ELT Calibration Campaign

at Herstmonceux, UK SLR Station

(WP 3100 and WP3200)

Contract No.: **4000112251/14/NL/FC**			CSRC Project: **771 ELT2**
In accordance with: **ACE-ESA-SOW-007**	ESA Co-ordinators: **Francesco Cattaneo, Rudolf Much**		CSRC Project Manager: **Wendy Dolejšková**
Prepared by:	Name: **Prof. Ivan Prochazka** **Dr. Josef Blazej** **Wendy Dolejskova**	Signature:	Date: **20/6/2016**
Quality Assurance:	Name: **Klára Marcianova**	Signature: Marcianova	Date: **22/6/2016**
ESA Approval:	Name:	Signature:	Date:

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1. Change Record

Issue	Date	Sheet	Description of change
1	20.6.2016	All	First version of the document

2. List of Acronyms

Abbreviation	Description
ACES	Atomic Clock Ensamble in Space
ELT	European Laser Timing
PFM	Proto Flight Model
GSC	Ground Station Calibration Model
ICD	Interface Control Document
UUT	Unit Under Test
SLR	Satellite Laser Ranging Station

3. Applicable and Reference Documents

	Reference	Title
AD1	ELT2-PL-771-001-CSRC Iss2	ELT Calibration Campaign Plan
AD2	ELT2-TR-771-008-CTU-CSRC Iss1	ELT Test Calibration Report at Graz SLR (WP 2100 and WP2200)
AD3	ELT2-TR-771-009-CTU-CSRC Iss1	ELT Calibration Device Package (WP 2100 and WP2200)
AD4	ELT2-PL-771-002-CTU-CSRC Iss1	Generic Calibration Test Plan and Schedule (WP 2100 and WP2200)
AD5	ELT2-TP-771-001-CTU-CSRC Iss1	Test Procedure for ELT Calibration at SLRs (WP 2100 and WP2200)
AD6	ELT2-TR-771-010-CTU-CSRC Iss1	Report on Operational Tests and Long-term Stability of the Final Timing Device (WP 2300)
AD7	ELT2-PL-771-003-CTU-CSRC Iss1	Specific Calibration Test Plan and Schedule, (WP 3200 and WP4200, rev. April 2016)
AD8	ACE-TP-13400-001-CSRC Iss2	Functional and Performance Test Procedures
AD9	ACE-TP-13400-007-CSRC Iss6	Final Performance Test Procedures
AD10	ACE-IS-13400-001-CSRC Iss7	ELT instrument ICD
AD11	ELT2-TR-771-013-CTU-CSRC Iss1	Test Readiness for ELT Calibration at SLR Herstmonceux, UK
AD12	ACE-ESA-TN-001, Iss4, 12.4.2013	Mission objectives and Scientific Requirements
AD13	ACE-SP-13400-001-AST	ELT Instrument Subsystem Specification
RD1	ELT2-TR-771-011-CTU-CSRC Iss1	Report on Final Performance Test and Relative Delays of ELT2 GCS and ELT PFM (after modification)
RD2	ELT2-TR-771-012-CTU-CSRC Iss1	Test Report on Determination of Absolute Delays of ELT2 GCS and ELT PFM (after modification)

4. INTRODUCTION

The overall objective of the project is to complete the calibration procedures of the ground stations participating in the European Laser Timing (ELT) project. The correct calibration of all the participating ground SLR stations is a prerequisite of correct operation of the entire ELT experiment.

A "twin" of the PFM ELT detector was built, identified as ELT Ground Station Calibration (ELT2 GSC) device. The ELT2 GSC detection delay has been compared to the ELT PFM and EM on 28-29/1/2016. See [RD1] and [RD2].
ELT2 GSC/EM together with the dedicated timing device and cabling, see [AD3], form the "Calibration Tool" – a reference for the worldwide network of cooperating laser stations.

5. SCOPE

This report describes the calibrations results, as acquired within one calibration mission, at Herstmonceux SLR station, UK.

Information for this document was prepared by Ivan Prochazka, Czech Technical University. For more details on performance requirements of the complete ELT link, see [AD12]. For more details on performances of the ELT instrument (ELT flight segment) see [AD13] ELT Instrument Subsystem Specification.

