

## PART V : SATELLITE LASER RANGING

### DETERMINATION OF POLAR MOTION AND EARTH ROTATION FROM LASER TRACKING OF SATELLITES

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#### ABSTRACT

Laser tracking of the Lageos spacecraft has been used to derive the position of the Earth's pole of rotation at 5-day intervals during October, November and December 1976. The estimated precision of the results is 0.01 to 0.02 arcseconds in both x and y components, although the formal uncertainty is an order of magnitude better, and there is general agreement with the Bureau International de l'Heure smoothed pole path to about 0.02 arcseconds. Present orbit determination capability of Lageos is limited to about 25 cm rms fit to data over periods of 5 days and about 50 cm over 50 days. The present major sources of error in the perturbations of Lageos are Earth and ocean tides followed by the Earth's gravity field, and solar and Earth reflected radiation pressure. Ultimate accuracy for polar motion and Earth rotation from Lageos after improved modeling of the perturbing forces appears to be of order  $\pm 5$  cm for polar motion over a period of about 1 day and about  $\pm 0.2$  to  $\pm 0.3$  milliseconds in U.T. for periods up to 2 or 3 months.

#### INTRODUCTION

The determination of polar motion and Earth rotation from the tracking of satellites is based on the concept that over a given period of time the motion of the satellite about the Earth is known with sufficient accuracy that for all practical purposes it is fixed in an inertial (reference) frame. In reality, the spacecraft is continuously perturbed by forces interior and exterior to the Earth and the orbit of the spacecraft is continuously evolving. The use of satellite orbits for polar motion and Earth rotation, therefore, reduces primarily to a problem in the determination of the spacecraft orbit and to the detailed understanding of the changes that the orbit goes through. Thus, key aspects are the process of orbit determination from tracking data and orbital stability.

The problems of orbit determination are associated with the quality,

quantity, and distribution of the tracking. Frequently, some or all of these factors are outside the control of the scientist using the data, but it is possible to plan and specify the requirements in each of these areas if the final quality of the required orbit is known. The orbit determination process is essentially deterministic and generally well understood although opinions may differ on the optimum mathematical techniques that should be used. The limiting factor in satellite techniques for polar motion and Earth rotation is clearly our degree of understanding (or predictability) of the evolution of the orbit over a period of time. Fortunately, the primary forces perturbing the orbits of satellites are known, and consequently it has been possible to design a spacecraft and its orbit to minimize the influence of these forces. This spacecraft, Lageos (Laser Geodynamics Satellite), was launched on May 4, 1976 into a high orbit nearly 6000 kilometers above the Earth's surface, and because of its altitude, is much less affected by poorly-known short wavelength features in the gravity field. The spacecraft is heavy (411 kg) and therefore almost unaffected by the perturbing forces of solar radiation, Earth albedo and air drag which severely perturb spacecraft of less weight at lower altitudes. Thus the Lageos spacecraft and orbit come close to acting as an artificial reference system in Earth orbit. A summary of Lageos and its orbit is given in Table 1.

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Table 1. Lageos Spacecraft and orbit.

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Launch:	May 4, 1976	
Spacecraft:	Spherical, 60 cm diameter	
	411 kg	
	426 retro-reflectors, each 3.8 cm in diameter	
Orbit:	Semi-major axis	12265 km
	Inclination	109.8 degrees
	Eccentricity	0.004
	Perigee height	5858 km
	Apogee height	5958 km

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Initial experiments to determine polar motion from laser tracking of satellites were conducted using the Beacon Explorer C spacecraft at 1000 km altitude. We were able to show that the variation of latitude could be determined at about the 1 meter level with this spacecraft over periods as long as eighteen months and that an estimate of Earth rotation could be derived over a short period of 3 weeks (Smith, et al., 1972; Kolenkiewicz, et al., 1974; Dunn, et al., 1977). It was clear, however, from these studies that perturbations of the spacecraft by the Earth's gravity field, Earth and ocean tides, air drag, etc., were limiting the capability and that a higher and heavier spacecraft (Lageos) was necessary. Further, all these investigations had been conducted with a single laser station and this was an additional limitation on the development of the technique.

