

# Space Geodesy Monitors Mass Transports in Global Geophysical Fluids

Large-scale mass transports in the Earth system produce variations in Earth's rotation, gravity field, and geocenter. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research that will lead to a better understanding of global mass transport processes and the Earth's dynamic responses.

To take full advantage of these advances, the International Earth Rotation Service (IERS), the organization that monitors the rotational motions of the Earth and related properties, saw the need in 1998 to create an infrastructure to facilitate the link between the space geodetic measurement and the geodynamic "global change" research communities [Dehant *et al.*, 1997]. Hence was born the IERS Global Geophysical Fluids Center (GGFC).

The GGFC builds upon the success of the IERS Sub-bureau for Atmospheric Angular Momentum (AAM), which had operated since 1989 and was responsible for obtaining AAM and related data products calculated by the world's major meteorological centers and disseminating them to users concerned with Earth rotation monitoring, prediction, and research [Salstein *et al.*, 1993]. The new GGFC greatly expands these activities to encompass: (i) all three geodynamic effects (rotation plus gravity and geocenter), because the Earth's changing gravity and geocenter have obvious impacts on the precise definition of the terrestrial and celestial reference frames that are central to IERS' measurements; and (ii) all geophysical fluids (not just the atmosphere), because they also make important contributions to the geodynamic effects (even though the atmosphere is often the largest contributor on a wide range of timescales). Table 1 summarizes this matrix of topics of interest to IERS GGFC.

## Description of the Physics

To illustrate these effects, consider a simple "solid Earth + atmosphere" system in which an air mass moves across the surface of an otherwise uniformly rotating solid Earth. Regardless of its driving mechanism, this air mass transport will have certain geodynamic consequences (Table 1). Via surface torques, the relative motion of the air mass imparts changes in the solid Earth's rotation, just as a

circus seal does by balancing itself on a rolling ball. Furthermore, the associated redistribution of mass changes the Earth's inertia tensor and, hence, its rotation. This process is analogous to a spinning ice skater who changes his rotation by moving his arms: he'd spin faster when drawing his arms closer to his body and vice versa, and he'd "wobble" if he does so in an asymmetric way. The above two effects are consequences of the conservation of angular momentum, which here dictates that the total angular momentum of the Earth plus atmosphere system stays constant.

A second geodynamic effect is the change in the gravity field produced by the moving air mass. In general, Newton's gravitational law states that a body produces its own gravity field around it according to the distribution of mass within the body. Therefore, a temporal change in the mass distribution will in general cause the gravity field to change with time.

Finally, the system is subject to the conservation of linear momentum, which dictates that it is the center of mass of the total Earth-plus-atmosphere system that should always obey celestial mechanics in its translational motion around the solar system, no matter how the air mass moves relative to the solid Earth. Relative to this combined center of mass—about which satellites orbit—the solid Earth's center of mass, with which observing ground stations move, would then undergo apparent but very slight motion. This is referred to as the geocenter motion. A physical analogy would be two masses connected by a spring and thrown into a trajectory.

Our real Earth is, of course, a lot more complex, and exciting, than the Earth-plus-atmosphere system described above. Any

geophysical process involving fluid mass transport (see Figure 1) will have its own geodynamic effects depending on its spatial and temporal characteristics. The signal observed by space geodetic techniques is the sum of all the individual signals.

## Space Geodetic Measurements

The Earth's rotation can be represented by a three-dimensional vector whose components consist of the rotational speed that determines the length-of-day and the orientation of the rotational axis. Variations of the latter are called nutations if relative to inertial space, or polar motion if relative to an Earth-fixed frame. For nearly three decades, space geodetic measurement precision has improved at the rate of one order of magnitude per decade. Satellite laser ranging (SLR) and very-long-baseline interferometry (VLBI) have been the workhorses in measuring Earth's rotation. Recent years have seen an increasing use of Global Positioning System (GPS) data especially for higher temporal resolution, and radio tracking data from the Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS) system. Sub-milliarcsecond precisions (corresponding to sub-centimeter precision if projected to the Earth's surface) are now routinely achieved in daily Earth orientation measurements, and a new VLBI project called CORE (Continuous Observation of the Rotation of the Earth) that promises uninterrupted hourly measurements with even higher precision is being implemented in phases.

