G2 Calibration Report: NIST-NRC-NIST

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Abstract

This report is a record of the calibration results of nrc4, the site receiver of NRC, and closure measurement of the trip NIST-NRC-NIST. Three sets of data were collected between MJD57541-57617 (June 2, 2016 and August 17, 2016) by simultaneous operation of a pair of co-located GNSS receivers. The purpose of this campaign was to measure the internal delay of the GPS receiver nrc4 and thereby calibrating the link between NIST and NRC for timing applications. The calibration campaign was initiated by NIST in consultation with NRC for fulfilling the G2 responsibility as per the guidelines set by BIPM [3].

Contents

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1 List of Acronyms

See table 1

Table 1: List of acronyms used in this report.

BIPM	Bureau International des Poids et Mesures, Sèvres, France
CCTF	Consultative Committee on Time and Frequency
CGGTTS	CCTF Global GNSS Time Transfer Standard format
CIPM	Comité International des Poids et Mesures
GNSS	Global Navigation Satellite System
IGS	International GNSS service
ITRF	International Terrestrial Reference Frame
nb05	NIST-owned GPS traveling system
NIST	National Institute of Standards and Technology
nist	4-letter code of NIST's primary GPS receiver
NRC	National Research Council
nrc4	NRC receiver that is to be calibrated
PPP	Precise Point Positioning
PPS	Pulse per second
RINEX	Receiver Independent Exchange format
TDEV	Time Allan deviation
TIC	Time Interval Counter

2 Description of the traveling GNSS receiver

The NIST Traveling System consists of two enclosures containing a rack-mount GPS receiver unit (nb05), a choke-ring antenna and antenna cable, a laptop, a time interval counter and two auxiliary cables (RG223 with BNC connectors) to be used for measuring the REFDLY for the traveling receiver.

The GPS unit nb05 contains a dual-frequency, multi-channel Novatel OEMV Propak-V3 receiver and a NIST-built auxiliary board that conditions the 10MHz and PPS signals to the GPS receiver and measures the time difference between the PPS output and input to the receiver, as well as the time difference between the PPS and 10MHz input signals.

The Novatel GNSS 750 choke-ring antenna is connected to the receiver with a 50 m long FSJ-50A cable. The time interval counter provided with nb05 is an HP53132A. Prior to this calibration campaign, nb05 was used to perform several calibrations for the MINOS experiment[1] lasting over more than a year: two thirds of the mis-closures were less than 1 ns, suggestive of the long-term stability of the receiver unit (together with the NIST-built auxiliary electronics). The setup for nb05 and nrc4 at NRC is shown in figure 1. For similar setup at NIST, please refer to figure 2.