The method of deriving polar motion from a satellite laser tracking network is different from the single station case because with a network, long-term stability of the orbit is not a requirement. Orbit stability is only required over the period (hours to days) over which a single pole position is desired. That is, for a five-day (mean) pole position orbit stability is only required over the five days. With a network of stations the determination of the pole position reduces to deriving the coordinates of that point (the pole) about which the network appeared to rotate during the period (five days, one day, etc.). From one period to the next there is no requirement for the orbit to be known; indeed, a different satellite can be used since the satellite is only a common object for all the tracking stations to observe. Common to all pole position determinations is the station coordinates of the laser systems and these must be well-known. It is in the coordinate system of the stations that the pole position is referred. For Earth rotation measurements (time), however, orbit stability is essential. The means by which Earth rotation can be derived from a satellite is to measure the relative rotation about the Earth's spin axis of the network (or station) with respect to the orbital plane of the spacecraft. In order for this measurement to be referred to an inertial frame the orbital plane must be unperturbed or its perturbations very predictable. Although the perturbations of the Lageos orbit are small the slow secular perturbation of the node of the orbit by effects not fully understood will always exist. Thus short-term variations in Earth rotation will be more easily (and accurately) observed with Lageos than long term changes. Further discussion of the measurement of polar motion and Earth rotation from spacecraft is given in Kolenkiewicz, et al. (1977).

#### LAGEOS RESULTS

The first eight months of tracking of the Lageos spacecraft by the Goddard Space Flight Center (GSFC) and Smithsonian Astrophysical Observatory (SAO) laser systems have been analyzed. During this period (May to December 1976) the GSFC lasers operated from sites in North America: Greenbelt, MD (Stalas); San Diego, CA (Moblas 3); Quincy, CA (Moblas 2); Bear Lake, UT (Moblas 1). During the first few months only the Stalas system was operational and during the last three months only the three lasers at San Diego, Quincy, and Bear Lake were in operation. The SAO lasers were located at Arequipa, Peru; Natal, Brazil; Orroral, Australia; and Mt. Hopkins, AZ in North America. The Orroral system did not begin operations until the latter part of 1976.

The quality of the data obtained from these systems was approximately 10 cm rms deviation for a single measurement from the GSFC system and approximately 1 meter from the SAO systems. The quality of orbit determination with the tracking data is summarized in Table 2. With the better data orbital fits of a few tens-of-centimeters were obtainable for orbital arcs of one month or more. However, it should be remembered that the three GSFC lasers that were used in the orbit determination were all located within about 1200 km of each other, and we therefore

cannot be sure that similar orbital fits would be obtainable if one of these stations had been in Australia. An upper limit on the "poorness" of these orbits is provided by the SAO Orroral laser in which orbital fits of better than 1 meter were regularly obtained with orbital arcs of 5 days in length.

Table 2. Lageos orbit fits with GSFC laser data.

	Orbital Fit
1 pass (45 minutes)	10 cm
5 days	25 cm
30 days	40 cm
50 days	50 cm

From the tracking data a set of 31 five-day orbital arcs were determined from which a set of station coordinates was derived (to be published elsewhere). Using these station coordinates 30-day orbital arcs were derived for each of the months, October, November and December 1976. During each 5-day period within each monthly arc the station network was rotated about the equatorial axes through Greenwich and  $90^\circ$  W longitude (parallel to the x and y polar coordinate axes) in order to better fit the tracking data to the orbit and thus provide an improved mean position of the pole during the 5-day period. The 30-day orbit of the spacecraft was then re-adjusted using the up-dated pole positions and each of the pole positions re-determined. This iterative procedure was continued until no change in the orbit or the pole was detectable between iterations. We found that the solution converged to better than  $10^{-3}$  arcseconds after only one iteration.

The x and y polar coordinates obtained from the Lageos data in the manner described are shown in Figures 1 and 2. Near the end of December there were only a few observed passes of the satellite. The recovered y value of the pole position for December 27 was very different from previous values and has been omitted from Figure 1. The formal uncertainty of each of the x values is approximately  $3 \times 10^{-3}$  arcseconds and approximately  $2 \times 10^{-3}$  arcseconds for y. Some variation in the uncertainty exists between the points and reflects the quantity and quality of the data. The y component is more strongly determined because most of the stations had longitudes in the region of  $90^\circ$  W.

The true uncertainty in both x and y is believed to be between 1 and  $2 \times 10^{-2}$  arcseconds for most of the data.

