A Study on the Role of High-Low Satellite-to-Satellite Tracking (SST) in Combination with Low-Low SST for Gravity Field Estimation

The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

Niusha Saadat, Srinivas Bettadpur, Peter Nagel
Center for Space Research, University of Texas at Austin

CSR
Center for Space Research

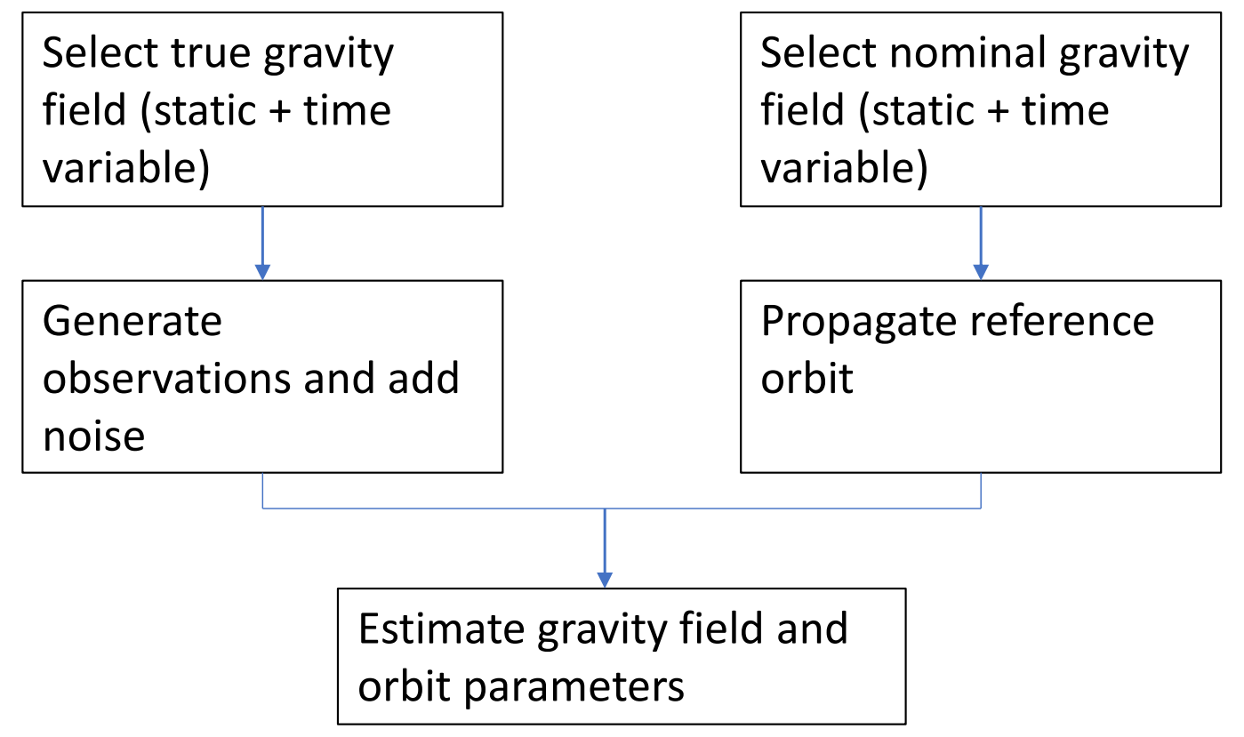
Introduction:

GRACE-FO gravity fields are derived using a combination of low-low and high-low SST data [1]. High-low SST data contributes crucial information for satellite positioning, timing, and long-wavelength gravity field information. Results from numerical simulation studies of the high-low configuration are presented to analyze the error contributions on the combined gravity field estimates.

