Benjamin F. Chao: Earth Rotational Variations Excited by Geophysical Fluids, IVS 2004 General Meeting Proceedings, p.38–46
http://ivscc.gsfc.nasa.gov/publications/gm2004/chao

Earth Rotational Variations Excited by Geophysical Fluids

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Abstract

Modern space geodetic measurement of Earth rotation variations, particularly by means of the VLBI technique, has over the years allowed studies of Earth rotation dynamics to advance in ever-increasing precision, accuracy, and temporal resolution. A review will be presented on our understanding of the geophysical and climatic causes, or "excitations", for length-of-day change, polar motion, and nutations. These excitations sources come from mass transports that constantly take place in the Earth system comprised of the atmosphere, hydrosphere, cryosphere, lithosphere, mantle, and the cores. In this sense, together with other space geodetic measurements of time-variable gravity and geocenter motion, Earth rotation variations become a remote-sensing tool for the integral of all mass transports, providing valuable information about the latter on a wide range of spatial and temporal scales. Future prospects with respect to geophysical studies with even higher accuracy and resolution will be discussed.

1. Introduction

For over two decades, the very-long-baseline interferometry (VLBI) has been a most powerful geodetic technique for measuring the Earth's rotation. Compared to other "workhorse" techniques of satellite-laser-ranging (SLR) or Global Positioning System (GPS) based on satellites, VLBI has the unique strength of being able to observe the geometrical orientation of the rotating Earth relative to the inertial space. (The celestial reference frame is best defined by distant celestial bodies, which is the subject of other invited papers in this Proceedings.) As such, geodetic VLBI data contain the information of:

1. The rotational speed, free from uncertainties suffered by satellite techniques due to their orbit drifts. These data yield the length-of-day (LOD) variation (used conveniently when the temporal sampling is longer than 1 day) or the universal-time (UT) variation (for sub-daily sampling where LOD loses its meaning.)
2. The rotational axis orientation, in both nutations and polar motion. In conventional terminology, nutations (including precession) are variations of the axis orientation relative to the inertial space, while polar motion is that relative to the terrestrial frame. Satellite techniques are unable to see nutations as can VLBI (because VLBI refers to the celestial frame), whereas VLBI can see polar motion as can satellite techniques (as the VLBI antennas are fixed on the terrestrial frame.)

Based on these Earth rotation data, this paper means to give a brief overview of the geophysical causes, or "excitations", of Earth rotation variations.

2. Angular Momentum Variations in Geophysical Fluids

Mass transports occurring in the atmosphere-hydrosphere-cryosphere-solid Earth-core system (the "global geophysical fluids") occur on all temporal and spatial scales. Large-scale mass transports in the Earth system produce variations in Earth's rotation, gravity field, and geocenter. See Chao et al. (2000), and the website of IERS' Global Geophysical Fluids Center http://ggfc.gsfc.nasa.gov/.

To illustrate the effect on Earth rotation, consider a simple "solid Earth + atmosphere" system where an air mass moves across the surface of an otherwise uniformly rotating solid Earth. Regardless of its driving mechanism, 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. A familiar analogy is a spinning ice skater changing 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 (whose sum is what's observed) are consequences of the conservation of angular momentum, which here dictates that the total angular momentum of the Earth + atmosphere system stays constant.

Our real Earth is of course a lot more complex, and exciting, than the above Earth + atmosphere system. Any geophysical process involving fluid mass transport will excite its own Earth rotation variations depending on its spatial and temporal characteristics. The signal observed by space geodetic techniques is the sum of all the individual contributions, which enter in the form of angular momentum (AM) variations. The latter consists of a "motion term" (due to relative motion of the geophysical fluids mass, e.g. winds and ocean currents) and a "motion term" (due to mass redistribution, e.g. air pressure changes and land water impoundment). As far as Earth rotation variation is concerned, these AM variations act as "excitation" sources, where the Earth responds in accordance with its physical properties: A schematic "Earth filter" for LOD and polar motion is given in Figure 1; for details see, e.g. Munk and MacDonald (1960).

<u>The atmospheric AM (AAM):</u> The most prominent contributions are perhaps weather effects, driven originally by solar radiation 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 appearing on weather maps indicate that different masses of air move around the planet as part of the general circulation. The wind thus produced shows a variation on short timescales of these synoptic motions, 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.

<u>The oceanic AM (OAM):</u> Mass transport also occurs in the oceans where 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 the GRACE mission is currently measuring the time-variable gravity signals coming from the ocean-bottom pressure changes. Numerical models of the oceanic general circulation allow the response of the oceans to these forcing mechanisms to be investigated in detail.

