# B2bLIB User Manual

B2bLIB: an open-source PPP-B2b embeddable RTKLIB decoding package

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GNSS+ under
Complex Conditions

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# 1 Introduction

With the completion of the BeiDou-3 Satellite Navigation System (BDS-3), China has been providing global services, including navigation, positioning, international search and rescue, and short message communication (Yang et al. 2019). In addition, BDS-3 supports featured services including satellite-based precise point positioning service via B2b signal (PPP-B2b), the BDS satellite-based augmented service, radio determination satellite service, regional and global short message communication service, and satellite-based search and rescue service (Yang 2021). The BDS-3 designed constellation comprises 30 satellites, including 24 medium earth orbit satellites (MEO), 3 geostationary orbit (GEO) satellites, and 3 inclined geosynchronous orbit satellites (IGSO). BDS-3 mainly transmits 6 signals including B1I, B3I, B1C, B2a, B2a+b and B2b. Broadcast via GEO satellites, the B2b signal delivers augmentation data, enabling real-time precise clock offset corrections and orbit error corrections without a network connection (CSNO 2020). This technology provides centimeter-level accuracy for static applications and decimeter-level accuracy for dynamic applications, enabling wide-area real-time high-precision positioning (Zhang and Wang 2025).

Since its launch, related studies have been conducted on the product accuracy and service performance of PPP-B2b. Results show that its augmentation messages exhibit smaller satellite-specific clock biases than GPS and achieve radial orbit errors of 0.056 m (BDS-3 MEO), 0.069 m (GPS), and 0.172 m (BDS-3 IGSO) relative to GFZ final products. (Tao et al. 2021; Lan et al. 2022; Zhang et al. 2022; Sun et al. 2023; Ouyang et al. 2023). For positioning performance, static BDS-3/GPS dual-system PPP attains RMS < 1 cm (E/N) and ~ 3 cm (U), and simulated kinematic PPP reaches < 2.5 cm, 3.5 cm, and 8.5 cm (N/E/U) after convergence (Tang et al. 2022). In real applications, static solutions achieve mean east, north, and up errors of 2.4 cm, 1.6 cm, and 2.3 cm, while kinematic PPP converges to 8.1 cm, 3.6 cm, and 8.0 cm RMS (Nie et al. 2021).

However, open-source software supporting B2b messages decoding remains scarce. Additionally, most open-source global navigation satellite system (GNSS) software is based on C/C++. To support user applications, a C/C++ PPP-B2b decoding package called B2bLIB has been developed. The B2bLIB decoding package seamlessly integrates with RTKLIB and is expected to promote research and application of the PPP-B2b and even other satellite-based augmentation systems.

# 2 Methodology of PPP-B2b

The mathematical model of PPP-B2b is given firstly, where the corrections are discussed comprehensively.

## 2.1 Mathematical Model of PPP-B2b

In the PPP-B2b service, the raw observation equations of dual-frequency (DF) observations can be written as (Li et al. 2019; Nie et al. 2019; Zang et al. 2019)

$$P_{r,\mathrm{IF}}^{s} = \rho_r^s + dt_r - dt^s + \xi_{r,\mathrm{IF}} - \xi_{\mathrm{IF}}^{s} + T_r^s + \varepsilon_{r,\mathrm{IF}}^{s} \tag{1}$$

$$\phi_{r,\mathrm{IF}}^{s} = \rho_r^s + dt_r - dt^s + \zeta_{r,\mathrm{IF}} - \zeta_{\mathrm{IF}}^{s} + T_r^z + N_{r,\mathrm{IF}}^{s} + \epsilon_{r,\mathrm{IF}}^{s} \tag{2}$$

where $P_{r,\mathrm{IF}}^{s}$ and $\phi_{r,\mathrm{IF}}^{s}$ denote the dual-frequency ionospheric-free (IF) code measurement and IF phase measurement, respectively; $\rho_r^s$ denote the geometric distance from the satellite to receiver; $dt_r$ and $dt^s$ are the receiver and satellite clock offsets, respectively; $\xi_{r,\mathrm{IF}}$ and $\zeta_{r,\mathrm{IF}}$ are the code and phase hardware delays in the receiver-end, respectively; $\xi_{\mathrm{IF}}^{s}$ and $\zeta_{\mathrm{IF}}^{s}$ are the code and phase hardware delays in the satellite-end, respectively; $T_r^z$ denote the tropospheric delay; $N_r^s$ denote the ambiguity parameter; $\varepsilon_r^s$ and $\epsilon_r^s$ are the code and phase measurement noise, respectively.

The other systematic errors are assumed to be corrected in advance, including phase center offset (PCO) and phase center variation (PCV), phase windup, relativistic effect, solid earth tide, ocean tide loading, pole tide, and earth rotation, etc. Also, the timing group delay (TGD) in BDS, TGD and inter-signal correction (ISC) in GPS are also considered and corrected. The corrections are provided in PPP-B2b service via B2b signal, including precise satellite orbits error correction, clock offset correction, and difference code bias (DCB) correction. These parameters are updated at 48 s, 6 s, and 48 s intervals, respectively. The valid time of satellite orbit error correction is 96 s, while that of satellite clock offset correction is 12 s. Due to the stability of satellite DCB, the valid time of DCB provided by PPP-B2b is 86,400 s

## 2.2 Orbit Error Correction

In the PPP-B2b service, satellite position corrections are applied by adjusting the broadcast ephemeris position using an orbit error correction vector. If the Issue of Data of Navigation (IODN) associated with the orbit error correction matches the Issue of Data of the Clock (IODC) from the broadcast ephemeris, the corrected satellite position $\mathbf{X}_{orbit}$ is given by (CSNO 2020):

$$\boldsymbol{X}_{\mathrm{orbit}} = \boldsymbol{X}_{\mathrm{broadcast}} - \boldsymbol{\delta X} \tag{3}$$

where $\boldsymbol{X}_{\mathrm{orbit}}$ is the corrected satellite orbit; $\boldsymbol{X}_{\mathrm{broadcast}}$ is the satellite position derived from the broadcast ephemeris; $\boldsymbol{\delta X}$ is the satellite position correction vector. The correction vector $\boldsymbol{\delta X}$ is computed as:

$$\boldsymbol{\delta X} = [\boldsymbol{e}_r \quad \boldsymbol{e}_a \quad \boldsymbol{e}_c] \cdot \boldsymbol{\delta O} \tag{4}$$

where $\boldsymbol{e}_r$, $\boldsymbol{e}_a$ and $\boldsymbol{e}_c$ are the unit vectors along the radial, tangential, and normal directions, respectively. $\boldsymbol{\delta O}$ is the orbit error correction parameters provided in the augmentation message. This formulation enables an accurate adjustment of the satellite position.

## 2.3 Clock Offset Correction

The satellite clock offset correction in PPP-B2b adjusts the clock offset obtained from the broadcast ephemeris using correction parameters from augmentation messages. The corrected satellite clock offset is computed as follows (CSNO 2020):

$$t_{\mathrm{satellite}} = t_{\mathrm{broadcast}} - \frac{C_0}{c} \tag{5}$$

where $t_{\mathrm{satellite}}$ is the precisely corrected clock offset; $t_{\mathrm{broadcast}}$ is the satellite clock offset derived from the broadcast ephemeris; $C_0$ is the clock offset correction parameter which is provided in the augmentation message; $c$ is the velocity of light.

## 2.4 Differential Code Bias Correction

In the PPP-B2b service, due to variations in satellite tracking modes, each observation contains a deviation associated with the signal tracking method. To achieve synchronous processing of multiple signals at different frequencies, it is necessary to first eliminate this deviation. The corrected observation is computed as follows (CSNO 2020):

$$\tilde{l}_{\mathrm{sig}} = l_{\mathrm{sig}} - \mathrm{DCB}_{\mathrm{sig}} \tag{6}$$

where $\tilde{l}_{\mathrm{sig}}$ is the observation after correction of the sig signal; $l_{\mathrm{sig}}$ is the observation directly captured by the sig signal receiver; $\mathrm{DCB}_{\mathrm{sig}}$ is the DCB corresponding to the signal.

Taking the BeiDou Navigation Satellite System as an example, if the user employs dual-frequency ranging signals B1Cp and B2ap, the DCB for the B1Cp signal, as provided in the PPP-B2b message, is denoted as $\mathrm{DCB}_{\mathrm{B1Cp}}$, while that for the B2ap signal is $\mathrm{DCB}_{\mathrm{B2ap}}$. The corresponding inter-code bias correction is then given by the following formula (CSNO 2020):

$$\tilde{l}_{\mathrm{B1Cp}} = l_{\mathrm{B1Cp}} - \mathrm{DCB}_{\mathrm{B1Cp}} \tag{7}$$

$$\tilde{l}_{\mathrm{B2ap}} = l_{\mathrm{B2ap}} - \mathrm{DCB}_{\mathrm{B2ap}} \tag{8}$$

For dual-frequency users, the ionosphere-free combination observation is computed as follows:

$$\tilde{l}_{\mathrm{IF}} = \frac{\gamma \tilde{l}_{\mathrm{B1Cp}} - \tilde{l}_{\mathrm{B2ap}}}{\gamma - 1} = \frac{\gamma l_{\mathrm{B1Cp}} - l_{\mathrm{B2ap}}}{\gamma - 1} - \frac{\gamma \mathrm{DCB}_{\mathrm{B1Cp}} - \mathrm{DCB}_{\mathrm{B2ap}}}{\gamma - 1} \tag{9}$$

with $\gamma = \frac{f_{\mathrm{B1Cp}}^2}{f_{\mathrm{B2ap}}^2}$, where $f_{\mathrm{B1Cp}}$ is the B1Cp carrier center frequency; $f_{\mathrm{B2ap}}$ is the B2ap carrier center frequency. This formulation ensures that dual-frequency users can accurately correct for differential code biases when applying the PPP-B2b service.

