GNSS time and frequency transfers and receiver calibrations: plans and implementations

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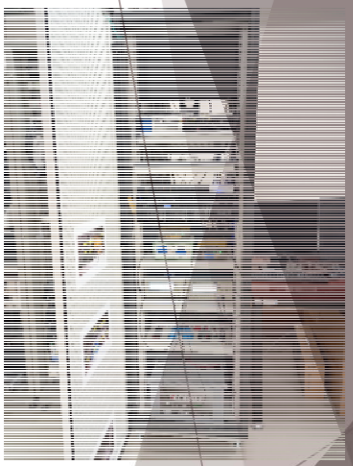
Content

1. Time and frequency metrology: time keeping and GNSS time transfer
2. GNSS common-view: short (common site) and long baseline (with PTB)
3. Results
4. Conclusions

Time and frequency laboratory

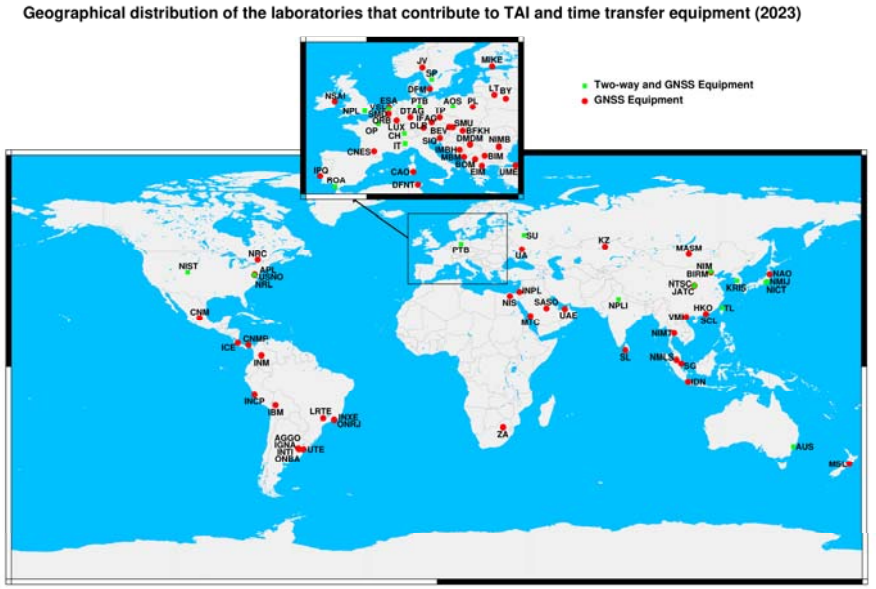


- Maintains Thailand's primary frequency standards
  - **Atomic clocks**: caesium frequency standards and hydrogen masers
  - **GNSS** time and frequency transfer **receivers**
- Provides measurement capabilities to be able to traceable to the International System (SI) of Units
  - **1 second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom**
- Researches on next generation atomic clocks and GNSS measurement methods to realise the SI second (Yb+ ion)

Virtual labs:
https://mx.nimt.or.th/?p=15925
Research innovations: https://mx.nimt.or.th/?p=15170
Thailand's first atomic clock developments:
https://www.youtube.com/watch?v=dAFJYtXUGDk
GNSS time and frequency transfers 8 episodes:
https://www.youtube.com/watch?v=gltV8RSfBLk&t=18s

GNSS signals at national standard labs

- Monitor atomic clocks via GNSS signals
- Report the findings on the ground clocks to International Bureau of weights and Measures (BIPM)
  - Differences between each maintaining clocks
  - Differences between maintained ground clocks and satellite vehicle clocks (REF – SV)
  - Differences between maintained ground clocks and assigned satellite system time (REF – SYS)
- BIPM provides records of TAI and UTC which show
  - Atomic clock performances
  - Timescale offsets (traceability to SI seconds)
- GNSS measurements at NIMT
  - MTTI: http://164.115.133.54/
  - MTME: http://164.115.133.59/
  - MTTN: http://164.115.133.57/



TAI Contribution Laboratories: https://webtai.bipm.org/ftp/pub/tai/other-products/maps/planisphere-2023.png

