MCOSB: an open-source software for multi-GNSS and multi-frequency code OSB estimation and analysis

User Manual

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Contents

1 Overview

Proper code bias processing is crucial for Global Navigation Satellite System (GNSS) positioning, navigation, and timing applications. In this case, the MCOSB software is designed and developed based on the MATLAB 2024b platform for multi-GNSS and multi-frequency code OSB estimation and analysis. The MCOSB software uses an improved code OSB estimation approach aided by the geometry-free and ionospheric-free (GFIF) observations. The MCOSB software consists of 4 main scripts including "ReadOBS.m", "ExtractMCB.m", "EstimateCOSB.m" and "AnalyzeCOSB.m", which has the following main functions:

(1) It includes some effective subfunctions, e.g., reading the multi-GNSS and multi-frequency observations, reading global ionospheric map (GIM) files, reading multi-GNSS precise orbit files, and plotting the GNSS station distributions, which can be provided to users for their other purposes.

(2) It can simultaneously estimate multi-GNSS and multi-frequency code OSBs using all available code types.

(3) It can generate the code OSB products in standard Solution Independent Exchange (SINEX) format for GNSS users to employed.

(4) It supports reading the SINEX files of code OSB products, and then can analyze the multi-GNSS and multi-frequency code OSB characteristics including availability, distribution, code OSB time series, and the standard deviation (STD) of code OSB

2 Methodology

2.1 Extraction of SPR MCB observable using GFIF model

For a given system, undifferenced and uncombined code observation equation can be formulated as follows

$$P_{r,i}^{s} = \rho_r^s + t_r - t^s + I_{r,i}^s + T_r^s + B_{r,i} + B_i^s + \varepsilon_{r,i}^s \tag{1}$$

where superscript s denotes the satellite; subscripts r and i denote the receiver and signal frequency, respectively; $P_{r,i}^{s}$ denotes the raw code observation; ρ_r^s denotes the satellite-to-receiver range; t_r and t^s denote the clock offsets at receiver and satellite end, respectively; $I_{r,i}^s$ and T_r^s denote the ionospheric delay and tropospheric delay, respectively; $B_{r,i}$ and B_i^s denote the code hardware delay at receiver and satellite end, respectively; $\varepsilon_{r,i}^s$ denotes the code observation noise.

Taking triple-frequency code observations on frequency i, j, and k as an example, the inter-frequency satellite-plus-receiver (SPR) multiple code bias (MCB) observable can be derived using the GFIF model to eliminate the frequency-independent terms and the first-order ionospheric error as follows

$$P_{r,ijk,\mathrm{GFIF}}^{s} = \alpha_{jk} P_{r,i}^{s} + \alpha_{ki} P_{r,j}^{s} + \alpha_{ij} P_{r,k}^{s} = \alpha_{jk} B_{r,i} + \alpha_{ki} B_{r,j} + \alpha_{ij} B_{r,k} + \alpha_{jk} B_{i}^{s} + \alpha_{ki} B_{j}^{s} + \alpha_{ij} B_{k}^{s} + \varepsilon_{r,\mathrm{GFIF}}^{s} \tag{2}$$

where $\varepsilon_{r,\mathrm{GFIF}}^{s}$ denotes the noise of GFIF observation. In this case, the inter-frequency MCB is defined as the combination of multiple code hardware delay, i.e., $MCB_{ijk}^{s} = \alpha_{jk} B_{i}^{s} + \alpha_{ki} B_{j}^{s} + \alpha_{ij} B_{k}^{s}$ at satellite end and $MCB_{r,ijk} = \alpha_{jk} B_{r,i} + \alpha_{ki} B_{r,j} + \alpha_{ij} B_{r,k}$ at receiver end. $\alpha_{jk} = \lambda_{k}^{2} - \lambda_{j}^{2}$, $\alpha_{ki} = \lambda_{i}^{2} - \lambda_{k}^{2}$, and $\alpha_{ij} = \lambda_{j}^{2} - \lambda_{i}^{2}$, where λ denotes carrier wavelength.

In addition, it is noted that the intra-frequency SPR MCB observation between different code types on the same frequency f is a special case using the GFIF model, which also eliminates the frequency-independent terms and the ionospheric error as follows

$$P_{r,f,xy,\mathrm{GFIF}}^{s} = P_{r,f,x}^{s} - P_{r,f,y}^{s} = B_{r,f,x} - B_{r,f,y} + B_{f,x}^{s} - B_{f,y}^{s} + \varepsilon_{r,\mathrm{GFIF}}^{s} \tag{3}$$

where subscripts x and y denote the reference code type and another code type on the same frequency (e.g., C1W and C1C for GPS). To further mitigate the observation noise and unmodeled errors, the SPR MCB observation can be extracted using an average operator over an observation period as follows

$$\begin{cases} SPR_{r,ijk}^{s} = \frac{1}{N} \sum_{t=1}^{N} (\alpha_{jk} P_{r,i,t}^{s} + \alpha_{ki} P_{r,j,t}^{s} + \alpha_{ij} P_{r,k,t}^{s}) \\ SPR_{r,f,xy}^{s} = \frac{1}{N} \sum_{t=1}^{N} (P_{r,f,x,t}^{s} - P_{r,f,y,t}^{s}) \end{cases} \tag{4}$$

where $\mathrm{SPR}_{r,ijk}^{s}$ and $\mathrm{SPR}_{r,f,xy}^{s}$ denote the extracted inter-frequency and intra-frequency SPR MCB observations, respectively; t denotes the observation epoch and N denotes the number of total epochs over the observation period.

2.2 Code OSB estimation of triple-frequency case

Assuming that total *n* satellites are observed for *u* receivers in the reference network, the raw OSB estimation model using the SPR MCB observables which satisfy carrier frequency $f_i > f_j > f_k$ (i.e., L1, L2, and L5 for GPS) is as follows

$$
\begin{bmatrix} \boldsymbol{SPR}_{1,ijk}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,ijk}^{s} \\ \boldsymbol{SPR}_{1,f,xy}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,f,xy}^{s} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \mathbf{0} & \mathbf{0} \\ & & & & & & -\boldsymbol{I} & -\boldsymbol{I} \\ & \boldsymbol{F} & & & \boldsymbol{F} & & \vdots & \vdots \\ & & & & & & -\boldsymbol{I} & -\boldsymbol{I} \end{bmatrix} \begin{bmatrix} \boldsymbol{B}_{i,x}^{s} \\ \boldsymbol{B}_{j,x}^{s} \\ \boldsymbol{B}_{k,x}^{s} \\ \boldsymbol{B}_{r,i,x} \\ \boldsymbol{B}_{r,j,x} \\ \boldsymbol{B}_{r,k,x} \\ \boldsymbol{B}_{f,y}^{s} \\ \boldsymbol{B}_{r,f,y} \end{bmatrix} \tag{5}
$$

