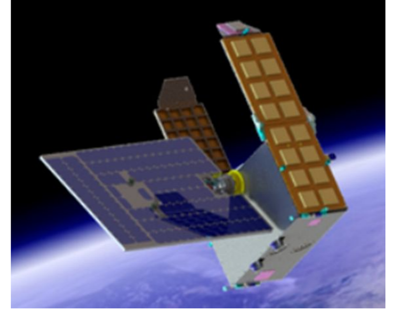
PLANETiQ
Golden, CO,
United States



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The Suitability of Broadcast Orbits for Precise Orbit Determination in Near-Realtime GNSS-RO Preprocessing

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Abstract: The PlanetiQ Pyxis GNSS-RO instrument implements a receiver-autonomous high-precision orbit determination solution based on the orbits and clocks in the GNSS navigation messages alone. This reduces data preprocessing system latency for weather and space weather analyses, nowcasts and forecasts which require rapid processing in near-realtime. It maximizes availability and reliability by replacing a dependency on ground-based networks' clock and orbit data with the GNSS system's own navigation data. NRT bending angle performance with the receiver-autonomous POD solution routinely exceeds that obtained with MGEX Rapid orbits and UCAR clocks.

Summary

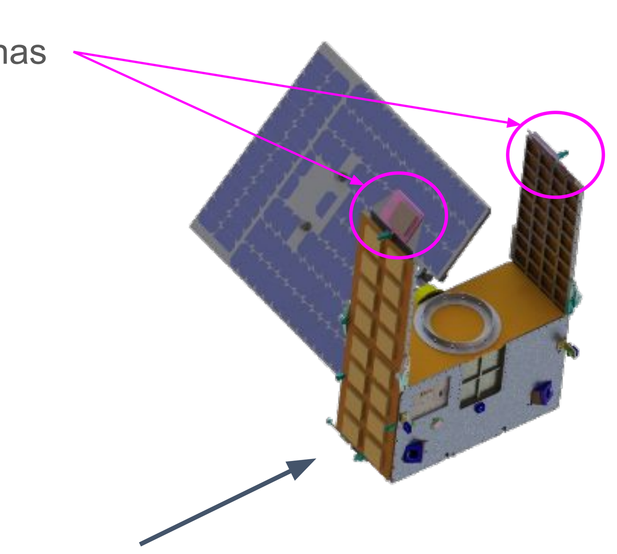
- GPS C/NAV orbits and clocks are adequate for use.
  - GPS L/NAV is inadequate today, and not necessary for dual-frequency RO on open-access signals
- BeiDou 3 and Galileo broadcast orbits are generally as accurate as GPS C/NAV.
  - BeiDou 3 B/CNAV-2 broadcast orbits clone the GPS C/NAV parameterization and fit intervals.
  - Galileo I/NAV clones the GPS L/NAV parameterization with a much faster 30-minute update rate and weighted least-squares fit strategy
- Velocity errors between MGEX final orbits and broadcast orbits were evaluated to < 0.1mm/s in radial velocity, and > 0.1mm/s in in-track velocity, predominantly due to mis-modeling of the C/G - phase center offset between MGEX and broadcast orbits. Radial velocity error is the predominant error source in RO applications.
- GLONASS broadcast orbit errors routinely exceed 1mm/s, are inadequate for NRT processing today, and were only briefly assessed for this work. GLONASS is not used for multi-GNSS POD at PlanetiQ today.
- Velocity and clock errors are uncorrelated between GNSS SV and may be used for accurate POD with sufficient observations.
- GNSS systems are closely aligned in space and provide jointly-consistent realizations of the ITRF (verified by others)
- GNSS system clocks are coarsely aligned to UTC with large inter-system offsets which must be observed.
  - GNOMES's 6-band receiver architecture also has inter-system dual-frequency DCB which must also be observed, and is difficult to distinguish from inter-system clock biases.

