National Aeronautics and Space Administration

New science capability in GRACE-like gravity missions with onboard gradiometers

Principal Investigator: Sheng-Wey Chiow (332); Co-Investigators: Nan Yu (332), Mitchell Rosen (University of Texas at Austin), Furun Wang (University of Texas at Austin), Srinivas Bettadpur (University of Texas at Austin)

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Objectives

Our objective was to develop the mathematical modeling framework and the measurement architecture necessary to exploit the extraordinary capability of cold atom technology for spaceborne gravity (and mass change) measurements with unprecedented resolution, accuracy, and flexibility. The Strategic Value of this research was to develop the roadmap for cold-atom technology capabilities to answer important climate science questions that are beyond today's gravity missions like GRACE, GOCE and GRACE Follow-On. Specific objectives included:

- Bound the architecture and performance trade-space for combined satellite-to-satellite tracking and cold-atom gradiometry scenario that address specific, critical science needs identified in community documents.
- Develop the right mix of global sampling and data analysis methods that provide desired spatio-temporal resolutions in presence of the long interrogation times of high-precision cold atom techniques.
- Develop a science measurement model, and related mathematical and estimation approaches for this blended architecture.

The results of this study would provide their Strategic Value by forming the basis for the eventual science traceability and requirements flowdown, and help assess the cost-benefits of development of such missions, and determine the value of their contributions to addressing tomorrow's climate science problems.

Background

Precision measurements of Earth's gravity field are critical to understanding our planet's mass transport and dynamic processes of the Earth system. The extended GRACE mission record has clearly demonstrated the value of such measurements. The next frontier in this field is to extend this understanding to the societal scales, which in the case of gravity measurements is enabled by greater accuracy, with its concomitant increase in spatial resolution. The UT collaborators have experience in high precision applications, and the JPL team is exploring new gravity measurement capabilities using quantum atomic sensors in the forms of accelerometry and gradiometry. A collaboration between the two institutes greatly strengthens our ability to enhance and improve future gravity measurement science and techniques guided by science applications.

Indeed, the previous SURP allowed the joint UT Austin and JPL study team to establish a one-of-a-kind analysis framework for use of a quantum gravity gradiometer (QGG). At the conclusion of that study, we discovered that a laser ranging interferometer (LRI)-equipped GRACE-FO mission coupled with a single-axis quantum gradiometer can dramatically improve the gravity science outcomes. The preliminary result indicated that addition of QGG data would provide an order of magnitude improvement of anticipated GRACE-FO gravity data.

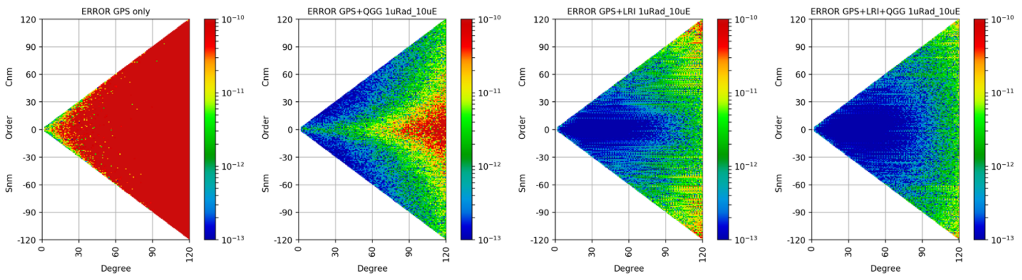

Figure 1. Gravity field recovery errors (for each degree and order spherical harmonic) predicted by a numerical simulation of contributions of measurement noise in the contributing observation-types. Blue/cold colors indicate very good quality of recovery, and red/hot colors indicate poor recovery. The middle-two panels show that the QGG (left) and the SST (right) are exactly complementary to each other in terms of the gravity mode to which the contribute the best. As a result, the total gravity field recovery (far right) is better than either alone.

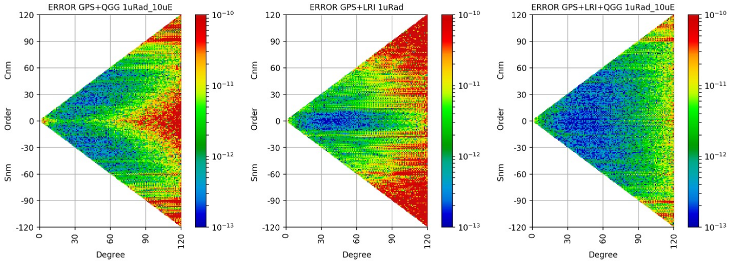

Figure 2. Same as Figure-1, but now the contributions from aliasing errors are included together with the contributions of instrument noise. The combination of LRI and QGG is better than either, and can resolve the limitations of the current mass change measurement capabilities.

Approach and Results

Through the work done in Year-2 (FY2021) of the effort, we were able to complete the assessment of the "points" in the design-space where the SST and the QGG provide the best blend of geodetic science outcomes in the presence of the principal limiting error sources. We were able to fully describe the root-causes of the gains from the hybrid SST and cross-track QGG configuration such that we obtained the principal benefits while not being constrained by the pointing error. In the process, graduate student Mitch Rosen successfully prepared and submitted his thesis on the way to obtaining an MS degree.

The approach continued with use of numerical simulations blended with analytical work. The numerical simulations were studied in two classes – the first included only the instrument measurement errors; and the second included both the numerical errors and the so-called "aliasing" errors. The latter are caused by the failure to adequately account for the rapid variability of the background gravity field model in the mass change estimation.

Figure-1 shows detailed view of the contribution from each observation type to the estimates of each degree and order harmonic coefficient of the gravity field, accounting for only the measurement noise. The simulation set-up is such that for each harmonic depicted in the image, small numbers (in cool/blue colors) indicate that the instrument errors had no impact on the gravity field estimate, and large numbers (hot/red colors) indicate a very poor recovery. From the left, we see that high-low GPS tracking is not sufficient to estimate any except the longest wavelength (continental-scale) modes of the gravity field. The second and third panels show that the SST contributes a strong determination of the low-degree and near zonal harmonics, but successively poor determination of the near-sectorials, the resonant harmonics, and the high-degree/order terms – all showing in yellow-orange-red colors. The parts in blue and green are the harmonic modes from which the GRACE and GRACE Follow-On science is being derived. The third panel shows that the cross-track QGG makes contributions that are exactly complementary to those of the LRI, being blue/green where the LRI shows yellow/red colors. This becomes of great significance when the aliasing errors are accounted for, as shown in **Figure-2**.

Significance/Benefits to JPL and NASA

The mass change measurements derived from data collected by GRACE and GRACE Follow-On are principally limited in their accuracy by the presence of "stripes" – north-south error artifacts that reflect the spatial counterpart of the error patterns in the middle panel of **Figure-2**. Numerous attempts have been made in the literature to remove this *post facto*, but all methods suffer from a simultaneous removal of the signals. These errors limit the full exploitation of future mass change measurement concepts. The hybrid SST+QGG concept studied here is shown to fix this problem at the source, without extraordinary pointing requirements. In this configuration, it is possible to now develop roadmaps for proper mix of of SST and QGG to obtain ever increasing accuracy in mass change measurements.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

PI/Task Mgr Contact
Email: Sheng-Wey.Chiow@jpl.nasa.gov

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