Aviation Week & Space Technology

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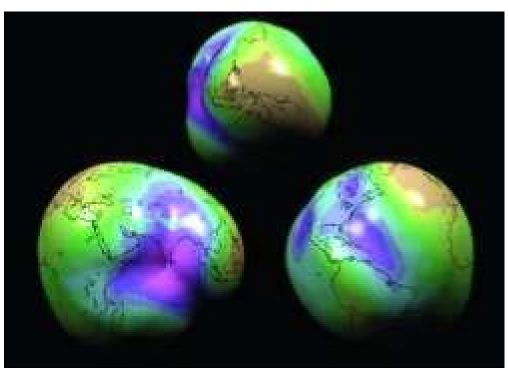
Orbiting Gravity Mappers Might Spot Oil Fields

FRANK MORRING, JR./WASHINGTON

New technologies for measuring changes in Earth's density could enable remote sensing of the interior

Oil companies as well as scientists will be watching the performance of a pair of research satellites set for launch this month that are designed to generate the most accurate Earth-gravity maps ever, tools that could help geologists target underground oil fields from space and Earth scientists gauge the impact on the planet's climate of burning that oil.

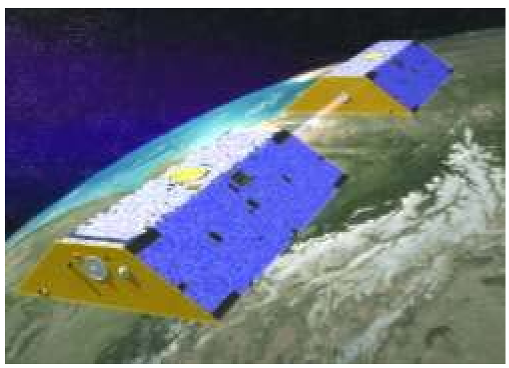


These whole-Earth gravity maps were produced by compiling ground-tracking data on 30 satellites. Measurements from orbit should dramatically improve accuracy.

Jointly funded by NASA and the German Aerospace Research Center (DLR), the $145-million Gravity Recovery And Climate Experiment (Grace) will primarily aid oceanographers studying the huge sea currents that shape Earth's climate. But the anticipated order-of-magnitude improvement in sensitivity that Grace is expected to provide may be enough to enhance the gravity measurements geologists already use in the search for oil.

Even if it turns out that the gravity signatures of oil and other subterranean minerals elude Grace, scientists at NASA's Jet Propulsion Laboratory (JPL) believe they could push well beyond that level of sensitivity with a demonstration of gravity-mapping technology based on quantum physics within five years. Quantum sensors would be a million times more sensitive than today's hardware, essentially rendering the Earth's surface transparent and producing detailed three-dimensional maps of its underground structure.

"That would be truly revolutionary," said Ghassem Asrar, NASA's associate administrator for Earth science. "For the first time we would be able to remotely sense the interior of the Earth, or some parts of the interior of the Earth, and say something about the properties of the target area, which directly relates to prospecting and determining what kinds of materials you have that are exerting this type of gravity effect."



U.S./German Grace system will use microwaves to measure the distance between two satellites, which will change with the density of the Earth below.

Eurockot is scheduled to launch the two identical Grace spacecraft together on Mar. 15 from the Plesetsk Cosmodrome in northern Russia. The Russo-European consortium will use its Rockot vehicle, a Russian SS-19 ICBM modified with a Breeze upper stage, for the launch. The twin satellites--each weighing 950 lb.--will be deployed to fly in formation, with one about 200 mi. in front of the other. As they move around the Earth in their circular 311-mi.-high orbits, inclined 89 deg. to the Equator, the distance between them will be measured continually with highly accurate K-band and K_a-band range finders. Changes in that distance will reflect changes in the gravity levels the two spacecraft encounter.

"The Earth's mass distribution is not homogeneous," said Byron Tapley, principal investigator on the Grace mission and director of the Center for Space Research at the University of Texas. "You can think of it as there being a blob here and a blob there. There are variations in the density of the Earth. These mass blobs, or mass density variations, attract the satellites differently. Coming across a point on the ground, the first satellite feels the mass blob earlier than the second satellite. It speeds up as a consequence of the attraction of this mass blob. It moves on past the mass blob and then the attraction is in the opposite direction, and as a consequence it slows down from that point on, and the satellite behind speeds up in response to it."

The Grace satellites will continually measure the distance that separates them with a precision of 10 microns or better. From that, analysts can extract the fluctuations in gravity as the satellites move around the Earth. Onboard Global Positioning System receivers will pinpoint locations for gravity mapping.

Over its five-year mission life, Grace will give researchers their best figures yet for the gravity field at any given point on the Earth's surface, averaging the satellites' repeated measurements to give a "static" map for scientists to use. But the sensitivity of the system will also allow the closest tracking yet of fluctuations of gravity over time, as the movement of water, magma and perhaps other liquids change the mass density of the planet at given locations.

