A preamble to the quantum sensor atomic interferometer gravity gradiometer technology white papers submitted to the MCDO study

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This preamble provides a brief overview of the quantum sensor gravity gradiometer technology white papers submitted to the MDCO study. These white papers, combined with performance simulations conducted as part of the study, represent a thorough evaluation of the technology in response to the 2017 ESAS Decadal Survey which notes: *"to make significant improvements that would advance studies of earthquakes, glacial isostatic adjustment, and glacier-scale processes would require constellations of gravity satellites, development of new gradiometer technology, or both."*, and notes: *"Achieving spatial scales of 100–200 km and an accuracy of <1 cm water equivalent RMS would require additional GRACE-FO satellite pairs and/or new technology such as an advanced gravity gradiometer."*

The two white papers provide the MCDO study with a comprehensive survey of the expected performance from quantum technology gravity gradiometers for future gravity missions. In addition, both document details concerning the state of laboratory prototype instruments, and an extensive engineering design of a flight instrument and technology demonstration mission. The two white papers should be viewed as congruent providing a complete assessment of the technology, its path to flight, and the expected performance from likely architectures. The white papers both:

a) show either a standalone or hybrid implementation demonstration mission would significantly improve the performance over the current SST/LRI GRACE-FO implementation.
b) indicate that a significant improvement in time variable gravity recovery from the implementation of a quantum sensor atomic interferometer gravity gradiometer,
c) demonstrate that current technology development makes it possible for a flight instrument within the decade,

Both white papers note the fact that full instrument sensitivity can only be validated in microgravity presents a significant challenge to the technology maturation, which could be through a flight technology demonstration mission as the next step.

(1) Luthcke, S.B., B. Saif, K. Fisher, L.R. Baird, B.D. Loomis, D. Everett, R. Banting, J. Piepmeier, M. Shappirio, D.D. Rowlands, ***Atomic Interferometer Gravity Gradiometer (AIGG) Instrument Technology Development Readiness, Flight Implementation, and Expected Performance***, NASA GSFC & AOSense Inc., Version 3.1, June 2021.

The manuscript describes the Atomic Interferometer Gravity Gradiometer (AIGG) instrument technology and summarizes the current state of a laboratory prototype AIGG instrument which achieved TRL-4 in the Fall of 2021. The manuscript also details the performance of an AIGG in several mission scenarios including a complete set of errors (e.g. instrument, orbit, attitude, atmosphere and ocean aliasing), and provides a summary of comprehensive engineering design and assessment through NASA GSFC Instrument Design Laboratory (IDL) and Mission Design Laboratory (MDL) studies. An Instrument Design Laboratory (IDL) study for a full sensitivity instrument is summarized providing design and implementation details, current TRL assessment, and remaining technical challenges.

The manuscript assumes that the AIGG instrument would initially be implemented as a technology demonstration and then could later be implemented in a full science mission to take advantage of the instrument's ultimate measurement performance. Therefore, the manuscript presents the AIGG's performance under both implementation scenarios. The technology demonstration instrument would have an interferometer length scale of 0.66 m and a sensitivity of 75 µE (per shot with a 20 second observation rate) capable of monthly gravity field recovery at the same performance as GRACE-FO but from a single satellite. The manuscript provides the engineering design and solution for beam alignment mechanisms to ensure closure of the interferometry and full performance compensating for launch alignment shifts, thermomechanical variations, translational and rotational motion. With the implementation of the beam alignment mechanisms the AIGG instrument can then be oriented in the radial direction and benefit from the significant improvement in performance. A summary of the Mission Design Laboratory (MDL) study for the technology demonstration mission is provided. The MDL engineering design and assessment provides a comprehensive analysis for a single satellite implementation whose data can be compared and validate to, and combined with, the data from an existing SST/LRI mission, or implementation on a planned existing gravity mission.

(2) Yu, Nan, S-w Chiow, S. Bettadpur, ***Mass Change Hybrid SST-QGG Technology Report,*** JPL & CSR Univ. Texas

The manuscript provides a brief summary of the state of the art in Quantum Gravity Gradiometer (QGG) using laser cooled ultra-cold atoms as ideal test masses and the quantum matter-wave property for atom interferometer (AI) displacement measurements congruent with the AIGG technology noted in the manuscript above. It provides instrument noise performance as well as attitude and alignment control assessments for a full sensitivity 10 µE instrument as well as the gravity recovery performance in a hybrid configuration combining the GRACE-FO SST measurements from a Laser Ranging Interferometer (LRI) with the gradiometer observations in a hybrid observing scenario. The hybrid scenario is targeted for several reasons, including its ability to combine the benefits of SST and gradiometry techniques, its potential for long mission durations at the typical SST mission altitudes, and for mitigation of stringent attitude control and determination requirements for gradiometers with such high precisions. The manuscript also provides a preliminary implementation description and performance assessment of a hybrid architecture, and demonstrates the significant improved time variable gravity recovery from the combined QGG gradiometer observations with the SST LRI observations. Preliminary spacecraft accommodation considerations are discussed for a hybrid implementation, as well as atom interferometer instrument considerations. A preliminary hybrid demonstration instrument is discussed with initial instrument design parameters. In addition, the manuscript identifies the technology gaps and their impact to the eventual full system realization. A technology roadmap

and maturation plan with component TRL assessment and new technologies are presented. Overall, it offers the hybrid architecture with a realistic QGG infusion plan into the upcoming MC mission with science gains while demonstrating the QGG concept for future MC missions.