Motivation:

- Previous studies have shown that hl-SST range data contributes limited, but critical, information for gravity field estimation [2]
    - hl-SST data contains information on the orbit (initial conditions) and a few low degree harmonics
    - Gravity field estimates derived from a combination of hl-SST and ll-SST data require precise hl-SST data for accurate high degree fields
- There is extensive literature on exploitation of high-low range tracking for this information – we take a closer look at using range rates between GPS and LEO
- This poster revisits the basis of this approach as a first step
    - We consider instantaneous range rate in this work, recognizing that practical observation schemes may be more complex

Methods:


Select true gravity field (static + time variable)

Generate observations and add noise

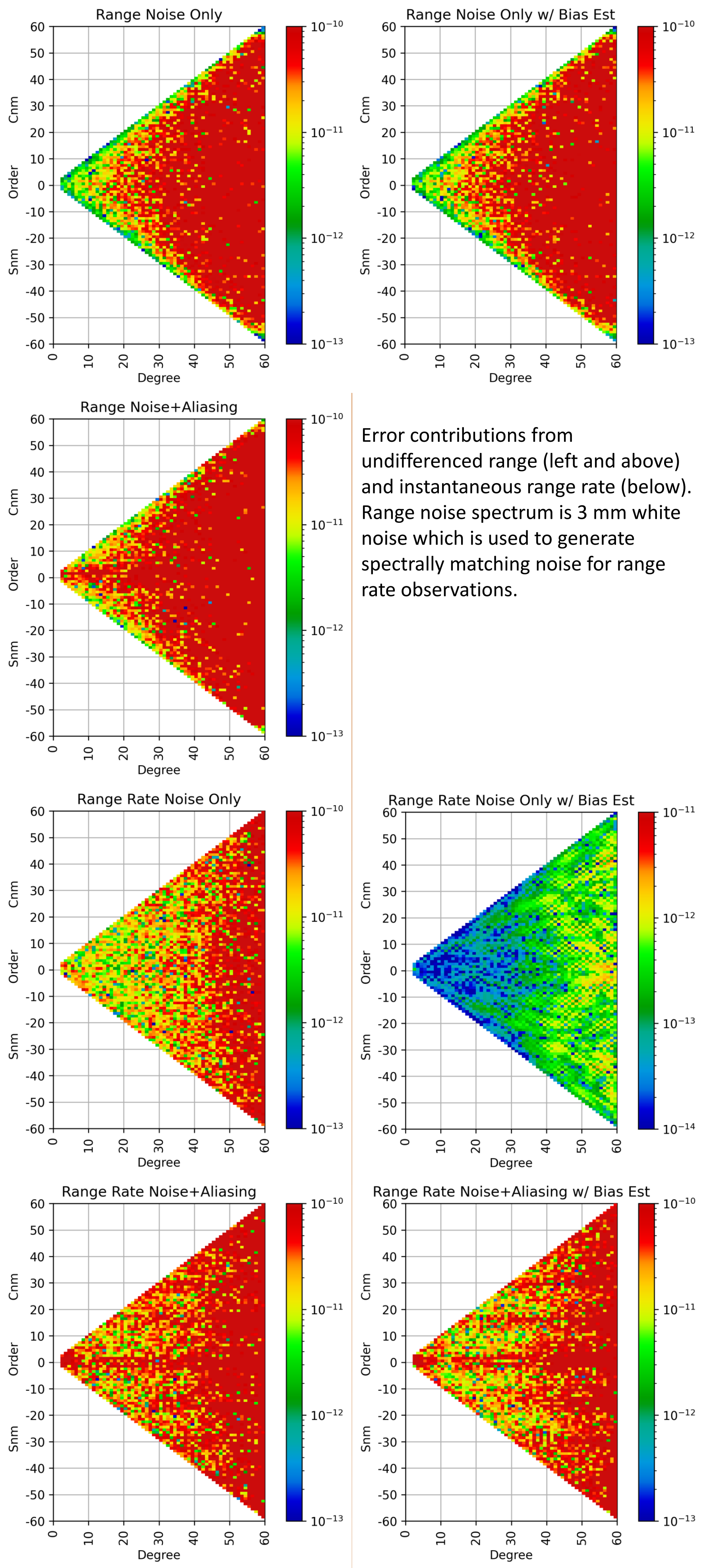
Select nominal gravity field (static + time variable)

