Chunghwa Telecom Laboratories

2024 Group 2 GNSS Calibration Report
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National Standard Time and Frequency Lab

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Summary

As one of the APMP G1 laboratories, TL conducted a relative calibration of the GNSS time transfer receivers of NPLI (National Physical Laboratory of India), India with respect to the calibrated TL receiver TLT5 which setup configuration is kept unchanged since 2020. The signal delays of TLT5 for GPS and Galileo were calibrated by BIPM as reported with CAL_ID 1001-2020 [1]. The receiver system TLM2 of TL was used as the traveling equipment to transfer the signal delays of TLT5 to the visited GNSS receivers LI2P, LIAA, LIAB, LIAC, and LIAF of NPLI. The data were collected between MJD 60327-60443 (18th January 2024 – 13rd May 2024) by simultaneous operation of pairs of co-located GNSS receivers. This campaign was declared to BIPM on 3rd January 2024 and followed as closely as possible the BIPM Guideline [2]. The results provided are the visited receivers' internal delays for GPS C1, P1, and P2 signals and the Galileo E1 and E5a signals. The results will be reported using Cal_ID 1011-2024.

1. Table of contents

List of Acronyms

BIPM	Bureau International des Poids et Mesures, Sèvres, France
CGGTTS	CCTF Generic GNSS Time Transfer Standard
APMP	The Asia Pacific Metrology Programme
IGS	International GNSS Service
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GAL	Galileo satellite navigation system
PPP	Precise Point Positioning
TL	Telecommunication Laboratories, Chunghwa Telecom, Taiwan
TLT5	TL G1 Reference receiver
TLM2	TL travelling receiver
NPLI	National Physical Laboratory of India
UTC(NPLI)	The standard time scale of NPLI
LI2P(LITI)	Visited receiver of NPLI
LIAA	Visited receiver of NPLI
LIAB	Visited receiver of NPLI
LIAC	Visited receiver of NPLI
LIAF	Visited receiver of NPLI
RINEX	Receiver Independent Exchange Format
R2CGGTTS	RINEX-to CGGTTS conversion software, provided by ORB/BIPM
DCLRINEX	differential calibration software using the pseudoranges directly read in the RINEX files, provided by the BIPM
TDEV	Time Deviation
TIC	Time Interval Counter
CABDLY	the antenna cable delay;
INTDLY	the internal signal delay (antenna + receiver internal);
REFDLY	the offset between the UTC reference point in the laboratory and the reference point of the receiver
SYSDLY	INTDLY + CABDLY

TOTDLY	**SYSDLY – REFDLY**
CLPDLY	**the offset between the calibration point in the laboratory and the reference point of the traveling receiver**

1. Description of equipment and operations

1.1 Traveling System

The TL Traveling System consists of a GNSS receiver TLM2 (Septentrio PolaRx5TR, which auto compensation mode was set to “ON” during all calibration trip), an antenna (Hemisphere A45), 50 meters LMR-200 antenna cable, a laptop, and two auxiliary cables (RG-316 and RG-58 with BNC connectors) to connect the calibration reference point and 10 MHz frequency reference of visited lab. The detail information can be found in the Annex A.1, TLM2 information sheet.

The delay from visited UTC reference point to calibration reference point are measured by TIC SR-620 (SN: 6091) provided by NPLI.

1.2 Visited Receivers

There were 5 GNSS receivers, LI2P (code name of rinex file is LIPI), LIAA, LIAB, LIAC, and LIAF, calibrated in this campaign. LI2P is Septentrio PolaRx3eTR receiver, LIAA, LIAB, LIAC are Mesit GTR-51 receivers, LIAF is Septentrio PolaRx4TR Pro receiver. Except LIAC, all their GPS L1C/L1P/L2P links were calibrated by 2018 NICT-NPLI-NICT calibration campaign (CAL_ID: 1013-2018) in 2018 [3] and the GPS L1C/L1P/L2P hardware delays of LIAA and LIAB were transferred according to the LITI due to their firmware upgraded in 2019 [4] (CAL_ID 1209_2019). The receivers LI2P, LIAA, LIAB, LIAC, and LIAF would calibrate their GPS P3 links and the receivers LIAA, LIAB, LIAC, and LIAF would calibrate their Galileo E3 links this time. The detail information can be found in their information sheets in Annex A.2 Information sheet of LI2P/LIAA/LIAB/LIAC/LIAF.

Table 1. Summary information on the calibration trip

Institute	Status of equipment	Dates of measurement	Receiver type	BIPM code	RINEX name
TL	Traveling	60327-60336	Septentrio PolaRx5 TR	TLM2	TLM2
TL	Group 1 reference	-	Septentrio PolaRx5 TR	TLT5	TLT5
NPLI	Group 2	60389-60398	Septentrio, PolaRx3eTR	LI2P	LITI
NPLI	Group 2	60389-60398	Mesit, GTR51	LIAA	LIAA

NPLI	Group 2	60389-60398	Mesit, GTR51	LIAB	LIAB
NPLI	Group 2	60389-60398	Mesit, GTR51	LIAC	LIAC
NPLI	Group 2	60389-60398	Septentrio, PolaRx4TR Pro	LIAF	LIAF
TL	Traveling	60434-60443	Septentrio PolaRx5 TR	TLM2	TLM2
TL	Group 1 reference	-	Septentrio PolaRx5 TR	TLT5	TLT5

2. Data Used

Since the reference, traveling, and visited receivers are all GNSS geodetic receivers and provide RINEX files, we use their pseudoranges directly read in their RINEX files by the software dclrinex provide by BIPM [5] dedicated to differential calibration.

3. Results of Raw Data Processing

The raw code differences of the pairs of co-located receivers during the data acquisition period, MJD column in Table 2, are generated by dclrinex. The inferred raw calibration results are taken as the median of the raw differences. The associated uncertainties are taken as the floor of their Tdev values (see Annex B). The values for INTDLY between a given pair of receivers are computed using Eq. (7) and given in Table 7.1 and 7.2.

Table 2. Summary information on the raw calibration results (all values in ns)

Pair	Date	C1	Unc.	P1	Unc.	P2	Unc.	E1	Unc.	E5a	Unc.
TLT5-TLM2	60327-60336	29.71	0.05	29.43	0.04	24.13	0.03	29.64	0.08	22.41	0.08
TLM2-LI2P	60389-60398	234.77	0.04	232.13	0.04	231.34	0.04	—	—	—	—
TLM2-LIAA	60389-60398	65.97	0.08	64.67	0.10	70.95	0.07	65.83	0.05	72.11	0.07
TLM3-LIAB	60389-60398	66.55	0.08	65.20	0.09	72.30	0.07	66.19	0.04	73.00	0.06
TLM4-LIAC	60389-60398	15.31	0.05	14.04	0.07	20.99	0.06	14.97	0.07	22.23	0.07
TLM5-LIAF	60389-60398	165.81	0.05	164.93	0.05	168.36	0.03	166.33	0.08	161.13	0.06
TLT5-TLM2	60434-60443	30.26	0.09	29.88	0.03	23.86	0.04	30.07	0.09	22.16	0.12

4. Calibration results

From the definition, the raw calibration results of a pair of receivers are equal to their TOTDLY difference:

$$\text{TOTDLY}_{\text{R}}(\text{code}) - \text{TOTDLY}_{\text{T, TL}}(\text{code}) = \text{RAWDIF}_{\text{R-T}}(\text{code}) \quad \text{........ (1)}$$

Where the TOTDLY_{R}(code) and $\text{TOTDLY}_{\text{T, TL}}$(code) are the TOTDLY of reference receiver and traveling receiver at TL respectively; the $\text{RAWDIF}_{\text{R-T}}$(code) is the raw calibration result of the reference and traveling pair read from Table 2. The code can be GPS C1/P1/P2 and Galileo E1/E5a.

We note the calibration reference point and UTC reference point may not be identical in each lab, for traveling receiver, its TOTDLY in reference and visited labs may be different, here we denote the TOTDLY of traveling receiver in reference lab TL to be $\text{TOTDLY}_{\text{T, TL}}$(code) and $\text{TOTDLY}_{\text{T, NPLI}}$(code) in visited lab .

The TOTDLY can be also expressed using SYSDLY and REFDLY; and the REFDLY is equal to the CLPDLY pluses the offset between the UTC reference point and calibration reference point in the lab:

$$\text{REFDLY}_{\text{T, TL}}(\text{code}) = \text{CLPDLY}_{\text{T}}(\text{code}) + \Delta\text{Ref\_Clb}_{\text{TL}} \quad \text{........ (2)}$$

Where the ΔRef_Clb is the offset between the UTC reference point and calibration reference point in the laboratory, the value of $\Delta\text{Ref\_Clb}_{\text{TL}}$ and $\Delta\text{Ref\_Clb}_{\text{NPLI}}$ may be different but the value CLPDLY_{T}(code) are all the same in the whole campaign due to we use the same reference 1 PPS cable for the traveling receiver in this trip. We have:

$$\begin{aligned}\text{TOTDLY}_{\text{T, TL}}(\text{code}) &= \text{SYSDLY}_{\text{T, TL}}(\text{code}) - \text{REFDLY}_{\text{T, TL}}(\text{code}) \\ &= \text{SYSDLY}_{\text{T, TL}}(\text{code}) - [\text{CLPDLY}_{\text{T}}(\text{code}) + \Delta\text{Ref\_Clb}_{\text{TL}}] \quad \text{........ (3)}\end{aligned}$$

4.1 Traveling System with Respect to The Reference System

From Eq. (1), (2), and (3), the $\text{RAWDIF}_{\text{R-T}}$(code) can be express by

$$\begin{aligned}&\text{RAWDIF}_{\text{R-T}}(\text{code}) \\ &= [\text{SYSDLY}_{\text{R}}(\text{code}) - \text{REFDLY}_{\text{R}}(\text{code})] \\ &- [\text{SYSDLY}_{\text{T}}(\text{code}) - \text{CLPDLY}_{\text{T}}(\text{code}) - \Delta\text{Ref\_Clb}_{\text{TL}}] \quad \text{....... (4)}\end{aligned}$$

Table 3.1 Traveling vs. Reference system (GPS, all values in ns)

Pair	Date	C1	P1	P2	P1-P2
		RawDIF	RawDIF	RawDIF	RawDIF
TLT5-TLM2	60327-60336	29.71	29.43	24.13	5.30
TLT5-TLM2	60434-60443	30.26	29.88	23.86	6.02
Misclosure	-	0.55	0.45	-0.27	0.72
Mean	-	29.99	29.66	24.00	5.66

Table 3.2 Traveling vs. Reference system (GAL, all values in ns)

Pair	Date	E1	E5a	E1-E5a
		RawDIF	RawDIF	RawDIF
TLT5-TLM2	60327-60336	29.64	22.41	7.23
TLT5-TLM2	60434-60443	30.07	22.16	7.91
Misclosure	-	0.43	-0.25	0.68
Mean	-	29.86	22.29	7.57

Table 3.1 and 3.2 are the raw difference values of traveling vs. reference receiver. We don't need to measure the REFDLY of the traveling and reference receivers because they will be vanished in the visited INTDLYs deriving processes.

4.2 Traveling System with Respect to the Visited Systems

Like Eq. (4), the raw difference of traveling receiver at visited lab (NPLI) can be expressed:

$$\begin{aligned} &RAWDIF_{T\text{-}V}(code) = \\ &[SYSDLY_T(code) - CLPDLY_T(code) - \Delta Ref\_Clb_{NPLI}] \\ &-[SYSDLY_V(code) - REFDLY_V(code)] \qquad \ldots\ldots\ldots (5) \end{aligned}$$

The ΔRef_Clb_{NPLI} is the offset from UTC(NPLI) reference point to the calibration reference point of NPLI.

