Sub-centimeter SLR precision with the SLRF2005/LPOD2005 network

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Abstract

Satellite Laser Ranging (SLR) offers the only unambiguous sub-centimeter range measurement to orbiting satellites. This capability finds many applications in addition to precision orbit determination (POD), which include a unique absolute measure of orbit accuracy, accurate altimeter range calibration, accurate definition of the Earth's center of mass, the most accurate definition of the geocentric gravitational coefficient (GM) and scale of a terrestrial reference network. Achieving sub-centimeter precision requires appropriate modeling of the satellite laser retro-reflector array (LRA) coupled in some cases with appropriate modeling of the satellite-dependant station detector characteristics, a highly accurate terrestrial reference frame, and appropriate attention to possible bias modeling of individual stations. We have processed Jason1/2, Lageos1/2, and TOPEX SLR tracking using the latest and most accurate POD models which include a GRACE-based static gravity, time varying gravity, and the highly accurate ILRS update of the rescaled ITRF2005 SLR complement, SLRF2005. SLRF2005 has been further updated, based on recommendations for the rescaling of ITRF2005, producing LPOD2005. Our analysis evaluates individual SLR station performance and systematic signals as observed from all four satellites. Several primary stations are identified as having significant range biases, which if untreated could lead to degradation in current levels of POD accuracy, and possibly degrade the results for other applications of the SLR measurement.

1. SLR processing and POD strategy

The current GSFC POD strategy allows SLR processing at the 1-cm level for Lageos 1/2 and Jason 1/2, and at the 1.5 cm level for TOPEX/Poseidon (TP) (Figure 1). Tests using the latest Precision Orbit Determination (POD) models have shown progressive improvement of the Lageos, Jason, and TP orbits. Table 1 illustrates improvement for the Jason-1 SLR/DORIS orbit based principally on the improvement in the orbit fit to the SLR data as these models are progressively improved. The culmination of these tests has led to the definition of the current GSFC POD recommended standards (Table 2) (Lemoine et al., 2008).
At this level of processing accuracy, even relatively small errors in station position or the presence of range biases at certain stations can be detected, and as will be shown, can produce significant and systematic orbit error.

2. SLRF2005 and LPOD2005

Upon its release in October 2006 the ITRF2005 SLR complement (Altamimi et al., 2007) offered improved stability and accuracy (Lemoine et al., 2007) over its predecessor, ITRF2000 (Altamimi et al., 2002). However, several factors prevented the immediate and direct use of ITRF2005 for processing SLR data: 1) the ITRF2005 scale, obtained from VLBI, was not compatible with the inherent SLR scale, 2) many stations with a history of tracking were not included, and new stations since 2005 were missing, 3) there is no official documentation of the biases applied in the ITRF2005 station solution. A complement to ITRF2005, called , ITRF2005s, which adopted the SLR-derived scale was later released, but like the ITRF2005 complement, it did not include all stations, nor reference a station bias history.

The aforementioned issues were solved with the terrestrial reference frame SLRF2005 (Luceri 2008) and with a consistent treatment of SLR biases defined by the ILRS Analysis Working Group. The terrestrial reference frame was obtained combining ITRF2000, ITRF2005 rescaled and a global SLR solution with data from 1993 to 2007 to add the new sites. The well defined set of station biases to be applied when using the SLRF2005 solution was also required. SLRF2005 shows improved POD performance over the ITRF2005s complement (Table 1).

A further improvement to the SLR complement was achieved with LPOD2005 version-9 (Ries 2008), refining four primary and 18 other station position/velocities of the complete SLRF2005 complement. Of special importance to POD is the improvement seen in the four primary stations (Figure 2). In addition to improved residual fits in the four LPOD2005 stations, the majority of stations show lower residuals, indicating an improvement in the Jason-1 orbit using LPOD2005 (Figure 2).

