Discontinuities at an active earthquake station: MOBLAS4

Peter Dunn and Van Husson

MONUMENT PEAK SLR and GNSS stations

Monument Peak is located close to the San Andreas fault

Large position shifts are expected and seen at times of large earthquakes: Discontinuities

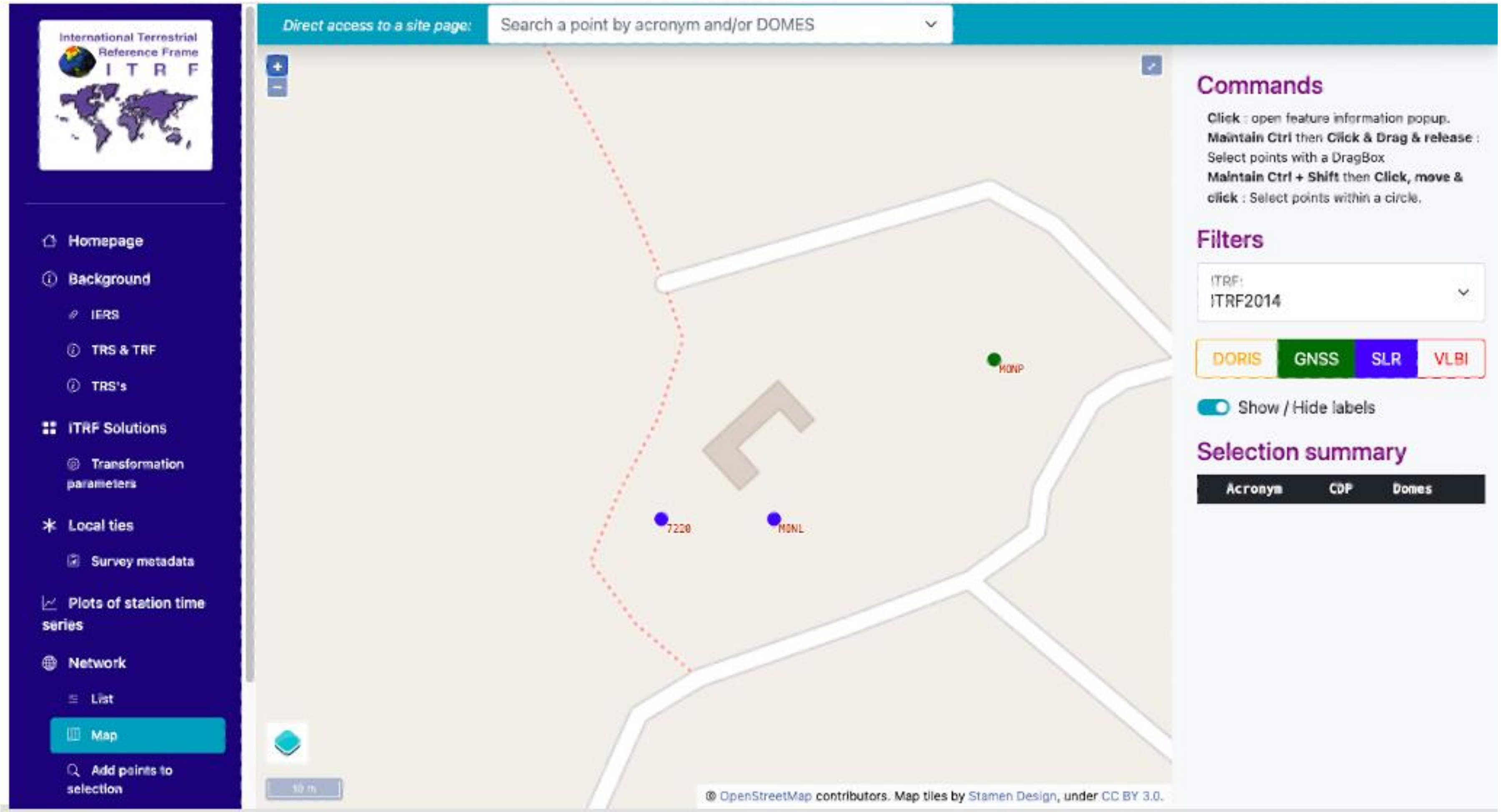
Engineering changes also cause apparent station position discontinuities.

The SLR Analysis Centers compensate for the non-geodetic features.
A Range Bias model is derived from the SLR data.
It is applied between discontinuities and the systems track on.

In contrast, GNSS Analysis Centers allow for frequent geodetic shifts.
These are modelled with empirical estimates in ITRF2020,

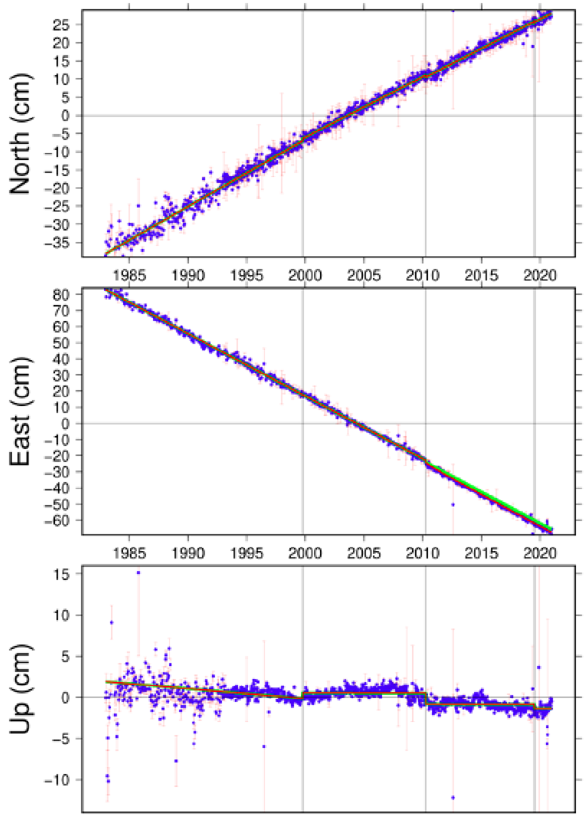
We compare the behavior of two strong co-located systems.
They each have different assignments for the times of discontinuity events.

