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Simulation of a Future SLR Satellite to Improve Low-Degree Gravity Estimates

E. S. Tucker[1], R. S. Nerem[1], and B. D. Loomis[2]

[1]Smead Aerospace Engineering Sciences, Colorado Center for Astrodynamics Research, University of Colorado Boulder, Boulder, CO, USA, [2]Geodesy and Geophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Key Points:

- We present a novel simulation analysis of a hypothetical future satellite laser ranging (SLR) satellite to improve low-degree time-variable gravity recovery
- Our results show a new low-inclination SLR satellite decorrelates low-degree even coefficients allowing for their independent recovery
- A new low-inclination SLR satellite improves recovery of the annual variation of the simulated mass change signal

Correspondence to:

E. S. Tucker,
evan.tucker-1@colorado.edu

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Author Contributions:

Conceptualization: E. S. Tucker, R. S. Nerem, B. D. Loomis
Formal analysis: E. S. Tucker, R. S. Nerem, B. D. Loomis
Investigation: E. S. Tucker
Methodology: E. S. Tucker, R. S. Nerem, B. D. Loomis
Project Administration: R. S. Nerem
Resources: R. S. Nerem, B. D. Loomis
Software: B. D. Loomis
Supervision: R. S. Nerem, B. D. Loomis
Validation: E. S. Tucker, R. S. Nerem, B. D. Loomis
Visualization: E. S. Tucker
Writing – original draft: E. S. Tucker
Writing – review & editing: E. S. Tucker, R. S. Nerem, B. D. Loomis

Abstract The Gravity Recovery and Climate Experiment (GRACE; 2002–2017) and GRACE Follow-On (2018-present) have observed Earth's monthly mass change with unprecedented spatial resolution. These missions have long relied on satellite laser ranging (SLR) measurements to replace the $C_{2,0}$ coefficient, which GRACE recovers poorly. Recent work has also shown the need for SLR-determined $C_{3,0}$ when GRACE operates with a single accelerometer. However, it was not until the 2012 launch of the Laser Relativity Satellite that the SLR data gained the sensitivity to recover $C_{3,0}$ accurately. These low-degree gravity coefficients represent large-scale mass transport and small changes in their values have implications for ice sheet, ocean mass, and water storage estimates. To fully exploit SLR's utility for time-variable gravity (TVG), future satellite orbits should be selected to maximize their sensitivity to the gravity field. In this work, we present results from a simulation study of a hypothetical SLR satellite in which we generate 1 year of data to satellites placed across varying inclinations. We also simulate seven current SLR satellites to show realistic improvements from the new satellite. When compared to the known truth input, a low-inclination satellite ($<\sim 45°$) most improves the low-degree gravity terms, especially the even zonals which show a significant decorrelation. From this, we investigate recovery of the annual variability in the simulated signal and find recovery of the sine component improves by up to 41%. This has important implications when considering future SLR satellites in the context of TVG.

Plain Language Summary Time-variable gravity (TVG) can be used to study the movement of surface water and ice on a monthly basis. While the Gravity Recovery and Climate Experiment (GRACE) has provided a 20-year record of TVG, it does not accurately measure certain large-scale signals. Satellite Laser Ranging (SLR) gravity estimates are conventionally used to supplement GRACE's insensitivity to parts of the gravity field. In 2012, the SLR satellite Laser Relativity Satellite launched and enhanced SLR's capability to observe the low-degree gravity field. Motivated by this, we simulate potential future SLR satellites to investigate their impact on TVG recovery. We find that a new SLR satellite can further support mass change observation by increasing the accuracy with which we estimate large-scale monthly gravity signals.

1. Introduction

Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) have measured Earth's monthly mass redistribution with a spatial resolution of up to 300 km for over 20 years (Landerer et al., 2020; Tapley et al., 2019). This extensive record of time-variable gravity (TVG) has transformed our understanding of mass transport in the hydrosphere, cryosphere, and solid Earth. At the largest scales, these missions have quantified ice loss in Greenland and Antarctica as well as provided an independent record of global ocean mass (Chen et al., 2020; Velicogna, 2009). The 2018 Earth Science Decadal Survey identifies Earth's mass change as a designated observable and highlights the need to maintain continuous, accurate measurements (National Academies of Sciences, Engineering, and Medicine, 2018).