GNSS signals at national standard labs

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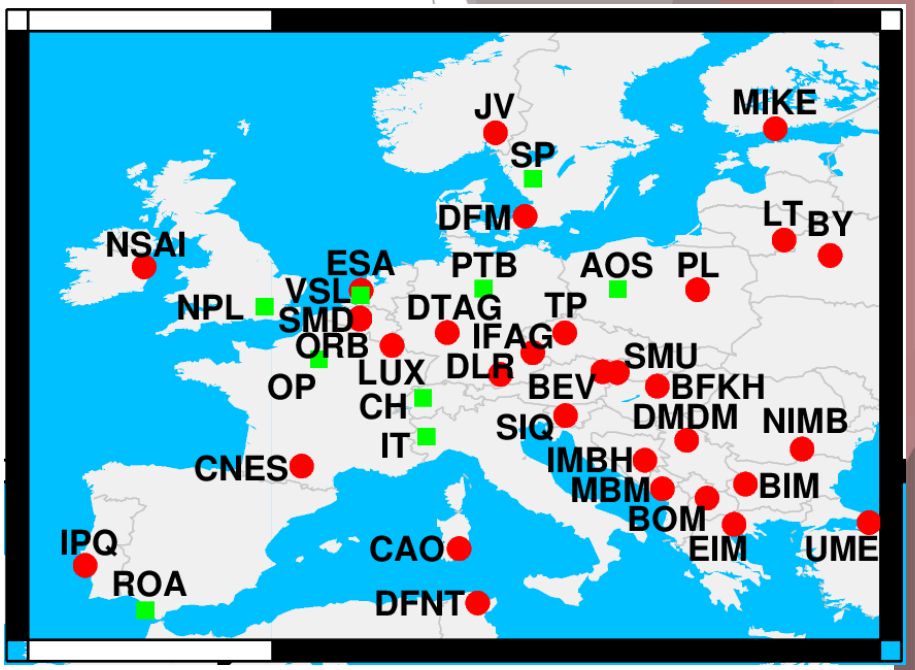
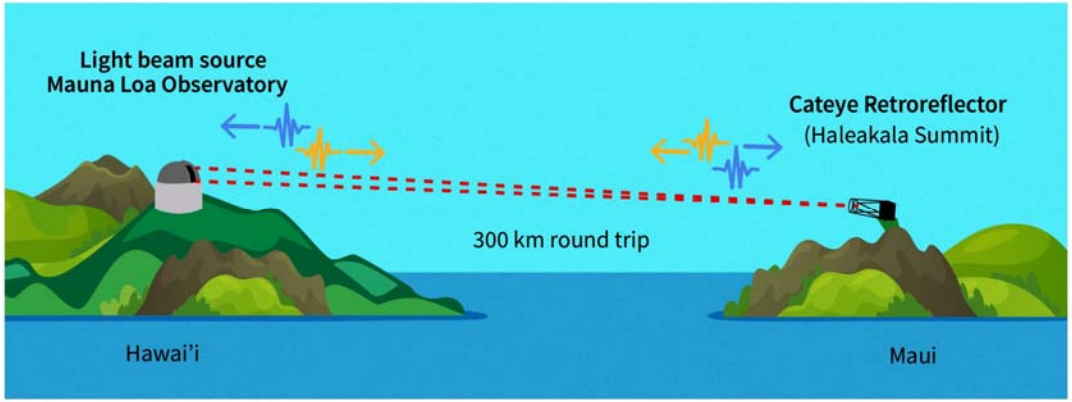


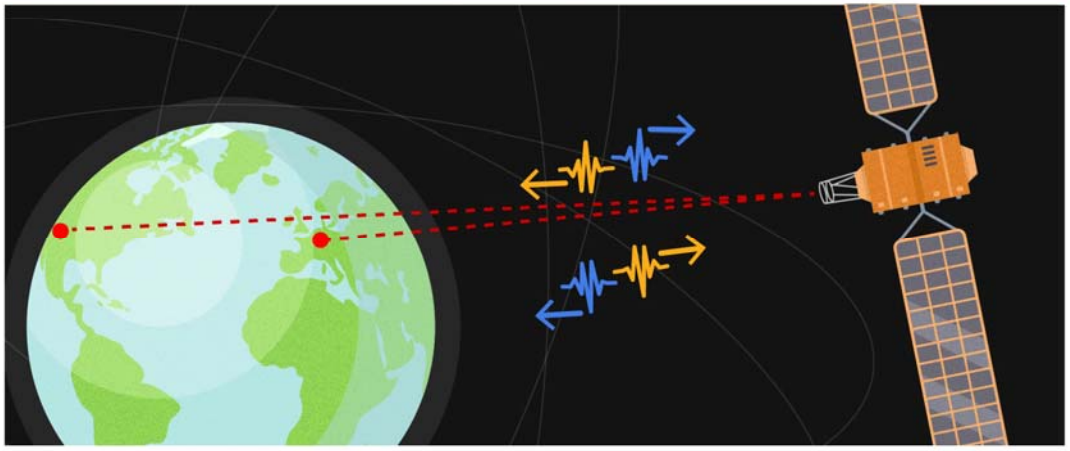
UTC(MIKE)

National Metrology Institute (NMI) of Finland, maintains the Finnish realisation of Coordinated Universal Time

