State of GRACE

Decoding Satellite Measurements of the Earth's Mass Distribution

On the most prosaic level, the Gravity Recovery and Climate Experiment (GRACE) is an orbiting satellite system whose scientific team produces a unique data product: a monthly map of the planet's gravity field. The hidden poetry behind the prose is this: GRACE lets us watch the Earth breathe.

GRACE's first static gravity field map, calculated at the Texas Advanced Computing Center (TACC), is two orders of magnitude more accurate than the best previous maps. Because of this unprecedented accuracy, GRACE is able to observe, for the first time, changes in the Earth's large-scale ocean currents, polar ice masses, and the masses of water in large river basins and underground aquifers. GRACE-derived models and measurements are yielding new insights into everything from deep ocean currents, ocean bottom pressure, and sea-level rise to soil moisture, groundwater transport, and crustal structure.

The results are most exciting and heartwarming for Dr. Byron Tapley, professor of aerospace engineering at The University of Texas at Austin, director of the university's Center for Space Research (CSR), who is NASA's principal investigator for the GRACE mission. "The data from GRACE, analyzed on the supercomputers at TACC, are helping to lead the geophysical research community to new realizations about the drivers of climate change," Tapley says.

"The major realization that we've come to," Tapley says, "is that mass transport among and between the oceans, atmosphere, and solid earth has a very discernible signal. Rather than being simply a gravity mission, obtaining the best static gravitational field, GRACE is also, and more importantly, a mass-monitoring mission."

The GRACE Mission

The Gravity Recovery and Climate Experiment (GRACE) is the first mission in NASA's Earth System Science Pathfinder project, which uses satellite-borne instrumentation to aid research on global climate change.

GRACE is an international project, a partnership between NASA and the Deutsches Zentrum Für Luft und Raumfahrt (DLR) in Germany. Dr. Byron Tapley of The University of Texas Center for Space Research (CSR) is the principal investigator, and Professor Christoph Reigber of the GeoForschungsZentrum in Potsdam is the co-principal investigator.

The twin GRACE satellites were launched on March 17, 2002, into coplanar, circular, polar orbits (inclined at 89 degrees) at an initial height of 500 kilometers. The satellites themselves comprise the "instrumentation"; additional instruments aboard the satellites (accelerometers, GPS receivers, and star cameras) measure the nongravitational effects (e.g., atmospheric drag) and obtain accurate orbital positioning and spacecraft orientation information.
The main data come from the K-band microwave intersatellite ranging system. The two spacecraft experience the Earth's gravity field at different positions, so they differentially accelerate or slow down as they pass over the Earth's massive mountain ranges or deep ocean trenches.

The ranging system precisely measures the distance changes between the twin satellites with time. These measurements, combined with other known measurements and models in a complex chain of data processing (for which the most computationally intensive processing is carried out at TACC), yield a map of the Earth's gravity field.

Static Gravity Field

The most notable early triumph of the GRACE mission was the publication by CSR of a new and much more accurate representation of the geoid, the gravity-determined absolute sea-level surface, which is the surface to which the oceans would go if all other influences (tides, currents, and wind effects) were absent. The deviation of the ocean surface from the geoid, caused by the currents, is called the ocean dynamic topography. An accurate geoid permits a globally accurate determination of ocean currents.

Thought of another way, the geoid is a surface along which the gravity potential is everywhere equal and to which the direction of gravity is always perpendicular. Owing to the uneven distribution of mass in the planet, the geoid is not a uniform surface like the surface of a sphere. The Earth is not exactly a sphere, either. It is oblate, flattened at the poles and bulging at the equator, and its crust contains irregularities like Mount Everest (+8,850 m) and the Marianas Trench (-10,911 m). Geophysicists measure the "height" or "depth" of such features from an ellipsoid of revolution, rotating with the Earth about its axis and centered at the Earth's center of mass. The geoid undulates about this ellipsoid a bit--the most extreme excursions are to 90 meters above or 105 meters below the ellipsoid. The ellipsoid is the same reference surface to which height measurements, such as those from the Global Positioning System, are usually referred.

CSR was ideally placed to lead the GRACE mission, Tapley notes. "The Center's primary focus has long been on using satellite assets to study the Earth," he says. "Our staff, faculty, and graduate students are interested in earth science disciplines from climatology to oceanography, from land use to hydrology--but our central strength has been in space geodesy, the exact measurement of the Earth from space."

Accuracy and precision are the name of the game here. "It was a big push to get down to centimeter accuracy in the geoid for a long time," Tapley says, "and now we've reached the millimeter level--and there are good reasons to go below that if we can do it. A precision gravity signal gives us the information to make all kinds of geophysical models much more accurate and give them greater predictive power."

Dynamic Mass Monitoring

The mass of the Earth is a constant (approximately 6 X 1024 kg), but the distribution of mass on the Earth's surface changes on a variety of time scales. The most obvious changes are the large-scale ocean tides raised by the combined forces of the Moon and Sun; since these are regular and predictable, they are easily accounted for. Much smaller changes in the Earth's gravity field are caused by mass and energy exchange among the air and water components. GRACE advances our knowledge of these (the Earth's "breathing exercises").