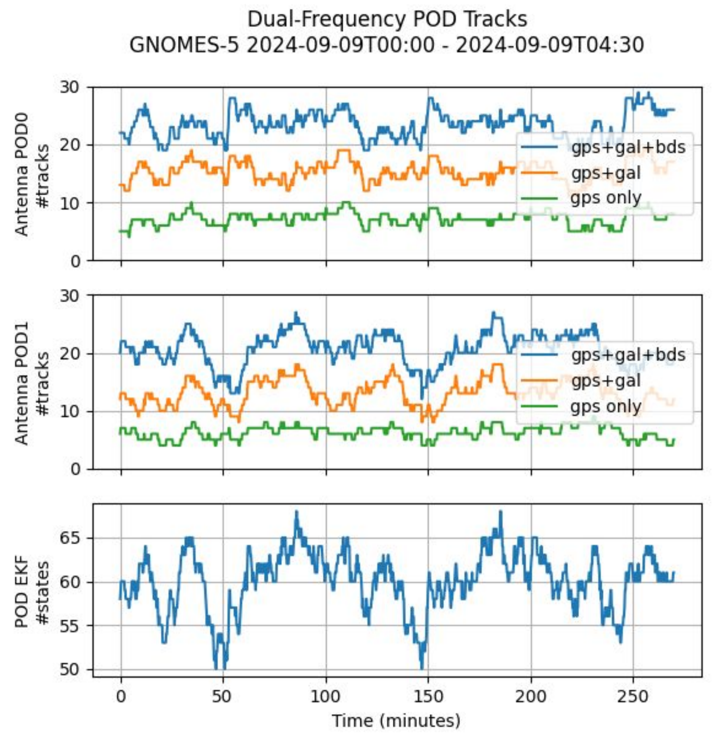
Receiver-Autonomous POD Highlights

- Constructed as a variable-order EKF, 1 Hz predict and update
- Delivered to NRT users in SP3 format
- EGM2008 force model to order and degree 31 (order and degree 127 tested)
- Observes a sum of slowly varying forces as one 3D perturbation state without attempt to separate and model them, including exospheric drag, solar pressure, lunar and solar gravity, solid earth tides, etc.
- Observes one dual-frequency phase-leveling state per unique track, 45 typical.
  - Inject configurable process error when broadcast clock, ephemeris, and integrity (CEI) datasets are updated to effectively observe discontinuities across broadcast CEI datasets.
  - Dynamically reconfigure state space mean and covariance matrices as tracks are acquired and lost.
- Observes 5x time-like bias states
  - 2x inter-constellation clock offsets (GPS - BDS, GPS - GAL) observe both differences in GNSS system times and receiver DCB.
  - 3x inter-antenna clock offsets (POD0-POD1) for each constellation account for remaining hardware delays
- Routinely delivers clock-limited performance < 0.2mm/s 4D velocity (6e-13 s/s)

POD Antennas:

- Dual microstrip "patch" antennas facing fore and aft
- All-sky dual-frequency tracking for GPS, GAL, BDS3, and GLONASS
- ~45 simultaneous tracks from {GPS, GAL, BDS3} typ.





or, "Modern GNSS is Actually Pretty Good"

System Verification Using Modified Allan Deviation of POD Track Excess Phase

Jointly validates the integrated system performance using the metric which matters most in RO applications: excess phase noise and excess phase rate stability. All of the following system components are exercised:

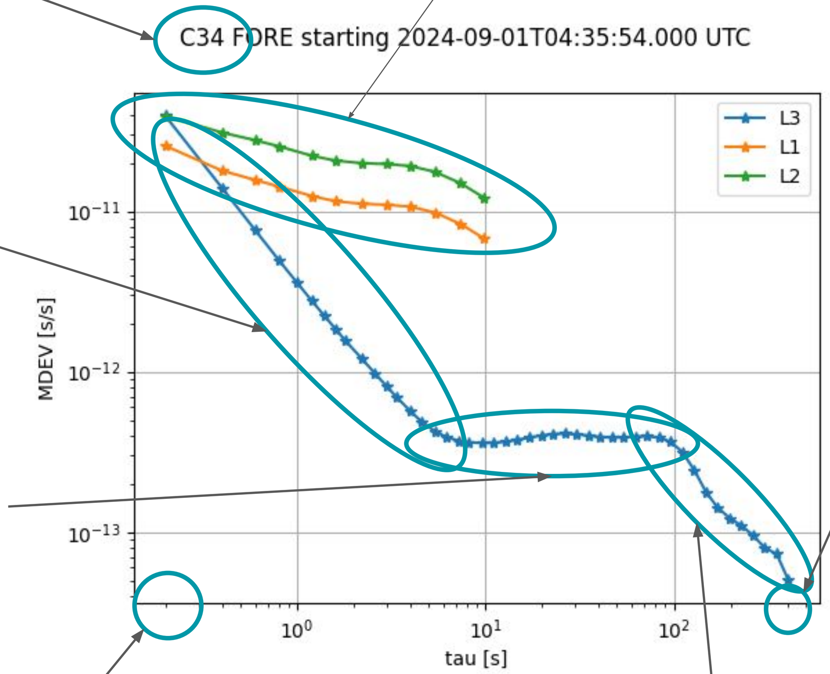
- Transmitter orbit accuracy
- Receiver POD solution
- Receiver clock steering software
- Transmitter and receiver clock stability
- Software consuming all of the above in the processing system