https://www.vttresearch.com/fi/tutkimusosaaminen/metrologia-vtt-mikes

GNSS time and frequency transfer



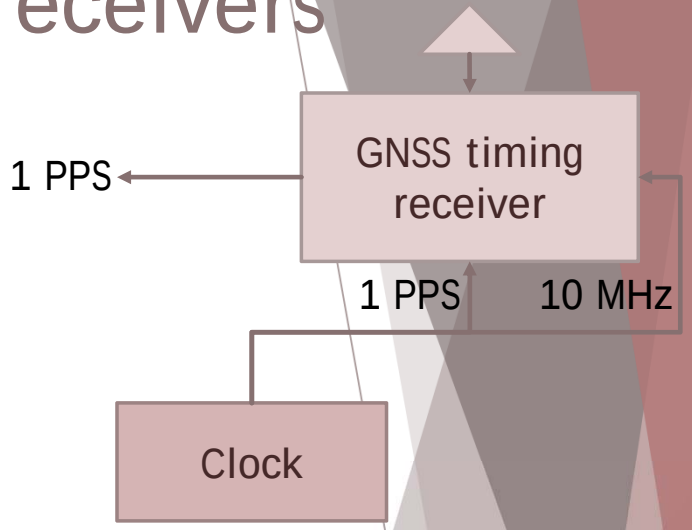


https://www.nist.gov/news-events/news/2023/06/nist-lays-groundwork-future-ultra-precise-timing-links-geosynchronous?fbclid=IwAR3ojIE0jgnKNeu7H-6ajjLi85hnfWnHhsW0o_w22ynMddDWqrTyXL6lvjY

GNSS time and frequency transfer receivers

- 10 MHz or 5 MHz and 1 pps inputs
- Special algorithm to
  - determine clock offsets and frequency offsets with navigation satellite system time i.e. GPS system time
  - synchronise receiver clock to defined UTC time system i.e. UTC(NIMT)
- Coordinates of the antenna have to be precisely determined to specified reference system i.e. ITRF2014
- Positioning abilities (static and RTK)
- Multi-frequencies

https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/archive/annex-1_operational-procedures-20181020.pdf
https://www.mesitasd.cz/en/defence-katalog-produktu/prijimac-gnss-pro-transfer-casu-a-frekvence-2
https://www.septentrio.com/en/products/gps/gnss-reference-receivers/polarx-5tr

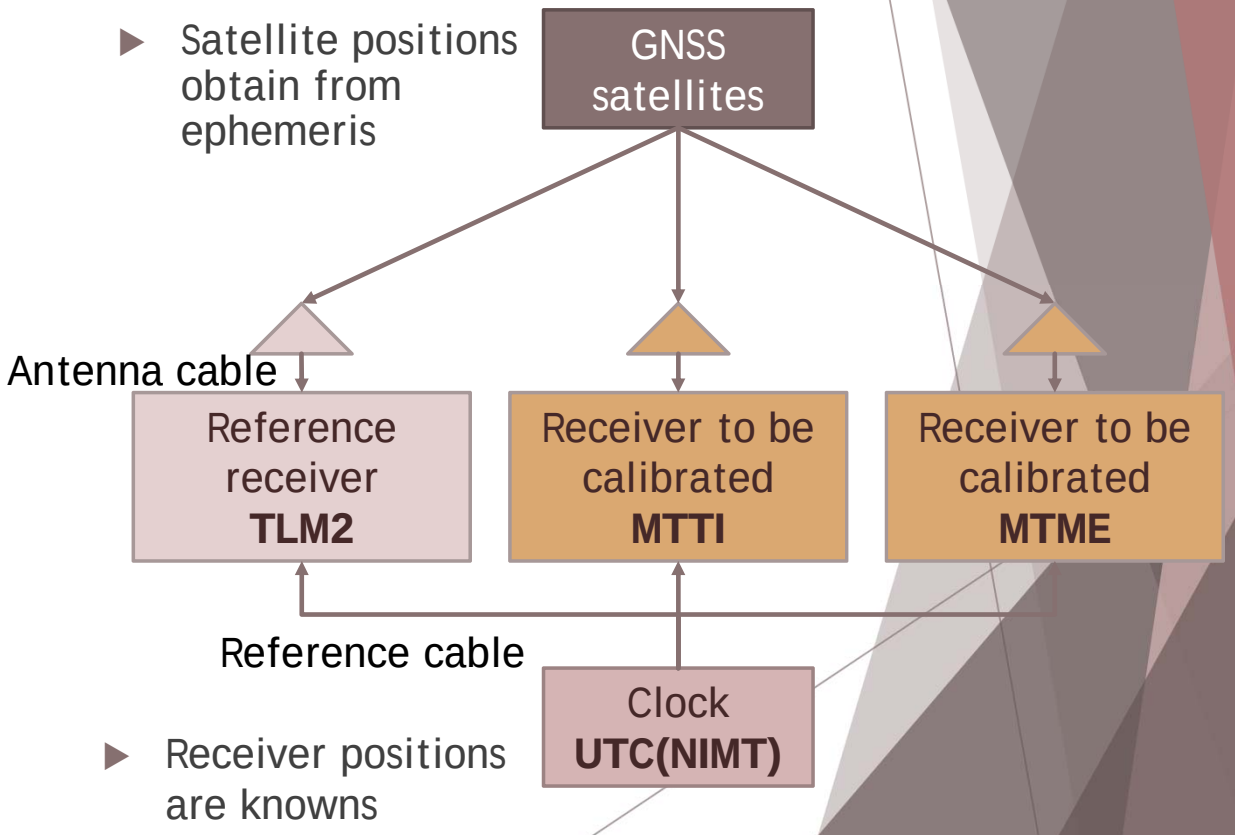


GNSS time and frequency receivers at NIMT

- MTTI:
  - Mesit GTR55
  - NOV850 NONE
- MTME:
  - Mesit GTR55
  - NOV850 NONE
- MTTN:
  - Septentrio PolaRx5TR
  - SEPCHOKE_B3E6_SPKE