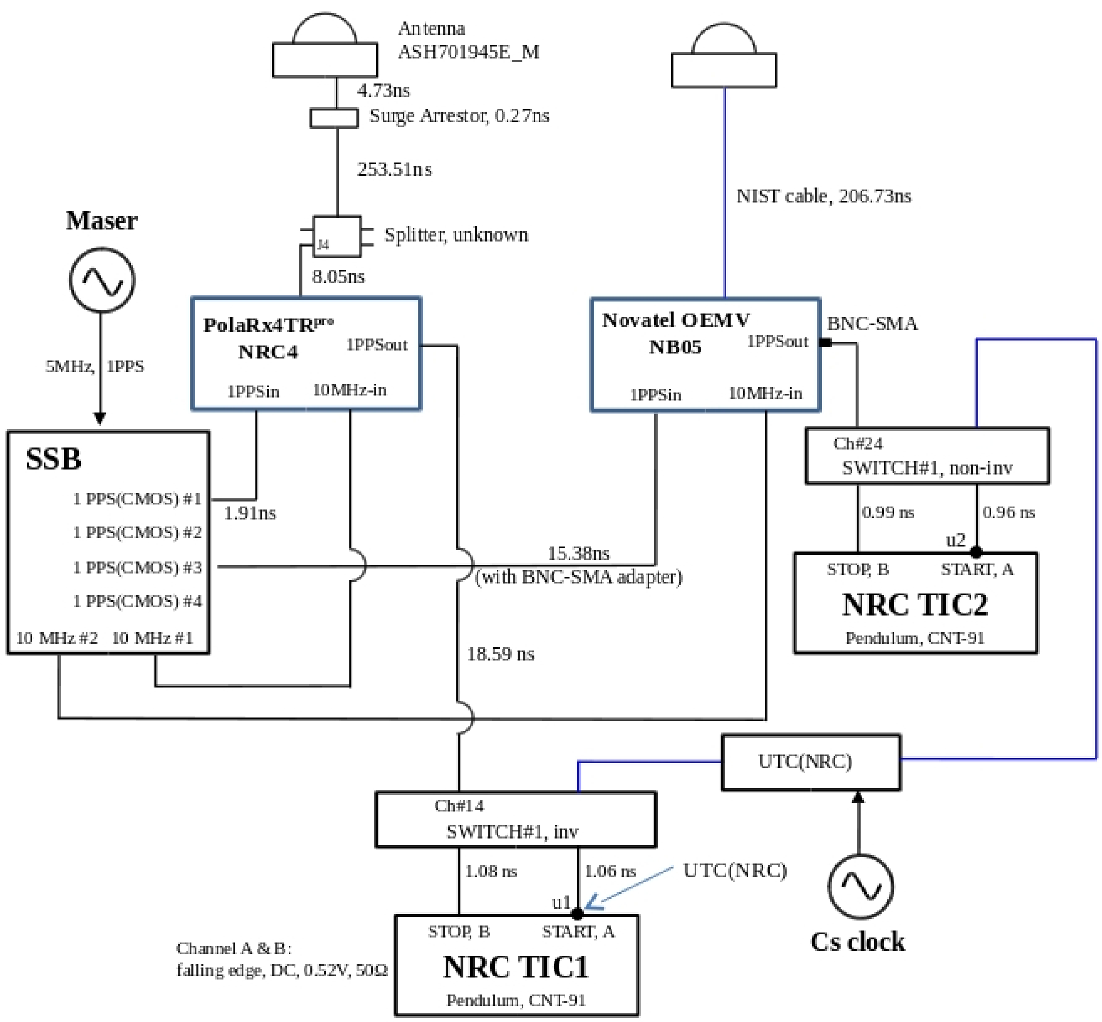

Figure 1: nrc4 and nb05 setup at NRC during the calibration campaign. Note that the reference point for this calibration is the 1PPS(CMOS)#1 in the block SSB and **NOT** UTC(NRC).

3 Results

The notation for various delays are consistent with that adopted in the BIPM guidelines[3]. A brief discussion of the various delays and their values for each pair (traveling- and station-receiver) are detailed next, followed by a discussion about computing raw difference of GPS code measurements.

3.1 Computing delays in the measurement setup

The difference of the total delay for a pair of co-located receivers is the sum of the delays incurred in the antenna cable(CABDLY) and the internal delay(INTDLY), minus the time offset at the latching point of the receiver as referenced to a fixed point, usually UTC(k)(REFDLY). For this calibration, the output of 1PPS(CMOS)#1 is set as a reference point which is different from UTC(NRC), see figure 1. The internal delay is comprised of both code- and frequency-dependent delays in the antenna and the receiver. After accounting for the baseline geometry, the difference in pseudoranges between a pair of receivers, say for P1, is given by

$$\mathrm{RAWDIF(P1)}_{\mathrm{A-B}} = \Delta\mathrm{CABDLY}_{\mathrm{A-B}} + \Delta\mathrm{INTDLY}_{\mathrm{A-B}} - \Delta\mathrm{REFDLY}_{\mathrm{A-B}}, \tag{1}$$

where $\mathrm{RAWDIF(P1)}_{\mathrm{A-B}}$ is the raw difference of pseudorange measurements of two receivers.

$\mathrm{RAWDIF(P2)}_{\mathrm{A-B}}$ is given by using the corresponding set of delays on the right hand side of Eq.(1). The notation for the receivers A and B correspond to the traveling- and station-receiver. $\Delta\mathrm{CABDLY}_{\mathrm{A-B}}$ and $\Delta\mathrm{REFDLY}_{\mathrm{A-B}}$ for nb05(A) and nrc4/nist (B) are given in table 2, referenced from Annex 1-3. Note that the delays for nist were revised as a result of the G1 campaign and the changes were implemented on April 28, 2016.

nb05 setup has provisions to log the REFDLY (both $\mathrm{X_P}$ and $\mathrm{X_O}$) and the procedure is outlined in the operating manual for nb05. Note that in table 2, we provide ΔCABDLY for L1 and L2 because for nb05 the values for CABDLY corresponding to L1 and L2 frequencies were determined separately at NIST. The difference between CABDLY for L1 and L2 are typically of the order of 0.5 ns or less. CABDLY for L1 and L2 are set to the same value if separate measurements are not made available.

