Systematic Error Analysis of DORIS Range-Rate Residuals for Precise Orbit Determination of Radar Altimeter Satellites

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Abstract

Several Earth observation missions equipped with radar altimeters rely on the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system for precise orbit determination (POD), which is essential for generating accurate geophysical products such as sea level variability and ice sheet elevation. The accuracy of these products is highly sensitive to orbit errors, as systematic biases can propagate into long-term climate datasets. Although DORIS provides stable and globally distributed observations, range-rate residuals — commonly used as a diagnostic measure of POD performance — often exhibit structured, non-random patterns, indicating the presence of unmodeled or mismodeled error sources within the observation and dynamic models.

In this study, long-term time series of DORIS range-rate residuals are analyzed across multiple satellite missions (HY-2C, Jason-3, Sentinel-6A, SWOT) and more than 54 ground stations to investigate systematic errors. The results reveal consistent elevation-dependent discrepancies, with larger residuals at low elevation angles (mean residual of −5.91 mm/s at 0–10° vs. −5.16 mm/s at 60–90° at the DIOB station), suggesting limitations in atmospheric modeling, antenna phase center corrections, and multipath effects. A detailed analysis of HY-2C observations at the BETB station reveals pronounced systematic variations, with residuals reaching up to ~40.05 mm/s, indicating the presence of a severe receiver clock anomaly. Statistical evaluation of the MAMC station dataset (HY-2C, January 2025) indicates a residual mean of 12.84 mm/s and a standard deviation of 0.56 mm/s. Furthermore, sequential application of receiver clock synchronization corrections at the MALE station reduces the residual mean from 13.8 mm/s to 1.1 mm/s and the standard deviation from 8.39 mm/s to 0.13 mm/s. These findings highlight the significant impact of clock-related errors and confirm the presence of common modeling deficiencies, emphasizing the need for improved correction strategies to enhance orbit determination accuracy and the reliability of derived geophysical products.

Keywords: DORIS, Precise Orbit Determination (POD), Doppler Range-Rate Residuals, Radar Altimetry, Satellite Geodesy .

Introduction

Radar altimeter missions such as HY-2C, Jason-3, Sentinel-6 Michael Freilich, and SWOT require centimetre-level orbit accuracy to support reliable sea-level, ocean circulation, and ice-sheet studies. The DORIS system provides Precise Orbit Determination (POD) through dual-frequency Doppler observations from a global network of over 54 ground beacons, enabling continuous all-weather tracking. Range-rate residuals (observed minus modelled Doppler shifts) are a key indicator of POD quality. Systematic residual patterns reveal unmodelled errors, including receiver clock synchronization errors, beacon frequency offsets, tropospheric and ionospheric delays, Antenna Phase Centre Correction errors. Identifying and mitigating these error sources is essential for improving orbit accuracy and the quality of radar altimetry products.

DORIS Range-Rate Observable

The observed range-rate is derived from DORIS Doppler measurements using carrier-phase differences between consecutive epochs:

$$V_{e\_r} = \frac{c}{f_e} \bullet \left(f_e - f_r - \frac{\phi(t_1) - \phi(t_2)}{\Delta t} \right)$$

$V_{e\_r} =$ relative velocity between emitter (beacon) and receiver (satellite)

$f_e =$ receiver (satellite) frequency

$f_r =$ emitter (beacon) frequency

$\phi(t_i) =$ carrier wave phase observation at instant t_i

$\Delta t =$ time interval, in seconds, between t_1 & t_2

$c =$ speed of light

The modelled range-rate is computed from the satellite's precise orbit and beacon coordinates, incorporating corrections for Earth rotation, tides, relativistic effects, and atmospheric propagation delays. Residuals quantify discrepancies between observations and models, revealing systematic errors such as receiver clock offsets, beacon frequency biases, atmospheric delay mismodelling, antenna phase centre errors, and multipath effects. Consequently, they are a key diagnostic for assessing and improving DORIS-based POD.

Data & Methodology

This study analyses DORIS range-rate residuals from four radar altimeter missions HY-2C, Jason-3, Sentinel-6A, and SWOT spanning February 2016 to January 2025, across more than 54 globally distributed ground stations including DJIB, MLAC, MAMC, DIOB, CIBINONG, KITAB, and BETB, representing diverse atmospheric and tracking environments.

Long-arc residuals are extracted per station–satellite pair and processed through a five-step sequential correction framework:

1. **Clock:** Remove receiver clock synchronisation bias
2. **Frequency:** Correct nominal-to-true beacon frequency offset
3. **Troposphere:** Apply atmospheric path delay correction
4. **Ionosphere:** Correct dispersive signal delay
5. **APCC:** Apply Antenna Phase Centre Corrections

Residuals are then binned by elevation angle (0–10° through 60–90°) and characterised statistically mean, standard deviation, min/max at each correction stage. Anomalous stations are flagged through inter-station comparison against the network-wide distribution, enabling detection of hardware faults, clock jumps, and local environmental effects.