# 3 Architecture of the B2bLIB

The detailed introduction to the structure of the B2b messages is given firstly. This is followed by a description of the architecture of the B2bLIB program.

## 3.1 Introduction to B2b Messages

The B2b messages used in this package are pre-decoded text files, categorized into four separate files based on message type. The format of Message Type 1 is as follows:

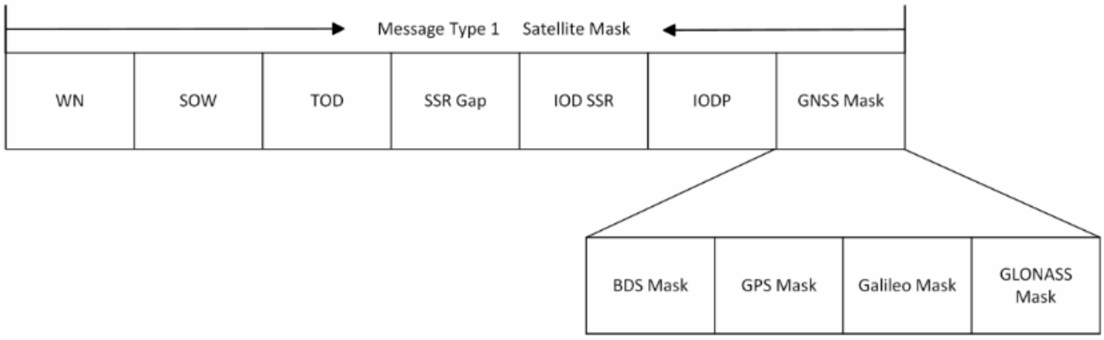



**Fig. 1** Format of Message Type 1

This message includes satellite mask information. WN, SOW, and TOD denote the BeiDou week number, seconds of the week, and seconds of the day, respectively. SSR Gap denotes the SSR update interval, with no reserved mask. IOD SSR denotes a change in the data generation configuration. To ensure proper matching, all data types must share the same IOD SSR value before use. Message Type 4 also contains an IODP field. When this field matches the IODP value in Message Type 1, the two messages are considered part of the same data group. The GNSS Mask includes the BDS Mask, GPS Mask, Galileo Mask, and GLONASS Mask, which correspond to the satellite mask information for BDS, GPS, Galileo, and GLONASS, respectively. A bit value of 1 denotes that differential corrections for the corresponding satellite are broadcast, while a bit value of 0 denotes that no correction is transmitted.. For detailed information, please refer to Appendix A.

The format of Message Type 2 is as follows:

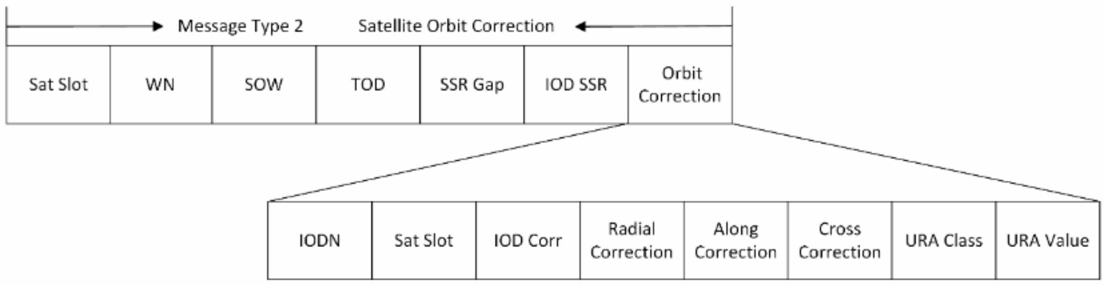



**Fig. 2** Format of Message Type 2

This message includes satellite orbit error correction parameters. Sat Slot denotes the position of the satellite in the mask. IODN denotes the data version number of the satellite clock and ephemeris broadcast by the GNSS downlink signal. It corresponds to the IODC field in the BDS CNAV1 and GPS LNAV messages. IODN is used to determine whether the ephemeris and clock parameters in the basic navigation message match the orbit corrections provided in Message Type 2. IOD Corr denotes the version number of the orbit and clock correction parameters. It is included in both Message Type 2 and Message Type 4. For a given satellite, if the IOD Corr values of the orbit and clock corrections are identical, the two can be used together. Satellite orbit error correction parameters include the Radial Correction, Along Correction, and Cross Correction, which correspond to the corrections in the radial, along, and cross directions of the satellite orbit, respectively. URA Class and URA Value denote the parameters used to calculate the User Range Accuracy index. For detailed information, please refer to Appendix B. The remaining parameters are identical to those in Message Type 1 and will not be described here or in the following sections.

The format of Message Type 3 is as follows:

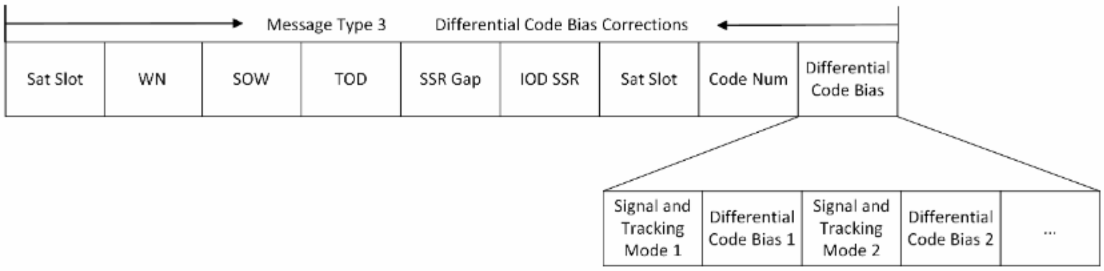



**Fig. 3** Format of Message Type 3

This message includes differential code bias correction parameters. Signal and Tracking Mode denote the signal component corresponding to the Differential Code Bias and the signal-receiving mode of that component. Code Num denotes the number of differential code bias included for each satellite. For detailed information, please refer to Appendix C.

The format of Message Type 4 is as follows:

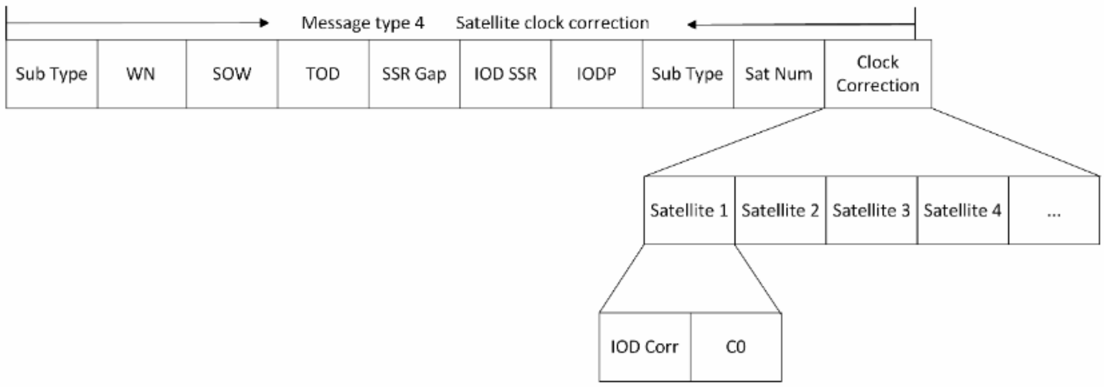



**Fig. 4** Format of Message Type 4

This message includes satellite clock offset correction parameters. Sub Type denotes the corresponding relationship between the satellite and the mask. Message type, mask, and Sub Type collectively determine the satellites corresponding to the clock offset corrections: all satellites whose masks are set to 1 are compressed in order of their slot locations in the mask. Sat Num denotes the number of satellites for which clock offset corrections are provided. C0 denotes the clock offset correction value. For detailed information, please refer to Appendix D.

