoch 0005: | 0.00000 | 0.00000   | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000  | 0.00000  | 0.00000  | 0.00000 | 0.00000 |
| Epoch 0006: | 0.00000 | 170.41060 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 17.18452 | 37.71762 | 47.81325 | 0.00000 | 0.00000 |
| Epoch 0007: | 0.00000 | 169.21639 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 17.14016 | 37.98050 | 47.05335 | 0.00000 | 0.00000 |
| Epoch 0008: | 0.00000 | 166.74931 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 17.20619 | 37.90358 | 46.77237 | 0.00000 | 0.00000 |
| Epoch 0009: | 0.00000 | 165.25314 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 15.73836 | 37.74839 | 46.46997 | 0.00000 | 0.00000 |
| Epoch 0010: | 0.00000 | 164.09089 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.22180 | 37.96126 | 47.20903 | 0.00000 | 0.00000 |
| Epoch 0011: | 0.00000 | 163.11176 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.83380 | 37.81412 | 47.71941 | 0.00000 | 0.00000 |
| Epoch 0012: | 0.00000 | 162.25150 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.69609 | 37.79785 | 47.53581 | 0.00000 | 0.00000 |
| Epoch 0013: | 0.00000 | 161.66234 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.01677 | 38.03709 | 47.04900 | 0.00000 | 0.00000 |
| Epoch 0014: | 0.00000 | 161.15183 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 15.68226 | 37.77123 | 46.67346 | 0.00000 | 0.00000 |
| Epoch 0015: | 0.00000 | 160.38521 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.50542 | 37.63392 | 46.33859 | 0.00000 | 0.00000 |
| Epoch 0016: | 0.00000 | 159.12480 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.65976 | 37.50459 | 46.41475 | 0.00000 | 0.00000 |
| Epoch 0017: | 0.00000 | 157.83829 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.48456 | 37.40403 | 46.30438 | 0.00000 | 0.00000 |
| Epoch 0018: | 0.00000 | 157.00238 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.25472 | 37.24393 | 46.27686 | 0.00000 | 0.00000 |
| Epoch 0019: | 0.00000 | 156.12873 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.07373 | 37.04107 | 46.05675 | 0.00000 | 0.00000 |
| Epoch 0020: | 0.00000 | 155.15940 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 15.93329 | 36.92658 | 45.88945 | 0.00000 | 0.00000 |
| Epoch 0021: | 0.00000 | 154.18936 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.05841 | 36.82520 | 45.68417 | 0.00000 | 0.00000 |
| Epoch 0022: | 0.00000 | 153.02225 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.24846 | 36.68029 | 45.68116 | 0.00000 | 0.00000 |
| Epoch 0023: | 0.00000 | 151.87403 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.34929 | 36.52656 | 45.74338 | 0.00000 | 0.00000 |
| Epoch 0024: | 0.00000 | 151.00554 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.36874 | 36.32905 | 45.60834 | 0.00000 | 0.00000 |
| Epoch 0025: | 0.00000 | 150.17355 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.53409 | 35.93875 | 45.31820 | 0.00000 | 0.00000 |
| Epoch 0026: | 0.00000 | 149.45661 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.53821 | 35.74039 | 45.20635 | 0.00000 | 0.00000 |
| Epoch 0027: | 0.00000 | 148.76614 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.87359 | 35.49386 | 44.96444 | 0.00000 | 0.00000 |
| Epoch 0028: | 0.00000 | 147.95507 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 16.94641 | 35.17642 | 44.91592 | 0.00000 | 0.00000 |

Figure 5.5.3 Example of output format for ROT, ROTI, and STEC results

The AATR results are saved in a list format to text files named after the corresponding station and satellite

system. Each row represents one time block, and the number of epochs spanned by each block depends on the settings in the XML file. Figure 5.5.4 shows an example of the AATR results.

| Block     | AATR    |
|-----------|---------|
| Block 01: | 0.41920 |
| Block 02: | 0.25623 |
| Block 03: | 0.25531 |
| Block 04: | 0.17505 |
| Block 05: | 0.20425 |
| Block 06: | 0.22489 |
| Block 07: | 0.19512 |
| Block 08: | 0.17170 |
| Block 09: | 0.17960 |
| Block 10: | 0.17544 |
| Block 11: | 0.32271 |
| Block 12: | 0.24659 |
| Block 13: | 0.12649 |
| Block 14: | 0.20507 |
| Block 15: | 0.25380 |
| Block 16: | 0.16091 |
| Block 17: | 0.17800 |
| Block 18: | 0.21411 |
| Block 19: | 0.11007 |
| Block 20: | 0.06791 |
| Block 21: | 0.07264 |
| Block 22: | 0.04325 |
| Block 23: | 0.13730 |
| Block 24: | 0.17746 |