Concurrently, satellite laser ranging (SLR) has served as a fundamental technique for satellite ephemeris estimation, gravity field observation, and reference frame determination for over 50 years (Pearlman et al., 2019). SLR has remained a favored technique due to its simplicity with the fundamental observable being the roundtrip travel time of a laser pulse. Additionally, SLR satellites are relatively cheap as they are passive spheres covered in corner cube reflectors. Their orbital lifespan is on the order of decades due to their low area-to-mass ratio, which makes them robust to non-conservative perturbations (e.g., atmospheric drag and solar radiation pressure). SLR has long supported TVG observation because of the accuracy with which it measures the long wavelength

Table 1
Simulation Force Models for Truth and Nominal Cases

Force	Truth model	Nominal model
Static gravity	GOCO06s	GOCO06s
Ocean tides	EOT11a	FES 2014
Non-tidal atmosphere and ocean	ESA ESM A+O	ESA ESM DEAL+AOerr
Hydrology and ice	ESA ESM H+I	None

components of the gravity field (Yoder et al., 1983). These low-degree observations are important as they capture large-scale geophysical processes. $J_2\left(=-\sqrt{5}C_{2,0}\right)$, for example, describes Earth's oblateness and can change over short timescales due to ice sheet melting (Nerem & Wahr, 2011). Loomis et al. (2020) quantified improvements to Antarctic mass flux from substituting SLR-derived $C_{3,0}$ into the GRACE solution. Other low-degree coefficients have been shown to influence terrestrial water storage estimates (e.g., Chen et al., 2005).

Following GRACE's launch, it became apparent that estimated $C_{2,0}$ values contained an anomalous ∼161-day signal that lacked a geophysical basis. The signal likely originates from temperature dependent cross-track accelerometer errors related to the β' angle of the satellites' orbit (Cheng & Ries, 2017). Since October 2016, GRACE and GRACE-FO have also had degraded estimates of $C_{3,0}$ owing to their operation in single accelerometer mode (Loomis et al., 2020). These accelerometers are critical for removal of non-conservative accelerations in data processing. In all but one of its final 7 months GRACE-B operated without its accelerometer to reduce power needs, requiring the use of an algorithm to transplant data from the functioning satellite (Bandikova et al., 2019). With GRACE-FO, one of the satellites has an underperforming accelerometer that necessitates the use of a similar transplant routine (Landerer et al., 2020). To maintain accuracy, it has become standard practice to replace $C_{2,0}$ and $C_{3,0}$ with SLR-derived values released as Technical Notes, the most recent of which, TN-14, contains $C_{2,0}$ values since 2002 and $C_{3,0}$ values since the 2012 launch of Laser Relativity Satellite (LARES; Loomis et al., 2020).

To mitigate the impact of the high correlation between $C_{2,0}$ and $C_{4,0}$, Loomis et al. (2019) forward modeled a GRACE-derived TVG model during data processing. Additionally, Loomis et al. (2020) showed that LARES serves an essential role in SLR-derived $C_{3,0}$ estimates due to its inclination, altitude, and area-to-mass ratio, even though LARES's primary mission is to measure relativistic phenomena (Ciufolini et al., 2012). In light of these recent advances, we seek to further the capability of SLR as a tool for TVG estimation. We therefore investigate a potential future SLR satellite with a focus on recovering monthly hydrology and ice signals. A constellation of seven existing orbiting satellites is simulated to establish a baseline solution representative of SLR's current limitations. We then simulate a hypothetical satellite placed at a fixed altitude across a range of inclinations. Within the closed-loop simulation environment, we assess the impact of the new satellite by comparing it to the baseline solution and known truth. Our results demonstrate that enhancing the current constellation's geometry with a low-inclination satellite decorrelates the even zonals and improves their independent recovery.

2. Methods

2.1. Simulation Configuration

Our procedure follows established methods to simulate mass-change missions (Loomis et al., 2012; Wiese et al., 2012, 2022). Table 1 reports the force models used in this study. In the first step, a set of *truth* observations are generated using a set of *truth* force models. Gaussian noise with 1 cm standard deviation is then added to these *truth* station-satellite range data. These noisy data are processed in a *nominal* run in which the normal equations are formed with a set of *nominal* force models. The difference between the *truth* and *nominal* models represents the uncertainty in the process. We use NASA/GSFC's orbit determination and parameter estimation software GEODYN to simulate observations and calculate partial derivatives (McCarthy et al., 2015).