$$Mod\sigma_y^2(\tau) = \frac{1}{2m^2\tau^2(N-3m+1)} \sum_{j=1}^{N-3m+1} \left\{ \sum_{i=j}^{j+m-1} [x_{i+2m} - 2x_{i+m} + x_i] \right\}^2$$

m: averaging ratio
x: phase measurement (excess phase, light-seconds)
τ: sample period (seconds)

GNSS SVs equipped with passive hydrogen masers, such as current-generation Galileo and BeiDou, provide somewhat better 10-100 second performance (4e-13 s/s) compared to GPS (5e-13 s/s), and far superior to GLONASS (1e-11 s/s)

L1 and L2 roll off slowly due to ionospheric structure, even at high elevation angles



Short-term clock performance is limited by white phase noise in the ionosphere-free linear combination. L3 consistently provides lower white noise than either L1 or L2 alone even at the 1 Hz rate.

Medium-term performance on a time scale of a neutral atmosphere GNSS-RO profile is based on relying on the hardware:

- Ultra-stable receiver master reference oscillator
- GNSS atomic clocks and RF hardware
- Software built to respect the hardware's capability
- Typically limited by flicker frequency noise

Minimum Elevation Mask

- Limits maximum MDEV analysis period
- Configurable
- Aligned to (or used to establish) POD solver's mask
- Avoids effects of F-layer scintillations, sporadic E, and neutral atmosphere on the analysis

5 Hz POD track carrier phase sampling

Long-term drift in the receiver's oscillator frequency is managed with software-based digital clock steering.

- Targets GNSS ensemble solution from GPS, BDS, GAL
  - Phase-aligned to GPS system time
- Low bandwidth control assures reliance on the hardware on RO profile time scales
- Simplifies excess phase analysis by maintaining receiver time aligned to GNSS system time for inertially-correct processing in a common coordinate time
- Every clock steering decision is telemetered for offline analysis and verification

Correction To GPS User Velocity Algorithm

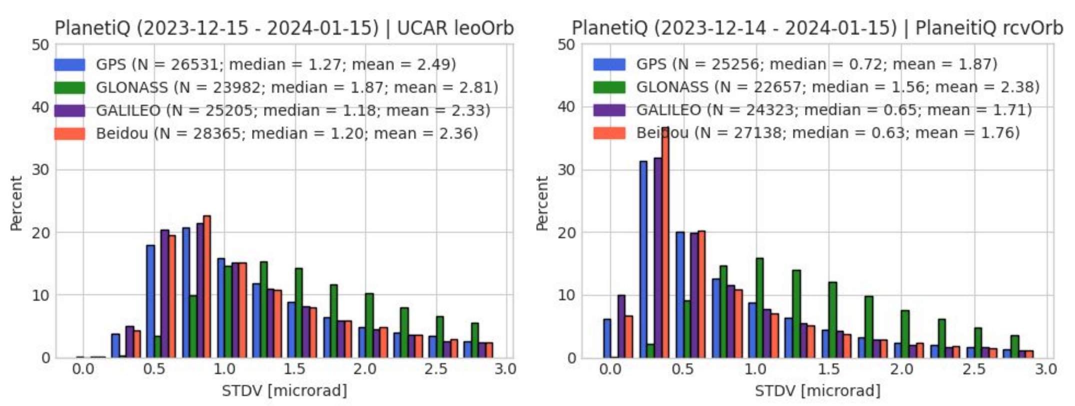
The (typically optional) Table 30-II user equations for SV velocity provided in IS-GPS-200L and later editions are inadequate for GNSS-RO preprocessing based on analytic expressions for the SV velocity and must be updated to include a higher-order term for mean motion. The correction reduces in-track error by 10-40x depending on the broadcast mean motion correction. Without this correction, C/NAV SV velocity error is significantly worse than L/NAV SV velocity.

