EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 84 NUMBER 16

22 APRIL 2003

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Geodesy Is Not Just for Static Measurements Any More

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After three decades and three orders of magnitude of advances, space geodesy is poised for prime time in observing the integrated mass transports that take place in the Earth system, from high atmosphere to the deep interior of the core. As such, space geodesy has become a new remote sensing tool, in monitoring climatic and geophysical changes with ever-increasing sensitivity and resolution.

The transports of mass and energy are key processes that determine the dynamics of our Earth system. The Earth system can be conveniently viewed through its components, so-called geophysical fluids—the atmosphere, hydrosphere, cryosphere, biosphere, lithosphere, and the deep interior of mantle and cores. All geophysical fluids undergo a host of mass transports for various reasons, external as well as internal. Studying these processes is undoubtedly a most interdisciplinary field in all of Earth sciences. However, mass transport has not received due attentions. For example, all ocean general circulation models (GCMs) working today do not correctly conserve the water mass; instead, they conserve the water volume under the Boussinesq approximation. Neither do the atmospheric GCMs in conserving the dry air mass, including those used daily for weather forecasts. A most critical piece in the global water mass puzzle, the large-scale land hydrological and cryospheric mass budget remains least known.

Modern space geodesy is thus to be exploited, for instance by assimilating the observables into models, to advance geophysical understanding of mass transports. Geodynamic observables in general include four distinct effects as consequences of the mass transports: the variations in Earth rotation, gravity, and geocenter, and surface deformations (e.g., *Chao et al.*, [2000]; or http://bowie.gsfc.nasa.gov/ggfc/). Today, the observations come from the space geodetic techniques of satellite laser ranging (SLR), very-long-baseline interferometry (VLBI), the Global Positioning System (GPS), and DORIS. Together they define our celestial and terrestrial reference systems, and measure the link between the two systems—the Earth rotation parameters—and the origin of the reference frame relative to the geocenter. The measurements are invariably "contaminated" by, and hence contain information of, station motions. By virtue of their geometric properties, these techniques make possible other precise measurements such as ocean radar altimetry, land/ice laser altimetry, GPS occultation for atmospheric sounding, interferometric synthetic aperture radar, and network ground movements. In addition, satellites' dynamic orbits determination can be used to determine the Earth's gravity field. The new technique of satellite-to-satellite tracking (SST), together with space-borne accelerometer, is now making a breakthrough in the precision of gravity measurements (e.g., GRACE Mission), and hence able to detect temporal variations in gravity at far unprecedented spatial resolutions.

None of the above successes would be possible if not for something of a space-geodetic "Moore's law," not uncommon in many scientific fields. Space geodesy has seen a ten-fold advancement every decade in the last two to three decades, in measurement precision, and in key cases, in spatial and temporal resolutions. On the other hand, in contrast to the typical remote sensing methodology that monitors the target parameters pixel by pixel, space geodesy senses certain integral properties of mass transport, hence is intrinsically limited in spatial resolution, and often in temporal resolution as well. Also, it senses the sum total of all mass transports, not discriminating the geophysical sources (except via the spatial weighting in the integral). See below for examples.

The first example (Figure 1) illustrates the order-of-magnitude advance w.r.t. length-of-day variation (ΔLOD) studies (cf., SESWG, 2002, http://solidearth.jpl.nasa.gov/). A series of zoom-in views allows finer details to be studied with respect to various geophysical excitation sources ranging from core flow, to El Niños, to ocean tides.

In the top panel, the good correspondence between the curves implies that the mass transport in the fluid core is the dominant cause of the decadal ΔLOD over the last 1 to 2 centuries. The middle panel zooms in on the last 20 years. One sees that the interannual ΔLOD is mainly caused by the anomalous mass transport (mostly in the east-west wind field) of the Southern Oscillation in the tropical Pacific-Indian Ocean. The bottom panel further zooms in on a 2-week period during the VLBI Cont94 campaign, showing that the ocean tides are responsible for most of the diurnal/semidiurnal ΔLOD. Clearly, very distinct geophysical processes are at work in causing Earth rotation variations on very distinct time scales, with a wide range of magnitude.

The second example (Figure 2) illustrates the technology advances in the enterprise of gravity field modeling. It shows orders of magnitude of technology improvement in measuring Earth's gravity field, afforded by a succession of space gravity mission concepts, in terms of sensitivity spectrum as a function of harmonic degree (inversely proportional to spatial resolution), out to degree on the order of 100 or spatial resolution of about 200 km. Compared to typical geophysical variability exemplified by the ocean dynamic height signal spectrum, tremendously increasing amount of information about the (integrated) mass transports in the geophysical fluids will be obtained.

