Orbit Determination and Gravity Recovery from GRACE-FO GPS Phase-Rate Data: Initial Results from a Novel Processing Scheme using Numerically Differentiated GPS Data

Niusha Saadat Srinivas Bettadpur

1. Introduction

Nominal GRACE(-FO) processing combines low-low (ll) and high-low (hl) satellite-to-satellite tracking (SST) observations to produce monthly gravity field estimates.

Low-low SST

- K-band ranging (KBR) or laser ranging interferometer (LRI) instruments measure inter-satellite range
- Ranges are CRN filtered to produce range-rate and range-acceleration [1]

High-low SST

- Undifferenced or double-differenced GPS code and phase pseudoranges

We often process variants of the ll-SST observations (range-rates or range-accelerations) which improve gravity field estimates, but hl-SST range-rates have rarely been revisited in a GRACE-like architecture. Our previous simulation studies show that if we process hl-SST range rates, gravity field results also improve [2].

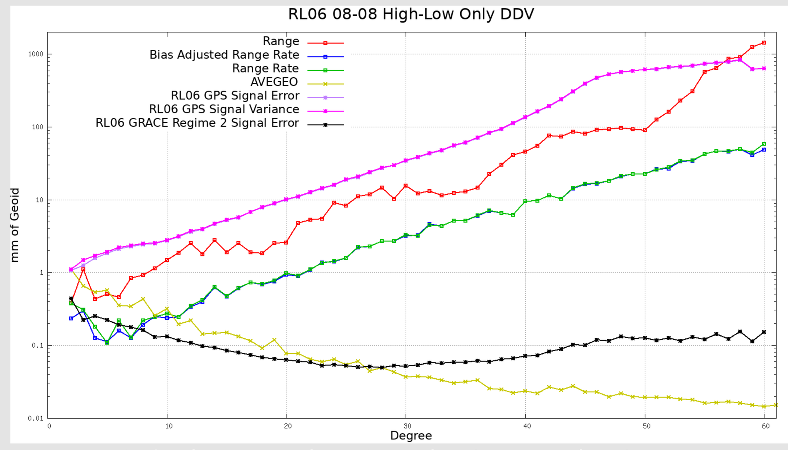

Figure 1. High-low only simulation solution error DDV

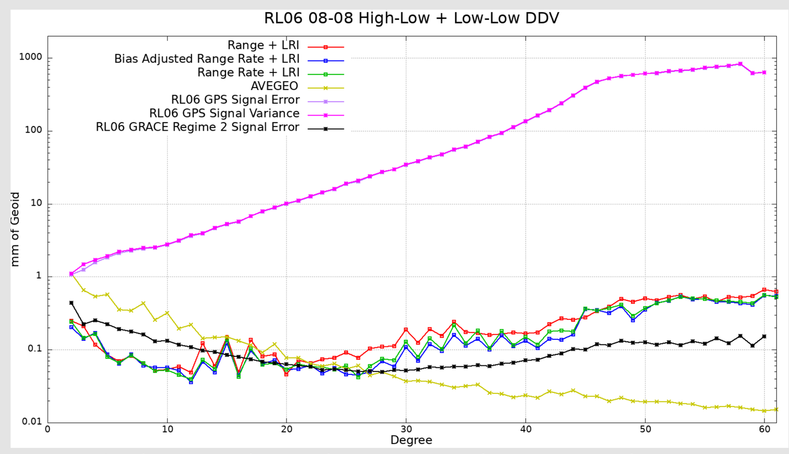

Figure 2. High-low + low-low simulation solution error DDV

The yellow AVEGEO line in the DDV plots below represents the time-variable signal being estimated in the simulations [3]. The range and range-rate lines are the simulation solution error (difference between AVEGEO and simulation estimate) DDV for GPS range and GPS range-rate simulations respectively.

2. Research Questions

- How can we use available data to generate high-low range-rate data (Doppler data is not downlinked)?
- How do we model this observation type for precise orbit determination?
- How do our initial results compare to simulation results?