where $\boldsymbol{SPR}_{u,ijk}^{s} = [SPR_{u,ijk}^{1}, \cdots, SPR_{u,ijk}^{n}]^{\mathrm{T}}$, $\boldsymbol{SPR}_{u,f,xy}^{s} = [SPR_{u,f,xy}^{1}, \cdots, SPR_{u,f,xy}^{n}]^{\mathrm{T}}$, $\boldsymbol{B}_{i,x}^{s} = [B_{i,x}^{1}, \cdots B_{i,x}^{n}]^{\mathrm{T}}$, $\boldsymbol{B}_{j,x}^{s} = [B_{j,x}^{1}, \cdots B_{j,x}^{n}]^{\mathrm{T}}$, $\boldsymbol{B}_{k,x}^{s} = [B_{k,x}^{1}, \cdots B_{k,x}^{n}]^{\mathrm{T}}$, $\boldsymbol{B}_{r,i,x} = [B_{1,i,x}, \cdots B_{u,i,x}]^{\mathrm{T}}$, $\boldsymbol{B}_{r,j,x} = [B_{1,j,x}, \cdots B_{u,j,x}]^{\mathrm{T}}$, $\boldsymbol{B}_{r,k,x} = [B_{1,k,x}, \cdots B_{u,k,x}]^{\mathrm{T}}$, $\boldsymbol{B}_{f,y}^{s} = [B_{f,y}^{1}, \cdots B_{f,y}^{n}]^{\mathrm{T}}$, $\boldsymbol{B}_{r,f,y} = [B_{1,f,y}, \cdots B_{u,f,y}]^{\mathrm{T}}$ ($f = i, j$ or k). $\boldsymbol{\alpha}_{kj} = \begin{bmatrix} \alpha_{kj} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \alpha_{kj} \end{bmatrix}$, $\boldsymbol{\alpha}_{ik} = \begin{bmatrix} \alpha_{ik} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \alpha_{ik} \end{bmatrix}$, and $\boldsymbol{\alpha}_{ji} = \begin{bmatrix} \alpha_{ji} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \alpha_{ji} \end{bmatrix}$. $\boldsymbol{F} = \begin{bmatrix} \boldsymbol{I} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots \\ \boldsymbol{I} & \mathbf{0} & \mathbf{0} \end{bmatrix}$ for $f = i$, $\boldsymbol{F} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} & \mathbf{0} \\ \vdots & \vdots & \vdots \\ \mathbf{0} & \boldsymbol{I} & \mathbf{0} \end{bmatrix}$ for $f = j$, and $\boldsymbol{F} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{I} \\ \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \boldsymbol{I} \end{bmatrix}$ for $f = k$. $\boldsymbol{I}$ is the identity matrix.

At this time, the rank deficiencies in equation (5) must be identified and eliminated to establish a full-rank estimable function model. Specifically, there exist three types of rank deficiencies. The first type of rank deficiency is caused by the linear dependencies between the code OSB parameters at the satellite and receiver end (i.e., $B_{f,\mathrm{type}}^{s}$ and $B_{r,f,\mathrm{type}}$). To eliminate this type of rank deficiency, one code OSB datum for each code type is chosen as a constraint condition. Hence, a commonly used zero-mean constraint condition for all involved satellites is added for each code OSB type as follows

$$
\sum_{s=1}^{n} B_{f,\mathrm{type}}^{s} = 0 \tag{6}
$$

where subscript type denotes all possible code types. After adding these zero-mean constraint conditions for each code type, the first type of rank deficiency can be eliminated and then the code OSBs at satellite and receiver end can be separated.

The second type of rank deficiency is caused by the linear dependencies between the inter-frequency code OSB parameters for each satellite (i.e., B_{i}^{s}, B_{j}^{s}, and B_{k}^{s}) and each receiver (i.e., $B_{r,i}$,

$B_{r,j}$, and $B_{r,k}$). To eliminate this type of rank deficiency, a zero-ionospheric-free constraint is added for each satellite and each receiver, which can be expressed as follows

$$\begin{cases} \alpha B_{i,x}^{s} + \beta B_{j,x}^{s} = 0 \\ \alpha B_{r,i,x} + \beta B_{r,j,x} = 0 \end{cases} \tag{7}$$

where $\alpha = \frac{f_i^2}{f_i^2 - f_j^2}$ and $\beta = -\frac{f_j^2}{f_i^2 - f_j^2}$. It is noted that the code types x on frequency i and j are selected using the reference code types for IGS clock products as shown in Table 1. In this case, the α and β are just the coefficients of ionospheric-free (IF) combination. Then, the estimated code OSBs are compatible with the precise satellite clock products provided by IGS.

Table 1 Reference code types for GPS, BDS-3, and Galileo

System	Reference code type
GPS	C1W/C2W
BDS-3	C2I/C6I
Galileo	C1X/C5X or C1C/C5Q

Both GF condition and IF condition need to be satisfied in GFIF model. Hence, the third type of rank deficiency is also caused by the linear dependencies between the inter-frequency code OSB parameters for each satellite and each receiver. To eliminate this type of rank deficiency, an inter-frequency GF observation is added for each pair of satellite and receiver, which can be expressed as follows

$$SPR_{r,ij}^{s} = B_{r,i,x} - B_{r,j,x} + B_{i,x}^{s} - B_{j,x}^{s} \tag{8}$$

where $SPR_{r,ij}^{s}$ denotes the SPR GF observable, which can be typically obtained by GF model using an external ionospheric model (e.g., GIM model). After adding all involved zero-mean and zero-ionospheric-free constraint conditions and GF observables, a full-rank estimable function model is established as follows

$$\begin{bmatrix} \boldsymbol{SPR}_{1,ijk}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,ijk}^{s} \\ \boldsymbol{SPR}_{1,f,xy}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,f,xy}^{s} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{SPR}_{1,ij}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,ij}^{s} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \boldsymbol{\alpha}_{kj} & \boldsymbol{\alpha}_{ik} & \boldsymbol{\alpha}_{ji} & \mathbf{0} & \mathbf{0} \\ & & & & & & -\boldsymbol{I} & -\boldsymbol{I} \\ & \boldsymbol{F} & & & \boldsymbol{F} & & \vdots & \vdots \\ & & & & & & -\boldsymbol{I} & -\boldsymbol{I} \\ \boldsymbol{G}_i & \boldsymbol{G}_j & \boldsymbol{G}_k & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{G}_f & \mathbf{0} \\ \boldsymbol{\alpha} & \boldsymbol{\beta} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{B}_{i,x}^{s} \\ \boldsymbol{B}_{j,x}^{s} \\ \boldsymbol{B}_{k,x}^{s} \\ \boldsymbol{B}_{r,i,x} \\ \boldsymbol{B}_{r,j,x} \\ \boldsymbol{B}_{r,k,x} \\ \boldsymbol{B}_{f,y}^{s} \\ \boldsymbol{B}_{r,f,y} \end{bmatrix} \tag{9}$$

where $\boldsymbol{G}_i = \begin{bmatrix} \boldsymbol{e} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}$, $\boldsymbol{G}_j = \begin{bmatrix} \mathbf{0} \\ \boldsymbol{e} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}$, $\boldsymbol{G}_k = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{e} \\ \mathbf{0} \end{bmatrix}$, $\boldsymbol{G}_f = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{e} \end{bmatrix}$; $\boldsymbol{\alpha} = \begin{bmatrix} \alpha & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \alpha \end{bmatrix}$, $\boldsymbol{\beta} = \begin{bmatrix} \beta & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \beta \end{bmatrix}$; $\boldsymbol{SPR}_{u,ij}^{s} = [SPR_{u,ij}^{1}, \cdots, SPR_{u,ij}^{n}]^{\mathrm{T}}$; $\boldsymbol{e}$ is a vector with all columns of element 1.