The GOCO06s model defines the static gravity field (Kvas et al., 2021). Errors in the static gravity field are not considered since TVG is the primary signal of interest. Ocean tides are defined by the Empirical Ocean Tide (EOT) Model 11a in the *truth* case and the Finite Element Solution (FES) 2014 model in the *nominal* case (Lyard

Table 2
Summary of Satellite Orbits and Estimated Parameters

	LAGEOS-1	LAGEOS-2	Starlette	Stella	Ajisai	Larets	LARES	New
Altitude (km)	5,860	5,620	800–1,100	810	1,500	690	1,440	1,440
Inclination (°)	110	53	50	99	50	98	70	10–170
Est. drag coef. C_D	None	None	Daily	Daily	Daily	Daily	Daily	Daily
Est. constant along track	3.5 days	3.5 days	None	None	None	None	None	None
Reflectivity coef. C_R	1.146	1.111	1.134	1.125	1.040	1.003	1.105	1.105
Relative weight[a]	1.0	1.0	0.16	0.16	0.10	0.07	0.28	0.28

[a]Weights for SLR7 are from Sośnica et al. (2015) and are normalized to LAGEOS-1.

et al., 2021; Savcenko & Bosch, 2012). Non-tidal atmospheric and oceanic variability forms a major error source for mass change missions due to undersampling and subsequent temporal aliasing of these high frequency signals. Because hydrology and ice signals are of interest in TVG analysis, the high frequency non-tidal effects are removed through an atmosphere and ocean dealiasing model, such as AOD1B (Dobslaw et al., 2017). To simulate these AOD errors we use the *A* and *O* components of the simulation-specific ESA Earth System Model (ESM) (Dobslaw et al., 2015). A realistically perturbed dealiasing model is given by DEAL+AOerr coefficients, which contain processes omitted by AOD1B and true errors across large and small scales (Bergmann-Wolf et al., 2015). Finally, the hydrology (*H*) and ice (*I*) signal is defined only in the *truth* run by ESA ESM H+I coefficients (Dobslaw et al., 2015). The *nominal* run uses no a-priori hydrology and ice model as this is the signal we seek to recover in the simulation.

2.2. Satellite Modeling

We simulate 7 SLR satellites ("SLR7"; Table 2) over 12 months in 7-day arcs: LAGEOS-1/2, Starlette, Stella, AJISAI, Larets, and LARES. We do not consider Beacon-C due to its irregular shape and sensitivity to non-conservative forces. This is consistent with the satellites and arc lengths used in the generation of Technical Note 14 (Loomis et al., 2020). All SLR satellites are defined with a truth drag coefficient C_D equal to 2. Our arc parameterization is based on Zelensky et al. (2014), with modifications for a simulation environment. No C_D are estimated for LAGEOS-1/2 due to their high altitude. For Starlette, Stella, AJISAI, Larets, and LARES, and the new satellite, C_D are estimated daily. A constant along-track term is estimated every 3.5 days for both LAGEOS satellites. We do not estimate other empirical accelerations as these parameters absorb gravity signals. Solar radiation pressure is modeled with the coefficients of reflectivity C_R listed in Table 2. The new satellite is given an area-to-mass ratio equal to that of LARES. At the end of each individual arc, partials for the arc parameters (e.g., satellite state, drag) and global parameters (Stokes coefficients for a $5 \times 5 + C/S_{6,1}$ field) are output. For each month, we combine 4 7-day normal equations from each satellite using the predefined weights in Table 2 (Sośnica et al., 2015). We use NASA/GSFC's Ncombine/Nsolve software packages to perform the combination and final inversion of the normal equations.

To narrow the search space for a new satellite, we fix all orbital elements except for inclination. The longitude of the node and mean anomaly will minimally impact the satellite's TVG sensitivity and are not considered a parameter of interest. We define the orbit as circular, which is the case for all the SLR7 except Starlette. For altitude we fix the new satellite at LARES's altitude (1,440 km). We simulated lower altitude cases and found the solution lacked sensitivity to this parameter. Lower altitude primarily affects sensitivity to short-wavelength features, whereas the low-degree SLR solutions recover long wavelengths. The selected altitude balances station observability, TVG sensitivity, and atmospheric drag. Inclination is varied from 10° to 170° in 5° increments. As the satellite approaches an equatorial orbit, fewer stations can observe it and thus we do not consider inclinations below 10°.

Figure 1 shows a map of the SLR ground stations used in this study and the groundtrack of observation points to the SLR7 for a single month. To accurately model tracking statistics for the SLR7, we use real data files for the 12 month period beginning 6 January 2019 to determine observation quantities and stations. For the hypothetical satellite, 6-hr sampled total cloud cover (TCC) data from NCEP/DOE Reanalysis II are used to impose tracking