Figure 5.5.4 Example of output format for AATR results

## 6. Visualization

The Python plotting scripts provided with IonoMoni support multi-station plotting for a single day. The directory structure under the plot folder is as follows:

Table 6.1 Plot Folder Structure

| plot                   |                                     |
|------------------------|-------------------------------------|
| <i>./data_aatr</i>     | Input folder for AATR plot data     |
| <i>./data_ccl</i>      | Input folder for CCL_STEC plot data |
| <i>./data_ppp</i>      | Input folder for PPP_STEC plot data |
| <i>./data_roti</i>     | Input folder for ROTI plot data     |
| <i>./output</i>        | Output folder for plot results      |
| <i>./PythonScripts</i> | Plot script folder                  |

### 6.1CCL\_STEC and PPP\_STEC Results Plotting

To plot the STEC results, the text output files generated by IonoMoni in either CCL\_STEC or PPP\_STEC mode must be used as input data. Fanyi1 These files should be placed in the *./data\_ccl* or *./data\_ppp* folder.

The following takes the processing of CCL\_STEC mode results as an example:

Open the *ccl\_stec\_plot.py* script located in the *./PythonScripts* folder, and modify the parameters in the main function as shown in Figure 6.1.1. The *site\_list* should include all stations to be plotted. The *year* and *doy* should correspond to the year and day of year of the input data, and *site\_list* should include all station names corresponding to the input data in the *./data\_ccl* folder.

```

# ===== Main entry point =====
if __name__ == "__main__":
    site_list = ["HKWS", "ABPO"]
    input_path = "../data_ccl"                      # Relative input path
    output_path = "../output"                       # Relative output path
    year = 2023
    doy = 330

batch_plot(site_list, input_path, output_path, year, doy)

```

Figure 6.1.1 Example of the main function in ccl\_stec\_plot.py

After running the script, the generated plotting results will be saved in PNG format to the *./output/ccl\_stec\_plot/<year>\_<doy>/<site>* directory.

## 6.2VTEC Map Plotting

To plot the VTEC map, the text output files generated by IonoMoni in either CCL\_STEC or PPP\_STEC mode must be used as input data. These files should be placed in the *./data\_vtec* folder. (The data for one station on a single day should include text output files for IPP longitude and latitude, as well as a text output file for VTEC.).

Open the *vtec\_map\_plot.py* script located in the *./PythonScripts* folder, and modify the parameters in the main function as shown in Figure 6.2.1. The *site\_list* should include all stations to be plotted. The system selected should match the input text files (GPS, BDS, GAL, GLO). The *year* and *doy* should correspond to the year and day of year of the input data, and *site\_list* should include all station names corresponding to the input data in the *./data\_vtec* folder.

```

# ===== Main entry point =====
if __name__ == "__main__":
    input_folder = r"../data_vtec" # Input data directory
    output_base = r"../output" # Output root directory
    sitelists = ["ABPO"] # Station list
    year = 2023
    doy = 330
    system = "GPS"
    plot_multi_station_vtec(
        input_folder, sitelists, system,
        output_base=output_base, year=year, doy=doy
    )

```

Figure 6.2.1 Example of the main function in vtec\_map\_plot.py

After running the script, the generated plotting results will be saved in PNG format to the *./output/vtec\_map\_plot/<year>\_<doy>/*directory. The output file is named following the convention *VTEC\_<system>-map\_lon<lon\_min><E/W>-<lon\_max><E/W>-lat<lat\_min><N/S>-<lat\_max><N/S>.png*, where *lon\_min* and *lon\_max* represent the minimum and maximum longitudes with *E* or *W* denoting east or west, and *lat\_min* and *lat\_max* represent the minimum and maximum latitudes with *N* or *S* denoting north or south.

## 6.3ROTI and AATR Results Plotting

To plot the results of ROTI or AATR, the text output files generated by IonoMoni in ROTI or AATR mode must be used as input data and placed in the *./data\_roti* or *./data\_aatr* folder, respectively.