Measuring Earth's global gravity field and its temporal variation requires special consideration. An external observer can sense gravity only if he is not "in orbit," that is, not in free-fall, as is an orbiting satellite. A satellite cannot directly "feel" the gravity, which is why a space-borne gravimeter is useless. However, a near-Earth satellite's detailed orbital trajectory does reflect the gravity field through which it traverses. Decades of precise orbit tracking data of many geodetic satellites have led to generations of increasingly refined models for the Earth's average gravity

Table 1. GGFC's topics of interest.

Geodynamic Effect	Physical Principle	Geophysical Fluids					
		Atmos.	Oceans	Hydrol.	Tides	Mantle	Core
Earth Rotation Variation	Cons. Angular Momentum (via torques)	✓	✓	✓	✓	✓	✓
Gravity Variation	Newton's Gravity Law	✓	✓	✓	✓	✓	✓
Geocenter Motion	Cons. Linear Momentum	✓	✓	✓	✓	✓	✓

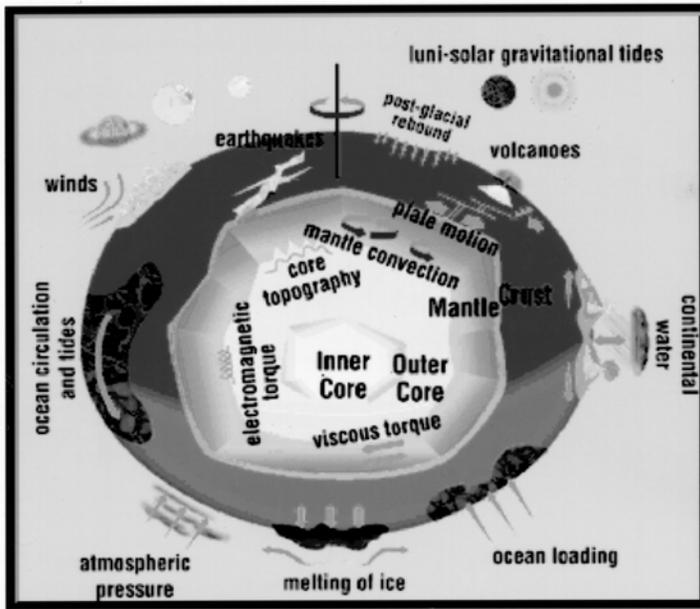


Fig. 1. Geophysical fluid processes that involve large-scale mass transports and produce variations in Earth's rotation, gravity field, and geocenter.

field in terms of the Stokes coefficients of its spherical harmonic expansion.

In particular, and more pertinent to the present discussion, the precise SLR technique has detected tiny temporal variations in the low-degree gravity field, and those more than a month long can now be clearly identified. The upcoming series of space gravity missions of CHAMP and GRACE employ satellite-to-satellite tracking techniques, and GOCE will carry a gravity gradiometer (which measures local gradient of gravity). These three missions will yield gravity information at much higher precision and geographical resolution. For example, GRACE promises to be able to resolve water-level-equivalent mass changes of only a centimeter over an area of a few hundred kilometers at a temporal resolution as short as 10 days [Wahr *et al.*, 1998].

On another front, satellite-based SLR, GPS, and DORIS data are beginning to reveal geocenter motion at the centimeter level. This motion manifests itself as a translation of the ground station networks with respect to the center of mass of the whole Earth system defined by satellite orbits. Mathematically, the three components of the geocenter translation vector correspond directly to the three Stokes coefficients of spherical harmonic degree 1 of the gravity field. Although in its infancy and still beset by many technical and modeling problems, geocenter motion measurements have prompted a number of recent geophysical investigations and will undoubtedly continue to do so [IERS, 1999a].