Table 2: REFDLY differences between station and traveling receivers

Pair	MJD	Δ REFDLY(ns)	Δ CABDLY(ns)	
			L1	L2[†]
nb05-nist	57541-57545	393.57 ± 0.17	-68.90	-69.38
nb05-nrc4	57584-57589	-128.87 ± 0.16	-60.00	-60.48
nb05-nist	57611-57617	393.65 ± 0.18	-68.90	-69.38

[†] L1 may be used instead of L2 for calculating RAWDIF(P2), if L2 are not readily available.

3.2 Computing raw difference of GPS code measurements

The RINEX files for a pair of co-located receivers during the data acquisition period, MJD column in table 2, are processed using a script provided by the BIPM which invokes a call to a fortran executable that solves the baseline between the phase centers of the two antennas from L1 and L2 phase differences[2, 5]. Subsequently, the P1 and P2 pseudorange differences are formed after accounting for the previously computed baseline. For both Novatel NIST station receiver(nist) and traveling receiver(nb05), the RINEX files were corrected for C1P1 bias[4]. The results are given in table 3. The values for ΔINTDLY between a given pair of receivers are computed using Eq.(1) and are given in table 4.

Table 3: Raw P1 and P2 differences between station and traveling receivers. The assigned uncertainties are the first minimum of the TDEV.

Pair	MJD	ΔP1(ns)	ΔP2(ns)
nb05-nist	57541-57545	-396.06 ± 0.12	-409.27 ± 0.12
nb05-nrc4	57584-57589	-2.43 ± 0.08	-18.62 ± 0.08
nb05-nist	57611-57617	-396.07 ± 0.07	-409.28 ± 0.10

Table 4: INTDLY for receiver(s)

Pair	ΔINTDLY(P1)(ns)	ΔINTDLY(P2)(ns)
nb05-nist$\|_{\text{start}}$	66.41	53.68
nb05-nrc4	-71.30	-87.01
nb05-nist$\|_{\text{end}}$	66.48	53.75
nb05-nist$\|_{\text{average}}$	66.44	53.71
nrc4-nist$\|_{\text{average}}$	137.74	140.72
MISCLOSURE(nb05-nist)	0.07	0.07

Representative plots of P1- and P2-RAWDIF are given in figures 3 and 4 for nb05 at locations NIST and NRC. We have assigned 0.1 ns for $\text{CABDLY}_{\text{nb05}}$ as it was measured fairly recently (less than a year). For the lab receivers, we have assigned a nominal uncertainty of 0.5 ns for $\text{CABDLY}_{\text{nist}}$ and $\text{CABDLY}_{\text{nrc4}}$.

4 Uncertainty estimates

The overall uncertainty of the differential calibration is the uncertainty of the link between two points(labs) over the duration of the calibration. The uncertainties, both statistical and systematic, associated with the GPS constellation and the traveling-receiver drop out. Therefore for a link comprising a pair of locations(labs), say A and B, the total uncertainty is

$$u_{A-B} = \left(u_A^2 + u_B^2\right)^{1/2}, \tag{2}$$

where $u_x = \left(u_{x,a}^2 + u_{x,b}^2\right)^{1/2}$, $x \equiv A, B$. $u_{x,a}$ is the total statistical uncertainty that arise due to the fluctuations in the RAWDIF. In formulating Eq.(2), we have assumed that the total statistical and systematic uncertainties are orthogonal to each other owing to statistical independence. The total uncertainty for each location are given at the end of tables 5 and 6.

The total systematic uncertainty,$u_{x,b}$ have components that are assumed to be statistically independent and hence orthogonal to each other. Therefore, like in Eq.(2), $u_{x,b}$ is equal to the norm of the vector whose components are the various systematic uncertainties. Misclosure is added to the systematic uncertainty at the closure location (NIST). For the RAWDIF, the values for the uncertainty corresponds to the minimum of TDEV. The final result of the link calibration is given in table 7.

