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A SLOW TRANSFORMATION

SESAR faces nontechnical hurdles

A conversation with Richard Brookes

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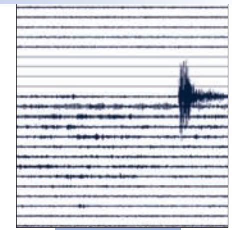


Measuring change in Earth's wobble

Pictures of widespread devastation leave no doubt: The 8.8-magnitude earthquake that struck coastal Chile on February 27 was strong. How strong? NASA scientists say it might have shifted the axis of Earth itself.

"If our calculations are correct, the quake moved Earth's figure axis by about 3 in. [8 cm]," says geophysicist Richard Gross of JPL in Pasadena, Calif.

You might think you would have noticed the Earth suddenly tilting 3 in. But that is not how the "figure axis" works. "The figure axis defines not how Earth is tilted, but rather how it is balanced," explains Gross.

Consider the following: The planet is not a perfect sphere. Continents and oceans are distributed unevenly around the Earth. There is more land in the north, more water in the south, a great ocean in the west, and so on. Because of these asymmetries, Earth slowly wobbles as it spins. The figure axis is Earth's axis of mass balance, and the spin axis wobbles around it.

"The Chilean quake shifted enough material to change the mass balance of our entire planet," Gross says.

A shifting figure axis is nothing new. On its own, the figure axis moves about 10 cm per year as a result of "Ice Age rebound." After the last great glacial period some 11,000 years ago, many heavy ice sheets disappeared. This unloaded the crust and mantle of the Earth, allowing the planet to relax or "rebound" back into a more spherical shape. The rebounding process is still under way, and so the figure axis naturally moves.

Measuring a seismic shift

The February Chilean quake may have moved the figure axis as much in a matter of minutes as it normally moves in a whole year. It was a seismic shift.

So far, however, it is all calculation and speculation. "We have not actually measured the shift," says Gross. "But I intend to give it a try."

The key is GPS. "Using a global network of GPS receivers, we can monitor the rotation of Earth with high precision," he says. He explains that changes in Earth's spin and the orientation of Earth's axes affect the phase and timing of signals we get from the satellites in Earth orbit.

GPS already monitors the seasonal changes in the planet's spin. Factors such as tides, winds, ocean currents and circulation patterns in the planet's molten core modulate its rotation on a regular basis. For instance, a typical day in January is about 1 msec longer than a typical day in June. The roughly six-month variation is driven mainly by seasonal winds. There are also changes on time scales of weeks, years, decades and centuries.

Earthquakes throw a "spike" into GPS signals, and Gross believes he can find it. "I have to take the GPS Earth rotation measurements and subtract the effects of tides, winds and ocean currents," he says. "Then the earthquake should stand out."

In addition to GPS, researchers use VLBI (very long baseline interferometry) to monitor Earth's rotation and figure relative to the quasars at the edge of the universe.

The real news

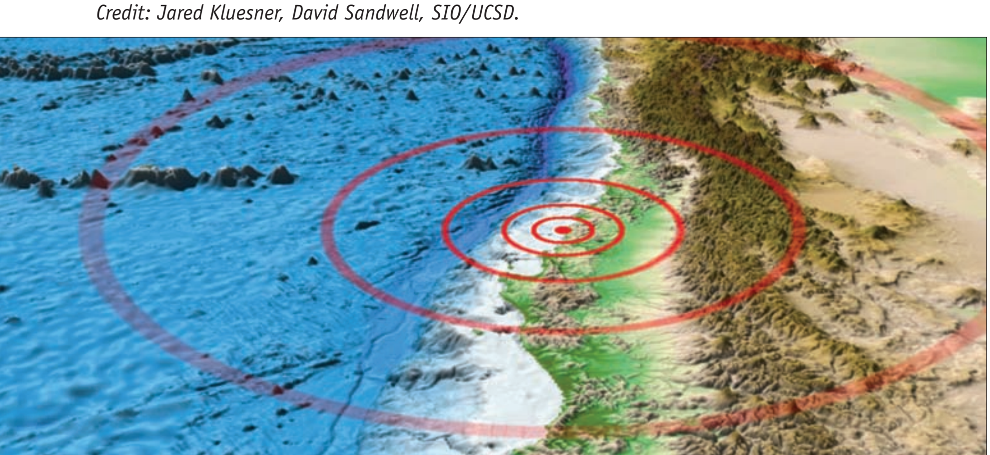
Recent news reports have focused on Earth's length of day, noting that the Chilean quake might have shortened days by as much as 1.26 microsec out of 24 hr. That is true. But it is also negligible compared to the normal effect of wind and tides, which can lengthen or shorten days a thousand times more than earthquakes can.

