Determination and analysis of Herstmonceux geodetic heights for the period between 1984 and 2022

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Abstract

Following the NERC Space Geodesy Facility (NSGF) Analysis Centre work carried out in the "Systematic Station Error Monitoring" (SSEM) pilot project work towards its submission for ITRF2020, we have conducted further research using the SATAN analysis package with the main goal to improve the quality of station height time series. A particular interest is whether the ITRF2020 height time series for Herstmonceux, publicly available online, contains contamination from the historical period when Stanford interval counters were used (1990-2007) and when their known range-dependent errors were not fully compensated.

We present results whereby potential systematic range errors are accommodated within the weekly LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2 solutions using no a-priori bias information except the measured Stanford errors. A comparison is carried out between the range-bias series where the Stanford systematics are accommodated and where they are not and their impact on the height series.

1. Introduction

The adopted scheme for the official International Laser Ranging Service (ILRS) contribution to ITRF2020 was a two-pass process: the first solutions from each ILRS analysis centre were used to solve simultaneously for station coordinates, Earth Rotation Parameters (EOPs) and station/satellite-dependent range biases. Then at the combination stage, mean values of the range biases from the separate analysis centers (ACs) solutions were determined over specific time intervals. These time intervals were based upon knowledge of systems' technology changes and epochs of clear changes in range-bias values. The series of mean biases were then used in a second series of solutions, where for most stations range biases were held at the mean values and *not* solved-for.

In this current work, our strategy is to carry out only the first stage; that is, to solve for the reference frame simultaneously with potential range biases for every station, as detailed in previous work [0]. In addition, a particular interest is whether the ITRF2020 height time series for Herstmonceux, publicly available online [0], contains contamination from the historical period when Stanford interval counters were being used (1990-2007) and when their known range-dependent errors were not fully compensated during the orbital analyses processes towards ITRF2020; such contamination has the potential to compromise long-term geophysical interpretation of the height series in this forebulge collapse zone.

We present results whereby systematic range errors are accommodated for 1994-2022 within every weekly LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2 solutions using no a-priori bias information at all except for the directly estimated time-of-flightdependent Stanford errors (for the period 1990-2007), that were determined from hardware measurements carried out on site. We argue that taking account of systematic errors during the orbital dynamic solutions, including those induced by the Stanford counters, improves the *accuracy* of the resulting height time series with little, although inevitably some, loss of *precision*. The resulting height time series is compared with modelled glacial isostatic adjustment (GIA) results for the Southeast of the United Kingdom.

2. Herstmonceux height time series from ITRF2020

Given the long timespan of observations (1983-2022), and special attention to reducing systematics as much as possible, e.g., single-photons, improving hardware at the SLR stations (for instance epoch-timers), prolific, the latest improvements regarding centre-of-mass corrections [0], etc.; as well as the ASC strategy of accommodating range-biases in dynamical solutions, the deduced site coordinates *should be* reaching Global Geodetic Observing System (GGOS) goals of mm-accuracy and 0.1mm/y stability. However, this is clearly not the case for the Herstmonceux site (in which we have vested interest), see Figure 1.

Looking at Figure 1, it can be noticed that some systematic features remain that clearly are of non-geophysical origin. In particular, there appears to be a height change of ~10mm for the period 1994-2002 and of ~8mm for the period 2002-2006, separated with a very clear 'jump' (indicated with an orange vertical line on Figure 1) in the height time series.

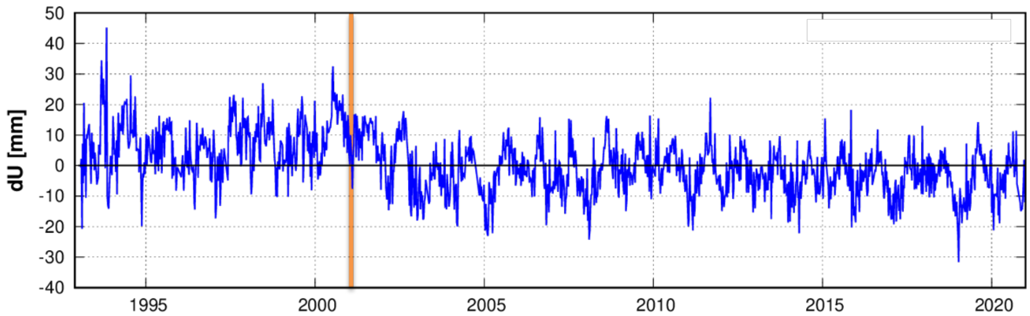

Figure 1: Height time series for Herstmonceux site for the period between 1994-2021.