2.3 Code OSB estimation of five-frequency case

Take BDS-3 as an example that can broadcast five-frequency signals. It is noted that only total three linear independent types of inter-frequency SPR MCB observations can be formed for each satellite among the five-frequency code observations which satisfy $f_i > f_j > f_k > f_m > f_n$ (i.e., B1C, B1I, B3I, B2b and B2a for BDS-3). It can be expressed as follows

$$\begin{bmatrix} SPR_{r,ijk}^{s} \\ SPR_{r,ijm}^{s} \\ SPR_{r,ijn}^{s} \end{bmatrix} = \begin{bmatrix} \alpha_{kj} & \alpha_{ik} & \alpha_{ji} & 0 & 0 & \alpha_{kj} & \alpha_{ik} & \alpha_{ji} & 0 & 0 \\ \alpha_{mj} & \alpha_{im} & 0 & \alpha_{ji} & 0 & \alpha_{mj} & \alpha_{im} & 0 & \alpha_{ji} & 0 \\ \alpha_{nj} & \alpha_{in} & 0 & 0 & \alpha_{ji} & \alpha_{nj} & \alpha_{in} & 0 & 0 & \alpha_{ji} \end{bmatrix} \begin{bmatrix} B_{i,x}^{s} \\ B_{j,x}^{s} \\ B_{k,x}^{s} \\ B_{m,x}^{s} \\ B_{n,x}^{s} \\ B_{r,i,x} \\ B_{r,j,x} \\ B_{r,k,x} \\ B_{r,m,x} \\ B_{r,n,x} \end{bmatrix} \tag{10}$$

where $\alpha_{\Delta\nabla} = \lambda_{\nabla}^{2} - \lambda_{\Delta}^{2}$ (the subscripts Δ and ∇ are wildcards for i, j, k, m, n). Then, a full-rank estimable function model is established for BDS-3 as follows

$$\begin{bmatrix} \boldsymbol{L}_{1,ijkmn}^{s} \\ \vdots \\ \boldsymbol{L}_{u,ijkmn}^{s} \\ \boldsymbol{SPR}_{1,f,xy}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,f,xy}^{s} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{SPR}_{1,jk}^{s} \\ \vdots \\ \boldsymbol{SPR}_{u,jk}^{s} \end{bmatrix} = \left[\begin{array}{cccccccccccc} \multicolumn{5}{c}{\boldsymbol{G}_{ijkmn}} & \multicolumn{5}{c}{\boldsymbol{G}_{ijkmn}} & \mathbf{0} & \mathbf{0} \\ \multicolumn{5}{c}{\vdots} & \multicolumn{5}{c}{\vdots} & \vdots & \vdots \\ \multicolumn{5}{c}{\boldsymbol{G}_{ijkmn}} & \multicolumn{5}{c}{\boldsymbol{G}_{ijkmn}} & \mathbf{0} & \mathbf{0} \\ \multicolumn{5}{c}{} & \multicolumn{5}{c}{} & -\boldsymbol{I} & -\boldsymbol{I} \\ \multicolumn{5}{c}{\boldsymbol{F}} & \multicolumn{5}{c}{\boldsymbol{F}} & \vdots & \vdots \\ \multicolumn{5}{c}{} & \multicolumn{5}{c}{} & -\boldsymbol{I} & -\boldsymbol{I} \\ \boldsymbol{G}_i & \boldsymbol{G}_j & \boldsymbol{G}_k & \boldsymbol{G}_m & \boldsymbol{G}_n & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{G}_f & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{I} & -\boldsymbol{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{array}\right] \begin{bmatrix} \boldsymbol{B}_{i,x}^{s} \\ \boldsymbol{B}_{j,x}^{s} \\ \boldsymbol{B}_{k,x}^{s} \\ \boldsymbol{B}_{m,x}^{s} \\ \boldsymbol{B}_{n,x}^{s} \\ \boldsymbol{B}_{r,i,x} \\ \boldsymbol{B}_{r,j,x} \\ \boldsymbol{B}_{r,k,x} \\ \boldsymbol{B}_{r,m,x} \\ \boldsymbol{B}_{r,n,x} \\ \boldsymbol{B}_{f,y}^{s} \\ \boldsymbol{B}_{r,f,y} \end{bmatrix} \tag{11}$$

where $\boldsymbol{L}_{u,ijkmn}^{s} = \left[\boldsymbol{L}_{u,ijkmn}^{1}, \cdots, \boldsymbol{L}_{u,ijkmn}^{n}\right]^{\mathrm{T}}$ with $\boldsymbol{L}_{u,ijkmn}^{n} = [SPR_{u,ijk}^{n}, SPR_{u,ijm}^{n}, SPR_{u,ijn}^{n}]^{\mathrm{T}}$. $\boldsymbol{G}_{ijkmn} = \begin{bmatrix} \boldsymbol{G} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \boldsymbol{G} \end{bmatrix}$ with $\boldsymbol{G} = \begin{bmatrix} \alpha_{kj} & \alpha_{ik} & \alpha_{ji} & 0 & 0 \\ \alpha_{mj} & \alpha_{im} & 0 & \alpha_{ji} & 0 \\ \alpha_{nj} & \alpha_{in} & 0 & 0 & \alpha_{ji} \end{bmatrix}$. $\boldsymbol{F}$, $\boldsymbol{G}_i$, $\boldsymbol{G}_j$, $\boldsymbol{G}_k$, $\boldsymbol{G}_m$, $\boldsymbol{G}_n$, and $\boldsymbol{G}_f$ can be derived similar to equation (9). The α and β are selected for frequencies j and k (i.e., B1I and B3I for BDS-3) to make the estimated OSBs be compatible with the precise satellite clock product. It is noted that, the above functional model of multi-frequency code OSB estimation is also suitable for Galileo by changing the i, j, k, m, and n to E1, E6, E5b, E5, and E5a frequency, respectively.

3 Architecture of the MCOSB software

3.1 Overall flowchart

Fig. 1 shows the overall flowchart of the MCOSB software, which includes 4 main procedures as follows:

(1) Prepare the required GNSS observation files and read multi-GNSS and multi-frequency raw code observations (abbreviated as ReadOBS).

(2) Prepare required SP3 and GIM files and read the satellite precise orbits and ionospheric information. Then, extract the satellite plus receiver (SPR) MCB observables for all available intra- and inter-frequency code types and extract the GF observables of correcting the ionospheric errors for the reference code types (abbreviated as ExtractMCB).

(3) Parameterize the OSB for each code type and apply all involved zero-mean and zero-ionospheric-free constraints to eliminate the model rank deficiencies. Then, establish a full-rank

normal equation and further estimate GNSS multi-frequency code OSBs (abbreviated as EstimateCOSB). Meanwhile, generate the code OSB products in standard SINEX format.

(4) Read the OSB SINEX files and analyze the multi-GNSS and multi-frequency code OSB characteristics including availability, distribution, code OSB time series, and the standard deviation (STD) of code OSB (abbreviated as AnalyzeCOSB).