Table 4.1 Traveling with respect to the visited system (GPS, all values in ns)

Pair	Date	ΔRef_Clb_{NPLI}	$REFDLY_V$	C1	P1	P2
				RawDIF	RawDIF	RawDIF
TLM2-LI2P	60389-60398	36.2	299.1	234.77	232.13	231.34
TLM2-LIAA	60389-60398	36.2	96.7	65.97	64.67	70.95
TLM2-LIAB	60389-60398	36.2	96.5	66.55	65.20	72.30
TLM2-LIAC	60389-60398	36.2	46.8	15.31	14.04	20.99
TLM2-LIAF	60389-60398	36.2	247.1	165.81	164.93	168.36

Table 4.2 Traveling with respect to the visited system (Galileo, all values in ns)

Pair	Date	ΔRef_Clb_{NPLI}	$REFDLY_V$	E1	E5a
				RawDIF	RawDIF
TLM2-LIAA	60389-60398	36.2	96.7	65.83	72.11
TLM2-LIAB	60389-60398	36.2	96.5	66.19	73.00
TLM2-LIAC	60389-60398	36.2	46.8	14.97	22.23

TLM2-LIAF	60389-60398	36.2	247.1	166.33	161.13

4.3 Visited Systems with Respect to Reference System

Combine Eq. (4) and (5), we get:

$RAWDIF(code)_{R\text{-}T} + RAWDIF(code)_{T\text{-}V}$

$= [SYSDLY_R(code) – REFDLY_R(code)] – [SYSDLY_V(code) – REFDLY_V(code)]$

$+ \Delta Ref\_Clb_{TL} – \Delta Ref\_Clb_{NPLI}$

$= TOTDLY_R(code) – TOTDLY_V(code) + \Delta Ref\_Clb_{TL} – \Delta Ref\_Clb_{NPLI}$

$= \Delta TOTDLY_{R\text{-}V}(code) + \Delta Ref\_Clb_{TL} – \Delta Ref\_Clb_{NPLI}$

or

$\Delta TOTDLY_{R\text{-}V}(code)$

$= RAWDIF(code)_{R\text{-}T} + RAWDIF(code)_{T\text{-}V} – \Delta Ref\_Clb_{TL} + \Delta Ref\_Clb_{NPLI}$ …… (6)

In TL, the calibration reference point and the UTC(k) reference point are identical, that is the $\Delta Ref\_Clb_{TL} = 0$. The $\Delta Ref\_Clb_{NPLI} = 36.2$ ns was measured by NPLI. The TOTDLY of traveling with respect to the visited system are listed in Table 5.1 and 5.2.

Table 5.1 Visited system with respect to the reference system (GPS, all values in ns)

Pair	Date	ΔRef_Clb_{NPLI}	$\Delta TOTDLY_{R\text{-}V}$		
			C1	**P1**	**P2**
TLT5-LI2P	60389-60398	+36.2	300.96	297.99	291.54
TLT5-LIAA	60389-60398	+36.2	132.16	130.53	131.15
TLT5-LIAB	60389-60398	+36.2	132.74	131.06	132.50
TLT5-LIAC	60389-60398	+36.2	81.50	79.90	81.19
TLT5-LIAF	60389-60398	+36.2	232.00	230.79	228.56

Table 5.2 Visited system with respect to the reference system (Galileo, all values in ns)

Pair	Date	ΔRef_Clb_{NPLI}	$\Delta TOTDLY_{R\text{-}V}$	
			E1	**E5a**
TLT5-LIAA	60389-60398	+36.2	131.89	130.60
TLT5-LIAB	60389-60398	+36.2	132.25	131.49
TLT5-LIAC	60389-60398	+36.2	81.03	80.72
TLT5-LIAF	60389-60398	+36.2	232.39	219.62

4.4 Uncertainty

In this section, we use the same method as [1] to determine the uncertainty of TOTDLY. We estimate all components that can affect the accuracy and determine a value u_{CAL} that is to be used as the accuracy of all GPS P3 and GAL E3 links at the epoch of calibration.

$$u_{CAL} = \sqrt{u_a^2 + u_b^2}$$

Where u_a and u_b are the statistical uncertainty the systematic uncertainty respectively.

The statistical uncertainty u_a originates from the Tdev of each pair of RAWDIF listed in Table 2 (graphs can be found in Annex B). We find the minimum for each TDEV curve, and then we choose the largest one among the minimums as the u_a.

The systematic uncertainty u_b is given by

$$u_b = \sqrt{\sum_n u_{b,n}^2}$$

Uncertainty values in column P3 are calculated according to $u^2_{P3}=u^2_{P1}+(1.545\times u_{P1-P2})^2$. Uncertainties for the Galileo delays are calculated according to $u^2_{E3}=u^2_{E1}+(1.261\times u_{E1-E5a})^2$. All possible terms to be considered in the sum are to be listed in Table 6.1 and 6.2. Values appear separately for each code (GPS C1, P1, and P2, GAL E1, and E5a) to compute a value u_{CAL} applicable to GPS P3 and GAL E3 links. We choose to compute u_{CAL} using for u_b the uncertainty $u_{b,TOT}$ of ΔTOTDLY$_{R\text{-}V}$ from Eq. (6). Table 6.1 and 6.2 presents all components of the uncertainty budget along with the uncertainty $u_{b.TOT}$ of ΔTOTDLY$_{R\text{-}V}$ from equation (6) and the resulting uncertainty value u_{CAL}. The items in Table 6 are separated into several categories.

- $u_{b,1}$ accounts for possible variation of the delays of the traveling receiver with respect to the reference receiver during this campaign. This is evaluated by the observed the mis-closure values in Table 3.1 and 3.2.
- $u_{b,11}$ and $u_{b,12}$ account for errors in the antenna coordinates. In general, they are estimated to be 3.0 cm (0.1 ns) because the standard uncertainty of the coordinates obtained with the data used for calibration is typically at or below this level. The $u_{b,13}$ and $u_{b,14}$ account for multipath effect. This is difficult to estimate, and 0.2 ns is conventionally used, following a discussion in the CCTF working group meeting on GNSS in 2017[6].
- $u_{b,21}$ and $u_{b,22}$ account for the measurement between the calibration reference point of the traveling receiver and the local UTC(k). The values $u_{b,21}$ = 0.0 ns since the calibration reference point is the UTC(k) reference point in TL.
- $u_{b,31}$ and $u_{b,32}$ account for the measurements between the reference point of the reference station and the local UTC(k). $u_{b,31}$ = 0.0 ns since the reference receiver TLT5 did not use REFDLY during calibration and time transfer, its INTDLY is in fact the TOTDLY; $u_{b,32}$ = 0.5 ns at the visited stations

NPLI, it includes at least one measurement with a TIC.

- $u_{b,41}$ and $u_{b,42}$ accounts for the measurement of CABDLY. $u_{b,41}$ = 0.0 ns since the reference receiver TLT5 did not use CABDLY in calibration and time transfer, its INTDLY is in fact the TOTDLY; $u_{b,42}$ = 0.5 ns at the visited stations NPLI, it includes at least one measurement with a TIC. We should note the visited station NPLI did not measure the CABDLY during this campaign.

Table 6.1 Uncertainty contributions of GPS link, Value P3 = P1+1.545×(P1−P2). All value in ns.

Unc.	C1	P1	P2	P1-P2	P3	Description
u_a(T-R)	0.09	0.04	0.04	0.06		Tdev of RAWDIF of TLT5 vs.TLM2 during MJD 60327-60336 and 60434-60443.
$u_{a,LI2P}$(T-V)	0.04	0.04	0.04	0.06		Tdev of RAWDIF of TLM2 vs. LI2P
$u_{a,LIAA}$(T-V)	0.08	0.10	0.07	0.12		Tdev of RAWDIF of TLM2 vs. LIAA
$u_{a,LIAB}$(T-V)	0.08	0.09	0.07	0.11		Tdev of RAWDIF of TLM2 vs. LIAB
$u_{a,LIAC}$(T-V)	0.05	0.07	0.06	0.09		Tdev of RAWDIF of TLM2 vs. LIAC
$u_{a,LIAF}$(T-V)	0.05	0.05	0.03	0.06		Tdev of RAWDIF of TLM2 vs. LIAF
$u_{a,LI2P}$	0.10	0.06	0.06	0.08	0.14	
$u_{a,LIAA}$	0.12	0.11	0.08	0.13	0.23	
$u_{a,LIAB}$	0.12	0.10	0.08	0.13	0.22	
$u_{a,LIAC}$	0.10	0.08	0.07	0.11	0.19	
$u_{a,LIAF}$	0.10	0.06	0.05	0.08	0.14	
	Misclosure					
$u_{b,1}$	0.55	0.45	-0.27	0.72	-	Observed misclosure of TLT5 vs. TLM2
	Systematic components related to RAWDIF					
$u_{b,11}$	0.10	0.10	0.10	0.14	-	Position error at TL
$u_{b,12}$	0.10	0.10	0.10	0.14	-	Position error at NPLI
$u_{b,13}$	0.20	0.20	0.20	0.28	-	Multipath effect at TL
$u_{b,14}$	0.20	0.20	0.20	0.28	-	Multipath effect at NPLI
	Link of the Traveling system to the local UTC(k) and CABDLY measurements					
$u_{b,21}$	0.00	0.00	0.00	0.00	-	ΔRef_Clb$_{TL}$ at TL (CLBDLY = REFDLY)
$u_{b,22}$	0.50	0.50	0.50	0.00	-	ΔRef_Clb$_{NPLI}$ at NPLI
$u_{b,TOT}$	0.81	0.74	0.65	0.85	1.50	Components of equation (6)
$u_{CAL0,LI2P}$					1.51	Composed of $u_{a,LI2P}$ and $u_{b,TOT}$
$u_{CAL0,LIAA}$					1.52	Composed of $u_{a,LIAA}$ and $u_{b,TOT}$
$u_{CAL0,LIAB}$					1.52	Composed of $u_{a,LIAA}$ and $u_{b,TOT}$
$u_{CAL0,LIAC}$					1.51	Composed of $u_{a,LIAA}$ and $u_{b,TOT}$
$u_{CAL0,LIAF}$					1.51	Composed of $u_{a,LIAF}$ and $u_{b,TOT}$
	Link of the Reference system to its local UTC(k)					

$u_{b,31}$	0	0	0			TLT5 did not use REFDLY to calculate P3
	Link of the Visited system to its local UTC(k)					
$u_{b,32}$	0.50	0.50	0.50			REFDLY of LI2P/LIAA/LIAB/LIAC/LIAF, did not measure during this campaign, added if NPLI can change reference cable
Antenna cable delays						
$u_{b,41}$	0.00	0.00	0.00			TLT5 did not use CABDLY to calculate P3
$u_{b,42}$	0.50	0.50	0.50			CABDLY of LI2P/LIAA/LIAB/LIAC/LIAF, did not measure during this campaign, added if NPLI can change reference cable
$u_{b,INT}$	1.07	1.03	0.96	0.85	1.66	Components of equation (7)
$u_{CAL0,LI2P}$					1.67	Composed of $u_{a,LI2P}$ and $u_{b,INT}$
$u_{CAL0,LIAA}$					1.68	Composed of $u_{a,LIAA}$ and $u_{b,INT}$
$u_{CAL0,LIAB}$					1.67	Composed of $u_{a,LIAB}$ and $u_{b,INT}$
$u_{CAL0,LIAC}$					1.67	Composed of $u_{a,LIAC}$ and $u_{b,INT}$
$u_{CAL0,LIAF}$					1.67	Composed of $u_{a,LIAF}$ and $u_{b,INT}$