In the POD tests we present herein, we apply a SLRF2005 bias strategy using the SLRF2005 complement and apply the LPOD2005 bias strategy using the LPOD2005 complement. The GSFC bias strategy is consistent with that of LPOD2005 but has been updated to estimate biases for all suspect stations (Table 3).

3. Primary stations with apparent station position/bias error

LPOD2005 significantly improves primary stations Zimmerwald, Riyadh, and Ajacio. LPOD2005 offers a critical improvement for the Zimmerwald station position, where the correct bias history has been applied in the station solution. In contrast, the Zimmerwald bias history was not applied in the SLRF2005 solution. Figure 3 shows the time series of Zimmerwald mean SLR residuals using each of the two complements. The mean SLR residuals reflect the presence of a range bias. The two series diverge following 2006 with the SLRF2005 position indicating the appearance of a bias in the Zimmerwald station from early 2006. In February 2006 the CSPAD detector/Stanford clock were replaced with equipment known to be bias free. It is the LPOD2005 coordinates which show no bias in the data, as expected, when a zero Zimmerwald bias is assumed in the POD processing. Figure 3 illustrates the intimacy between a station solution and the bias history applied when forming that solution, and consequently implies that the same bias history be applied using the new coordinates in subsequent processing of SLR data.

The Riyadh velocity is improved in LPOD2005. Error in velocity will result in the increase in the SLRF2005 position error over time, and this is seen in Figure 4 showing an increase in mean residuals for this station.

Even with LPOD2005 several stations still show mean residual trends, the most prominent of which are Herstmonceux and Wetzell. The presence of such an apparent varied bias history for Wettzel (Figure 5) would make it difficult , if not impossible to achieve a bias-free station solution. The GSFC bias strategy adopts the estimation of a bias/arc for this station (Table 3). The February 12, 2007 appearance of an apparent 1.2cm bias for Herstmonceux was unexpected (Figure 6) and could not be immediately explained. The GSFC strategy was to estimate a bias/arc for this station from February 12, 2007 (Table 3). Subsequently it was determined that an incorrect bias history was applied in the ITRF2005 Herstmonceux station solution. Several months following these tests LPOD2005 (version 11) was updated with a new station position estimate for Herstmonceux.

In the interest of brevity other SLR stations which show less prominent trends in the mean SLR residuals are not presented in this paper. Please see the Zelensky et al., 2008 OSTS presentation for a more complete description.

4. Orbit sensitivity to station position/bias error

A long-term increase in mean SLR residuals is seen in Jason-1 POD using the SLRF2005 complement (Figure 7) and confirmed with Jason-2 POD (Zelensky et al., 2008). The presence of such a trend provides ample warning that the estimation of geodetic parameters or a stable orbit reference for altimetry may be compromised by systematic error. Using LPOD2005 and the GSFC bias strategy (Table 3) the trend in mean residuals is greatly diminished (Figure 7) and the residual fits improved (Table 1).

The orbit differences between SLR/DORIS orbits using SLRF2005 and LPOD2005 show radial rms differences of up to 8-mm / cycle and differences in the mean-Z of up to -15 mm. with a possible trend (Figure 8). Such orbit error is significant for altimeter data analysis, where mm/y levels of accuracy are required for mean sea level trends. Figure 8 illustrates that only a few small primary SLR station position/bias errors are sufficient to degrade the SLR/DORIS precision orbit.

5. Conclusion

The current GSFC POD strategy allows 1-cm SLR processing of the Lageos and Jason satellites. At this level differentiating between station biases and position/velocity error is difficult but critical for further improvements in SLR station position/velocity estimates. Our POD tests have shown that only a few SLR station position/bias errors are sufficient to degrade this level of processing accuracy, and have illustrated that an accounting for a station's explicit bias history is an integral component of any SLR station solution.

SLRF2005 is the ITRF2005s SLR complement expanded for completeness and reflects the inherent TRF SLR-scale. SLRF2005 was the first SLR complement distributed with a bias history. LPOD2005 updates only a small subset of the SLRF2005 stations.