Table 5: Uncertainties for the common-clock, co-located measurements of nb05 at NRC

quantity	uncertainty	P1(ns)	P2(ns)
$\text{RAWDIF}_{\text{nb05}-\text{nrc4}}$	u_a	0.08	0.08
nb05 antenna position	$u_{b,11}$	0.05	
nrc4 antenna position	$u_{b,12}$	0.05	
nb05 multipath	$u_{b,13}$	0.10	
nrc4 multipath	$u_{b,14}$	0.10	
$\text{REFDLY}_{\text{nb05}}$	$u_{b,21}$	0.13	
$\text{REFDLY}_{\text{nrc4}}$	$u_{b,22}$	0.10	
$\text{CABDLY}_{\text{nb05}}$	$u_{b,31}$	0.10	
$\text{CABDLY}_{\text{nrc4}}$	$u_{b,32}$	0.50	
$\Delta\text{INTDLY}_{\text{nb05}-\text{nrc4}}$	u_{NRC}	0.60	0.60

Using the uncertainty estimates from tables 6 and 5 and applying it to the values computed in table 4 the results for ΔINTDLY(P1) and ΔINTDLY(P2) are summarized in table 7. Using the adopted values for the internal delays for nist from the latest BIPM calibration of NIST receiver[8] (also given in Annex A for NIST) along with values from table 7, the inferred internal delays for nrc4 are given in table 8.

5 Additional Notes

The antenna coordinates were not specified in the Annex A for nrc4. We use NRCan[6] PPP 5-day average using nrc4 RINEX files for MJDs 57584-57588 (epoch coinciding with nb05 at NRC, see table 2) for estimating the ITRF antenna coordinates. The results are given in table 9. Of course, the choice of the date is arbitrary, provided the antenna position stays fixed.

Since we have already processed the RINEX files using NRCan-PPP for estimating the antenna coordinates for nrc4, likewise, the time difference $[\text{utc(k)-gps}]_{\text{nrc4}}$ can also be obtained. Carrying out the same procedure for nist using IGS precise orbits and clock correction files, we obtain

$$\Delta t_{\text{nist}-\text{nrc4}}|_{\text{PPP}} = 22148.56 \text{ ns.} \tag{3}$$

Comparing Eq.(3) with common-view P3[7],

$$\Delta t_{\text{nist}-\text{nrc4}}|_{\text{P3}} = 22148.19 \text{ ns.} \tag{4}$$

We note that the above comparison is presented as additional information that might be useful in the future for analyzing time transfer results between NIST and NRC when all the delays computed during this calibration are applied correctly. The difference in the values (equations 3 and 4) is due to precise orbits used with PPP as opposed to the brdc files that were used in P3 computation.

Table 6: Uncertainties for the common-clock, co-located measurements of nb05 at NIST

quantity	uncertainty	P1(ns)		P2(ns)	
		begin	end	begin	end
$\mathrm{RAWDIF}_{\mathrm{nb05-nist}}$	u_a	0.12	0.07	0.12	0.10
nb05 antenna position	$u_{b,11}$	0.05			
nist antenna position	$u_{b,12}$	0.05			
nb05 multipath	$u_{b,13}$	0.10			
nist multipath	$u_{b,14}$	0.10			
$\mathrm{REFDLY}_{\mathrm{nb05}}$	$u_{b,21}$	0.13	0.14	0.13	0.14
$\mathrm{REFDLY}_{\mathrm{nist}}$	$u_{b,22}$	0.10	0.05	0.10	0.05
$\mathrm{CABDLY}_{\mathrm{nb05}}$	$u_{b,31}$	0.10			
$\mathrm{CABDLY}_{\mathrm{nist}}$	$u_{b,32}$	0.50			
$\Delta\mathrm{INTDLY}_{\mathrm{nb05-nist}}$		0.57	0.57	0.56	0.57
$\Delta\mathrm{INTDLY}_{\mathrm{nb05-nist}}\|_{\mathrm{max}}/\sqrt{2}$		0.41		0.41	
Misclosure/2	$u_{b,1}$	0.03		0.03	
$\Delta\mathrm{INTDLY}_{\mathrm{nb05-nist}}$	u_{NIST}	0.40		0.40	

Table 7: ΔINTDLY for receiver the link NIST-NRC

Pair	ΔINTDLY(P1) (ns)	ΔINTDLY(P2) (ns)
nrc4-nist	137.74 ± 0.7	140.72 ± 0.7

Table 8: INTDLY for receiver nrc4

Rcvr	INTDLY(P1) (ns)	INTDLY(P2) (ns)
nrc4	65.70	68.90

Table 9: Cartesian and Ellipsoidal coordinates for nrc4

Cartesian		Ellipsoidal	
X	1112801.201 (m)	Lat	45 27 13.558 (dms)
Y	-4341502.318 (m)	Lon	-75 37 25.013 (dms)
Z	4522925.113 (m)	H	82.779 (m)

