Initiative for Estimating the QZSS Reference Frame

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INTRODUCTION

Japanese regional Navigation Satellite system, Quasi Zenith Satellite System (QZSS) has provided various services e.g. Sub-meter Level Augmented Service (SLAS), Centi-meter Level Augmented Service (CLAS) and PNT service based on international terrestrial reference frame (ITRF) so far. On the other hand, the other GNSSs, GPS, GLONASS, Galileo, BeiDou, have its own reference frame (RF) in order to maintain its satellite operation and quality of services being independent of other geodetic observation techniques and other GNSS. Japanese QZSS has a weakness in point of view of its own terrestrial reference frame.

Japan Aerospace eXploration agency (JAXA) has developed fully original Precise Orbit Determination (POD) software, MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) since 2011 (Kawate et al., 2023) . Geospatial Information Authority of Japan (GSI) and JAXA have collaborated on POD of GNSS satellites and achieved to join in Analysis Center(AC)s of International GNSS Service(IGS) because of its high-quality of POD products. Our POD software, MADOCA and operational experience as an IGS AC allow us to establish an optimized TRF for QZSS (QTRF). It will improve resilience of QZSS operation and its quality of services.

OBJECTIVE

The objective of this study is to establish the realization of the Quasi-Zenith Terrestrial Reference Frame (QTRF), which is fully optimized RF for QZSS. The QTRF is designed to maintain centimeter-level consistency with the International Terrestrial Reference Frame (ITRF), ensuring that the positional differences of common ground stations remain within 2 cm at the 95% confidence level. The QTRF catalogue provides precise positions and velocities of ground tracking stations used for QZSS PNT services. To ensure long-term reliability, the framework supports timely updates following significant crustal deformation caused by earthquakes and adopts non-linear post-seismic deformation (PSD) models which is consistent with those employed in the ITRF. In addition, the construction of QTRF is based exclusively on observation data from QZSS and GPS, ensuring independence from other geodetic data sources.

METHODS

(1) **<u>GNSS Positioning</u>** - Precise orbit determination was performed using GPS and QZSS observations from 2017 to 2025 utilizing about 160 IGS network stations and the MADOCA software. Based on the estimated satellite orbits and clocks, precise positioning of approximately 170 ground tracking stations which included QZSS intrinsic tracking stations was conducted using the MADOCA software.

(2) **<u>Determination of discontinuity</u>** - Positional discontinuities caused by earthquakes and observational equipment changes were identified manually referencing seismic information and station history records.

(3) **<u>Linear Modeling</u>** - Linear displacement of stations were modeled for each the Solution Number (SOLN) adopted in ITRF2020 and IGS20, in which station coordinates and velocities are defined for specific observation periods.

(4) **<u>Non-Linear Modeling</u>** - Non-linear station displacements were modeled using an original algorithm based on the Markov chain Monte Carlo (MCMC) method, enabling efficient and stable estimation of post-seismic deformation from station position time series.

Linear Modeling

For linear SOLN period (no PSD period), we estimate linear model based on following observation equation and LSQ method.

$$X = X_0 + v(t-t_0) + \sum_{f=1}^{2}\left(S_f \sin(2\pi f(t-t_0)) + C_f \cos(2\pi f(t-t_0))\right)$$