### Geophysical Fluids

The magnitude of the geodynamic effects produced by a particular mass transport is approximately proportional to the ratios of (net transported mass)/(Earth mass) and (net transport-distance)/(Earth radius). Many

processes are below the detection threshold because of the relatively small mass or short distances involved. Examples include volcanic outgassing; volcanic eruptions where most material stays in the local area; landslides and rock/mud flows, however great; thermal expansion and/or freezing of ocean water, however extensive; floating icebergs; intercontinental trade of petroleum and other commercial goods; and building of cities and the Great Wall of China. Biomass variations may be of marginal importance.

However, there are many fundamental geophysical processes involving large-scale mass transports that do cause measurable geodynamic effects (Figure 1), but even they produce signals typically no larger than 1 part in ten billion [e.g., Chao, 1994]. The most prominent are perhaps weather effects, which are originally driven by solar radiative input and related over much of the globe to the Earth's rotational Coriolis force and modified by atmosphere-ocean and atmosphere-land interactions. The meteorological pressure systems seen on weather maps indicate that different masses of air move around the planet as part of the general circulation. Thus, the winds produced show a variation of these synoptic motions on short timescales, but they are strong as well on longer scales related to intraseasonal, seasonal, and interannual oscillations. Interannual anomalies associated with El Niño/La Niña are of particular interest in this regard, especially because they are part of the system that produces very strong zonal wind anomalies across the Pacific Ocean and elsewhere from the tropics to higher latitudes [e.g., IERS, 1999b]. Remarkably, the length of day showed a very clear strong signal during the recent 1997-1998 El Niño event and in earlier ones, also.

Mass transport also occurs in the oceans. There it is mainly caused by tidal forcing,

surface wind forcing, atmospheric pressure forcing, and thermohaline fluxes. Satellite altimetry can measure changes in the sea-surface height caused by these forcing mechanisms, and GRACE (and CHAMP to a certain extent) will soon be able to infer changes in the ocean-bottom pressure. Numerical models of the oceanic general circulation allow detailed investigation of the response of the oceans to these forcing mechanisms and allow quantities such as the angular momentum associated with oceanic mass transport to be modeled and compared with Earth rotation measurements. Recent studies have shown that nontidal oceanic mass transport can measurably change the length of the day [e.g., Marcus *et al.*, 1998] and can also cause the Earth to wobble as it rotates [e.g., Ponte *et al.*, 1998].

Large mass transports/redistributions occur as tides at all tidal periods. The tides involve mass transports and angular momentum exchanges within the Earth system at periods ranging from subdaily to 18.6 years. Earth tides, ocean tides, and atmospheric tides all contribute to geodynamic variations, and all are readily observable with modern techniques. The Earth's body tide is responsible for large length-of-day variations at monthly and fortnightly periods; the ocean tides are the dominant cause of diurnal and semidiurnal variations in both rotational rate and polar motion. The geodetic measurements are stimulating improvements to all fluid and solid tidal models.

Redistribution of water mass stored on the continents occurs on a variety of time scales. Seasonal and shorter time scales involve precipitation, evaporation, and runoff, with storage of water in lakes, streams, soil, and biomass. Over longer time scales, storage variations in ice sheets and glaciers signal climate changes, while ground water storage changes take place in deeper aquifers. Some of these hydrological processes are fundamentally regulated by vegetation, but all are ultimately exchanged with and hence reflected in atmospheric water content and sea level in an intricate budget. Water mass redistribution involving these various reservoirs and mechanisms has been shown to have observable effects on Earth rotation, geocenter, and gravity field changes. However, the variety of transport mechanisms and storage reservoirs makes the task of globally monitoring water storage on land extremely challenging. Indeed, this is considered to be a first-order problem for the climate community and is being pursued at every major climate research center.

Accounting for 68% of the total mass and 89% of the moment of inertia of the entire Earth, the solid, but non-rigid, mantle is perpetually in motion as well. Some motions are caused by external forces, including tidal deformation, atmospheric and oceanic loading, and occasional meteorite impacts. For internal processes, volcanic eruptions and pre-seismic, coseismic, and post-seismic dislocations associated with an earthquake act on short time scales. On longer time scales, present-day post-glacial rebound, surface processes of soil erosion and deposition, and tectonic activity such as plate motion, orogeny, and

internal mantle convection all transport large masses over long distances. Finally, the entire solid Earth undergoes an equilibrium adjustment in response to the secular slowing down of the Earth's spin due to tidal friction.