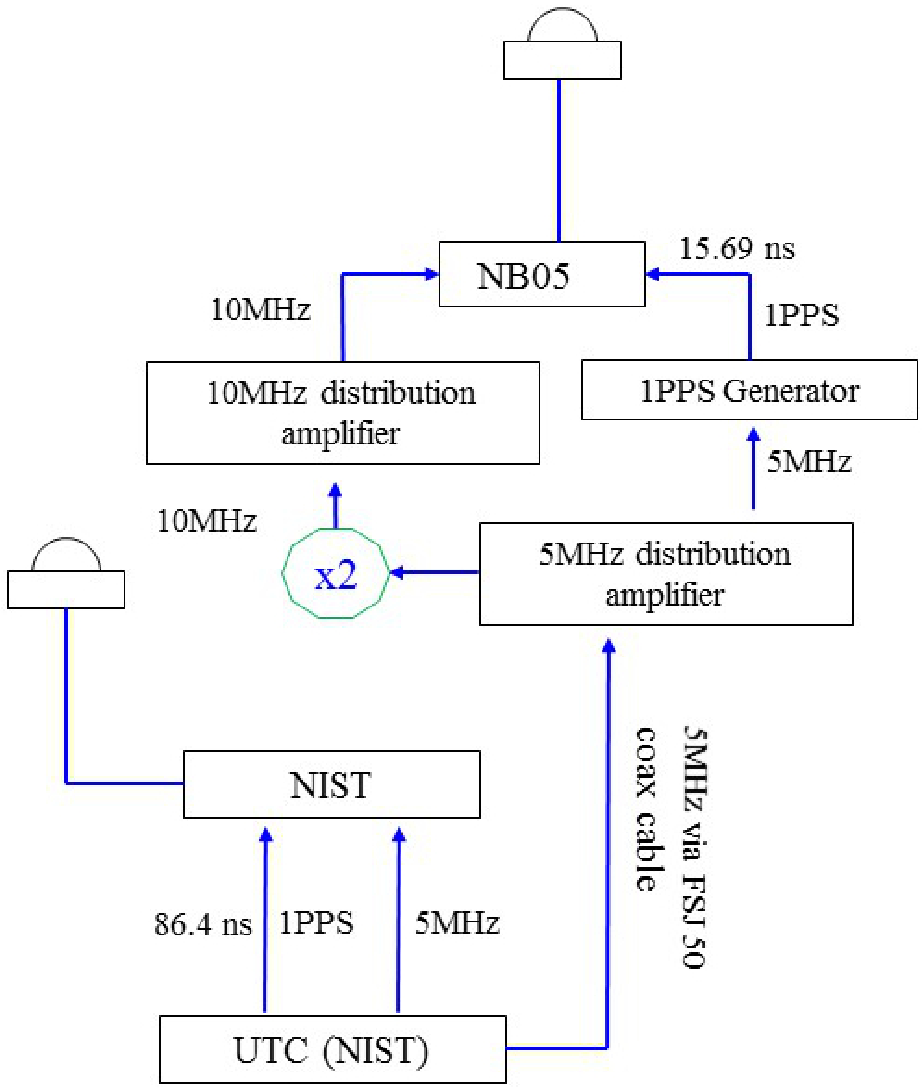

Figure 2: nist and nb05 setup at NIST during the calibration campaign

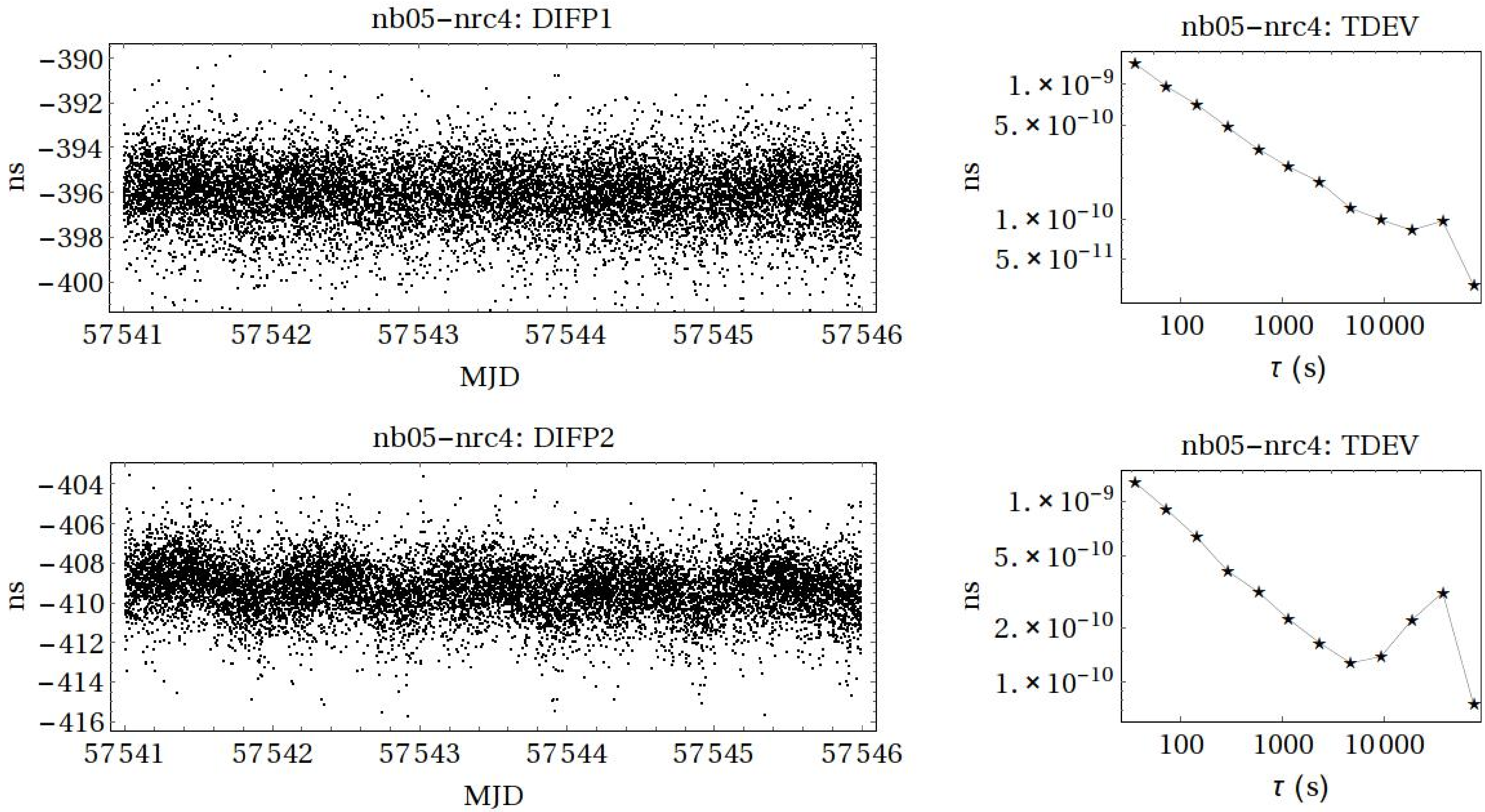

Figure 3: P1 and P2 raw differences and TDEV at NIST

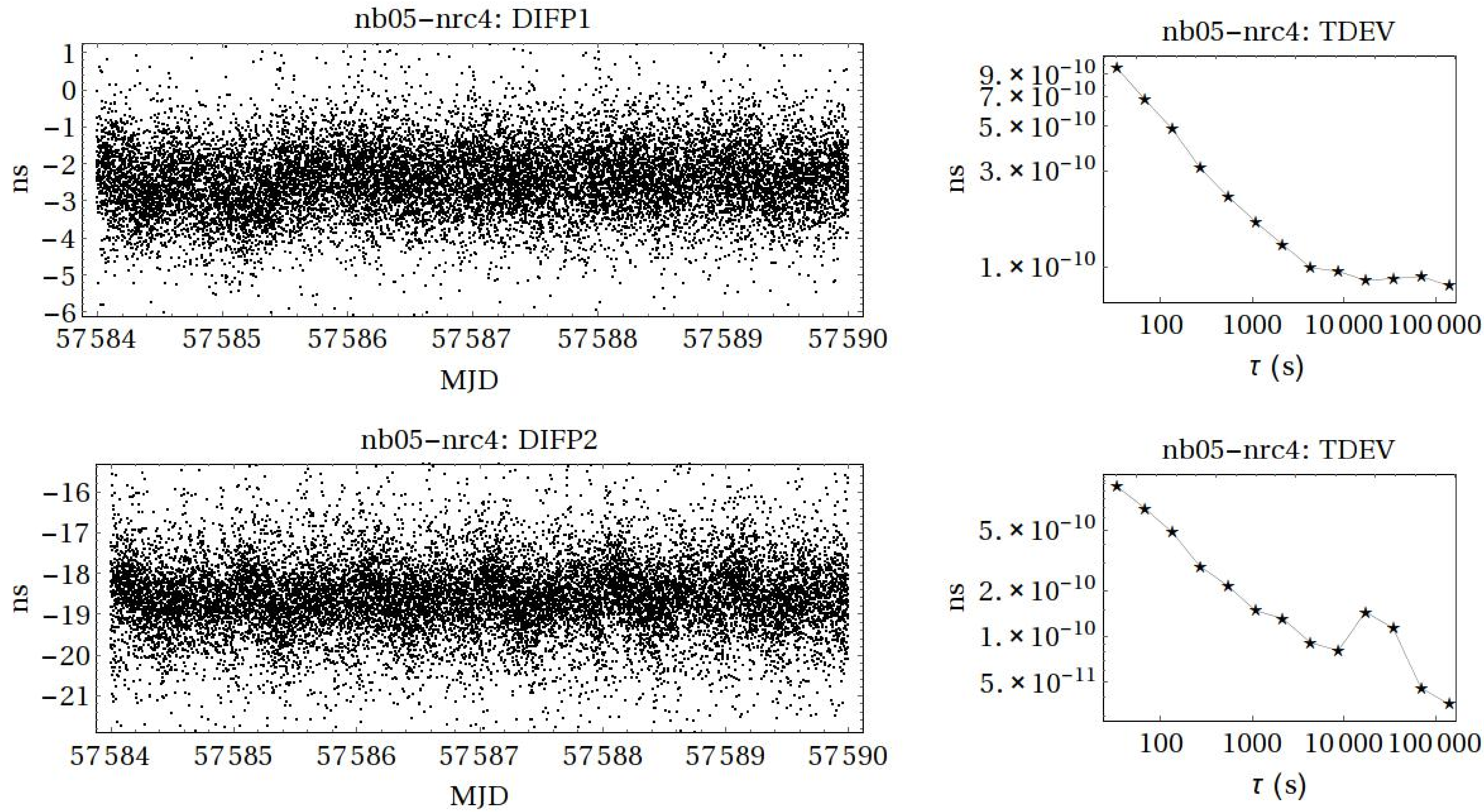

Figure 4: P1 and P2 raw differences and TDEV at NRC

6 Secondary information

1. Appendix A: Attached separately.
2. Data files: ftp//ftp.nist.gov/pub/pml/688gps/nist_nrc.tar.gz

References

[1] S. Römisch, et al. Synchronization between remote sites for the MINOS experiment, Proceedings of 44th PTTI, 2012

[2] ftp://ftp2.bipm.org/pub/tai/publication/gnss-calibration/doc-soft/

[3] ftp://ftp2.bipm.org/pub/tai/publication/gnss-calibration/guidelines/

[4] ftp://dgn6.esoc.esa.int/CC2NONCC/

