

This manuscript presents GIFT-BDS, a regional ionospheric dataset that uses the quasi-fixed geometry of BeiDou GEO observations to provide continuous STEC records and TEC-gradient products over China. The relatively stable ionospheric pierce point geometry offers advantages for monitoring temporal ionospheric variations. The manuscript is generally clear and well organized, and the authors appropriately distinguish short-term STEC stability, internal consistency, and morphological comparisons with GIM-derived products. The application examples illustrate the dataset's potential for studying regional ionospheric structures and their relationship with GNSS positioning performance. The dataset is of interest to the community, although several aspects of the product definitions, processing procedures, and interpretation would benefit from clarification.

Response: We thank the reviewer for the careful review and overall positive assessment of the GIFT-BDS dataset. The comments helped us clarify several aspects of the product definitions, Level-2 generation, positioning-related interpretation, and quality-control procedures. The manuscript has been revised accordingly. The main changes are summarized as follows:

#1 We clarified the inter-IPP vector orientation, distinguished the unsigned GIX magnitude from the signed directional gradient components, and revised the corresponding equations.

#2 We clarified that GIXstd describes within-cell gradient variability and does not represent uncertainty in the grid-cell mean.

#3 We clarified that Level-2 products are generated by sampling 30-s Level-1 observations at 15-min intervals, defined the two-sample requirement for each grid cell, and specified the time-tag and missing-data conventions.

#4 We clarified that GIX is primarily an indicator of the regional TEC gradient environment and expanded the discussion of its potential use for positioning quality control and observation weighting.

#5 We clarified that the quality-control settings are not adjusted for ionospheric conditions and that strong disturbances may reduce data availability through tracking-related gaps.

Detailed point-by-point responses are provided below. For ease of review, all corresponding changes in the revised manuscript are highlighted in red.

Comment 1. Equation (9) defines GIX using the absolute value of the along-baseline TEC gradient, which is appropriate for describing gradient intensity. However, GIX_x and GIX_y are subsequently interpreted as signed directional components. Please clarify how the baseline orientation is defined and how the direction of TEC increase is retained when calculating these components. This is particularly relevant to the interpretation of the GIX_y sign reversal around the EIA crest.

Response: We thank the reviewer for identifying this ambiguity in the distinction between the unsigned GIX magnitude and the signed directional gradient components.

In practice, each retained IPP pair is treated as an ordered pair (i, j) , and the directed baseline is defined from IPP i to IPP j . The baseline azimuth, $\theta^{(i,j)}$, is measured clockwise from geographic north. The signed along-baseline VTEC gradient is calculated as

$$g_V^{(i,j)}(t) \equiv \frac{\partial T_V^{(i,j)}}{\partial s^{(i,j)}} \Big|_t = \frac{T_V^j(t) - T_V^i(t)}{s^{(i,j)}} \quad (8)$$

A positive value of $g_V^{(i,j)}$ indicates that VTEC increases from IPP i toward IPP j . GIX is defined as the unsigned magnitude $|g_V^{(i,j)}|$, whereas GIX_x and GIX_y are obtained from the signed gradient $g_V^{(i,j)}$ through zonal and meridional projections. Their signs therefore retain the direction of TEC increase, with positive x and y denoting eastward and northward directions, respectively. Accordingly, the sign reversal of GIX_y around the EIA crest represents the reversal of the meridional TEC-gradient direction across the crest.

The released Level-2 products were calculated using the correct formulation. The corresponding revisions in Sect. 3.2.3 are provided below.

“Spatial-gradient products are derived from pairs of simultaneous IPP observations. For two IPPs, i and j , a directed inter-IPP vector from IPP i to IPP j is constructed on the ionospheric thin shell. Its magnitude $S^{(i,j)}$ is the great-circle distance between the two IPPs, and its azimuth angle $\theta^{(i,j)}$ is measured clockwise from north. Due to the near-stationary GEO observation geometry, both $S^{(i,j)}$ and $\theta^{(i,j)}$ vary only slowly with time. The signed TEC spatial gradient along the directed inter-IPP vector is estimated as:

$$g_V^{(i,j)}(t) \equiv \frac{\partial T_V^{(i,j)}}{\partial S^{(i,j)}} \Big|_t = \frac{T_V^j(t) - T_V^i(t)}{S^{(i,j)}} \quad (8)$$