The third example (Figure 3) illustrates the integral natures of space geodetic measurements, and the order-of-magnitude diversity among the geophysical sources. A host of geophysical processes contribute to the observed "secular" decrease in the Earth's oblateness J_2, with a wide range of magnitude. The thick curve gives the SLR-derived, post-1980 interannual variation of J_2 (which is to be superimposed on the nominal J_2 value of 0.001082627), taken from *Cox and Chao* [2002]. The pre-1980 data (not shown), from which a secular decrease in J_2 was first identified and attributed to the post-glacial rebound (PGR), was followed by increasingly better J_2 data which show increasingly more details in the variation, culminating in the recent finding that "the Earth turning fatter at the waist"—a post-1998 J_2 anomaly that reversed the secular decreasing trend.

What are the causes for the secular decrease of -2.8×10^{-11}/year in J_2 (the slope on the thick curve) in the first place? Rather than attributing the latter entirely to PGR, let's examine a few other possibilities that are also plotted in Figure 3.

First, the secular spinning down of the Earth (cf. a general lengthening in ΔLOD in Figure 1's top panel) due to tidal braking implies a secular "rounding" of the Earth, decreasing

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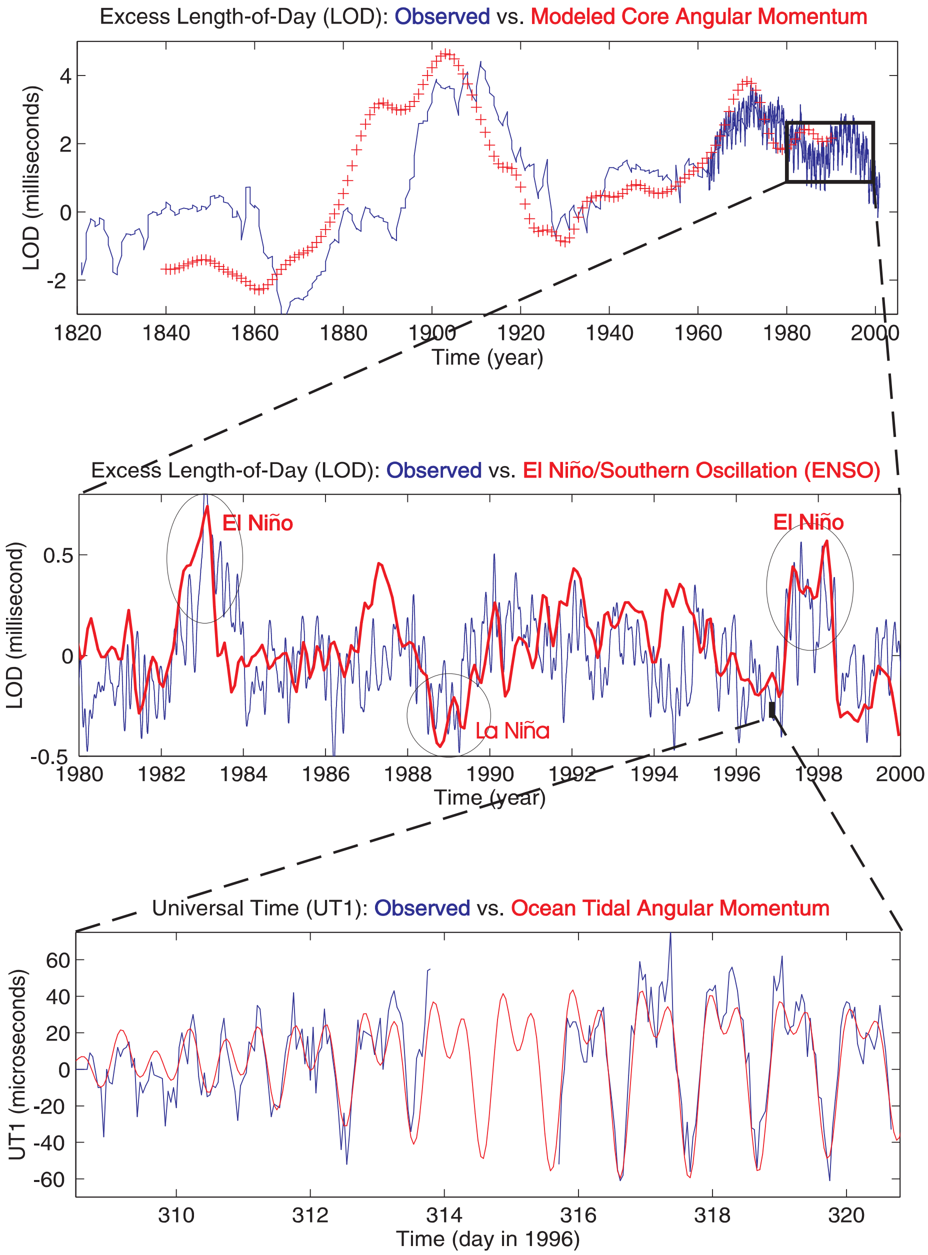