The large-scale circulation of the oceans can be known much more accurately using GRACE measurements. Dr. Srinivas Bettadpur of CSR is Science Operations Manager for GRACE. He notes that many satellite missions--most recently the very successful TOPEX/POSEIDON (T/P) satellite--have used microwave altimetry to obtain mean sea surface heights around the globe to an accuracy of about 2 centimeters. "But these must be combined with a precise geoid to compute the absolute dynamic topography, and hence the total currents, of the world's oceans," Bettadpur says.

Global hydrographic mapping has long delineated the major ocean currents, but the data points for such maps are obtained from slowly steaming ships. The high spatial resolution of T/P was thus a great advance. "Before GRACE, the geoid was not sufficiently accurate for the currents to be correctly derived from the T/P data, despite the accurate sea surface height measurements," Bettadpur says. "Now we know much more about the Antarctic circumpolar current, which extends almost to the ocean floor; we also have better measurements of currents in the tropical regions."

While global atmospheric circulation and global ocean circulation are better defined and modeled than ever, Tapley notes, little is known still about a large class of seasonal, climate-related variations. These occur in the distribution of water on land masses and in underground aquifers. "Hydrologists and climate modelers have been eager to obtain accurate measurements of groundwater storage and surface water volumes, especially in places where there has been little instrumentation or remote sensing, and we find that the gravity field measurements made by GRACE can tell us a lot about both of those," he says.

Last summer, Tapley, Bettadpur, CSR senior research scientist Dr. John C. Ries, CSR graduate student Paul F. Thompson, and NASA/JPL scientist Dr. Michael M. Watkins published a major article in Science illustrating GRACE's capabilities for observing water storage and release. Monthly GRACE gravity maps of the Amazon and Orinoco basins revealed significant errors in previous hydrological models, and the new data greatly increase knowledge of the water budget in these regions. "An elevation change of a few centimeters of surface water in the Amazon," the authors noted, "can be equivalent to water flows greater than the average discharge of the Mississippi River" (Science 305, p. 504, 23 July 2004). GRACE hydrology has proved to be accurate for the well-observed Mississippi basin, which bolsters confidence in the GRACE results for the Amazon, where basin-wide measurements are sparse.

Role of TACC

Currently, the science team calculates one gravity field map per month, using the Longhorn (IBM Power 4) systems at TACC. The principal calculations are inversions of the spherical harmonic expansion of the gravity field equations. The estimated coefficients reflect the "bumps" and "valleys" in the Earth's geoid. The more coefficients estimated (i.e., the higher the "degree and order" of a solution), the more accurate is the representation of the Earth's gravity field. The number of coefficients the scientists use depends on the quality and coverage of the data and the availability of large-scale computational resources.

"We have been producing monthly maps because it takes about 30 days for the satellite ground track to more or less cover the globe at large," Tapley says. "I think there were two major paradigm shifts with the GRACE mission. First, we stopped looking at gravity as a mean quantity and fully embraced it as an indicator of mass flux, a time-variable signal that requires monitoring. For our computing, that means calibrating repeated measurements to assure that changes represent physical phenomena, not measurement error change or processing error change. The second shift, which depends on the first, is to the ability to compute gravity fields in a monthly window. In the mid-1990s, using data from multiple satellites, we might work for two years to get a solution to degree and order 70, maybe 5000 coefficients. Now we are able to go to degree and order 160 routinely, with some 25,000 coefficients--and the size of the covariance matrix is the square of that. Operationally, then, we are computing a problem that is two orders of magnitude larger in only five percent of the time."

Project scientist Dr. John Ries agrees. "Without the capacity of the TACC machines, we would not be able to do what we're doing." Tapley, Bettadpur, and Ries are expecting to challenge the machines further during the rest of the GRACE mission (the nominal lifetime of the mission is five years, although the research it has stimulated will go on for much longer). "TACC allows us to experiment," Ries says, "and to search for the optimal processing strategy. I've been able to get solutions to degree and order 360 in under a week, out of our dedicated Longhorn nodes, with code that has been parallelized so efficiently that it runs at half the theoretical maximum for the machine." Bettadpur adds, "We have been able to do some 1200 experiments using various realizations of the GRACE data together with the best current atmospheric general circulation and ocean models. None of this would have been possible without our partnership with TACC."

"We're certainly expecting to continue that partnership," Tapley says, "not only for CSR's GRACE data activities, but also for all current CSR activities in geophysics. CSR runs the Mid-American Geospatial Information Center, under the direction of Dr. Gordon Wells, who is helping to lead a TeraGrid Science Gateway project through TACC, using our skills to develop a real-time flash flood modeling capability."

Other CSR projects also involve a lot of computation, and Tapley expects to keep CSR working in space as the nation studies and engages in future missions to the Moon and Mars. "We are delighted to have in TACC a partner in our computational efforts. TACC can focus on efficient computation as we focus on getting good science out of the missions," he says. "Our graduate students can devote their time to enlarging their understanding of the science and not to system administration, while TACC uses its special expertise to anticipate hardware needs and train us to use new capacities and capabilities."