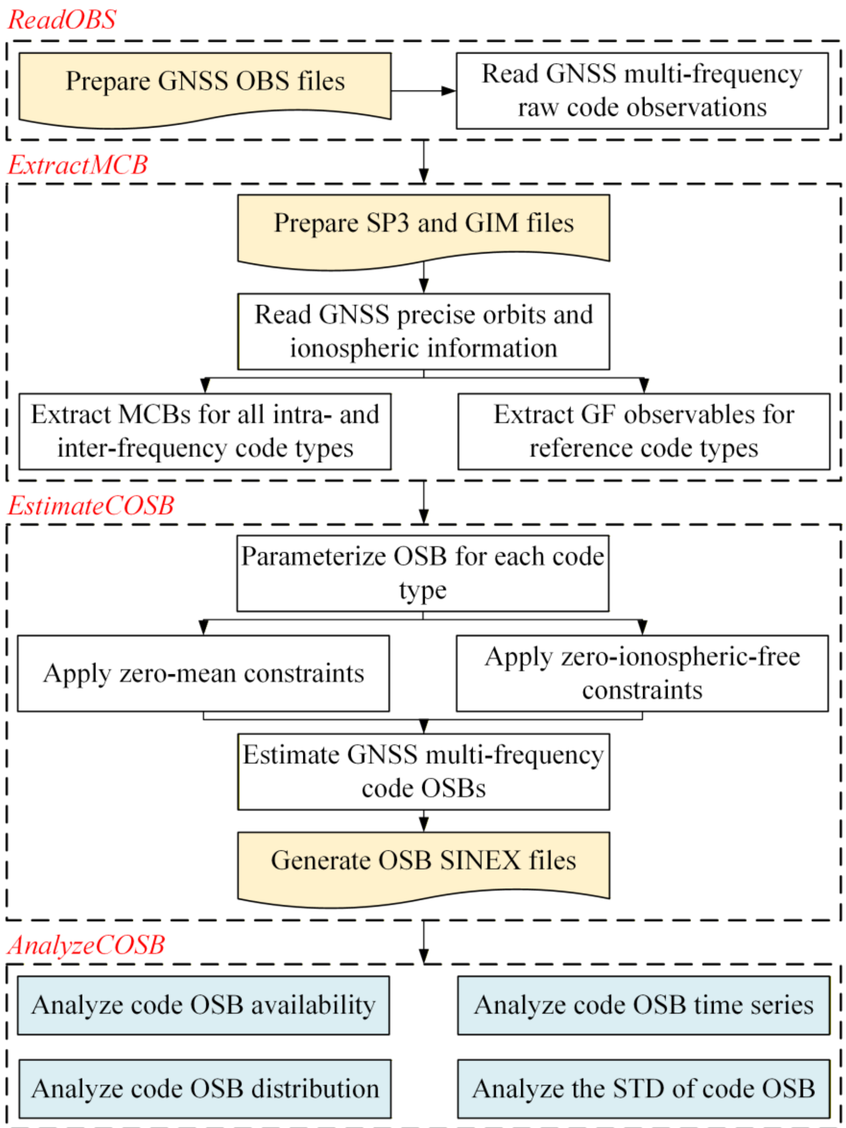


Fig. 1 Overall flowchart of the MCOSB software

3.2 Directory structure

Fig.2 depicts the directory structure of the MCOSB software, including 10 folders and 4 scripts. Specifically, “1_FilesOBS” folder includes the GNSS observation files; “2_FilesSP3” folder includes the satellite precise orbit files; “3_FilesION” folder includes the ionospheric GIM files;

“4_FilesOSB” folder includes the code OSB SINEX files estimated from the MCOSB software; “5_FilesAnalysis” folder includes the code OSB SINEX files used for OSB analysis; “MCB” folder includes the MCB observables extracted from the MCOSB software; “MCOSBToolbox” folder includes the subfunctions and basic data of the MCOSB software; “OBS” folder includes the read observation data; “OSB” folder includes the estimated code OSB data; “STA” folder includes the read GNSS station data. In addition, “ReadOBS” script is used for reading multi-GNSS and multi-frequency raw code observations; “ExtractMCB” script is used for reading the satellite precise orbits and ionospheric information, and extracting the SPR MCB observables for all available intra- and inter-frequency code types and the GF observables for the reference code types; “EstimateCOSB” script is used for estimating the multi-GNSS and multi-frequency code OSB and generating the code OSB products in standard SINEX format; “AnalyzeCOSB” script is used for reading the OSB SINEX files and analyzing the code OSB characteristics including availability, distribution, code OSB time series, and the STD of code OSB.

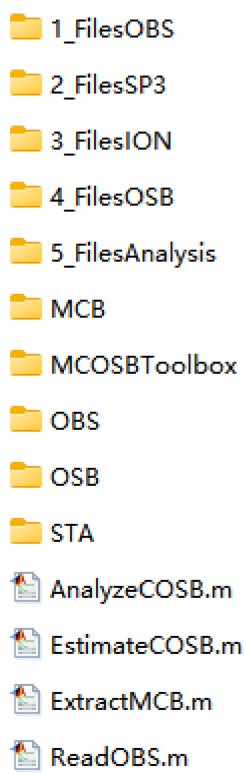


Fig. 2 Directory structure of the MCOSB software

4 How to run the MCOSB software

4.1 Environment requirement

Although the MCOSB software is designed and developed based on the MATLAB 2024b platform, the debugging and usage of the MCOSB software supports almost all MATLAB versions.

4.2 Data Preparation

To estimate multi-GNSS and multi-frequency code OSB products using the MCOBS software, the GNSS observation files from global or regional networks should be download and prepared in the "1_FilesOBS" folder. To calculate the satellite precise coordinates, the satellite precise orbit files should be download and prepared in the "2_FilesSP3" folder. Additionally, to correct the ionospheric error in the GF observable, the ionospheric GIM files should be download and prepared in the "3_FilesION" folder. Figs. 3 to 5 show the example of corresponding files required in each folder.

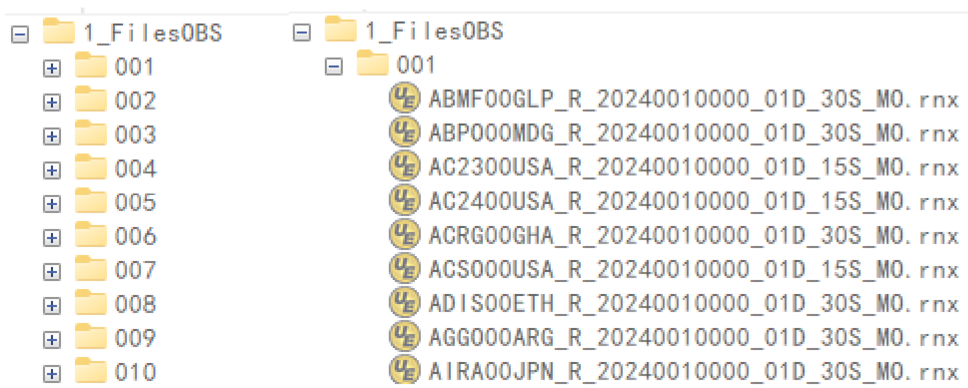


Fig. 3 Example of corresponding files required in the "1_FilesOBS" folder

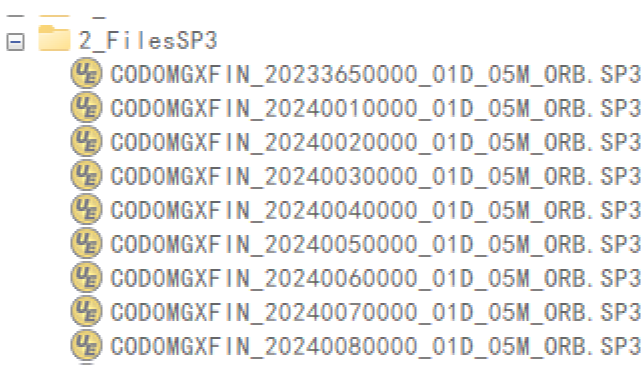


Fig. 4 Example of corresponding files required in the "2_FilesSP3" folder

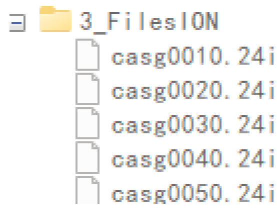
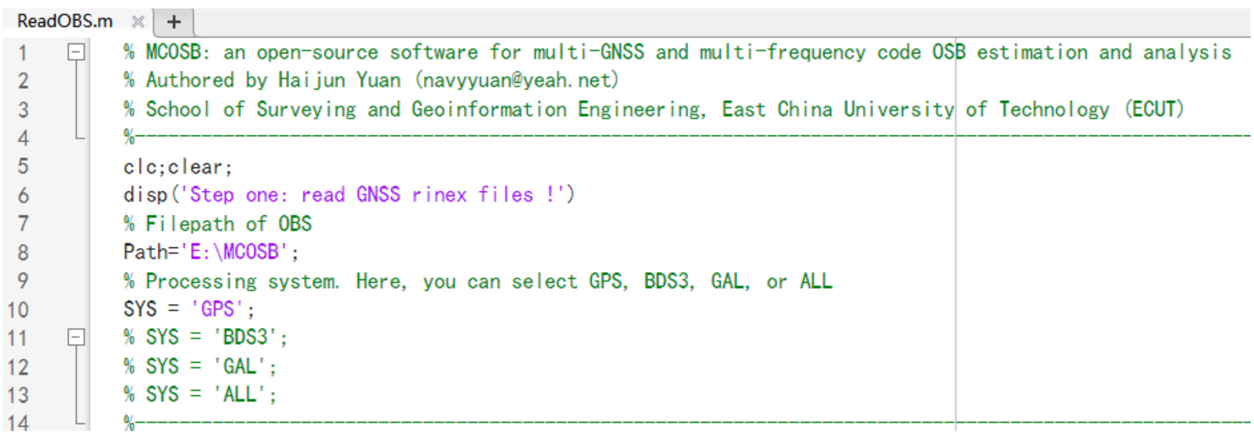