<u>The tidal AM (TAM):</u> 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. 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

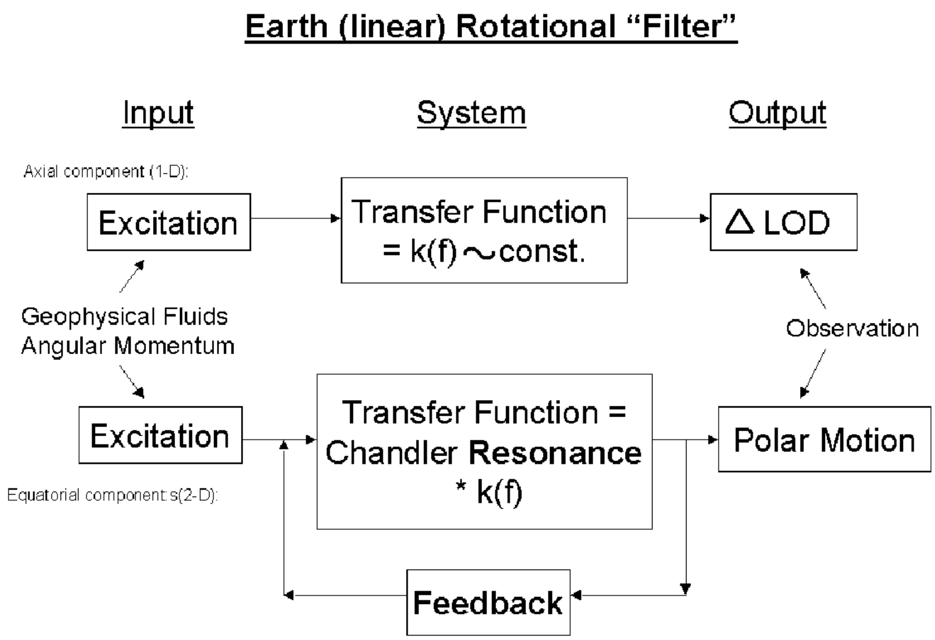

Figure 1. Schematic "Earth filter" for LOD and polar motion, linking the input excitations to the output observations.

diurnal and semidiurnal variations in both rotational rate and polar motion.

The hydrological AM (HAM): Redistribution of water mass stored on the continents occurs on a variety of timescales. Seasonal and shorter time scales involve precipitation, evaporation, and runoff, with storage of water in lakes, streams, artificial reservoirs, soil, and biomass. Over longer timescales, storage variations in ice sheets and glaciers signal climate change, 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 an extremely challenging task. Indeed, this is considered to be a first order problem for the climate community, and is being pursued at every major climate research center.

The mantle AM (MAM): The solid, but non-rigid, Earth is perpetually in motion as well. There are motions caused by external forces, including tidal deformation, atmospheric and oceanic loading, and occasional meteorite impacts. For internal processes, volcanic eruptions and pre-seismic, co-seismic and post-seismic dislocations associated with an earthquake act on short timescales. On longer timescales, 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.

The core AM (CAM): 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 timescales, 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.

3. LOD/UT1 Variations and Polar Motion

Figure 2 shows a sample of modern LOD and polar motion data, obtained by weighted combination of VLBI, SLR, and GPS observations (Gross, 2000). Figure 3 gives a schematic spectrum of the LOD/UT1 variations expected (and observed) in terms of geophysical fluids contributions. Many periodic and quasi-periodic signals peak above a generally red spectrum, much of which is known to be due to AAM and, to a lesser extent, OAM and HAM. The long-period tidal signals are much stronger than the diurnal and semidiurnal ones because the long-period tidal potential's (and hence the corresponding TAM in the solid Earth) zonal nature strongly influences LOD/UT, while the diurnal + semidiurnal tidal signals (as well as a small portion of the long-period tidal signals) in LOD/UT1 only come from the oceanic TAM (e.g., Chao and Ray, 1998). The annual and semiannual peaks are excited by the combination of AAM + OAM + HAM, which all have strong seasonality (for a review, see, e.g., Dickey, 1993; Eubanks, 1993).