Figures 1 and 2 show good general agreement between the smoothed BIH values and the Lageos results for most of the three-month period. However, we do not believe the large departure in x from the smoothed

BIH in December 1976 is real. At the present time we do not have an explanation of this difference but stress that the Lageos results presented here are preliminary. The results described were obtained using the GEM 10 gravity field model (Lerch, et al., 1977) and the Geodyn orbit determination program.

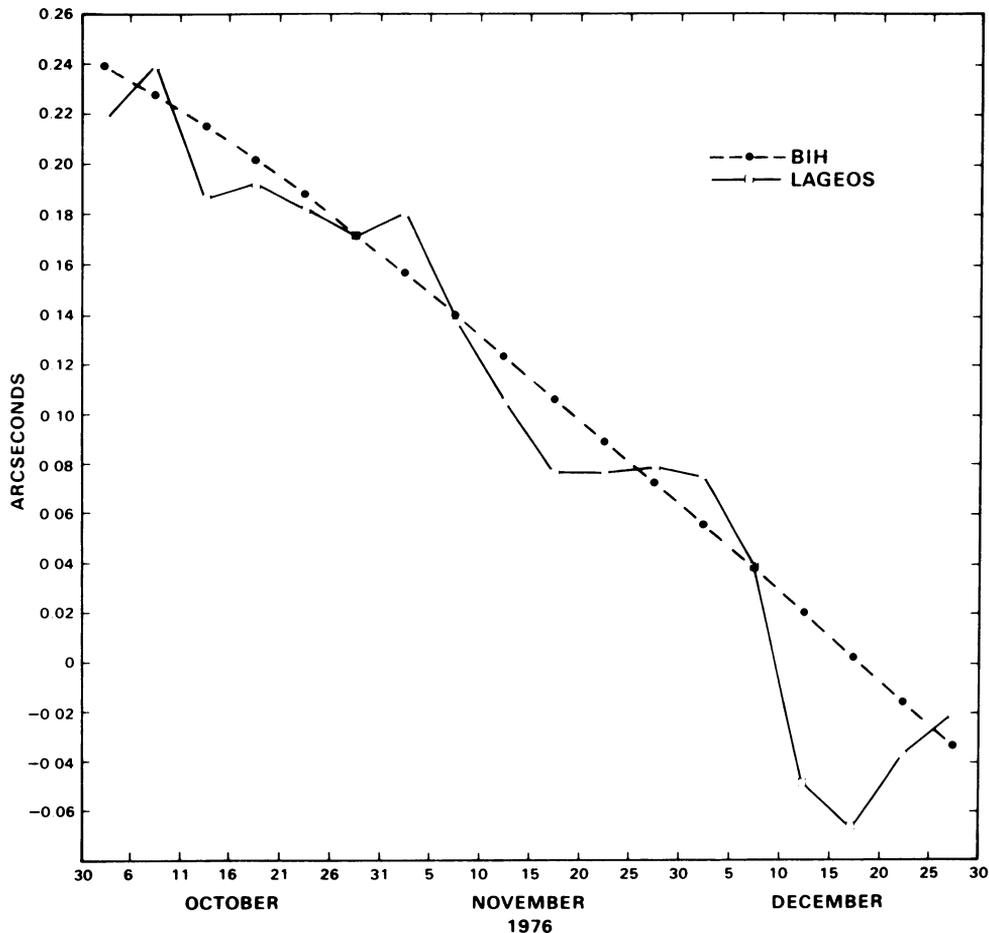


Figure 1. X-component of polar motion.

#### LIMITATIONS

As described in the Introduction the accuracy of polar motion and universal time determined from Lageos tracking data is limited by orbit stability. Simulations that we have performed (Kolenkiewicz, et al., 1977) indicate accuracies of the order of 1 or  $2 \times 10^{-3}$  arcseconds in polar motion are possible over a few days even from a single station