[5] http://www.bipm.org/wg/CCTF/WGGNSS/Allowed/BIPM_guidelines_V3/Annex-3_Computation-procedure-Rinex_V2.pdf

[6] http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/tools-applications/10925

[7] P Defraigne and G Petit, Time transfer to TAI using geodetic receivers, Metrologia, vol. 40, no. 4, pp 184, 2003

[8] ftp://ftp2.bipm.org/pub/tai/publication/gnss-calibration/group1/1001-2014/tm243_group1-reference-values_v7.pdf

Annex A - Information Sheet

Laboratory:	NIST
Date and hour of the beginning of measurements:	154, 2016, 00:30:00
Date and hour of the end of measurements:	158, 2016, 23:59:30

Information on the system

	Local:	**Travelling:**
4-character BIPM code	nist	nb05
• Receiver maker and type: Receiver serial number:	Novatel OEM4-G2	Novatel OEMV NAP11260003
1 PPS trigger level /V:	1.0	0.5
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Andrea FSJ-50A N	Andrea FSJ-50A (T2) N
Length outside the building /m:	65	25
• Antenna maker and type: Antenna serial number:	Novatel 702	Novatel GNSS 750 NDE 10480003
Temperature (if stabilised) /°C		

Measured delays /ns

(if needed fill box "Additional Information" below)

	Local:	**Travelling:**
• Delay from local ~~UTC~~ *reference clock* to receiver 1 PPS-in, X_P	66.69 ± 0.02 *	465.45 ± 0.13 ***
Delay from 1 PPS-in to internal Reference (if different), X_O	19.70 ± 0.10 *	14.51 ± 0.04 **
• Antenna cable delay, X_C	275.5	206.6 (L1),206.12 (L2)
Splitter delay (if any)	N/A	N/A
Additional cable delay (if any)	N/A	N/A