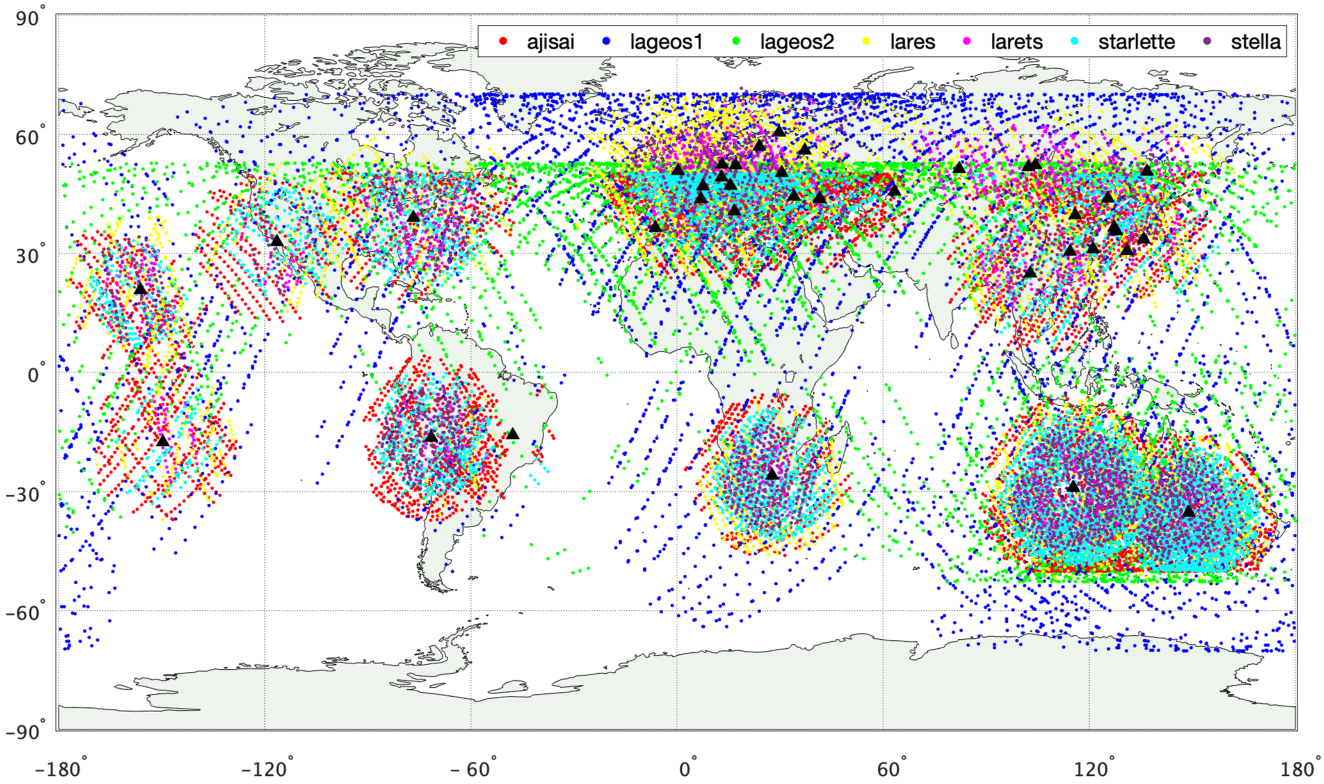

Figure 1. Groundtrack of observation points to SLR7 for the month beginning 28 April 2019 with ground stations shown as black triangles.

statistics (Kanamitsu et al., 2002). After generating all possible passes, we discard those where the fraction of sky covered exceeds two-thirds at the observing station and pass time. If the cloud cover is sufficiently low, we run a Bernoulli trial with probability (1-TCC)/2.5. On a success, a fraction of the pass is observed up to (1-TCC) and otherwise it is discarded. We determined the 2.5 downscaling factor empirically by calibrating the number of observations to a simulated LARES to approximately match the actual number. The downscaling simply means that factors other than weather impact the observability of a pass (e.g., staffing, maintenance). This downscaling agrees with Glaser et al. (2019) who also used TCC data albeit with a different pass-selection scheme. A 15° elevation cutoff is used for all satellites. The number of simulated observations to the new satellite varies with inclination, with the mean number of monthly observations ranging from about 1,200 to 6,000. The number of observations drops from about 4,000 to 2,000 for a satellite inclined at 40° versus 20°, respectively. LARES, for example, averaged 5,416 ± 1,172 observations per month over the simulation timespan. The variability is due to the previously described observability factors. We do not model station velocities and therefore do not estimate station positions. Likewise, we do not estimate station-specific biases.