MONUMENT PEAK SLR and GNSS stations



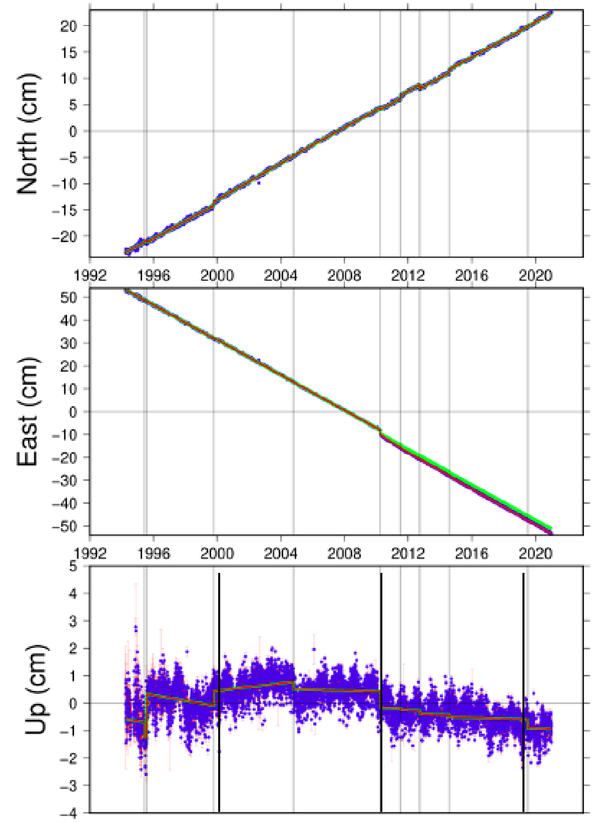
ITRF2020
MONL(SLR) and MONP(GNSS)

7110_40497M001 trajectory



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

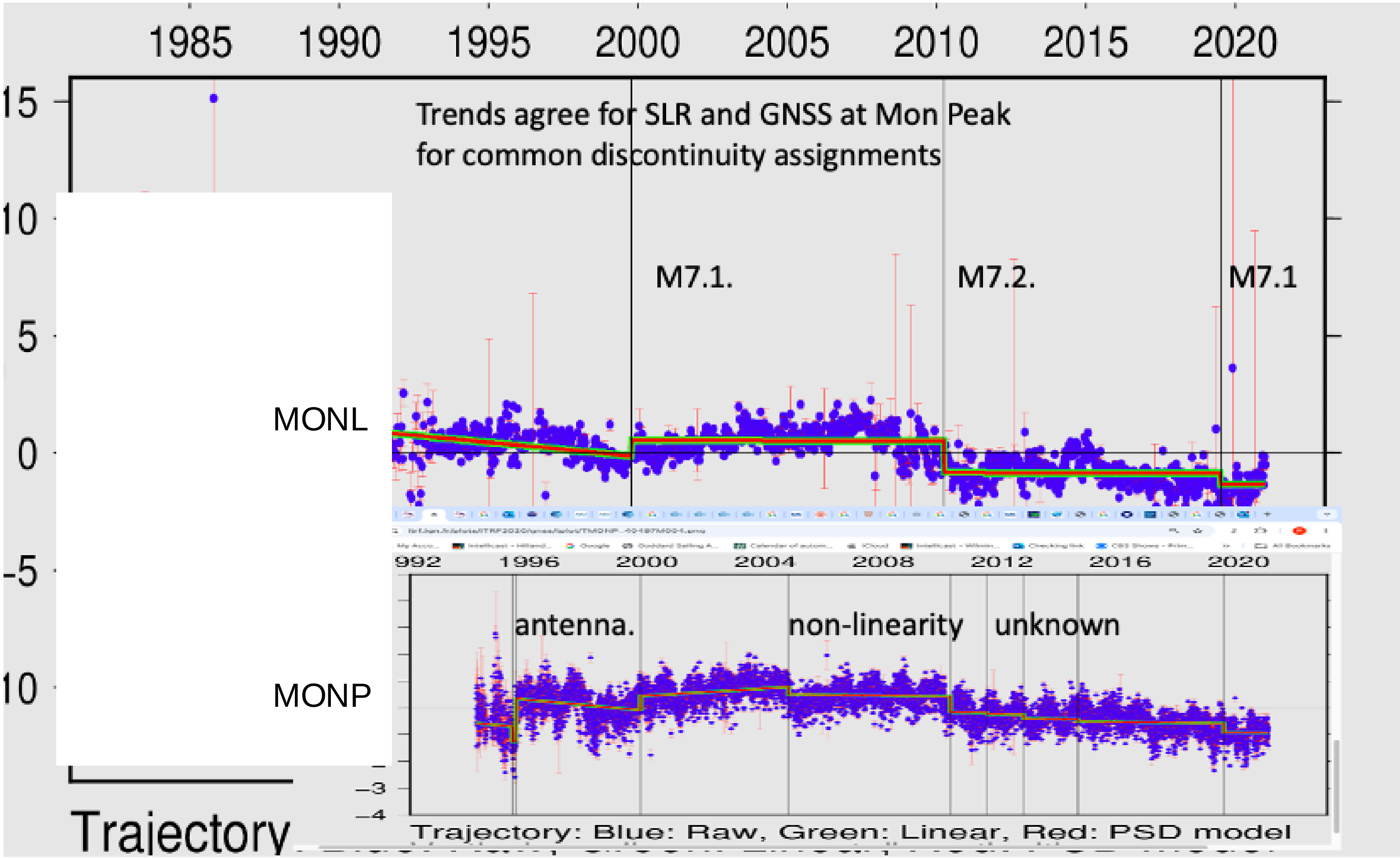
MONP_40497M004 trajectory



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

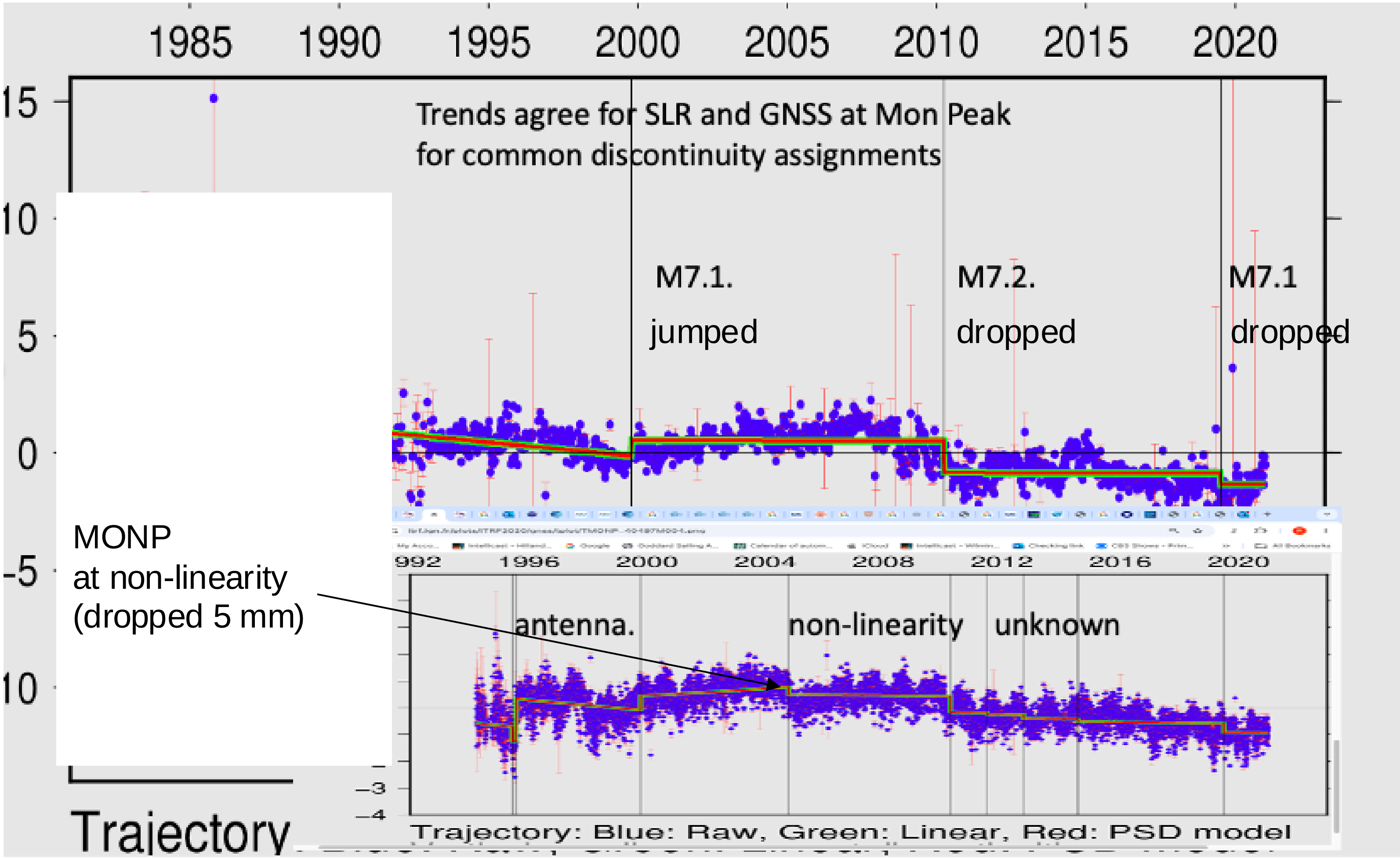
MONL/7110 and MONP show similar displacements at earthquake times