## 3.2 Introduction to the B2bLIB Program

The B2bLIB program employs B2b messages for PPP in accordance with ICD specifications. The program is primarily divided into two components: message reading and message processing. Message processing is further divided into two components: one uses MT2 and MT4 for satellite position calculation, and the other uses MT3 for DCB correction. The process flowchart is as follows:

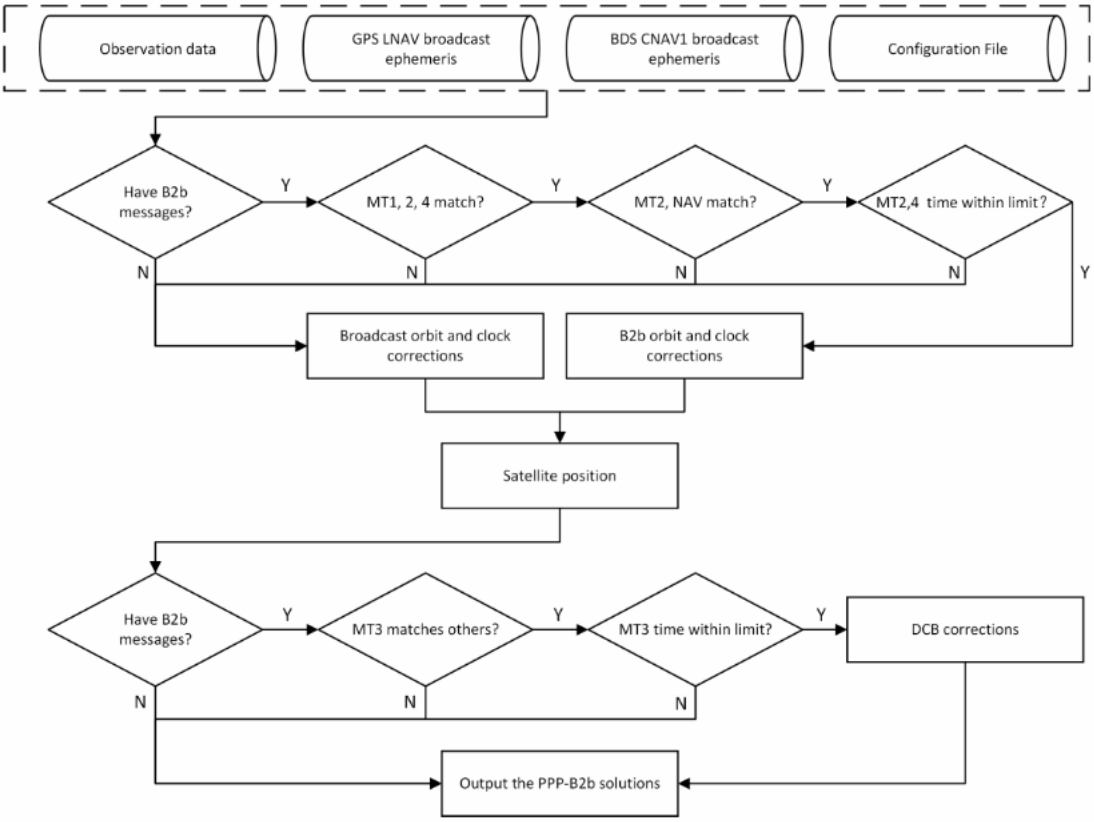


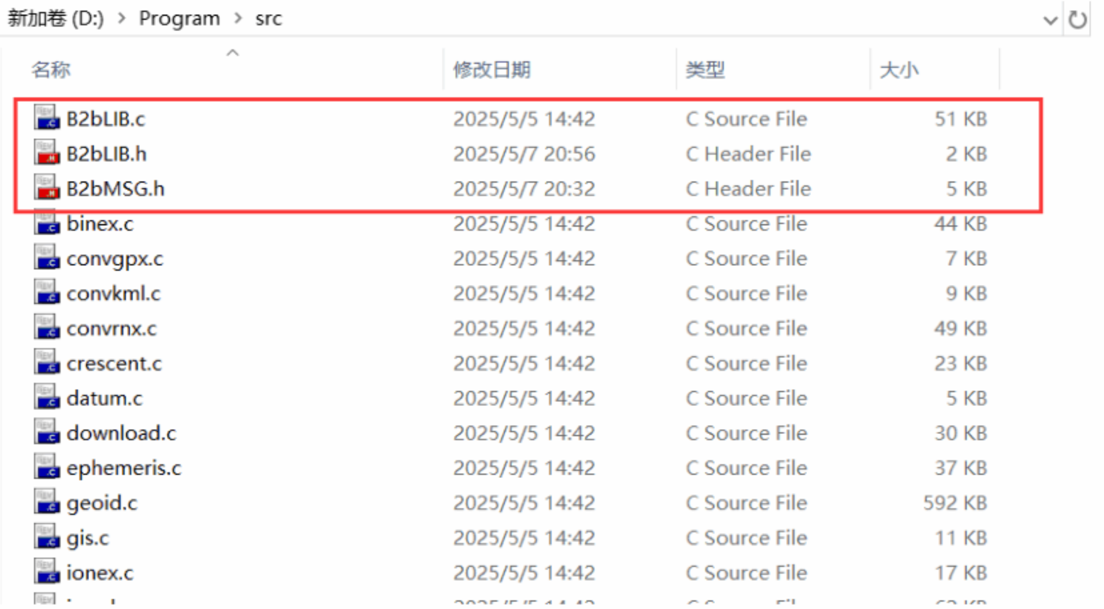

**Fig. 5** Flowchart of the B2bLIB

The essential input files for the B2bLIB program include the observation file, configuration file, GPS LNAV broadcast ephemeris, and BDS CNAV1 broadcast ephemeris. These ephemerides can be extracted from Rinex 4.0 files. If B2b message data is available, it corrects orbit errors and clock offsets. If a satellite does not match a B2b message, the program reverts to broadcast ephemeris for orbit error corrections and clock offset corrections. For DCB corrections, if a satellite matches a B2b message, the program applies DCB correction; otherwise, it outputs the positioning result directly.

# 4 Download

No additional libraries need to be downloaded. The B2bLIB executable file and its dependencies are all included within the " Program " folder. The contents are as follows:


B2b messages are relatively difficult to obtain; therefore, we provide several B2b messages for reference. Additionally, we provide a complete learning project for reading and using B2b messages, which helps users quickly familiarize themselves with the software. The B2bLIB is a specialized software package designed for receiving and processing B2b messages. The source code for processing B2b messages with the B2bLIB is stored in the " Program/Src" folder. The contents of this folder are as follows:




# 5 How to Run the B2bLIB

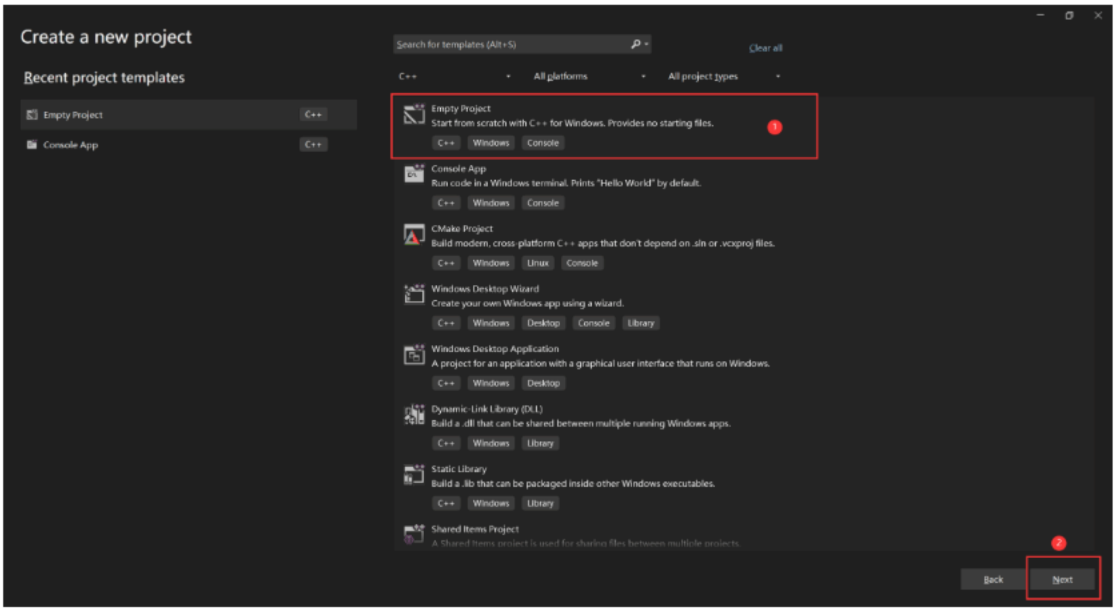
## 5.1 Compile

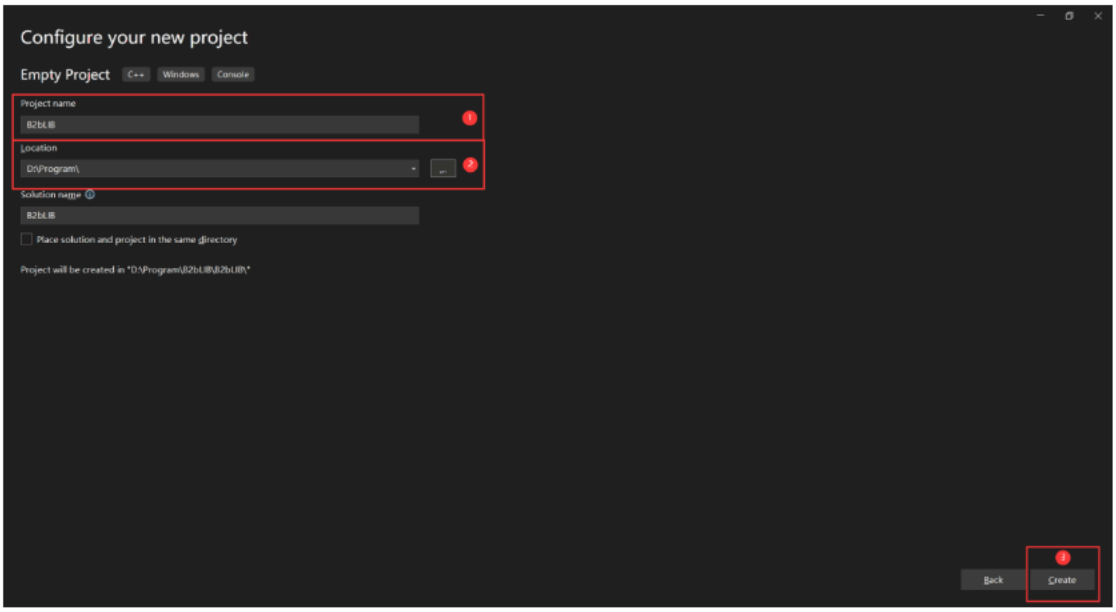
**Step 1: Prepare the Source Code.**

The source code for the B2bLIB is located in the "src" folder, as shown below:


**Step 2: Create a New Project.**

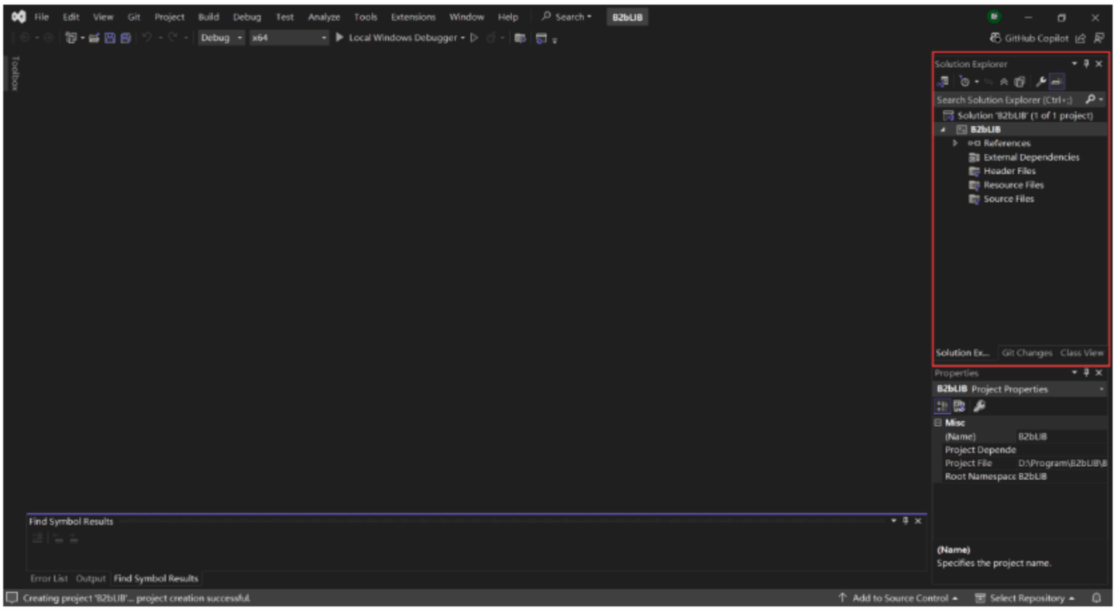
Visual Studio 2022 software is required for this process. Create a new project named " B2bLIB," as shown below:



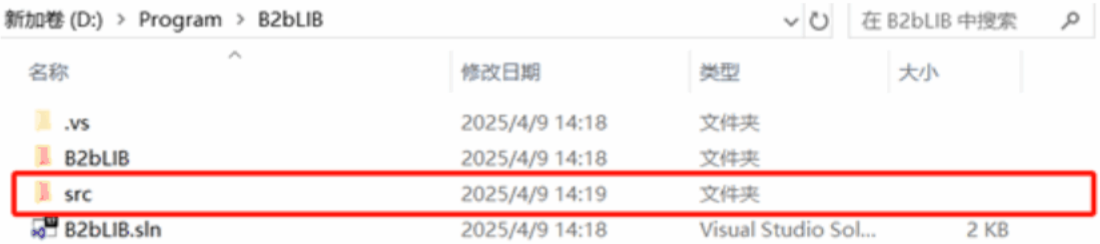

Note: The project should be created in the same folder as the test data; otherwise, the input file paths must be manually modified

Upon completion, the result will appear as shown below:

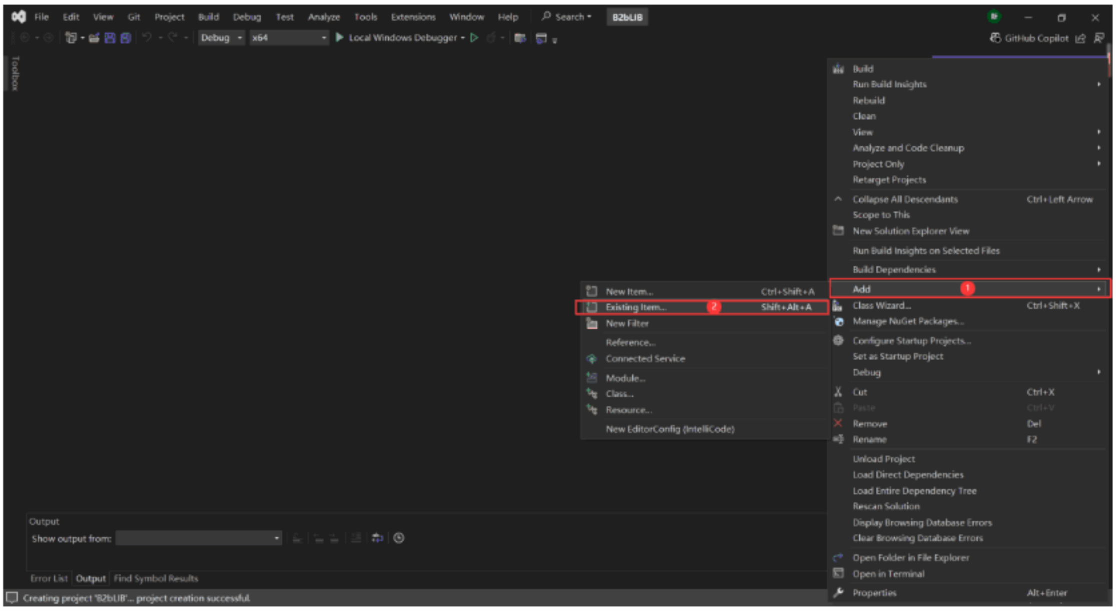


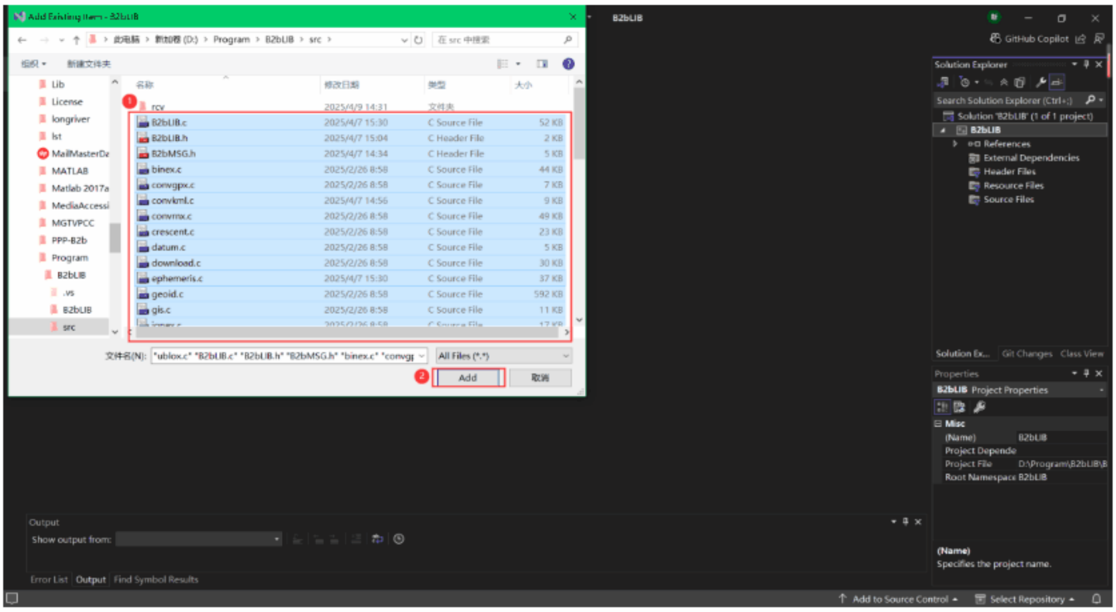

**Step 3: Import the Source Files.**

Copy the contents of the "src" folder into the project directory for " B2bLIB."