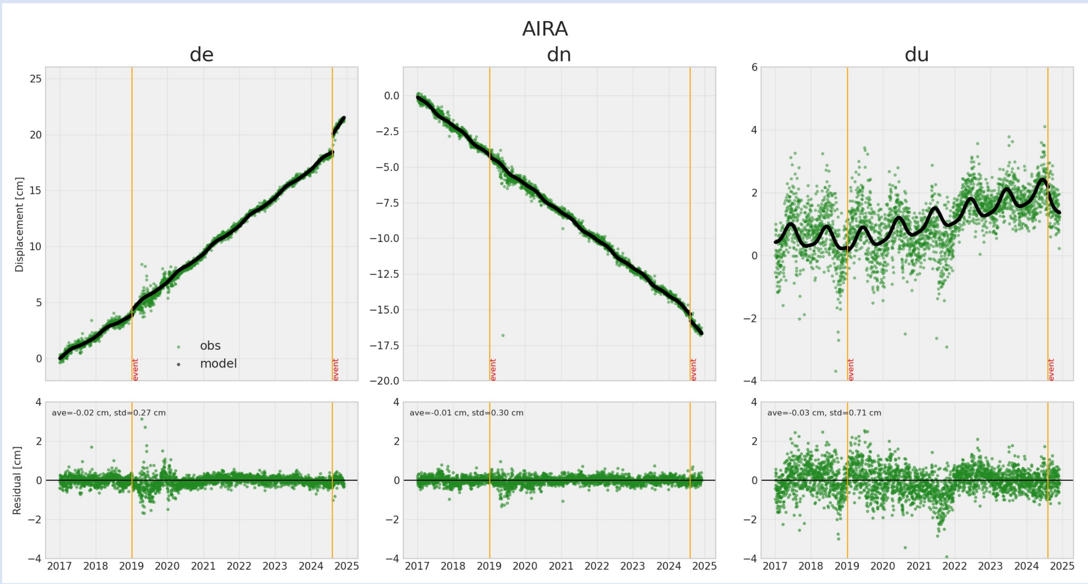
Non-Linear Modeling

MCMC is a method for approximating the probability distribution of unknown parameters by generating samples using a Markov chain. The model parameters were set as follows.

- Position/velocity of first epoch (X,Y,Z,Vx,Vy,Vz)
- PSD model (Log, Exp, Log+Exp, Exp+Exp, Log+Log)
- Annual/semiannual component
  $A\sin(2\pi t) + B\sin(2\pi t)$
  $A\sin(4\pi t) + B\sin(4\pi t)$