SLR and GNSS Heights on the same scale

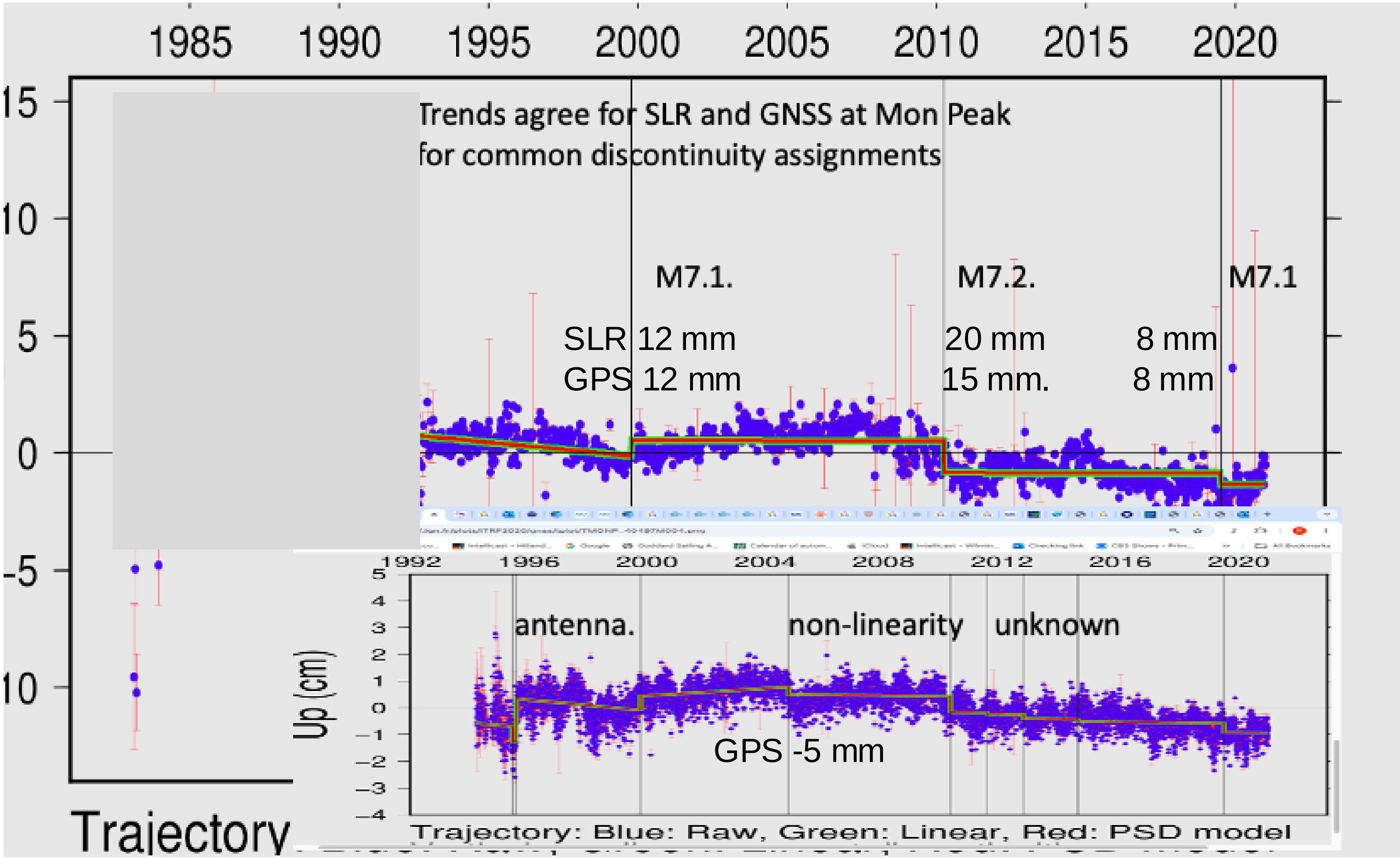


SLR cf. GNSS
Known earthquake discontinuities show matching vertical displacement
Empirical discontinuities show conflicting vertical displacement

SLR and GNSS Heights on the same scale



SLR and GNSS Heights on the same scale



MOB4 only detects significant vertical displacement at known earthquake events

Discontinuities at an active earthquake station: MOBLAS4

SUMMARY

MOB4 SLR exhibits steady vertical motion between earthquakes.

In ITRF2020, discontinuities are introduced at known earthquake occurrence times

The vertical displacements of SLR and GNSS agree at most earthquake discontinuity times.

MOB4 only detects significant vertical displacement at known earthquake events.