The following takes the processing of ROTI mode results as an example:

Open the *roti\_plot.py* script located in the *./PythonScripts* folder, and modify the parameters in the main

function as shown in Figure 6.3.1. The **year** and **doy** should match the year and day of year of the input data, **rot\_unit** should be consistent with the unit setting used in the XML configuration when the input data was generated, and **site\_list** should include all station names corresponding to the input data in the **./data\_ccl** folder.

```
if __name__ == "__main__":
    base_input_path = "../data_roti"
    base_output_path = "../output"
    year = 2023
    doy = 330
    rot_unit = "min" # "sec" means ROT unit is TECU/sec; "min" means TECU/min
    site_list = ["HKWS", "ABPO"] # Add your station names here

    batch_plot_roti_rot(base_input_path, base_output_path, year, doy, rot_unit, site_list)
```

Figure 6.3.1 Example of the main function in roti\_plot.py

After running the script, the generated plotting results will be saved in PNG format to the **./output/roti\_plot/<year>\_<doy>/<site>** directory.

#### 6.4 Example of Plotting Results

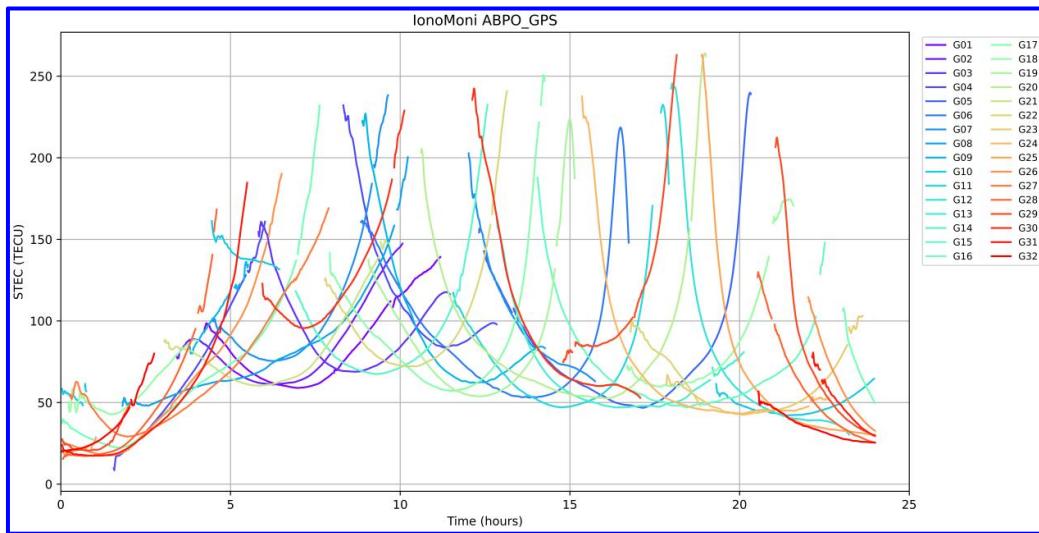


Figure 6.4.1 Plotting Example Based on CCL\_STEC Results

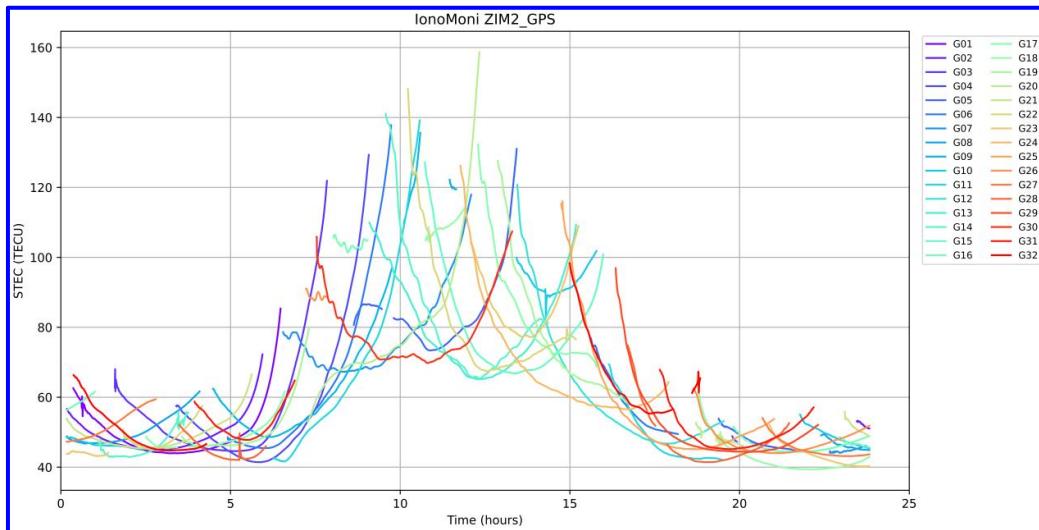


Figure 6.4.2 Plotting Example Based on PPP\_STEC Results

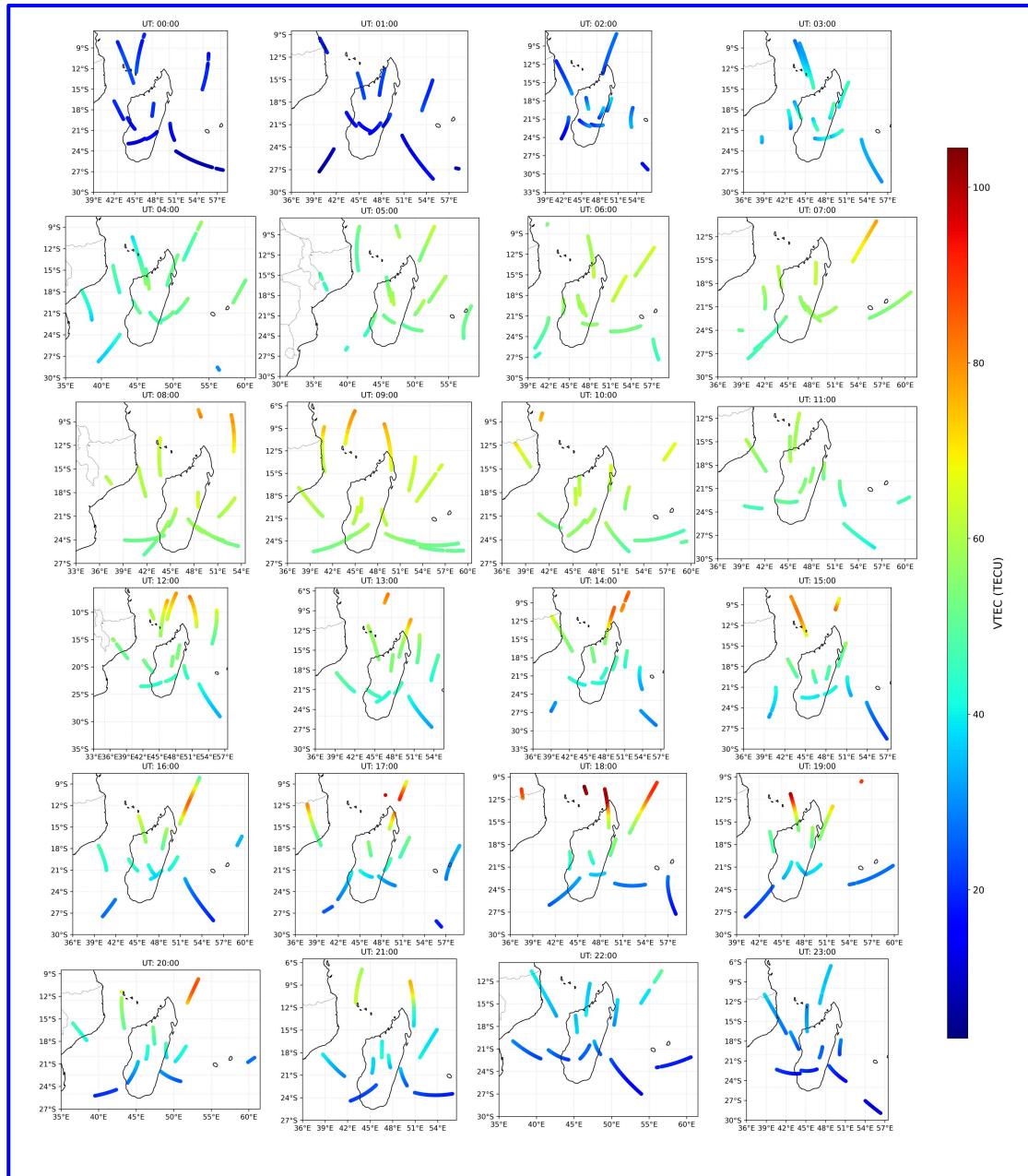


Figure 6.4.3 VTEC Map Plotting Example Based on CCL\_STEC Results

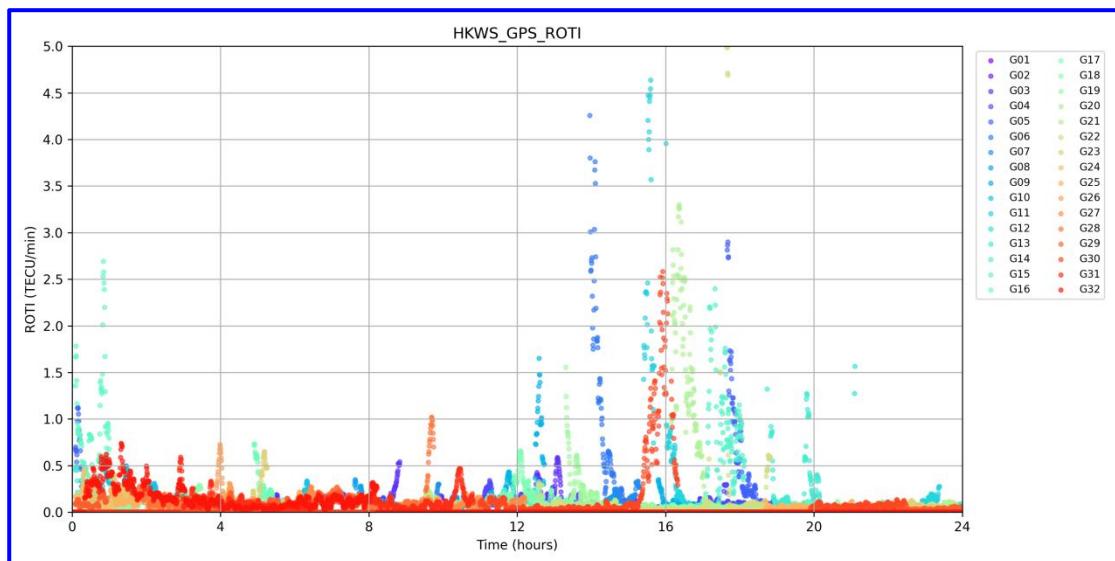


Figure 6.3.3 Plotting Example Based on ROTI Results

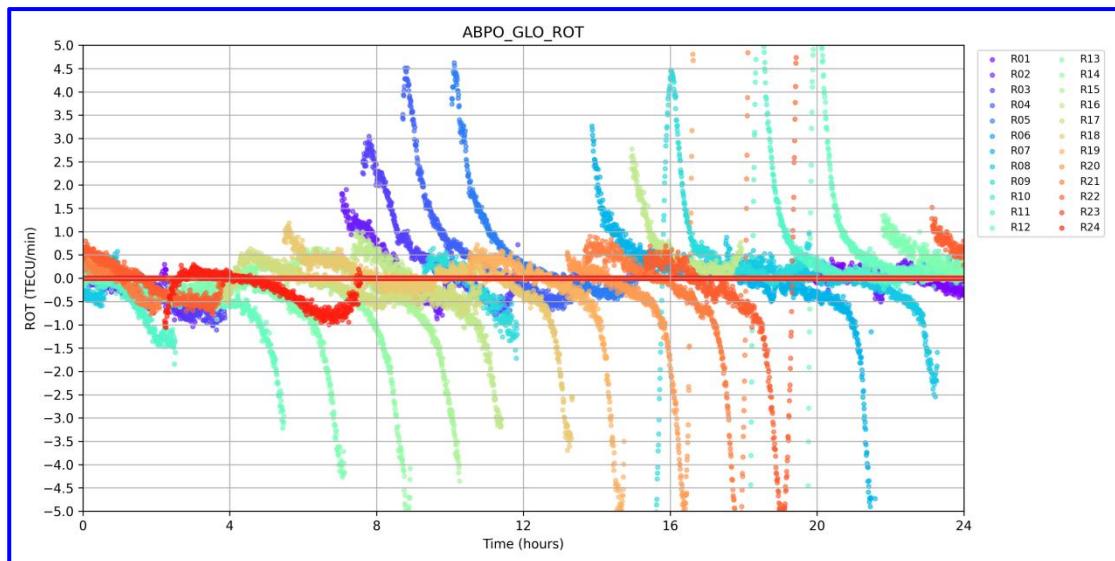


Figure 6.3.4 Plotting Example Based on ROT Results

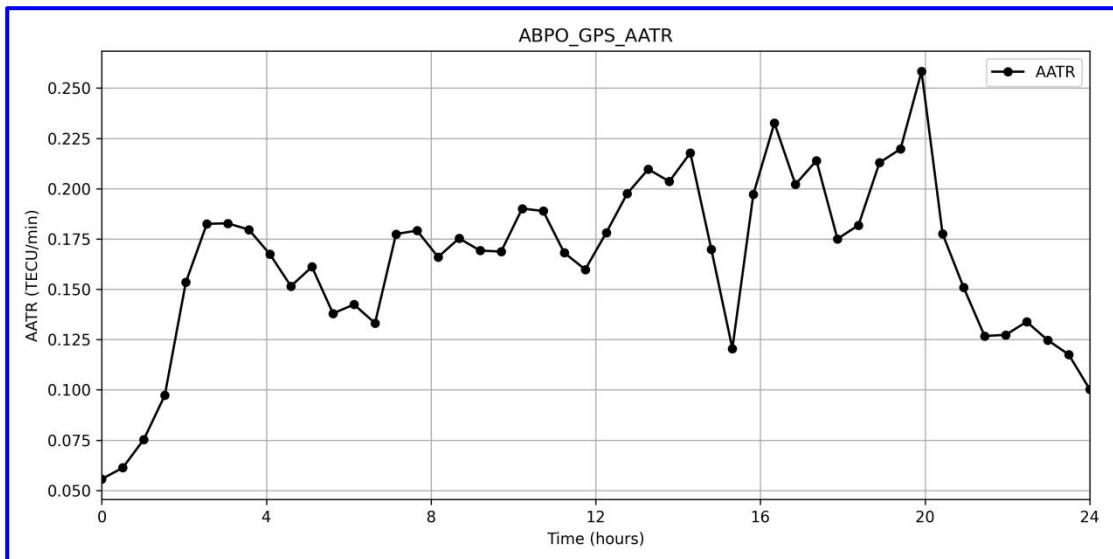


Figure 6.3.4 Plotting Example Based on AATTR Results