Fig. 5 Example of corresponding files required in the “3_FilesION” folder

4.3 Data Preprocessing

After preparing the required files, the data preprocessing should be conducted before code OSB estimation. The main procedures of data preprocessing in the MCOSB software are as follows

(1) **The “ReadOBS” script** should be conducted to read multi-GNSS and multi-frequency raw code observations, as shown in Fig. 6.



```
% MCOSB: an open-source software for multi-GNSS and multi-frequency code OSB estimation and analysis
% Authored by Haijun Yuan (navyyuan@yeah.net)
% School of Surveying and Geoinformation Engineering, East China University of Technology (ECUT)
%-----------------------------------------------------------------------------------------------------
clc;clear;
disp('Step one: read GNSS rinex files !')
% Filepath of OBS
Path='E:\MCOSB';
% Processing system. Here, you can select GPS, BDS3, GAL, or ALL
SYS = 'GPS';
% SYS = 'BDS3';
% SYS = 'GAL';
% SYS = 'ALL';
%-----------------------------------------------------------------------------------------------------
```

Fig. 6 “ReadOBS” script

Here, you should input the correct file path of the MCOSB software depending on the users, such as “Path=E:\MCOSB”. In addition, you should select which system to process such as GPS, BDS-3, Galileo, or all systems by the setting of “SYS”. In this case, the read observation data and station information will be stored in the “OBS” and “STA” folder, respectively. For example, Figs. 7 and 8 show the read observation data and station information.

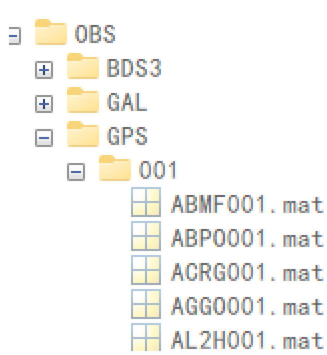


Fig. 7 Read observation data

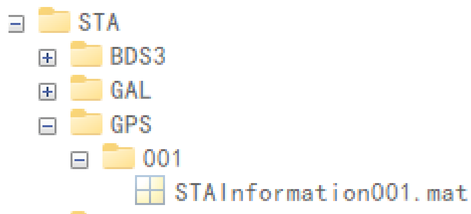
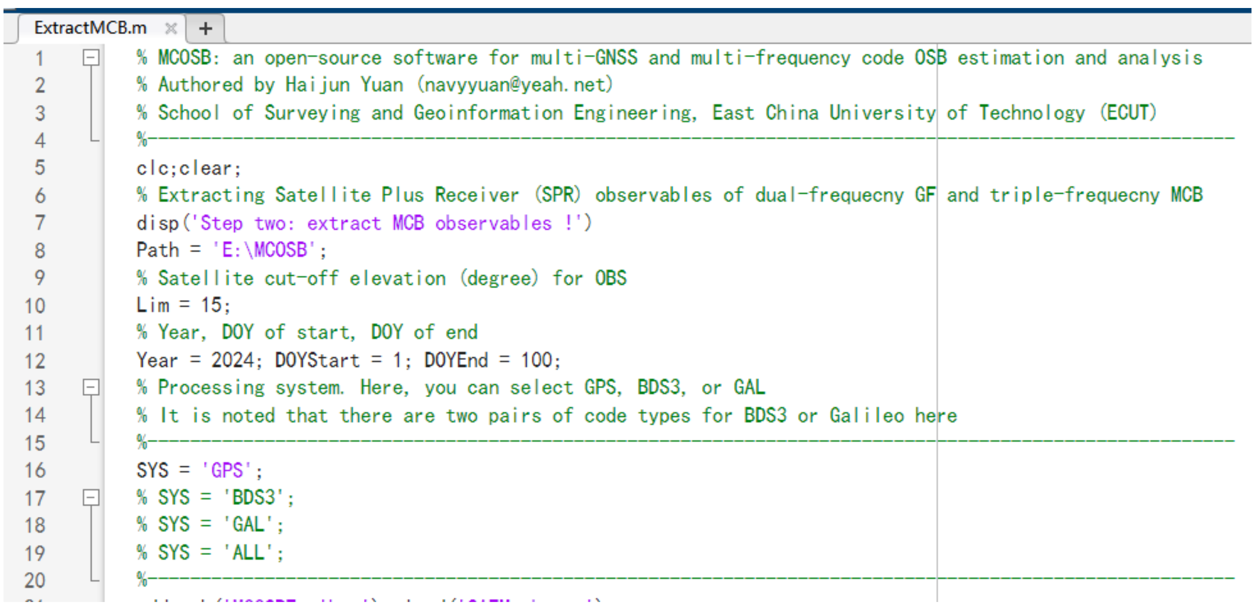


Fig. 8 Read station information

(2) **The “ExtractMCB” script** should be conducted to read the satellite precise orbits and ionospheric information, and extract the SPR MCB observables for all available intra- and inter-frequency code types and the GF observables for the reference code types, as shown in Fig. 9.



```
% MCOSB: an open-source software for multi-GNSS and multi-frequency code OSB estimation and analysis
% Authored by Haijun Yuan (navyyuan@yeah.net)
% School of Surveying and Geoinformation Engineering, East China University of Technology (ECUT)
%------------------------------------------------------------------------------------------------------
clc;clear;
% Extracting Satellite Plus Receiver (SPR) observables of dual-frequecny GF and triple-frequecny MCB
disp('Step two: extract MCB observables !')
Path = 'E:\MCOSB';
% Satellite cut-off elevation (degree) for OBS
Lim = 15;
% Year, DOY of start, DOY of end
Year = 2024; DOYStart = 1; DOYEnd = 100;
% Processing system. Here, you can select GPS, BDS3, or GAL
% It is noted that there are two pairs of code types for BDS3 or Galileo here
%------------------------------------------------------------------------------------------------------
SYS = 'GPS';
% SYS = 'BDS3';
% SYS = 'GAL';
% SYS = 'ALL';
%------------------------------------------------------------------------------------------------------
```

Fig. 9 “ExtractMCB” script

Here, you should input the correct file path of the MCOSB software depending on the users, such as “Path=E:\MCOSB”. In addition, you should set the satellite cut-off elevation such as 15° for observation processing to mitigate the multipath and unmodeled errors. The year, DOY of start and DOY of end for observation processing should also be set. You should select which system to process such as GPS, BDS-3, Galileo, or all systems by the setting of “SYS”. Notably, there are two pairs of code types for BDS3 and Galileo here. In this case, the extracted SPR MCB and GF observables will be stored in the “MCB” folder. For example, Fig. 10 shows the extracted SPR MCB observables.