3. GPS Phase-Rate Observation Creation

Doppler data is not downlinked, so we must generate the high-low range-rates from the GPS range data. We process the level-1A GPS (GPS1A) data to create 1 Hz carrier phases that we can numerically differentiate. This procGPS1A product is analogous to the level-1B GPS data, but the carrier phase is kept at 1 Hz instead of the 0.1 Hz downsampled GPS1B data.

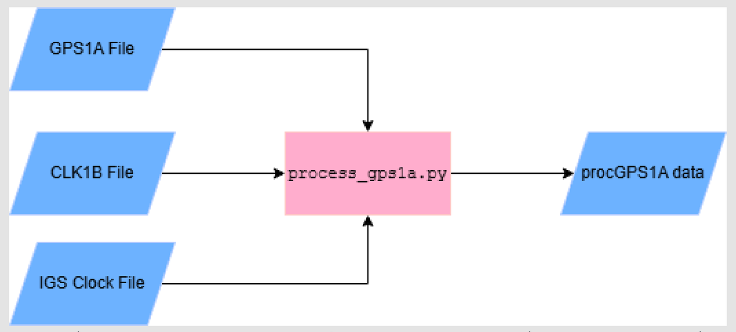

Figure 3. GPS1A (raw receiver observations), CLK1B (receiver clock corrections), and IGS clock (GPS clock corrections) are used to create "procGPS1A" data

Spectral decomposition of the carrier phase residuals aids in our choice of a numerical differentiation method. Differentiation amplifies noise (higher frequencies), so we desire a method that will attenuate noise but not signal.

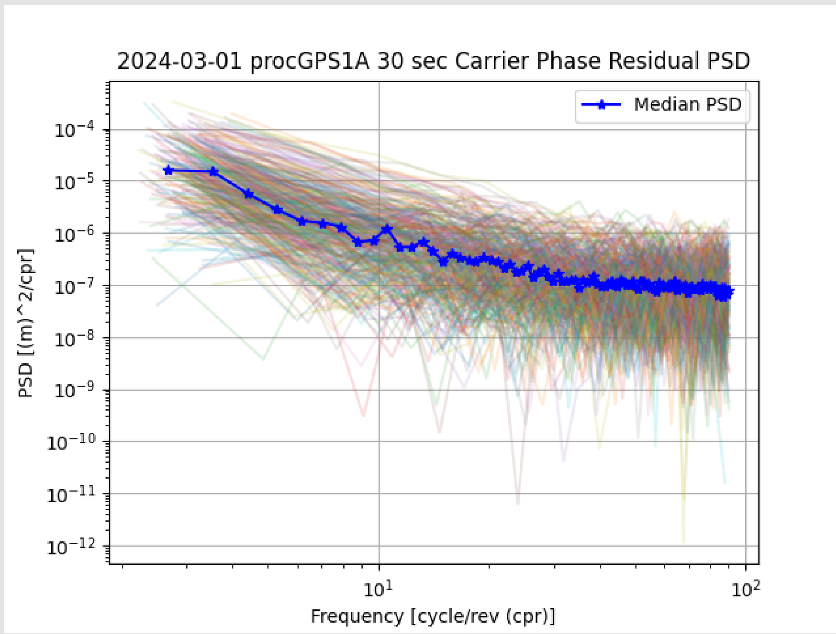

Figure 4. Carrier phase residual PSD for all passes over a day. The spectrum begins to flatten towards the end starting at roughly 60 cpr.

The magnitude response of various digital filters is shown below. For this presentation, we use a Savitzky-Golay filter with a degree 3 polynomial and 19 point window. This has given the best results out of the choices in the plot below. Continued efforts are ongoing to test filters with different magnitude response properties. While the Savitzky-Golay filter has given the best results, the high frequencies are not completely attenuated which could be the cause for some inaccuracy.