Table 6.2 Uncertainty contributions of GAL link, E3 = E1+1.261×(E1-E5a), all values in ns

Unc.	E1	E5a	E1-E5a	E3	Description
u_a(T-R)	0.09	0.12	0.15		Tdev of RAWDIF of TLT5 vs.TLM2 during MJD 60327-60336 and 60434-60443.
$u_{a,LIAA}$(T-V)	0.05	0.07	0.09		Tdev of RAWDIF of TLM2 vs. LIAA
$u_{a,LIAB}$(T-V)	0.04	0.06	0.07		Tdev of RAWDIF of TLM2 vs. LIAB
$u_{a,LIAC}$(T-V)	0.07	0.07	0.10		Tdev of RAWDIF of TLM2 vs. LIAC
$u_{a,LIAF}$(T-V)	0.08	0.06	0.10		Tdev of RAWDIF of TLM2 vs. LIAF
$u_{a,LIAA}$	0.10	0.14	0.17	0.24	
$u_{a,LIAB}$	0.10	0.13	0.17	0.23	
$u_{a,LIAC}$	0.11	0.14	0.18	0.25	
$u_{a,LIAF}$	0.12	0.13	0.18	0.26	
Misclosure					
$u_{b,1}$	0.43	-0.25	0.68	-	Observed mis-closure of TLT5 vs. TLM2
Systematic components related to RAWDIF					
$u_{b,11}$	0.10	0.10	0.14	-	Position error at TL
$u_{b,12}$	0.10	0.10	0.14	-	Position error at NPLI
$u_{b,13}$	0.20	0.20	0.28	-	Multipath effect at TL
$u_{b,14}$	0.20	0.20	0.28	-	Multipath effect at NPLI
Link of the Traveling system to the local UTC(k)					

$u_{b,21}$	0	0	-	-	ΔRef_Clb$_{TL}$ at TL (CLBDLY = REFDLY)
$u_{b,22}$	0.50	0.50	-	-	ΔRef_Clb$_{NPLI}$ at NPLI
$u_{b,TOT}$	0.73	0.64	0.81	1.26	Components of equation (6)
$u_{CAL0,LIAA}$				1.28	Composed of $u_{a,LIAA}$ and $u_{b,TOT}$
$u_{CAL0,LIAB}$				1.28	Composed of $u_{a,LIAB}$ and $u_{b,TOT}$
$u_{CAL0,LIAC}$				1.29	Composed of $u_{a,LIAC}$ and $u_{b,TOT}$
$u_{CAL0,LIAF}$				1.29	Composed of $u_{a,LIAF}$ and $u_{b,TOT}$
Link of the Reference system to its local UTC(k)					
$u_{b,31}$	0	0	-	-	TLT5 did not use REFDLY to calculate E3
	Link of the Visited system to its local UTC(k)				
$u_{b,32}$	0.50	0.50	0.00	-	REFDLY of LI2P/LIAA/LIAB/LIAC/LIAF, did not measure during this campaign, added if NPLI can change reference cable
Antenna cable delays					
$u_{b,41}$	0	0	-		TLT5 did not use CABDLY to calculate E3
$u_{b,42}$	0.50	0.50	0.00		CABDLY of LI2P/LIAA/LIAB/LIAC/LIAF, did not measure during this campaign, added if NPLI can change reference cable
$u_{b,INT}$	1.02	0.96	0.81	1.44	Components of equation (7)
$u_{CAL0,LIAA}$				1.46	Composed of $u_{a,LIAA}$ and $u_{b,INT}$
$u_{CAL0,LIAB}$				1.46	Composed of $u_{a,LIAB}$ and $u_{b,INT}$
$u_{CAL0,LIAC}$				1.46	Composed of $u_{a,LIAC}$ and $u_{b,INT}$
$u_{CAL0,LIAF}$				1.46	Composed of $u_{a,LIAF}$ and $u_{b,INT}$

5. Final results for the visited systems

The Final results are presented for each visited system as they need to be entered to produce timing data in the CGGTTS format, i.e., in the form of INTDLY. The value INTDLY for each visited station, $INTDLY_V$, can be obtained by using equation (7).

The calibrated INTDLYs of visited lab can be derived:

$$INTDLY_V(code) = TOTDLY_R(code) - \Delta TOTDLY_{R\text{-}V}(code) - CABDLY_V(code) + REFDLY_V(code) \quad \ldots\ldots (7)$$

Using the $TOTDLY_R$ values reported in 1001-2020 for the Reference system TLT5 and the values $CABDLY_V$, $REFDLY_V$, ΔRef_Clb$_{NPLI}$ from the information sheet (Annex A), **Table 7.1 and 7.2** then reports $INTDLY_V$ for all visited systems. The uncertainty value u_{cal} for P3 is obtained from **Table 6.1 and 6.2**. It is used by the BIPM to assign the value u_b which will apply to all links to which the system participates.

Table 7.1 Summary of final results of GPS link

Reference System	Cal_Id	Date		TOTDLY/ns		
				C1	**P1**	**P2**
TLT5	1001-2020	[1]Feb. 02, 2021		206.1	204.0	202.9
Visited stations	**Cal_Id**	**Date**	**u_{CAL} (P3)/ ns**	**INTDLY/ns**		
				C1	**P1**	**P2**
TLT5-LI2P	1011-2024	May. 25, 2024	1.7	54.2	55.1	60.5
TLT5-LIAA	1011-2024	May. 25, 2024	1.7	37.7	37.3	35.6
TLT5-LIAB	1011-2024	May. 25, 2024	1.7	37.7	37.2	34.7
TLT5-LIAC	1011-2024	May. 25, 2024	1.7	38.4	37.9	35.5
TLT5-LIAF	1011-2024	May. 25, 2024	1.7	52.3	51.4	52.6

Table 7.2 Summary of final results of GAL link

Reference System	Cal_Id	Date		TOTDLY/ns	
				E1	**E5a**
TLT5	1001-2020	[2]Feb. 02, 2021		206.3	204.1
Visited stations	**Cal_Id**	**Date**	**u_{CAL} (E3)/ ns**	**INTDLY/ns**	
				E1	**E5a**
TLT5-LI2P	1011-2024	May. 25, 2024	1.5	38.2	37.3
TLT5-LIAA	1011-2024	May. 25, 2024	1.5	38.4	36.9
TLT5-LIAB	1011-2024	May. 25, 2024	1.5	39.1	37.2
TLT5-LIAC	1011-2024	May. 25, 2024	1.5	52.1	62.7

Acknowledgements

The authors appreciate colleagues in NPLI for their efforts on shipment, installation of the traveling equipment and data collection.

[1] The date performed the calibration id 1001-2020

[2]

Annexes

Annex A: Information sheets

A.1 Information sheet of TLM2

Laboratory:	TL
Date and hour of the beginning of measurements:	2023-07-09 00:00:00 UTC
Date and hour of the end of measurements:	2023-07-18 23:59:00 UTC

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	TLT5	TLM2
● Receiver maker and type: Receiver serial number:	Septentrio PolaRx5TR 3227923	Septentrio PolaRx5TR 4701426
1 PPS trigger level /V:	1 V	1 V
● Antenna cable maker and type: Phase stabilised cable (Y/N):	Andrew FSJ yes	LMR-200 no
Length outside the building /m:	~ 30	~10
● Antenna maker and type: Antenna serial number:	SEPCHOKE_B3E6 SPKE 5303	Hemisphere A45 A45280600336
Temperature (if stabilised) /°C	23	23

Measured delays/ns		
	Local:	**Travelling:**
● Delay from local UTC to receiver 1 PPS-in:	14.593±0.017 ns	0[3]
Delay from 1 PPS-in to internal Reference (if different):	-	-
● Antenna cable delay:	No measurement	No measurement
Splitter delay (if any):	Null	(1)
Additional cable delay (if any):	Null	(1)

Data used for the generation of CGGTTS files	
● INT DLY (GPS) /ns:	
● INT DLY (GAL) /ns:	
● CAB DLY /ns:	
● REF DLY /ns:	
● Coordinates reference frame:	WGS-84
Latitude or X /m:	–
Longitude or Y /m:	–
Height or Z /m:	–

General information	
● Rise time of the local UTC pulse:	1 ns

[3] The reference cable of TLM2 is connected to the UTC(TL) reference point.

● Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	23 ± 1 ˚C
Set humidity value and uncertainty:	No humidity control

(1) For a trip with closure, not needed if the traveling equipment is used in the same set-up throughout.

A.2 Information sheet of LI2P/LIAA/LIAB/LIAC/LIAF

Laboratory:	NPLI
Date and hour of the beginning of measurements:	**20th March 2024**
Date and hour of the end of measurements:	**29th March 2024**

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	LI2P (CGGTTS), LITI (Rinex)	TLM2
• Receiver maker and type: Receiver serial number:	Septentrio, PolaRx3eTR 2002984	Septentrio, PolaRx5TR 4701426
1 PPS trigger level /V:		
• Antenna cable maker and type: Phase stabilised cable (Y/N):		
Length outside the building /m:	~20m	
• Antenna maker and type: Antenna serial number:	Septentrio, SEPCHOKE_MC 5025	Hemisphere, A45 A45280600336
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	96.1	#36.2
Delay from 1 PPS-in to internal Reference (if different):	203.0	
• Antenna cable delay:	150.0	
Splitter delay (if any):		
Additional cable delay (if any):		

Data used for the generation of CGGTTS files	
• INT DLY (GPS) /ns:	52.9(C1), 53.1(P1), 58.3(P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	150.0
• REF DLY /ns:	299.1
• Coordinates reference frame:	ITRF
Latitude or X /m:	+1243910.22
Longitude or Y /m:	+5462560.48
Height or Z /m:	+3038747.16

General information	
• Rise time of the local UTC pulse:	<5ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	$22^0C \pm 1^0C$
Set humidity value and uncertainty:	50%±10%

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	LIAA	TLM2
• Receiver maker and type: Receiver serial number:	Mesit Defence, GTR51 1704141	Septentrio, PolaRx5TR 4701426
1 PPS trigger level /V:	1V	
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Belden	
Length outside the building /m:	~20m	
• Antenna maker and type: Antenna serial number:	Novatel, GPS-703-GGG NEG17070062	Hemisphere, A45 A45280600336
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	96.7	#36.2
Delay from 1 PPS-in to internal Reference (if different):		
• Antenna cable delay:	132.9	
Splitter delay (if any):		
Additional cable delay (if any):		

Data used for the generation of CGGTTS files	
• INT DLY (GPS) /ns:	36.1(C1), 35.2(P1), 32.9(P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	132.9
• REF DLY /ns:	96.7
• Coordinates reference frame:	ITRF
Latitude or X /m:	1243910.24
Longitude or Y /m:	5462558.20
Height or Z /m:	3038750.85

General information	
• Rise time of the local UTC pulse:	<5ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	22^0C±1^0C
Set humidity value and uncertainty:	50%±10%

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	LIAB	TLM2
• Receiver maker and type: Receiver serial number:	Mesit Defence, GTR51 1704142	Septentrio, PolaRx5TR 4701426
1 PPS trigger level /V:	1V	
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Belden	
Length outside the building /m:	~20m	
• Antenna maker and type: Antenna serial number:	Novatel, GPS-703-GGG NEG17130019	Hemisphere, A45 A45280600336
Temperature (if stabilised) /°C		