GNSS common-view and common-clock measurements (short baseline)

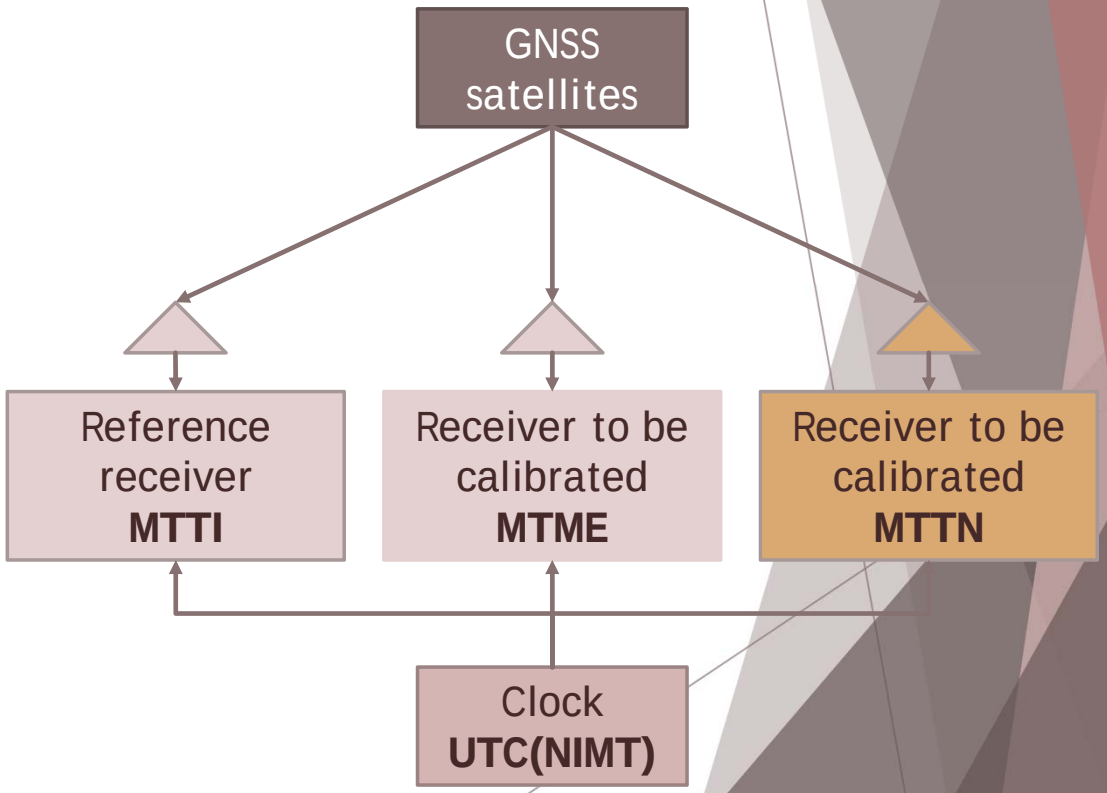
- Receivers are connected to the common clocks and observed common satellites (co-location)
- Relative calibration delays; provided by the BIPM G1 and G2 receiver calibration scheme
- Determine total delays comprise of receiver internal delay, antenna cable delay and reference delay with its computed measurement uncertainty
- Measured duration is 4-7 days
- Internal delays are for GPS L1 L2 and Galileo E1 E5a



https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/

GNSS common-view and common-clock measurements (short baseline)

- GNSS receiver calibration transfer
  - MTTI and MTME are calibrated through BIPM calibration scheme
  - MTTN is a new installed receiver at NIMT
- Follow BIPM procedure for computing raw difference of GNSS code measurements for geodetic receiver (annex 3 dclrinex)
- RINEX: station observations, navigation and IGS broadcast navigation message



https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/

GNSS receiver calibration results

ID	Calibrated date	CAB	REF	INT GPS C1	INT GPS P1	INT GPS P2	uCal0 (C/A)	uCal0 (P3)	ΔuCAL	Applied MJD
MTTI	16 September 2022	214.7	23.9	12.4	12.2	9.8	2.5	2.5	0.0	59947
MTME	16 September 2022	214.5	24.6	16.0	13.6	8.2	2.5	2.5	0.0	59947
MTTN	8 July 2023	250.7	35.2	28.2	26.7	23.0	2.5	2.5	1.0	60174