6. ELT CALIBRATION REPORT FROM CALIBRATION CAMPAIGN AT HETRSTMONCEUX, UK SATELITE LASER STATION

Ivan Prochazka, Josef Blazej, CTU in Prague, Czech Republic
Robert Sherwood, Graham Appleby, et al., Herstmonceux SLR, NERC, UK

May 23–27, 2016

6.1 General

The ELT Calibration Device was used to complete the ELT related delays calibration of the Herstmonceux SLR for the ACES–ELT project participation. The calibration mission was completed May 23–27, 2016.

6.2 Test Hardware

The measurements were carried out using the ELT detector package (EM), the preliminary version of the ELT Calibration Timing unit, ELT related cable No. 4 and a set of ELT calibrated connectors and signal converters and appropriate ELT Calibration software package. The SLR system under test was a standard configuration of Herstmonceux SLR system.

Figure 1 - ELT Calibration Device installed in a dome in front of the Herstmonceux SLR system. SLR system telescope (right top), ELT detector (black, top center), ELT calibration Timing (bottom), process control and data acquisition PC (bottom left).

6.3 SLR Main System Parameters

SLR system:	Laser	10 ps, 532 nm, 1 kHz nominal
	Timing electronics	Herstmonceux, based on Dassault modules, precision ~8 ps
Clock frequency:		10 MHz generated by T4Science Hydrogen maser 10 MHz signal distributor by TimeTech
Time reference:		Local time scale based on T4Science Hydrogen maser, GPS steered 1 pps signal distributor by TimeTech
Time reference point:		input connector of SLR timing system (Input of an additional input comparator unit)
Time reference levels:		positive pulse, leading edge, trig. level +1.500 V

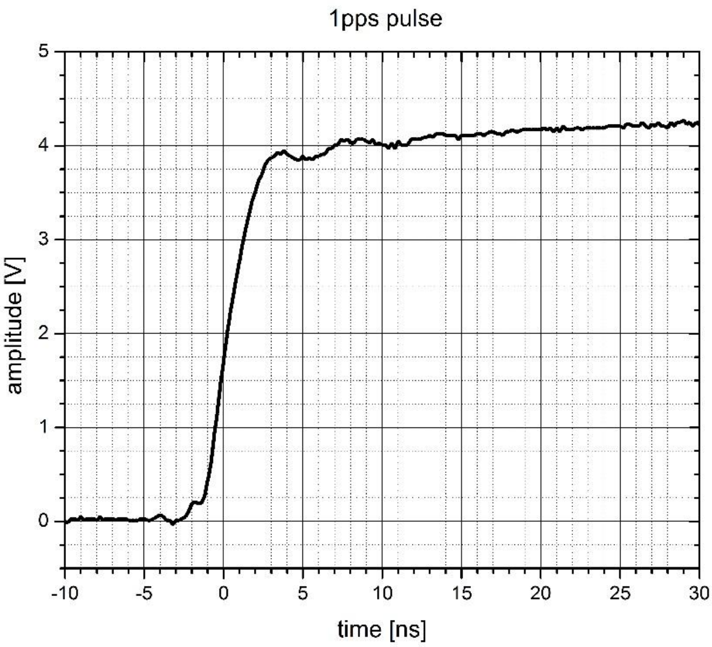

Figure 2 - Time signal “1 pps” on the input of SLR and ELT timing electronics, oscilloscope bandwidth 1 GHz. The trigger level of +1.500 V was used. Signal slew rate ~1 V/ns.

6.4 Measurement Procedure

Location and Survey
The ELT detector package (EM unit) was installed in front of the SLR system transmitter telescope on its optical axis. The distance of ELT invariant point to the SLR system horizontal axis was measured repeatedly by different surveyors and using independent scales, see Appendix. Considering the reproducibility of different survey methods the value 1909±2 mm was adopted. It corresponds to a propagation delay of 6.367±0.006 ns.

ELT Detector Gating
The ELT detector was externally gated by a signal from the laser Start output inserting an additional delay of 999 µs. The detector was activated about 750 ns before photons of interest arrival. The laser and the gate signals were operated with a standard rate of 1 kHz.