Measured delays /ns		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	96.5	#36.2
Delay from 1 PPS-in to internal Reference (if different):		
• Antenna cable delay:	132.2	
Splitter delay (if any):		
Additional cable delay (if any):		

Data used for the generation of CGGTTS files	
• INT DLY (GPS) /ns:	36.3(C1), 35.5(P1), 32.3(P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	132.2
• REF DLY /ns:	96.5
• Coordinates reference frame:	ITRF
Latitude or X /m:	+1243910.03
Longitude or Y /m:	+5462557.56
Height or Z /m:	+3038752.09

General information	
• Rise time of the local UTC pulse:	<5ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	22^0C±1^0C
Set humidity value and uncertainty:	50%±10%

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	LIAC	TLM2
• Receiver maker and type: Receiver serial number:	Mesit Defence, GTR51 1704143	Septentrio, PolaRx5TR 4701426
1 PPS trigger level /V:	1V	
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Belden	
Length outside the building /m:	~20m	
• Antenna maker and type: Antenna serial number:	Novatel, GPS-703-GGG NEG17170032	Hemisphere, A45 A45280600336
Temperature (if stabilised) /°C		

Measured delays /ns (if needed fill box "Additional Information" below)		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	46.8	#36.2
Delay from 1 PPS-in to internal Reference (if different):		
• Antenna cable delay:	133.0	
Splitter delay (if any):		
Additional cable delay (if any):		

Data used for the generation of CGGTTS files	
• INT DLY (GPS) /ns:	36.8(C1), 35.8(P1), 32.4(P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	133.0
• REF DLY /ns:	
• Coordinates reference frame:	ITRF
Latitude or X /m:	+1243955.57
Longitude or Y /m:	+5462604.47
Height or Z /m:	+3038662.68

General information	
• Rise time of the local UTC pulse:	<5ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	22^0C±1^0C
Set humidity value and uncertainty:	50%±10%

Information on the system		
	Local:	**Travelling:**
4-character BIPM code	LIAF	TLM2
• Receiver maker and type: Receiver serial number:	Septentrio, PolaRx4TR Pro 3009587	Septentrio, PolaRx5TR 4701426
1 PPS trigger level /V:		
• Antenna cable maker and type: Phase stabilised cable (Y/N):	RG213	
Length outside the building /m:	~20m	
• Antenna maker and type: Antenna serial number:	Septentrio, SEPPOLANT_X_MF 9940	Hemisphere, A45 A45280600336
Temperature (if stabilised) /°C		

Measured delays /ns (if needed fill box “Additional Information” below)		
	Local:	**Travelling:**
• Delay from local UTC to receiver 1 PPS-in:	96.8	#36.2
Delay from 1 PPS-in to internal Reference (if different):	150.3	
• Antenna cable delay:	168.9	
Splitter delay (if any):		
Additional cable delay (if any):		

Data used for the generation of CGGTTS files	
• INT DLY (GPS) /ns:	50.8(C1), 49.6(P1), 50.5(P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	168.9
• REF DLY /ns:	247.1
• Coordinates reference frame:	ITRF
Latitude or X /m:	1243909.953
Longitude or Y /m:	5462559.754
Height or Z /m:	3038747.793

General information	
• Rise time of the local UTC pulse:	<5ns
• Is the laboratory air conditioned:	Yes
Set temperature value and uncertainty:	22^{0}C±1^{0}C
Set humidity value and uncertainty:	50%±10%

Diagram of the experiment set-up:

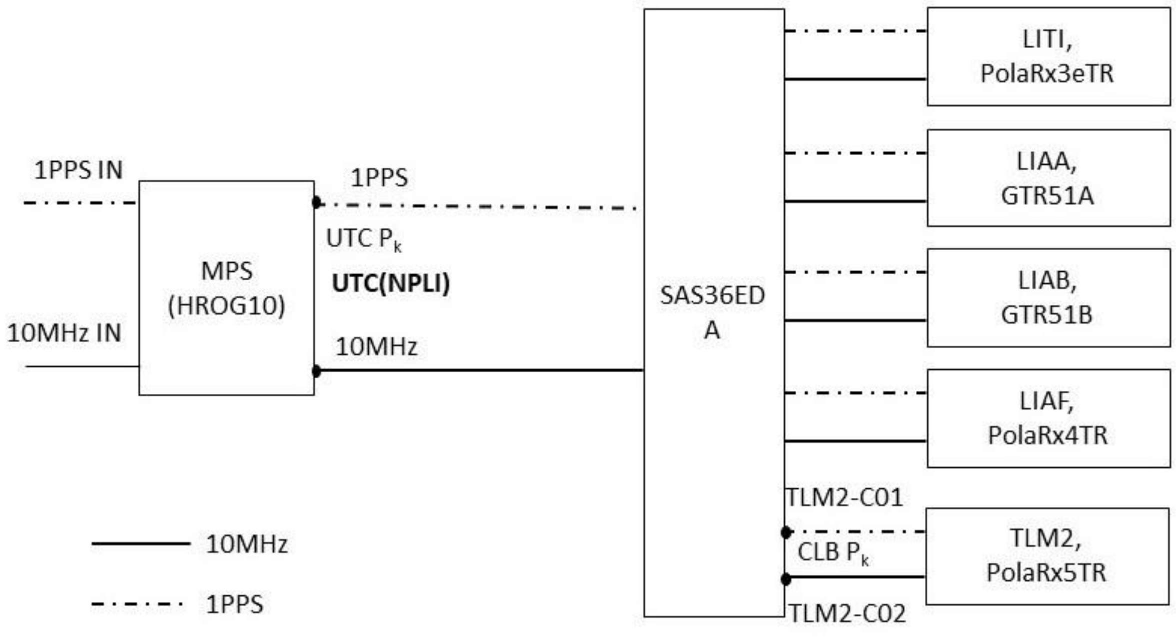


Figure1: Experimental set-up of Primary Timescale GNSS Receiver with G2 calibrator

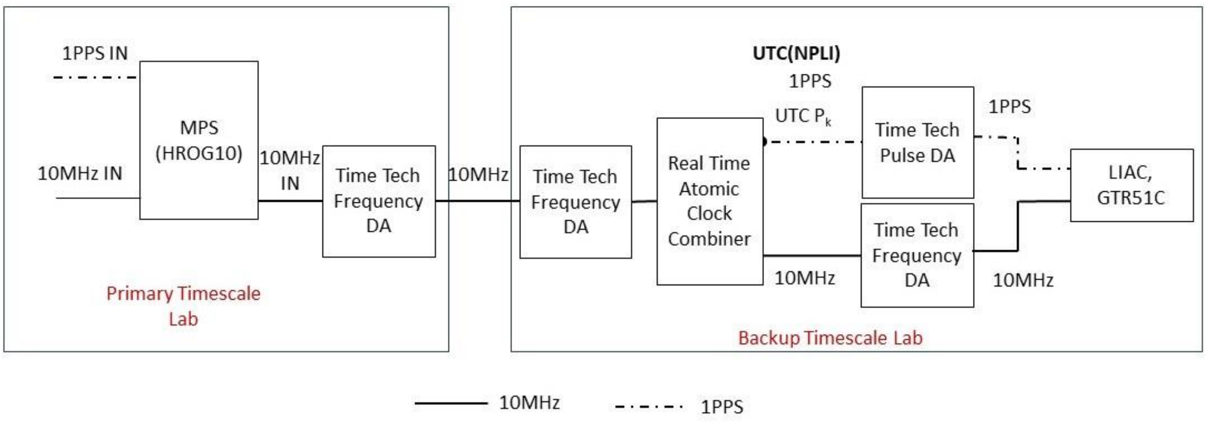


Figure2: Experimental set-up of Backup Timescale GNSS receiver calibration

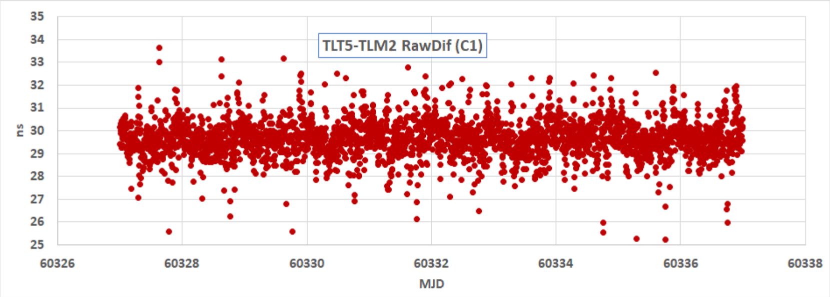
Log of Events / Additional Information:

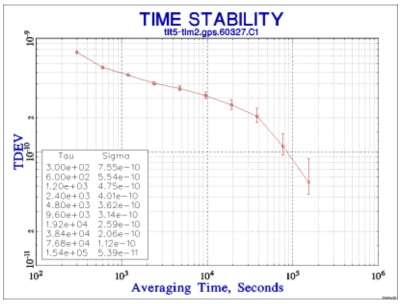
Time interval counter (TIC), model SR620, maker Stanford Research Systems is used to measure delays.

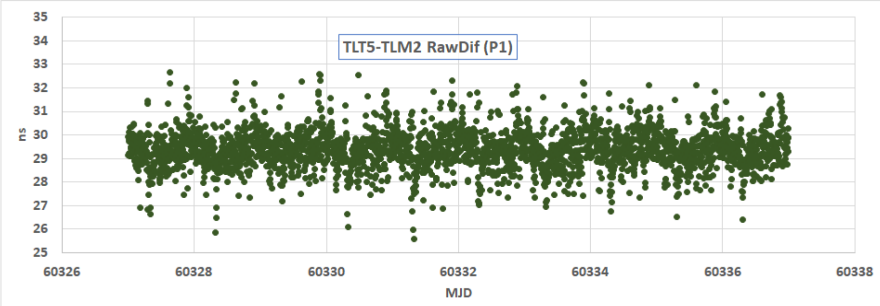
TIC serial no. 6091 used for local receivers

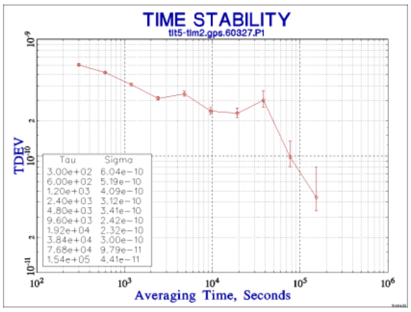
#UTC (NPLI) to 1PPS input of the TLM2 (CLB P_k).

