remote sensing

Communication

An Improved Next Generation Gravity Mission

Peter L. Bender

JILA, University of Colorado, Boulder, CO 80309-0440, USA; pbender@jila.colorado.edu

Abstract: There is an opportunity to make a major reduction in the acceleration noise level for the first Next Generation Gravity Mission by replacing the accelerometers used on the GRACE Follow-On Mission by a highly simplified version of the Gravitational Reference Sensors flown very successfully on the LISA Pathfinder mission of ESA. The reduced measurement noise level can make possible much-improved measurements of the short-period and short-wavelength variations in the geopotential. This would be particularly from the along-track analysis of the results, which can permit repeat measurements about half a day apart along ground tracks within 200 km of each other over a substantial part of the globe. Such a mission would permit considerably improved testing of geophysical models for the geopotential variations due to changes in the Earth's mass distribution.

Keywords: rapid earth mass variations; short wavelength earth mass variations; simplified gravitational reference sensors

check for updates

Citation: Bender, P.L. An Improved Next Generation Gravity Mission. *Remote Sens.* **2022**, *14*, 948. https://doi.org/10.3390/rs14040948

Academic Editors: Luca Massotti and David N. Wiese

Received: 6 December 2021
Accepted: 10 February 2022
Published: 16 February 2022

1. Introduction

By 1992, it was being suggested that laser interferometry could be used for measuring changes in the separation between low–low satellites [1,2]. By 2008, it became clear that highly simplified gravitational reference sensors (GRSs) that were being developed for milli-Hz gravitational wave observations in space could further increase the accuracy of GRACE-type missions (see, e.g., McNamara, Vitale, and Danzmann [3]).

Of course, the disturbances affecting Earth satellites due to strong variations in atmospheric drag, radiation pressure, and the magnetic field are far stronger than those experienced by spacecraft during gravitational wave observations in space. Thus, tradeoffs have to be considered between the degree of relaxation of the overall GRS accuracy requirement and the necessary mission cost for reducing the spurious accelerations of the satellites. To make such tradeoffs, design studies and tests of a much-simplified GRS and of other satellite design requirements are being carried out under NASA support [4,5].

The measurement accuracy improvement from using laser interferometry rather than microwave ranging between satellites to determine changes in their separation has been clearly demonstrated on the GRACE Follow-On mission [6]. Far higher accuracy GRS performance than needed for Next Generation Gravity Missions (NGGMs) was demonstrated on the ESA LISA Pathfinder Mission [7].

For determining global averages of the geopotential changes over periods of 10 days or longer, the main limitation on the usefulness of the possible much-improved instrumental measurement accuracy comes from temporal aliasing. Changes in the geopotential over time scales shorter than the global averaging time cannot be separated. However, an approach often called line-of-sight gravity difference (LGD) analysis was suggested many years ago to partially avoid this limitation. A rigorous version of this approach has been presented by Ghobadi-Far et al. [8]. Since then, a number of examples of the value of this approach for determining rapid and short-wavelength variations in the geopotential along track have been published [9–12]. At short wavelengths, the measurement accuracy of NGGMs can be sufficient to determine the short-period geopotential variations directly from single-revolution arcs, except at very low frequencies below roughly 10 cycles per revolution.

Another way of looking at the value of along-track analysis is that it permits direct comparisons of different geophysical models for the geopotential variations in regions of particular interest, without the limitation of temporal aliasing. The geophysical models usually are based on a number of different types of geophysical information, such as rainfall, evapotranspiration, seepage into deeper groundwater layers, runoff, etc. While different types of geopotential variations, such as from total water storage or from local atmospheric mass variations, can give similar frequencies of variations, it is less likely that they will have similar spatial variations also.

In Section 2, a particular suggested design for a high-accuracy NGGM that can be flown quite early is given. Section 3 contains the conclusions concerning the advantages of the suggested approach.

2. Results: Design for Early Next Generation Gravity Mission

It is assumed that the NGGM to be flown early would have a single pair of satellites in a near-polar orbit, with laser interferometer measurements of changes in the satellite separation. The accelerometers flown on the GRACE and GRACE Follow-On missions would be replaced by the highly simplified gravitational reference sensors being developed under NASA support [4,5]. The acceleration noise level for these sensors is taken to be 1×10^{-12} m/(s^2)/(Hz$^{0.5}$) at frequencies of 1 to 100 mHz.