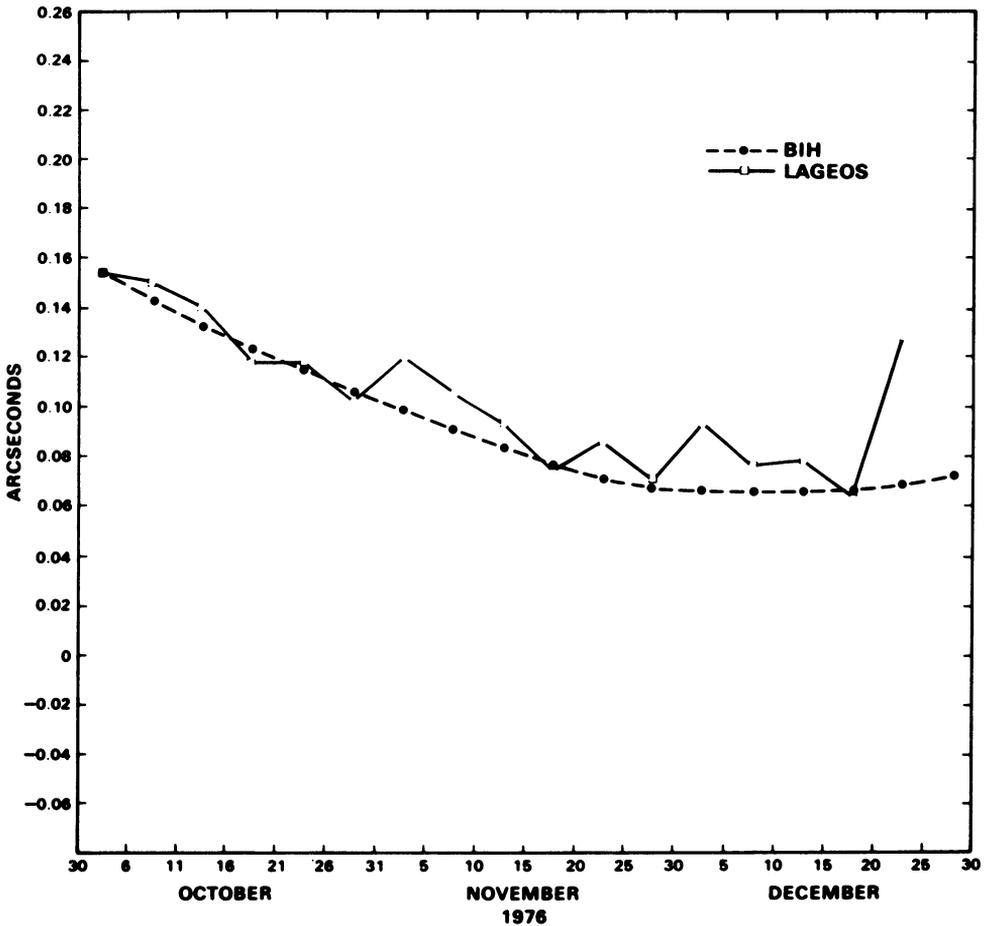


Figure 2. Y-component of polar motion.

and can find no perturbing forces which, in principle, cannot be adequately modeled for Lageos at the  $10^{-3}$  arcsecond level. These include gravity, station coordinates, Earth mass, solar radiation pressure, and Earth albedo radiation, although the latter is extremely complex and difficult to assess (Smith, 1970). For Earth rotation the limitation appears to be albedo and ocean tides. Our estimate of the nodal perturbation by uncertainties in albedo is a few thousandths of a second of arc after a few months based on a comparison with uncertainties in direct solar radiation effects which we always find to be greater than, or comparable to, albedo. Ocean tides are at present even less well known but will probably be completely modelable after a few years of tracking. The ocean (and solid Earth) tides perturb the orbital inclination and node, producing periodic and near-secular terms in the latter. These terms in the acceleration of the orbit may be the present limitation on using Lageos for measuring U.T. Our present assessments

of these forces on the orbital inclination and node are shown in Table 3.

Table 3. Lageos orbit perturbations during first 230 days after launch.