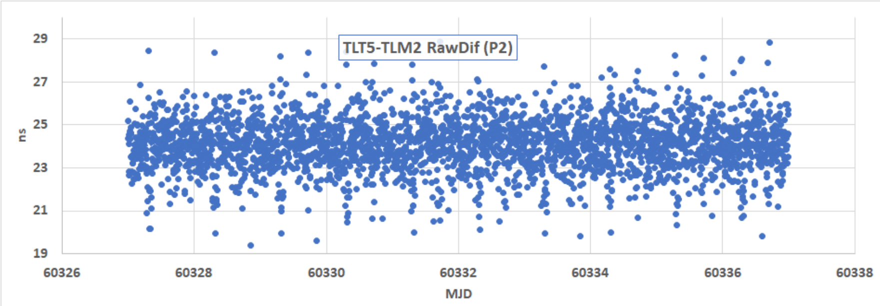
Annex B: Plots of raw data and Tdev analysis
B.1 reference vs. traveling

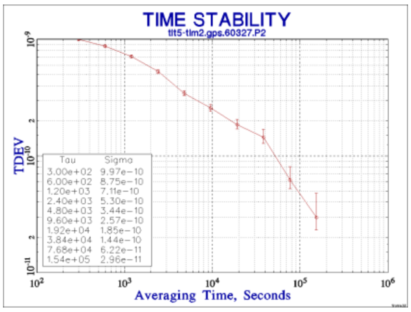


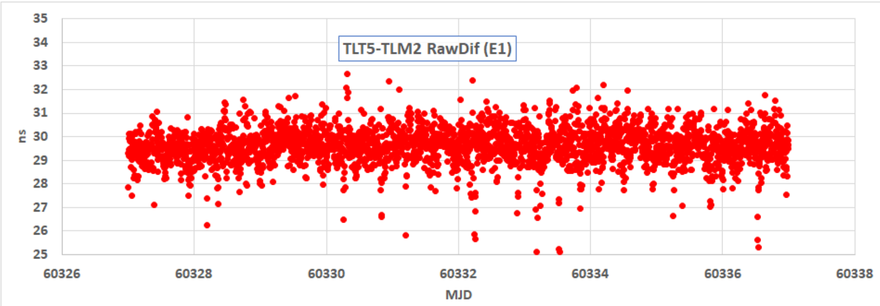


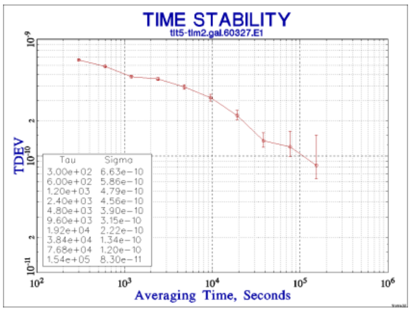


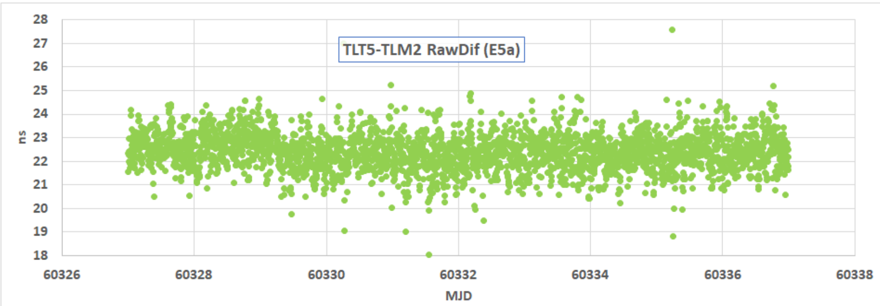


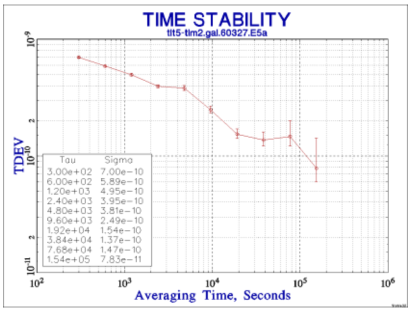




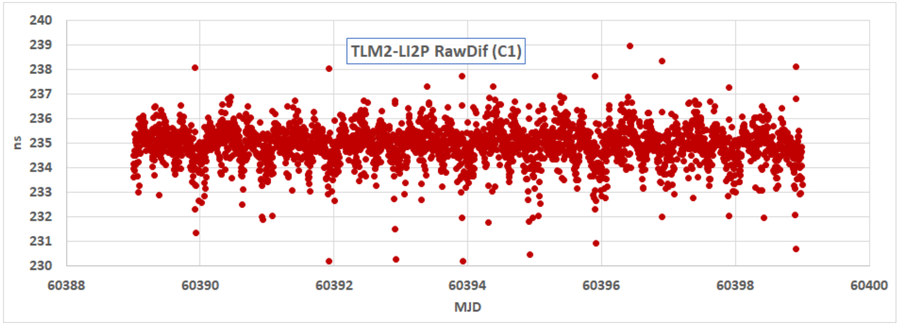


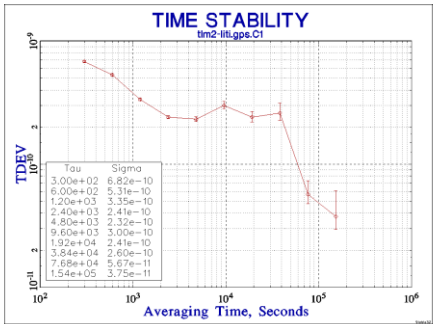


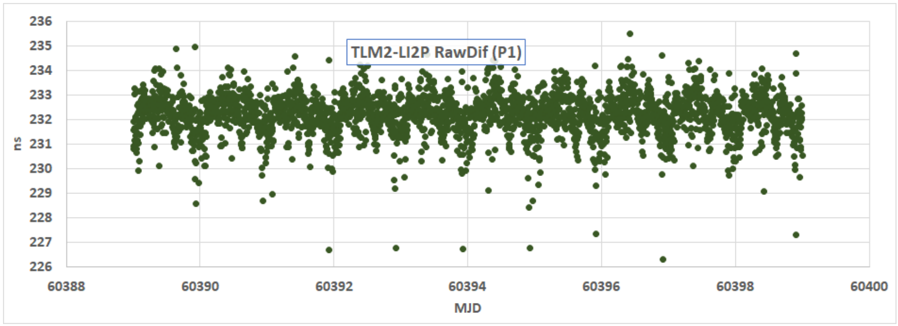


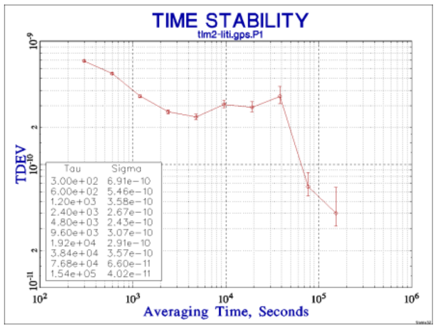


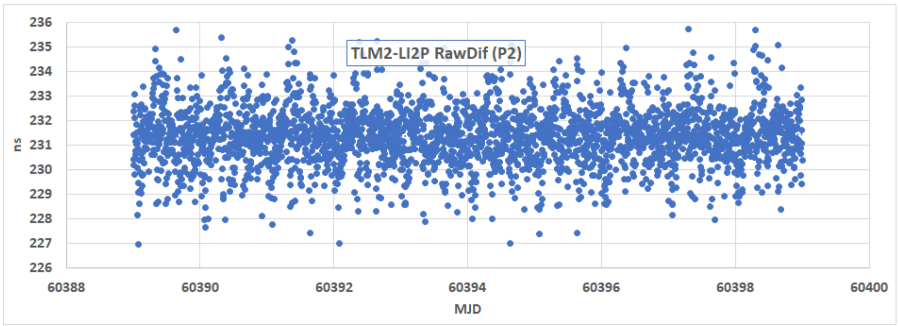
B.2 traveling vs. visited, LI2P (LITI)