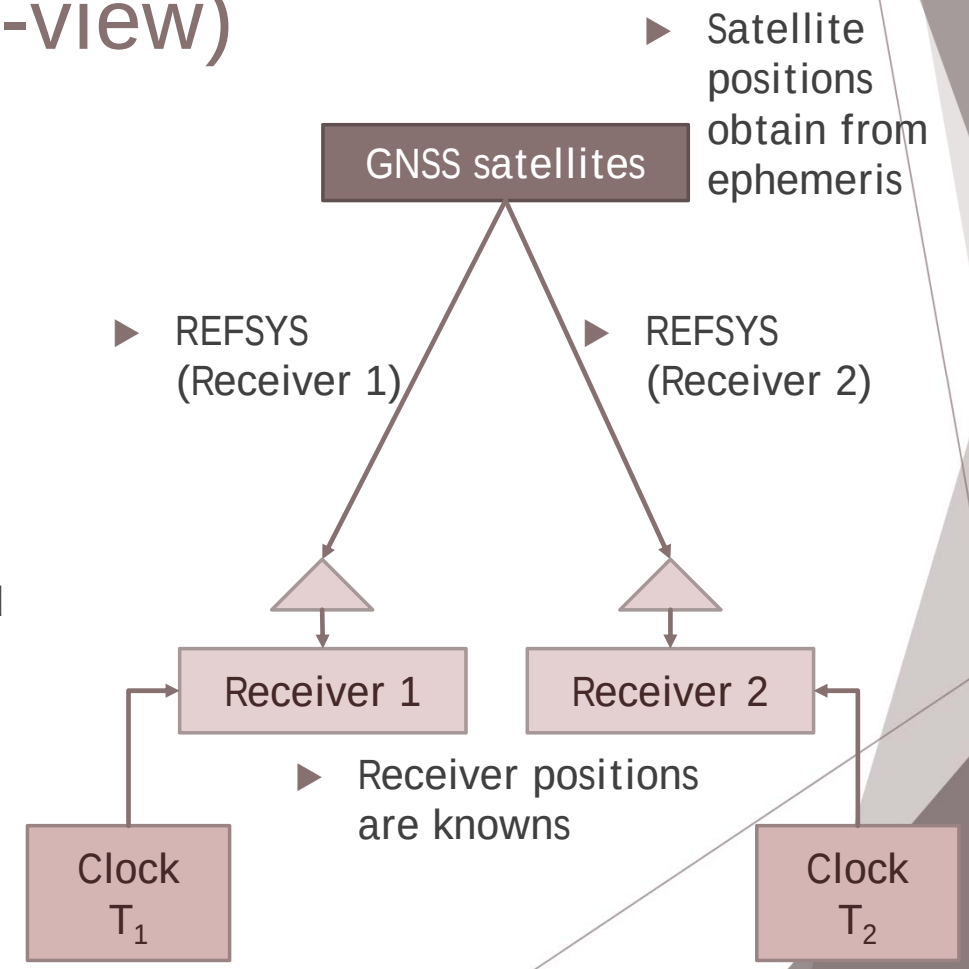
ID	Calibrated date	CAB	REF	INT Galileo E1	INT Galileo E5a	uCal0 (E1)	uCal0 (E5a)	ΔuCAL	Applied MJD
MTTI	16 September 2022	214.7	23.9	12.9	12.4	2.5	2.5	0.0	59947
MTME	16 September 2022	214.5	24.6	16.9	10.9	2.5	2.5	0.0	59947
MTTN	8 July 2023	250.7	35.2	28.4	27.3	2.5	2.5	1.0	60174

https://webtai.bipm.org/ftp/pub/tai/publication/time-calibration/Current/1016-2022_GPSP3-GALE3_NIMT_V1-1.pdf

GNSS time and frequency transfer technique (common-view)

- Two or more receivers observe a single physical source at the same time
- Each receiver measures the arrival time of the signal from the source with respect to its local clock
- Two measurements are subtracted
- Signal path delays are measured and modelled
- System time is GPST, GLONASST, GST, BDST

Common-view = REFSYS(Receiver 1) - REFSYS(Receiver 2)