The first step in the investigation into possible reasons for the systematic features shown in Figure 1 was to consider the mean range-bias values stemming from the SSEM project. It was found that for the period between 1993 to 29 September 2002 the values for LAGEOS are -6.4mm (and -6.5mm for LAGEOS-2), while from 29 September 2002 until 04 February 2007, the values were -11.4mm and -11.1mm. The main question that arose was, what is the reason for these range-bias values?

3. History of Stanford counters at Herstmonceux

According to the station logs and personal communication with the station manager, the following Stanford counters were used:

- SR620a – used from 1994 until 30/06/1999 (has characteristics as a function of range); period indicated with green line on Figure 2 .
- SR620d – used from 01/07/1999 until 11/02/2007 (has minimal range-dependent error); period indicated with orange line in Figure 2.
- From 11/02/2007 a high-quality event timer, dubbed HxET [0], was developed.

In order to understand the characteristics of range-dependent range bias that has been in Herstmonceux SLR measurements since October 1994, extensive tests on the linearity of the Stanford counters at satellite ranges were carried out in-house using an on-loan high precision event timer and reported by [0][0][0].

These tests revealed that the range-dependent range bias present in Herstmonceux data is caused by subtle non-linear effects in Stanford SR620 counters. Based on this work, a correction table (values provided in Table 1) as a function of range was compiled and issued in SLRMail 0891 in 2002 January. The email stated:

> *"that for maximum accuracy in interpretation of Herstmonceux (7840) data obtained in the period 1994 October 1 until 2002 January 31 inclusive (shown with red line in Figure 2), the correction table should be used to determine the appropriate range-dependent correction that must be added to the time-of-flight given in the normal point data."*

From 2002 February these corrections were applied at the station as part of its routine pre-processing of all laser range measurements [0].

The validity of the correction table given in SLRMail 0891 was later confirmed by [0] in October 2006, when HxET construction was completed at Herstmonceux. In addition to validation of the corrections announced in SLRMail 0891, HxET also provided an opportunity to conduct more detailed tests of non-linearity effects caused by Stanford counters, in particular their behavior at close range - the errors in this time-region will directly affect calibration ranging results and thus all satellite ranges from the SLR station [0]. There were two main outcomes from these tests. One stated that at the effective range of the SGF primary calibration target (~100m), the non-linearity of the counter adds an average of ~50ps (~7mm) error into the observed range. In addition to that, [0] also reported that there was no account taken for the effect on total delay of a glass neutral density filter – amounting to a 1.5mm error. Hence, 8.5mm should be added to all Herstmonceux satellite ranges between 1994-2007.

Figure 2 graphically shows time periods where different Standford counters were used, together with the corresponding corrections that should have been properly taken into account.

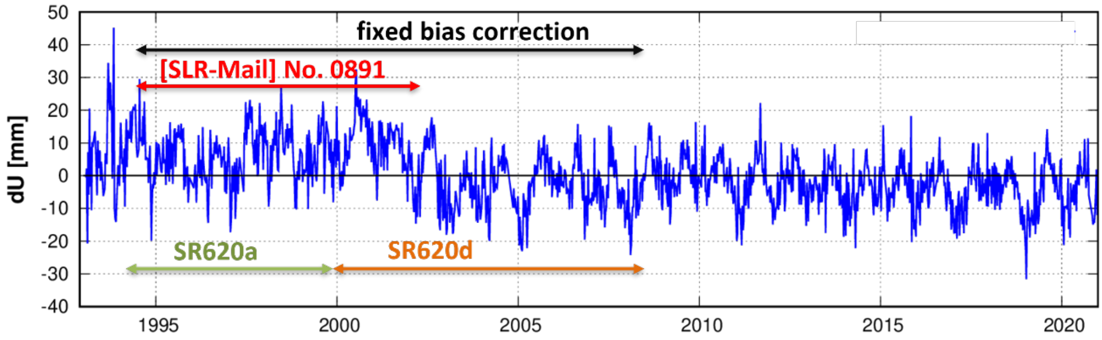

Figure 2: Herstmonceux height time series for the period between 1993-2022 with indicated periods for different Stanford counters and corresponding corrections that should be taken into account.