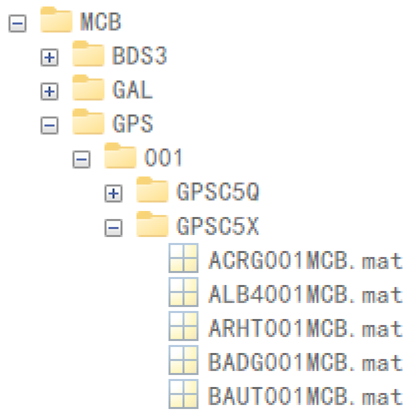


Fig. 10 Extracted SPR MCB observables

4.4 Code OSB estimation

The "EstimateCOSB" script should be conducted to estimate multi-GNSS and multi-frequency code OSB products, as shown in Fig. 11.

```
EstimateCOSB.m
% MCOSB: an open-source software for multi-GNSS and multi-frequency code OSB estimation and analysis
% Authored by Haijun Yuan (navyyuan@yeah.net)
% School of Surveying and Geoinformation Engineering, East China University of Technology (ECUT)
%-----------------------------------------------------------------------------------------------
clc;clear;
disp('Step three: estimate multi-GNSS and multi-frequency code OSB products !')
Path = 'E:\MCOSB';
% Year, DOY of start, DOY of end
Year = 2024; DOYStart = 1; DOYEnd = 100;
%-----------------------------------------------------------------------------------------------
% Processing system. Here, you can select GPS, BDS3, GAL, or ALL
% SYS = 'GPS';
% SYS = 'BDS3';
% SYS = 'GAL';
SYS = 'ALL';
%-----------------------------------------------------------------------------------------------
```

Fig. 11 "EstimateCOSB" script

Here, you should input the correct file path of the MCOSB software depending on the users, such as "Path=E:\MCOSB". In addition, you should select which system to process such as GPS, BDS-3, Galileo, or all systems by the setting of "SYS". In this case, the estimated multi-GNSS and multi-frequency code OSBs will be stored in the "OSB" folder, and the generated code OSB products in standard SINEX format will be stored in the "4_FilesOSB" folder. For example, Figs. 12 and 13 show the estimated code OSBs and the generated code OSB products, respectively.

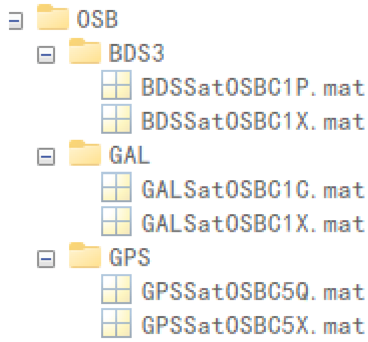


Fig. 12 Estimated code OSBs

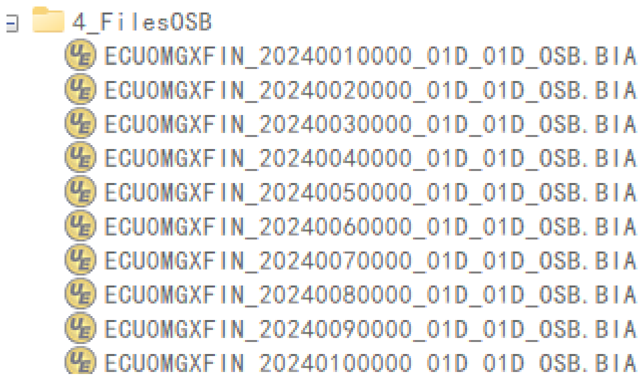


Fig. 13 Generated code OSB products

4.5 Code OSB analysis

The "AnalyzeCOSB" script should be conducted to analyze the multi-GNSS and multi-frequency code OSB characteristics including availability, distribution, code OSB time series, and the STD of code OSB, as shown in Fig. 14.

AnalyzeCOSB.m

```
% MCOSB: an open-source software for multi-GNSS and multi-frequency code OSB estimation and analysis
% Authored by Haijun Yuan (navyyuan@yeah.net)
% School of Surveying and Geoinformation Engineering, East China University of Technology (ECUT)
clc; clear;
%-------------------------------------------------------------------------------------------------------
clc;clear;
disp('Step four: analyze multi-GNSS and multi-frequency code OSB characteristics !')
Path = 'E:\MCOSB';
% e.g., CAS, ECU
Center = 'ECU';
% Plot station distribution, 1 for on and 0 for off
Staion = 1;
% Plot which day
DOY = 1;
%-------------------------------------------------------------------------------------------------------
```

Fig. 14 "AnalyzeCOSB" script

Here, you should input the correct file path of the MCOSB software depending on the users, such as "Path=E:\MCOSB". In addition, you should select which analysis centers to analyze such as

ECU and CAS by the setting of "Center". You should select whether to plot the station distribution and which day to plot by configuring the "Station" and "DOY" settings, respectively. It is noted that the OSB SINEX files of different analysis centers should be prepared in the "5_FilesAnalysis" folder, as shown in Fig. 15.

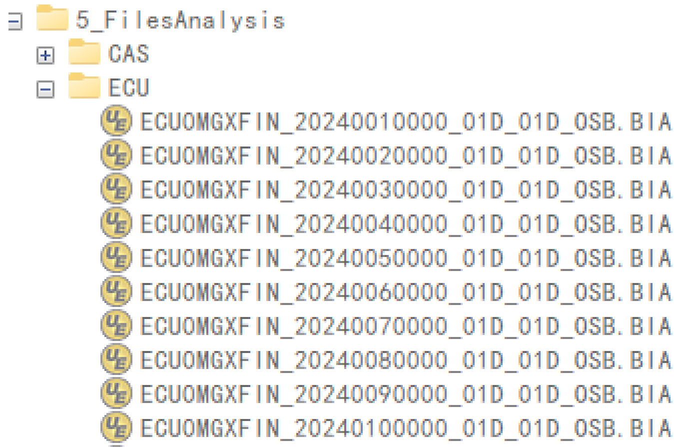


Fig. 15 "5_FilesAnalysis" folder

For example, Fig. 16 depicts the distributions of the selected hundreds of GNSS stations.

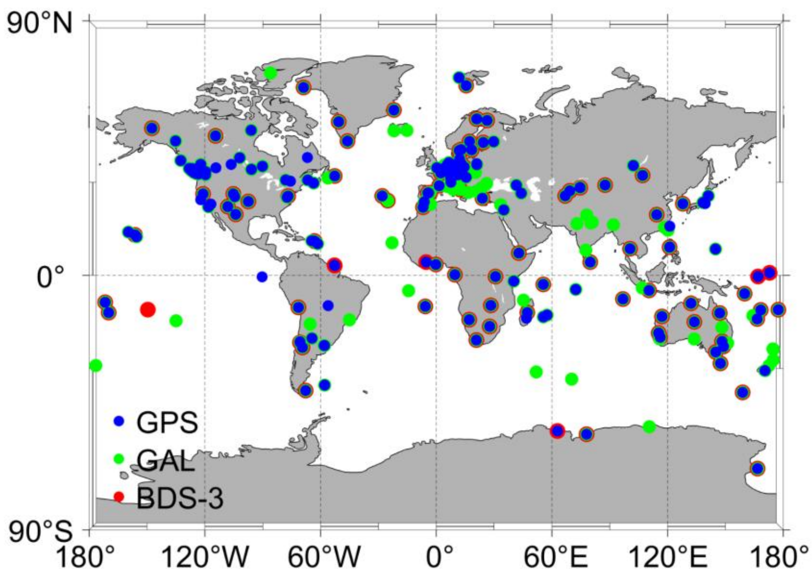


Fig. 16 Distributions of the selected hundreds of GNSS stations from the MGEX network

The MCOSB software supports analyzing the availability of code OSB products by reading the OSB SINEX files. Fig. 17 shows the code OSB availability of each satellite on DOY 001-100 based on the MCOSB software. Certainly, the code OSB availability from other GNSS analysis centers (e.g., CAS and CODE) can also be analyzed by reading the OSB SINEX files, as shown in Fig. 18.