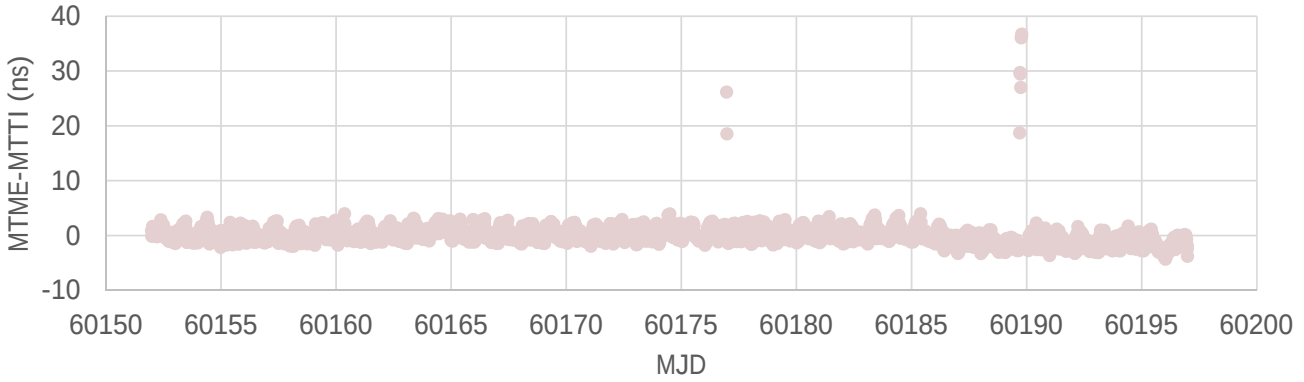


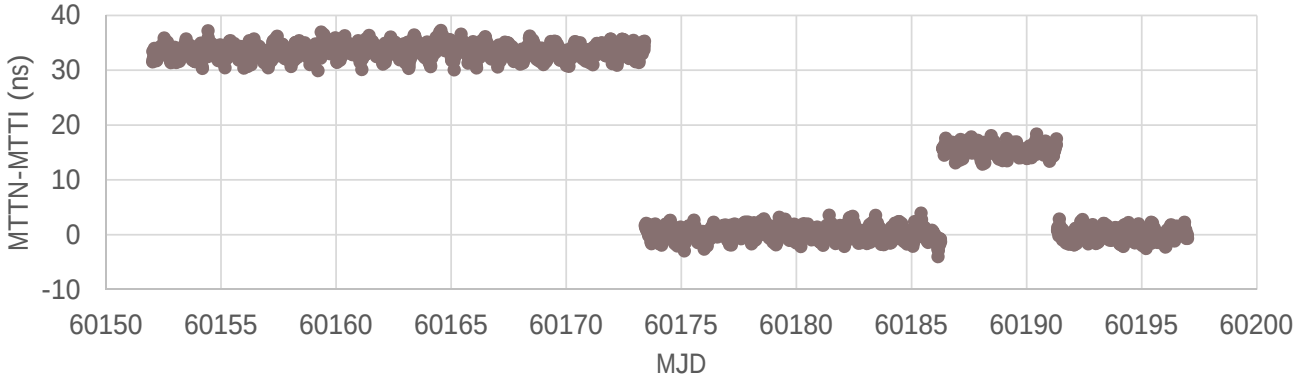
Result comparisons at NIMT

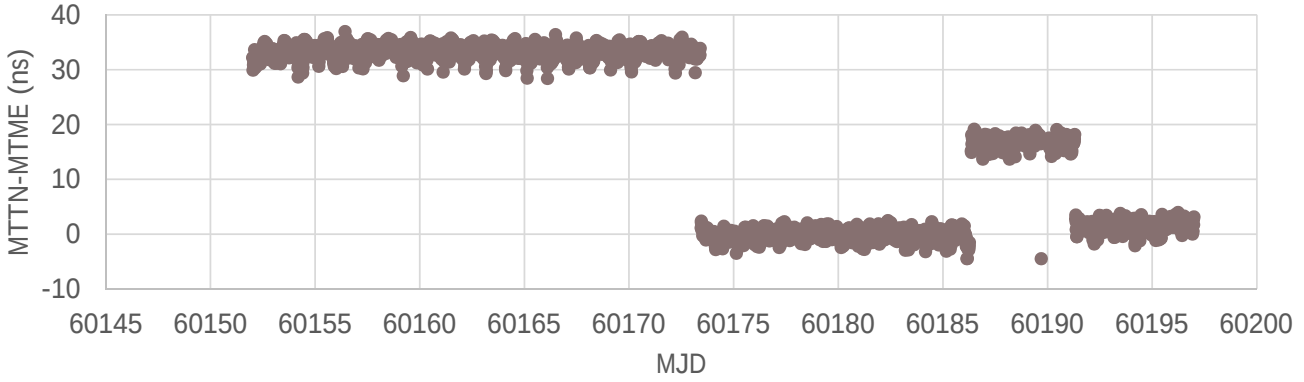
MTTN

- Observed a daily diurnal effect (L3P), GPS only
- MJD 60152-60172: Applying GNSS calibration delay parameters (RG213)
- MJD 60173-60186: Change antenna cable to be a double shielded cable (LMR300)
- MJD 60187-60196: Change antenna cable back to a single shielded antenna cable (RG213)

https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/group2/2022/1016-2022/Calibration%20Transfer%20Report_NIMT.pdf



