Lageos 2 spin rate and orientation

Roger Wood [1], *Toshimichi Otsubo* [2] *& Robert Sherwood* [1]

[1] NERC Space Geodesy Facility, UK
[2] Communications Research Laboratory, Japan

Abstract

The Herstmonceux photometer system (which allows brightness measurements of sunlit satellites to be made simultaneously with laser ranging) has been upgraded to provide 1 millisecond time resolution. Precise timing of solar glints from the front faces of the corner-cube reflectors on Lageos 2 over a 2-year period has yielded a detailed record of the slowing of the satellite's rotation and an accurate determination of the precessional behaviour of the spin axis. These data make possible precise modelling of the non-gravitational forces on the satellite and contribute powerfully to evaluations of their evolution in the long-term.

Introduction

Each Lageos satellite (see *e.g.* Minott *et al.* 1993) carries 426 retro-reflectors inset in the outer aluminium shell surrounding a solid brass cylinder. Each reflector is mounted with its front face perpendicular to the radius vector at the mounting point. Reflectors are distributed over the whole surface of the sphere in rings, equally spaced along lines of "latitude" (where the "equator" is the great circle perpendicular to the axis of rotation of the satellite). Immediately either side of the "equator" are rings of 32 reflectors: then, moving towards the "poles", successive rings have 32, 31, 31, 27, 23, 18, 12, 6, 1 (at the "pole") reflectors, giving a total of 213 in each hemisphere. 422 of the reflectors are made of fused silica and 4 of germanium. Figure 1 shows the resultant distribution of reflectors on the surface of the satellite.

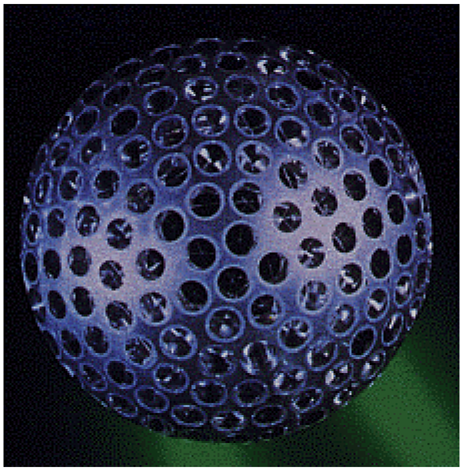

Figure 1. *Lageos 2 showing the distribution of retro-reflectors.*

When the Lageos satellites were separated from their launch vehicles they were spun to enhance stability and minimise the effects of differential solar heating. As Lageos revolves around the Earth the sunlit hemisphere of the body of the satellite reflects sunlight in all directions and a faint image (stellar magnitude ~V=12) is visible at night whenever the satellite is not in the Earth's shadow. In addition sunlight is reflected from the front faces of the retro-reflectors producing a diverging pattern of beams that rotates at twice the spin rate of the satellite. Each reflected beam is a narrow cone of divergence 30 arcminutes, the angular diameter of the Sun as seen from the Earth. At certain points in the Lageos orbit it sometimes happens that a beam is reflected directly into an SLR telescope in which case an alert observer would see a large, but short-lived, increase in the brightness of the image. Such brightenings are called *solar glints* and reach stellar magnitude ~V=9, a factor ~20 brighter. Because the rotation of Lageos 2 is fast compared with the time it takes for the orbital motion to change the particular geometry required for a glint, glints tend to occur in bursts from successive reflectors in one ring as the satellite rotates: a schematic of the geometry is shown as Figure 2.

For many passes, as the relative orientations of Sun, satellite and station change, there are several bursts of glints, each from a different ring of reflectors. Just occasionally the change in orientation due to rotation is very nearly compensated by the orbital motion and there is a prolonged period (up to 10 minutes in some cases) of glints all from a single ring.

This paper describes upgrades to the Herstmonceux photometer system that have allowed precise measurement of glints, and gives the results of determinations of the rotation period and spatial orientation of the Lageos 2 satellite.

