

Analysis and Validation of PlanetiQ RO TEC Data Processed by PlanetiQ, CDAAC, and STAR

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Objectives

- Deepen understanding of radio occultation and its limitations
- Develop a methodology for comparing global TEC data over long periods
- Identify anomalies/errors in the processed data and find their sources

Accomplishments

- Found a method to track TEC changes that condenses data while preserving relevant changes
- Performed tests to search for causes of DCB drift
- Found possible sources of anomalous bimodality in leveling error histograms

RO TEC Technique

- Track pseudorange and phase of descending satellite
- Difference between simultaneous measurements isolates ionospheric contribution

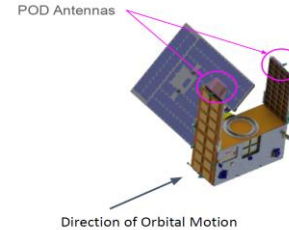


Figure 1: PlanetiQ GNOMES Satellite. Credit: Jonathan Brandmeyer, PlanetiQ, 2025.

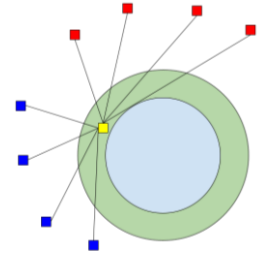


Figure 2: Radio Occultation Diagram. Red/Blue: GNSS Constellations. Yellow: LEO Satellite. Green/Blue: Ionosphere/Earth

Fundamental Equations

- Pseudorange derived TEC → Absolute measurement, low SNR

$$P_1 \equiv P_2 - P_1 = (\gamma - 1)d_{ion} + \Delta b_{s_i} + \Delta b_{r_j} + \Delta mp + \Delta \epsilon_P$$

- Phase derived TEC → Only relative measurements, high SNR

$$L_1 \equiv L_1 - L_2 = (\lambda_1 N_1 - \lambda_2 N_2) + (\gamma - 1)d_{ion} - \Delta b_{s_i} - \Delta b_{r_j} - \Delta mp - \Delta \epsilon_L$$

- Final Conversion to TEC includes leveling correction

$$TEC_{\Phi} = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)} [(L_1 - L_2) - (\Delta_1(P_1, \phi_1) - (\Delta_2(P_2, \phi_2)))]$$

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Daily Mean TEC Difference

CDAAC, STAR, PIQ

CDAAC, STAR, PIQ

- Filter satellites with erroneous DCB
- VTEC Transformation
- Filter combinations for GNSS provider, start time, occultation length

- Mean and standard deviation per day of matched occultations

Drawbacks

- Less information than TEC maps; shows no regional variation though is useful for observation of TEC drift over time

VTEC Transformation

$$VTEC = TEC / \frac{4000km + h}{\sqrt{(4000km + h)^2 - h^2 \cos(Z)^2}}$$

- Useful to filter out low elevations
- Relies on thin shell approximation, inaccurate considering horizontal gradients

Unstable DCB → Unstable TEC Difference

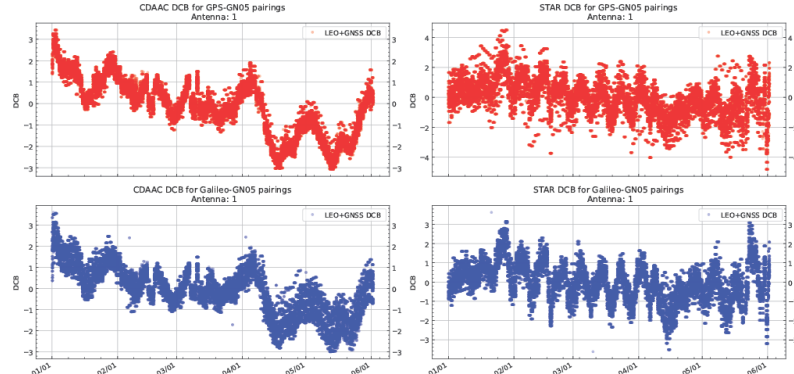


Figure 3: LEO+GNSS DCB for 5 months of 2026. Row 1: CDAAC and STAR for GPS-GN-05 pairings. Row 2: CDAAC and STAR for Galileo-GN05 pairings