The real news, as Gross sees it, is the possible shift in Earth's figure axis. The geophysicist has a very "JPL perspective" on the issue: "The antennas we use to track spacecraft en route to Mars and elsewhere are located on Earth. If our tracking platform shifts, we need to know about it."

No one has ever measured a shift in Earth's axis due to an earthquake before. Back in 2004, Gross looked for a shift from the magnitude-9.1 quake in Sumatra, but failed to find a signal. The Sumatra quake was less effective in altering Earth's figure axis because of its location near the equator and the orientation of the underlying fault. The Chilean quake, albeit weaker, may have produced a bigger shift.

The stage is set for discovery. "Computing power is at an all-time high. Our

Scientists will map the rupture site of the 8.8-magnitude earthquake in Chile. Credit: Jared Kluesner, David Sandwell, SIO/UCSD.



The research vessel Melville will take advantage of an unprecedented opportunity. Credit: SIO/UCSD.

models of tides, winds and ocean currents have never been better. And the orientation of the Chilean fault favors a stronger signal."

In a few months Gross hopes to have the answer.

A century-old mystery

In 2000 Gross offered a solution to one of the wobbles manifested by the spinning Earth: the century-old mystery of Earth's "Chandler wobble." The phenomenon is named for its 1891 discoverer, Seth Carlo Chandler Jr., a U.S. businessman turned astronomer. The Chandler wobble is one of several wobbling motions exhibited by Earth as it rotates on its axis, much as a top wobbles while it spins.

Scientists have been particularly intrigued by the Chandler wobble, whose cause has remained a mystery even though it has been under observation for over a century. Its period is only around 433 days, or just 1.2 years, meaning it takes that amount of time to complete one wobble. The wobble amounts to about 20 ft at the North Pole. It has been calculated that the Chandler wobble would be damped down, or reduced to zero, in just 68 years, unless some force were constantly acting to reinvigorate it.

But what is that force, or excitation mechanism? Over the years, various hypotheses have been put forward, such as atmospheric phenomena, continental water storage (changes in snow cover, river runoff, lake levels or reservoir capacities), interaction at the boundary of Earth's core and its surrounding mantle, and earthquakes.

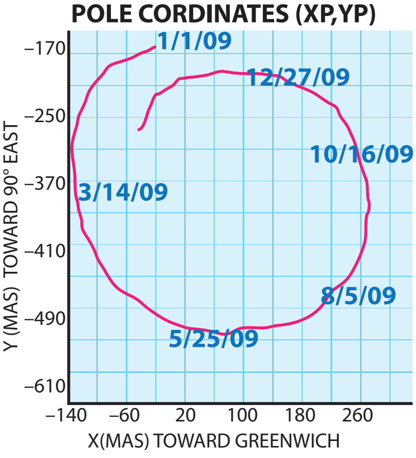
Writing in the August 1, 2000, issue of *Geophysical Research Letters*, Gross reported that the principal cause of the Chandler wobble is fluctuating pressure on the bottom of the ocean, caused by temperature and salinity changes and wind-driven changes in the circulation of the oceans. He determined this by applying numerical models of the oceans to data on the Chandler wobble obtained during the years 1985-1995. These numerical models had become available only recently through the work of other researchers. Gross calculated that two-thirds of the Chandler wobble is caused by ocean-bottom pressure changes and the remaining one-third by fluctuations in atmospheric pressure. He says the effects of atmospheric winds and ocean currents on the wobble are minor.

Monitoring Earth's rotation

Gross credits the wide distribution of the data that underlay his calculations to the creation in 1988 of the International Earth Rotation Service, based in Paris. Through its various bureaus, he writes, the service enables the kind of interdisciplinary research that led to his solution of the Chandler wobble mystery.

The International Earth Rotation and Reference System Service (IERS) is tasked with monitoring the irregularities of the Earth's rotation.

The variability of the Earth-rotation vector relative to the body of the planet or in inertial space is caused by the gravitational torque exerted by the Moon, Sun and planets, displacements of matter in different parts of the planet and other excitation mechanisms.



The normal wobble of Earth's axis since January 2009 is reported by the International Earth Rotation Service. The grid is scaled in milliarcseconds, one of which equals 1/3,600,000 deg.

The observed oscillations can be interpreted in terms of mantle elasticity, Earth flattening, structure and properties of the core-mantle boundary, rheology of the core, underground water, oceanic variability and atmospheric variability on time scales of weather or climate. Understanding the coupling between the various layers of our planet is also a key aspect of this research.

Several space geodesy techniques contribute to the permanent monitoring of the Earth's rotation by IERS. For all these techniques, the IERS applications are only one part of their contribution to the study of planet Earth and the rest of the universe.