## 7. Batch Processing

The Python batch processing scripts provided with IonoMoni support multi-day and multi-station data processing. The directory structure under the `batch_process` folder is as follows:

Table 7.1 Directory Structure of the `batch_process` Folder

| <b>batch_process</b>         |  |
|------------------------------|--|
| <code>./data</code>          | Input data folder                      |
| <code>./ini</code>           | INI configuration folder               |
| <code>./project</code>       | Output results folder                  |
| <code>./PythonScripts</code> | Python batch processing scripts folder |
| <code>./sitelist</code>      | Station list folder                    |
| <code>./xml</code>           | XML folder                             |

Descriptions of the scripts in the `PythonScripts` folder are as follows:

Table 7.2 Directory Structure of the `batch_process` Folder

| <b>Python Script</b>                   | <b>Description</b>   |
|--|--|
| <code>run_cmd_IonoMoni_multi.py</code> | Main script for IonoMoni batch processing                    |
| <code>gnss_sitelist_io.py</code>       | Provides a general interface for reading GNSS station files  |
| <code>gnss_ini_tool.py</code>          | Manages the data pool and reads input data                   |
| <code>gnss_print_tool.py</code>        | Outputs key information to the terminal                      |
| <code>gnss_run_tool.py</code>          | Provides command-line operation and execution functions      |
| <code>gnss_timestran_tool.py</code>    | Handles time format conversion and calculation in processing |

The batch processing Python scripts of IonoMoni use INI files to configure corresponding XML files for each station on each day, enabling automated data processing. The `run_IonoMoni.ini` configuration file is described as follows:

Table 7.3 Directory Structure of the batch\_process Folder

| <b>Configuration Node</b> | <b>Description</b>   |
|---------------------------|--|
| <b>function</b>           | CCL_STEC PPP_STEC ROTI AATR  |
| <b>beg_time</b>           | Start time <YYYY DOY>  |
| <b>end_time</b>           | End time <YYYY DOY>  |
| <b>int_time</b>           | Calculation interval (in days)   |
| <b>site_path</b>          | Path to the station list file  |
| <b>project_path</b>       | Path to the output result files  |
| <b>IonoMoni</b>           | Path to the IonoMoni executable program  |
| <b>IonoMoni_xml</b>       | Path to the batch processing template XML file   |
| <b>rinexo_name</b>        | Observation file name, e.g., <SITE><DOY>0.<YY>o  |
| <b>rinexc_name</b>        | Precise clock offset file name,<br>e.g., COD0MGXFIN_<YYYY><DOY>0000_01D_30S_CLK.CLK    |
| <b>rinexn_name</b>        | Broadcast ephemeris file name, e.g., brdc<DOY>0.<YY>p                                  |
| <b>bia_name</b>           | DCB file name,<br>e.g., CAS0MGXRAP_<YYYY><DOY>0000_01D_01D_DCB.BSX                     |
| <b>sp3_name</b>           | Precise ephemeris file name,<br>e.g., COD0MGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3       |
| <b>three_sp3_name</b>     | 3Days Precise ephemeris file name,<br>e.g., COD0MGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3 |
| <b>ifcb_name</b>          | IFCB file name, e.g., ifcb_<YYYY><DOY>   |
| <b>upd_name</b>           | UPD file name, e.g.,<br>upd_wl_<YYYY><DOY>_GREC upd_nl_<YYYY><DOY>_GREC                |
| <b>system_de</b>          | Planetary ephemeris file, e.g., jpleph_de405_great                                     |
| <b>system_atx</b>         | Antenna file, e.g., igs20_2290.atx   |
| <b>system_bld</b>         | Ocean tide loading file, e.g., oceanload   |
| <b>system_eop</b>         | Earth orientation parameters file, e.g., poleut1                                       |
| <b>system_path</b>        | Path to system files   |
| <b>rinexo_path</b>        | Path to observation files  |
| <b>rinexc_path</b>        | Path to precise clock offset files   |
| <b>rinexn_path</b>        | Path to broadcast ephemeris files  |
| <b>bia_path</b>           | Path to differential code bias files   |
| <b>sp3_path</b>           | Path to precise ephemeris files  |
| <b>three_sp3_path</b>     | Path to 3days precise ephemeris files  |
| <b>upd_path</b>           | Path to uncalibrated phase delay files   |

After preparing the data in the ./data folder, configure the run\_IonoMoni.ini file as shown in Figure 7.3.

To perform multi-day data processing, users need to enter the command:

```
>> cd /d <install_dir>\IonoMoni\batch_process\PythonScripts
>> python run_cmd_IonoMoni_multi.py ^
    -year <YYYY> -beg <DOY_START> -end <DOY_END> ^
    -ini ..\ini\run_IonoMoni.ini
```

After the batch processing is completed, a corresponding output directory will be automatically created, and the batch processing results will be saved in the ./project/<function>/<YYYY>\_<DOY> folder, which contains the daily XML configuration files and text result files (PPP\_STEC mode will additionally include FLT result files).

```
[IonoMoni]
# function
function = PPP_STEC
# begin time
beg_time = 2023 305
# end time
end_time = 2023 306
# interval (day)
int_time = 1
# site list
site_path = .../sitelist/site_list.txt
# output path
project_path = .../project/PPP_STEC
# program path
IonoMoni = ../../out/build/release-with-xml/IonoMoni.exe
# template xml
IonoMoni_xml = .../xml/IonoMoni.xml

[data_pool]
# input files and path
system_de = jpleph_de405_great
system_atx = igs20_2290.atx
system_b1q = oceanload
system_eop = poleutl
system_path = .../data/sys
rinexo_name = <SITE><DOY>0.<YY>o
rinexc_name = CODOMGXFIN_<YYYY><DOY>0000_01D_30S_CLK.CLK
rinexn_name = brdc<DOY>0.<YY>p
bia_name = CASOMGXRAP_<YYYY><DOY>0000_01D_01D_DC.BSX
sp3_name = CODOMGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3
three_sp3_name = CODOMGXFIN_<YYYY><DOY>0000_01D_05M_ORB.SP3
ifcb_name = ifcb_<YYYY><DOY>
#The Configuration Node is retained but not used in computation.
upd_name = upd_w1_<YYYY><DOY>_GREC`upd_n1_<YYYY><DOY>_GREC
rinexo_path = .../data/obs/<YYYY>/<DOY>
rinexc_path = .../data/clk
rinexn_path = .../data/rinexn
bia_path = .../data/bia
sp3_path = .../data/sp3
three_sp3_path = .../data/sp3
ifcb_path = .../data/ifcb
#The Configuration Node is retained but not used in computation.
upd_path = .../data/upd
```

Table 7.3 Directory Structure of the batch\_process Folder

## 8. Data preparation

Different modes of IonoMoni require different input files.