GNSS not so much

Discontinuity assignments for SLR and GNSS

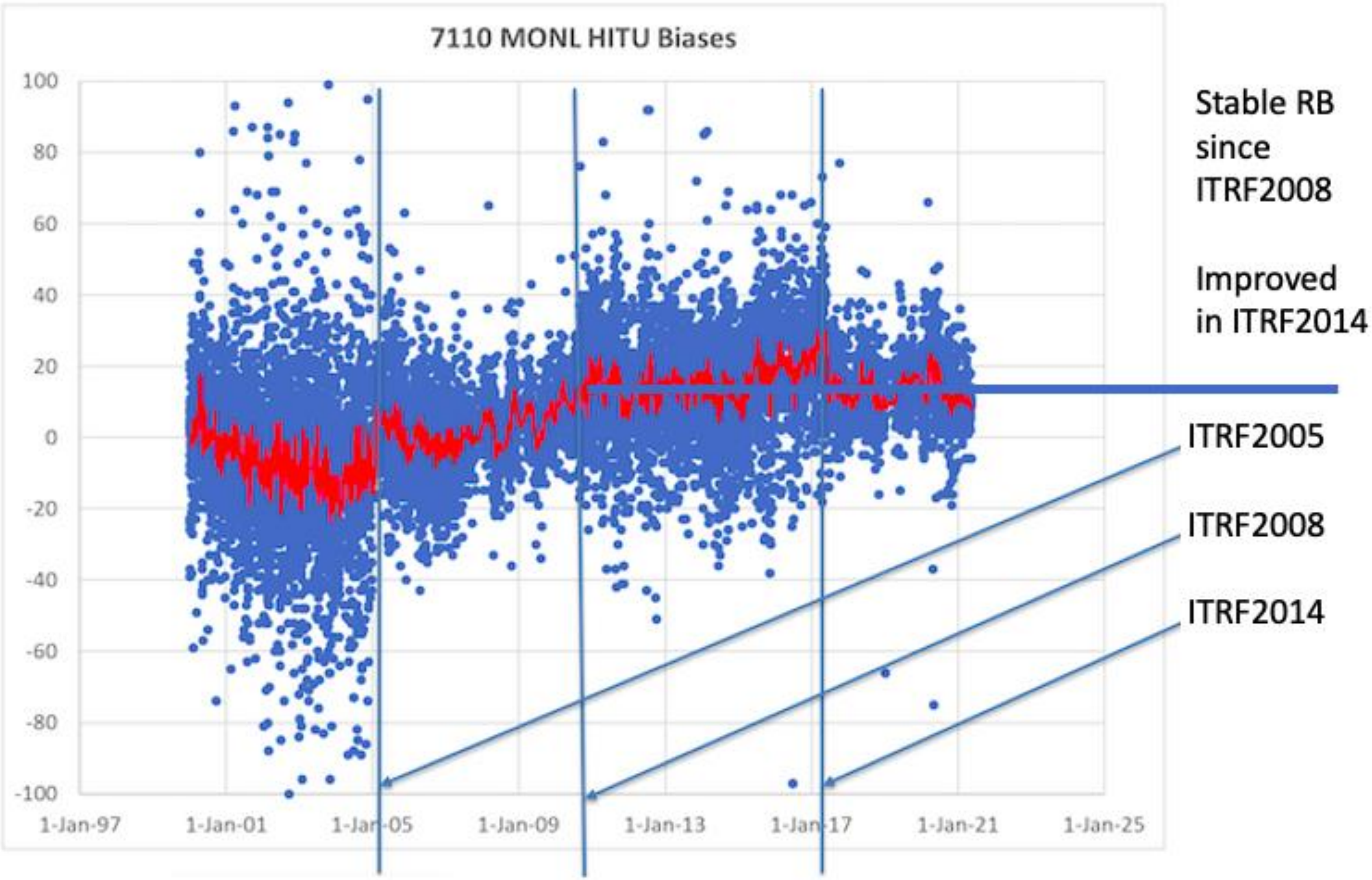
- 7110 A 1 L 00:000:00000 99:289:35204 P - EQ M7.1 - Hector Mine, CA Earthquake
- 7110 A 2 L 99:289:35204 10:094:81643 P - EQ M7.2 - 12km SW of Delta, B.C., MX
- 7110 A 3 L 10:094:81643 19:187:11993 P - EQ M7.1 - 2019 Ridgecrest Earthquake Sequence
- 7110 A 4 L 19:187:11993 00:000:00000 P -
- 7110 A 1 L 00:000:00000 99:289:35204 V - EQ M7.1 - Hector Mine, CA Earthquake
- 7110 A 2 L 99:289:35204 00:000:00000 V -

- MONP A 1 P 00:000:00000 95:169:00000 P - antenna change
- MONP A 2 P 95:169:00000 95:213:68400 P - antenna change
- MONP A 3 P 95:213:68400 99:289:35204 P - EQ M7.1 - Hector Mine, CA Earthquake
- MONP A 4 P 99:289:35204 04:291:00000 P - non-linearity
- MONP A 5 P 04:291:00000 10:094:81643 P - EQ M7.2 - 12km SW of Delta, B.C., MX
- MONP A 6 P 10:094:81643 11:188:00000 P - unknown
- MONP A 7 P 11:188:00000 12:268:00000 P - unknown
- MONP A 8 P 12:268:00000 14:210:00000 P - unknown
- MONP A 9 P 14:210:00000 19:187:11993 P - EQ M7.1 - 2019 Ridgecrest Earthquake Sequence

In ITRF2020 , discontinuities are introduced at known earthquake occurrence times

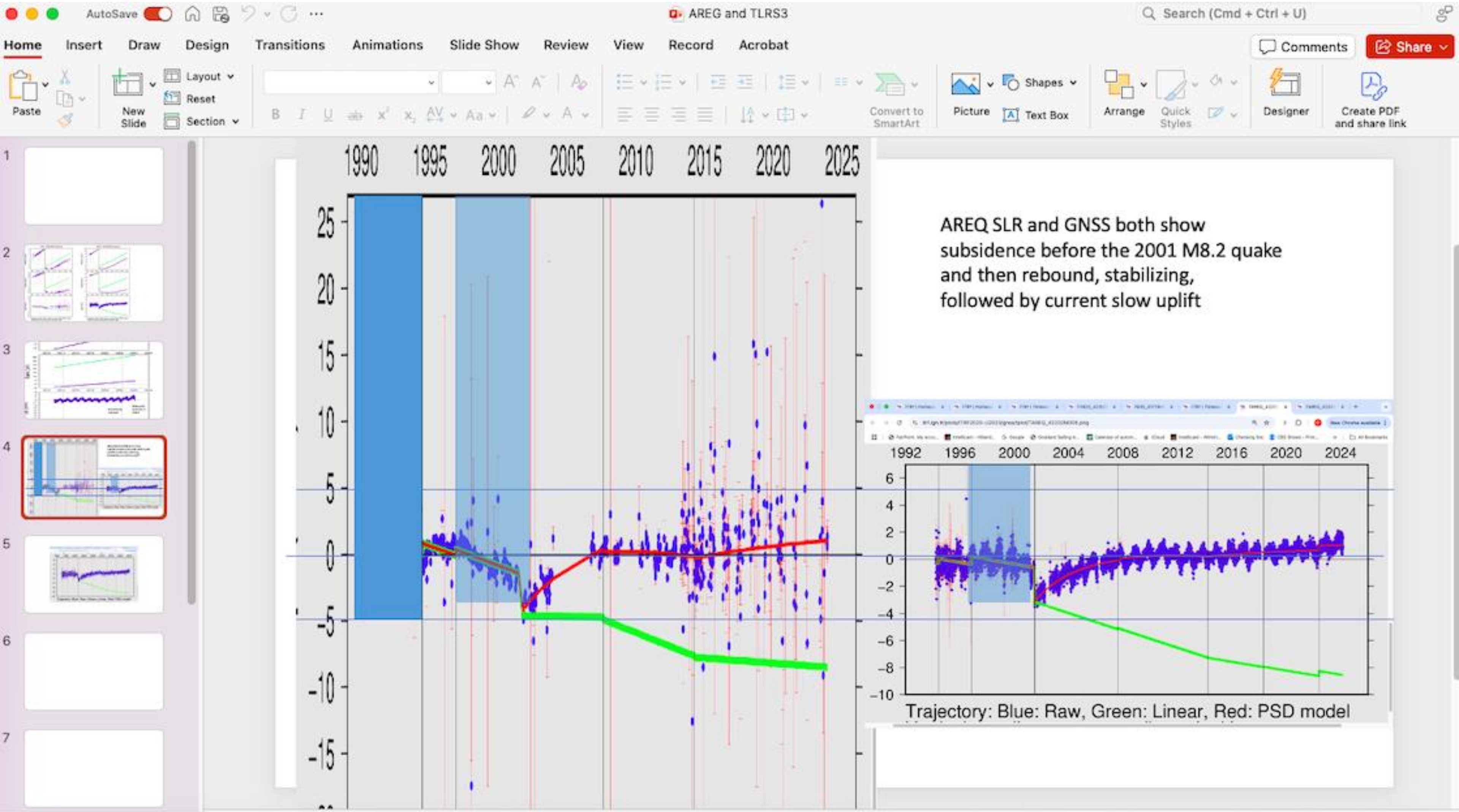
At Monument Peak more discontinuities are assigned to the GNSS system MONP than to MOB4.
Some MONP events are due to uncalibrated vertical antenna displacements.
Some are ‘unknown’.