Propagate reference orbit

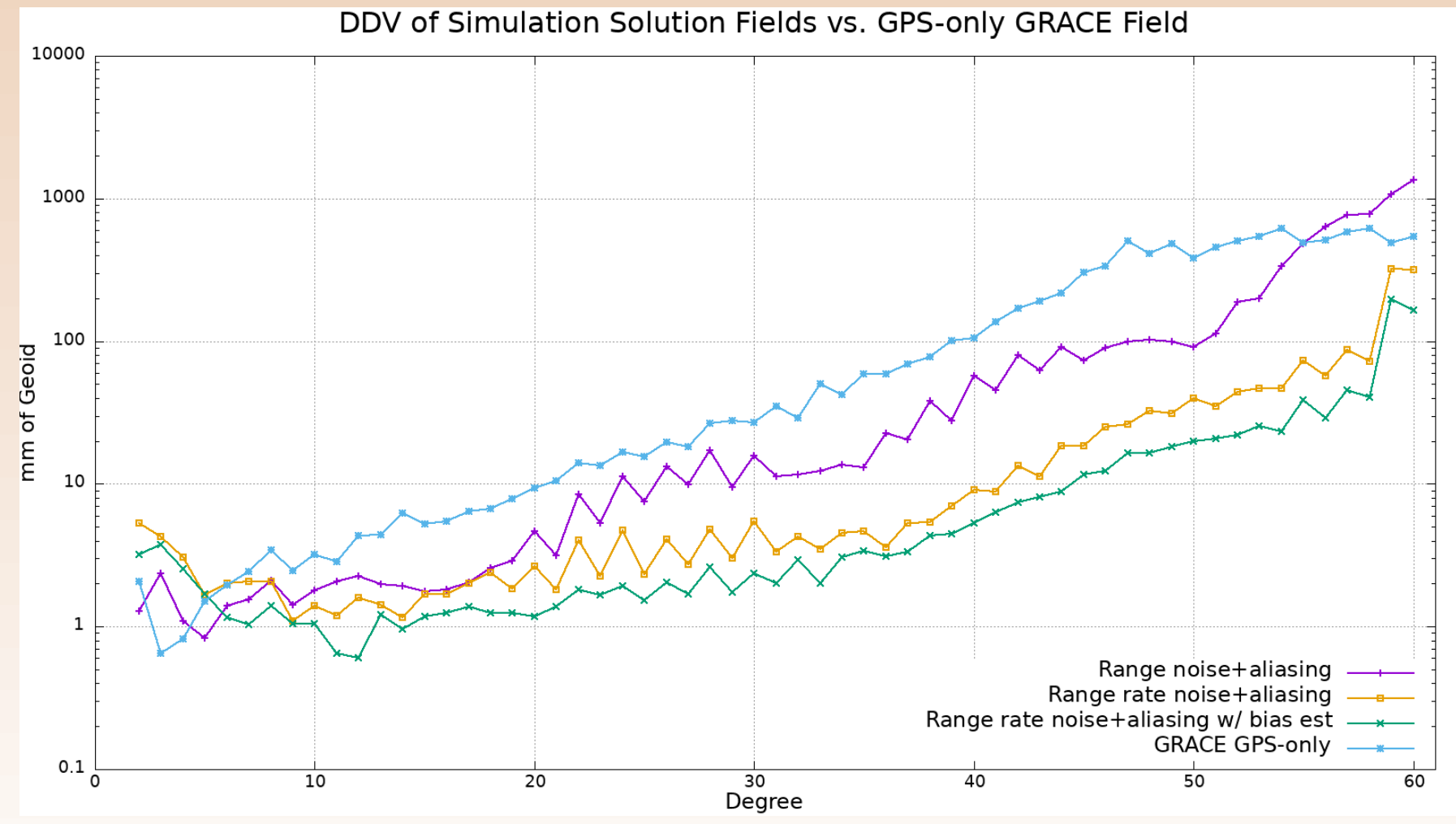
Estimate gravity field and orbit parameters

- In this simulation study, error is added to instantaneous range or range rate observations to analyze how well the observable recovers the true gravity signal
- Time variable gravity dealiasing error [3] is incorporated by using a different time variable gravity model for the true and nominal fields
    - This is recognized to be the largest error source in time variable gravity estimation

Simulation Results:



Error contributions from undifferenced range (left and above) and instantaneous range rate (below). Range noise spectrum is 3 mm white noise which is used to generate spectrally matching noise for range rate observations.



- Range observations are undifferenced high-low phase converted range [4].

$$\rho^{obs} = \rho^{true} + c * (dt^{LEO} - dt^{GPS}) + N\lambda + \epsilon$$

dt^{LEO} : LEO receiver clock offset
dt^{GPS} : GPS clock offset
N : phase cycle ambiguity
ϵ : measurement noise, ionospheric delay, etc.