	Error	Orbital Inclination (degrees)	Nodal Position (degrees)
Solar radiation pressure	10%	$3 \times 10^{-7}$ (3cm)	$4 \times 10^{-7}$ (4cm)
Earth albedo pressure	100%	$4 \times 10^{-7}$ (4cm)	$6 \times 10^{-7}$ (7cm)
Earth and ocean tides	10%	$6 \times 10^{-5}$ (7m)	$2 \times 10^{-5}$ (2m)
Gravity	(*)	$3 \times 10^{-7}$ (3cm)	$1.5 \times 10^{-6}$ (17cm)

\*Difference between Goddard Models 9 and 10 (GEMS 9, 10)

The inclination is probably the single most important parameter for estimating polar motion, and the node for estimating U.T. It should be noted that Table 3 shows the perturbation during a 230-day period, and that for polar motion periods of 5 days or less, the perturbation will be considerably smaller for all secular or long period effects. If the ocean tides can be adequately modeled then the ultimate polar motion accuracy is probably of the order 5 cm, over averaging times from 1 to 5 days, and about 0.2 to 0.3 milliseconds in U.T. over 3 months. The date when this capability will be approached will probably be around 1981-2, assuming continued development of systems and models.

## CONCLUSIONS

Five-day polar motion has been derived from Lageos laser tracking for the period October through December 1976 with a precision of 0.01 to 0.02 arcseconds. Although the data were frequently of only 1 meter quality, never more than seven stations tracking, and the period only 3 months duration, these preliminary results demonstrate that Lageos can be used for determining polar motion as originally envisaged prior to the launch of the spacecraft. Improvements in the quality of the results can be expected over the next few years as more stations begin to track Lageos at the 10 cm level, as our modeling of the perturbing forces improves (particularly Earth and ocean tides), and as the quantity and regularity of the tracking increases. As far as can be determined at the present time there appears to be no perturbing forces which should not be adequately modelable in the next few years to ultimately permit 5 cm daily polar motion determinations and 0.2 millisecond U.T. measurements.

## REFERENCES

- Dunn, P. J., Smith, D. E., and Kolenkiewicz, R.: 1977, *J. Geophys. Res.* 82, pp. 895-897.
- Kolenkiewicz, R., Smith, D. E., and Dunn, P. J.: 1974, in G. Veis (ed.), "The Use of Artificial Satellites for Geodesy and Geodynamics", National Technical University of Athens, Athens, pp. 813-823.
- Kolenkiewicz, R., Smith, D. E., Rubincam, D. P., Dunn, P. J., and Torrence, M. H.: 1977, *Phil. Trans. R. Soc. Lond. A.* 284, pp. 485-494.
- Lerch, F. J., Klosko, S. M., Laubscher, R. D., and Wagner, C. A.: 1977, "Gravity Model Improvement Using GEOS-3 (GEM 9 and 10)", Goddard Space Flight Center, X-921-77-246.
- Smith, D. E.: 1970, in B. Morando (ed.), "Dynamics of Satellites", Springer-Verlag, Berlin, pp. 284-294.
- Smith, D. E., Kolenkiewicz, R., Dunn, P. J., Plotkin, H. H., and Johnson, T. S.: 1972, *Science* 178, pp. 405-406.

## DISCUSSION

- P. Paquet: What is the present rms error of the 5-day polar coordinates obtained by this method?
- D. E. Smith: The internal precision of each 5-day value is approximately 0.001 arcsec. The consistency between the 5-day values is about 0<sup>h</sup>01<sup>m</sup> rms and the rms deviation with respect to BIH values is nearly 0<sup>h</sup>02<sup>m</sup>.
- P. Paquet: You quoted errors of between 20 cm and 50 cm in the station coordinates. How many days of observations were used in these determinations?
- D. E. Smith: 150 days of observations were used to determine the coordinates of all the tracking stations. Three sub-sets, each of 50 days, showed differences ranging from a few centimeters to over 50 cm. The poorest determinations were for some of the Smithsonian stations that only had one meter ranging capability. I estimate the general accuracy of this network to be near 20 cm for the better stations and about 50 cm for the weaker stations.
- P. Brosche: Which model of oceanic tides was used? I recommend Dr. Zahel's newest model including self attraction and loading.
- D. E. Smith: We did not model the ocean tides - only those of the solid Earth. However, it is clear from our investigations that the ocean tides must be included and we shall try several models on the Lageos data.
- P. Brosche: What is the reason that the satellite laser techniques does not give tremendously better results than lunar laser ranging?
- E. C. Silverberg: This is a common misunderstanding brought about by the fact that the satellite workers report "accuracy" as their single-shot uncertainty, while lunar workers average many shots and report normal point "accuracy". In fact, the single-shot uncertainty is usually numerically greater for lunar systems than for satellite systems, but the slowness of the lunar orbit permits more averaging of data