4. Evaluation of solutions with all corrections properly applied

In order to fully understand and correctly accommodate Stanford systematics, we have conducted our own internal reprocessing in which range-biases were estimated for every 7-day arc for Herstmonceux SLR data along with station coordinates and EOPs. Range-dependent and fixed value errors (described in previous section) were applied to normal-point range values as appropriate. Special attention was then given into investigating the impact on estimated range-biases and on the station height time series.

Figure 3 shows derived LAGEOS range-biases referring to three different solution sets: SGF solutions used for purposes of the SSEM project (green), internal SGF solutions with range-dependent corrections applied (orange) and with range-dependent corrections plus the fixed range-bias value (blue) applied as appropriate.

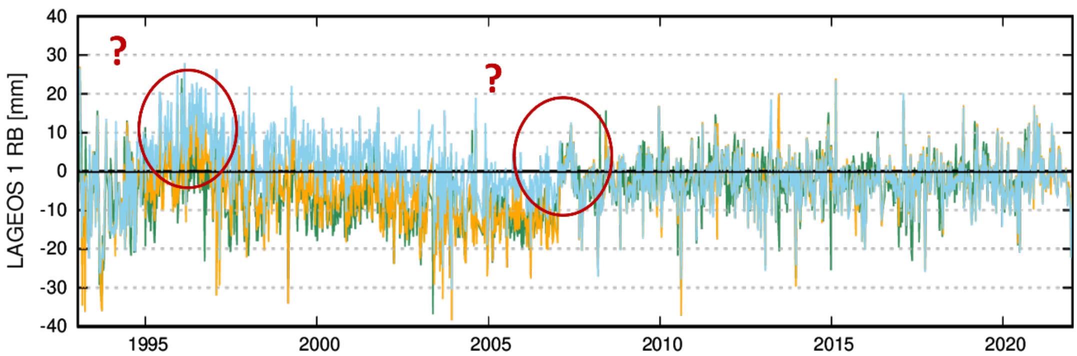

Figure 3: Time series of LAGEOS range-biases referring to the Herstmonceux station between 1993-2021. With green SGF solutions for the SSEM Pilot Project are shown, orange solutions with application of the Stanford biases and in blue solutions with application of Stanford biases plus the fixed range-bias.

Taking into consideration only the range-dependent corrections, appears not to have a significant impact on the estimated range-biases. On the other hand, when both corrections (range-dependent and fixed value error) were properly applied, we obtained an average value of LAGEOS range-biases of ~2mm, for the period between 1999-2005. However, there are still some open questions that require further investigation; in particular, for two periods, namely 1995-1997 and the beginning of 2007, see Figure 3.

Finally, Figure 4 shows a revised Herstmonceux geodetic height time series. Standard errors shown result from a full covariance analysis during the process of transforming the coordinates from geocentric rectangular to geodetic relative to the standard ellipsoid. Outliers based on large standard errors have been excluded from the fit, where annual, semi-annual and linear terms were fitted to the time series. According to analysis presented in [0] [0], modeled glacial isostatic adjustment (GIA) for this forebulge (collapsing) site is ~-0.4mm/yr. However, we find that the linear term is -0.12 +/- 0.04 mm/yr, indicating that a significant discrepancy still remains between laser range measurement and currently available GIA models.