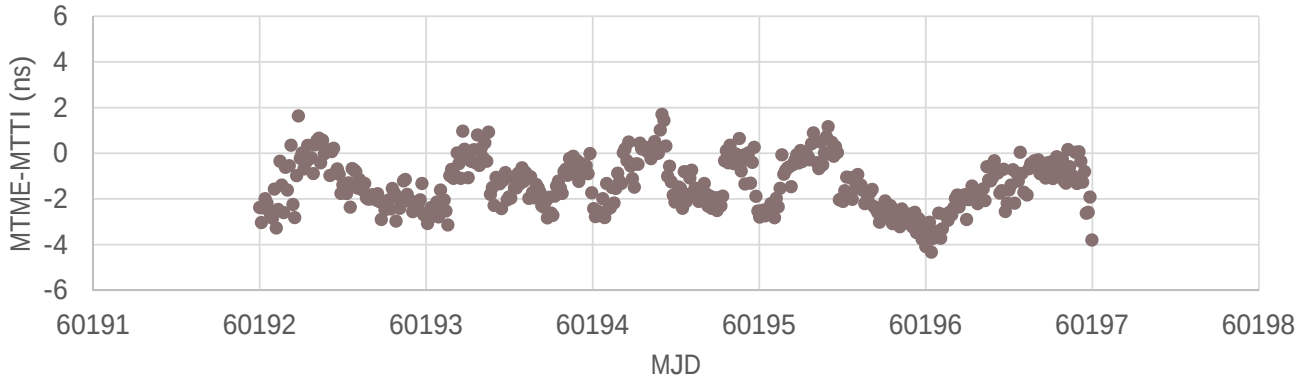


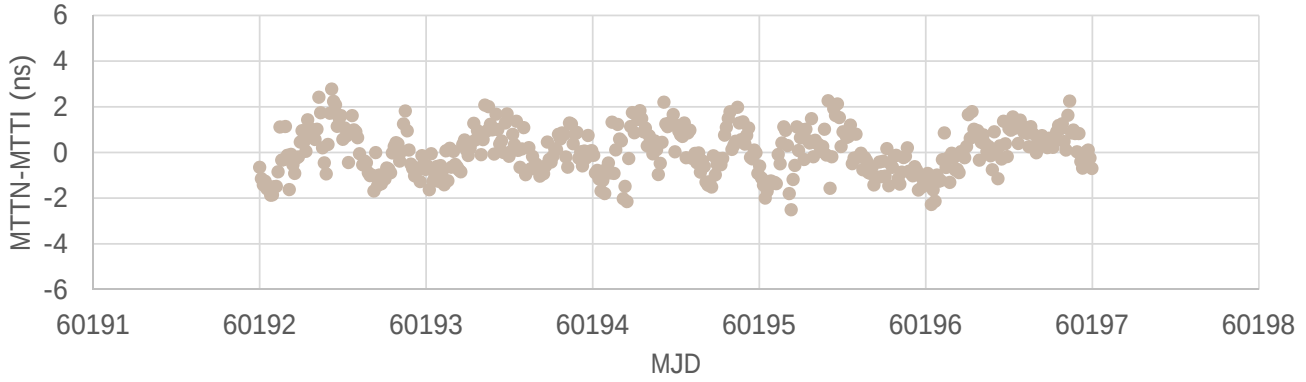


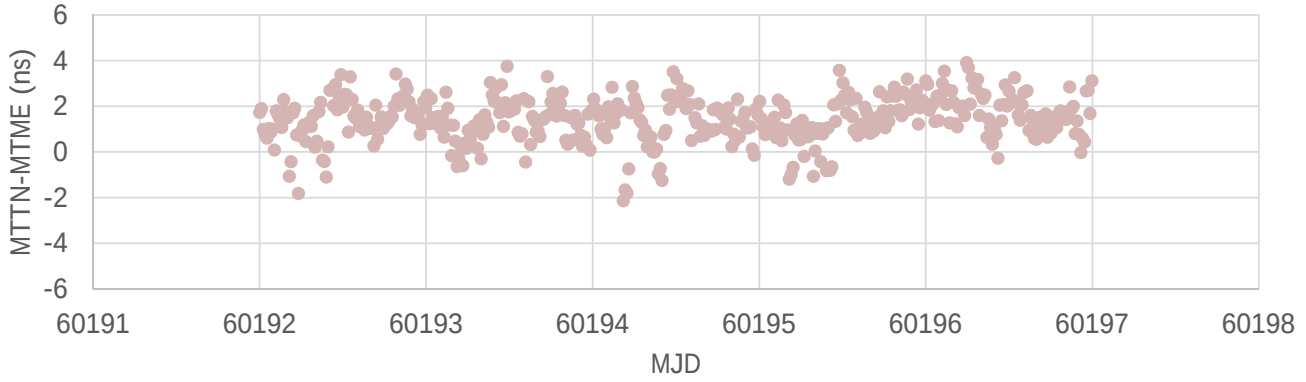
Result comparison at NIMT

MTTN

- MJD 60192-60196: Change antenna cable back to a single shielded antenna cable (RG213)