In summary:

- An explicit station bias history should be distributed with every SLR station solution set.
- SLRF2005, based on ITRF2005s, offers a comprehensive station set and explicit station bias history, a significant improvement over the ITRF2005-SLR-scaled station set.

- LPOD2005, based on SLRF2005, significantly improves primary stations Zimmerwald, Riyadh, and Ajacio.
- The use of LPOD2005 significantly improves the Jason SLR/DORIS orbits.
- Even with LPOD2005 several stations still show mean residual trends, the most prominent of which are Herstmonceux and Wetzell. Subsequent to this analysis it was determined an incorrect bias history was applied in the ITRF2005 Herstmonceux solution, and consequently LPOD2005 was updated with a new position for Herstmonceux.
- The generation of a comprehensive station set and the improvement of several station position/velocities, was realized by SLRF2005 followed by LPOD2005. These ITRF releases represent an essential service provided to the SLR community.

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Table 1. Significant improvements to GSFC 2008 POD Standards					
test name	Jason-1 SLR/DORIS residual summary cycles 1-21	doris rms (mm/s)	slr (cm)		xover rms (cm)
			mean	rms	
nominal 2007	itrf2005(s)_merged (itrf2000), ggm02c	**0.3976**	**-0.073**	**1.519**	**5.730**
trf2005	+ slrf2005/dpod2005 (version 1.1)	**0.3979**	**0.086**	**1.508**	**5.732**
eigen_gl04s	+ switch to eigen gl04s	**0.3979**	**0.081**	**1.479**	**5.728**
tidal_com/eop	+ tidal CoM (got4.7) & tidal EOP	**0.3978**	**0.073**	**1.428**	**5.724**
cr_panel	…. + tune Cr=0.929	**0.3978**	**0.074**	**1.409**	**5.727**
lpod2005	….+ lpod2005 + lra phase map	**0.3978**	**-0.041**	**1.324**	**5.725**

Table 2. GSFC POD Standards summary (October 2008)	
Reference frame and displacement of reference points	
SLR	**SLRF2005 + LPOD2005**
DORIS	**DPOD2005**
Earth tide	**IERS2003**
Ocean loading	**Got4.7 all stations**
Tidal CoM &EOP	**Got4.7; VLBI high frequency terms**
Gravity	
Static	**Eigen-Gl04s**
Time varying	**Linear C20-dot, C21-dot, S21-dot (IERS2003) + 20x20 annual terms from GRACE**
Atmospheric	**ECMWF, 50x50@6hrs**
Tides	**Got4.7 (ocean); IERS2003 (Earth)**
SLR measurement	
Biases	**Consistent with SLRF2005/LPOD2005**
LRA/CoM (mm)	**TP: model, JA1/2: -49, L1/2: -251 / -245(RGO)**

Table 3. GSFC SLR Bias Strategy Summary (November 19, 2008)			
Station		sigma wt cm	Bias treatment
name	number		
mcdo	70802419	10	estimate troposphere scale 950306-960126, 960126-960425, 960435-960508
gorf	71050725	10	estimate time bias/pass 990304 -990308, 9900429-990501
mnpe	71100411	10	estimate range bias/arc 960827-961004
tahi	71240801 71240802	10	estimate range bias/arc 040501-040701
gorf t4	71301403		estimate range bias/arc 920422 → present
holl	72102312	10	estimate time bias/arc 990629 – 990804
chac	72371901	30	estimate pass x pass range bias
beij	72496101	30	apply +40 mm 990304-020305
rich	72951102 72951103 72951501	10	estimate range bias/arc 941124-941214
zimm	78106801	10	apply -18 mm 961215–970709

