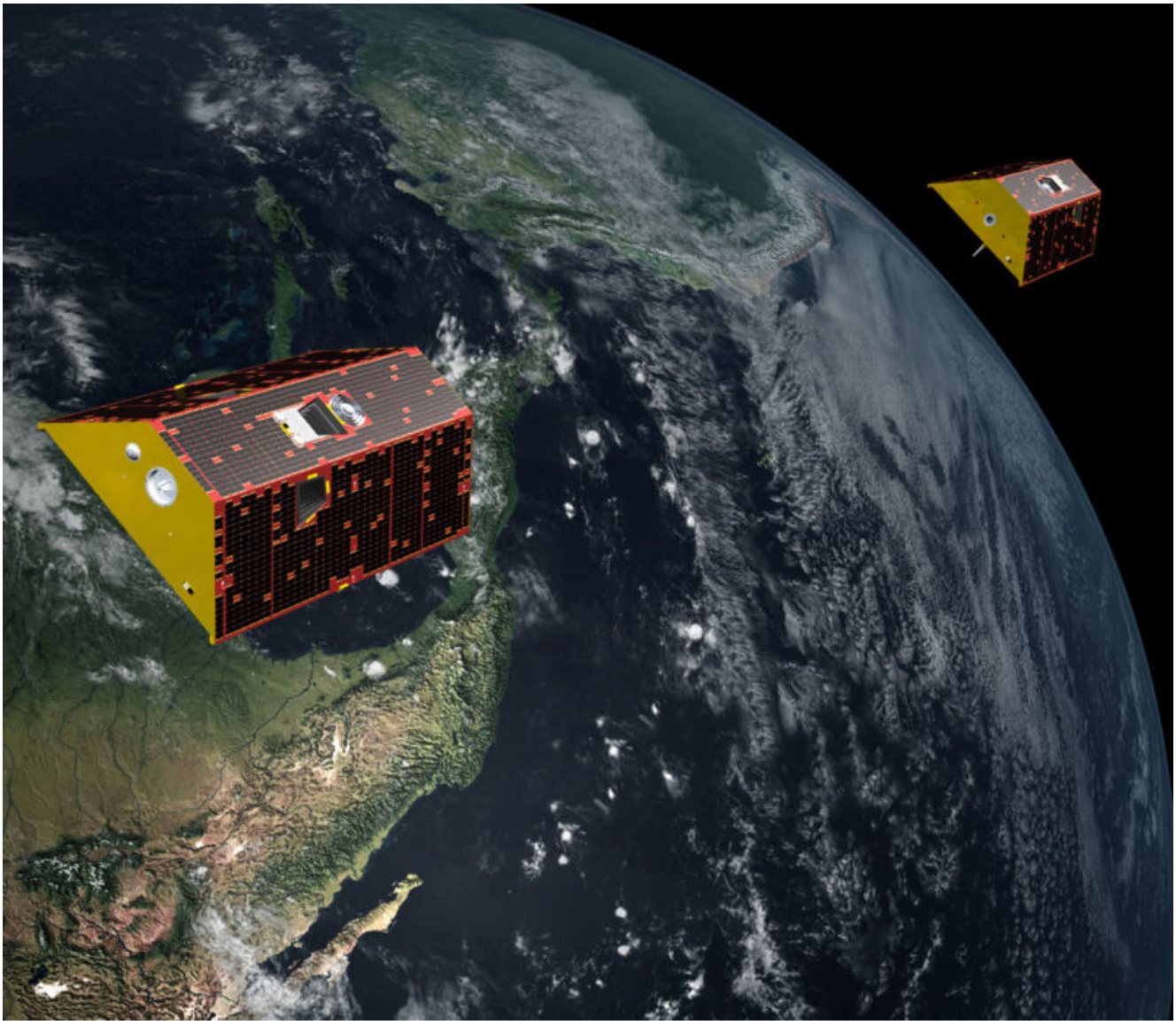
Satellites play chase to measure gravity, achieve picometer accuracy



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The spinoffs from gravitational wave detectors are not just new scientific discoveries. The technology also has other uses. A good example of this is the gravity-measuring mission,

GRACE Follow On, which was launched last year. The first reports on its laser rangefinder's performance have been released, and it makes for impressive reading.