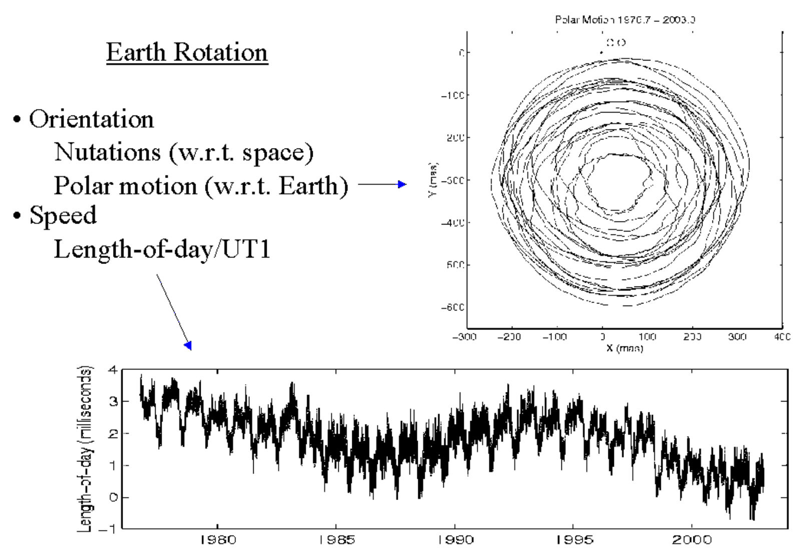

Figure 2. A sample of modern LOD and polar motion data, obtained by weighted combination of space geodetic observations including VLBI.

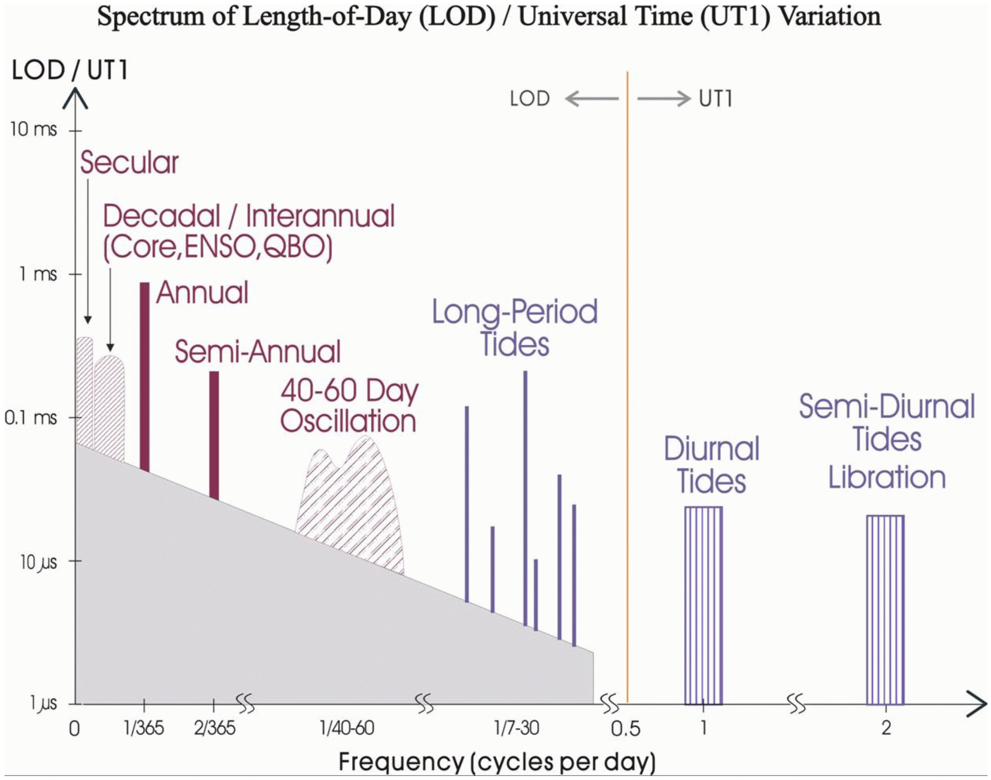

Figure 3. A schematic spectrum of the LOD/UT1 variations expected (and observed) in terms of geophysical fluids contributions.

Figure 4 illustrates some of the most important findings in the geophysical excitation of LOD/UT variations over the years (Chao, 2003). 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 LOD change over the last 1-2 centuries. The middle panel zooms in on the last 20 years. One sees that the interannul LOD variation 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 LOD changes. Clearly, very distinct geophysical processes are at work in exciting Earth rotation variations on very distinct timescales, with a wide range of magnitude.

Figure 5 gives the counterpart schematic spectrum of the polar motion, showing a much more complex physical nature than Figure 3. The positive frequency means prograde motion/excitation while the negative frequency the retrograde motion/excitation. Also given is the "nutation" frequency scale, which is shifted with respect to the polar motion frequency by 1 cycle per day, which is the conversion between the terrestrial reference frame and the inertial reference frame as realized by the celestial frame observed by VLBI.