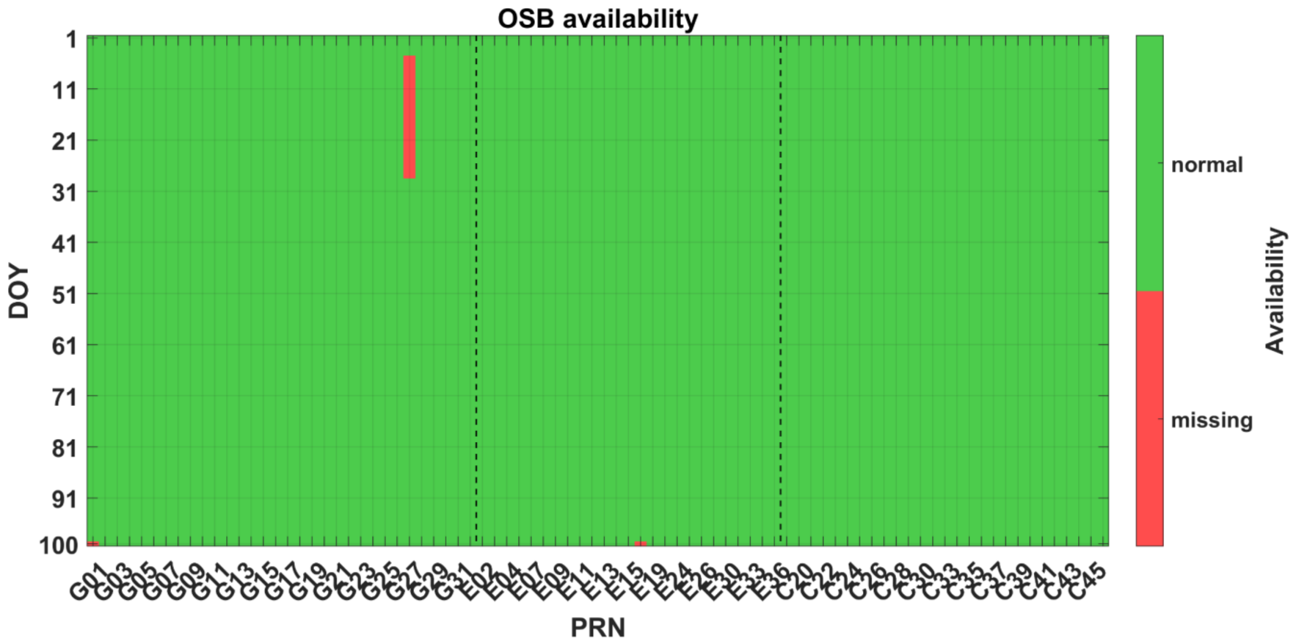


Fig. 17 Code OSB availability of each satellite on DOY 001-100, where the green and red blocks denote the normal and missing OSB products, respectively

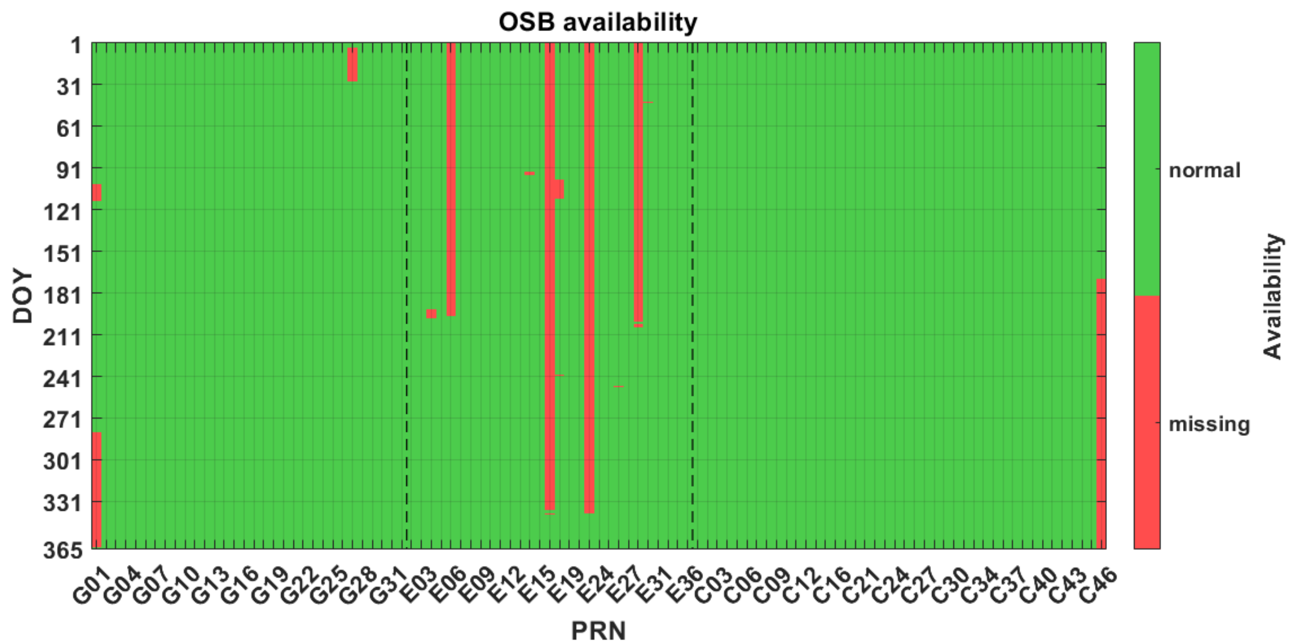


Fig. 18 Code OSB availability of each satellite on DOY 001-365 for CAS products, where the green and red blocks denote the normal and missing OSB products, respectively

Although the MCOSB software can estimate and analyze the multi-GNSS and multi-frequency code OSBs, due to the space limitations, Figs. 19 and 20 representatively depict the box plot of estimated GPS C1W and C2W OSB of each satellite based on the MCOSB software.