MONL SLR Performance



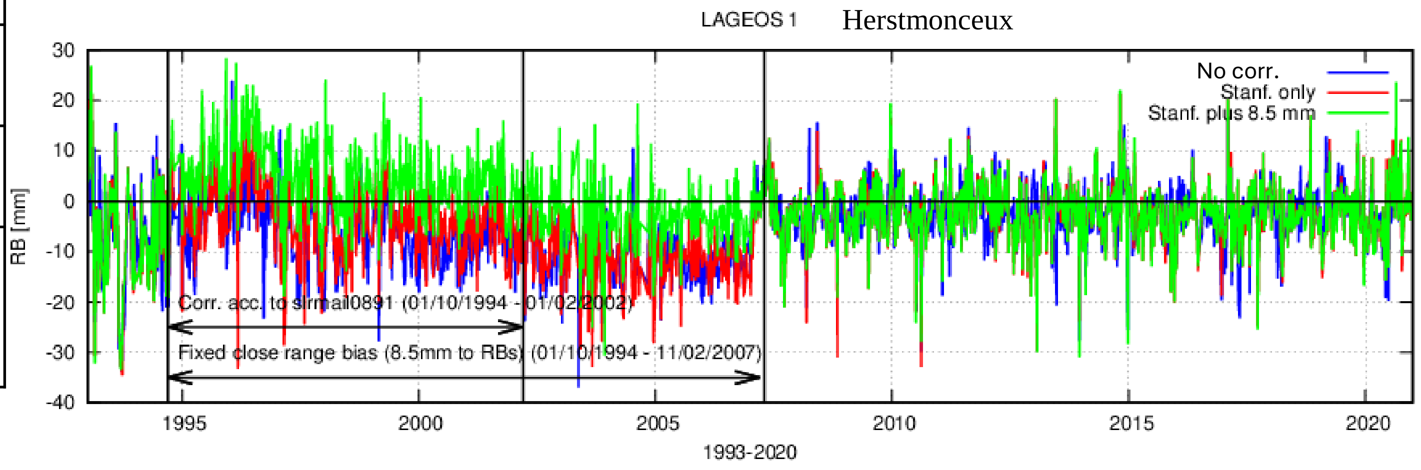
HITU RB Analysis shows that MOB4 SLR exhibits stable vertical behavior .

AREQ SLR and GNSS



Update on Stanford counters

Station	Period (according to station log)	Model
Herstmonceux (7840)	from 1994 to 30/06/1999 and from 01/07/1999 to 11/02/2007	SR620a[1] SR620d[2]
Borowiec (7811)	from 07/05/2002 onwards	SR620
San Fernando (7824)	from 10/08/2001 to 30/08/2022	SR620i
Potsdam (7841)	from 20/07/2001 to 19/04/2011	SR620
Zimmerwald* (7810)	from 01/01/1997 to 28/12/2004 and from 28/12/2004 to 03/02/2006	SR620 #0236 SR620 #3113



*According to ZIMM station log: since 29/05/2002 counter calibration values relative to the Herstmonceux reference are applied to the observations.

[1] has measured characteristics as function of range

[2] has minimal range-dependent error

* Please see Susnik et all, "Determination and analysis of Herstmonceux geodetic heights 1984-2022", 22nd ILRS Workshop, 2022 for more detail.

Correction tables for identified stations

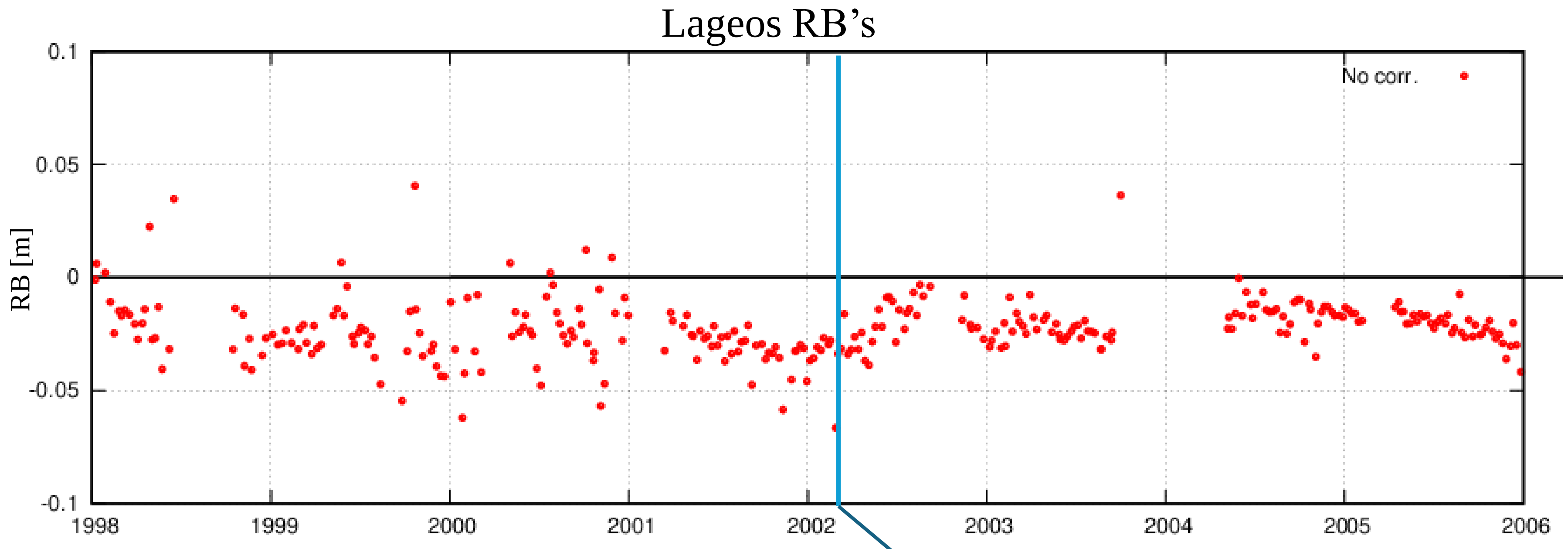
SFEL	
Range (ms)	Correction (ps) to 2-way time-of flight
5	55
10	60
15	60
20	57
25	55
30	60
35	55
40	55
45	55
50	50
55	45
60	50
65	50
70	55
80	55
90	55
100	55
110	55
120	55
130	55
140	55
150	55
155	55