The Earth presents two rotational resonances across the spectrum. One is the Chandler wobble resonance (as mentioned in Figure 1), representing the elastic Earth's version of the Eulerian

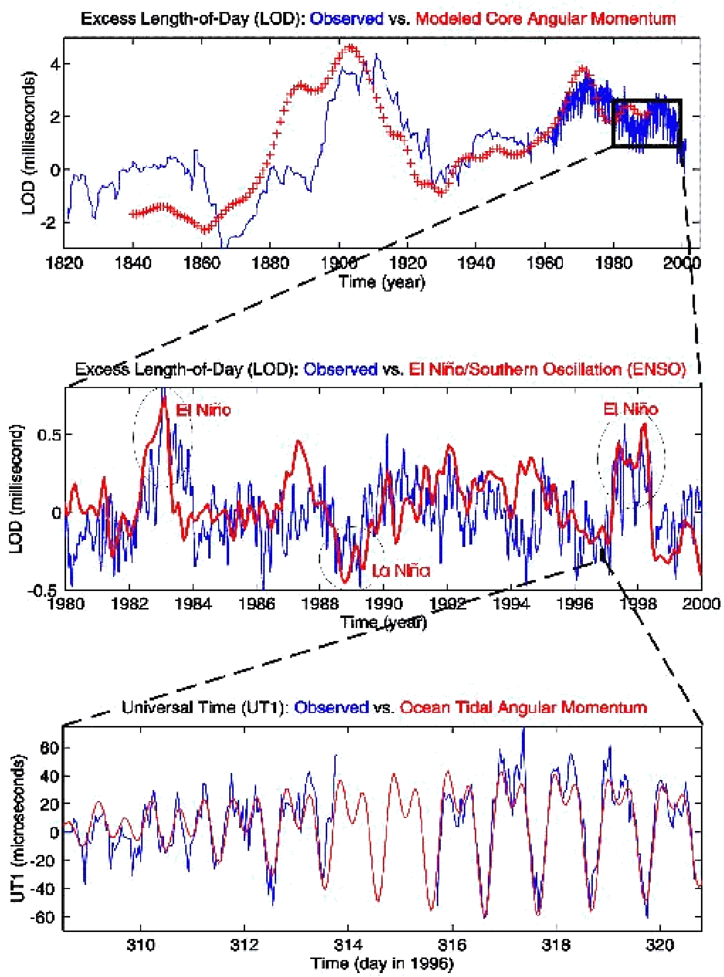

Figure 4. Zoom-in views examining the LOD/UT1 variations with respect to various geophysical excitation sources ranging from core flow, to El Niños, to ocean tides.

wobble. The other is the so-called free-core-nutation (FCN) resonance due to the dynamical motion of the fluid outer core. FCN resides in the nutation band although its origin has nothing to do with tides, some of which are close enough so that their responses are magnified by this resonance. There is a third resonance, but at the zero nutation frequency (hence not "oscillatory"), giving rise to the astronomical precession. It should be emphasized that VLBI is currently the only technique that is sensitive to, and precise enough to measure the signals in the nutation band, although gyrometers are beginning to show exciting potentials, such as large ring-laser interferometers (Schreiber and Klugel, 2003).

As a result of the resonances in the Earth's polar motion "filter" as depicted in Figure 1, the observed polar motion is not the excitation function; rather it is the convolution of the excitation function with the resonance functions (e.g., Munk and MacDonald, 1960). Therefore, a numerical procedure of de-convolution has to be conducted to convert the observed polar motion into its