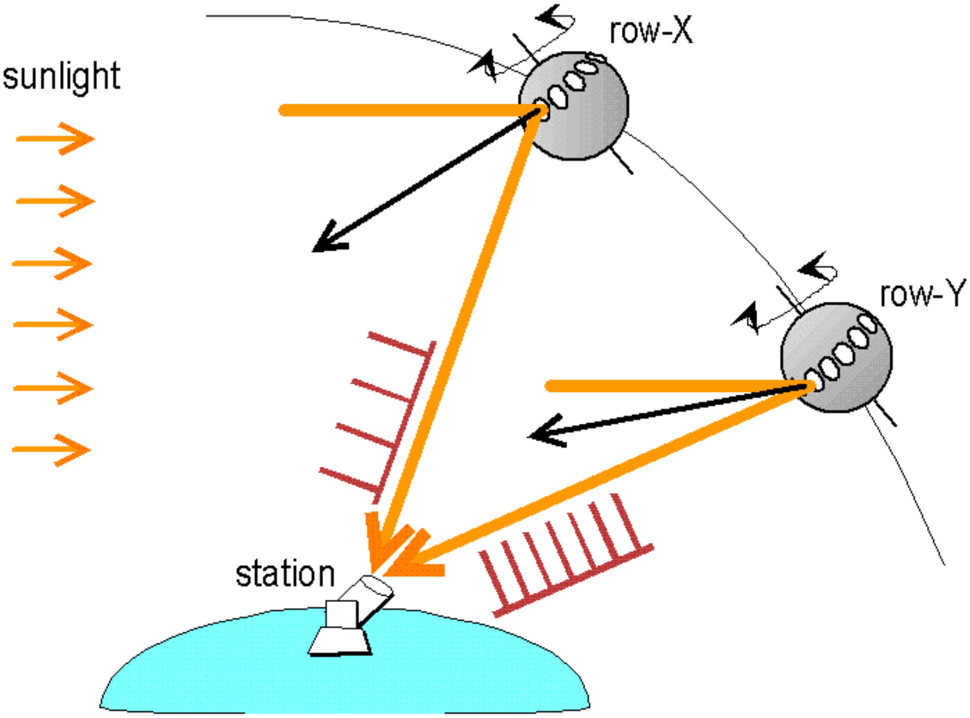

Figure 2. *How solar glints occur. Note that, at different points in the orbit, Sunlight is reflected towards the telescope from different rows; and that rows with fewer reflectors give rise to longer intervals between glints.*

Photometer upgrade

In the Herstmonceux SLR telescope collimated light enters the detector box at the Cassegrain focus and is split by a dichroic mirror: green light (a 3nm-wide spectral band centred on the laser wavelength) passes straight through for laser ranging; all other wavelengths are reflected to a side port of the box where they may be viewed using a TV camera or input to a photometer. In the original system the detector was a rather ancient photomultiplier and photons were counted with a Stanford counter at a timing resolution (limited by the speed of the RS232 communication link) of about 20ms. Both these items have been replaced. The new photon counting photomultiplier is a Hamamatsu H7155 chosen for its low dark count (~100cps), excellent pulse-pair resolution (~70ns) and wide spectral response (300−650nm). The device is compact, lightweight (75g) with an entrance window of 8 mm diameter on to the photo-cathode, and requires only 250mW from a +5V DC supply, all of which features make it ideal for mounting on the telescope. The output pulses from the photomultiplier are fed to a Keithley KPCI-3140 counter board mounted in a PCI slot of a standard PC. The board is supplied with the same high quality 10MHz timebase (a quartz crystal disciplined by GPS) that is used for the laser ranging system. One of the board's counters is configured to count 10MHz pulses to create precisely timed sampling bins (in this case 1ms each) whilst another counts the photon events from the photomultiplier in each of these time bins. The time-stamped counts are then written to the PC's hard disk at the end of each bin.

Observations

In the observations reported here the satellite image in "non-green" light was first viewed via the TV and centred in the focal plane iris before being switched to the photometer for photon counting. By utilising the light diverted by the dichroic in this way it is possible to conduct photometric measurements at the same time as the system is being used for its primary purpose of laser ranging. Outgoing laser pulses are strongly back-scattered by dust and water vapour in the atmosphere above the telescope, resulting in photon counts hugely in excess of any seen from sunlight reflected from the satellite. However, they are of very short duration, just a few tens of nanoseconds, and only occupy a single time bin. Thus, with the laser firing 13 times a second, fewer than 2% of the 1ms bins are contaminated by laser light, and they are easily discriminated from reflected sunlight by the magnitude of the count.