Data used for the generation of CGGTTS files

• INT DLY (GPS) /ns:	-72.03 (P1), -71.79 (P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	275.5
• REF DLY /ns:	86.4
• Coordinates reference frame:	WGS84
Latitude or X /m:	-1288398.360
Longitude or Y /m:	-4721697.040
Height or Z /m:	4078625.500

General information

• Rise time of the local UTC pulse:	3 ns
• Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	
Set humidity value and uncertainty:	

* Dec 9, 2015

** averaged over measurement duration

*** 449.76 ± 0.05 (avg. from meas. After 12 Dec 2015) added to 15.69 ± 0.13

Annex A - Information Sheet

Laboratory:	National Research Council Canada
Date and hour of the beginning of measurements:	197, 2016, 00:30:00
Date and hour of the end of measurements:	202, 2016, 23:59:30

Information on the system

	Local:	**Travelling:**
4-character BIPM code	nrc4	nb05
• Receiver maker and type: Receiver serial number:	Septentrio, PolaRx4TR^{pro} 31022286	Novatel OEMV NAP11260003
1 PPS trigger level /V:	1.0	0.5
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Andrea, Heliax, LDF2-50 Y	Andrew FSJ1-50A (T2) N
Length outside the building /m:	1.5 m	2.5 m
• Antenna maker and type: Antenna serial number:	ASH701945E_M SNOW CR52002205	Novatel GNSS 750 NDE 10480003
Temperature (if stabilised) /°C		

Measured delays /ns

(if needed fill box "Additional Information" below)

	Local:	**Travelling:**
• Delay from local ~~UTC~~ *reference clock* to receiver 1 PPS-in:	1.91	15.38 ± 0.10
Delay from 1 PPS-in to internal Reference (if different):	142.88 before calibration 142.90 after calibration	0.55 ± 0.08
• Antenna cable delay:	266.29	206.6
Splitter delay (if any):	unknown	N/A
Additional cable delay (if any):	Surge arrester: 0.27	N/A

Data used for the generation of CGGTTS files

• INT DLY (GPS) /ns:	
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	
• REF DLY /ns:	
• Coordinates reference frame:	
Latitude or X /m:	
Longitude or Y /m:	
Height or Z /m:	

General information

• Rise time of the local UTC pulse:	2.532 ns
• Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	21.3 ºC ± 0.25 ºC
Set humidity value and uncertainty:	44.5% ± 5%

Annex A - Information Sheet

Laboratory:	NIST
Date and hour of the beginning of measurements:	224, 2016, 00:30:00
Date and hour of the end of measurements:	231, 2016, 23:59:30

Information on the system

	Local:	Travelling:
4-character BIPM code	nist	nb05
• Receiver maker and type: Receiver serial number:	Novatel OEM4-G2	Novatel OEMV NAP11260003
1 PPS trigger level /V:	1.0	0.5
• Antenna cable maker and type: Phase stabilised cable (Y/N):	Andrea FSJ-50A N	Andrea FSJ-50A (T2) N
Length outside the building /m:	65	25
• Antenna maker and type: Antenna serial number:	Novatel 702	Novatel GNSS 750 NDE 10480003
Temperature (if stabilised) /°C		

Measured delays /ns

(if needed fill box "Additional Information" below)

	Local:	Travelling:
• Delay from local ~~UTC~~ *reference clock* to receiver 1 PPS-in, X_P	66.69 ± 0.02 *	465.43 ± 0.14 ***
Delay from 1 PPS-in to internal Reference (if different), X_O	19.70 ± 0.10 *	14.61 ± 0.05 **
• Antenna cable delay, X_C	275.5	206.6 (L1),206.12 (L2)
Splitter delay (if any)	N/A	N/A
Additional cable delay (if any)	N/A	N/A

Data used for the generation of CGGTTS files

• INT DLY (GPS) /ns:	-72.03 (P1), -71.79 (P2)
• INT DLY (GLONASS) /ns:	
• CAB DLY /ns:	275.5
• REF DLY /ns:	86.4
• Coordinates reference frame:	WGS84
Latitude or X /m:	-1288398.360
Longitude or Y /m:	-4721697.040
Height or Z /m:	4078625.500

General information

• Rise time of the local UTC pulse:	3 ns
• Is the laboratory air conditioned:	yes
Set temperature value and uncertainty:	
Set humidity value and uncertainty:	

* Dec 9, 2015
** averaged over measurement duration
*** 449.76 ± 0.05 (avg. from meas. After 12 Dec 2015) added to 15.67 ± 0.14