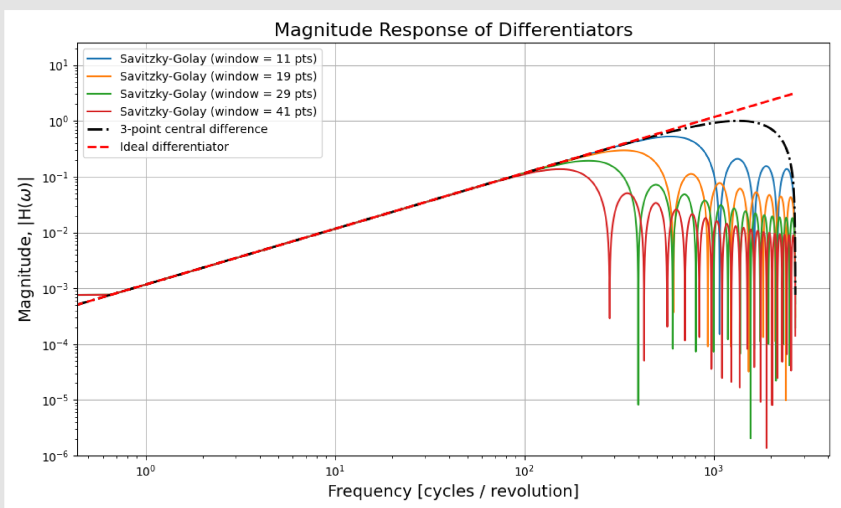

Figure 5. Larger window lengths begin attenuation at lower frequencies, but ripple effects are still present at high frequencies.

4. Phase-Rate Observation Model

The observation model for the phase rate is shown below.

$$\dot{\Phi}(T_R) = \dot{\rho}(T_R, T^S) + c\dot{\delta t}_R + \dot{\delta GR} + (\dot{\delta PR})^S + \epsilon$$

$$\dot{\rho} = \frac{\hat{\rho}\cdot(\mathbf{v}^S - \mathbf{v}_R)}{1 + \frac{1}{c}(\hat{\rho}\cdot\mathbf{v}^S)}$$

It is derived from the equation for the ionosphere free, undifferenced carrier phases used to fit the procGPS1A data.

$$\Phi(T_R) = \rho(T_R, T^S) + c\delta t_R + N + \omega + \delta GR + (\delta PR)^S + PCV + \epsilon$$

- ρ: range
- δt_R: receiver clock offset
- N: pass ambiguity
- ω: phase wind-up
- δGR: general relativistic effect
- $(\delta PR)^S$: periodic relativistic effect of GPS clock
- PCV: phase center variation

Corrections for ω and PCV are precomputed and removed from the carrier phase prior to differentiation; the other terms have analytical models or are estimated ($\dot{\delta t}_R$). Ongoing research is being done on how to best parameterize and estimate $\dot{\delta t}_R$, the receiver clock drift. For the following results, we estimate it as a pass-wise constant.

5. Orbit Comparison Results

GPS-only orbit

- Only fit using GPS data, nominal models for forces, and heavy empirical parameterization

Reference orbit

- Uses all GRACE-FO sensor data (accelerometer, star camera, etc.)
- Orbit used to write partials for gravity field estimates

Both orbit cases were run for a nominal (undifference code and phase) orbit and phase-rate only orbit.

Orbit	Sat	3D Mean [m] (Med/Mean/Min/Max)	3D RMS [m] (Med/Mean/Min/Max)
GPS-only	GF-1	0.009/0.012/0.001/0.034	0.098/0.099/0.080/0.129
	GF-2	0.035/0.034/0.005/0.073	0.102/0.101/0.082/0.126
Reference	GF-1	0.043/0.104/0.012/1.754	0.153/0.189/0.105/1.465
	GF-2	0.051/0.076/0.023/0.599	0.154/0.183/0.106/0.905

Table 1. March 2024 trajectory difference between orbits using GPS phase-rate vs nominal code and phase

The 3D mean and RMS are calculated for each arc (nominally 1 day) and the statistics for all the arcs in the month are presented. There is a clear discrepancy between the phase-rate orbits and the GPS-UD orbits. The GPS-only orbits are closer aligned due to the use of many empirical parameters. This points to a deficiency in the observation modeling and/or orbit parameterization (hinted at earlier with the clock drift parameter).

6. Gravity Field Results

The gravity field results depict that the inaccurate phase-rate orbits degrade the solution quality. This is very evident in the high-low only solutions, whereas the ll-SST observations stabilize parts of the combined solution.