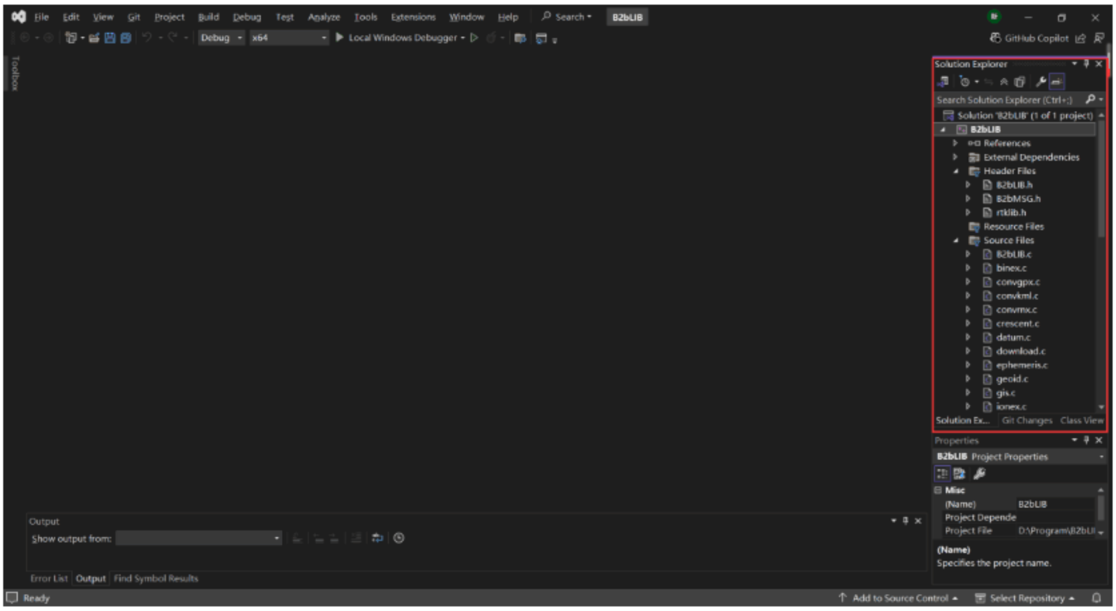



Add all the files from the "src" folder to the project：

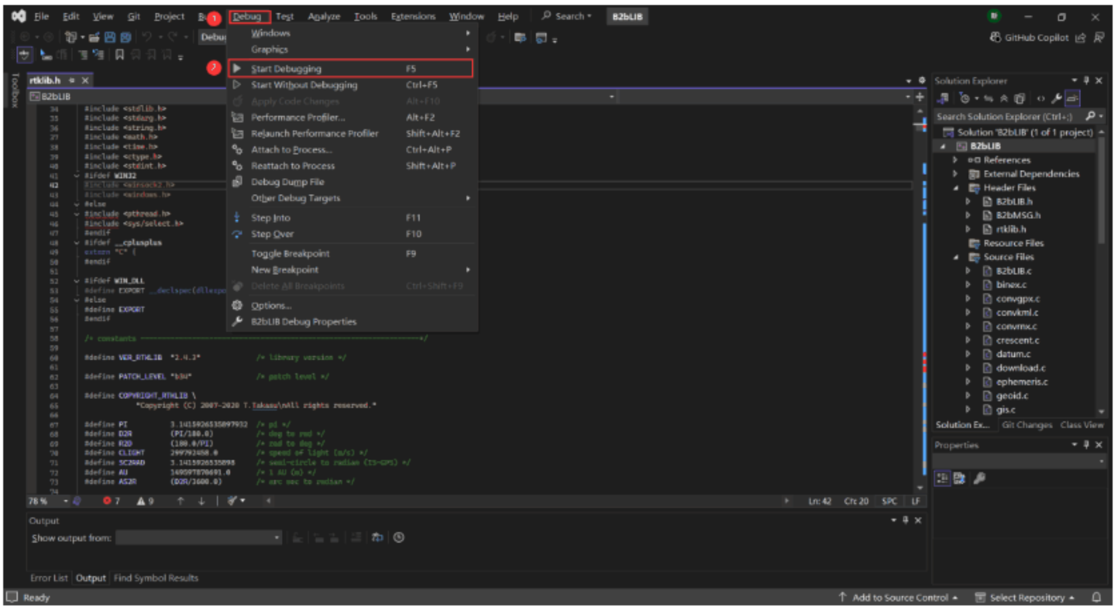


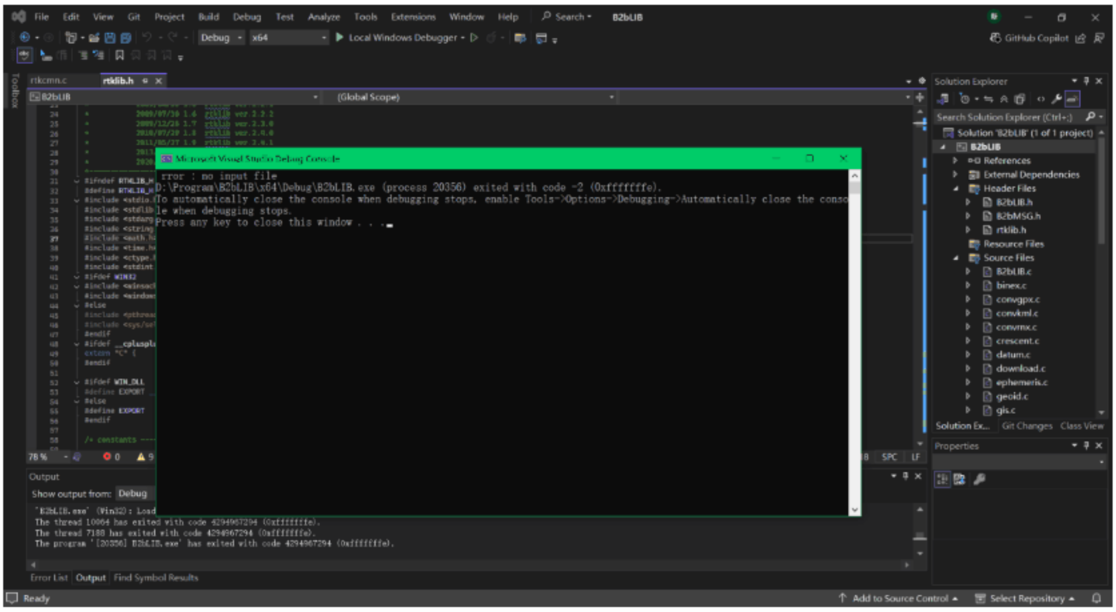

The result will appear as shown below:




## Step 4: Debug.



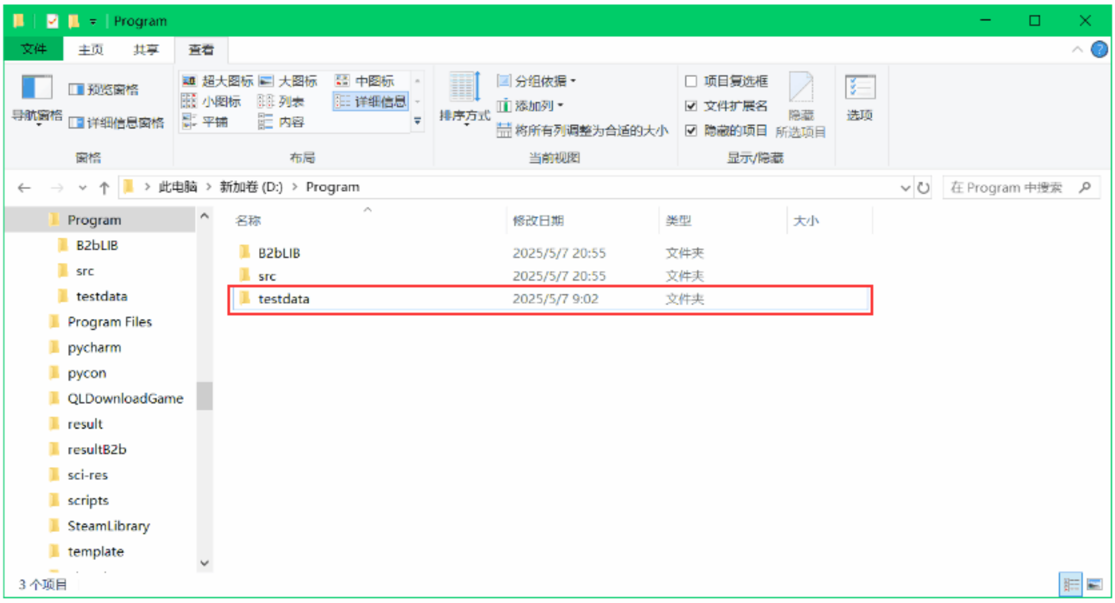

If the debugging is successful, the result will appear as shown below:




## 5.2 Run

### Step 1: Prepare Files.

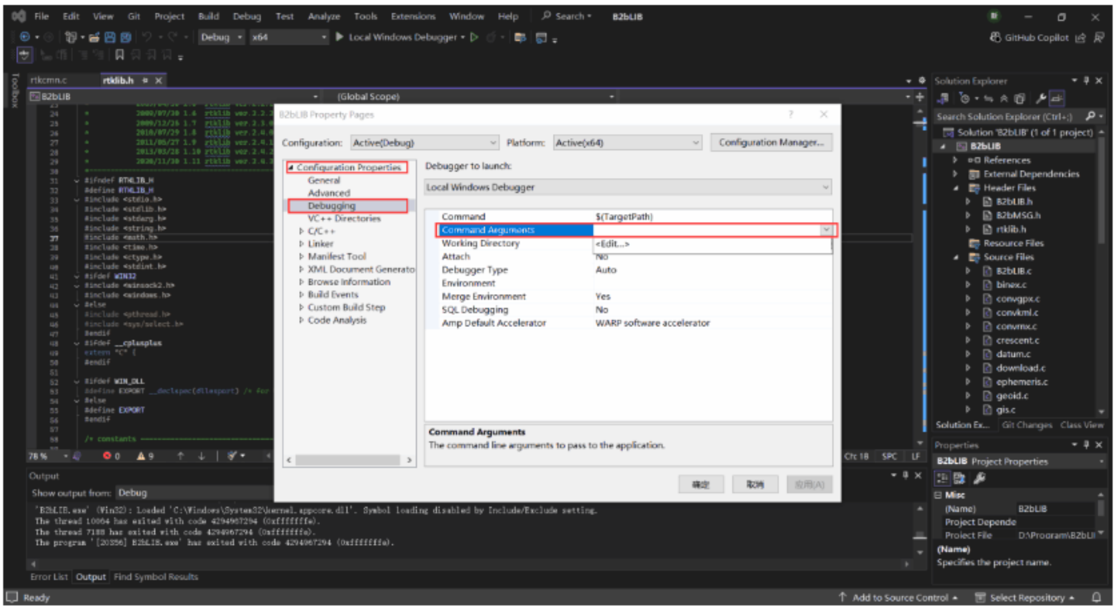
The test data is located in the "testdata" folder:




The specific contents are as follows:

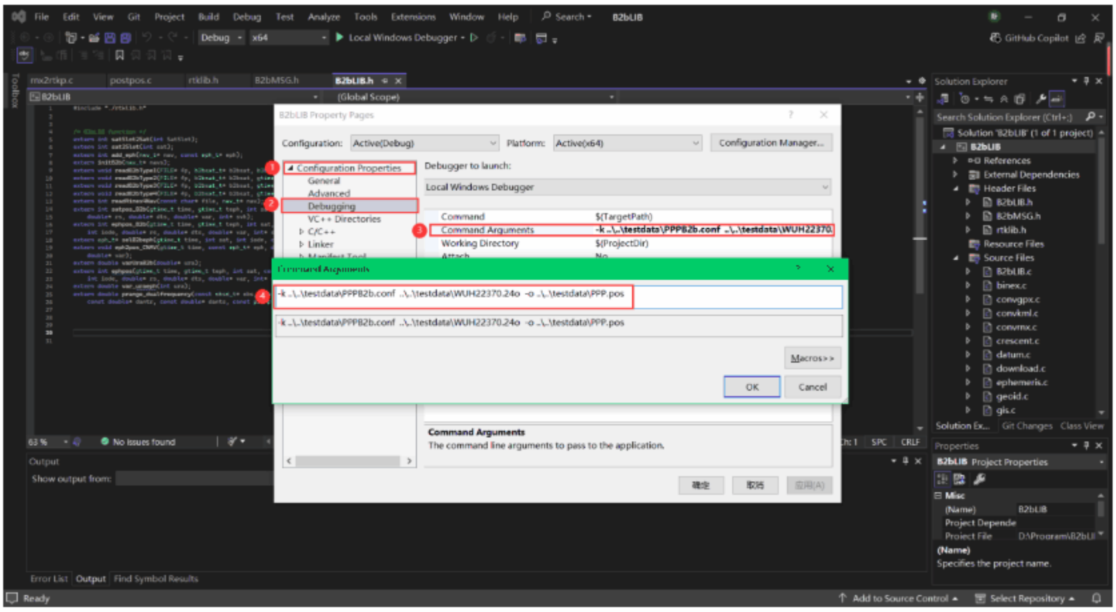

**Step 2: Set Configuration File, Observation File and Output File Paths.**

Enter the following properties interface:




Input:

-k ..\..\testdata\PPPB2b.conf ..\..\testdata\WUH22370.24o -o ..\..\testdata\PPP.pos

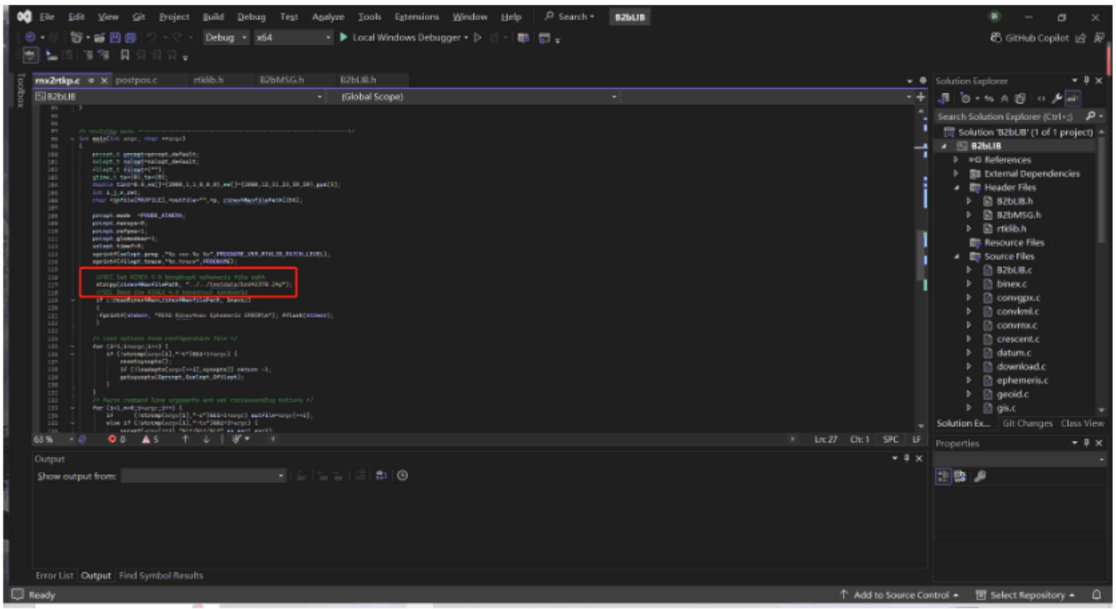



Note: When the project is created in the same directory as the test data, the path can be used as is.

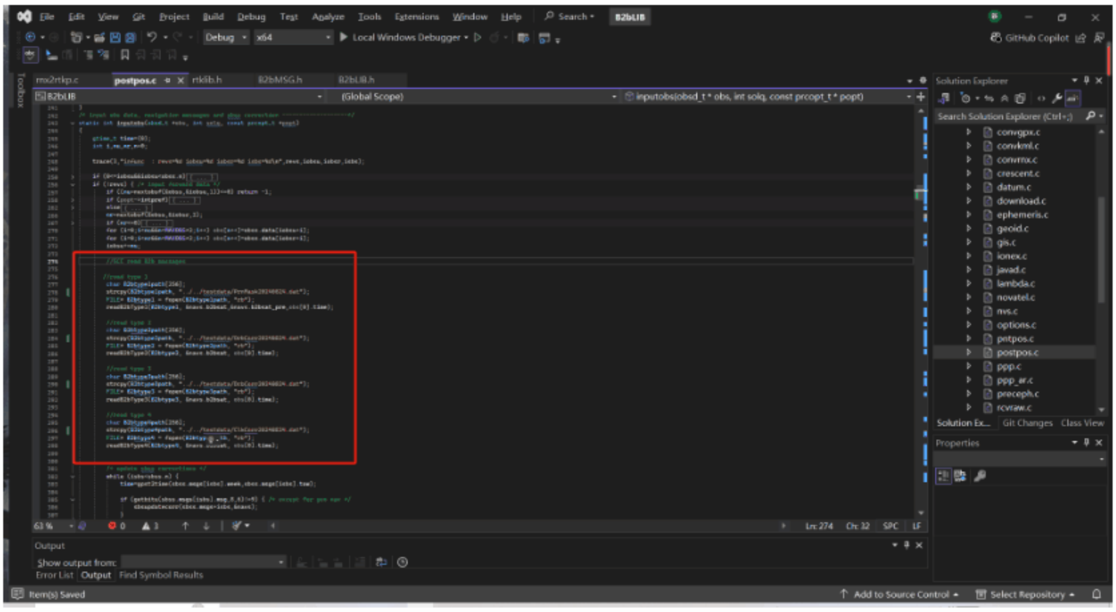
**Step 3: Set Broadcast Ephemeris and B2b Message Paths.**

If the project is created in the same folder as the test data, this step can be skipped.