ZIMM	
Range (ms)	Correction (ps) to 2-way time-of flight
5	75
10	65
15	55
20	55
25	52
30	50
35	50
40	50
45	55
50	47
55	45
60	50
65	45
70	50
80	50
90	50
100	50
110	50
120	55
130	55
140	55
150	55
155	55

POTS	
Range (ms)	Correction (ps) to 2-way time-of flight
5	20
10	25
15	30
20	35
25	35
30	30
35	32
40	22
45	20
50	18
55	20
60	22
65	30
70	30
80	30
90	30
100	25
110	25
120	25
130	25
140	25
150	25
155	25

BORO	
Range (ms)	Correction (ps) to 2-way time-of flight
5	20
10	15
15	12
20	15
25	15
30	15
35	12
40	12
45	10
50	15
55	10
60	12
65	12
70	12
80	12
90	12
100	12
110	12
120	10
130	10
140	10
150	10
155	10

ZIMM station – period when Stanford counters when used



since 29/05/2002 counter calibration values relative to the Herstmonceux reference are applied to the observations.

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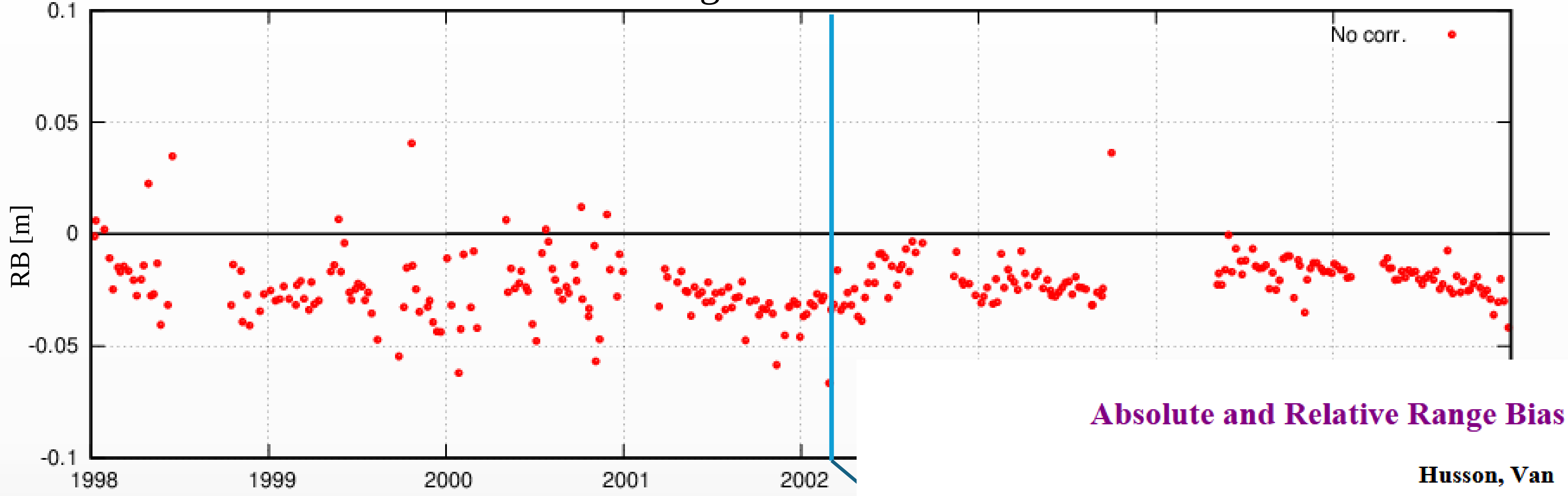
ZIMM station – period when Stanford counters when used

Lageos RB's



since 29/05/2002 counter c

According to paper/proceeding from Husson, Van:
In May 2002, Zimmerwald fixed a 14.5mm
range bias error.

Absolute and Relative Range Bias Detection Capabilities

Husson, Van

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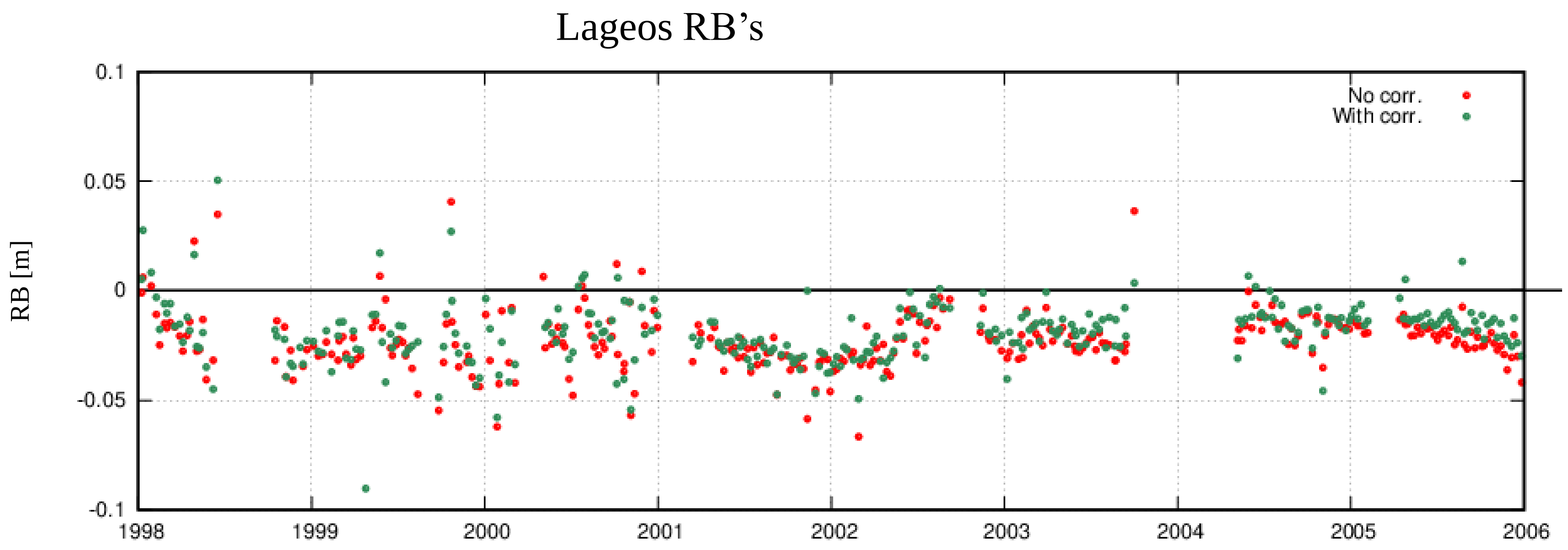
Abstract: The computed orbit is the final yardstick in accessing ILRS data quality. The absolute accuracy of orbit determination depends ultimately on the quality and quantity of data, but is a trailing (not leading) indicator of 'true' network performance. In order to successfully monitor improvements is laser ranging technology, analysis techniques continually need to be enhanced. This is mandatory for the ILRS is to achieve its vision of mm level accuracy.