3. Results and Discussion

Here we report results for a 12 months simulation of a new satellite placed at 1,440 km altitude and varied inclinations. Figure 2 reports the percent improvement in the RMS of the difference between the truth and estimate with respect to the SLR7 solution. The even zonals (Figure 2a) show large improvements with the addition of a low-inclination satellite in both prograde and retrograde configuration. The maximum RMS error reduction is 75% at 30° and 88% at 20° and 25° for $C_{2,0}$ and $C_{4,0}$, respectively. With a new satellite placed above 45° inclination, the observed improvements rapidly diminish. For the odd zonals a low-inclination satellite generally reduces the RMS with a lower magnitude than with the even zonals. The constellation better recovers $C_{5,0}$ with the addition of a satellite up to 30° as well as between 55° and 75°, with the latter range being only a few percent better than the SLR7. We observe a similar pattern with $C_{3,0}$, although the lowest inclinations (≤20°) do not improve the sensitivity to this coefficient. For $C_{3,0}$ and $C_{5,0}$, the largest reductions are 65% at 30° and 58% at 25°, respectively. Figure 2b reports the percent improvement in the RMS of truth minus estimate to the $C_{n,1}$

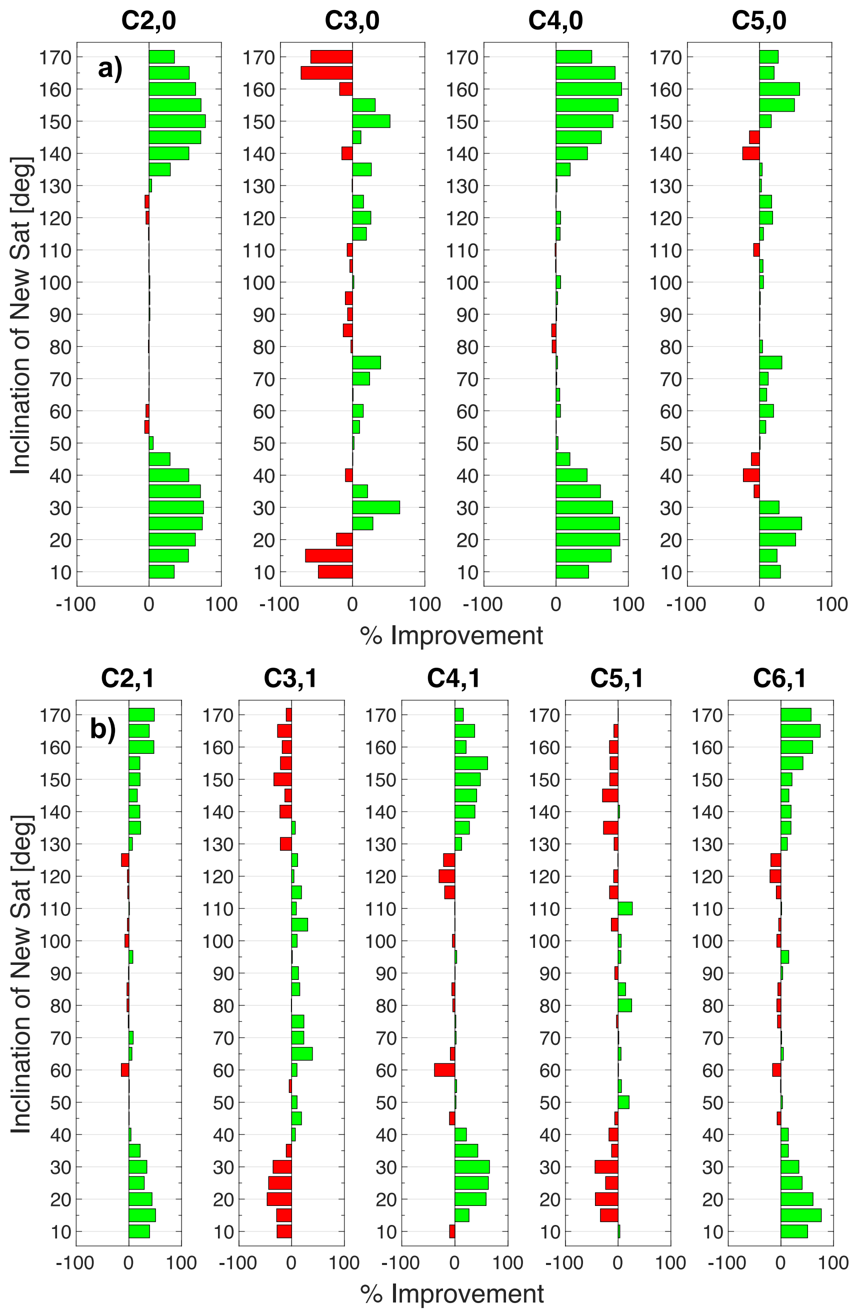

Figure 2. Percent improvement in RMS of difference between truth and estimate with respect to SLR7 for (a) zonal coefficients and (b) $C_{n,1}$ coefficients. Green bars highlight an improved (reduced) RMS and red bars show an increased RMS.

coefficients. As with the zonal coefficients, the even degrees show a distinct pattern in that they benefit most from a new satellite at ≤40° prograde inclination. With respect to the direction of motion, the even degrees are slightly asymmetric as a retrograde satellites shows improvements to ≤50°.

