COMPARISON OF SLR MEASUREMENTS AND ORBITS WITH GLONASS AND GPS MICROWAVE ORBITS

G.M Appleby
NERC Space Geodesy Facility, UK

T. Otsubo
Communications Research Laboratory, Tokyo.

Abstract

The large number of satellite laser range measurements made to the GLONASS satellites during the IGEX-98 and continuing IGLOS campaigns, as well as continuing global SLR tracking of GPS-35 and -36, presents the opportunity to make detailed independent comparisons with published navigational orbits.

We make the comparisons in two complementary ways; first we determine weeklong orbits from the global sets of SLR data, and compare those orbits to the published GPS and GLONASS microwave orbits derived by the Berne Centre for Orbit Determination in Europe (CODE). Second we compare directly the individual laser range measurements from a number of SLR sites with the corresponding computed ranges obtained from the CODE orbits.

We discuss the results, which suggest agreement between the orbits at a level of better than 20cm radially and reveal the presence of small systematic biases in the scale of the microwave orbits, the magnitude of which appears to be satellite dependent.

Introduction.

One of the increasing uses to which SLR observations are being put is to calibrate results from other space geodetic systems. For instance SLR measurements have been used to calibrate via precise orbit determination the radar altimeters on the ERS satellites and the GPS/DORIS-derived orbit of the TOPEX/POSEIDON mission. In this paper we discuss the role of SLR in monitoring the precision of orbital information on navigational satellites that is determined operationally from radiometric data; we call the later ‘microwave orbits’. We carry out this comparison in two distinct ways; firstly we compute independent orbits using SLR data alone and compare with the microwave orbits; secondly we compare laser range measurements directly with the corresponding distances derived from the microwave orbits. The ILRS network continues to make regular observations of three GLONASS and two GPS satellites. In this analysis we use some 12,000 SLR normal point ranges from the network for GL 70 (slot 4), GL 72 (slot 22) and GL 79 (slot 9) from the period 1999 January 17 – 1999 August 29. For GPS-35 and 36 we use some 6,000 normal points for the period 1999 January 17 – 2000 May 30.

GPS and GLONASS SLR orbits.

Using our in-house orbit determination and SLR analysis software *SATAN* we computed seven-day orbital arcs for the three GLONASS and two GPS satellites. For each orbital arc we solve for initial state vector, a single coefficient of solar radiation, along-track and 1-per-rev along-track empirical accelerations. The GLONASS satellites are on the whole well observed by the network and on average about 250 normal points are analysed for each orbital arc. The GPS satellites, with smaller reflector arrays, are much more difficult to observe and we usually have only about 70 normal points to analyse for each arc. Typical values of the post-fit residual RMS are between 5-10cm. In this analysis we do not solve for empirical parameters to model the reflector-array effects that are known to be present for the high-energy ranging systems and which are discussed in detail in Otsubo *et al* (2001). This level of sophistication, which can account for apparent range bias of 2-3cm is not necessary for the present discussion, but is treated in detail in the second section of this paper where range measurements are compared directly with microwave orbits.

For each of our orbital arcs we take the daily CODE orbits, which are given in SP3 format with respect to a terrestrial reference frame (Greenwich Meridian and True Equator of Date) and with 15-minute epochs coincident with the GPS timescale. We convert the SLR orbits from J2000 to this same reference frame, at UTC epochs corresponding to the CODE ephemeris epochs. We can then directly compare the two orbits, both as differences in geocentric rectangular coordinates, and by resolving the differences into along-track, across-track and radial directions.

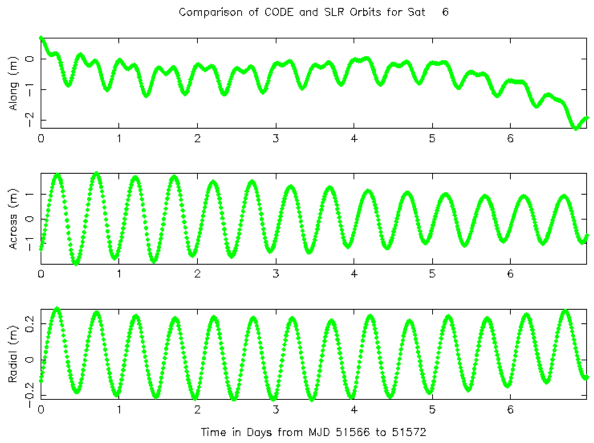

Figure 1. Differences at 15-minute intervals between CODE microwave and SLR orbits for GPS-36.

A representative example of the results is shown in Figure 1 for GPS-36 for the seven-day arc beginning on 2000 January 23. Clearly seen in these plots are once-per-rev (12-hour) periodic differences, which is a typical result when two slightly different orbits are compared. Overall we find agreement between our laser-based orbits and the microwave orbits at a level of about 50cm RMS in the along-track and across-track differences, and about 10cm RMS in radial differences.

In order further to quantify the differences, we have taken the geocentric rectangular coordinates of the microwave orbits for each satellite for a typical 7-day orbital arc and mapped them onto the equivalent coordinates from our SLR-based orbits by solving for the coefficients of a 7-parameter Helmert transformation. A summary of the results is given below, where the symbol $\mathbf{\Delta i}$ refers to a translation in the $\mathbf{i}^{\mathbf{th}}$ coordinate and the symbol $\boldsymbol{\theta}\mathbf{i}$ refers to rotation about the $\mathbf{i}^{\mathbf{th}}$ coordinate.

$\Delta x, y \sim \pm 0 \rightarrow 2$ cm; $\Delta z \sim +5 \rightarrow 10$ cm;
$\theta x, y \sim \pm 0.2$ mas; $\theta z \sim \pm 2$ mas;
Scale ≡ 0 → 5 cm in difference in sizes of orbits.

The translation and rotation parameters of the Helmert transformation are seen to be fairly small, with only the $\mathbf{\Delta z}$ values being consistently positive and significantly non-zero. This offset may reflect systematic problems at the level of a few cm in either or both of the types of orbit as a result of non-homogeneity of tracking stations in the global networks. A similar explanation may be given for the lack of a consistent result for the relative scales of the SLR and microwave orbits. Particularly for the GPS satellites, too few SLR measurements were available to give consistent, high-quality orbital information.

Therefore, the results of this section of the analysis must be confined to the statement that the SLR and microwave GLONASS and GPS orbits agree at the level of about 10cm radially, with a consistent 5-10 cm translation between them along the Z-axis.

Direct evaluation using SLR measurements;

GLONASS.

In the next two sections we consider the results of direct comparison between microwave orbits and SLR measurements. This is likely to be a more powerful test of the quality of the microwave orbits since the comparison is not degraded by potential systematic effects in the orbits that we determined using the SLR data, which at least for the GPS satellites is quite sparse. The method does, however, only provide a check on the range of the satellites as computed from the microwave orbits. Although for these high-orbiting satellites a range error will be dominated by an orbital radial error, some contamination from say an along-track error is inevitable. In this part of the analysis we used all 12,000 SLR Normal point ranges from the global network for the three GLONASS satellites. It is worth noting here that our initial orbit determination process using the SLR data showed very few outlying points and since it is mainly the more able, prolific systems that regularly range to GLONASS, we are confident that most of the SLR Normal point data used in this analysis is potentially accurate to better than 20mm.

At the epoch of each laser range measurement from each tracking station we compute from the CODE geocentric ephemeris the expected range to the centre of the laser-retro array. The CODE orbits do not include velocities, so to interpolate to the expected time of arrival of the laser pulse at the array, we use the velocity of the satellite as determined with sufficient accuracy from our previous orbital determination using the SLR data. We take for the distance of the phase centre of the laser-retro array from the satellites' centres of mass the standard value of 1510mm. We also assume that the attitudes of the satellites are nominal, that is the satellite-fixed z-axis is directed towards the geo-centre and the solar arrays are normal to the direction to the Sun. Then for each range measurement we compute the range difference, which we call SLR-CODE. The results for GLONASS-72 (slot 22) are shown in Figure 2.

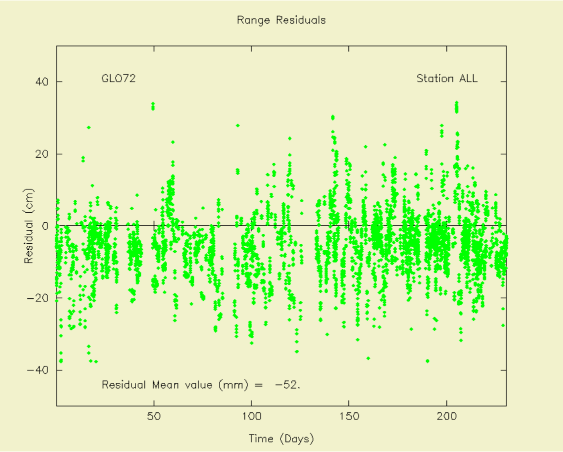

Figure 2. SLR-CODE differences of GLONASS-72 for all stations as a function of time.

The results for all three satellites combined are that the mean value of the differences is -42mm, with a residual RMS scatter about the mean of 15cm. This scatter is a further indication of the precision of the CODE orbits in the radial direction, and is in good agreement with our estimate of this quantity from the comparison of SLR and CODE orbits. The mean offset of -42mm is in accord with the mean result of -39mm obtained by Ineichen *et al* (1999) from a similar analysis using nine GLONASS satellites during the period 1998 October to 1999 May. However, a further conclusion from the present study is that the mean value of the range difference appears to be both satellite and tracking station dependent. Our previous experience with spherical satellites suggests that we might expect, for the following reasons, that SLR systems working at high return levels would obtain shorter range-measurements to an extended array than for ‘single photon’ systems. During the course of a pass for which individual returns are of single photons, we would expect to sample returns spatially distributed over the whole surface of the array. For a system working at much higher return levels, photons arriving from parts of the array closest to the station will preferentially be detected and the resulting range measurements will be systematically shorter than for the single-photon systems. If this effect were present in the GLONASS measurements, we would expect there to be for high-energy systems a systematic range variation as a function of the incident angle of the laser pulse to the reflector array. Further, we should be able to use this functional dependence to solve for an ‘effective’ array size. This effect was successfully detected and modeled by Otsubo *et al* (2001) during a dynamical orbital solution using SLR observations.

In this investigation, we use a subset of our SLR-CODE range residuals as obtained by the high-energy systems, predominantly the systems at Goddard, Grasse, Monument Peak, McDonald, Wettzell and Yarragadee.

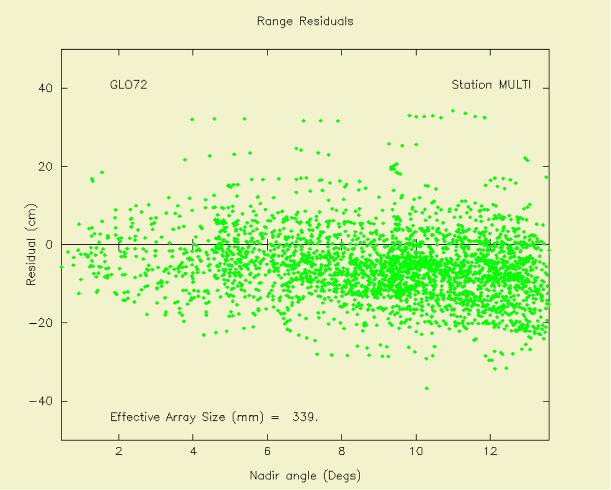

Figure 3. SLR-CODE differences for high-energy SLR systems, plotted as a function of nadir angle at the satellite.

Figure 3 shows the SLR-CODE measurements for those systems for satellite GLONASS-72 (slot 22) plotted against the angular direction at the time of each range measurement of the station with respect to the satellite's nadir; this angle is zero when the satellite is in a station's zenith, and reaches approximately 14^o when the satellite is close to the horizon. It is clear from the figure that the (negative) values of SLR-CODE depart further from zero as the nadir angle increases.

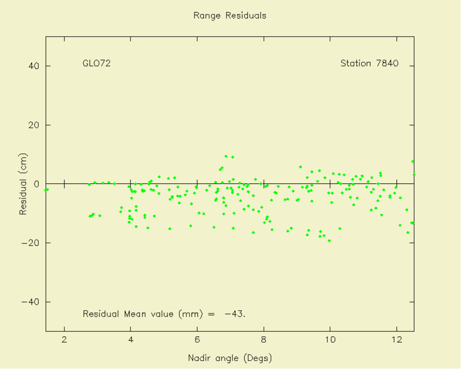

Figure 4. SLR-CODE differences for the Herstmonceux single-photon SLR system, plotted as a function of nadir angle at the satellite.

By way of illustration, we show in Figure 4 the results for station 7840 Herstmonceux, which works strictly at single-photon levels of return (Appleby *et al*, 1999). For this station, as expected, there is no obvious systematic variation of SLR-CODE values as a function of nadir angle.

We now use the functional dependence for the high-energy systems to solve for an 'effective' reflector array size required to remove this 'bias' introduced into the measurement process as a result of the large array size on the GLONASS satellites, noting that it is this very array size that enables a large number of range observations to be made. The mean value of the effective array size for the three GLONASS satellites is

25±3 cm, with values for each satellite being 15, 34 and 27cm for GLONASS 70, 72 and 79 respectively.

Having determined the effective array size for the high-energy systems, we remove the average effect from each range normal point and can then combine the data with that from the single-photon systems. We then obtain a better estimate for each satellite of the mean offset between the CODE orbits and the SLR measurements. The results for each satellite, before and after removing the array effect as described, are given in Table 1.

Satellite Name	**'Biased' SLR-CODE mm**	**Corrected SLR-CODE mm**
G70	**-66 ± 4**	**-44 ± 5**
G72	**-52 ± 4**	**-31 ± 4**
G79	**- 9 ± 7**	**+15 ± 7**

Table 1. Mean values for each satellite of SLR-CODE measurements, both un-corrected and corrected for systematic array-induced bias.

The clear satellite-specific nature of the offsets shown in Table 1 might be interpreted as indicating differences in the locations of the phase centres of the reflector arrays on each satellite with respect to their centres of mass, on the assumption that the CODE orbits accurately describe the motion of the satellites' centres of mass. However, an SLR-only dynamical solution for G72 and G79 (Otsubo *et al,* 2001) finds offsets between the centres of mass and the reflector arrays for these satellites of -46 and –38 mm respectively, which are in conflict with our results. Taken together with our results in Table 1, this result supports the existence both of bias in the CODE orbits, which could be the result of uncertainty in the locations of the phase centres of the microwave transmitter arrays, and the presence of an un-modeled radial force as suggested by Eanes *et al*, (1999) and Otsubo *et al* (2001).

Direct evaluation using SLR measurements;
GPS

We report here an analysis of the quality of the CODE orbits for GPS-35 and -36, which has been carried out in the same way as for the GLONASS satellites. During the period of the analysis, 1999 January 17 to 2000 May 30, some 6,000 laser range normal points were obtained by the ILRS network. Taking into account the longer time-span of this data set, this represents only one-third of the amount of data for each satellite and reflects the greater difficulty in tracking the small reflector arrays on the GPS satellites, particularly during daytime. However, there is still a sufficient quantity of global SLR data to perform a direct comparison with ranges computed from the CODE orbits. As for the GLONASS satellites, we assume that the attitudes of the satellites are nominal, that is the satellite-fixed z-axis is directed towards the geo-centre and the solar arrays are normal to the direction to the Sun. We take the satellite-fixed coordinates of the centre of the laser reflector arrays from Degnan and Pavlis (1994) and for each laser range normal point form the difference SLR-CODE.

The mean value of SLR-CODE for the two satellites for the whole period of the analysis is -55mm, with an RMS scatter about the mean of about 15cm. This indicates that as for the GLONASS satellites, the radial precision of the CODE orbits is about 15cm. There is a slight, but probably insignificant, difference in the mean values of SLR-CODE for the two satellites; -52mm and -59mm for GPS-35 and -36 respectively. The results for GPS-35 are shown in Figure 5.

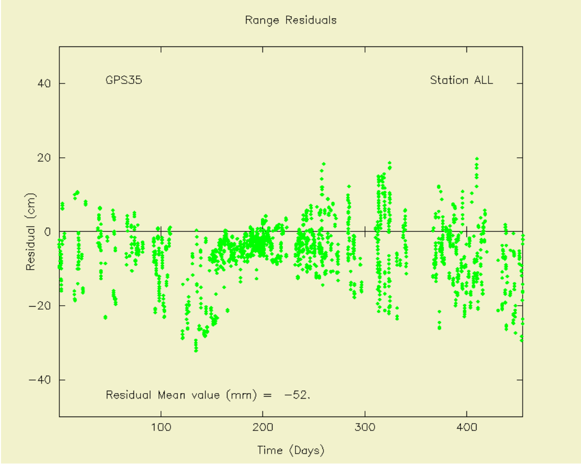

Figure 5. SLR-CODE differences for GPS-35.

We would not expect there to be an SLR-system-dependent range 'bias' given the relatively small reflector arrays on the GPS satellites, but since the arrays are mounted off-centre the SLR-CODE measures do provide a test of the satellites' true attitude with respect to the assumed nominal attitude. There is some evidence in the results of times, particularly during satellite eclipse periods, when the attitude is non-nominal and for which a modified attitude model should be used; one such occurrence is apparent in Figure 5 from day 120-160 during which GPS35 is undergoing eclipses during each orbit. More work will be carried out on this aspect of the comparison in due course. However, there remains an offset of some -55mm in the SLR-CODE results, which may either be due to an error in the assumed value of the distance of the phase centre of the laser reflector array from the satellites' centres of mass, or an error in the scale of the CODE orbits similar to that implied by our GLONASS results. Again the latter might imply either the presence of an un-modeled radial force or contamination of the CODE orbit by an error in the assumed phase centre of the microwave transmissions on each satellite. Resolution of this problem can only begin if the integrity of the assumed location of the reflector array is closely scrutinised.

Conclusions

The main conclusions of this study are:
The radial RMS precision of the CODE GLONASS and GPS precise orbits is about 15cm;
The deduced radial error in the CODE GLONASS orbits is satellite specific; after removing an offset of approximately -20mm due to the large laser reflector arrays, the offset varies from -44 to +15mm for the three satellites considered;
The deduced radial error in the CODE GPS orbits is about -55mm and not significantly different for the two satellites;
It is possible that errors in the published values of the locations of the laser reflector arrays may explain some of these discrepancies, but there is evidence that there also exist radial errors, whose cause is currently unknown, in the CODE precise orbits;
The SLR technique provides a very valuable independent check on the quality of orbits determined from radiometric data. It is considered that the technique should be employed for new-generation navigation systems such as GALILEO.

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