Laser Ranging Contributions to Earth Rotation Studies

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Abstract

The groundwork for a new field in the geophysical sciences, space geodesy, was laid in the 1960s with the development of satellite and lunar laser ranging systems, along with the development of very long baseline interferometry systems, for the purpose of studying crustal plate motion and deformation, the Earth's gravitational field, and Earth orientation changes. The availability of accurate, routine determinations of the Earth orientation parameters (EOPs) afforded by the launch of the LAser GEOdynamics Satellite (LAGEOS) on May 4, 1976, and the subsequent numerous studies of the LAGEOS observations, has led to a greater understanding of the causes of the observed changes in the Earth's orientation. LAGEOS observations of the EOPs now span 32 years, making it the longest available space-geodetic series of Earth orientation parameters. Such long duration homogenous series of accurate Earth orientation parameters are needed for studying long-period changes in the Earth's orientation, such as those caused by climate change. In addition, such long duration series are needed when combining Earth orientation measurements taken by different space-geodetic techniques. They provide the backbone to which shorter duration EOP series are attached, thereby ensuring the stability of the final combined series. And if rapidly reduced, lunar laser ranging measurements have the potential to contribute to near-real-time UTI determination.

Introduction

The Earth's rotation, encompassing both the rate of rotation and the location of the rotation axis with respect to the Earth's crust, is not constant but exhibits minute changes on all observable time scales from subdaily to decadal and longer [for a recent review see, e.g., *Gross*, 2007]. Changes in the Earth's rate of rotation amount to a few parts in 10^8, corresponding to changes of a few milliseconds (ms) in the length of the day; changes in the location of the rotation axis with respect to the Earth's crust, known as polar motion, amount to about a part in 10^6, or several hundred milliarcseconds (mas). Length-of-day (LOD) variations consist largely of: (1) decadal variations of a few milliseconds in amplitude thought to be caused by interactions between the Earth's core and mantle, (2) tidal variations having periods between 12 hours and 18.6 years caused directly by the deformation of the solid Earth in response to the action of the luni-solar tide raising potential and indirectly by the interaction of the ocean tides with the solid Earth, and (3) forced variations on intraseasonal to interannual time scales caused primarily by changes in the strength and direction of the winds with the effects of atmospheric surface pressure and oceanic currents and bottom pressure being of relatively minor importance.

Polar motion consists largely of: (1) a forced annual wobble having a nearly constant amplitude of about 100 mas, (2) the free Chandler wobble having a variable amplitude ranging between about 100 to 200 mas, (3) quasi-periodic variations on decadal time scales having amplitudes of about 30 mas known collectively as the Markowitz wobble, (4) a linear trend having a rate of about 3.5 mas/yr, and (5) smaller amplitude variations occurring on all measurable time scales. In general, the causes of the observed polar motion are not as well understood as are those of the observed length-of-day variations, although a growing body of evidence suggests that on intraseasonal to interannual time scales polar motion is caused largely by a combination of atmospheric and oceanic processes, with atmospheric surface and ocean-bottom pressure variations being more important than those of winds and currents *[Gross et al.*, 2003]. However, on decadal time scales atmospheric and oceanic processes do not appear to be energetic enough to excite polar motion to its observed levels *[Gross et al.*, 2005]. Core-mantle interactions also appear to be ineffective in exciting polar motion on decadal time scales [e.g., *Greff-Lefftz and Legros*, 1995; *Hide et al.*, 1996]. If progress is to be made in understanding the cause of decadal polar motion, then of primary importance is the continued availability of accurate and stable polar motion series of long duration.

Decadal Polar Motion

Figure 1 shows three different decadal polar motion series that were produced by applying a lowpass filter with a cutoff period of 6 years to the series of International Latitude Service [ILS; *Yumi and Yokoyama*, 1980] optical astrometric polar motion measurements (top solid green curve), the series of Hipparcos [*Vondrak et al.*, 1998] optical astrometric polar motion measurements (middle solid blue curve), and the SPACE96 [*Gross*, 1997] combination of space-geodetic polar motion measurements (bottom solid red curve). As can be seen, the decadal variability exhibited by these three polar motion series is very different. There is very little agreement between the SPACE96 series, which is based on highly accurate space-geodetic measurements, and the ILS and Hipparcos series which are based on less accurate optical astrometric measurements.