The satellite orbit inclination is assumed to be within 0.1 deg of polar, and the altitude is chosen to be somewhat lower than the early altitude for GRACE Follow-On. However, so that the satellites can be flown in a drag-free mode with a quite simple thruster system, altitudes below 400 km were not considered. A good choice appears to be the near-circular orbit at 418 km altitude, giving a repeat ground track of 170 revolutions in 11 sidereal frame days. This orbit gives orbit crossings between upward and downward passes at 49 deg lat separated by about half a day, and similar crossings at -49 deg lat. The +49 and -49 deg latitude crossings give opportunities for checking on very short period variations in the geopotential and for checking on short-period errors in the models for the variations, including, in particular, those for the atmospheric mass variations.

With the assumed satellite orbits and non-gravitational acceleration noise level, the expected geopotential variation accuracy can be compared with the expected uncertainty over land from the existing atmospheric, oceanographic, and hydrological mass variation models (see Dobslaw, et al. [13]). A rough comparison has been made by Kang and Bender [14]. The results indicate that the model uncertainties would be roughly equal to the along track measurement uncertainty at about 80 cycles/rev, lower at higher frequencies. Over the oceans, it is expected that the improved determination of the atmospheric mass variations would be of particular scientific value because of the poorer knowledge of atmospheric conditions there, but the other variations at medium to short wavelengths also would be measured better.

Other simulations of an early NGGM, similar to the one discussed above, also have been based on a single pair of satellites in near-polar orbits with separations of a few hundred kilometers but with much improved accelerometers, such as the MicroSTAR accelerometers described in [15], instead of simplified GRSs. The satellite altitudes have ranged between about 350 and 500 km, and recently it has been assumed that laser interferometer measurements would be made of changes in the satellite separation. The tradeoffs between different mission designs involve, particularly, the need for rapid demonstration of flight readiness for designs using simplified GRSs.

3. Conclusions

It appears that the benefits of the improved measurement accuracy in the suggested mission would be particularly important for spatial frequencies from roughly 50 cycles/rev to 100 cycles/rev. In this frequency band, the enhanced measurement accuracy would be valuable in comparing different geophysical models for the geopotential variations, and thus, in understanding the basic geophysics involved better. At still higher spatial frequencies, most of the benefit is likely to come from better measurements of the effects of special events, such as earthquakes.

Concerning the satellite design and construction, a major factor is that flying the simplified gravitational reference sensor as the sensor for the gravitational accelerations would considerably simplify the satellites, compared with flying them as a technology demonstration, along with conventional accelerometers. The mass, volume, and power for the simplified gravitational reference sensors do not appear to be substantially larger than those for conventional accelerometers that have nearly similar accuracy, within an order of magnitude. Their basic principle has been fully demonstrated [4,5]; however, the main reason for the suggested approach is that it would simplify the overall satellite design greatly, to just fly one of the two systems. Moreover, the main sensor housing for each type of system would be freer of disturbances, such as thermal variations, if it is located at or very near the center of mass of the satellite. If conventional accelerometers are the primary instruments for the mission, they would presumably have the most favored location, and the simplified gravitational reference sensors would have to contend with increased disturbing effects.

The orbit suggested for the satellite pair has a particular advantage for observing mass variations with both short wavelengths and short periods, such as rapid atmospheric mass variations. As stated earlier, the orbit altitude is 418 km, which gives 170 orbital rotations in 11 sidereal days. The passes for which the ground tracks cross at plus or minus 49 deg latitude and about half a day apart will have their ground tracks stay within 200 km of each other at latitudes further than 35 deg from the equator. This would help considerably in determining whether the differences of the short-period and short-wavelength variations observed are real or are due to measurement noise.

Overall, the near-term scientific benefits of flying the suggested mission instead of one with about the same measurement accuracy requirements as GRACE Follow-On appear to be substantial. Moreover, if a second satellite pair with a lower inclination can be flown fairly soon afterward through collaboration between ESA, NASA, and a number of agencies from other countries, major improvements in the scientific results globally can be expected.