The measurements of Earth's rotation are under the form of time series of the so-called Earth Orientation Parameters. Universal Time (UT), polar motion and the celestial motion of the pole (precession/nutation) are determined by VLBI. The satellite-geodesy techniques, GPS, satellite laser ranging and DORIS (Doppler orbit determination and radiopositioning integrated on satellite) determine polar motion and the rapid variations of UT.

The satellite-geodesy programs used in the IERS give access to the time variations of Earth's gravity field, reflecting the evolution of the globe's shape, as well as the redistribution of masses in the planet. They have also detected changes in the location of the center of mass of the Earth relative to the crust. This discovery makes it possible to investigate global phenomena such as mass redistributions in the atmosphere, oceans and solid earth.

UT and polar motion are available daily with an accuracy of 0.5 mas (milliarcseconds), and celestial pole motion data are available every five to seven days at the same level of accuracy. This estimation of accuracy includes both short-term and long-term noise. Subdaily variations in UT and polar motion are also measured on a campaign basis. Past data, going back to the 17th century in some cases, also are available.

Exploring the rupture site

JPL's researchers are not the only scientists interested in the consequences of the Chilean earthquake. Others, funded by the National Science Foundation (NSF) and affiliated with the Scripps Institution of Oceanography (SIO) at the University of California at San Diego, are undertaking an expedition to explore the rupture site of the 8.8-magnitude quake, which was one of the largest in recorded history.

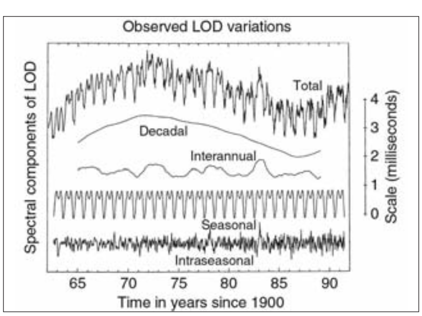
The scientists hope to capitalize on a unique scientific opportunity to capture fresh data from the event. They will study changes in the seafloor that resulted from movements along faults and submarine landslides.

The "rapid response" expedition, called the Survey of Earthquake And Rupture Offshore Chile, will take place aboard the research vessel Melville. The Melville was conducting research off Chile when the earthquake struck.

"This rapid response cruise is a rare opportunity to better understand the processes that affect the generation and size of tsunamis," says Julie Morris, NSF division director for ocean sciences. "Seafloor evidence of the quake will contribute to understanding similar earthquake regions worldwide."

The rapid response mission includes swath multibeam sonar mapping of the seafloor to produce detailed topographic maps. Data from mapping the earthquake rupture zone will be made public soon after the research cruise ends, Morris says.

The new information will be compared with prequake data taken by scientists at Germany's Leibniz Institute of Marine Sciences (IFM-GEOMAR).



The chart shows observed changes in Earth's length of day caused by tides, winds, ocean currents and other factors. (From Treatise on Geophysics, *2007, section 3.09, "Earth Rotation Variations—Long Period" by Richard Gross.)*

Several years ago IFM-GEOMAR researchers conducted a detailed multibeam mapping survey off Chile. Their data will be valuable for comparisons with the new survey to expose changes from the earthquake rupture.

"We would like to know if the genesis of the resulting tsunami was caused by direct uplift of the seabed along a fault, or by slumping from shaking of sediment-covered slopes," says Dave Chadwell, an SIO geophysicist and chief scientist of the expedition. He says they will look for disturbances in the seafloor, including changes in reflectivity and possibly shape, by comparing previous data with the new rapid response data.

The rapid response cruise is possible because Melville is currently in Chilean waters, where a research team has been conducting an investigation of the geology and biology of the Chilean margin.

"This is a unique case in which we have the shipboard assets, the scientific agenda and the funding all in place," says Bruce Appelgate, associate director for ship operations and marine technical support at SIO. "The earthquake was a tragedy for the people of Chile, but we hope this opportunity enables important new discoveries that can help us plan for future events."

The logistical details of undertaking the expedition are enormous and constantly evolving because of uncertainties regarding transportation infrastructure in Chile. Port facilities are limited by widespread earthquake devastation, which has made fueling and provisioning the ship difficult.

Chadwell and SIO scientist Peter Lonsdale, plus graduate students Jared Kluesner and Ashlee Henig, and Scripps Geological Data Center analyst Aaron Sweeney will be aboard Melville for the eight-day expedition.

The scientists, along with Scripps researchers Mike Tryon and Mark Zumberge, also will deploy depth sensors on the seafloor to record possible abrupt vertical motions over the next year.

Joining the U.S. scientists will be Chilean researchers Juan Díaz and Matias Viel González from Universidad Católica in Valparaíso, as well as scientists from IFM-GEOMAR.

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