Figure 3 reports the timeseries of all coefficients in the solution for the truth, SLR7 estimate, and SLR7+30° estimate. From this figure, we see the new satellite most affects the even degree zonals and order 1 terms in an absolute sense. Particularly interesting is the recovery of $C_{4,0}$, where the SLR7 overestimates the annual variability and the addition of a low-inclination satellite dramatically reduces the error. The $C_{4,1}$ term similarly benefits from the addition of the hypothetical satellite, as does $S_{4,1}$ to a lesser magnitude. Although the odd zonals show minor improvements with a new satellite, the SLR7 already recovers them reasonably well with LARES in the

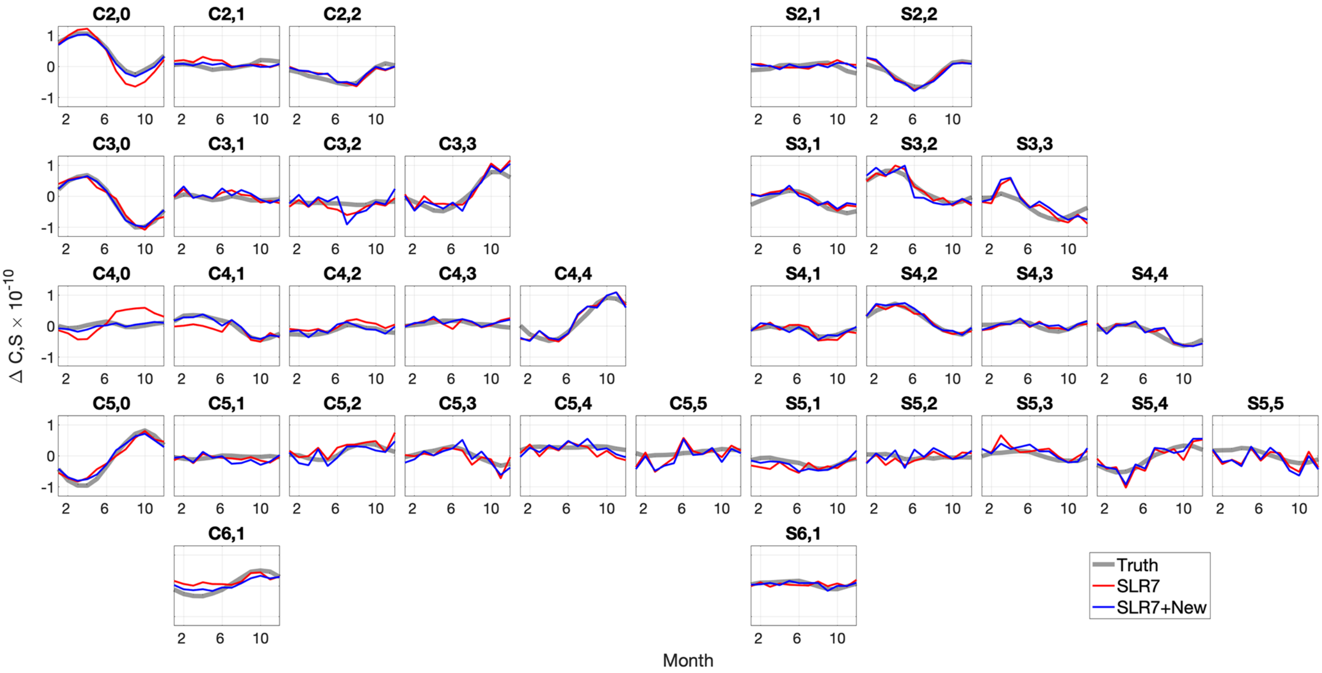

Figure 3. Timeseries of all coefficient values for truth (black), SLR7 estimate (red), and SLR7+New estimate (blue), where the new satellite is at 30° inclination.

solution as noted in previous work (Loomis et al., 2020; Sośnica et al., 2015). In other estimated parameters, the changes from the new satellite are generally small compared to the SLR7 solution.