Fig. 1. (top panel): The blue curve is the entire ΔLOD data set that human kind ever acquired (the post-1960 densification of data resulted from the advent of the atomic clock); the red curve is the corresponding ΔLOD caused by the angular momentum variation of the fluid outer core according to estimations based on surface geomagnetic records [cf. http://www.astro.oma.be/SBC/]. (Middle panel zoom-in): The blue curve is VLBI measurement, after removal of the seasonal terms due to mass transports of meteorological origin and tidal forces; the red curve is the Southern Oscillation Index reflecting the strength of the El Niño-La Niña sequence (Bottom panel zoom-in): The blue curve is the hourly ΔUT1 data (integrated ΔLOD, notice the units in micro-seconds); the red curve is that predicted by the oceanic tidal angular momentum variation [see http://bowie.gsfc.nasa.gov/ggfc/tides/], estimated from tide models based on TOPEX/Poseidon ocean altimeter data.

J_2. According to MacCullagh's formula, that effect is only about -5 x 10^{-13}/year, contributing no more than 2% of the observed J_2 rate.

Second, it was known that earthquakes have cumulatively been making the Earth rounder as well (see http://bowie.gsfc.nasa. gov/ggfc/ mantle.htm). During the last 25 years, this earthquake-induced secular rate of J_2 has been two orders of magnitude smaller than the observed.

A third contribution comes from an anthropogenic source-reservoir water impoundment behind the world's large dams for the last half century. Their cumulative effect also has been a general lowering of J_2 at a rate comparable to that of tidal braking. There are other possible contributions coming from long-term climate change in the geophysical fluids; for example, in the cryosphere (e.g., ice-sheet/glacier melting, possibly having an opposite sign), oceans, and land hydrology, as well as mass flow in the outer core and possible rotational variation of the inner core. Their magnitudes are largely unknown at present. Obviously, PGR is by no means the only source for secular J_2 change, although presumably the dominant one.

On the interannual time scale, the enigmatic post-1998 J_2 anomaly is under active research in identifying its cause(s), likely in the hydrosphere and/or cryosphere. It also sheds light on the significance of previous less prominent J_2 fluctuations, which may prove to be not just data errors after all.

The above examples demonstrate how space geodesy is becoming a powerful tool in monitoring climatic and geophysical changes. At the same time, they also accentuate the integral nature of the geodynamic observables, and the unique challenges we face in interpreting the data and making optimal applications of the data under their limitations in spatial and temporal resolutions.

Acknowledgments

This article is based on an address given by the author at the IERS (International Earth Rotation Service) Workshop on Combination Research and Global Geophysical Fluids, held in Munich, Germany, 18–21 November 2002. The following persons have provided valuable inputs: Chris Cox, John Gipson, Richard Gross, Richard Holmes, Weijia Kuang, Chopo Ma, Dennis McCarthy, and Richard Ray. Encouragement from John LaBrecque and support from NASA's Solid Earth and Natural Hazards Program are acknowledged.

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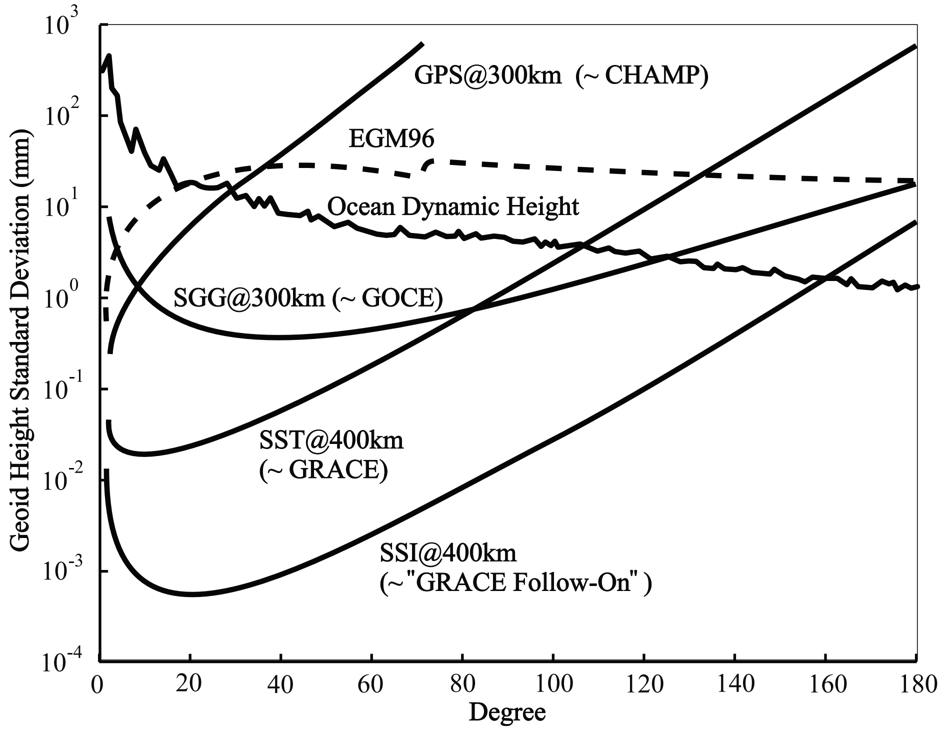