Optical Signal Strength
The optical signal strength has been adjusted by inserting optical neutral density filters in transmitted beam path. The optical attenuation was set to a configuration when the useful signal strength corresponded to mostly single photon echoes. It was secured by an echo signal rate of 8 – 15 %. The additional optical signal delay caused by optical filters is applied as a correction to recorded epochs of laser fire. For each of the optical filters inserted this correction is applied. Thus there is no need to apply any additional signal propagation correction to measured values.

Time Scales Settings
The SLR and ELT epoch timing systems used a common source of 10 MHz clock frequency. The "1 pps" timing signal was applied using a common cable with BNC connector. It was connected to the SLR and ELT synchronization inputs consecutively. On ELT timing unit the additional BNC(F) to SMA(M) converter having a signal propagation delay of 0.096 ns was used. The trigger slopes and levels were set to identical values of positive, +1.500 V. The timing jitter of the "1 pps" signal was measured using the ELT timing device. It was rather high, typically 35 ps rms. That is why the ELT timing unit time scale was set using averaging over consequent pulses to lower the influence of this jitter and variations, see later.

6.5 Calibration Results

Each measurement series consisted of 20 – 40 seconds of data acquisition by both systems (SLR, ELT). The SLR data were acquired by 1 kHz rate, the ELT data were acquired by a maximum data rate for the ELT Calibration Device which is 500 readings per second. Considering the echo signal strength corresponding to a data rate of 5 – 15 % it means typically 1500 signal photons were detected and time tagged in each series. The recursive "2.2 × σ" data filtering algorithm has been used to process the measured data. This filtering algorithm is a standard one for processing of photon counting data acquired in ELT experiment.
A number of modifications of the setup was implemented within the measurement series No. 1 to No. 6 with an aim to optimize the calibration procedure. That is why the results of these series are not listed in this report. The key problem was identified in a pair of "1 pps" and "10 MHz" signals and its consistency. Both measurement systems (SLR and ELT) detected significant changes of a phase of "1 pps" versus the clock frequency of "10 MHz". In Figures 3a and 3b there are plots of fractional epochs of arrival of "1 pps" pulse to the

ELT Timing unit input. Note the large fluctuation of arrival times exceeding 30 ps rms and mainly the significant systematic components. The origin of these systematic components was not identified. The moving average over 90 seconds was plotted for illustration. The extreme values of systematic effects are plotted in Figure 3b. Note the “jump” of nearly 200 ps in “1 pps” pulse phase versus the clock frequency source.

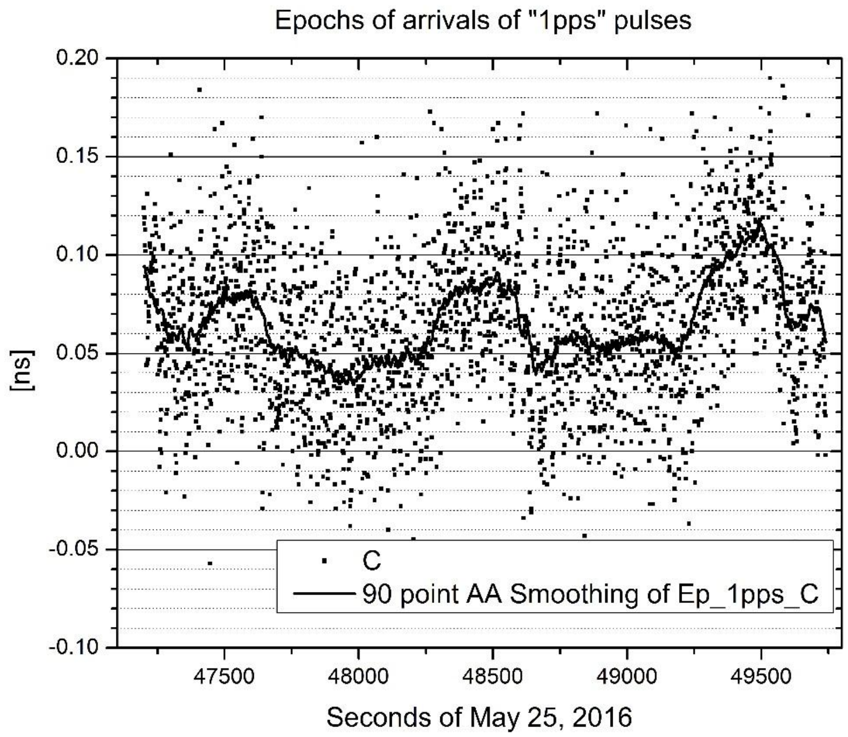

Figure 3a - Plot of fractional epochs of arrival of “1 pps” pulse to the ELT Timing unit input, “standard behavior”. Note the moving average changes reaching ±50 ps