Due to SLR's low observation numbers and inhomogeneous tracking (Figure 1), its utility as a TVG tool remains limited to low-degrees. Certain low-degree coefficients display high correlations, especially terms of the same order and parity as seen in the mean values in Figure 4. This figure shows the addition of a low-inclination satellite strongly impacts the correlations. With a satellite added at 25–30° inclination, the even zonals and order 1

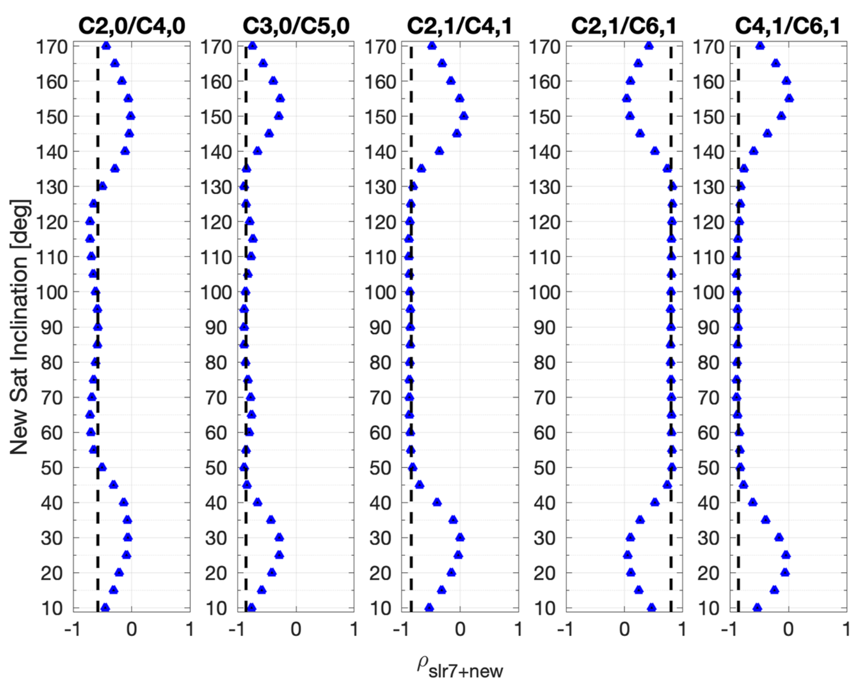

Figure 4. Twelve-month mean correlation coefficient for SLR7+New (triangles) and SLR7 (dashed line).

terms show a near total decorrelation. The even zonals show a minimum correlation of $\rho_{\text{slr7+30°}}^{C20,C40} = -0.07$. This is nearly an order of magnitude lower than the SLR7 correlation, $\rho_{\text{slr7}}^{C20,C40} = -0.6$, and has wide implications for SLR's ability to independently estimate $C_{2,0}$ and $C_{4,0}$. The same hypothetical satellite mitigates the correlation of the odd zonals, but they still show joint-variability with $\rho_{\text{slr7+30°}}^{C30,C50} = -0.29$. Note that while correlations are an indicator of solution quality, they do not depend on the actual data. However, our results show the effect of a low-inclination satellite seen in Figure 4 appears to follow the patterns in Figure 2.

Recovery of the annual variability is one way to examine the science value of our results. Figure 5 shows spatially the errors (with respect to truth) in the sine component of the annual variation computed to degree and order 5. The SLR7 displays the largest errors at near-equatorial latitudes, especially over the Amazon where there exists a large annual signal. The area-weighted RMS of the error is reduced by up to 41% with the addition of a low-inclination satellite. From Figure 5 it is apparent that a low-inclination satellite mitigates areas of high error seen in the SLR7 solution. A satellite placed at ≥45° adds less information and does not impact the solution as strongly. Small improvements of ∼10% are seen with a new satellite between [70° and 80°]. Looking at Table 2, a low-inclination satellite would add significant geometric diversity whereas a mid to high-inclination satellite does not contribute as much new information.

4. Conclusions

We have conducted a novel analysis of a hypothetical future SLR satellite to improve low-degree gravity recovery. When estimating a $5 \times 5 + 6, 1$ gravity field, our results demonstrate significant improvements with the addition of a low-inclination SLR satellite (<∼45°). Despite the limited number of low-latitude ground stations, our simulations show sufficient tracking data can exist to a potential low-inclination satellite. The low-inclination satellite most significantly reduces errors for the even degree zonals and order 1 coefficients. The correlations between these coefficients are also reduced by up to an order of magnitude with the low-inclination satellite. We have shown that this allows for better separability during estimation. Reducing errors in the low-degree coefficients has important implications for ocean mass, ice flux, and terrestrial water storage estimates. We find that a new SLR satellite can better recover part of the annual variability by up to 40% compared to the current SLR7. The independent determination of these coefficients remains essential to support accurate mass change observations from GRACE-FO. While launching a single new satellite will significantly benefit the SLR constellation, future studies could explore the addition of multiple new SLR satellites. We also plan to use our simulation setup to investigate the impact additional ground stations will have on TVG recovery.