Orbital analysis techniques (i.e. collocation, short arc, long arc) have their own inherent strength and weaknesses and will be characterized in terms of absolute and relative range bias detection capabilities. Some new bias detection techniques will be explored and evaluated.

ZIMM station – period when Stanford counters when used



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Properly ‘handling’ Stanford counter error has subtle effect on the estimated range biases.

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

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(4) Peraton Inc.

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.

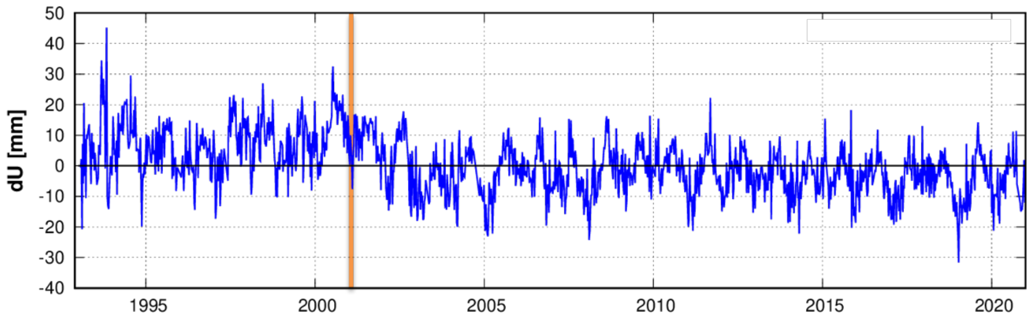

Figure 1: Height time series for Herstmonceux site for the period between 1994-2021.

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.

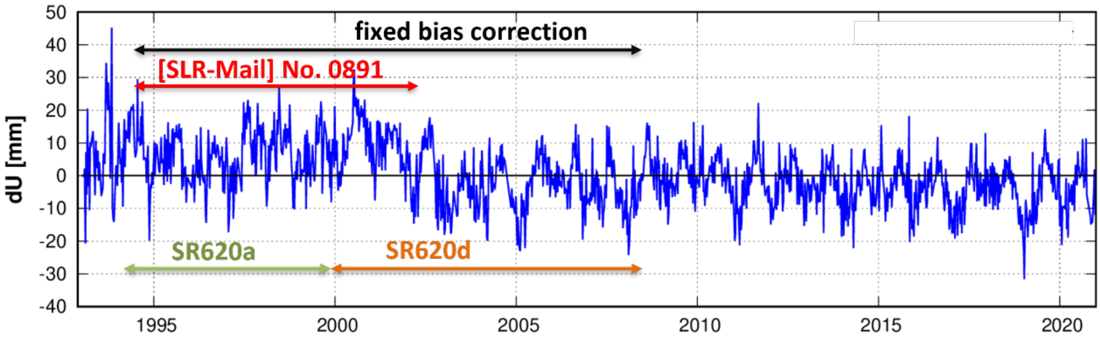

Figure 2: Herstmonceux height time series for the period between 1993-2022 with indicated periods for different Stanford counters and corresponding corrections that should be taken into account.

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.

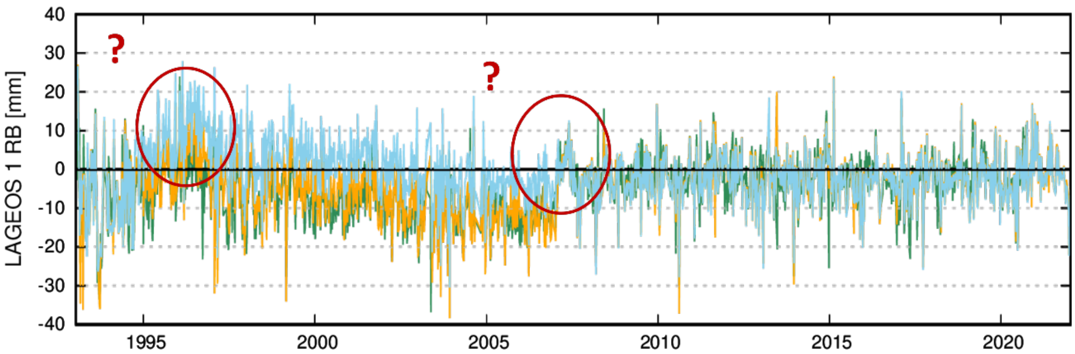

Figure 3: Time series of LAGEOS range-biases referring to the Herstmonceux station between 1993-2021. With green SGF solutions for the SSEM Pilot Project are shown, orange solutions with application of the Stanford biases and in blue solutions with application of Stanford biases plus the fixed range-bias.

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.

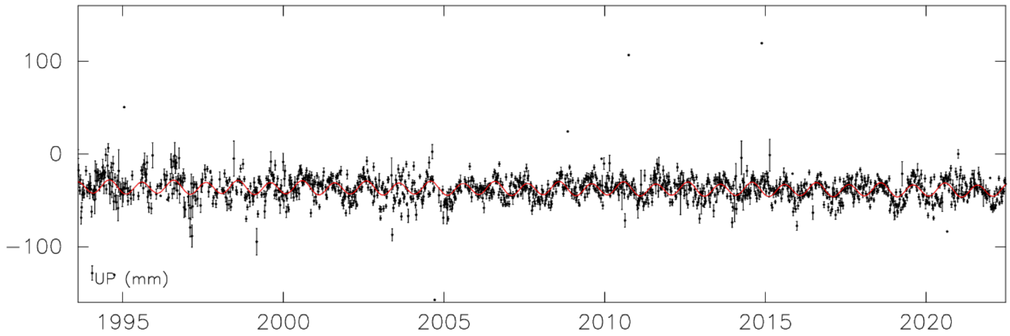

Figure 4: Height time series for Herstmonceux site for the period between 1994-2021, obtained when applying range-dependent and fixed value error (described in previous section) to normal-point ranges as appropriate.