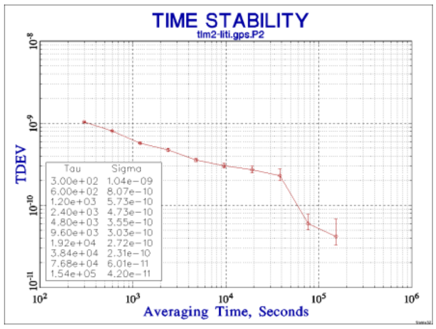




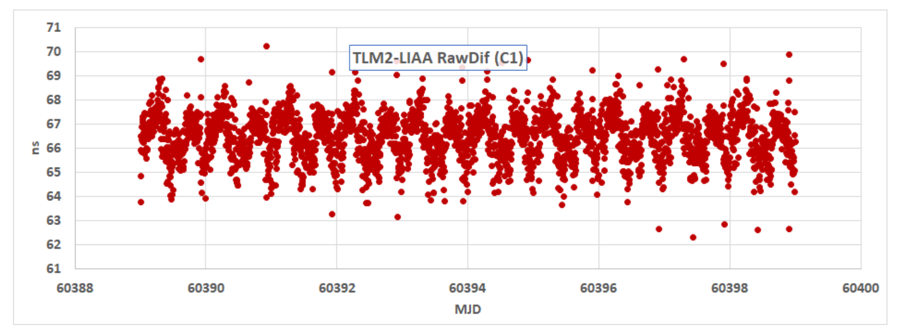


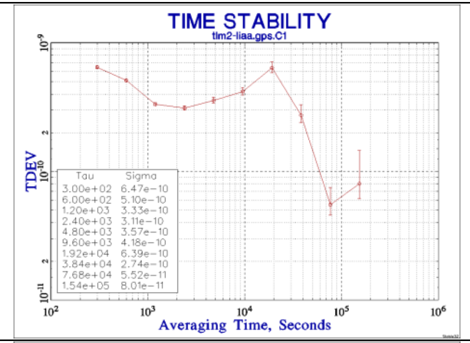


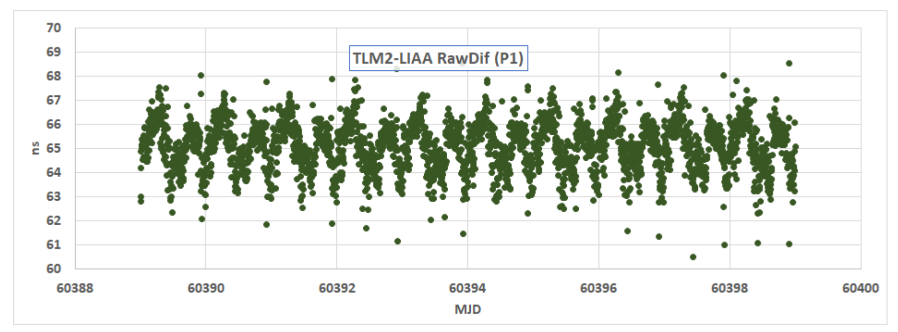


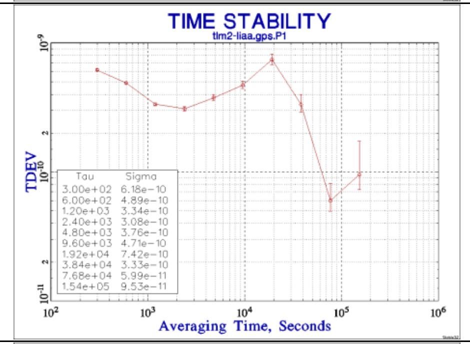


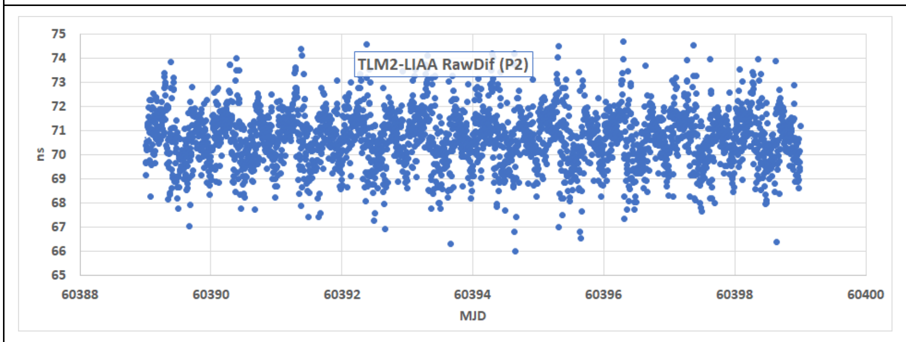
B.3 Traveling vs. visited, LIAA

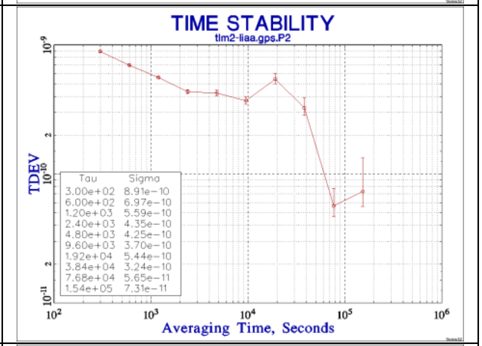


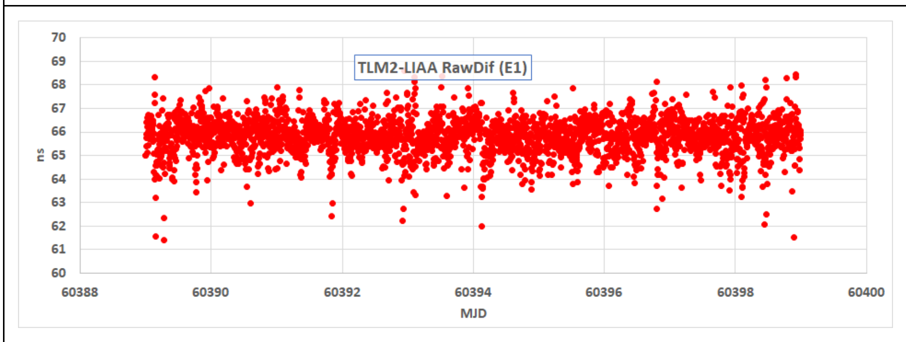


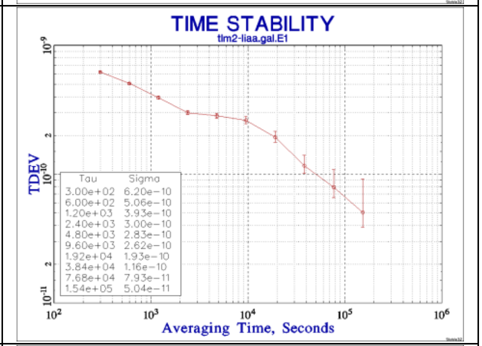


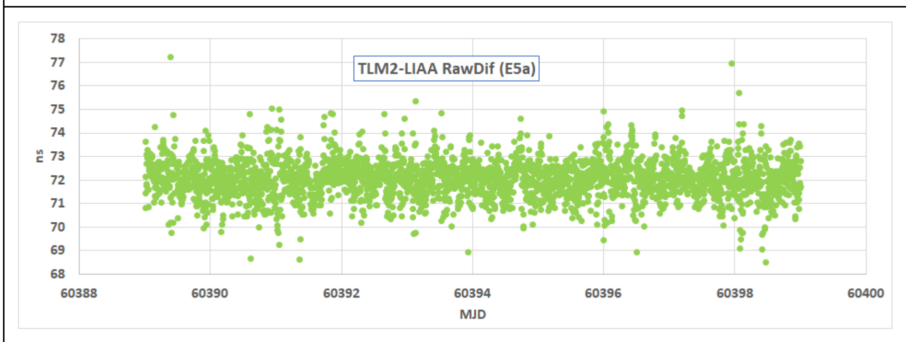


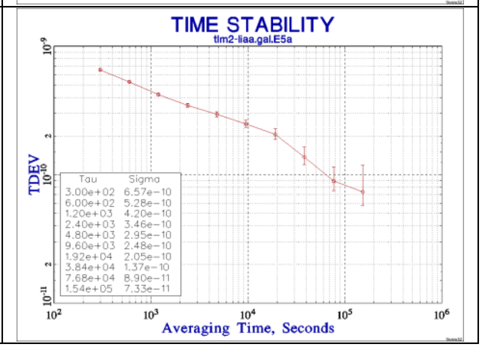




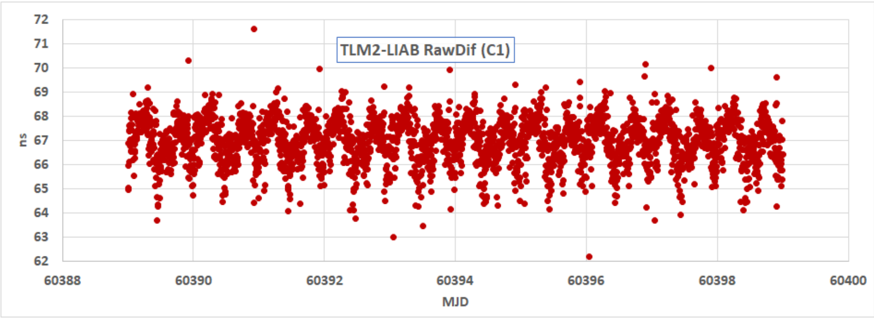


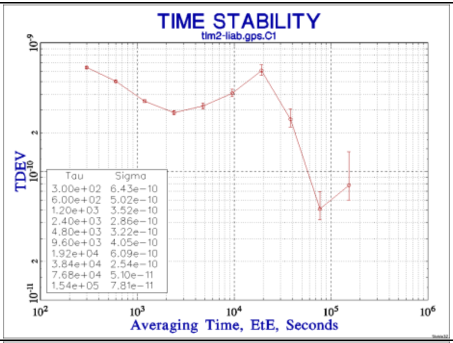


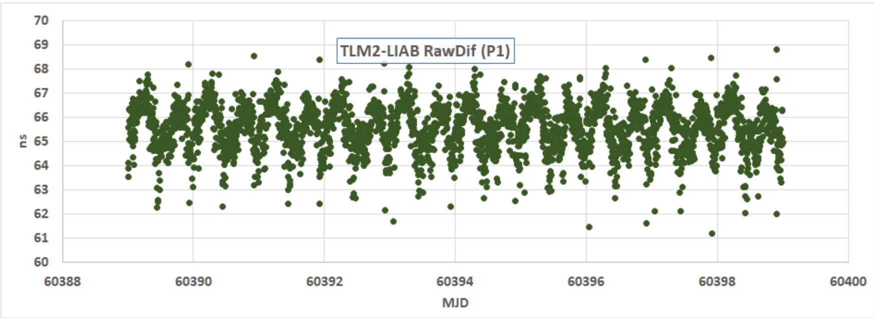


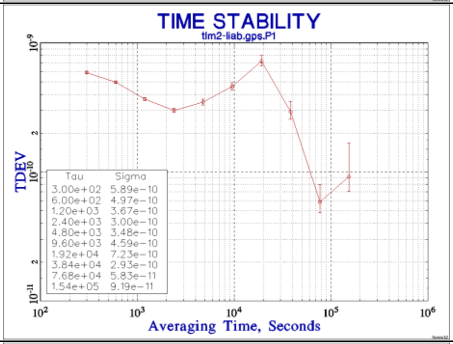


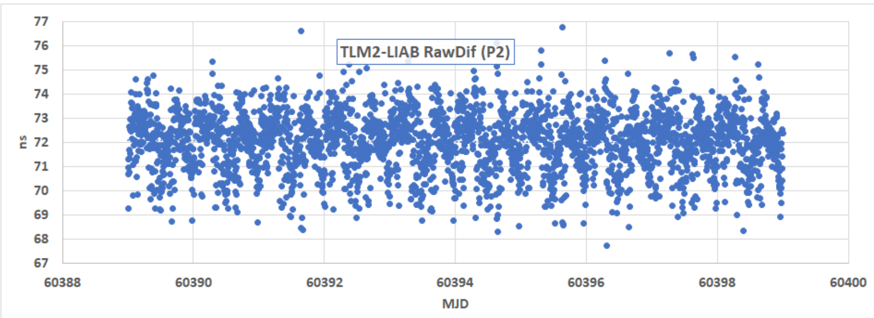
B4. Traveling vs. visited, LIAB

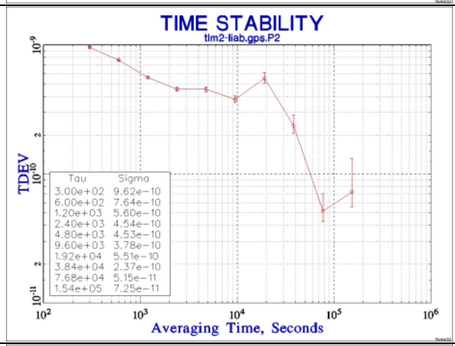


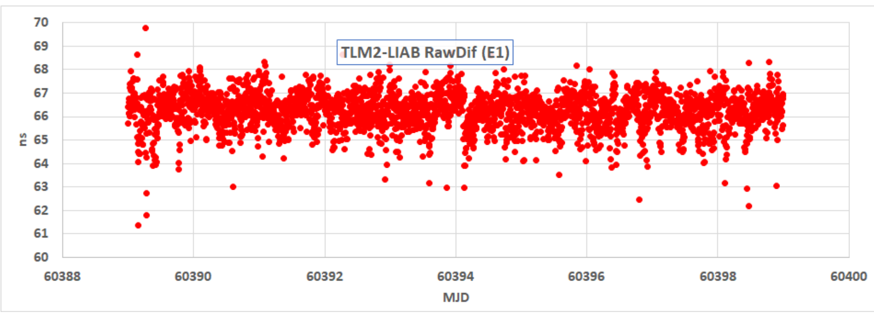


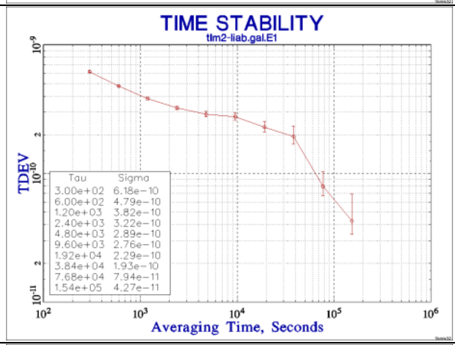