Deeper in the solid Earth, the fluid outer core is constantly turning and churning in association with the geodynamo's generation of the magnetic field. The variation of the core angular momentum can evidently be inferred from surface observations of the geomagnetic field or modeled by physical hypotheses and the equations of motion that drive and govern the geodynamo and hence the core flow. This core angular momentum has been compared to the observed variations of the length-of-day at decadal time scales, while torques at the core-mantle and inner core boundaries have been evaluated. The recent seismological finding of a differential rotation of the solid inner core is also under evaluation in this context.

In this sense, the entire Earth system consists of several geophysical fluid components. Various types of torques acting on the boundaries between the geophysical fluids exchange angular momentum among the fluids, thus exciting Earth rotational variations. These torques include (i) frictional torque, in the form of wind stress over land and ocean surfaces, ocean bottom drag, and viscous stress at the core-mantle and inner core boundaries; (ii) pressure torque acting across topography that exists between atmosphere-land, ocean-land, and core-mantle boundaries; (iii) gravitational torque acting on density anomalies at distance; and (iv) magnetic torque generated by the geodynamo that acts on the core-mantle and inner core boundaries.

In addition, subtler interactions exist among the geophysical fluid components that would modify the Earth's response. Notable examples include mantle elastic/inelastic yielding under surface loading, the ocean's inverted-barometer behavior (or the departure from it), and the extent of coupling at the core-mantle and inner core boundaries. They are, in general, functions of the time scale under which the effect in question applies.

### GGFC Organization and Functions

Philosophically, the GGFC provides a link between two user communities. On the one hand is the geodetic measurement community, who wants to better understand their measurements, to further develop measurement requirements and strategies, and to be able to better predict and quantify the variabilities. On the other hand, the geophysical modelers

want to interpret the geodetic measurements in terms of various geophysical processes based on models and/or observations. They may want to better model the geophysical fluid processes by utilizing the independent information and constraints provided by the space geodetic measurements and infer Earth's properties by examining its dynamic responses and behavior.

Established in January 1, 1998, of the IERS's 10th anniversary, the GGFC is coordinated from NASA Goddard Space Flight Center's Laboratory for Terrestrial Physics. The GGFC is responsible for promoting related science and outreach activities, including collective publications, dedicated symposia and special sessions at professional meetings, and assistance in coordinating and supporting various international projects and observational campaigns. The actual functions of the GGFC reside in its seven Special Bureaus (SBs) that were also established in 1998. Each SB is responsible for activities related to a certain fluid component or aspect of the Earth system. The primary functions of the SBs are data and information acquisition, archiving, and dissemination; intercomparison and assessment of data products; recommending conventions and standards; and providing a forum for professional exchanges and discussions.

Building on three decades of development and advances, modern space geodesy has matured and become an effective tool for remote sensing of a variety of global geophysical processes. At the heart of it is the unique capability of remote sensing of global mass transports that constantly occur in all parts of geophysical fluids. The IERS's GGFC and its SBs are well situated to support and provide services to the research community in this new interdisciplinary field.

Individual SB Web sites have been developed as the major mechanism for data dissemination and communication. The GGFC coordinating center has a portal Web site at <http://bowie.gsfc.nasa.gov/ggfc/>. The SB Web sites are:

- Atmosphere: <http://www.aer.com/groups/diag/sb.html>
- Oceans: <http://euler.jpl.nasa.gov/sbo/>
- Hydrology: <http://www.csr.utexas.edu/research/ggfc/>
- Tides: <http://bowie.gsfc.nasa.gov/ggfc/tides/index.html>
- Mantle: <http://bowie.gsfc.nasa.gov/ggfc/mantle.html>
- Core: <http://www.astro.oma.be/SBC/main.html>
- Gravity/Geocenter: (under construction)

Two mirror Web sites have also been established to enable easier access from different parts of the world: <http://ggfc.u-strasbg.fr> at Strasbourg, France (courtesy of P.Gegout), and <http://www.miz.nao.ac.jp> at Mizusawa, Japan (courtesy of Y.Tamura).

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