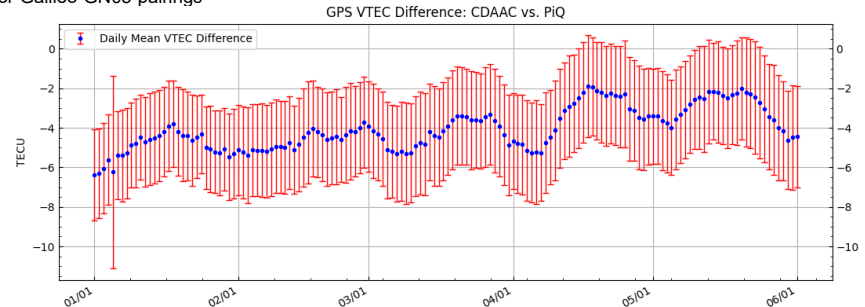


Figure 4: Average GPS daily VTEC difference between PIQ and CDAAC for 5 months of 2026

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Phase TEC Leveling Error

- Phase measurements receive a constant offset to bring them into agreement with pseudorange TEC
- Noise in the pseudorange means there is ambiguity in this constant → this is leveling error

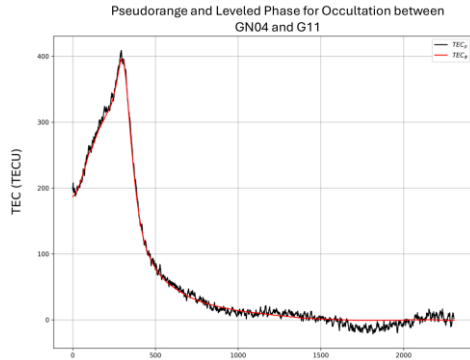


Figure 5: Phase derived TEC (red) and pseudorange derived TEC (black) for a given occultation between gnomes leo satellite GN04 and gps satellite G11

- Despite leveling, there are still correlated errors in the differences
- Satellite reflections and multipath are to blame → apply multipath correction
- Leveling error after correction should only vary due to noise → expect a single mode in histogram

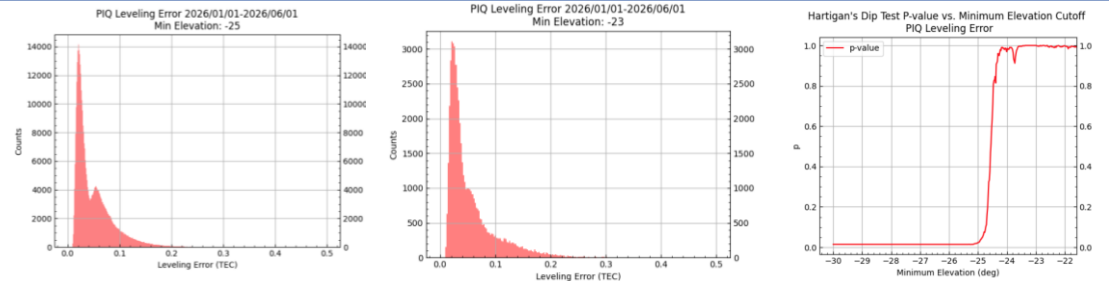


Figure 6: Panels 1 & 2: Leveling error histograms of PlanetiQ data filtered at -25 and -23 degrees, respectively. Panel 3: Hartigan's dip test p-values of distributions filtered at higher resolution

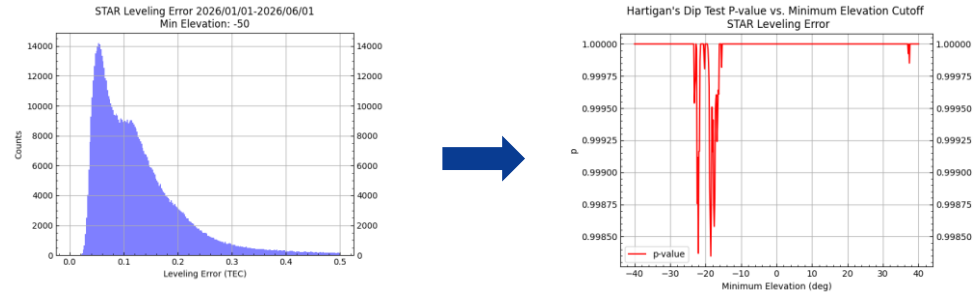


Figure 7: Panel 1: STAR Leveling error histogram filtered at -50 degrees. Panel 2: Hartigan's dip test as minimum elevation increases for star

Next Steps

- Use modern VTEC transformation to compare against IRI and other datasets
- Explore stability of different DCB measurement methods