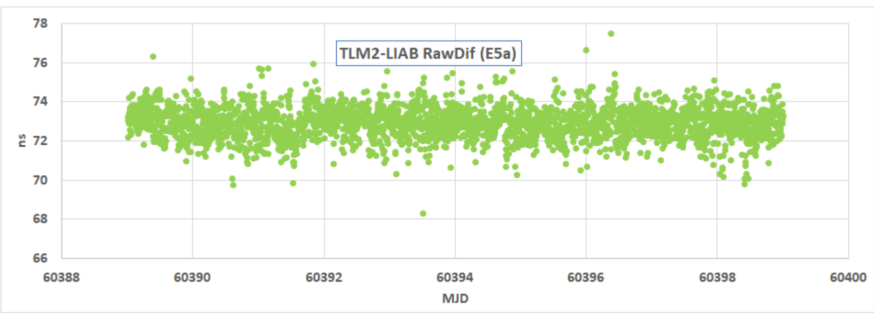


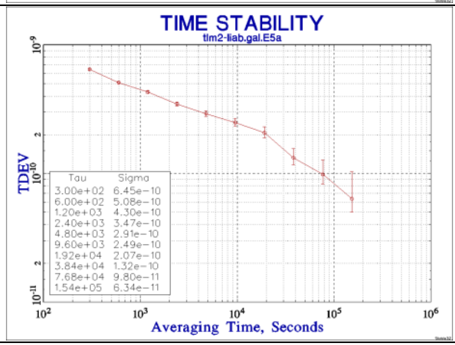




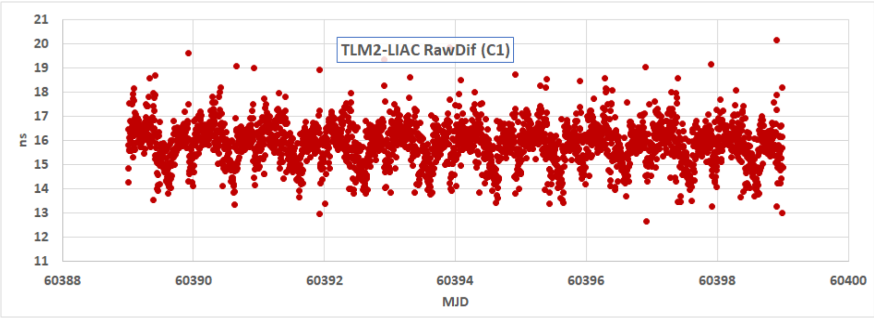


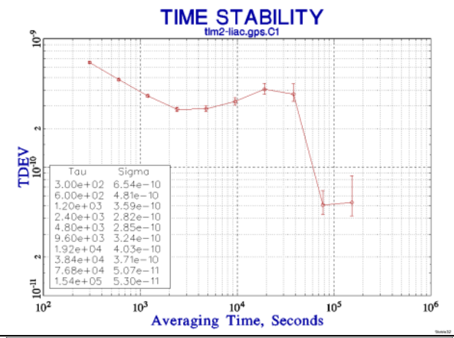


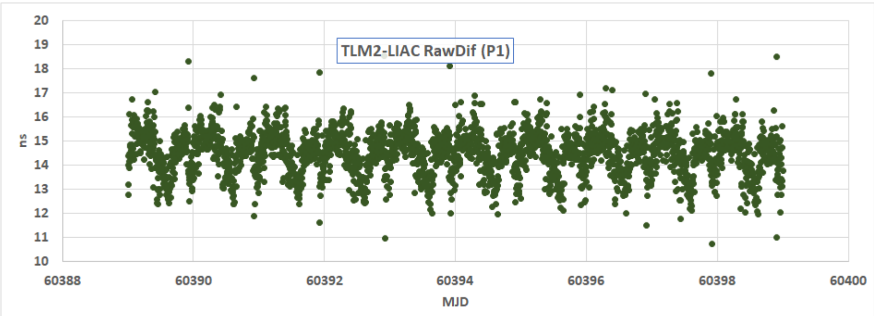


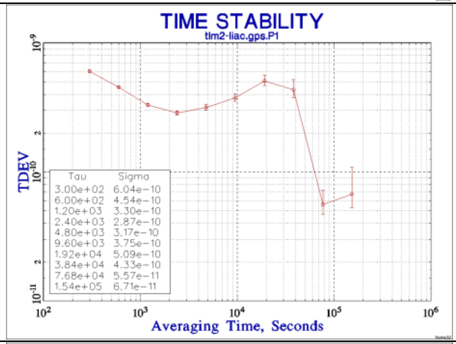


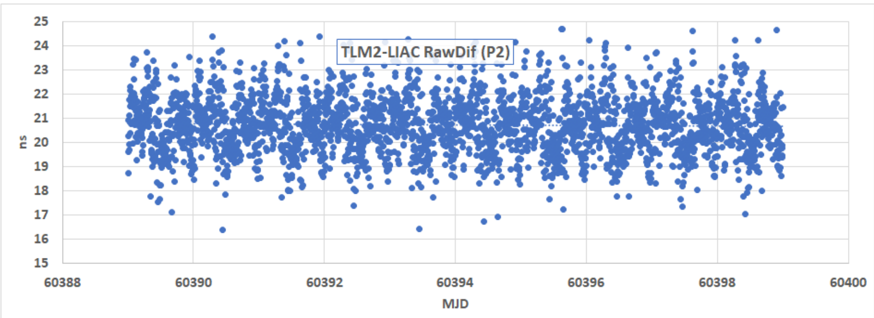
B5. Traveling vs. visited, LIAC

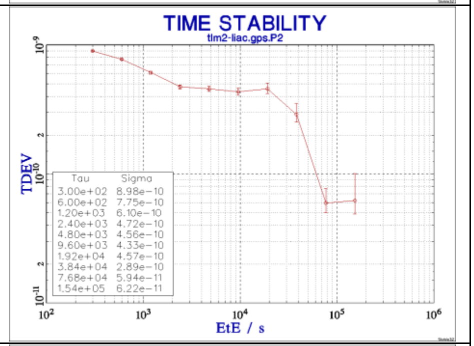


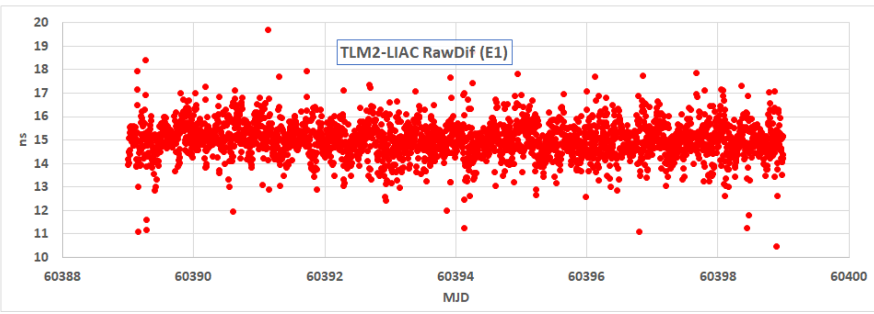


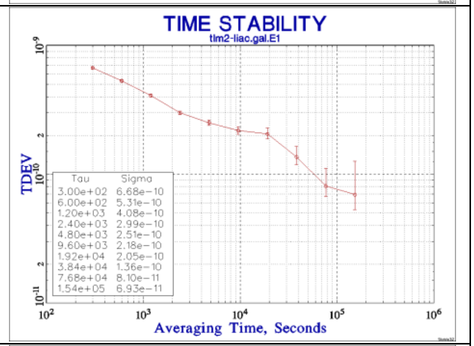


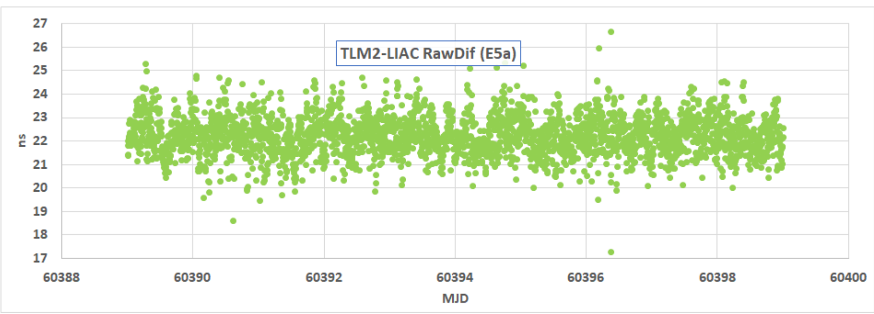


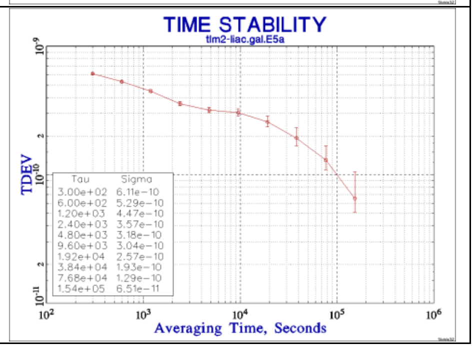












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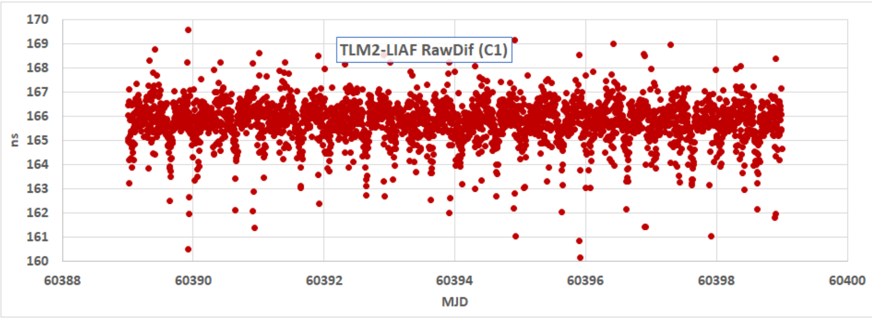
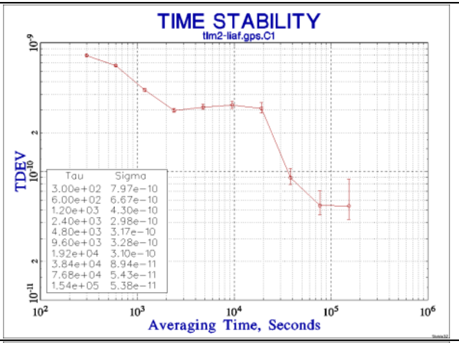
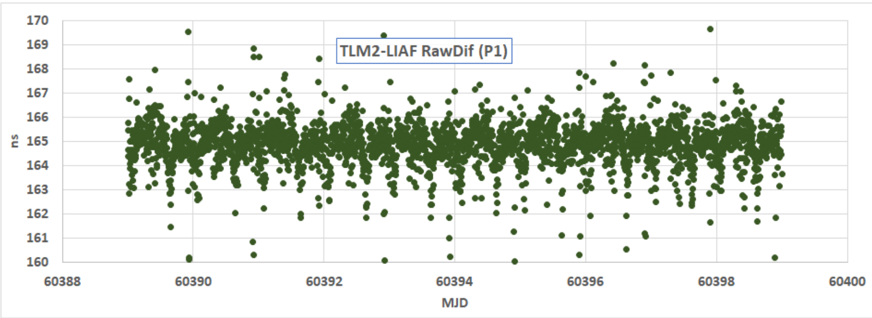
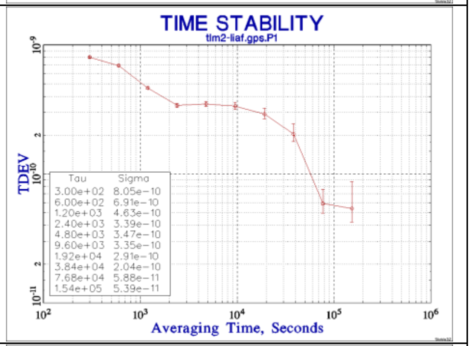
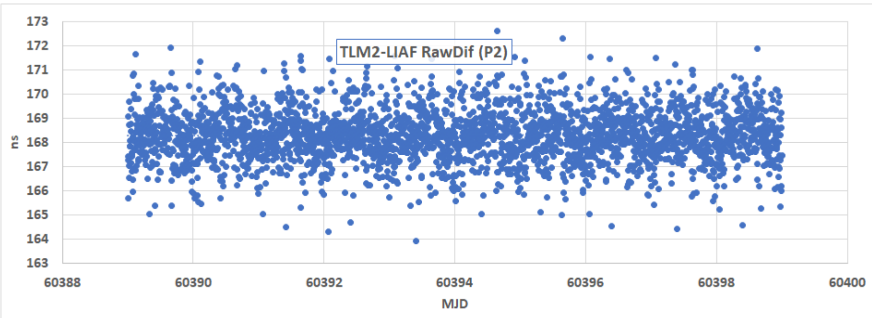
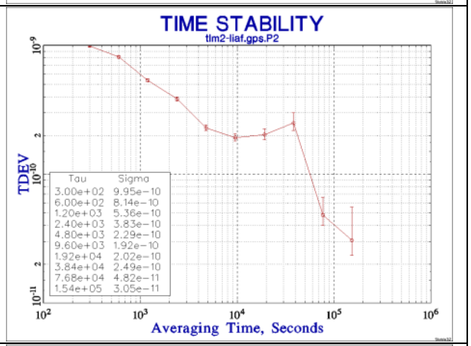