Gravitational wave detectors work by measuring tiny changes in the distance between two mirrors. Ripples in space-time cause a tiny oscillation in that distance, which is then detected by comparing the phase shift between light that has traveled between the two mirrors and light that has traveled along a path that was unaffected by the gravitational wave. To put it in perspective, a gravitational wave detector measures changes that are far smaller than the diameter of an atom and are more like the diameter of a single proton.

The gravity of GRACE

Similar technology found its way into space to increase the sensitivity of Earth-monitoring instruments. On Earth, we have stationary detectors that wait for gravitational waves to pass through them. In orbit, the detector is moving and can measure subtle changes in the Earth's gravitational field.

That brings us to GRACE—a backronym for gravity recovery and climate experiment—a pair of satellites that orbited the Earth at a fixed distance from each other. Or they would be fixed if the Earth's gravity didn't change in time and space. GRACE used a radar system to measure the distance between the two satellites to track those changes, providing information about the gravitational field it was traveling through.

Changes in that distance could be translated into local measurements of the acceleration due to gravity. This, in turn, is used to measure things like the volume of water in aquifers.

GRACE turned out to be hugely useful but, like all satellite missions, eventually died. In this case, the battery on GRACE-2 failed, and the pair was cremated in the Earth's

atmosphere. The follow-up to GRACE, called GRACE-FO (follow on), was launched in 2018.

GRACE-FO is mostly a copy of GRACE, but scientists took the opportunity to include a new distance-measuring tool that would outperform the old GRACE radar system. This, if successful, would mean that the measurement data would not put a limit on how we interpreted the data. Instead, models of the tides would need to be improved.

It also just happens that the technology required to do this sort of station-keeping measurement is exactly the technology required for LISA (a proposed space-based gravitational wave observatory). The LISA pathfinder mission was hugely successful but, being a single satellite, could not test station-keeping technologies. So, in many ways, the GRACE-FO satellites are also a lightweight LISA pathfinder mission.

Smooth running

Since June 14, when contact was established with the satellites, scientists have been testing the laser range-finder system. And, to put it simply, it absolutely smashes the design specifications. Over a time period between 5 and 1,000 seconds, the system should be able to detect distance changes of 2 to 40 billionths of a meter between two satellites that are separated by 220km. However, the team reports sensitivity as low as *300 trillionths of a meter*. To put this in perspective, the radar system on the original GRACE was sensitive to changes at about the 10 micrometer level.

How do you achieve this sort of accuracy? In short, with lasers. More seriously, a laser beam on the master satellite is stabilized to have a very precise frequency. That laser is shot at the slave satellite. This in itself is an achievement because the laser has to be continuously aimed in the right direction (the radar system manages this with a fixed

antenna). The slave satellite uses the incoming light (all 25nW of it) to do two things. First it uses a tiny amount to check that the laser is pointing in the right direction. The remainder of the light is used to set the phase of its own laser, which is sent back to the master satellite—the received laser light is too weak to just be reflected back.

The light that is received at the master acquires a phase shift relative to the transmitted light that is proportional to the distance between the two satellites. Since the distance is continuously changing, this is measured as an additional frequency in the received laser spectrum. Hence, a frequency measurement of the incoming laser spectrum becomes a measurement of distance, which, in turn, becomes a measurement of acceleration due to gravity.

In the short term, this means that GRACE-FO data will be even better than expected, and the modelers are going to have to get back to work. In the long term, it means that more of the technology for LISA will be validated with the additional benefit of a long-term robustness study. In the very short term, it gave me some good weekend reading.

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