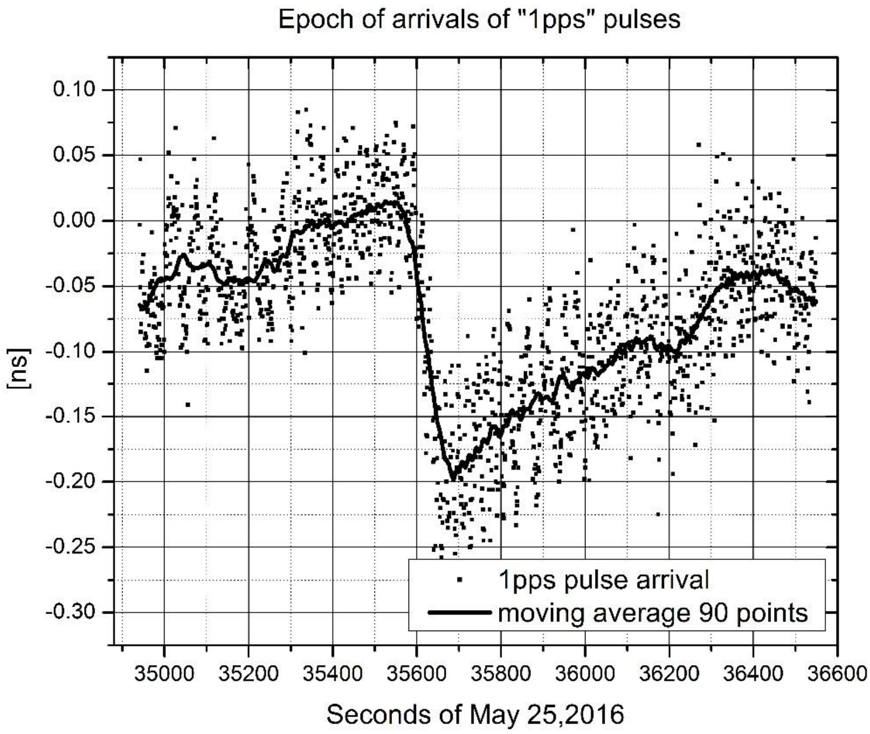

Figure 3b. Plot of fractional epochs of arrival of “1 pps” pulse to the ELT Timing unit input, extreme situation. Note the “jump” exceeding 200 ps.

The timing characteristics of “1 pps” signal expressed as Time Deviation TDEV is plotted in Figure 4. The data displayed in Figure 3a were used for this calculation.