The most reliable estimates of decadal polar motion are those determined from spacegeodetic measurements. The only space-geodetic polar motion series that span the entire duration of SPACE96 are those determined from lunar and satellite laser ranging [*Gross*, 1997]. Figure 1 therefore demonstrates that the very nature of decadal polar motion was not known until the advent of the space-geodetic measurement techniques of lunar and satellite laser ranging. These laser ranging measurements must continue to be taken and reduced for Earth orientation parameters in order to provide the accurate and stable series of long duration required to investigate and uncover the cause of decadal polar motion variations

Combined Earth Orientation Series

Each of the modem, space-geodetic measurement techniques of lunar laser ranging (LLR), satellite laser ranging (SLR), very long baseline interferometry (VLBI), and the global positioning system (GPS) is able to determine the Earth orientation parameters. But each technique has its own unique strengths and weaknesses in this regard. Not only is each technique sensitive to a different subset and/or linear combination of the Earth orientation parameters, but also the averaging time for their determination is different, as is their duration, the interval between observations, and the precision with which they can be determined. By combining the individual Earth orientation series determined by each technique, a series of the Earth's orientation can be obtained that is based upon independent measurements and that spans the greatest possible time interval. Such a combined Earth orientation series is useful for a number of purposes, including a variety of scientific studies, and as an a priori series for use in data reduction procedures.