Substituting Eq. (6) into Eq. (8) gives:

$$g_V^{(i,j)}(t) = \left(\frac{T_S^j}{M(\delta^j)} - \frac{T_S^i}{M(\delta^i)} \right) \cdot \frac{1}{S^{(i,j)}} + \frac{1}{S^{(i,j)}} \cdot \left(\frac{\xi^j}{M(\delta^j)} - \frac{\xi^i}{M(\delta^i)} \right) \quad (9)$$

A positive value of $g_V^{(i,j)}$ indicates that VTEC increases from IPP i toward IPP j . The unsigned magnitude of the spatial TEC gradient along the inter-IPP vector is defined as:

$$\nabla T_V^{(i,j)}(t) = \left| g_V^{(i,j)}(t) \right| \quad (10)$$

and is used as the GIX. The corresponding signed zonal (x) and meridional (y) components are given by:

$$\frac{\partial T_V^{(i,j)}}{\partial x} \Big|_t = g_V^{(i,j)}(t) \sin \theta^{(i,j)} \quad (11)$$

$$\frac{\partial T_V^{(i,j)}}{\partial y} \Big|_t = g_V^{(i,j)}(t) \cos \theta^{(i,j)} \quad (12)$$

The signed $g_V^{(i,j)}$ preserves the direction of TEC increase in both components. Positive x and y denote the eastward and northward directions, respectively.

The spatial variation of the temporal VTEC gradient is derived from the difference in temporal derivatives between the two IPPs:

$$\frac{\partial^2 T_V^{(i,j)}}{\partial x \partial t} = \left(\frac{\partial T_V^j}{\partial t} - \frac{\partial T_V^i}{\partial t} \right) \cdot \frac{\sin \theta^{(i,j)}}{S^{(i,j)}} \quad (13)$$

$$\frac{\partial^2 T_V^{(i,j)}}{\partial y \partial t} = \left(\frac{\partial T_V^j}{\partial t} - \frac{\partial T_V^i}{\partial t} \right) \cdot \frac{\cos \theta^{(i,j)}}{S^{(i,j)}} \quad (14)$$

In practice, each inter-IPP gradient estimate is assigned to the midpoint of the great-circle arc connecting IPPs i and j . This midpoint is used as the representative location of the gradient sample in the subsequent gridding procedure.” (Lines 247–270)

Comment 2. GIXstd represents the dispersion of pairwise gradient samples within a grid cell. Its value may also depend on the number and geometry of the contributing inter-IPP pairs, and some pairs may share common IPPs. Please clarify that GIXstd is a descriptive measure of within-cell sample variability rather than the statistical uncertainty of the grid-cell mean.

Response: We thank the reviewer for this clarification. GIX_{std} is a descriptive measure of the variability among gradient samples within a grid cell rather than the statistical uncertainty of the grid-cell mean. Its value depends on the number and geometry of the contributing inter-IPP pairs, and some pairs may share common IPPs.

We have revised Sect. 3.2.5 accordingly. The corresponding revision is provided below.

“In addition, the within-cell standard deviation of the contributing spatial-gradient samples is calculated as

$$\sigma(\nabla T_V) = \sqrt{\langle (\nabla T_V)^2 \rangle - \langle \nabla T_V \rangle^2} \quad (15)$$

where $\langle \cdot \rangle$ denotes the arithmetic mean over all valid samples within the grid cell. This quantity is released as GIX_{std} and provides a descriptive measure of the variability among gradient samples within each grid cell. Its value depends on the number and geometry of the contributing inter-IPP pairs, and some pairs may share common IPPs. Therefore, GIX_{std} is not interpreted as the statistical uncertainty of the grid-cell mean.”
(Lines 326–332)

Comment 3. Please explain how the 15-min Level-2 products are generated from the 30-s Level-1 observations. Are they instantaneous samples at 15-min intervals, averages over 15-min windows, or products of another aggregation procedure? The temporal aggregation, time-tag convention, and treatment of missing observations should be specified. Please also clarify whether the minimum requirement of two valid samples per grid cell refers to distinct inter-IPP pairs or includes repeated observations of the same pair.