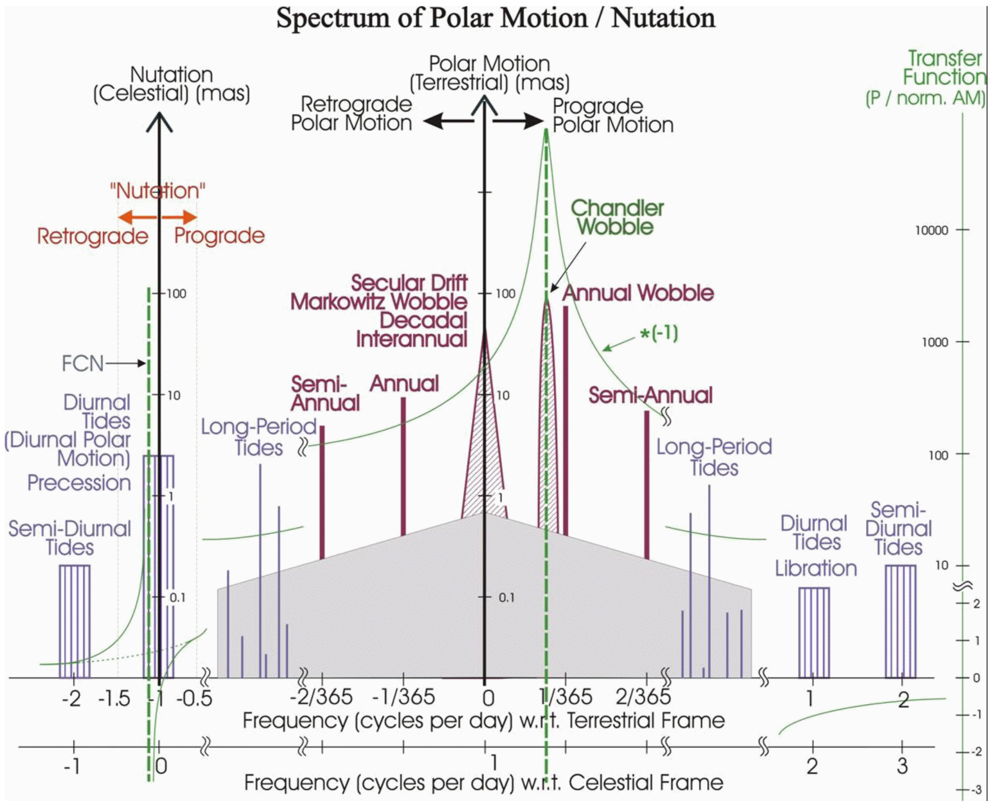

Figure 5. A schematic spectrum of the polar motion/nutation expected (and observed) in terms of geophysical fluids contributions.

excitation function, before it can be compared with the geophysical fluids' AM variations. Among other things, the frequencies and Q-values of the resonances need to be well-determined for the de-convolution. Considerable research has been devoted to this subject (see Figure 6 below.)

For the most part, geophysical and meteorological excitations for the polar motion are similar to those for the LOD/UT1 variation (for a review, see, e.g., Dickey, 1993; Eubanks, 1993). For example, the AAM and to a lesser extent the OAM have been found to be the major contributors in exciting the polar motion (e.g., Gross, 2003). For the TAM, the main difference from the case of LOD/UT1 excitation is that the largest contribution comes from the tesseral terms in the tidal potential corresponding to the retrograde diurnal tides generated in the solid Earth (while, as in the case of LOD/UT1, other smaller tidal signals come from oceanic TAM) (e.g., Chao and Ray, 1998). Empirically, the frequency band around the retrograde diurnal is characterized as the "nutation band", where the signals are absorbed into the nominal nutation solutions of VLBI. Hence such signals are absent from VLBI's polar motion solution given, e.g., in Figure 2.

4. Epilogue

VLBI observes the Earth rotation variations in LOD/UT1 and nutation/polar motion. Under the so-called space-geodetic "Moore's law", that space geodesy is seeing a ten-fold advancement in precision and temporal resolution every decade in the last 2-3 decades, these Earth rotation variations have been studied in increasingly more detail, as illustrated in Figure 4. Together with time-variable gravity observations, traditionally coming from SLR but in recent years from the CHAMP and GRACE satellite missions, space geodesy has become a powerful remote sensing tool for monitoring our changing environment on this restless planet (NASA, 2003). The scientific utilities of these data are two-fold: In the forward direction, the data provide information for better understanding of geophysical fluids' mass transports and dynamics, independent of and complementary to other observations for geophysical, meteorological, and climatic changes. In the inverse direction, in investigating the relationship between the excitation sources and the Earth's rotational responses, many important, but often subtle, properties and dynamical behavior of the Earth can be deduced or constrained. Figure 6 gives a list of such parameters, whose better understanding and modeling can benefit by the Earth rotation observations, to different extents depending on the precision and resolutions of the available data.

Inverse Inference

(from Earth rotation data to Earth properties and dynamics)

- Core-mantle coupling (*f*, mechanism, direction)
- Inverted-Barometer (*f*, **r**)
- Love numbers (*f*)
- Ocean tidal response
- Chandler period, Chandler *Q*
- FCN period, FCN *Q* (FCN = Free Core Nutation)
- Core ellipticity/topography
- Libration
- Core equatorial ellipticity
- Inner core parameters
- Mantle conductivity
- Mantle viscosity
- Mantle heterogeneity
- …

Figure 6. A list of many important properties and dynamical behavior of the Earth that can be deduced or constrained by studying the relationship between the excitation sources and the Earth's rotational responses.

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