"UP THROUGH the middle of the 1990s decade, we viewed gravity as effectively a static quantity, so that we measured one time, and then we're done," said Tapley, who holds the Clare Cokrell Williams chair in aerospace engineering at Texas. "This mean gravity field is the dominant signal, and it's orders of magnitude larger than a time-varying component that we've been seeing for a number of years. It's associated with the mass transport in the Earth's dynamical system--water leaving the atmosphere, going onto the land, being deposited as snow, going into the underground aquifers, running off or being impounded in lakes."

Grace was designed to track those temporal changes in gravity fields, particularly the seasonal changes associated with the movement of water. Tapley said researchers believe they will be able to use the temporal Grace data to infer the amount of water in large river basins.

"If we get the full level of performance on orbit that we expect to get, then we should be able to see these changes, and be able to correlate them with local measurements in aquifer levels around something the size of the Mississippi Basin in North America," he said. "By making a few measurements there, one would be able to interpret the signal that one would get from Grace and get a handle on what the amount of water that is actually stored in the aquifer would be."

Tapley said Grace is expected to be able to resolve the gravity impact from a disc of material or liquid 1-cm. (0.3937-in.) thick and about 300 km. (186 mi.) across. Its orbit will produce a new map of the whole Earth surface every 30 days, for a total of 60 mappings over the five-year service life. The static gravity "mean field" will be the average of those maps, while the temporal measurements most likely will be reported as seasonal variations from that average. With that information, oceanographers and Earth scientists will be able to refine what has been learned from a variety of other operating or planned spacecraft, particularly the Topex-Poseidon/Jason data set on ocean height.

Radar altimeters on the Topex-Poseidon spacecraft and its successor, Jason-1, have given oceanographers a relative view of the irregular shape of the ocean surface as massive currents move beneath it. But while they can spot and track currents that swell the surface, the altimeter data alone do not reveal just how much water is moving in the currents. By adding in the Grace gravity data, researchers will be able to calculate the size of deep-ocean currents and the amount of heat they carry, since both heat and gravity contribute to the sea-surface height.

"The ocean currents are important because they're the vehicle that moves heat from the Equator to the northern latitudes and makes the place we live a much more temperate environment than it would be otherwise," Tapley said. "Understanding this is very important in understanding global climate change."

Similarly, incorporating gravity data will enable researchers to calculate long-term changes in sea level and--combined with polar-ice altimetry from the upcoming Ice, Cloud, and Land Elevation Satellite (ICESat) mission--changes in the thickness of the polar ice sheets. After oceanography and global climate change studies, Tapley said "the next big push" with Grace data will be in solid-Earth science.

"In trying to understand the internal structure of the Earth, the mass variations inside the Earth have a lot to say about the circulation patterns of the mass going on inside, the way the continents move, the way the continental plates hit one another and dive down or go underneath," he said. "There's a gravitational signal associated with all this activity."

OIL GEOLOGISTS also use gravity measurements made at the surface in connection with seismic data to locate underground oil deposits. Just as a more accurate worldwide gravity map will help scientists studying the effects of human activities like burning fossil fuels on the ice sheets and mean sea level, it could help geologists find more oil to burn.

"All of those surface gravity measurements are essentially, to some extent, limited by the very long wavelength components of this mean gravity field," Tapley said. "You need to know where you are, and you need to remove that mean gravity field properly to be able to fully interpret the high-resolution data, so it's clear that we will bring a great deal to the table by using this extremely accurate long-wavelength gravity field that will come out of Grace."

The work of Tapley and his team drew interest from the oil exploration industry in the mid-1990s, when the team was formulating its proposal. "In the earlier processes of the proposal stage, we got an indication from a couple of the oil companies indicating that they would view this particular data as being extremely important in the exploration-related areas," Tapley said. But ultimately the companies decided not to invest in the work, considering the possibility of a payoff as too slim.

"I suspect that if we go out and prove it properly, it's possible that there may be someone coming in later on to pick up and partner with the government to try to develop it," Tapley said. "A number of these techniques, once they get to the point where the government has demonstrated them, at least in the remote sensing community, then we've had private enterprise coming in and picking up the technology that's been developed and spinning it off and putting it into a commercial product."

Also on the drawing board is a Grace follow-on that uses laser range-finding between satellites to shrink the system's gravity resolution from hundreds of kilometers to tens of kilometers, according to Michael Watkins, Grace project scientist at JPL. With lasers, the distance between satellites could be measured in nanometers rather than microns, he said.

But sensitive as they are, the K-band microwave-based distance measurements that will generate the Grace gravity database and the laser measurements of its potential follow-on pale in comparison with the atomic-level sensitivity researchers at JPL hope to achieve by applying quantum physics to the task. By using laser cooling to slow the motion of cesium atoms, the atoms themselves can be used in place of light for extremely precise interferometric measurements of the pull of gravity on the atoms.