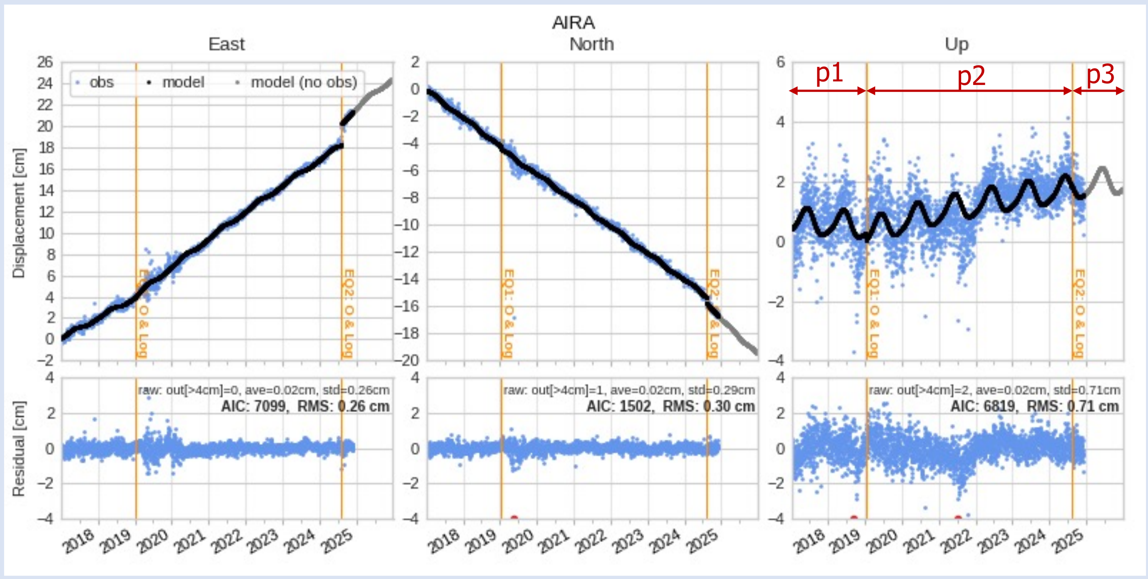
RESULT

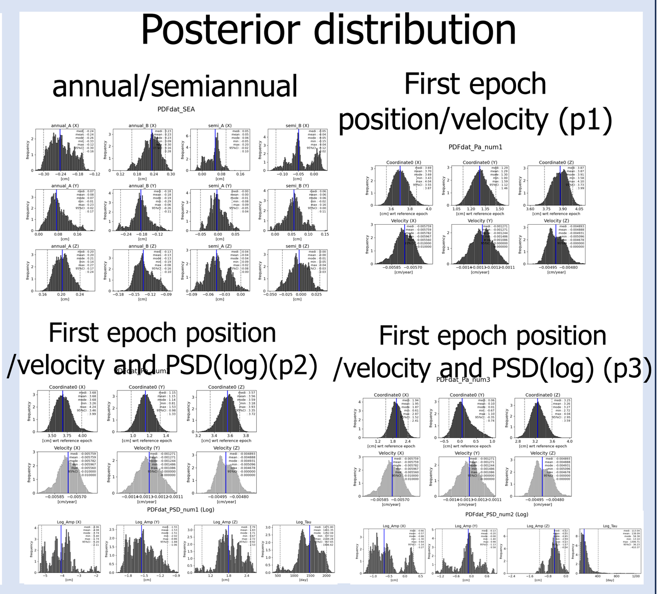
Linear Modeling



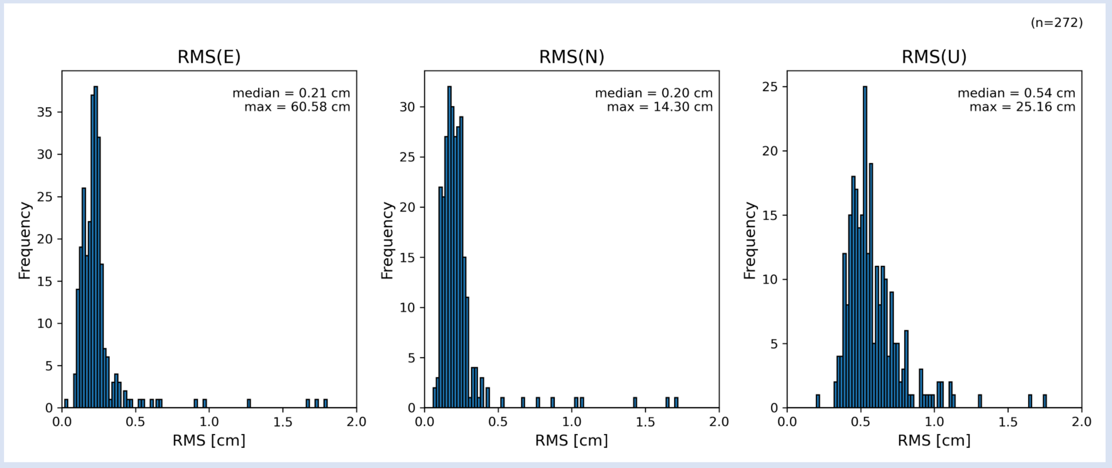
These two figures show the estimation results for the linear modeling of IGS station AIRA. The 3 upper panels presents the position time series together with the fitted model, while the lower panels shows the corresponding residuals. The vertical dashed lines indicate changes in solution numbers (soln), which were identified based on the occurrence of earthquakes and related events. The residuals show a std of approximately 3 mm in the horizontal components (de, dn) and 7mm in the vertical component (du), demonstrating that the station positions are well modeled by linear and annual/semi-annual frequency terms. It should be noted, however, that this result was obtained using a piecewise linear (PWL) model, and that post-seismic deformation (PSD) was not explicitly estimated in this analysis.

Non-Linear Modeling





For the estimation of the post-seismic deformation (PSD) model, the MCMC sampling results are shown in the histogram figures, and the median values of the obtained posterior probability distributions were adopted as the estimated model parameters (time series and residual plots). Even across the earthquake event, the residual scatter remains at approximately 3 mm in the horizontal components and 7 mm in the vertical component, indicating that the estimation results are reliable.



MCMC-based estimation was performed for all stations, and the RMSE values were summarized as a histogram.

No site-specific tuning has been applied; nevertheless, stable estimation has been achieved through automatic adjustment.

CONCLUSIONS

Ground station positions were estimated using the MADOCA software employed for JGX product generation, with satellite orbits and clocks fixed. The estimation was performed using combined GPS and QZSS observations. The resulting position time series were modeled using both linear and non-linear approaches. In both cases, reliable estimation can be readily achieved when prior information on discontinuities, such as earthquakes or equipment changes, is available. The non-linear model is particularly advantageous for estimating post-seismic deformation (PSD).Although none of the analyzed stations exhibited extremely large displacements, stations with moderate seismic-induced variations were selected, and the estimation results showed good agreement. At present, parameter tuning has not yet been fully optimized; further tuning is expected to improve estimation accuracy and contribute to a more robust realization of QTRF.

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