Set the broadcast ephemeris path under the main function:



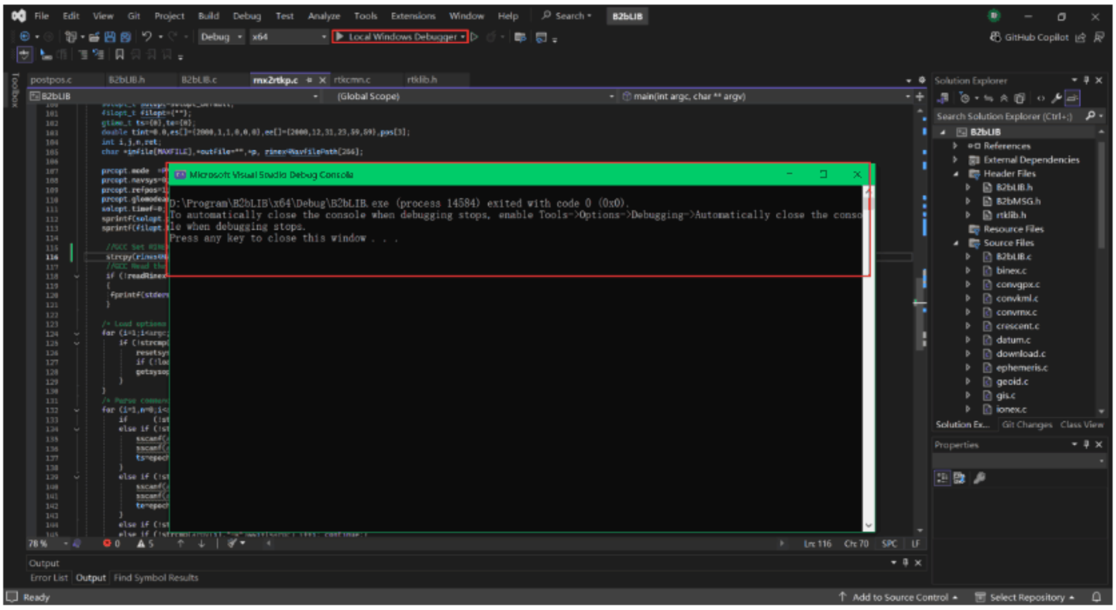

Set the B2b message path under the inputobs function:



Note: Ensure the B2b message order matches the one shown in the image above.

**Step 4: Run.**

Run the program, The following interface and output file will be generated:




# 6 Results and Verification

Previous chapters stated that the final result generates a PPP.pos file. This file contains the observation epoch (GPST), PPP coordinates, PPP status (Q), number of valid satellites (ns), and PPP coordinate variance， as shown in. Fig. 6-11 show the number of satellites, PDOP values, and positioning errors for BDS-only, GPS-only, and BDS/GPS, respectively.