Fig. 2. Standard deviation spectra (for a 3-month period) of the gravity field as a function of the spherical harmonic degree. The "EGM96" curve represents our present level of knowledge about Earth's gravity field, derived from orbit tracking data from dozens of satellites spanning 4 decades plus land survey and ocean altimetry data [see http://cddisa.gsfc.nasa.gov/926/egm96/]. The "GPS" sensitivity spectrum, for a generic high (GPS)-low SST with onboard accelerometer, is realized by the CHAMP Mission launched in 2000 [see http://op.gfz-potsdam.de/champ/]. The "SST" spectrum, for a nominal low-low microwave SST between a tandem pair of satellites, is becoming a reality with the launch of the GRACE Mission in 2002 [see http://www.csr.utexas.edu/grace/]. The "SGG" spectrum will be that carried out by the GOCE Mission gradiometer to be launched in 2005. The "SSI" spectrum represents what can be anticipated from a GRACE-type SST using laser interferometry technique, possibly after 2008. Figure is courtesy of NAS [1997].

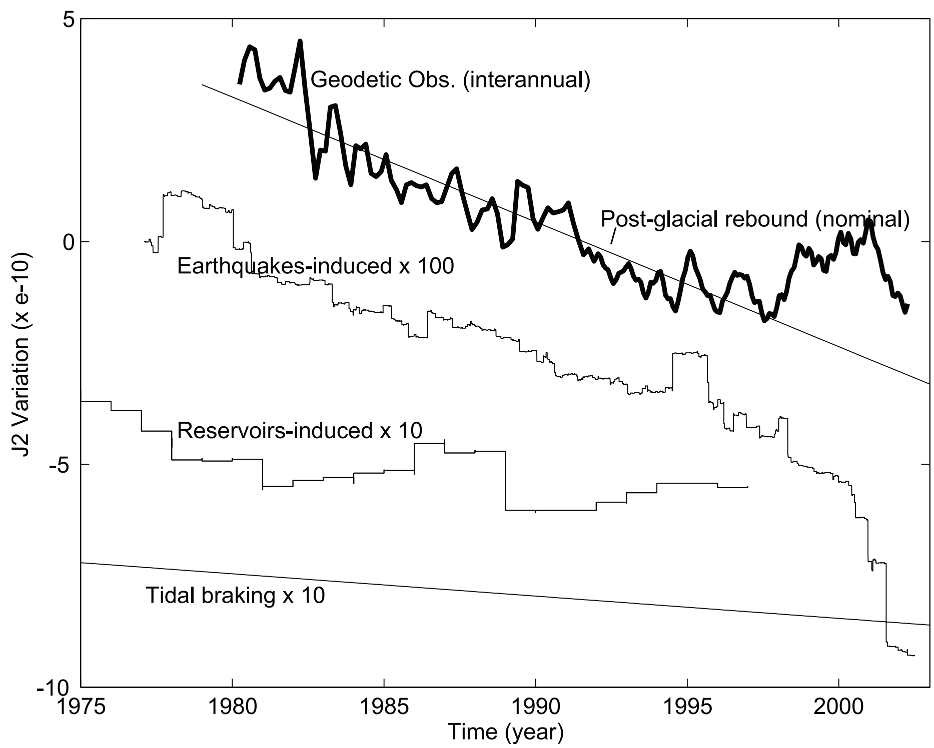

Fig. 3. A host of geophysical processes contribute to the observed "secular" decrease in the Earth's oblateness J_2. The thick curve gives the SLR-derived, post-1980 interannual variation of the J_2 in units of 10^{-10}. The atmospheric and tidal contributions have been removed, as is any additional seasonal signals. The other curves represent the computed corresponding J_2 variations induced by tidal braking, major earthquakes, and large artificial reservoirs. For clarity, the curves are vertically offset; note the magnifying factors.