- Range rate observations are instantaneous range rates.

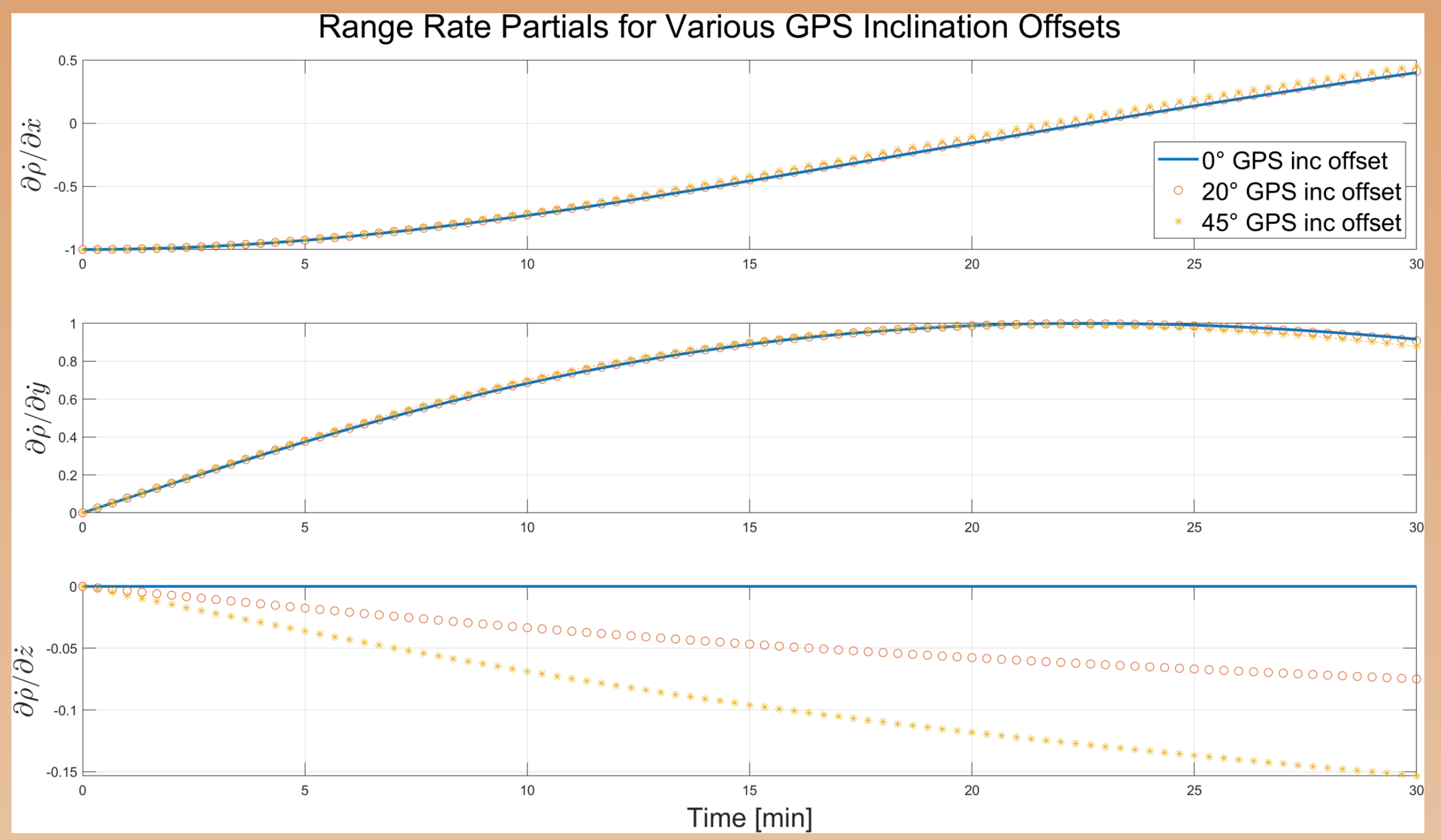
$$\dot{\rho}^{obs} = \hat{\boldsymbol{e}}_{\rho} \cdot [\boldsymbol{v}_{GPS} - \boldsymbol{v}_{LEO}] + \epsilon$$