Result and Discussion

Jason-3 long-term RMS of 0.402 mm/s is consistent with published DORIS POD benchmarks (Bonnefond et al. 2021)], ~0.40 mm/s for Jason-3 cite the specific value so reviewers can verify, but the gradual upward trend over 3 years warrants continued monitoring of model drift.

Inter-station spread (3.46 – 40.05 mm/s for HY-2C) confirms that station-specific errors are not fully captured by current POD models. Per-station corrections and improved phase centre calibrations are needed.

Elevation dependence at DIOB shows a −0.75 mm/s bias increase from 60–90° to 0–10°, consistent with tropospheric delay dominance. The large spread (σ = 25.98 mHz at 0–10° (or convert to range-rate: add one parenthetical "≈ X mm/s" using λ·Δf conversion for DORIS S1 band at 2036.25 MHz)) also indicates ionospheric scintillation.

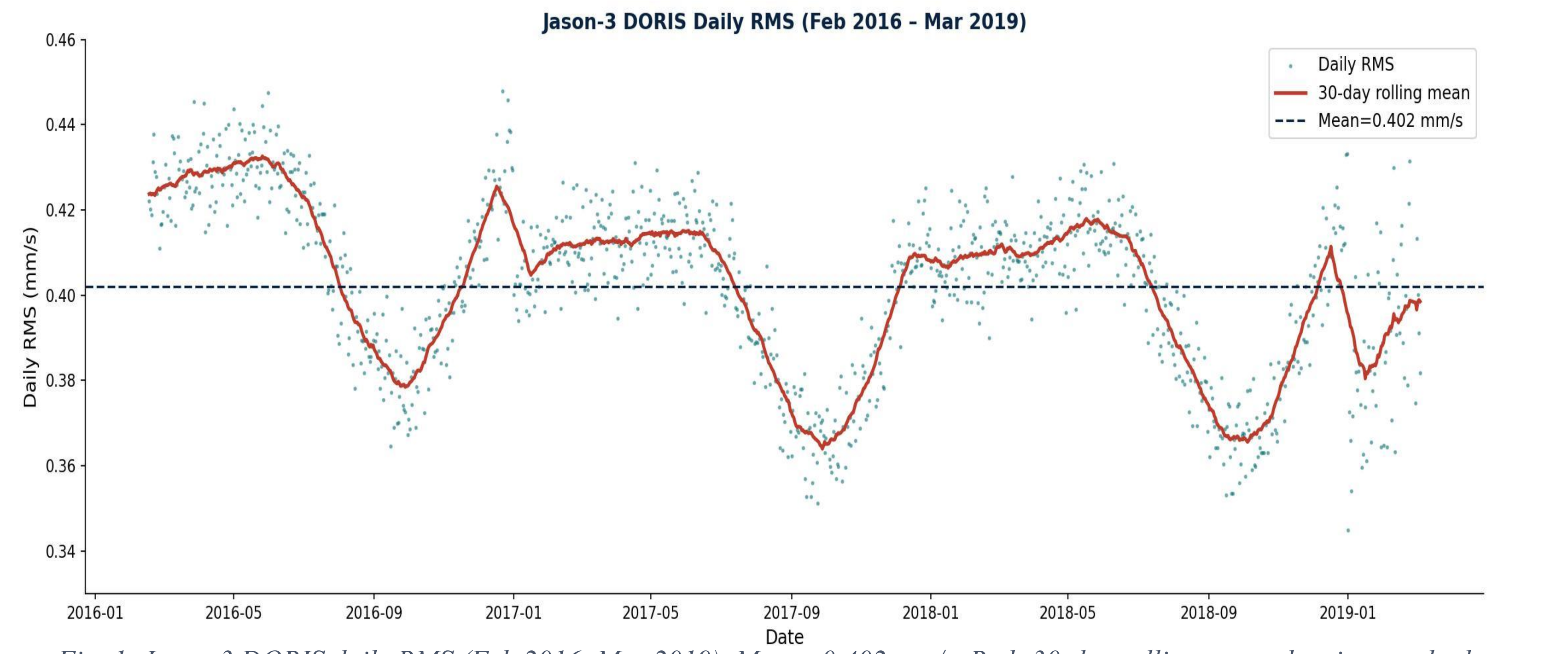

Fig. 1. Jason-3 DORIS daily RMS (Feb 2016–Mar 2019). Mean=0.402 mm/s. Red: 30-day rolling mean showing gradual upward drift, possibly due to progressive atmospheric model or APCC degradation.