Funding: This research was partially funded by NASA under Award Number NNX16AF16G.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Colombo, O.L.; Chao, B.F. Global Gravity Change in 2001. In *Geodesy and Physics of the Earth: Geodetic Contributions to Geodynamics*; Reigber, C., Ed.; Springer: Berlin/Heidelberg, Germany, 1992; pp. 71–75.
2. Bender, P.L. Integrated laser Doppler method for measuring planetary gravity fields. In *From Mars to Greenland: Charting Gravity with Space and Airborne Instruments*; Colombo, O.L., Ed.; Springer: New York, NY, USA, 1992; pp. 63–72.
3. McNamara, P.; Vitale, S.; Danzmann, K. LISA Pathfinder. *Class. Quantum. Grav.* **2008**, *25*, 114034. [CrossRef]
4. Alvarez, A.D.; Bevilacqua, R.; Hollis, H.; Mueller, G.; Knudston, A.; Patel, U.; Sanjuan, J.; Wass, P.; Conklin, J.W. A Simplified Gravitational Reference Sensor for Satellite Geodesy. *arXiv* **2021**, arXiv:2107.08545v3.
5. Conklin, J.; Davila Alvarez, A.; Bennett, S.; Bevilacqua, R.; Doughty, N.; Hollis, H.; Mueller, G.; Knudtson, A.; Leitch, J.; Lee, J.; et al. Simplified Gravitational Reference Sensors for Future Earth Geodesy Missions, Talk 71. In Proceedings of the GRACE Follow-On Science Team Meeting, Virtual Conference, 12–20 October 2021.
6. Abich, K.; Abramovici, A.; Amparan, B.; Baatzsch, A.; Okihiro, B.B.; Barr, D.C.; Bize, M.P.; Bogan, C.; Braxmaier, C.; Burke, M.J.; et al. In-orbit performance of the GRACE Follow-On laser ranging interferometer. *Phys. Rev. Lett.* **2019**, *123*, 031101. [CrossRef] [PubMed]
7. Armano, M.; Audley, H.; Auger, G.; Baird, J.T.; Bassan, M.; Binetruy, P.; Born, M.; Bortoluzzi, D.; Brandt, N.; Caleno, M.; et al. Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results. *Phys. Rev. Lett.* **2016**, *116*, 231101. [CrossRef] [PubMed]
8. Ghobadi-Far, K.; Han, S.C.; Weller, S.; Loomis, B.D.; Luthcke, S.B.; Mayer-Gürr, T.; Behzadpour, S. A transfer function between line-of-sight gravity difference and GRACE intersatellite ranging data, and an application to hydrological surface mass variation. *J. Geophys. Res. Solid Earth* **2018**, *123*, 9186–9201. [CrossRef]

9. Ghobadi-Far, K.; Han, S.C.; Allgeyer, S.; Tregoning, P.; Sauber, J.; Behzadpour, S.; Mayer-Gürr, T.; Sneeuw, N.; Okal, E. GRACE gravitational measurements of tsunamis after the 2004, 2010, and 2011 great earthquakes. *J. Geod.* **2020**, *94*, 65. [CrossRef]
10. Ghobadi-Far, K.; Han, S.C.; McCullough, C.M.; Wiese, D.N.; Yuan, D.N.; Landerer, F.W.; Sauber, J.; Watkins, M.M. GRACE Follow-On Laser Ranging Interferometer Measurements Uniquely Distinguish Short-Wavelength Gravitational Perturbations. *Geophys. Res. Lett.* **2020**, *47*, e2020GL089445. [CrossRef]
11. Han, S.C.; Ghobadi-Far, K.; Yeo, I.Y.; McCullough, C.M.; Lee, E.; Sauber, J. GRACE Follow-On revealed Bangladesh was flooded early in the 2020 monsoon season due to premature soil saturation. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2109086118. [CrossRef] [PubMed]
12. Han, S.C.; Yeo, I.Y.; Khaki, M.; McCullough, C.M.; Lee, E.; Sauber, J. Novel Along-Track Processing of GRACE Follow-On Laser Ranging Measurements Found Abrupt Water Storage Increase and Land Subsidence During the 2021 March Australian Flooding. *Earth Space Sci.* **2021**, *8*, e2021EA001941. [CrossRef] [PubMed]
13. Dobslaw, H.; Bergmann-Wolf, I.; Forootan, E.; Dahle, C.; Mayer-Gürr, T.; Kusche, J.; Flechtner, F. Modeling of present-day atmosphere and ocean non-tidal de-aliasing errors for future gravity mission simulations. *J. Geod.* **2016**, *90*, 423–436. [CrossRef]
14. Kang, K.; Bender, P.L. Improved Measurements of Short-Period Mass Variations with Future Earth Gravity Missions. *J. Geophys. Res. Solid Earth* **2021**, *126*, e2020JB020720. [CrossRef]
15. Christophe, B.; Foulon, B.; Liorzou, F.; Lebat, V.; Boulanger, D.; Huynh, P.A.; Zahzam, N.; Bidel, Y.; Bresson, A. Status of Development of the Future Accelerometers for Next Generation Gravity Missions. In *International Symposium on Advancing Geodesy in a Changing World*; Freymueller, J.T., Sánchez, L., Eds.; Springer Nature Switzerland AG: Cham, Switzerland, 2019; pp. 85–89.