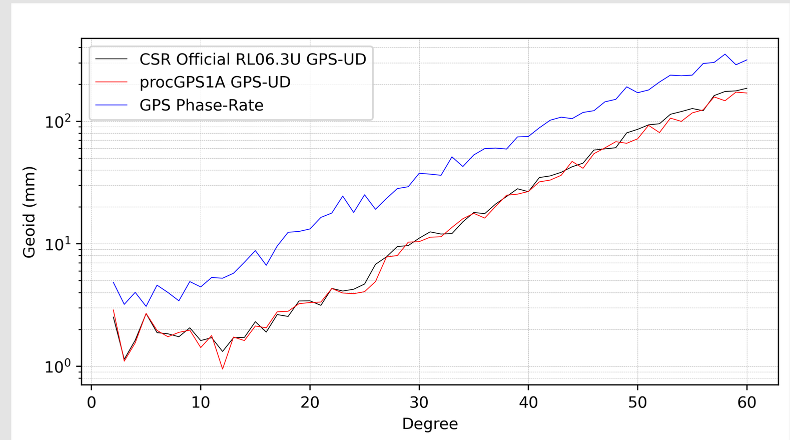

Figure 6. March 2024 high-low only solution DDV

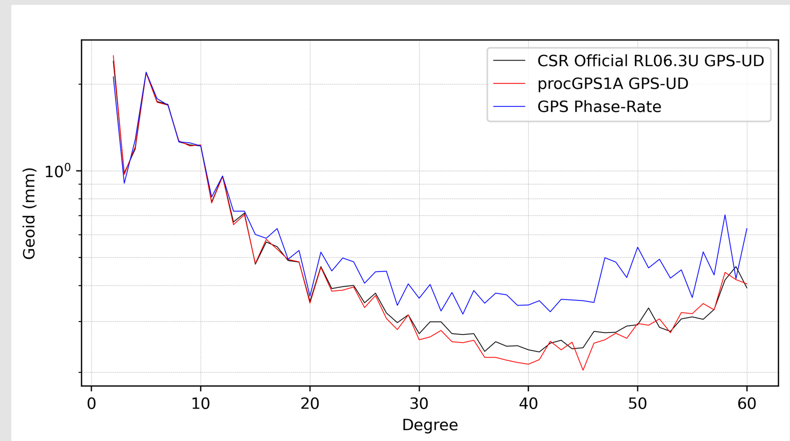

Figure 7. March 2024 high-low + low-low solution DDV

5. Conclusions

Summary

- Overview of our ongoing efforts of generating and modeling GPS-to-LEO range-rates from differentiated carrier phase observations
- Current results for both orbit and gravity quality are degraded, likely due to some mismodeled/poorly-parameterized parameters (e.g., clock drift), but we are continuing to iterate and improve upon on our processing scheme

Future Work

- Investigate different digital filters for potentially improved stopband properties
- Improve parameterization of the receiver clock drift
- Explore relative weighting schemes for hl-SST and ll-SST range-rates

This presentation showcases initial results from our current iteration of efforts of using GPS carrier phase-rate data for POD and gravity field estimation. Current results are erroneous but work is ongoing to improve them and replicate what is seen in simulation.

This work is funded by JPL Contract 1604489 (GRACE Follow-On Phase E). The use of resources of the Texas Advanced Computing Center is gratefully acknowledged.

[1] H. Y. Wen, G. Kruizinga, M. Paik, W. Bertiger, C. Sakumura, T. Bandikova, and C. Mccullough, "Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) Level-1 Data Product User Handbook," Sept. 2019.

[2] N. Saadat, S. Bettadpur, C. McCullough, and P. Nagel, "A Quantitative Analysis of the Contributions of High-Low Satellite-to-Satellite Tracking (SST) Observations used for Gravity Field Estimation," Tech. Rep. EGU24-3215, Copernicus Meetings, Mar. 2024.

[3] P. F. Thompson, S. V. Bettadpur, and B. D. Tapley, "Impact of short period, non-tidal, temporal mass variability on GRACE gravity estimates," *Geophysical Research Letters*, vol. 31, no. 6, 2004.