"If we could laser cool the atoms, then we could use the atom waves instead of light waves in realizing an interferometer to measure very precise phases," said Lute Maleki, a senior research scientist at JPL who runs the lab's quantum sciences and technology group. "And since atoms have mass, they couple to gravity fields, and so you can measure precise influence of the gravity field on the atoms by looking at any kind of a phase shift in these atom waves."

LASER COOLING SLOWS the atoms to the point that their wavelength is comparable to that of light, and so may be manipulated with pulses of light to make an interferometer that is extremely sensitive to changes in the gravity field as the interferometer moves across it. Unlike a conventional gravity gradiometer, which uses accelerometers to measure the acceleration of falling weights, a quantum gravity gradiometer would use the interferometers to measure changes in gravity.

"The atoms are the proof mass that's falling, and we measure the influence of gravity on them by looking at the influence of gravity on the phase of this atomic wave," Maleki said. "Each one of the interferometers is an accelerometer, and then two of them would make a one-axis gravity gradiometer. In order to make a 3-D measurement, you need to have a pair of these on all three axes."

Potentially, a quantum gravity gradiometer would be a million times more sensitive than the gravity gradiometers currently used in oil exploration. Applied in connection with topographical and other data, it may be possible to map underground structures much as the Grace data will be used with satellite-derived ocean-height data to map deep-sea currents.

NASA IS SPENDING about $400,000 a year on the three-year Quantum Gravity Gradiometer Project at JPL. The principle has already been demonstrated in the laboratory, according to Maleki, and work is underway on a laboratory prototype for space use. The Pasadena, Calif.-based facility plans to seek funding for a flight demonstration on a space shuttle or high-flying aircraft, a step Maleki said would take about five years to prepare.

"We want to be doing this from space, so that you can fly this, and then map under the surface from space," he said. "Because this is a reference to an atom . . . it has very high accuracy, and it will be a particularly useful technique for looking at things which are dynamic and changing. You can look at it at some point and come back and look at it a half a year later, or whatever, and see how it has changed."

Although its promise for Earth science is undisputed, space-based gravity mapping ultimately may yield to airborne gravity mappers in the search for oil and other minerals. Lockheed Martin has adapted gravity gradiometers originally developed as navigation devices for Trident nuclear submarines to help prospectors pinpoint mineral deposits from the air. One company--Australia's BHP Billiton--is already flying its "Falcon" system under a 10-year license for Lockheed Martin hardware on Cessna Grand Caravans. The company, which has been working on an airborne gravity gradiometer since 1993, has found the technique useful to varying degrees in finding nickel, copper, zinc, manganese and even diamonds and gold.

Bell Geospace Inc. of Houston has used a ship-mounted three-axis Lockheed Martin gradiometer to map the salt domes associated with oil and gas deposits, and is preparing an airborne version of its own. Test surveys using the airborne system are scheduled this spring, beginning over well-defined salt domes along the U.S. Gulf Coast and extending to other known sites elsewhere in the U.S. that will be picked to test the system's resolution.

The systems used by the two companies weigh on the order of 1,000 lb. and cost "a few million dollars" each. Their range is limited, forcing pilots to fly as low as safely possible to get the best readout with their mechanical accelerometers, using laser altimeters to give the necessary terrain information. A Lockheed Martin source said the company hopes to lower the cost of its equipment by making them digital, but conceded their range makes them useless for space applications.

"It won't tell you a whole lot when you're that far away," the source said, asking not to be otherwise identified. "The farther away you get from the target, you get to the point where the noise is greater than the signal."

Rice University researcher Manik Talwani plans to test the Australian Falcon gear in Southern California at the end of this month over a 10-km. square along the San Andreas Fault in an experiment supported by the National Science Foundation and several oil companies.

"There is a drill site there that the academic people want to drill," he said. "We have just got money to make a survey over the drill site to find out ahead of drilling what's down there."

TALWANI, an expert in oil exploration who holds the Schlumberger Chair for Advanced Studies and Research at Rice, said "there is an important commercial and potential use" for the Lockheed Martin gravity gradiometer, noting that the device may also be useful in detecting the motion of underground magma for predicting volcanic eruptions in populated areas.

On the other hand, Talwani said, space-based gravity mapping may not have the ideal resolution for oil exploration. The Grace measurements probably won't be sensitive enough, while quantum-based mapping may be too sensitive, he said.

"It might seem counterintuitive, but in terms of accuracy for determining minerals and so on, we might need a factor of 10 beyond what the Lockheed Martin gradiometer does," he said. "If you think of two sensors, 50 cm. apart, basically we are talking about one trillionth of the force of gravity is the difference between these two instruments that the Lockheed gradiometer can detect. So if the JPL instrument wants to detect something which is one millionth of one trillionth, it sounds very good, but I think the utility of this thing for exploration purposes stops far before you go to a millionth."