$\hat{\boldsymbol{e}}_{\rho}$: LEO to GPS range unit vector
$\boldsymbol{v}$: satellite velocity vector
ϵ : measurement noise

- Range simulations establish baseline to be contrasted against
    - hl-SST provides information on low degree and sectorial harmonics (low frequency signals)
- Range rate performs better up to mid degrees
    - Range rate bias estimate improves estimates by an order of magnitude
    - Range rate sectorials appear to be less accurate than range sectorials
- Dealiasing error causes large degradation of the solutions
    - Zonals are heavily impacted
    - Range rate cases continue to outperform range solutions

$$\begin{bmatrix} x(t) \\ y(t) \\ z(t) \\ \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} -3x_0 - \frac{1}{n^2}f_R - \frac{2}{n}\dot{y}_0 \\ \frac{2}{n}\dot{x}_0 - \frac{4}{n^2}f_T \\ z_0 - \frac{1}{n^2}f_N \\ \dot{x}_0 - \frac{2}{n}f_T \\ 6nx_0 + 4\dot{y}_0 + \frac{2}{n}f_R \\ \dot{z}_0 \end{bmatrix} \cos(nt) + \begin{bmatrix} \frac{1}{n}\dot{x}_0 - \frac{2}{n^2}f_T \\ 6x_0 + \frac{4}{n}\dot{y}_0 + \frac{2}{n^2}f_R \\ \frac{1}{n}\dot{z}_0 \\ 3nx_0 + 2\dot{y}_0 + \frac{1}{n}f_R \\ -2\dot{x}_0 + \frac{4}{n}f_T \\ \frac{1}{n}f_N - nz_0 \end{bmatrix} \sin(nt) + \begin{bmatrix} \frac{2}{n}f_T \\ -6nx_0 - 3\dot{y}_0 - \frac{2}{n}f_R \\ 0 \\ 0 \\ -3f_T \\ 0 \end{bmatrix} t + \begin{bmatrix} 0 \\ \frac{-3}{2}f_T \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} t^2 + \begin{bmatrix} 4x_0 + \frac{1}{n^2}f_R + \frac{2}{n}\dot{y}_0 \\ y_0 - \frac{2}{n}\dot{x}_0 + \frac{4}{n^2}f_T \\ \frac{1}{n^2}f_N \\ \frac{2}{n}f_T \\ -6nx_0 - 3\dot{y}_0 - \frac{2}{n}f_R \\ 0 \end{bmatrix}$$

- Variational equations [5] depict contributions to periodic, secular, or constant errors
    - Shown for constant radial, transverse, and normal accelerations
    - Coupled terms are difficult to separate – or put another way, any (but not all) of the coupled terms may be adjusted in an estimation scheme
- Solving for instantaneous range rate bias is akin to solving for radial and transverse accelerations; which compensates to some extent the mismodeled accelerations due to aliasing errors



Range rate partials for a linearized orbit with initial condition errors and perturbing acceleration in RTN directions. Radial and transverse information is impacted less by inclination offset during GPS to LEO passes. Out of plane information is highly dependent on the relative inclination of the GPS orbit. Bias estimate is driven by radial and transverse directions since there is no constant term in linearized out of plane velocity expression.

Future Work:

- Study clever methods of extracting high-low range rate data from available signal content

Sharing is encouraged

Acknowledgements:

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.

References:

[1] B. D. Tapley, S. Bettadpur, M. Watkins, and C. Reigber, “The gravity recovery and climate experiment: Mission overview and early results,” Geophysical Research Letters, vol. 31, no. 9, Art. no. 9, 2004, doi: https://doi.org/10.1029/2004GL019920.
[2] C. M. McCullough, “Gravity field estimation for next generation satellite missions,” PhD Thesis, University of Texas at Austin, Austin, Texas, 2017.
[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, Art. no. 6, 2004, doi: https://doi.org/10.1029/2003GL019285.
[4] H. J. Rim, “Topex orbit determination using GPS tracking system,” PhD Thesis, University of Texas at Austin, 1992.
[5] W. H. CLOHESSY and R. S. WILTSHIRE, “Terminal Guidance System for Satellite Rendezvous,” Journal of the Aerospace Sciences, vol. 27, no. 9, Art. no. 9, 1960, doi: 10.2514/8.8704.