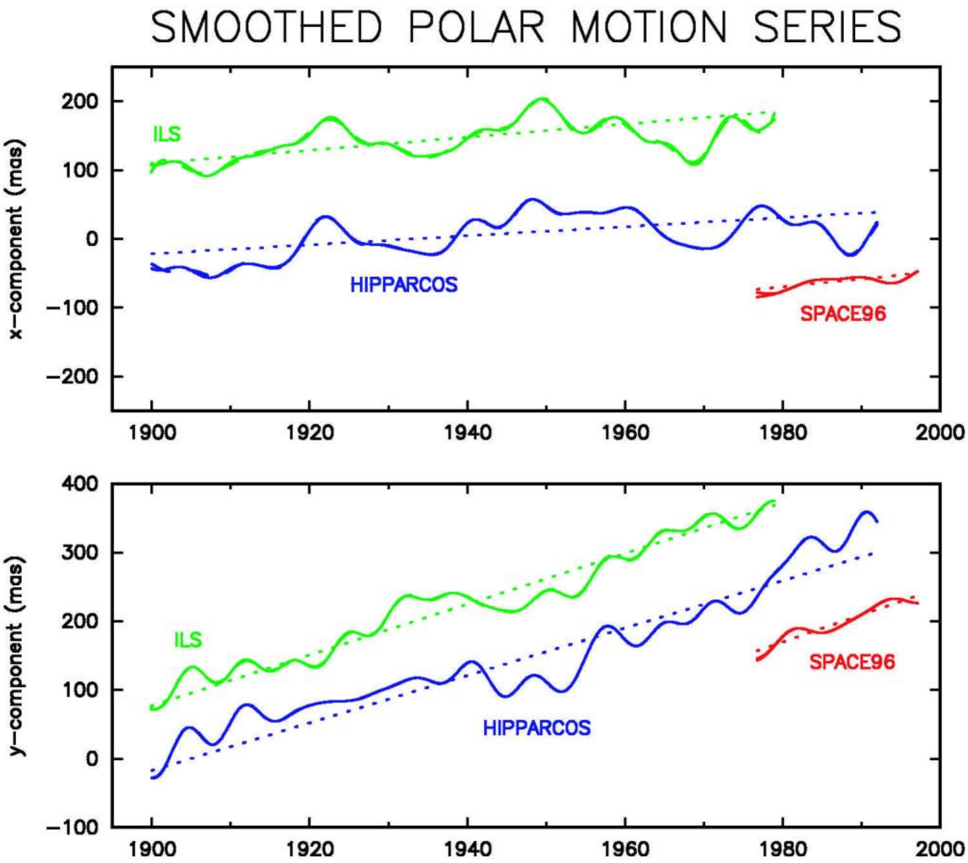

Figure 1. The x-component (top panel) and y-component (bottom panel) of decadal polar motion determined by applying a lowpass filter with a cutoff period of 6 years to the optical astrometric measurements of the International Latitude Service (top solid green curve), the Hipparcos optical astrometric polar motion series (middle solid blue curve), and the SPACE96 combination of space-geodetic polar motion measurements (bottom solid red curve). By convention, the x-component of polar motion is positive towards the Greenwich meridian and the y-component is positive towards 90^{o}W longitude. For clarity of display, 100 mas have been added to the ILS series, and 100 mas have been subtracted from the SPACE96 series. After Figure 1 of *Gross and Vondrak* [1999].

For two decades, reference Earth orientation series have been generated at the Jet Propulsion Laboratory (JPL) in support of interplanetary spacecraft tracking and navigation. These series, the latest of which is known as SPACE2007, are produced by using a Kalman filter to combine Earth orientation series taken solely by space-geodetic measurement techniques [*Gross et al.*, 1998]. A number of corrections to the individual space-geodetic series must be made in order to ensure that they are consistent with each other prior to being combined. In particular, corrections to the bias and rate of each series must be determined and applied in order to make sure that they are aligned with each other prior to combination. Stable, internally self-consistent EOP series of long duration are required when determining these bias-rate corrections in order to ensure that the corrections made to the other shorter duration series are determined consistently with each other so that no residual bias-rate difference exists between the series being combined.

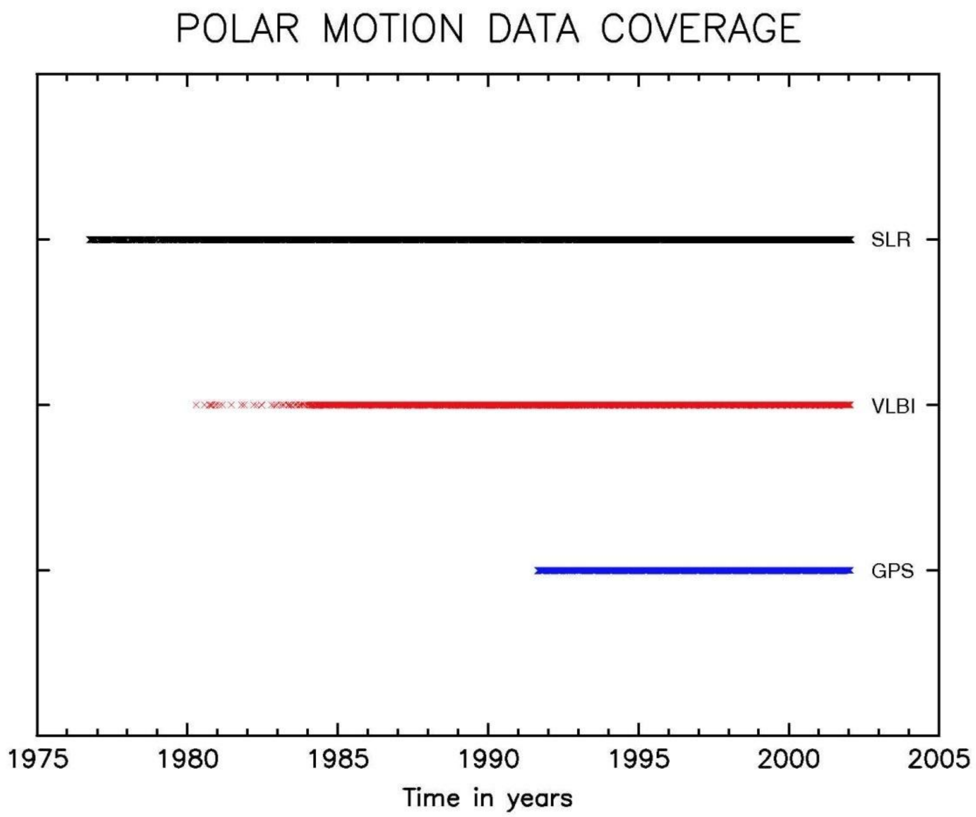

Figure 2. Epochs of the SLR, VLBI, and GPS polar motion measurements that were combined to form the SPACE2001 Earth orientation series.