Response: We thank the reviewer for requesting this clarification. The 15 min Level-2 products are generated as snapshots from the 30 s Level-1 records at 15 min intervals from 00:00 to 23:45 UTC. Each Level-2 output uses the Level-1 records at the corresponding 30 s epoch, and the time tag therefore represents the actual observation epoch. IPP-based samples are assigned according to their IPP locations, while inter-IPP-based samples are assigned according to the corresponding vector midpoints. The samples within each grid cell are then spatially averaged.

Missing or quality-controlled Level-1 observations are omitted. At each Level-2 output epoch, a grid cell is retained only when at least two valid samples fall within that cell. For the IPP-based variables, these are valid IPP samples within the same $1^{\circ} \times 1^{\circ}$ grid cell. For the inter-IPP-based variables, they are samples from distinct inter-IPP vectors whose midpoints fall within the same $0.25^{\circ} \times 0.25^{\circ}$ grid cell. Repeated observations of the same inter-IPP vector at adjacent epochs do not contribute to the same Level-2 output.

We have revised Sect. 3.2.5 accordingly. The corresponding revision is provided below.

“The Level-2 products are released as gridded regional ionospheric products. All Level-2 products have a temporal resolution of 15 min. **They are generated at 15 min intervals from 00:00 to 23:45 UTC using the Level-1 records at the corresponding 30 s epochs. The Level-2 time-tag corresponds to the sampling epoch.** The released Level-2 dataset includes the following variables: VTEC, VTEC_t, ROTI, GIX, GIX_{std}, GIX_x, GIX_y, GIX_{t,x}, and GIX_{t,y}. Their spatial resolutions, units, and source quantities are summarized

in Table 4. The IPP-based variables, including VTEC, ROTI, and the temporal derivative $\frac{\partial T_V}{\partial t}$, are mapped onto a $1^\circ \times 1^\circ$ grid according to the IPP locations. The inter-IPP-based variables, including GIX, GIX_x, GIX_y, GIX_{t,x}, and GIX_{t,y}, are mapped onto a $0.25^\circ \times 0.25^\circ$ grid according to the inter-IPP vector midpoints. The value in each grid cell is calculated as the arithmetic mean of all valid samples within that cell. Missing or quality-controlled Level-1 records are omitted.

At each output epoch, a grid cell is retained only when it contains at least two valid samples. For inter-IPP-based variables, these samples are derived from distinct inter-IPP vectors whose midpoints fall within the same grid cell.” (Lines 315–324)

Comment 4. The positioning examples show an association between enhanced GIX and degraded PPP/NRTK performance. Please clarify whether GIX is intended primarily as an indicator of regional ionospheric conditions or as a quantitative measure of the ionospheric errors affecting these positioning solutions. This distinction matters because the relationship depends on the positioning strategy, observing geometry, and treatment of ionospheric delays. The potential use of GIX for positioning quality control or observation weighting could also be mentioned, while noting that these applications would require further evaluation.

Response: We thank the reviewer for this clarification. GIX is primarily an indicator of the regional TEC gradient environment rather than a quantitative measure of the ionospheric error in a specific PPP or NRTK solution. Therefore, the positioning examples in Sect. 4.2 are used to show the association between regional gradient activity and positioning performance. We have revised Sect. 4.2 to clarify this distinction. We also expanded the discussion of the potential use of GIX for positioning quality control and observation weighting. These applications require further evaluation.

The corresponding revisions in Sect. 4.2 are provided below.