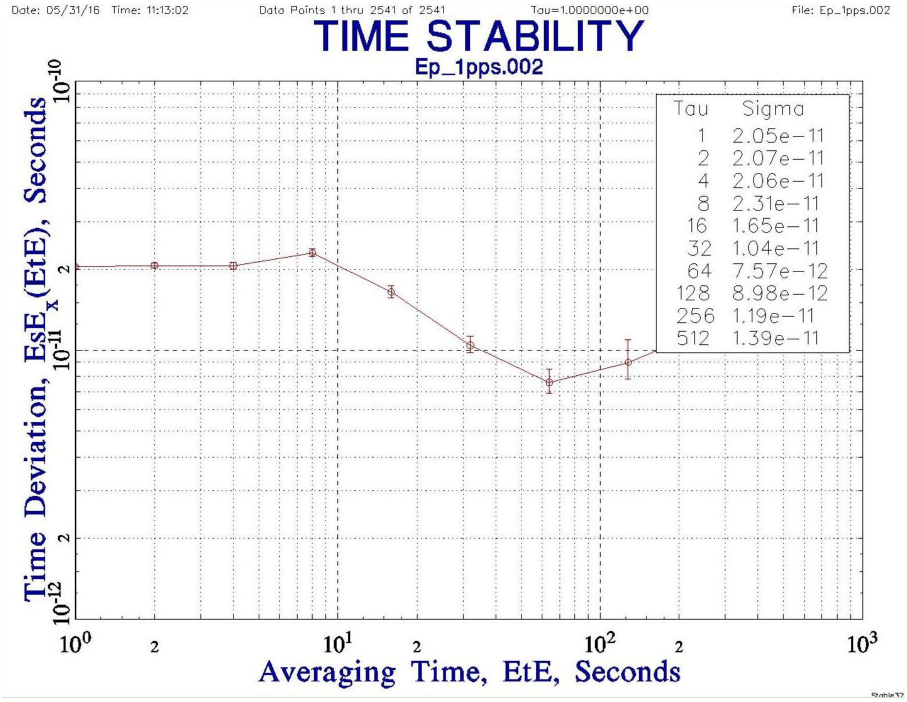

Figure 4 - Timing characteristics of “1 pps” signal expressed as Time Deviation TDEV.

From Figure 4 one can also note non¬ standard data distribution. The time deviation has its minimum for averaging times of 50 to 100 seconds. That is why the averaging time of 90 seconds has been selected for adjustment of time scales of both SLR and ELT epoch timing systems.

The sample of measured data – epoch differences is plotted in Figure 5.

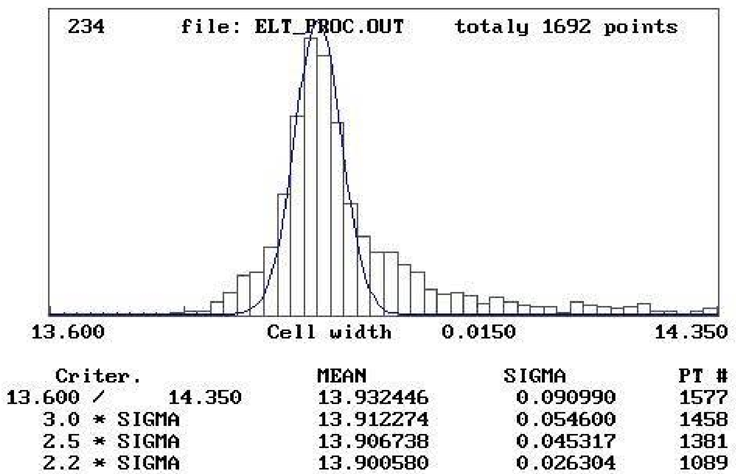

Figure 5 - Histogram of measured epoch (ELT–SLR) differences in series No. 11. All epochs are in ns. Note the measurement jitter of ~26 ps rms.

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The overall system performance in a sense of Time deviation TDEV is plotted in Figure 6. One can note the value TDEV < 1 ps at 25 to 80 s integration time.