IS-GPS Eqn.	Corrected	Term
	$\dot{n}_A = \Delta\dot{n}_0/2$	Corr. mean motion rate
	$\dot{M} = n_A + \dot{n}_A t_k$	Mean anomaly rate
$\dot{E} = \frac{n_A}{1 - e\cos E_k}$	$\dot{E} = \frac{\dot{M}}{1 - e\cos E_k}$	Eccentric anomaly rate

Δn_A, n_0, $\Delta\dot{n}_0$ are given in the navigation message.
n_A, e, E_k, and t_k are calculated in the SV position equations.

Performance *Improvements* With PlanetiQ Receiver-Autonomous POD *rcvOrb* versus Bernese *leoOrb*

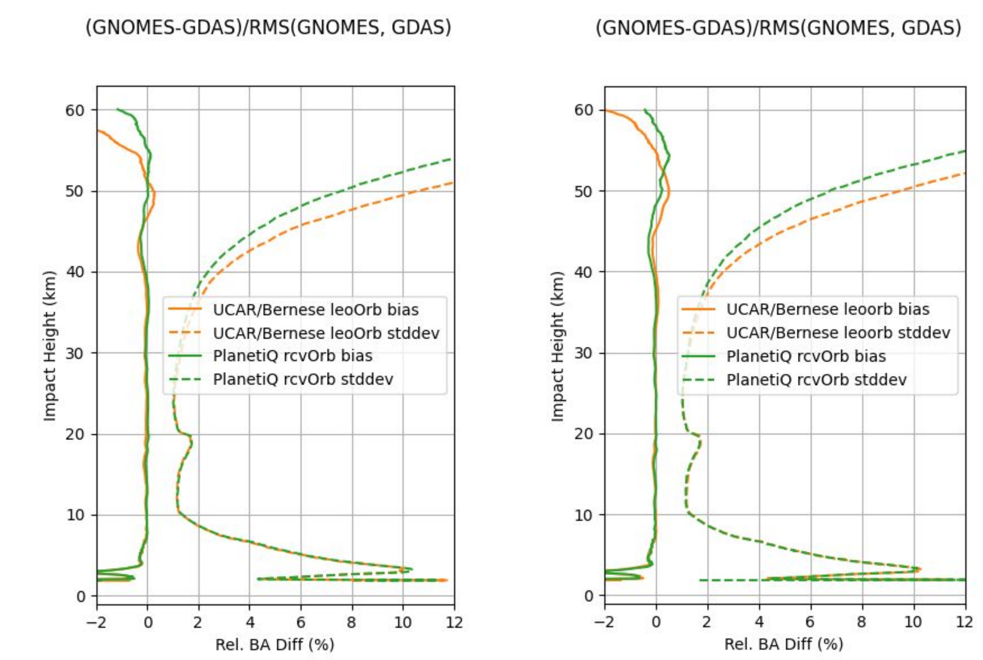
Expected result: Improved system reliability and reduced latency with acceptable performance degradations in the upper stratosphere.
Actual result: Also improved BA noise *and bias* performance in the stratosphere.



UCAR processing system operated by UCAR during DO-2 with *Bernese* POD *leoOrb*

UCAR processing system concurrently operated by AER with PlanetiQ *rcvOrb*, BDS broadcast clocks, and otherwise identical config

- Measure standard deviation of bending angle noise in 60-80 km, profile-by-profile. A standard benchmark of RO instrument performance at UCAR. Commonly used to show that "all RO is basically the same"
- Replacing UCAR leoOrb with PlanetiQ rcvOrb shows large reductions in median noise for BDS, GAL, and GPS. All RO is not the same!
  - Small reductions in noise for GLO, limited by poor Tx clocks
- Significant population shift to lower noise for all tracks
- < 1 urad RMS noise routinely observed
- BeiDou processing in the AER case using broadcast clocks essentially tied for best performance with Galileo!
- PlanetiQ rcvOrb under evaluation for DO-4 at NOAA



- PlanetiQ rcvOrb in service at AER instead of leoOrb since June, 2023, primarily to improve system reliability. BA statistical improvement was an unexpected benefit.
- Four-constellation GNSS-RO performance shown here, much stronger perf available when GLO is excluded
- Has shown consistently better stddev of bending angle in the uppermost stratosphere, and comparable performance in the "core" region and lower troposphere.
- rcvOrb also shows improvement in mean bias, primarily through impact on negative outliers.