Figure 3 shows a plot of counts from a typical Lageos 2 pass following the satellite from a low elevation, through the period above 30° during which the laser was fired, and then a short section below 30° again as the satellite set. The various constituent contributions can easily be identified. The central sector shows the very bright laser noise. Underlying this (and seen throughout the whole pass) is the low level background made up of "sky" plus the steady light reflected from the body of Lageos 2. Rising above the background are six bursts of glints labelled A−F. Other occasional features are caused by stars crossing the aperture or the observer switching briefly to the TV to recentre the image in the iris. Within each burst, shown in greater detail in the lower half of the figure, the regularity of glints is immediately apparent.

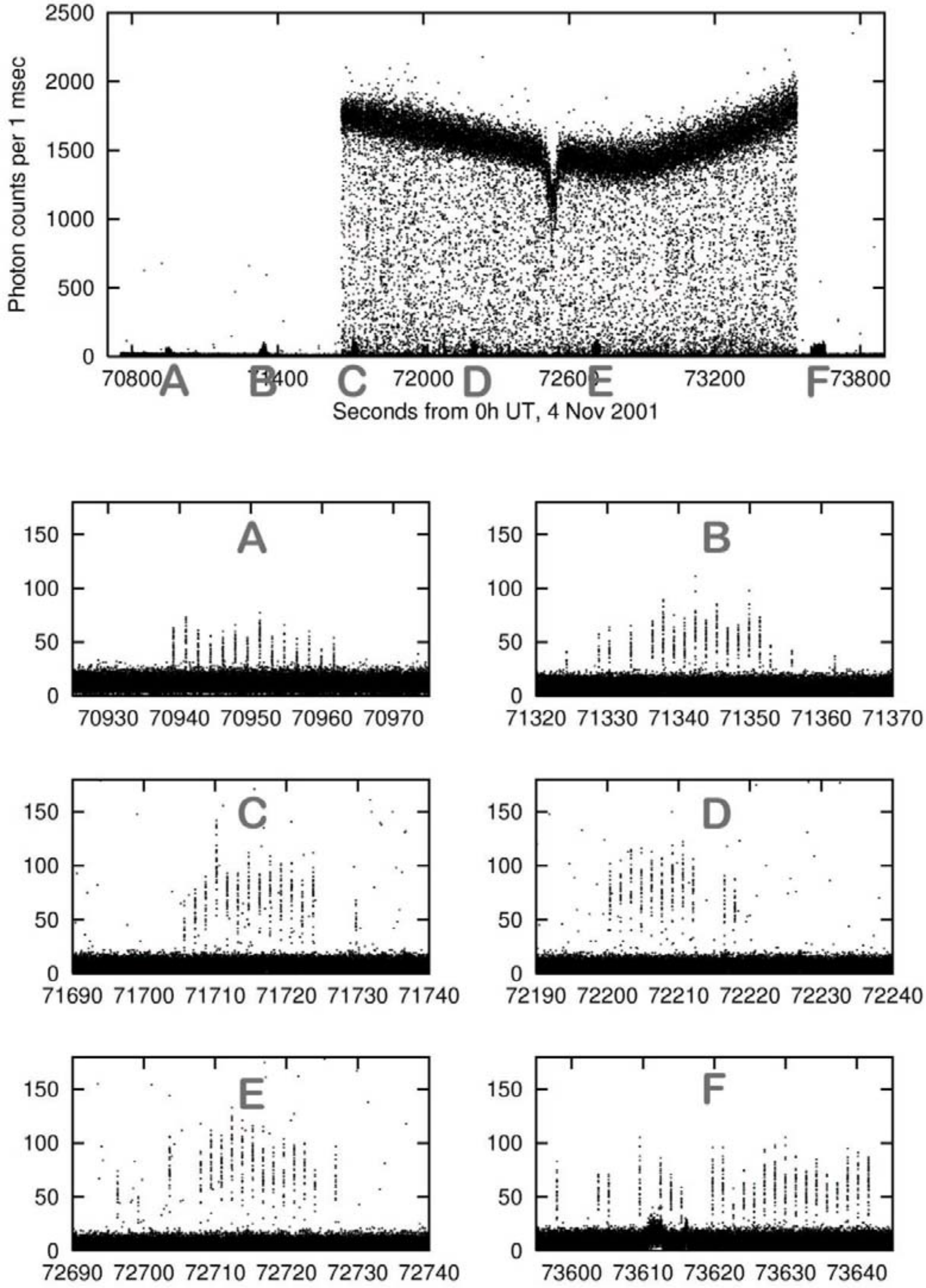

Figure 3. *A Lageos 2 pass showing photometry with laser ranging (the central, high noise section) and six separate bursts of solar glints (A – F).*

Spin period determination

It is clear that if we know from which row of reflectors the glints come, we know how many reflectors there are in that row. It is then a simple matter to determine the rotation period by multiplying together the mean time interval between glints and the number of reflectors in the row. In practice, of course, the information from a single burst of glints is not enough to fix the identity of the row. However, in a pass such as the example above, where there are several separate bursts, it is usually the case that the mean interval between glints is well determined and differs from burst to burst. Then the inverse of the ratios between the different mean intervals is found to match very closely the ratios between the known numbers of reflectors in different rows (see the first paragraph of the introduction). Thus, for some bursts, it is possible to state unambiguously the precise number of reflectors in the glinting row, and hence which row it was. (Strictly speaking there is always a two-fold ambiguity because the reflector pattern is symmetrical about the equator of the satellite – more on this below). Indeed it was just this line of reasoning, applied to our early multi-burst passes, which enabled us to deduce the rotation rate.

As more and more data were gathered over several months, analysis of the multi-burst passes gave a series of very accurate values for the spin period, which indicated a steady, near-exponential increase in the period with time, as shown in Figure 4. With the regular nature of the slow down well established, it was possible to go back to passes with only one or two bursts and interpolate between the multi-burst values to get a very close approximation to the spin period at the time of those passes. In almost all cases the interpolated period in combination with the mean glint interval in the burst was enough to give a clear-cut determination of the number of reflectors in the glinting row; and the argument can then be reversed to provide the actual spin period at the epoch of the pass.

Bianco *et al* (2001) have examined ranging observations of Lageos 2 made at the new Matera Laser Ranging Observatory, and deduced the spin rate from spectral analysis of the range residuals. Their values agree very well with those presented here. But it is clear, even from the relatively limited time-span of their data coverage, that the method is best suited to rapid satellite rotation and does not yield any information about spin axis orientation.

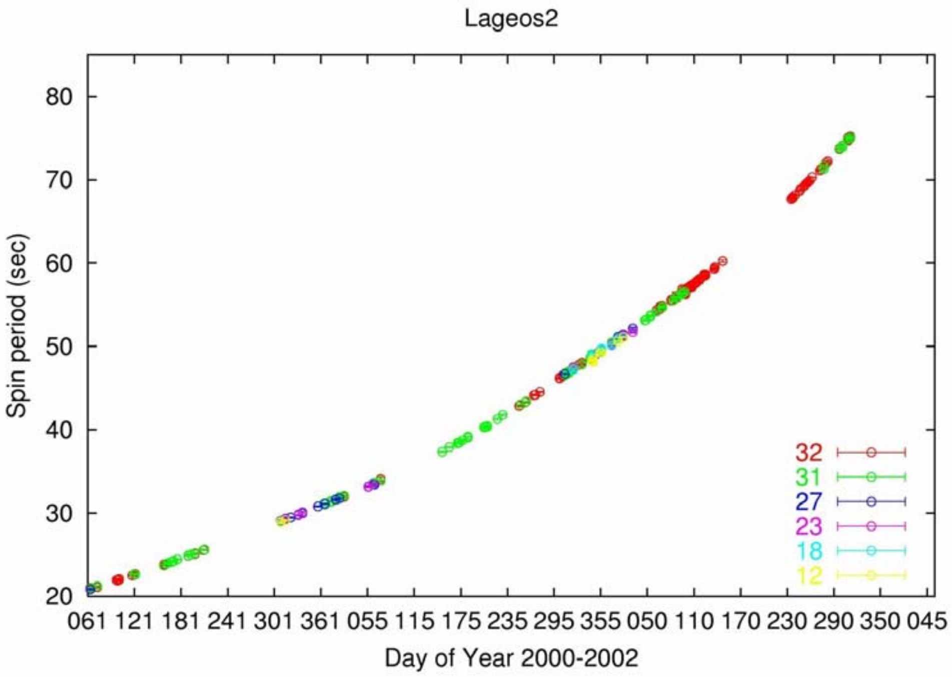

Figure 4. *Spin period history (colour-coded by the number of reflectors per row).*

Spin axis orientation

Figure 2 shows the geometrical condition for a solar glint to be observed at the surface of the Earth. The radius vector at the mount location of the reflector (*i.e.* the perpendicular to the front face of the reflector) must bisect the angle, at the satellite, between the direction to the Sun and that to the telescope. For a given pass the satellite's orbit and the Earth's rotation can be used to compute the precise orientation of this radius vector in space. If we know from which reflector row the glints originate, then we know from the structure of the satellite the angle (call it α) between the radius vector and the spin axis. So at the time of the glint, knowing the position of the radius vector in space, the spin axis can lie anywhere on the surface of the cone of half-angle α formed by rotation about the radius vector. The projection of that cone on to the celestial sphere forms a small circle centred on the point of intersection of the radius vector: each point on the circumference this circle represents a possible direction for the spin axis. In general we cannot uniquely identify the glinting row by deducing the number of reflectors in it: there is always a corresponding row in the opposite hemisphere of the satellite; and in the case of the rows near the satellite equator, it may be any one of four rows. Thus, having deduced the number of reflectors in the glinting row from the photometry, the above argument can be applied to each row with that number of reflectors, and each will generate its own small circle on the celestial sphere according its corresponding value of α.

In cases where only a single burst of glints is seen the direction of the spin axis remains undetermined. However, for multi-burst passes we can, for each burst, determine the number of reflectors in the glinting row, define the “spin axis” cones corresponding to each row with this number of reflectors, and plot each matching small circle on the celestial sphere. During one pass we can be confident that the absolute orientation of the spin axis will change very little, so that each burst should give the same result. Figure 5 shows all the possible small circles relating to the bursts in Figure 3 plotted on the sky. It is immediately clear that there is only a single point common to just one small circle from each burst, and that must represent the position of the spin axis at the time of the pass. For passes with fewer bursts the axis solution is less well defined, and so an automated identification scheme was used. The celestial sphere was divided into small cells and, for each candidate circle, each cell was assigned a weight based on the shortest distance to a point on the circle. A total weight for the pass was then formed by multiplication in each cell of the individual weights from each circle. The cell with the highest weight was then adopted as the axis solution. In the best cases the axis position may be determined within about 0.1 of a degree, but always better than 1 degree.

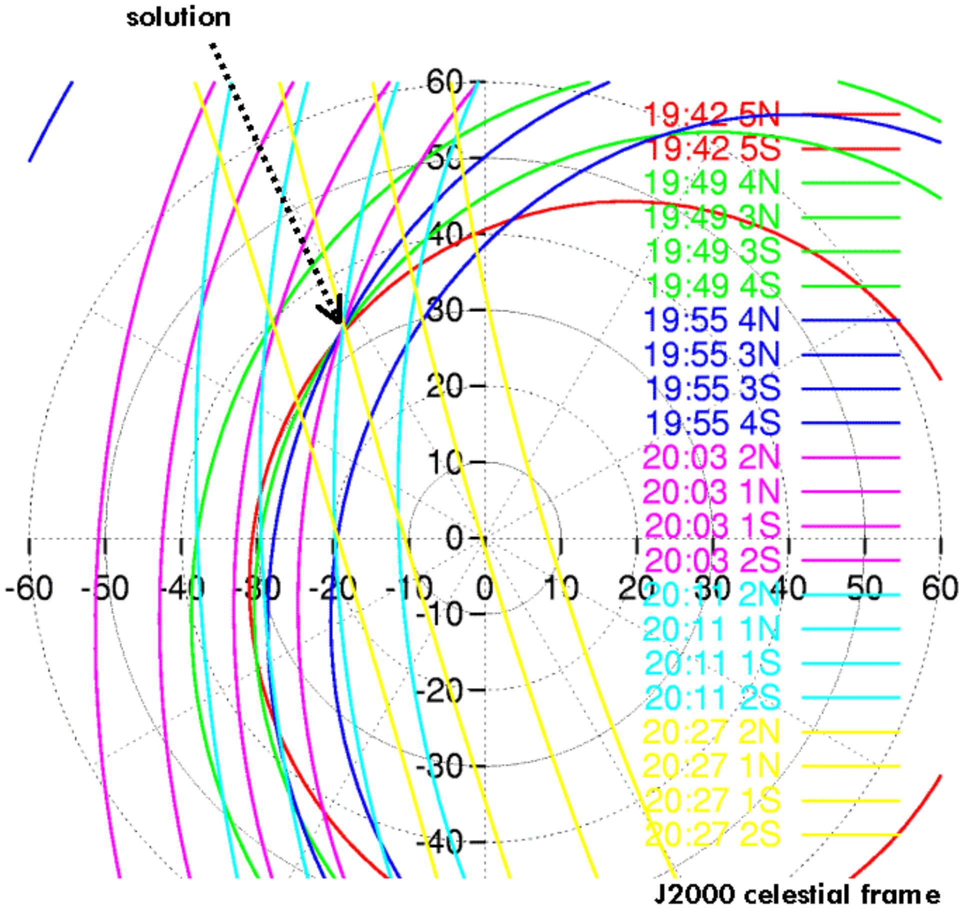

Figure 5. *The spin axis solution from the data shown in Figure 3.*

The positions determined in this way are gathered in Figure 6 and demonstrate that the spin axis has undergone considerable movement over the period of the observations. This precessional behaviour is in good agreement with expectations of a metal body rotating in the Earth's magnetic field (Bertotti & Iess 1991) and provides the raw data for those wishing to construct detailed models.

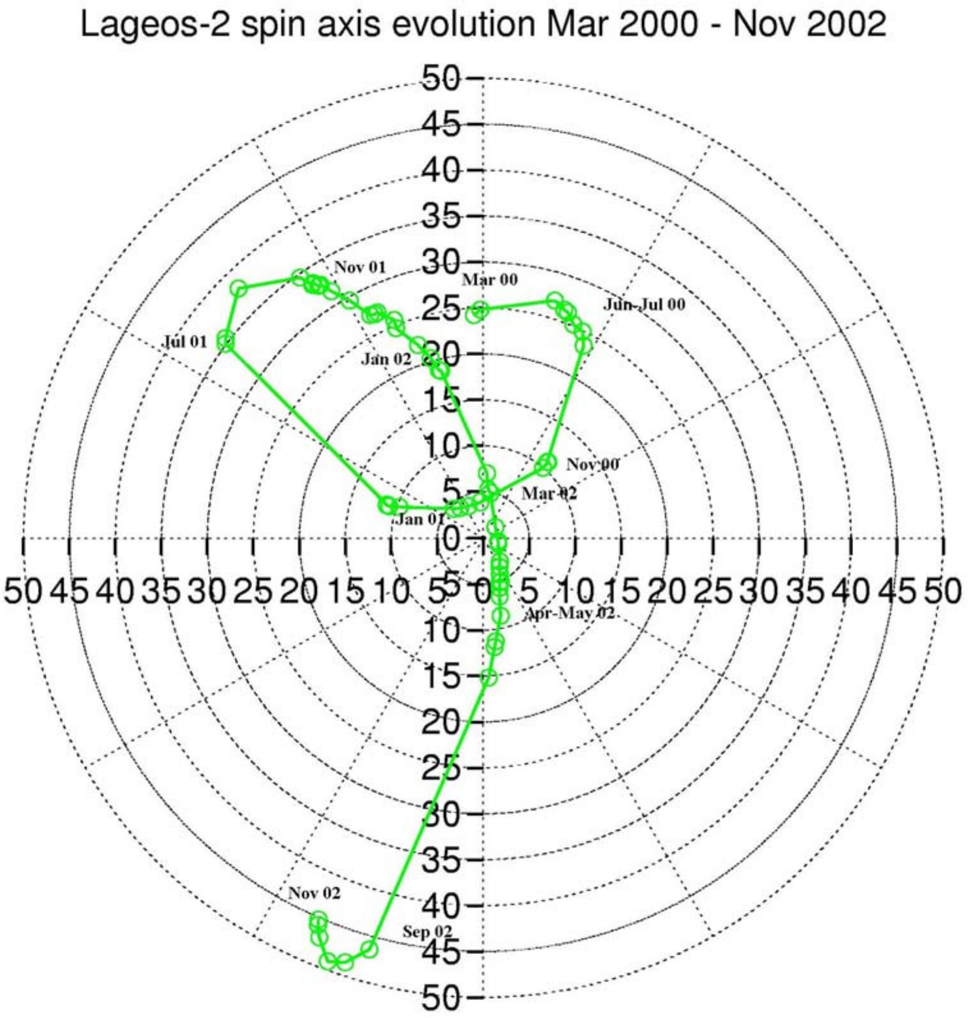

Figure 6. *Lageos 2 spin axis precession plotted on the celestial sphere. At the centre is the north celestial pole (i.e. the direction in space of the Earth's axis of rotation).*

Refinements

Brief mention is made here of two interesting matters of detail that can also be derived from these data. Minor misalignments (~15 arcminutes) in the orientations of individual reflectors in their mountings can be deduced by close examination of patterns in the bursts of glints. Misalignments in longitude show as uneven time intervals between glints in a burst; misalignments in latitude may cause glints from a particular reflector to appear slightly ahead of the main burst, or to be absent at the start of a burst, according to the direction of misalignment. There are firm indications that such effects are detectable in our data and we propose to investigate them more fully before attempting a definitive report. Studies of these signatures hold out the hope of being able to map the orientations of individual reflectors in each ring, and thus determine the exact phase of the rotation.

The data also reveal the actual sense of rotation of Lageos 2. Because the satellite is moving in its orbit while glint observations are being made, any period of rotation derived from them is, strictly speaking, a synodic period rather than a sidereal period. Since the relative positions of Sun, orbiting satellite and telescope on the rotating Earth are different for each pass, the relationship of the synodic period to the sidereal period at that time will depend on the exact circumstances of the pass. For a given pass these circumstances are well known, with the exception of the direction of rotation of the satellite. So for one of the long-burst passes we investigated the effect of correcting the (raw) synodic period to the sidereal period assuming first that the satellite was rotating one way, and then that it was rotating the opposite way. Figure 7 shows a plot of measured spin period versus time based on data from a long-burst pass. The central line is a plot of the raw data, while the upper and lower lines show the results of correcting for satellite spin in an ‘anticlockwise’ sense (*i.e.* the *same* as the Earth) and a ‘clockwise’ sense, respectively. We consider that ‘clockwise’ rotation gives sidereal periods much more consistent with the long-term slowing of the satellite – and we conclude that Lageos 2 rotates in the *opposite* sense to the Earth.

We also made a very similar analysis for a number of ‘ordinary’ passes covering a 2-week interval in 2001 December and found exactly the same result – ‘clockwise’ satellite spin gives superior long-term consistency. For maximum precision all determinations of spin rate should be reduced to the sidereal frame in this way.

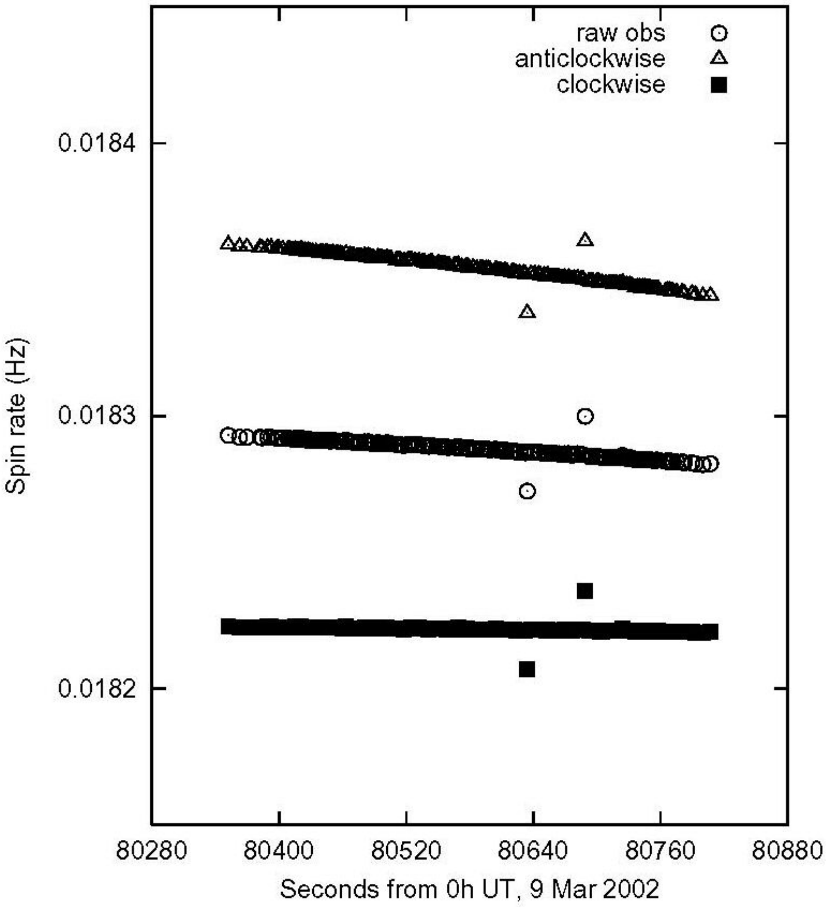

Figure 7. *Correcting synodic period results to sidereal assuming both 'clockwise' and 'anticlockwise' spin for Lageos 2. 'Clockwise' is preferred.*