For **CCL\_STEC** mode, the required input files include: observation data, precise orbit data, and Differential Code Bias (DCB) files.

For **PPP\_STEC** mode, the required input files include: observation data, broadcast ephemeris, precise orbit data, precise clock products, Differential Code Bias (DCB), IGS antenna files, planetary ephemeris files, ocean tide loading files, and Earth Orientation Parameters (EOP) files.

For **ROTI** and **AATR** modes, the required input files include: observation data and precise orbit data.

The detailed format descriptions and acquisition methods for these input files are listed in Table 8.1.

Table 8.1 Format Descriptions and Acquisition Methods for Input Files

| <b>Input files</b>  | <b>File Description</b>      | <b>Format Description and Acquisition Methods</b>  |
|---------------------|------------------------------|--|
| <b>RINEXO</b>       | GNSS Observations            | <a href="https://files.igs.org/pub/data/format/rinex304.pdf">https://files.igs.org/pub/data/format/rinex304.pdf</a><br><a href="https://cddis.nasa.gov/archive/gnss/data/daily/">https://cddis.nasa.gov/archive/gnss/data/daily/</a>                     |
| <b>RINEXN</b>       | Broadcast Ephemeris          | <a href="https://files.igs.org/pub/data/format/rinex304.pdf">https://files.igs.org/pub/data/format/rinex304.pdf</a><br><a href="https://cddis.nasa.gov/archive/gnss/data/daily/2024/brdc/">https://cddis.nasa.gov/archive/gnss/data/daily/2024/brdc/</a> |
| <b>SP3</b>          | Precise Orbit                | <a href="https://files.igs.org/pub/data/format/sp3d.pdf">https://files.igs.org/pub/data/format/sp3d.pdf</a><br><a href="https://cddis.nasa.gov/archive/gnss/products/">https://cddis.nasa.gov/archive/gnss/products/</a>                                 |
| <b>RINEXC</b>       | Precise Clock Products       | <a href="https://files.igs.org/pub/data/format/rinex_clock304.txt">https://files.igs.org/pub/data/format/rinex_clock304.txt</a><br><a href="https://cddis.nasa.gov/archive/gnss/products/">https://cddis.nasa.gov/archive/gnss/products/</a>             |
| <b>DCB</b>          | Differential Code Bias       | <a href="https://files.igs.org/pub/data/format/sinex_bias_100.pdf">https://files.igs.org/pub/data/format/sinex_bias_100.pdf</a><br><a href="https://cddis.nasa.gov/archive/gnss/products/bias/">https://cddis.nasa.gov/archive/gnss/products/bias/</a>   |
| <b>UPD</b>          | Uncalibrated Phase Delay     | <a href="https://github.com/GREAT-WHU/GREAT-UPD/blob/main/doc/GREAT-UPD_1.0.pdf">https://github.com/GREAT-WHU/GREAT-UPD</a><br><a href="https://github.com/GREAT-WHU/GREAT-UPD">https://github.com/GREAT-WHU/GREAT-UPD</a>                               |
| <b>jpleph_de405</b> | Planetary Ephemeris          | <a href="https://ssd.jpl.nasa.gov/planets/eph_export.html">https://ssd.jpl.nasa.gov/planets/eph_export.html</a><br><a href="https://ssd.jpl.nasa.gov/ftp/eph/planets/Linux/">https://ssd.jpl.nasa.gov/ftp/eph/planets/Linux/</a>                         |
| <b>oceanload</b>    | Ocean Tide                   | <a href="http://holt.oso.chalmers.se/loading/example.blq.html">http://holt.oso.chalmers.se/loading/example.blq.html</a><br><a href="http://holt.oso.chalmers.se/loading">http://holt.oso.chalmers.se/loading</a>   |
| <b>poleut1</b>      | Earth Orientation Parameters | Refer to the GREAT-PVT_manual_1.0.pdf located in the ./poleut1 folder under the IonoMoni root directory.   |
| <b>atx</b>          | Antenna                      | <a href="https://files.igs.org/pub/station/general/antex14.txt">https://files.igs.org/pub/station/general/antex14.txt</a><br><a href="https://files.igs.org/pub/station/general/pcv_archive/">https://files.igs.org/pub/station/general/pcv_archive/</a> |