GRAIL AT MERCURY: COHERENT LASER TRACKING FOR GEOPHYSICS.

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Introduction: Knowledge of the interior structure of planets is important to study the formation and evolution of the solar system, and recent developments in SmallSat technology are opening up opportunities to study various planetary bodies. While the GRAIL mission [1], a unique planetary mission dedicated to gravity, was very successful and revolutionized lunar science, it cannot easily be replicated at other bodies due to size, mass, and cost. Recent development in photonics and optometrics enable new approaches for more compact satellite-to-satellite tracking, such as the Compact Coherent Laser Ranging (CCLR) technology we have studied. This would enable high-accuracy gravity mapping with SmallSats at other planetary bodies, in particular the planet Mercury.

Mercury plays a key role as an end member of terrestrial planet formation which was emphasized in the NRC Planetary Science Decadal Survey [2]. Indeed, although the gravity field of Mercury was observed from radio tracking of the MESSENGER spacecraft during its orbital mission between 2011 and 2015 [3-5], the low spatial resolution is not sufficient to answer many key questions about the planet's thermal and tectonic history, the impact formation processes, and the state of the crust. The joint ESA-JAXA BepiColombo mission, launched in 2018 and scheduled to arrive at Mercury in 2025, will strive to address these. However, measurements that would significantly improve gravity field resolution will not be possible with BepiColombo [6].

Optical Tracking: Satellite-to-satellite tracking (SST) gravity missions such as GRACE on Earth and GRAIL at the Moon (Figure 1) can also be performed at *optical wavelengths*, with better precision. This was demonstrated by the GRACE Follow-On mission. Further leveraging optical telecom advances, significantly smaller resources are required and can enable SmallSat mission concepts [7]. As demonstrated at Earth and the Moon, SST can provide global, near-uniform coverage, well suited to further geophysical and geological studies, and our compact innovative technology will enable such a mission to be undertaken at Mercury, and beyond.

Objectives: More accurate gravity data are needed to advance our understanding of Mercury's internal structure on a par with the Moon after GRAIL, and thus better gauge the influence of key parameters in planetary evolution. As such, our science objectives, enabled by CCLR, are to: (1) Determine the thermal evolution of Mercury's lithosphere and crust; (2) Understand impact formation and subsequent modification; (3) Characterize the deep interior.

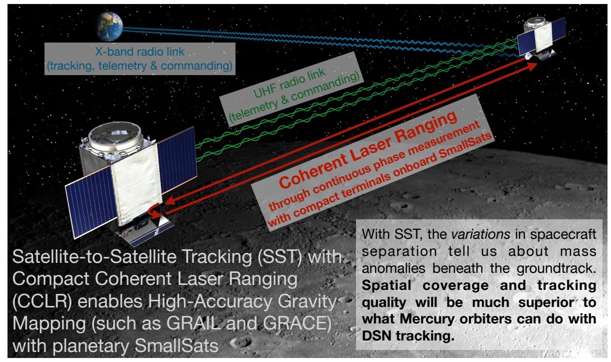

***Fig. 1.** Illustration of SST measurement concept.*

Mission Concept: Two SmallSat will be placed in a stable 200-km orbit. The master spacecraft will be tracked from Earth and CCLR terminals onboard each will provide the science measurements. To achieve these goals, a range-rate accuracy of 0.03 µm/s is required (Fig. 2).

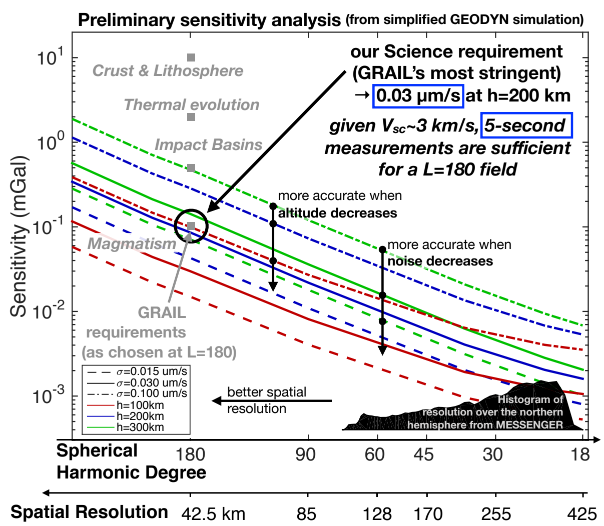

***Fig. 2.** Simulated gravity recovery vs resolution.*

Challenges: In addition to the technological development required to fully miniaturize SST optical tracking, a SmallSat pair mission to Mercury presents challenges. Foremost is the thermal environment; in Mercury orbit, the solar radiation is an order of magnitude greater than in Earth orbit, and spacecraft experience extreme temperatures. MESSENGER used a solar shield covered in heat-resistant ceramic cloth, but the reflected and thermal radiation from the Mercury surface are also strong contributors to the spacecraft thermal balance. A related challenge is the pointing control and stability in the presence of strong thermal changes over the orbital timescale. The pointing requirements to conduct SST optical tracking are more stringent than at radio wavelengths.

Another challenge is propulsion, as entering Mercury's orbit requires a large ΔV capability. The use of multiple gravity assists were enabling to the MESSENGER (with a ΔV~2.3 km/s [8]) and Bepi-Colombo missions, at the cost of a longer cruise phase. MESSENGER also did some "solar sailing" while in cruise, which saved precious ΔV and benefited its extended mission.

Summary: Some important questions are left unanswered after MESSENGER, and new ones are raised given our deeper knowledge of Mercury. Better gravity is a critical dataset for such future studies, and CCLR is an optical SST transponder technology that will allow SmallSats to execute such a mission at lower cost.

References: [1] Zuber et al. (2012), *SSR*, 178. [2] Squyres et al. (2011), NRC. [3] Smith et al. (2012), *Science*, 335. [4] Mazarico et al. (2014), *JGR*, 119. [5] Verma and Margot (2016), *JGR*, 121. [6] Iess et al. (2009), *Acta Astron.*, 65. [7] Yang et al. (2016), 2016 IEEE Aerospace Conference. [8] Santo et al. (2001), Planet. Sp. Sci., 49.