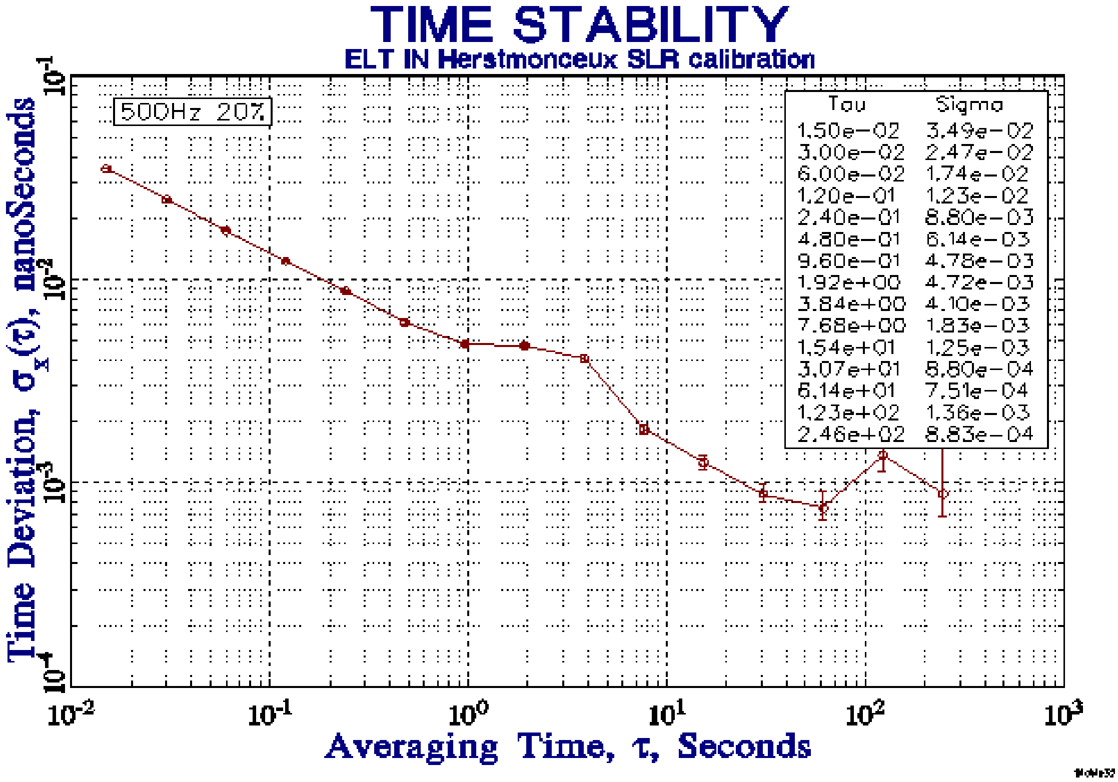


Figure 6 - Overall system performance in a sense of Time deviation TDEV. One can note the value TDEV < 1 ps at 25 to 80 s integration time

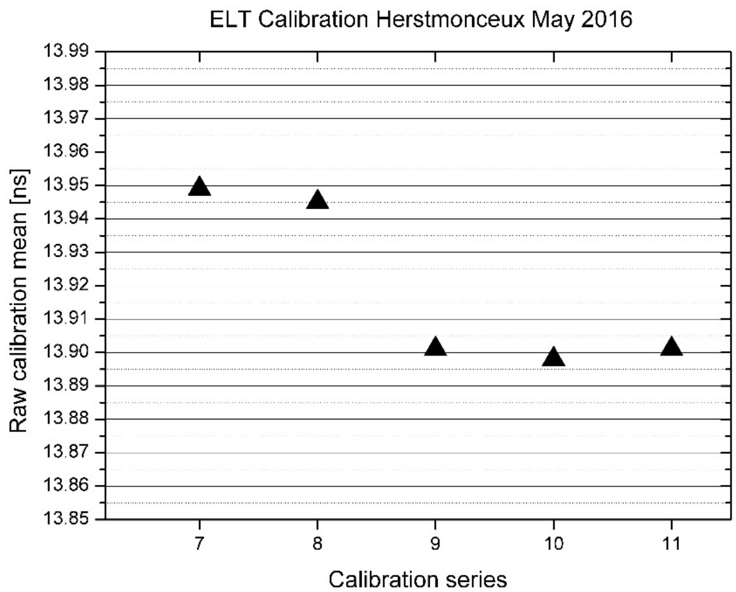


Figure 7 - Raw calibration mean values in series No. 7 to 11.

Table 1. Calibration results summary, Herstmonceux, May 24–25, 2016

Series No .	cal. mean raw data [ns]	connect or added [ns]	geometry subtracted [ns]	ELT Calibration [ns]
	#2	#3	#4, i.e. (B)	(C)
7	13.949	14.045	7.678	−1.543
8	13.945	14.041	7.674	−1.547
9	13.901	13.997	7.630	−1.591
10	13.898	13.994	7.627	−1.594
11	13.901	13.997	7.630	−1.591
mean	13.919±0.023	14.015	7.648	**−1.573±0.027**

Calibration results comments

- Raw calibration mean values are plotted in Figure 7.
- The series No. 7 and 8 and No. 10 and 11 were completed without time scales re-set. Note the differences between these two pairs well within a statistical spread of the mean values of ±2 ps.
- The both time scales were re-synchronized just before series No. 9 and No. 10. This explains the "jump" between series No. 8 and No. 9.
- The overall mean values is 13.919±0.023 ns (rms)
- The peak to peak spread is 51 ps well coinciding to the properties of the local time scale performance.