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

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

ILRS QCB Meeting

01/27/2025

Claudia Carabajal

Agenda

Agenda:

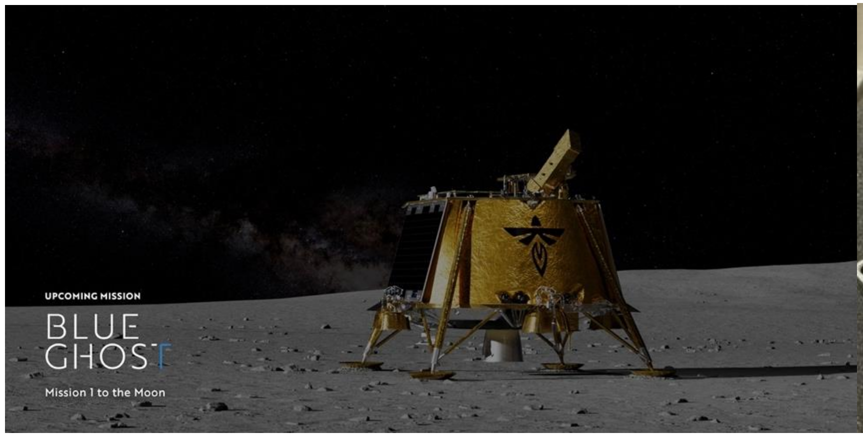
•Peter Dunn will present on “Discontinuities at an Active Earthquake Site: MOB4”.
•Alex Belli will present to the ILRS QCB the results of his performance analysis for Core stations presented at the last AGU in Washington, DC, recently presented at the last ILRS CB meeting.
•Andreja/Graham: Update on the Stanford Timers.
•ILRS updates.
•Others…?

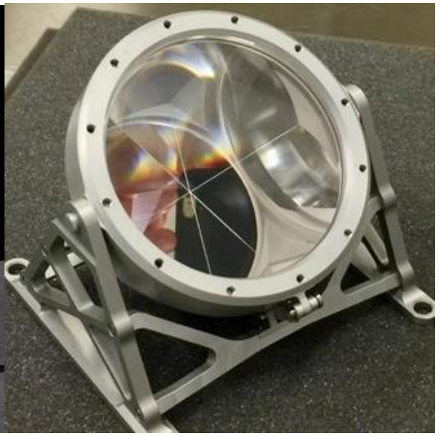
Agenda, Notes, and materials from the last QCB meeting on July 15th, 2024 will be posted here:
https://ilrs.gsfc.nasa.gov/science/qcb/qcbActivities/index.html

Mission Updates/New Missions

- NGLR-1 (Next Gen Retroreflectors Launch to the Moon - UMD Physics)

NGLR-1 Mission was approved by the ILRS GB.
Mission was informed.
Firefly Aerospace's Blue Ghost Mission 1 successfully Launched at1:11 a.m. EST on January 15, 2025 and began its 45-Day transit to the Moon. The NGLS-1 mission will be contacted. Preparing to support the mission. https://fireflyspace.com/missions/blue-ghost-mission-1/
Landing is expected for March 2nd, 2025.
Difficulties establishing conversation with Mission contacts.





Mission Updates/New Missions

ETS-9

- CDDIS contacted by **ETS-9 (Engineering Test Satellite-9) mission (JAXA)** to upload predictions.
- There is no record of a MSRF, but the mission is listed as a ”Future Mission”.
- Missions Website: https://www.satnavi.jaxa.jp/files/project/ETS-9/en/

Engineering Test Satellite-9 is a demonstration satellite to achieve next generation geostationary satellite communication that will be internationally competitive in the 2020s. To achieve this, Engineering Test Satellite-9 will verify communication technology that meets market needs, and satellite bus (platform) technology to load communication instruments.

- Contacted the MSC, and no MSRF has been located.
- No contacts identified for the mission.
- Will follow up with other JAXA contacts for information.

Station Updates

Xian Station, China

- New Station application (Xian) under review by the NEWG. The site log seems complete. **PAD 7329 and System ID 84** will be assigned. Review questions from the NEWG will be pass to the station colleagues by 1/17, and the station will be advised to apply for a DOMES number, and document anything else needed on the Site Log.
- A 1993 document was found which listed this PAD as being assigned to a VLBI station.

The CDDIS has been assigning CDP/monument numbers for the SLR and VLBI stations. These are supposed to be unique but it recently came to our attention that the tables we were references before assigning the CDPs did not contain some values found in a published 1993 document: https://ntrs.nasa.gov/api/citations/19930012185/downloads/19930012185.pdf [ntrs.nasa.gov].

- We are trying to assess the impact of these overlaps, listed below and if corrections need to be made. We contacted Zuher and Frank about it:

SLR
7115 – Goldstone Venus on the 1993 document; Goldstone Mars on SLR internal table
7231 – Goldstone Mar on the 1993 document; Wuhan currently
7306 – Tokati on the 1993 document; Tsukuba currently
7308 – Tokyo on the 1993 document; Koganei (under Closed/Inactive Stations)
7317 – Minami Daito Jima on the 1993 document; Ishioka currently (under Engineering Stations)
7548 – Tuscany on the 1993 document; Cagliari (under Closed/Inactive Stations)
7701 – Oberpfaffenhofen on the 1993 document; Tenerife currently

VLBI
7222 – Mojave in 1993 doc; Goldstone on CDDIS system (Might be the same site)
7239 – La Silla in 1993 doc; Cerro Tololo on CDDIS system (Might be the same site, both in Chile)
7314 – Mizusgsi in 1993 doc; Mizusawa on CDDIS system (Might be the same site)
7610 – Monument Peak in 1993 doc; Kitt Peak on CDDIS system
7618 – Peterborough in 1993 doc; Hancock on CDDIS system (Might be the same site)

DOMES Numbers Changes Proposals

DOMES numbers proposals – Responses from the ILRS

Submitted input to the ISO proposal for DOMES assignation changes after collecting responses from ILRS CB and ASC.

Three proposals are similar to the current DOMES scheme:

- Proposal 1 : CCC TTT SSSS NN
- Proposal 2 : CCC SSSSS T NNN GG
- Proposal 3: CCC SSS T NN

Three proposals are substantially different from the current DOMES scheme:

- Proposal 4: OOOOSS T NN
- Proposal 5: DOIs
- Proposal 6: UUIDs

After consulting with the ILRS CB/ASC

In order of Preference (as stated in the form):

1. **Proposal 2: CCC SSSSS T NNN GG**
2. **Proposal 3: CCC SSS T NN**
3. **Proposal 4: OOOOSS T NN**

Station Survey and Plan:

Review Committee will be reconvening to wrap up feedback to contacted stations

- Need to set up a date.
- Will distribute summaries as of October to the group.
- ILRS CB is working on another message to be sent to stations after discussions at the ILRS CB. meeting, to remind him of the importance of tracking Geodetic Satellites and encourage them to improve performance. Inputs needed to put together a comprehensive message.

Mission Reports:

Review Committee will be reconvening to wrap up feedback to contacted missions

- Last report received was from ICESat-2.
- Need to set up a date.
- Will distribute summaries/comments received.
- Based on the evaluations, need to also evaluate the need for updates to the mission reports to try to get the answers needed. In addition, the right missions contacts need to be included to expand the science benefit perspective in the answers received.

- Suggestion to hold during the Station Clinics as session to discus Station Surveys and Mission Reports at Arequipa Wor

ILRS ASC webpage (NASA/UMBC AC):

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING