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Centre-of-mass values for precise analysis of LAGEOS, Etalon and Ajisai 1980-2013

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Abstract. *One of the limiting factors in reaching the scientific goal of 1-mm accuracy satellite laser ranging to the geodetic satellites is referring the range observations to the centres of mass (CoM) of the spherical satellites. The cube-corner retroreflectors that are distributed over the surfaces of the geodetic satellites LAGEOS (diameter 0.60m), Etalon (1.29m) and Ajisai (2.15m) give rise to broad, complex temporal distribution of the return laser pulses. Accurate modelling of the characteristics of the detection of those pulses that takes account of the various laser station technologies is required in order to minimize the potential for attributing error in the computed value of the CoM correction to apparent range error. Such systematic effects can be more than 10 mm for the two LAGEOS and up to several cm for Ajisai and the two Etalon satellites. Earlier theoretical results (Otsubo and Appleby, JGR, 2003) have been used to develop tables of CoM corrections and their uncertainties that are applicable in a simple way when analysing range data from all the ILRS stations that have operated from 1980 onwards. The ILRS Analysis Centres will use the corrections for re-processing work during 2013 towards the ILRS contribution to ITRF2013*

Introduction

  It has been established for some years that in order to derive as accurate as possible laser-range CoM values for the geodetic satellites, a variety of factors have to be taken into account before choosing the appropriate value. The main conclusion of previous work in this area, most recently that of Otsubo and Appleby (2003), is that tracking station characteristics such as laser pulse-width, type of detector, return signal-strength and post-processing philosophy together lead to a range of possible CoM values that for LAGEOS span as much as 10mm. In this current work we took the theoretical values from the Otsubo and Appleby (2003) analysis, and associated time-dependent CoM values with each of the tracking stations that have contributed to the ILRS effort for the period 1980 to date. The vital resource to carry out this work is the individual site logs that are available through the ILRS website; for each station the site logs specify existing hardware, software and return-energy levels and, as importantly, track the changes in any of these components that often take place over the years, as improvements towards greater capability and higher precision are implemented. These changes, say an upgrade in detector from a multi-photon photomultiplier tube to a single-photon avalanche diode and perhaps a shorter laser pulse, can change the appropriate CoM value for LAGEOS by more than 5mm and considerably more for Ajisai and the Etalon satellites.

Implementation A difficulty in application of the Otsubo and Appleby (2003) results was that it was left to the laser range analyst to identify each ILRS station with the broad hardware and software characteristics that were used in the paper to develop the various CoM values. For example, the paper gives a CoM value of 250mm to be used for LAGEOS observations made by stations with micro-channel-plate detectors, multi-photon operation and 200ps laser pulse width. In fact these are

the characteristics of stations belonging to the NASA Network, and it is noteworthy that our derived CoM value of 250mm is very close to that (251mm) determined for those particular characteristics in the LAGEOS-2 pre-launch measurements (Minott *et al*, 1993). But clearly a time-dependent table directly linking individual site numbers to CoM corrections will be much more convenient to use and enable automatic processing. As far as practical, the current work reported here has taken all the stations that have or continue to operate during the period from 1980 to date and used the results in the paper to estimate an appropriate CoM value, and importantly, to associate with that value an estimate of its error, derived from the stated operational practice. For instance, if a station states in its log file that it works strictly at single-photon levels of return, the results in Otsubo and Appleby (2003) suggest that a small value, perhaps ±1mm, would be an appropriate error estimate on the given CoM value. An example of this high-precision situation is shown in Figure 1, where the modelled satellite signature curve (in red) is seen to fit the real laser range residuals extremely well.
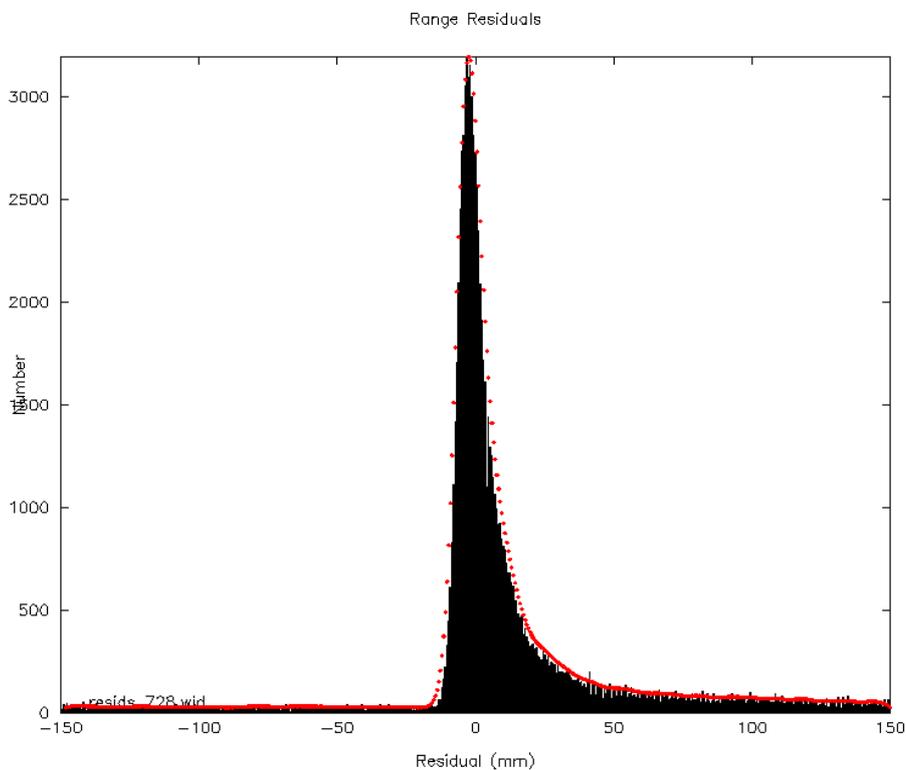

Figure 1 LAGEOS range residuals obtained by a station working with a SPAD and at single-photon returns; the theoretical model of the expected distribution is shown as the red curve

A greater degree of variability in operational return-rate will, on the other hand, increase the uncertainty of the mean value of the CoM correction. Tables of values of CoM corrections for LAGEOS and Etalon, along with a simple Fortran interrogation code, have been released and evaluated during a short time-span pilot study conducted by the ILRS Analysis Centres (ACs) under the direction of the ILRS Analysis Working Group. This work, including an evaluation by the authors of six months of LAGEOS analysis using the new CoM tables, has been reported previously (Appleby, *et al*, EGU 2012). To summarise that work, weekly solutions using the SGF SATAN code from October 2011 to March 2012 for orbits, station coordinates and EOPs were carried out with and without the new CoM values for LAGEOS and Etalon, where 'without' means that the standard CoM value for LAGEOS of 251mm was used for all stations except Herstmonceux, where

the value (245mm) derived by Otsubo and Appleby (2003) was used. The results from the six-month evaluation showed only a minimal change in the mean scale of the reference frame of 0.03ppb between the 'with' and 'without' solutions. However, individual station successes in this approach include the following example from the Potsdam (7841) laser ranging station that underwent a valuable upgrade to kHz repetition rate and single-photon detection in mid-2011. The appropriate CoM value before the upgrade was estimated from the LAGEOS table to be 251mm, and after the upgrade to be 245mm, a difference of 6mm. In Figure 2 we show a 'range bias' plot for the station (courtesy of V. Luceri, e-GEOS S.p.A., Matera), where the same value of CoM (251mm) had been used in the analysis both prior and post-upgrade. The apparent jump in bias is 8mm, and in the sense that a correct application of appropriate CoM values will reduce the 'bias' to 2mm.
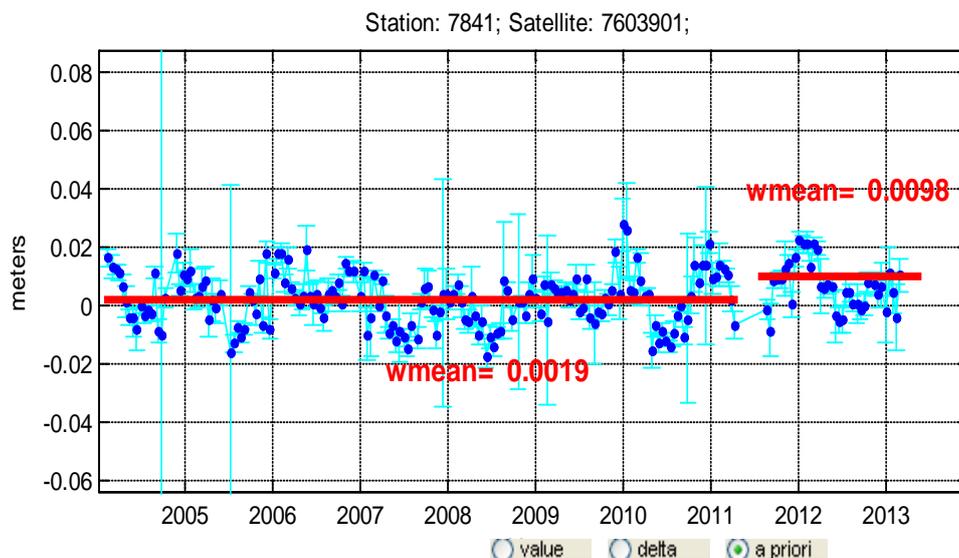

Station: 7841; Satellite: 7603901;

wmean= 0.0098

wmean= 0.0019

Figure 2 Change of range bias of 8mm before and after a system upgrade at Potsdam, courtesy e-GEOS. A difference of 6mm is to be expected and will be accommodated by application of the appropriate pre- and post-upgrade CoM values (251 and 245mm respectively)

It is also considered likely that a longer evaluation of the station and time-dependent CoM values will reveal greater differences, and ideally improvements, in the scale of the reference frame, since during the 1980s and 1990s extensive hardware changes were taking place at several of the stations, the effects of which on the appropriate CoM values as given in the new tables have not yet been evaluated in reference frame solutions. The ILRS Analysis Centres that will carry out reference frame solutions towards the submission for the ITRF2013 realisation will use the tables for LAGEOS and Etalon.

Ajisai We report here the addition of a table of Ajisai CoM values and correspondingly-updated Fortran code, and carry out a short orbital evaluation. Ajisai is densely observed by the ILRS network and has been used in recent multi-satellite analyses for experimental determination of the terrestrial reference frame (e.g., Sosnica, *et al*, 2013, these proceedings, paper 13-0114) and it is expected that use of appropriate CoM values for all the satellites will enhance such results. The table was developed in the same way as for LAGEOS and Etalon from the work of Otsubo and Appleby (2003) and the ILRS site logs. An extract from the Ajisai table is shown here in Table 1.

Stn	Start Date			End Date			Pulse	Sys	Ret	filter	Calσ	Lσ	mx,	mi,	mean CoM
7328	01	04	1997	01	01	2050	35	CSPA	NSM	2.5	8	15	1023	985	**1004**
7335	01	04	1997	01	02	2001	35	CSPA	NSM	2.5	8	15	1023	985	**1004**
7337	01	01	1997	31	31	2001	35	CSPA	NSM	2.5	8	15	1023	985	**1004**
7339	01	04	1997	13	13	2001	35	CSPA	NSM	2.5	8	15	1023	985	**1004**
7355	28	12	1999	31	31	2050	30	CSPA	NC	2.5	15	30	1023	985	**1004**
7356	28	12	1999	31	31	2050	30	CSPA	NSM	2.2	15	30	1023	990	**1007**
7357	30	06	2002	31	31	2050	40	CSPA	NC	2.5	8	15	1023	985	**1004**
7358	25	03	2002	31	31	2050	50	MCP	NC	3.0	1	5	1025	1015	**1020**
7403	10	07	1992	31	31	2050	200	MCP	CFM	3.0	5	10	1017	1009	**1013**

Table 1 Detail from the new Ajisai table of CoM values; the same format applies to the existing LAGEOS and Etalon tables

- Sys refers to station detector – CSPAD, MCP, etc.
- Ret refers to return signal – NSM=No control, Single to multi-photon
    - NC =No control
    - CFM=Controlled, few to multi-photon
- Filter = rejection level (σ) during post-processing
- Calσ = single-shot precision (σ) from calibration ranging
- Lσ = single-shot precision (σ) from LAGEOS ranging
- mx, mi, mean CoM = Maximum, minimum and mean (recommended) value of Ajisai CoM value (mm) appropriate for this station within this time-frame.

Testing The new table was tested by carrying out precise orbit determination for Ajisai using the in-house SATAN code that is routinely used for SGF ILRS reference frame solutions. Three and 7-day orbital arcs were fitted to the global Ajisai normal point data set for August 2013, with and without calling the Ajisai CoM table; the ILRS default CoM value of 1010mm was used for the 'without' solutions. The results were similar to the experience with tests of the LAGEOS CoM values discussed above. At best a marginal improvement of about 1% in post-fit residual RMS was achieved. However, we continue to contend that it is important to model this important effect as accurately as possible since such systematic bias will affect reference frame scale determination as well as aliasing into apparent range bias at the stations.

Conclusion We have described the rationale behind the development of site- and time-specific centre-of-mass tables for the geodetic satellites LAGEOS, Etalon and Ajisai. Tables for all three satellites are available for instance through the EDC (http://ilrs.dgfi.badw.de/index.php?id=6) and a simple Fortran code that returns the appropriate CoM correction during a POD process is also available. The LAGEOS and Etalon tables are now in routine use by the ILRS Analysis Centres for the primary daily reference frame solutions and will be used for the ILRS solutions towards the next realisation of the International Reference Frame, ITRF2013.

References

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