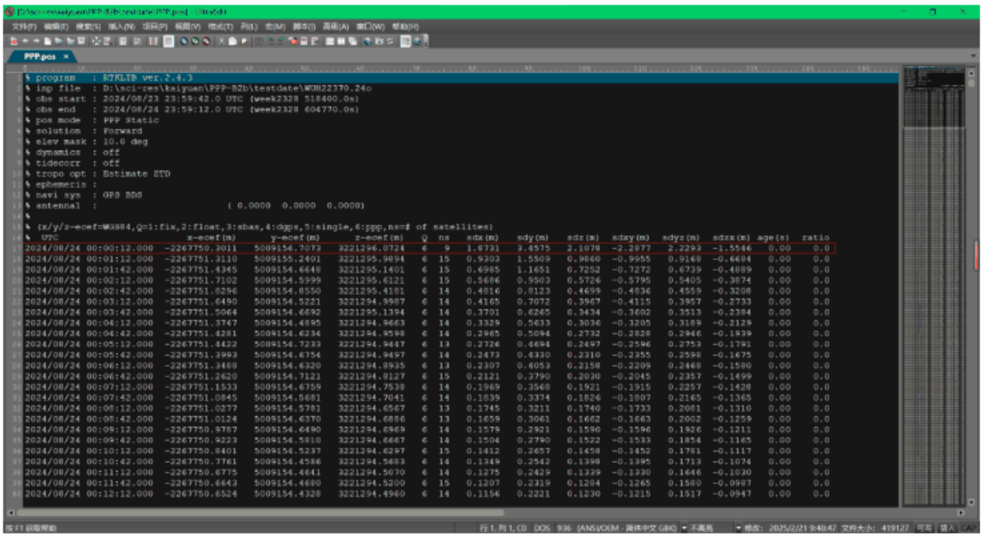


**Fig. 6** Example of final file

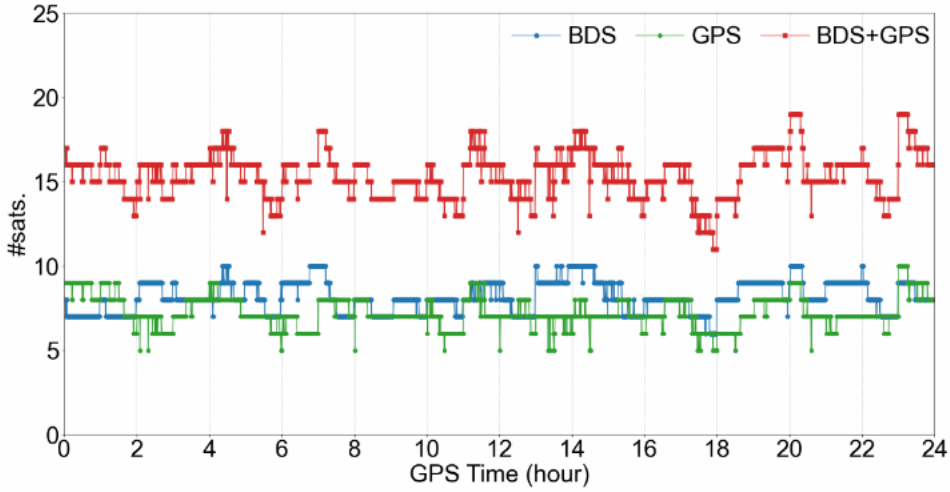



**Fig. 7** Numbers of BDS (blue), GPS (green), and BDS+GPS (red) satellites

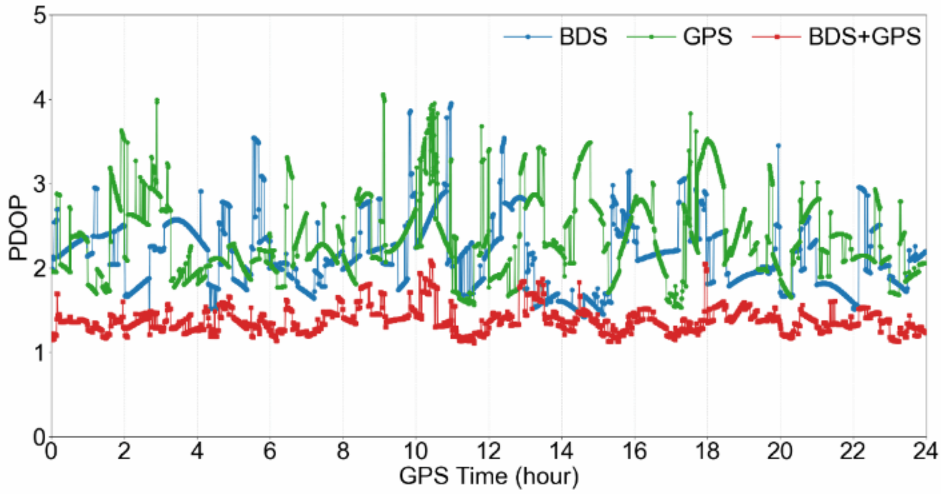



**Fig. 8** PDOP values of BDS (blue), GPS (green), and BDS+GPS (red)

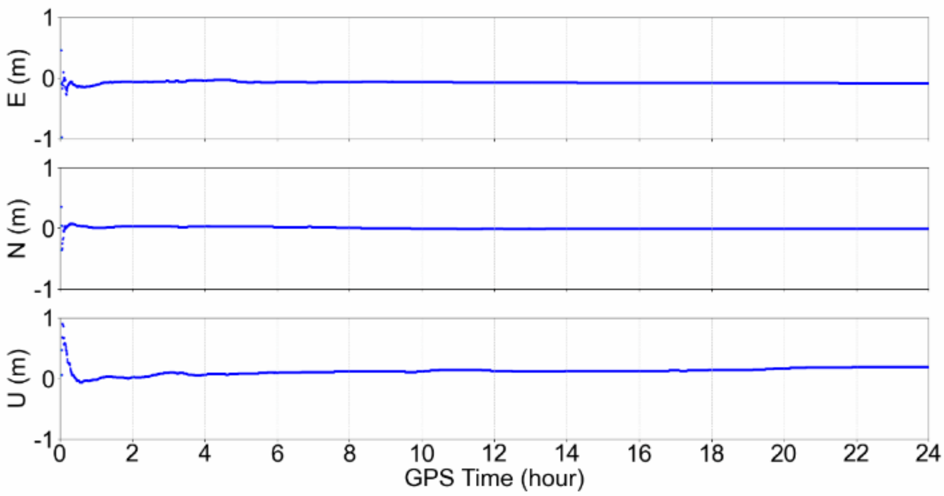



**Fig. 9** BDS positioning errors in E, N, and U directions

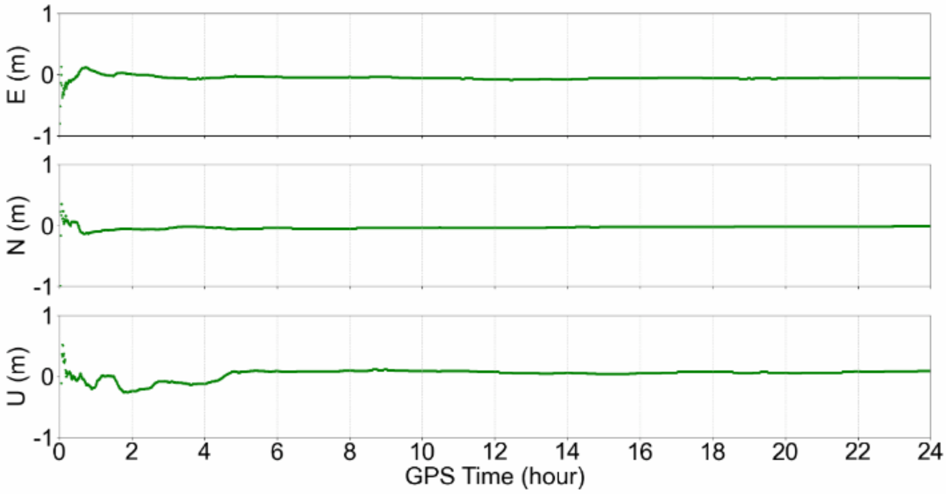



**Fig. 10** GPS positioning errors in E, N, and U directions

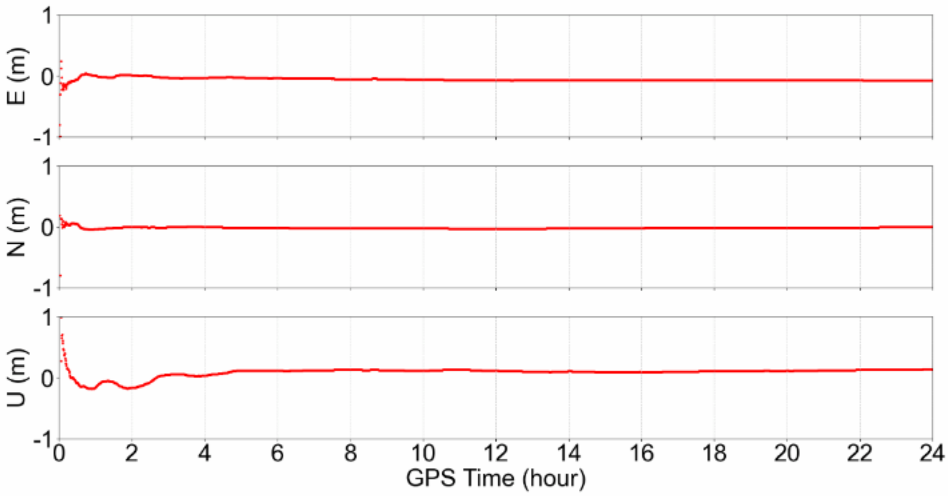



**Fig. 11** BDS+GPS positioning errors in E, N, and U directions

# 7 Appendix

In this appendix, supplementary information is given for the four types of B2b messages, respectively.

## 7.1 Message Type 1

The satellite mask assignment of the message type 1 is described in Table 1.

**Table 1** Satellite mask assignment of the message type 1

| Mask | Name | Scale factor | Range | Basic description |
|---|---|---|---|---|
| BDS mask | Satellite slot 1 | 1 | 0~1 | Broadcasting ID of the first satellite of BDS |
| | to slot 63 | 1 | 0~1 | Broadcasting ID of the 63rd satellite of BDS |
| GPS mask | Satellite slot 64 | 1 | 0~1 | Broadcasting ID of the first satellite of GPS |
| | to slot 100 | 1 | 0~1 | Broadcasting ID of the 37th satellite of GPS |
| Galileo mask | Satellite slot 101 | 1 | 0~1 | Broadcasting ID of the first satellite of Galileo |
| | to slot137 | 1 | 0~1 | Broadcasting ID of the 37th satellite of Galileo |
| GLONASS mask | Satellite slot 138 | 1 | 0~1 | Broadcasting ID of the first satellite of GLONASS |
| | to slot 174 | 1 | 0~1 | Broadcasting ID of the 37th satellite of GLONASS |

## 7.2 Message Type 2

The formula for calculating URA is:

$$\mathrm{URA[mm]} \leq 3^{\mathrm{URA_{CLASS}}}(1 + 0.25 \times \mathrm{URA_{VALUE}}) - 1 \tag{8}$$

where URA is the user range accuracy in mm.

When URAI = 000000 (binary), it means that URA is undefined or unknown, and the corresponding satellite correction is not reliable.

When URAI = 111111 (binary), it means that URA>5466.5 mm.

## 7.3 Message Type 3

The "signal and tracking mode" indicates the signal component corresponding to the differential code bias and the signal-receiving mode of that component. See Table 2 for specific definitions.

**Table 2** Definitions of signal and tracking modes

| ID of signal and tracking mode | BDS | GPS | GLONASS | Galileo |
|---|---|---|---|---|
| 0 | B1I | L1 C/A | G1 C/A | Reserved |
| 1 | B1C(D) | L1 P | G1 P | E1 B |
| 2 | B1C(P) | Reserved | G2 C/A | E1 C |
| 3 | Reserved | Reserved | Reserved | Reserved |
| 4 | B2a(D) | L1C(P) | Reserved | E5a Q |
| 5 | B2a(P) | L1C(D+P) | Reserved | E5a I |
| 6 | Reserved | Reserved | Reserved | Reserved |
| 7 | B2b-I | L2C(L) | Reserved | E5b I |
| 8 | B2b-Q | L2C(M+L) | Reserved | E5b Q |
| 9 | Reserved | Reserved | Reserved | Reserved |
| 10 | Reserved | Reserved | Reserved | Reserved |
| 11 | Reserved | L5 1 | Reserved | E6 C |
| 12 | B3 I | L5 Q | Reserved | Reserved |
| 13 | Reserved | L5 I+Q | Reserved | Reserved |
| 14 | Reserved | Reserved | Reserved | Reserved |
| 15 | Reserved | Reserved | Reserved | Reserved |

## 7.4 Message Type 4

Message type, mask, and Sub Type collectively determine the satellites corresponding to the clock offset corrections: all satellites whose masks are set to 1 are compressed in order of their slot locations in the mask. See Table 3 for the correspondence of SubType1 and satellites.

**Table 3** Correspondence of subtype1 and satellites in message type 4

| Subtype ID | Corresponding satellites |
| --- | --- |
| 0 | The 1st ~ 23rd of the satellites whose masks are set to "1". |
| 1 | The 24th ~ 46th of the satellites whose masks are set to "1". |
| 2 | The 47th ~ 69th of the satellites whose masks are set to "1". |
| 3 | The 70th ~ 92th of the satellites whose masks are set to "1". |
| 4 | The 93th ~ 115th of the satellites whose masks are set to "1". |
| 5 | The 116th ~ 138th of the satellites whose masks are set to "1". |
| 6 | The 139th ~ 161th of the satellites whose masks are set to "1". |
| 7 | The 162th ~ 184th of the satellites whose masks are set to "1". |
| 8 | The 185th ~ 207th of the satellites whose masks are set to "1". |
| 9 | The 208th ~ 230th of the satellites whose masks are set to "1". |
| 10 | The 231th ~ 253th of the satellites whose masks are set to "1". |
| 11 | The 254th ~ 255th of the satellites whose masks are set to "1". |
| Other values | Reserved |

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# 9 Disclaimer

The experiment is carried out in Visual Studio 2022 environment. With the update of the software, proper modifications of the code may be needed. Some bugs may still exist in the B2bLIB, comments and suggestions are welcome to send to the authors.

# 10 Contact us

GCC research group of dedicated developers earnestly seeks your valuable insights and suggestions to improve the B2bLIB. We welcome all users to share and exchange technical details, as well as provide improvement suggestions. Here are our contact details:

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