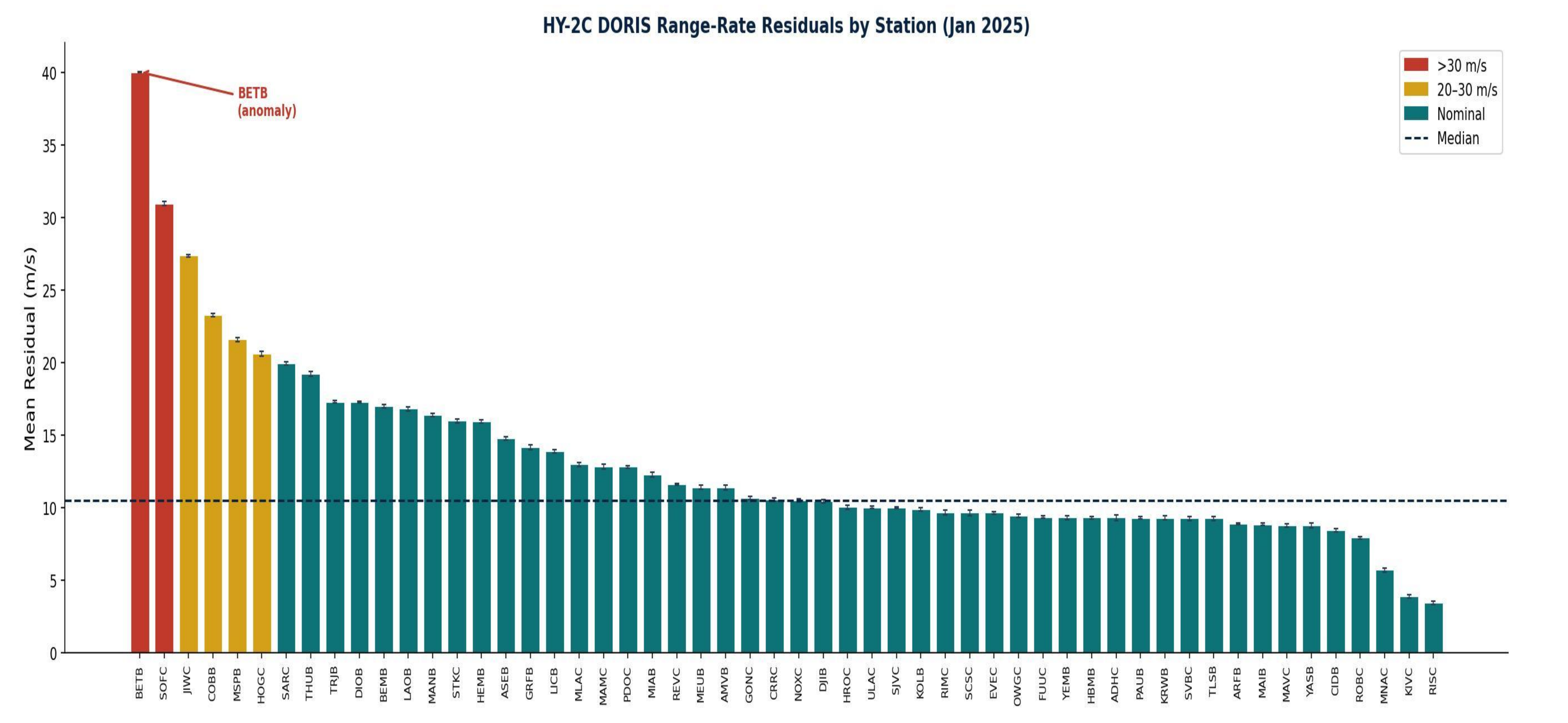

Fig. 2. Mean range-rate residuals for 54 DORIS stations (HY-2C, Jan 2025). BETB anomaly at 40.05 m/s; RED >30 mm/s, GOLD 20–30 mm/s, TEAL nominal. Median = 10.51 mm/s(dashed).

Table-2: DORIS DIOB Station: Average Doppler Residual by Elevation Range

Elevation Range (deg)	Avg Observed Range Rate (m/s)	Avg Calculated Range Rate (m/s)	Avg Residual Range Rate (m/s)
0–10	-673.57	-667.66	-5.91
10–20	-438.93	-433.30	-5.64
20–30	-24.92	-19.71	-5.21
30–40	-8.41	-3.23	-5.17
40–50	9.95	15.14	-5.18
50–60	-95.42	-90.26	-5.16
60–90	-131.23	-126.07	-5.16

Conclusion

Long-term DORIS residual analysis across HY-2A/C, Jason-3, Sentinel-6A/B, SARAL, and SWOT reveals consistent elevation-dependent biases and large inter-station variability.

Elevation-dependent residuals at DIOB (0–10°: −5.91 m/s vs. 60–90°: −5.16 m/s) confirm tropospheric and ionospheric delay as primary low-elevation error sources requiring improved modelling.

Jason-3's stable long-term RMS (~0.402 mm/s over 2016–2019) demonstrates system baseline performance; the gradual upward trend calls for ongoing quality monitoring.

References

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