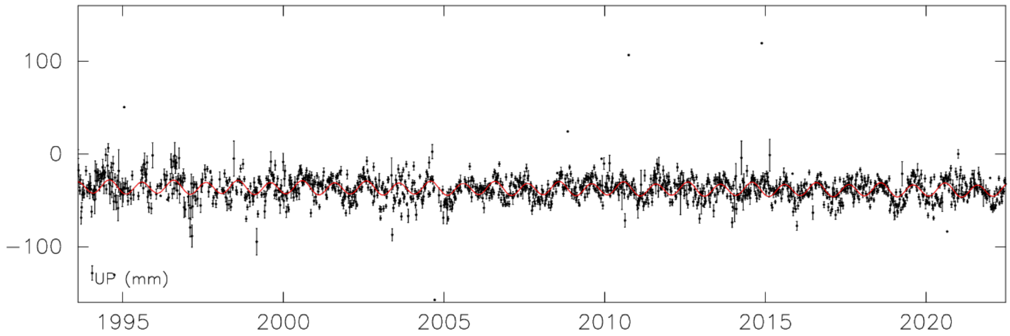

Figure 4: Height time series for Herstmonceux site for the period between 1994-2021, obtained when applying range-dependent and fixed value error (described in previous section) to normal-point ranges as appropriate.

5. Conclusions

Extensive research into station logs and analysis software has been carried out, which revealed that for the period 1994-2007, the range-dependent errors imposed by the Stanford counters were regrettably *not properly* taken into account in these or the previous SSEM solutions. Furthermore, an additional fixed bias of 8.5mm for the whole period (from close-range counter error) was not applied when appropriate. Even though that analysis showed that properly taking into account those errors imposed by the Stanford counters, there are still some open questions that require further investigation. In particular for two periods,1995-1997 and at the beginning of 2007. Comparison between the resulting height time series and modelled GIA results showed a discrepancy between the two which will require further investigation.

References

G. Appleby, J. Rodríguez, and Z. Altamimi, Z. Assessment of the accuracy of global geodetic satellite laser ranging observations and estimated impact on ITRF scale: estimation of systematic errors in LAGEOS observations 1993–2014. *J Geod* **90**, 1371–1388 (2016). https://doi.org/10.1007/s00190-016-0929-2.

https://itrf.ign.fr/en/homepage

J. Rodríguez, G. Appleby, and T. Otsubo. Upgraded modelling for the determination of centre of mass corrections of geodetic SLR satellites: impact on key parameters of the terrestrial reference frame. *J Geod* **93**, 2553–2568 (2019). https://doi.org/10.1007/s00190-019-01315-0

G. Appleby, P. Gibbs, R. Sherwood, and R. Wood, 1999. Achieving and maintaining sub-centimetre accuracy for the Herstmonceux single-photon SLR Facility, Proceedings of Laser Radar Ranging and Atmospheric LIDAR Techniques II, Proc. SPIE Int. Soc. Opt. Eng., 3865, 52- 63.

P. Gibbs, 2002. Stanford Counter Comparison Results, Proceedings of EUROLAS Workshop ‘Detecting and eliminating errors in the EUROLAS network’, Herstmonceux, UK

P. Gibbs, G. Appleby and C. Potter, 2006. A reassessment of laser ranging accuracy at SGF Hersmonceux, UK. Proceeding of 15th International Workshop on Laser Ranging, Canberra, Australia, October 15-20, 2006.

G.A Milne, I Shennan, B.A.R Youngs, A.I Waugh, F.N Teferle, R.M Bingley, S.E Bassett, C Cuthbert-Brown, and S.L Bradley, 2006. Modelling the glacial isostatic adjustment of the UK region. *Phil. Trans. R. Soc. A.* ***364**: 931–948.*

K. Vardić, P.J. Clarke, P. Whitehouse, 2021: NCL20: A global GNSS velocity field for estimating tectonic plate motion and testing GIA models. PANGAEA, https://doi.org/10.1594/PANGAEA.935079.

Appendix

Table 1: Correction table as a function of range, provided in SLRMail 0891.

Range [ms]	Correction (ps) to 2-way time-of flight	Range [ms]	Correction (ps) to 2-way time-of flight
0	0	68	86
2	35	70	87
4	48	72	101
6	52	74	100
8	73	76	83
10	77	78	80
12	91	80	76
14	92	82	78
16	100	84	84
18	120	86	74
20	109	88	79
22	120	90	82
24	111	92	73
26	115	94	85
28	112	96	79
30	97	98	80
32	100	100	76
34	87	102	83
36	82	104	79
38	75	106	78
40	72	108	73
42	73	110	85
44	62	112	82
46	61	114	76
48	50	116	75
50	54	118	78
52	48	120	75
54	53	122	62
56	52	124	72
58	54	126	67
60	74	128	56
62	71	130	70
64	75	130	70
66	84		