Figure 2 shows the epochs of the SLR, VLBI, and GPS polar motion measurements that were combined to form the earlier SPACE2001 series [*Gross*, 2002]. The SLR measurements, which as can be seen are of longer duration than either the VLBI or GPS measurements, span the entire time interval of the SPACE2001 series. In fact, the starting epoch of SPACE2001 is determined by the starting epoch of the SLR series. The stability of the SLR series allows consistent bias-rate corrections to be determined for the shorter duration VLBI and GPS series, thereby ensuring the stability of the final combined EOP series. Due to its accuracy, stability, and long duration, the SLR series is the backbone to which other space-geodetic series are attached when combining them.

Near Real-Time UT1 Determination from LLR

Only two independent combinations of UT1 and the polar motion parameters $p_x(t)$ and $p_y(t)$ can be determined by analyzing lunar laser ranging measurements taken at a single station, namely, UT0 and the variation of latitude $\Delta\varphi_i(t)$ at that station (e.g., Moritz and Mueller, 1988, p. 425):

$$\Delta\phi_i(t) \;=\; x_p(t)\cos\lambda_i \;-\; y_p(t)\sin\lambda_i \tag{la}$$

$$UT0_i(t) \;-\; TAI(t) \;=\; U(t) \;+\; x_p(t)\sin\lambda_i\tan\phi_i \;+\; y_p(t)\cos\lambda_i\tan\phi_i \tag{lb}$$

where (φ_i and λ_i are the nominal latitude and longitude of station i and the variable $U(t)$ is defined by $U(t) \equiv UT1(t) - TAI(t)$. A rotation of the Earth about an axis connecting the station with the origin of the terrestrial reference frame does not change the distance between the station and the Moon, and hence this component of the Earth's orientation cannot be determined from single station LLR observations.

Equation (1b) shows that LLR measurements of UT0 can be used to determine UT1 if independent estimates of polar motion are available. In particular, if UT0 could be rapidly determined from LLR measurements and if polar motion estimates were also rapidly available then LLR measurements could be used to rapidly determine UT1. In principle this should be possible because unlike VLBI the LLR observation files are quite small and could be rapidly sent electronically to analysis centers for rapid reduction to UT0. Since GPS estimates of polar motion are also rapidly available, LLR has the potential of determining UT1 within hours of data acquisition, making it competitive in latency with eVLBI.

Discussion and Summary

Earth orientation parameters determined from laser ranging measurements to the Moon and artificial satellites of the Earth span a greater time interval than do those determined by any other space-geodetic measurement technique. Simultaneously processing the entire history of laser ranging measurements ensures that the resulting series of Earth orientation parameters is stable and internally self-consistent. The accurate and stable Earth orientation series of long duration derived from laser ranging measurements are required for both investigating long-period changes in the Earth's orientation, which in the case of polar motion are still of unknown origin, and for combining Earth orientation measurements taken by different techniques. Analysis centers are encouraged to continue to derive Earth orientation parameters from all available laser ranging measurements, including those beginning with the launch of LAGEOS1 on May 4, 1976 and not just those taken since 1983. By using all available laser ranging measurements, an accurate and stable EOP series of ever increasing duration will continue to be available for investigating the causes and consequences of Earth orientation variations.

Of all the space-geodetic measurement techniques only lunar laser ranging and very long baseline interferometry are able to determine Universal Time. If lunar laser ranging measurements could be rapidly processed then they could contribute to near-real-time UT1 determination. Such rapidly available estimates of UT1 are needed for a number of purposes including the prediction of GNSS satellite orbits and the tracking and navigation of interplanetary spacecraft.

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