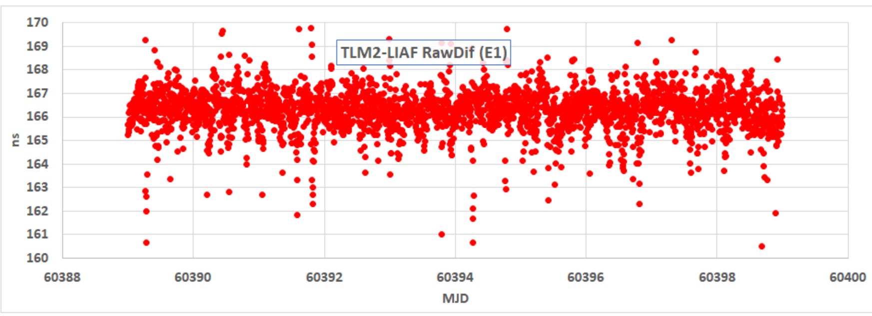


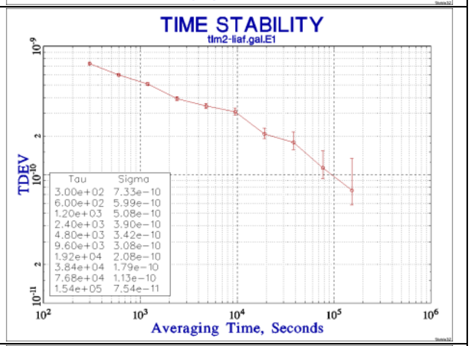


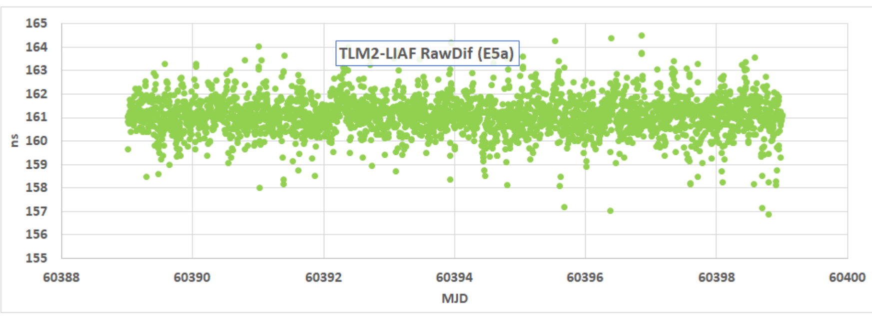


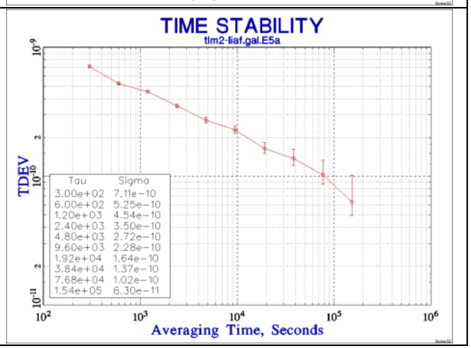




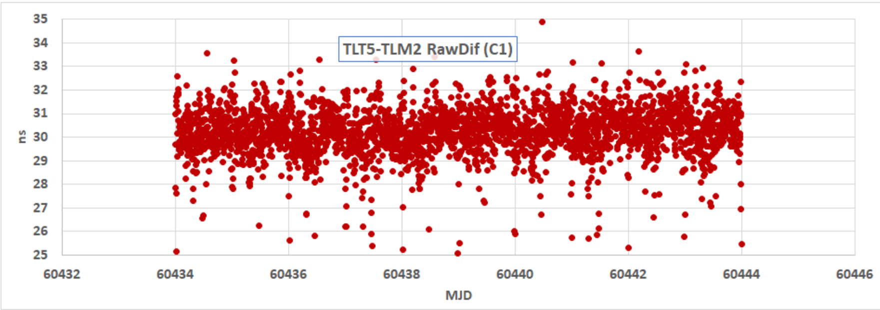


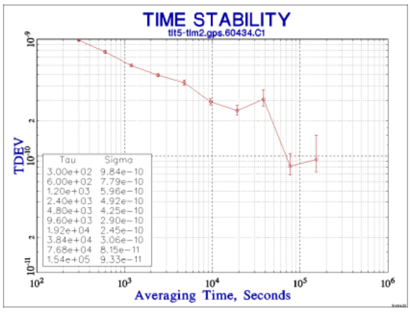


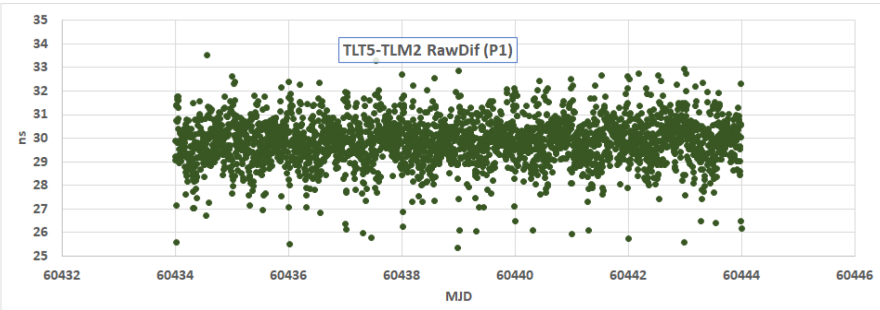


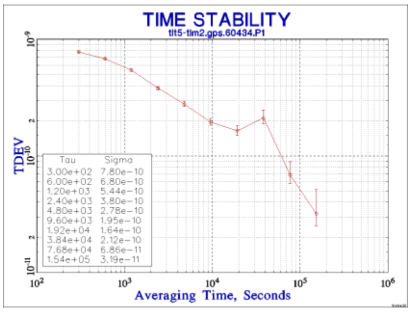


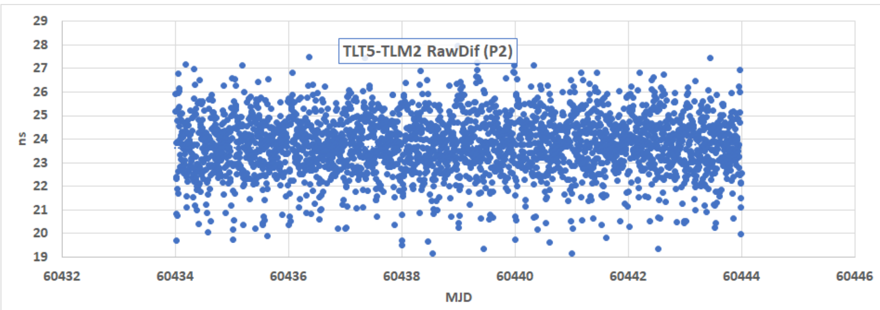
B.7 reference vs. traveling, closure

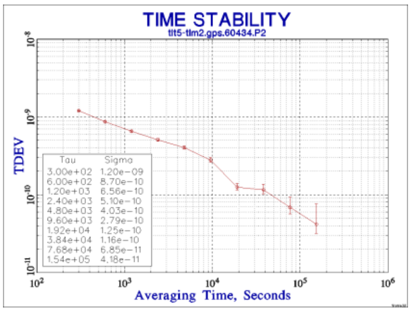


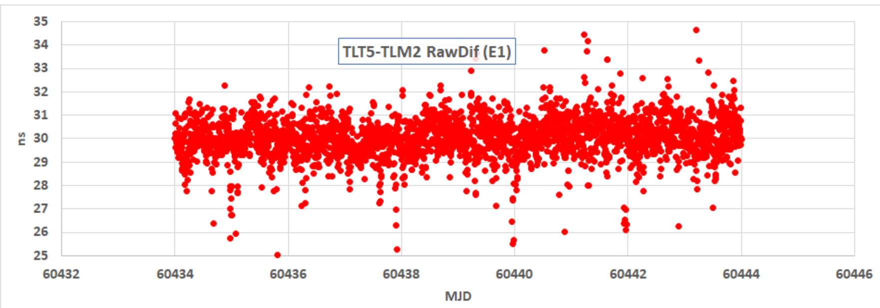


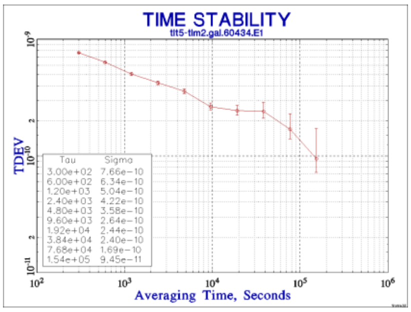


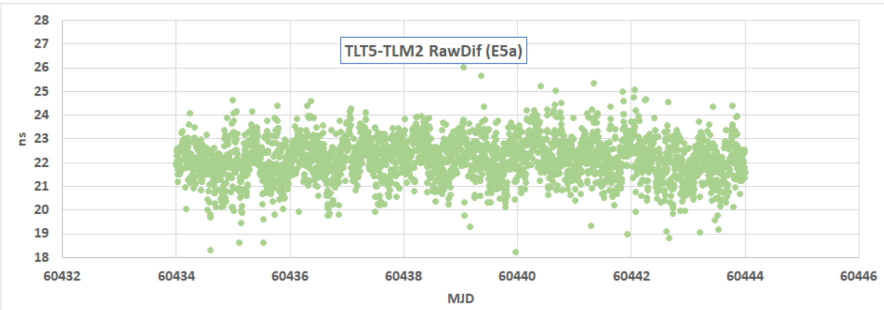


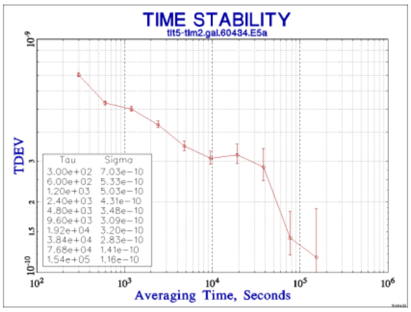












Reference

[1] BIPM "2020 Group 1 GPS calibration trip", ftp://ftp2.bipm.fr /pub/tai/publication/gnss-calibration/group1/1001-2020

[2] BIPM guidelines for GNSS calibration, V4.0, 05/08/2021

[3] https://webtai.bipm.org/ftp/pub/tai/publication/time-calibration/Current/1013-2018_GPSP3C1_NPLI_V1-0.pdf

[4] https://webtai.bipm.org/ftp/pub/tai/publication/time-calibration/Current/1201-2019_GPSP3C1_NPLI-TC_V1-0.pdf

[5] BIPM guidelines Annex3 "Procedure for computing raw difference of GNSS code measurements for geodetic receivers", V3.2, 12/07/2021

[6] W. Lewandowski, C. Thomas, 1991, *"GPS Time transfers,"* Proc. IEEE, Vol. 79, No. 7, 991-1000

[7] G. Petit et al. BIPM TM212, Nov. 2012

[8] J. Kouba, P. Heroux, 2002, "Precise Point Positioning Using IGS Orbit and Clock Products," GPS Solutions, Vol 5, No. 2, 12-28

[9] W. Lewandowski, C. Thomas, 1991, "GPS Time transfers," Proc. IEEE, Vol. 79, No. 7, 991-1000

[10] P. Defraigne and G. Petit, "CGGTTS-Version 2E: an extended standard for GNSS time transfer", Metrologia 52 (2015) G1