Data Availability Statement

The data in this work were generated and processed with GEODYN and Ncombine/Nsolve provided by the NASA/GSFC. SLR data are obtained from the NASA's space geodesy archive, CDDIS (https://cddis.nasa.gov/archive/slr/data; access instructions: https://cddis.nasa.gov/Data_and_Derived_Products/CDDIS_Archive_Access.html). Total cloud cover data are obtained from the NOAA Physical Sciences Laboratory (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html).

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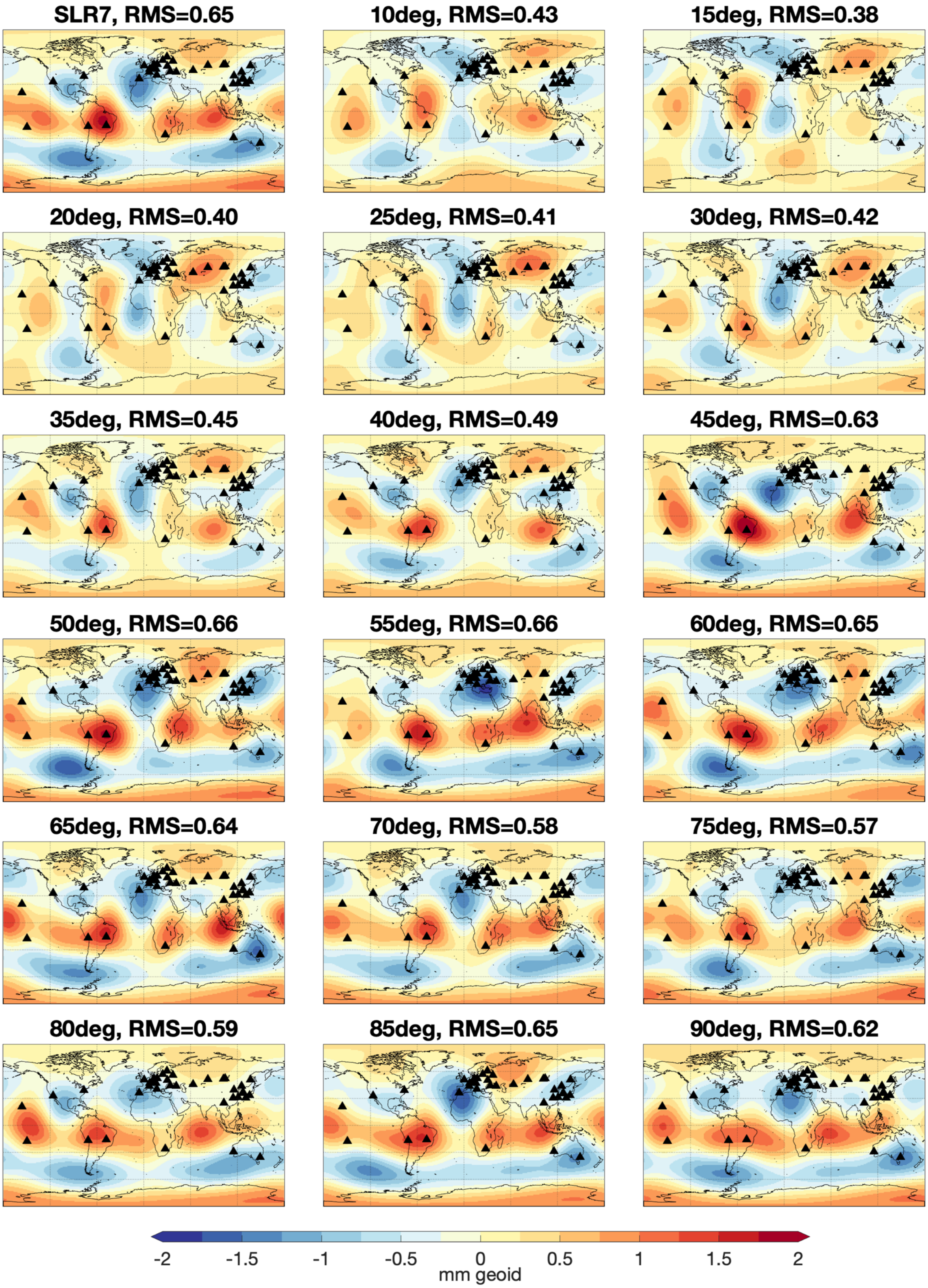

Figure 5. Error in the sine component of the annual variation computed to degree and order 5 expressed in mm geoid. Shown are results for the SLR7 (top left) and SLR7+New for all prograde inclinations.

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