ELT Calibration value calculation

1. At first the epoch differences (ELT − SLR) have been evaluated, see coll. #2 of Table 1.
2. The values were corrected for additional delay caused by BNC to SMA converter (+0.096 ns), see col. #3 of Table 1.
3. The geometry of the experiment was applied. It means the propagation delay (6.367 ns) from a SLR mount ref. point to the ELT Detector package ref. point was subtracted, see col. #4 of Table 1. The result corresponds to a calibration constant "B".
4. The ELT calibration constant "C" was calculated from values of coll. #4 by subtracting propagation delays of signal cable No. 4 (7.114±0.002 ns) and detector package (2.107±0.014 ns). The resulting ELT Calibration value is −1.573±0.027 ns.

6.6 Conclusion

- The ELT calibration of the SLR station in Herstmonceux, UK, was performed May 24 – 26, 2016.
- **The ELT calibration value "C" in a sense of absolute delay correction of the station is −1.573 ± 0.027 ns.**

Comments

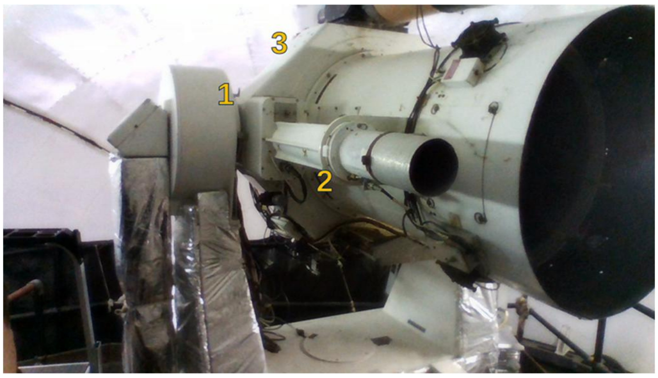
- The ranging stability of SLR station in Herstmonceux, UK as catalogued in ILRS web pages is 20 ps rms and 80 ps peak to peak.

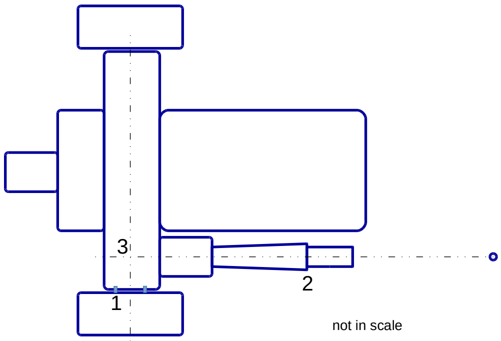
- This stability/spread coincides quite well with the spread in ELT calibration constant of 27 ps rms and its peak to peak value of 51 ps.

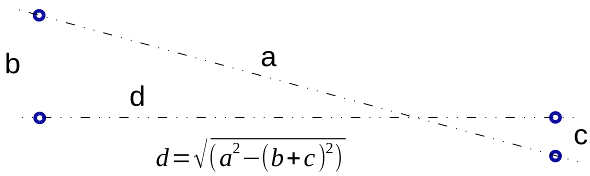
Problem areas – items to be resolved before the ELT missions:
- Laser fire control, laser fire in pre-determined epoch shot by shot,
- Consistency of 10 MHz and “1 pps” signals generated by a local time scale.

Herstmonceux, Prague, May 31, 2016

7. APPENDIX MOUNT SURVEY







off-axis corrections

1st method (J.B.)
Tape ruler, from ELT pin to inner side of two symmetrical holders on (1).
Horizontal off-axis 145±5 mm, vertical off-axis 105±5 mm on mount side, 45±5 mm on a pin side.
Distances: 1995±2 mm and 1858±2 mm, (B: 2156±2 mm, 2020±2 mm)
Calculation: sqrt(center2 – off-axis2), 1926.5
Result: **1915**±5 mm (pin B: 2077±5 mm), diff = 162±7 mm

2nd method (most reliable)
Solid ruler and laser range finder from ELT pin to transmitting telescope front plane (2).
Vertical off axis on ELT side 45±5 mm
Distances: 1137±1 mm by solid ruler, 1138 mm by laser rangefinder
Distance from the mount drawing (by Toby Shoobridge) 770.4 mm
Result: **1908**±0.5 mm

3rd method (J.B.)
Tape ruler from point above mirror position (3)
Vertical off-axis 179±1 mm and 45±5 mm on a pin side
Distance: 1924±1 mm
Result: **1911**±2 mm

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