	(blue)		apply +68 mm 970709–970717 apply -64 mm 970730 – 970903 apply -18 mm 970903-980000 apply -26 mm 980101-020529 apply -20 mm 020529-041228 apply -26 mm 041228-060206
	88106801 (ir)	10	estimate range bias/arc 020801 - 060621
	68106801 (green)	10	estimate range bias/arc 080401 → present
boro	78113802	10	estimate range bias / pass 920422- 990722 estimate tropo bias / arc 920422- 980701
sfef	78306901	10	estimate range bias/arc 920422 → present
gras	78353102	10	estimate range bias/arc 920422 → present
pots	78365801	10	apply +18.5 mm 940101-940130
simo	78383602	20	estimate range bias/arc 920422 → present
graz	78393401	10	estimate range bias/arc 920422 – 960930 estimate tropo bias/arc 020610 – 021210
rgo	78403501	10	estimate range bias/pass 940113-940121 apply -2.5 mm 941001-020201 apply +5.5mm 020201-070210 estimate range bias/pass 070210 → present
orrl	78432502	10	estimate pass x pass range bias
mate	79417701	10	apply -14 mm 070216 00:00 - 070222 11:00 apply -28 mm 070222 11:00 - 070706 08:00 apply -22 mm 070706 08:00 - 070830 00:00 apply -25 mm 070830 00:00 - 071022 14:00
wetz	88341001	10	estimate range bias/arc 920422 → present

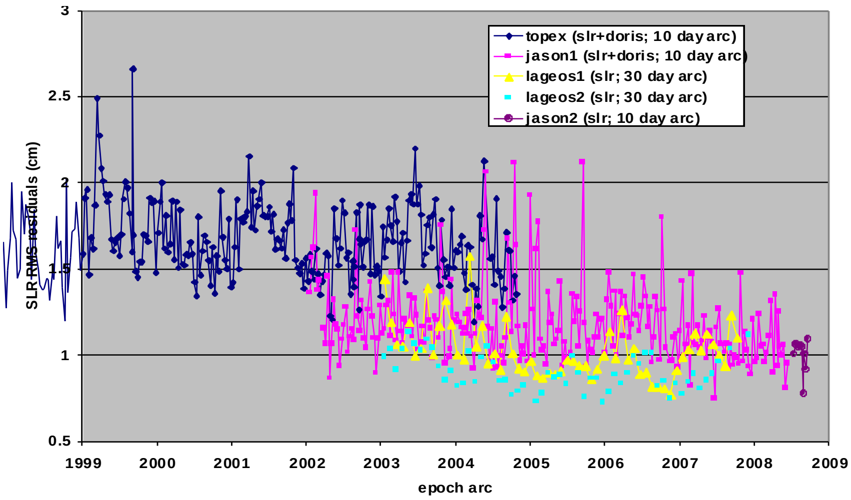

Figure 1. SLR Processing at GSFC

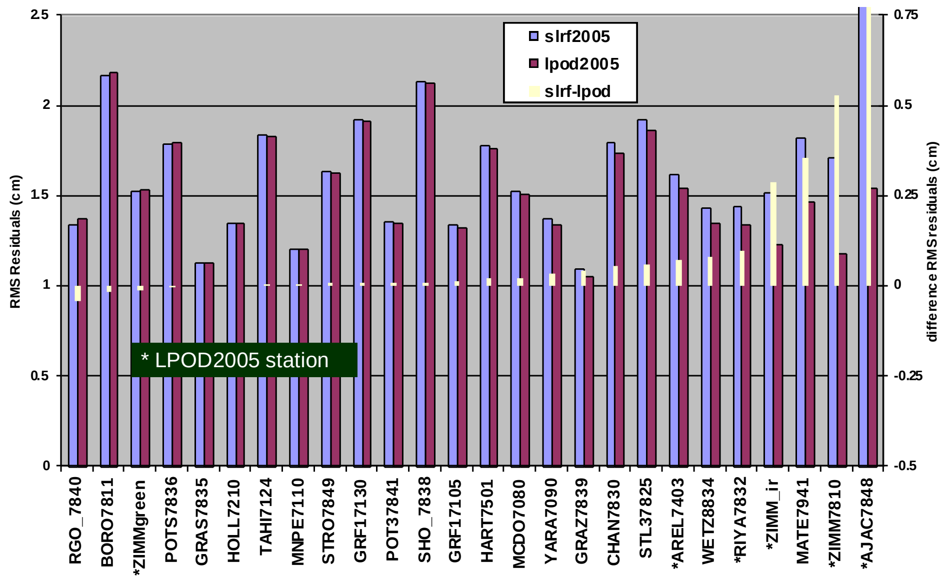

Figure 2. SLRF2005 / LPOD2005 primary station performance over Jason-1 cycles 1-237

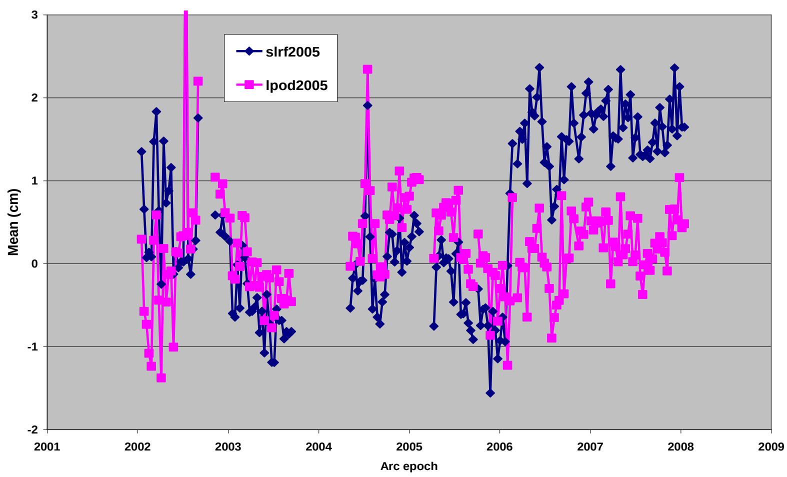

Figure 3. Jason-1 Zimmerwald (blue) mean SLR residuals

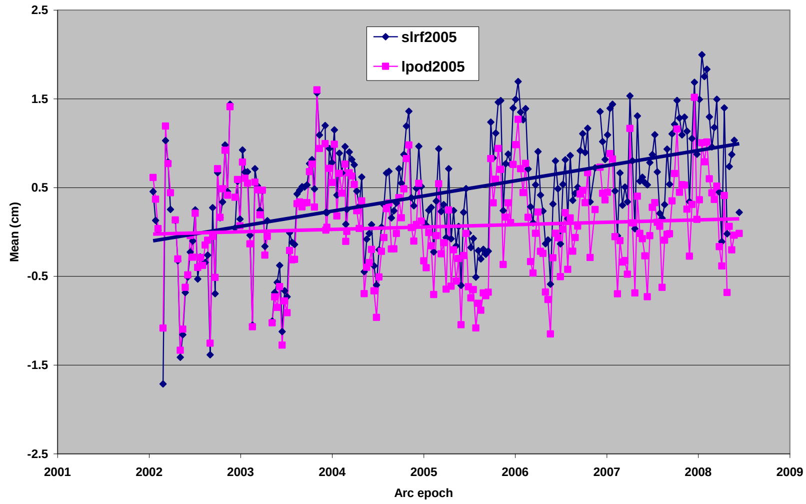

Figure 4. Jason-1 Riyadh mean SLR residuals

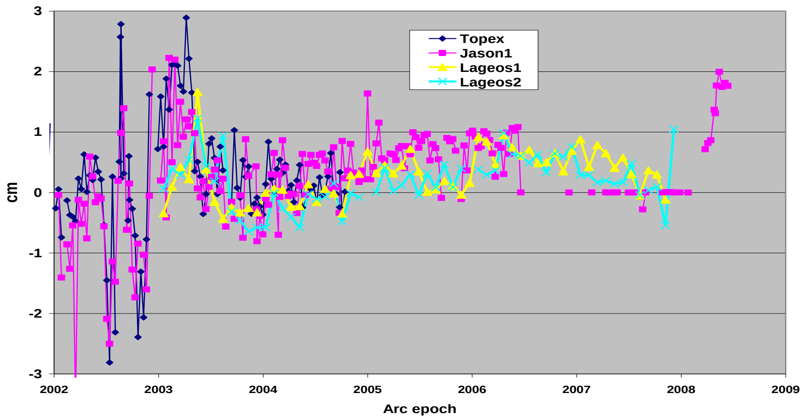

Figure 5. Wettzel mean SLR residuals

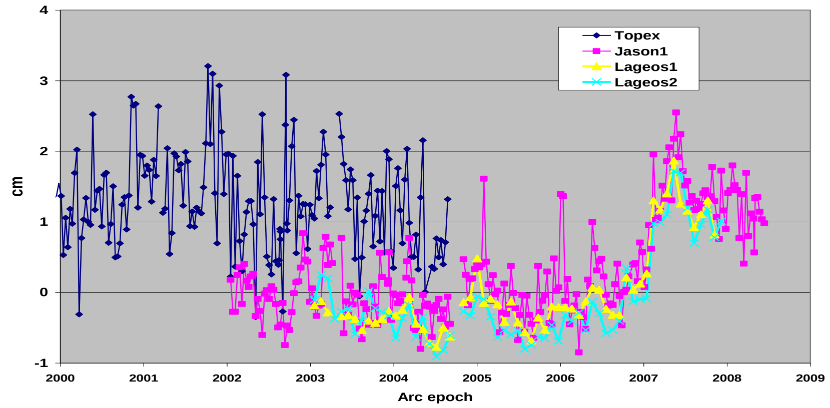

Figure 6. Herstmonceux mean SLR residuals

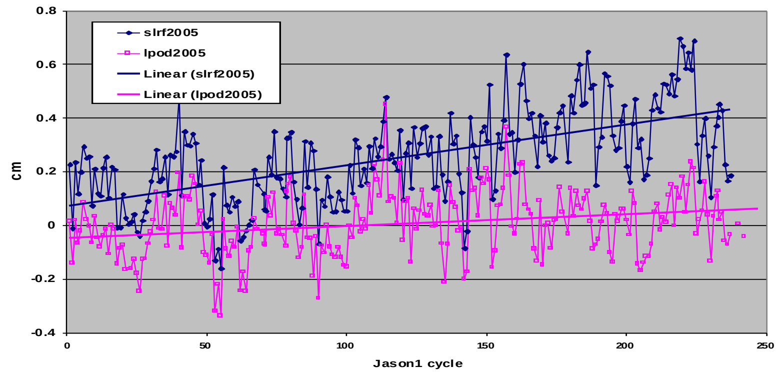

Figure 7. Jason-1 mean SLR residuals

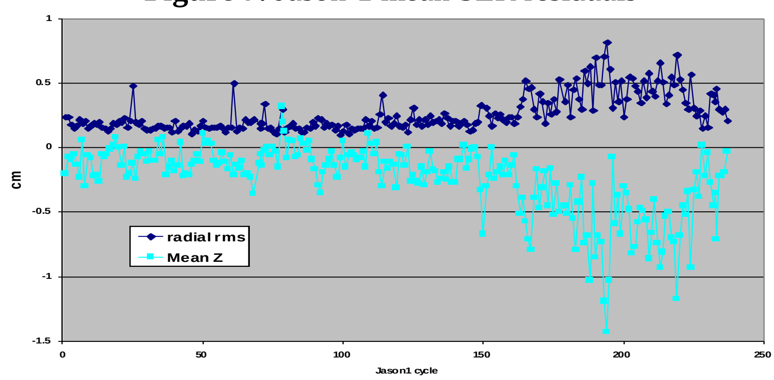

Figure 8. Jason-1 LPOD2005-SLRF2005 SLR/DORIS orbit differences