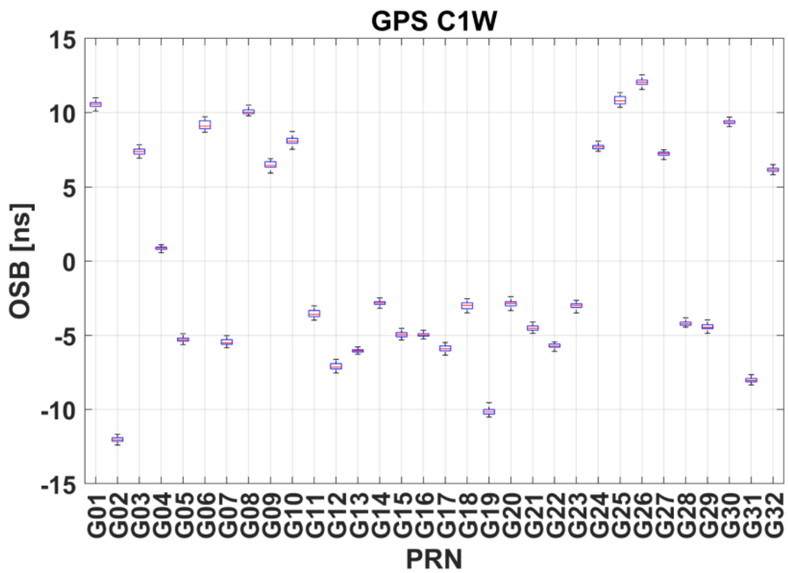


Fig. 19 Box plot of estimated GPS C1W OSB of each satellite

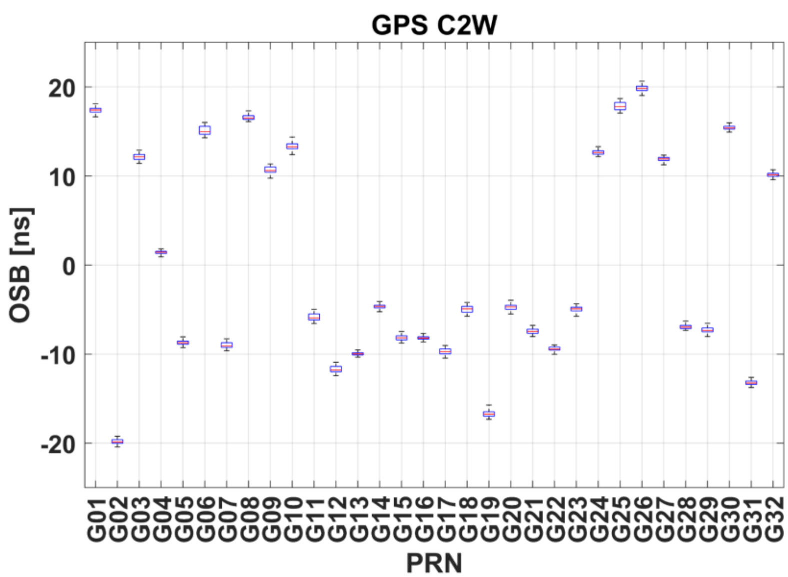


Fig. 20 Box plot of estimated GPS C2W OSB of each satellite

Figs. 21 and 22 representatively show the time series of estimated C2I and C6I OSB for each BDS-3 satellite based on the MCOSB software. Fig. 23 depicts the STD of code OSB for each Galileo code type. In conclusion, the MCOSB software can estimate the stable and reliable multi-GNSS and multi-frequency code OSB products for GNSS users.

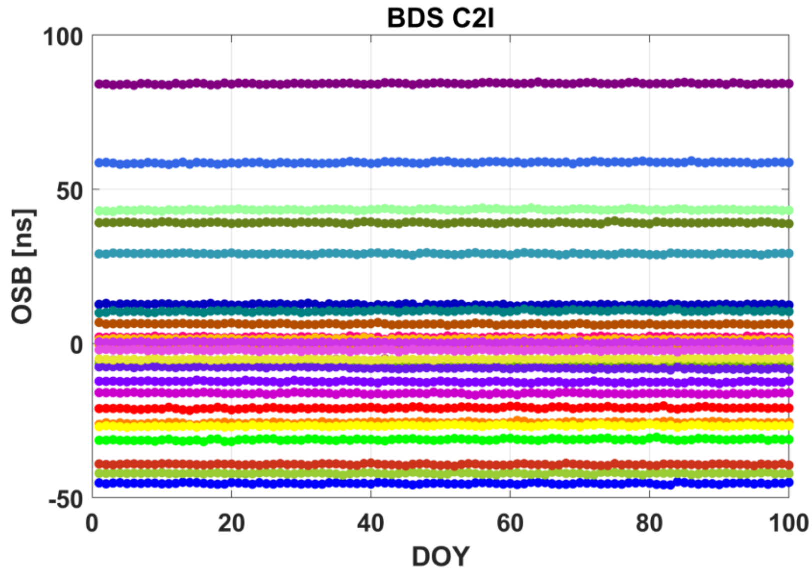


Fig. 21 Time series of estimated C2I OSB of each BDS-3 satellite, where each colored dot denotes the result of each BDS-3 satellite

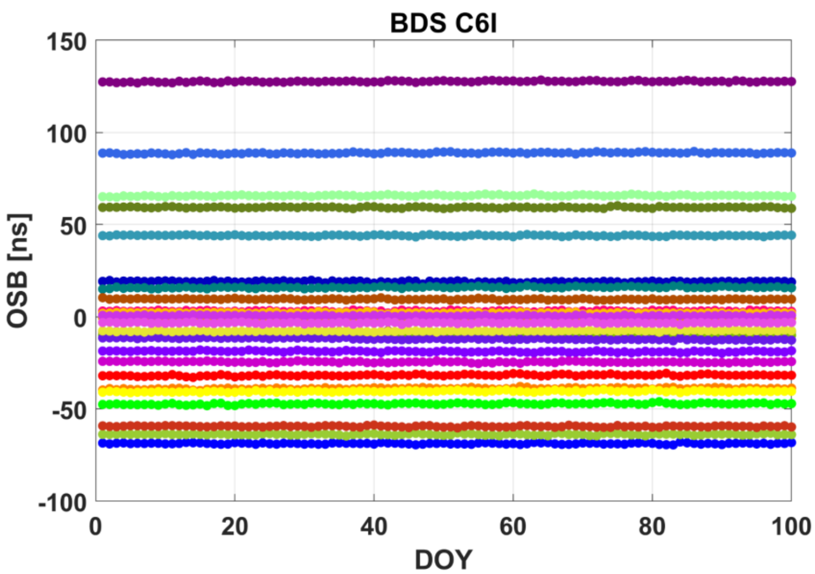


Fig. 22 Time series of estimated C6I OSB of each BDS-3 satellite, where each colored dot denotes the result of each BDS-3 satellite

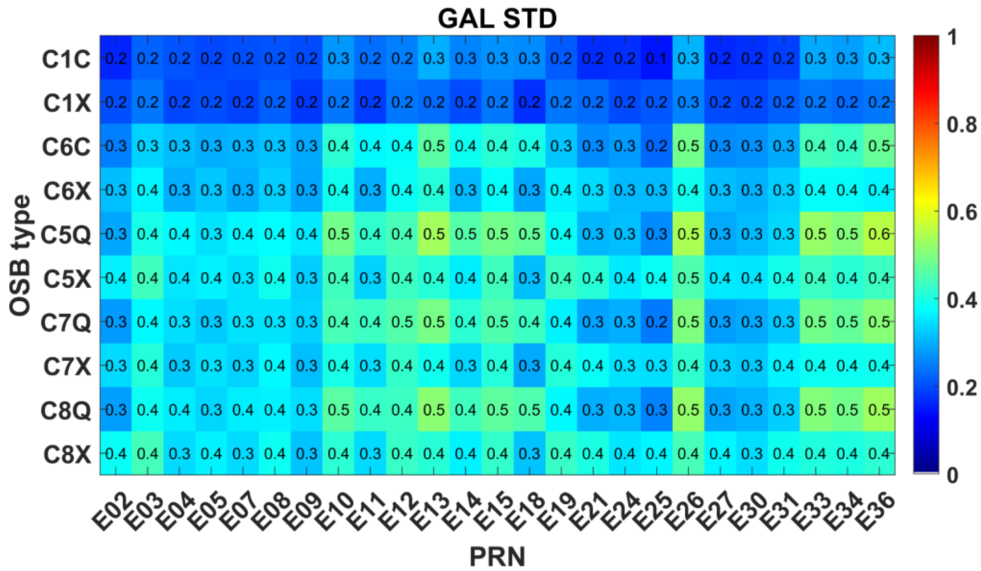


Fig. 23 STD of code OSB for each Galileo code type

5 Acknowledgement

We would like to than the MGEX, CAS, and CODE for providing the GNSS datasets and required products. Part subfunctions are modified from M_GIM (Zhou et al. 2023) and raPPPid (Glaner and Weber 2023), we are grateful to their early work.

6 Disclaimer

The code OSB estimation is carried out in the MATLAB 2024b environment. Some bugs may still exist in the MCOSB software, comments and suggestions are welcome to send to the authors.

7 Contact us

We earnestly seek your valuable insights and suggestions to improve the MCOSB software, and we welcome all users to share and exchange technical details. The MCOSB software are publicly accessible via the GitHub repository at https://github.com/GCCLib.