Orbiting laser interferometer to measure Earth’s gravity

Robert Spero

The GRACE Follow-on mission will use laser measurements of the distance between a pair of orbiting spacecraft to make gravity maps of Earth.

Researchers working in a NASA/German partnership are preparing for the 2017 launch of the first inter-spacecraft laser interferometer. The interferometer will be used on the GRACE Follow-on mission to measure variations in Earth’s gravity with unprecedented detail. The mission is patterned after the original GRACE (Gravity Recovery and Climate Experiment), which was launched in 2002 and is expected to operate for a few more years. Both GRACE and its follow-on use phase-sensitive microwave transponders as their primary instruments to continuously monitor the separation between a pair of identical satellites in low earth orbit (see Figure 1). The only change for Follow-on is the addition of the laser interferometer, which will make the same measurement as the microwave system but with at least 20 times better accuracy. The laser instrument is a technology demonstrator, meant to pave the way for future gravity missions that rely exclusively on lasers.

Measuring gravity by monitoring the separation between a pair of orbiting satellites is the invention of physicist Milo Wolff. Over 40 years ago, Wolff suggested using either microwaves or newly invented lasers. He proposed that the same technique could also be applied to the moon, other planets, and even their satellites. Wolff’s bold proposal is finally taking off: the GRAIL (Gravity Recovery and Interior Laboratory) mission, using instrumentation derived from GRACE, is now making gravity maps of the moon.

In a recent interview, Wolff cited generous funding, the excitement of the Apollo era, and a famous science fiction author as inspiration. “There were many mission projects underway at [the Massachusetts Institute of Technology], and new ideas were encouraged because the government was paying for them. Everyone was excited,” Wolff said. He identified safety concerns for astronauts walking and driving on the moon as motivation for measuring the moon’s gravity, and mineral exploration for measuring Earth’s. As it turned out, the priceless data returned by GRACE is associated with water, not gold or platinum.

The satellites’ precessing polar orbits cover the entire earth in one month. The average separation of 200km between the satellites changes with variations in the gravity field, which in turn are generated by features such as mountains, lakes, and glaciers below. Most of the gravity is static, giving a still portrait of Earth (see Figure 2). Time-varying gravity is revealed by high-precision measurements, brought to life by time-lapse movies. The gravity of Earth appears to breathe in and out over the years, mostly in response to the ebb and flow of water. GRACE has monitored the large-scale movement of water and ice, tracked the levels of rivers, lakes, and underground reservoirs, and verified groundwater depletion in India as well as drought in Australia and the United States. It has also measured the melting of polar ice and the resulting increase in sea level.

While Wolff was thinking about satellites and gravity, he was living in Sri Lanka and working with Arthur C. Clarke to establish that country’s first science education faculty. They collaborated on a technical paper, in what must have been an intellectually expanding experience for both the science fiction writer and the physicist.

Wolff recalls comparing microwave and laser measurements: “At that time, Doppler laser was a new technology, so this was a useful experimental technique to try it out. Combining it with microwave Doppler acted to confirm the data.” In the
intervening decades, laser metrology has surpassed microwave metrology. Since the laser wavelength of 1 micron is smaller than the 1cm microwave wavelength by a factor of $10^4$, lasers provide inherently greater sensitivity for a given detected power, and higher detected power because the beams are much narrower. The optical and electronic techniques needed for laser measurements are under development at the Jet Propulsion Laboratory and the Max Planck Institute for Gravitational Physics (MPI).

Figure 3 shows an overview of the optical design under development in Germany at MPI and SpaceTech GmbH Immenstaad. The lasers on satellites S and P are nonplanar ring oscillators, manufactured by the Tesat-Spacecom. Heterodyne measurements at both satellites use a strong (approximately 1mW) local oscillator that is derived from the fraction of laser light that leaks through the beam splitter onto the photodetector. The local oscillator effectively amplifies the weak (approximately 100pW) incoming light from the distant spacecraft when the two beams interfere. The heterodyne frequency is typically 10MHz, with a fluctuation of several megahertz from relative velocity fluctuations. The laser on satellite S is stabilized by Pound-Drever-Hall locking to a thermally isolated Fabry-Perot reference cavity, 7cm in length (not shown). The resulting frequency noise will be approximately 30Hz/$\sqrt{\text{Hz}}$ in the 10–100MHz signal band. Frequency noise is the strongest contributor to the distance measurement error budget, which totals approximately 100nm/$\sqrt{\text{Hz}}$. The laser at satellite P is phase-locked to the incoming light, with a fixed offset frequency of several megahertz. The round-trip distance measurement is contained in the phase of the heterodyne signal measured at S.

Since fluctuations in spacecraft orientation are larger than the beam divergence, a high-speed mirror is needed to keep the beam from each spacecraft centered on its partner. The error sensor for the beam-steering control system is a two-axis differential wavefront measurement system. The heterodyne signal is split on the detector into four spatial quadrants, and the phase difference between quadrants provides high-accuracy tracking of misalignments. The steering mirrors will also be used during initial acquisition, when each spacecraft’s laser beam hunts for the alignment that finds the other.

Because the laser’s role as technology demonstrator is secondary to the microwave system, the prime real estate along the spacecraft centerline is occupied by the microwave apparatus. The laser beams, therefore, make a circuit around the center by reflecting off a set of three mirrors. These mirrors form a virtual corner cube, making the measurement equivalent to what would be attained with centered beams. The virtual corner cube is under development at The Australian National University.

The system will be tested after the lasers are turned on in orbit, and new, more detailed maps of Earth’s gravity begin to be generated. We have gone a long way toward realizing Wolff’s
vision. Asked if he had foreseen how his idea would play out, Wolff said, “The future is always more exciting than the past, as science fiction writers know.”

The laser ranging instrument development at the Jet Propulsion Laboratory, California Institute of Technology, is the work of a group consisting of Glenn de Vine, Kirck McKenzie, William Klipstein, Brent Ware, and the author, and is performed under contract with NASA. The author thanks Patricia O’Sullivan for helpful comments.

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Robert Spero serves as technologist for GRACE Follow-on’s Laser Ranging Interferometer.

References