“GNSS positioning performance can be notably affected by ionospheric disturbances, particularly under conditions of rapid spatial and temporal variations in electron density. Such effects are typically more pronounced during disturbed ionospheric periods, when ionospheric irregularities such as EPBs and sharp TEC gradients occur more frequently. GIX quantifies the magnitude of horizontal TEC spatial gradients and serves as an indicator of the regional TEC gradient environment. Previous studies have reported associations between enhanced GIX and degraded PPP performance during geomagnetic storms (Fu et al., 2025b; Nykiel et al., 2024). In this section, GIFT-BDS is used to illustrate the association between regional TEC gradient activity and PPP/NRTK positioning performance.” (Lines 506–514)

“The enhanced and rapidly varying GIX values are consistent with the passage of EPB-related gradient structures over the region. Increased NRTK errors occur during intervals of enhanced GIX, showing a temporal association between regional TEC gradient activity and positioning degradation. This event-level comparison illustrates the correspondence between regional TEC gradient activity and GNSS positioning performance.” (Lines 523–528)

“The probability of large NRTK errors increases with GIX, whereas the moderate-error range does not show the same monotonic behavior. These results further show a statistical association between enhanced regional TEC gradients and degraded NRTK positioning performance. Additionally, regional GIX information could support positioning quality control by identifying periods or areas with enhanced TEC gradient activity. It could also provide auxiliary information for observation weighting. Further evaluation is needed to determine how these applications depend on positioning strategies, satellite geometry, and ionospheric delay treatment.” (Lines 548–554)

Comment 5. Please clarify whether the same quality-control procedures and thresholds are applied under quiet and disturbed ionospheric conditions. Strong disturbances can produce genuine rapid TEC variations as well as increased tracking problems, making it important to distinguish physical signals from observational errors. It would be helpful to discuss whether these fixed thresholds may reduce data availability during strong disturbances.

Response: We thank the reviewer for raising this point. The epoch- and arc-level quality-control procedures use the same settings under quiet and disturbed ionospheric conditions, without event-dependent adjustment.

First, during the generation of the Level-1 STEC records, the same elevation screening, cycle-slip detection, data-gap identification, and carrier-to-code leveling procedures are applied throughout the dataset. Strong ionospheric disturbances may cause loss of lock or signal interruption, leading to gaps in the raw carrier-phase observations. These gaps may reduce data availability during disturbed intervals.

Second, the LOS-level stability criterion is evaluated separately for each daily receiver-satellite LOS. The mean absolute detrended STEC residual is calculated using only epochs with ROTI below $0.3 \text{ TECU min}^{-1}$, and the 0.15 TECU threshold is used to determine whether the daily LOS is retained. The threshold is not applied to individual high-ROTI epochs. Thus, high-ROTI disturbed epochs are not selectively removed by this criterion.

We have clarified these points in Sect. 3.1.2. The corresponding revisions are provided below.

“Quality control is implemented at the epoch, arc, and LOS levels. At the epoch and arc levels, elevation screening, cycle-slip detection, data-gap identification, and continuous-arc segmentation are applied to define valid carrier-phase arcs for each receiver-satellite link (Kim et al., 2014). **These procedures use the same settings under quiet and disturbed ionospheric conditions. Strong disturbances may reduce data availability when signal interruptions or loss of lock, leading to gaps in the carrier-phase observations.** Carrier-to-code leveling and DCB corrections are then applied to these

valid arcs to generate absolute STEC time series. To avoid retaining receiver-satellite links with persistently unstable behavior, the overall stability of each LOS STEC record is further checked using a detrended STEC residual. The residual is computed using a 5 min moving window (Ma et al., 2022):

$$STEC_{\text{res}}(t) = STEC(t) - \overline{STEC}_{5 \text{ min}}(t) \quad (2)$$

where $\overline{STEC}_{5 \text{ min}}(t)$ denotes the moving-average STEC within the 5 min window centered at epoch t . The residual series $STEC_{\text{res}}(t)$ is used as a LOS-level stability indicator. This criterion is evaluated separately for each daily receiver-satellite LOS. A daily receiver-satellite LOS is excluded if the mean absolute residual during quiet ionospheric periods ($ROTI < 0.3$ TECU/min) exceeds 0.15 TECU. The 0.15 TECU threshold is applied to the daily LOS and not to individual high-ROTI epochs. This criterion is used to remove links with persistently unstable residual behavior, which may be caused by receiver-related problems or unstable observations. The retained LOS STEC records are used to form the released Level-1 product and provide the observational basis for the Level-2 products.” (Lines 188–203)