Future observations

With the rotation of Lageos 2 slowing by more than a third each year it will not be long before the number of bursts of glints per pass falls below that required to make a satisfactory determination of spin axis orientation. It is hoped that maintaining a programme of observations from Herstmonceux, whenever Lageos 2 is available at night, will make it possible to monitor the spin period with sufficient accuracy that it is still possible to identify glinting rows individually. In order to succeed in doing so it would be particularly helpful to supplement the Herstmonceux data with other photometry, ideally from other stations well-distributed in longitude: any SLR station regularly ranging to Lageos is urged to consider obtaining complementary photometry.

Conclusions

Time-stamped photometry at millisecond resolution is shown to be a powerful tool for detailing the rotation and orientation histories of the Lageos 2 satellite. Over the two years of observations the period of rotation has slowed smoothly at a near-exponential rate of just less than 1% per week, or 38% per year, during which time the spin axis has precessed about the Earth's magnetic field in a well-defined pattern. Inclusion of such comprehensive data allows analysts to model the non-gravitational forces on the satellite very precisely (Rubincam *et al.* 1997; Metris *et al.* 1999; Andres *et al.* 2002). Indeed this increased precision has been of particular benefit to those seeking to exploit the very high stability of the Lageos orbits in pursuit of subtleties of gravity field determination (Dunn *et al.* 1999), refinements to the International Terrestrial Reference Frame (Altamimi *et al.* 2002), and definitive tests of general relativity (Vespe 1999; Lucchesi 2001).

Acknowledgements

We thank David Walters for his careful work in integrating the photometer hardware into the operational system; and all the Herstmonceux observers for their enthusiastic and continuing assistance in gathering these valuable data.

References

Altamimi, Z., Boucher, C. & Sillard, P., 2002. "New trends for the realization of the International Terrestrial Reference System", *Advances in Space Research* **30**, 175-184.

Andres, J.I., Noomen, R., Bianco, G., Currie, D. & Otsubo, T., 2002. "The spin axis behaviour of the LAGEOS satellites", *Geophysics Research Abstracts* **4**, No. EGS02-A-02994.

Bertotti, B. & Iess, L., 1991. "The rotation of LAGEOS", *Journal of Geophysical Research* **96**, 2431-2440.

Bianco, G., Chersich, M., Devoti, R., Luceri, V. & Selden, M., 2001. "Measurement of LAGEOS-2 rotation by satellite laser ranging observations", *Geophysics Research Letters* **28**, 2113-2116.

Dunn, P., Torrence, M., Kolenkiewicz, R., *et al.*, 1999. "Earth scale defined by modern satellite ranging observations", *Geophysics Research Letters* **26**, 1489-1492.

Lucchesi, D.M., 2001. “Reassessment of the error modelling of non-gravitational perturbations on LAGEOS 2 and their impact in the Lens-Thirring determination”, Planetary *& Space Science* **49**, 447-463.

Metris, G., Vokrouhlicky, D., Ries, J.C., *et al.* 1999. “LAGEOS spin axis and non-gravitational excitations of its orbit”, *Advances in Space Research* **23**, 721-725.

Minott, P.O., Zagwodzki, T.W., Varghese, T. & Selden, M., 1993. “Pre-launch optical characterisation of the laser geodynamic satellite (LAGEOS 2)”, *NASA Technical Report* TP-3400.

Rubincam, D.P., Currie, D.G. & Robbins, J.W., 1997. “LAGEOS I once-per-revolution force due to solar heating”, *Journal of Geophysical Research* **102**, 585-590.

Vespe, F., 1999. “The perturbations of earth penumbra on LAGEOS II perigee and the measurement of Lens-Thirring gravitomagnetic effect”, *Advances in Space Research* **23**, 699-703.