

Laser Ranging Contributions to Monitoring and Interpreting Earth Orientation Changes

Richard S. Gross

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

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 26 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 homogeneity of the final combined series.

1 Introduction

Laser ranging measurements to the Moon and artificial satellites of the Earth have been routinely made for more than three decades. The series of Earth orientation parameters (EOPs) determined from these laser ranging measurements span a longer time interval than do those of any other space-geodetic measurement technique. The accurate and stable EOP series of long duration that have been determined from laser ranging measurements are required for investigating long-period variations in the Earth's orientation. They are also required when combining Earth orientation series in order to ensure the stability of the final combined series.

2 Earth Orientation Variations

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 reviews see, e.g., *Munk and MacDonald*, 1960; *Lambeck*, 1980, 1988; *Eubanks*, 1993]. 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 [e.g., *Ponsar et al.*, 2003 and references therein], (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 [e.g., *Gross et al.*, 2003b]. 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.

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

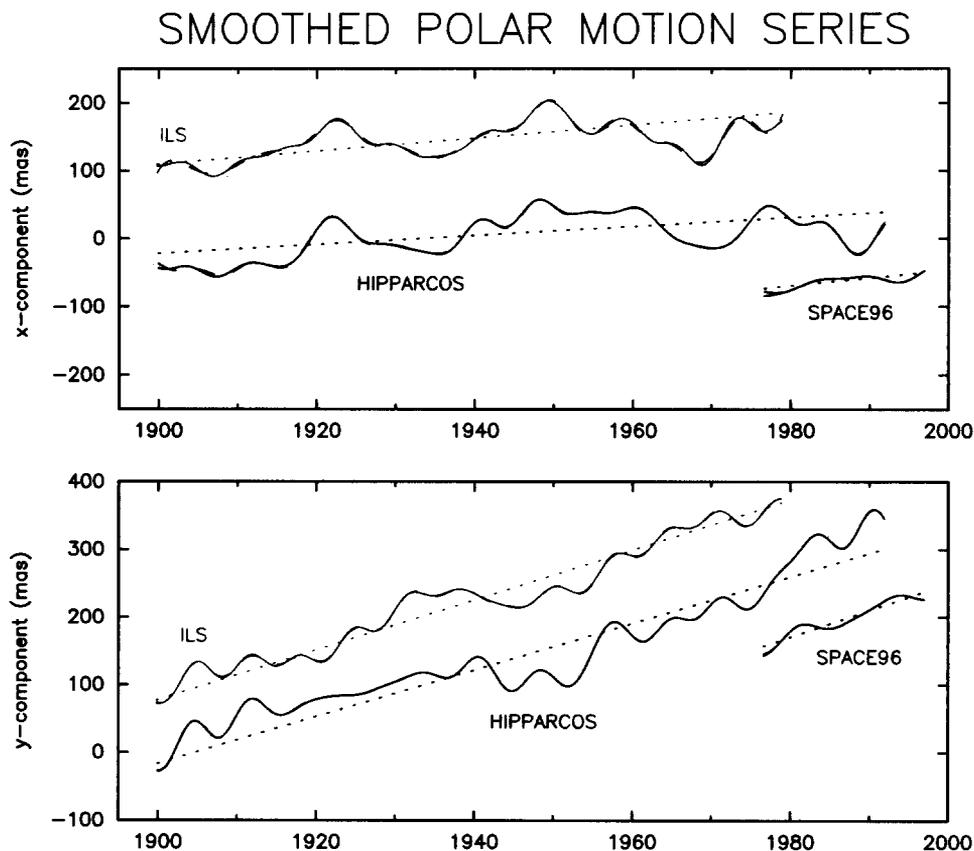


Figure 1. The x -component (top panel) and y -component (bottom panel) of decadal polar motion determined by applying a lowpass filter with a cutoff period of 6 years to the optical astrometric measurements of the International Latitude Service (top solid green curve), the Hipparcos optical astrometric 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°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 Vondrák* [1999].

intraseasonal to interannual times 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 [e.g., *Gross et al.*, 2003a]. 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.*, 2003a]. Core-mantle interactions also appear to be ineffective in exciting polar motion on decadal time scales [e.g., *Hide et al.*, 1996 and references therein]. 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.

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 [*Vondrák 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 space-geodetic 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 to determine the 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.

3 Combined Earth Orientation Series

Each of the modern, 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 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.

For more than a decade, 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 SPACE2001 [*Gross*, 2002], 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 together. 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 for 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 shows the epochs of the SLR, VLBI, and GPS polar motion measurements that were combined to form SPACE2001. 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.

4 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

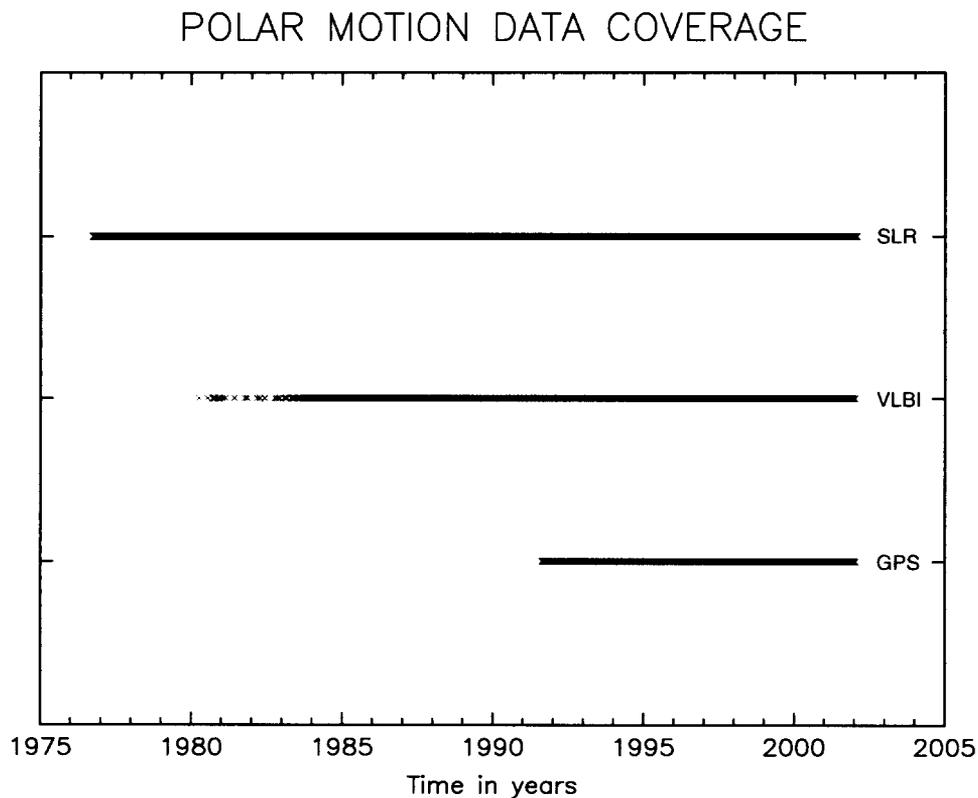


Figure 2. Epochs of the SLR, VLBI, and GPS polar motion measurements that were combined to form the SPACE2001 Earth orientation series.

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 LAGEOS I 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.

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