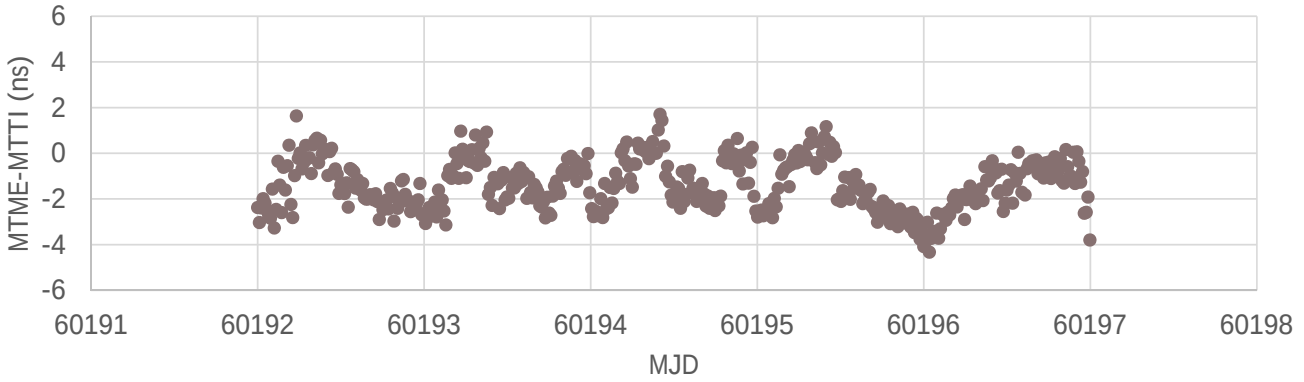


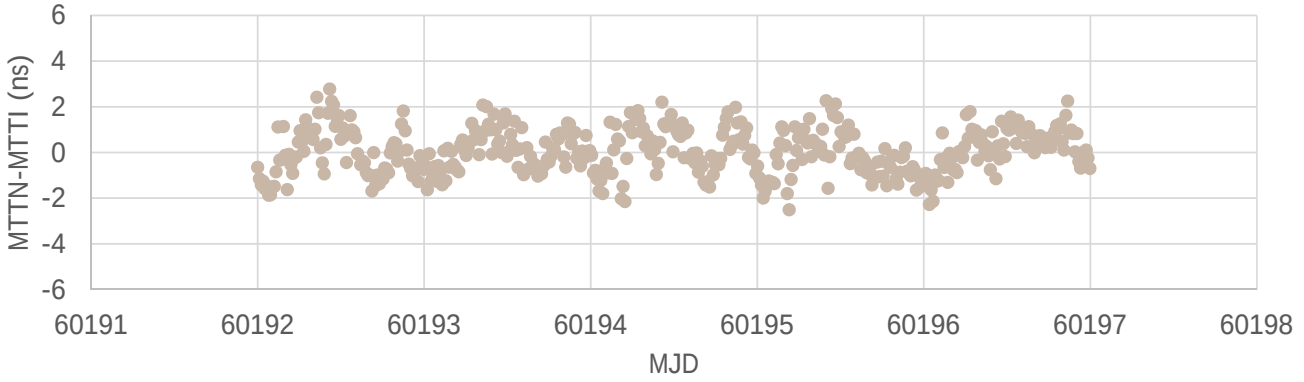
Result comparison at NIMT

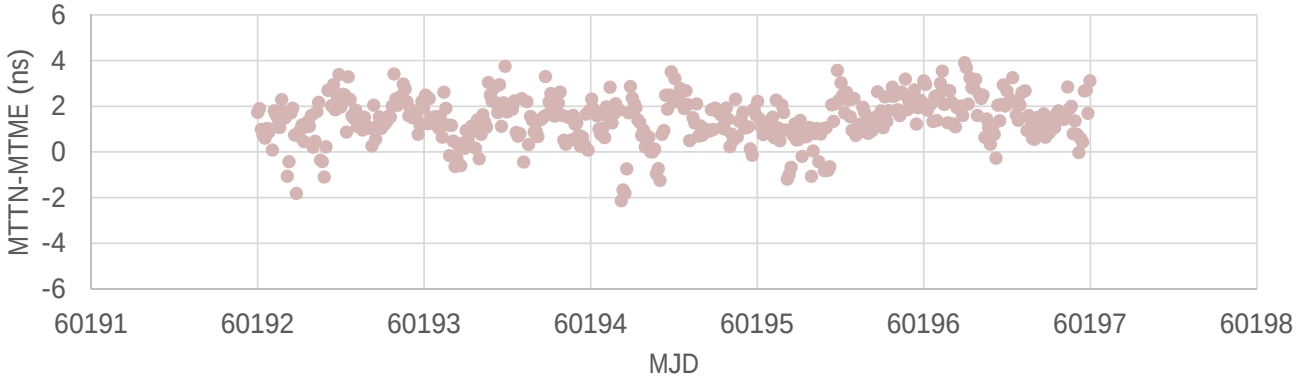
MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTME	MTTI	-1.44	1.05	-3.27	1.63	6	11	L3P
60193	MTME	MTTI	-1.24	0.95	-3.14	0.97	6	11	L3P
60194	MTME	MTTI	-1.02	1.09	-2.82	1.70	6	11	L3P
60195	MTME	MTTI	-1.59	1.24	-3.76	1.16	6	11	L3P
60196	MTME	MTTI	-1.59	1.08	-4.33	0.16	5	11	L3P

MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTTN	MTTI	-0.03	1.10	-1.87	2.77	6	11	L3P
60193	MTTN	MTTI	0.09	0.81	-1.63	2.07	6	11	L3P
60194	MTTN	MTTI	0.19	1.03	-2.15	2.20	6	11	L3P
60195	MTTN	MTTI	-0.26	1.01	-2.51	2.26	6	11	L3P
60196	MTTN	MTTI	0.22	0.88	-2.28	2.25	6	11	L3P

MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTTN	MTME	1.4	0.96	-1.83	3.40	6	11	L3P
60193	MTTN	MTME	1.32	0.90	-0.65	3.74	6	11	L3P
60194	MTTN	MTME	1.23	1.08	-2.15	3.50	6	11	L3P
60195	MTTN	MTME	1.34	1.00	-1.2	3.56	6	11	L3P
60196	MTTN	MTME	1.82	0.87	-0.29	3.9	5	11	L3P







GNSS time and frequency receivers at PTB

- PTBB:
  - Septentrio PolaRx5TR
  - Leica AR25

https://www.bipm.org/en/time-ftp/circular-t

5 - Time links used for the computation of TAI, calibrations information and corresponding uncertainties.

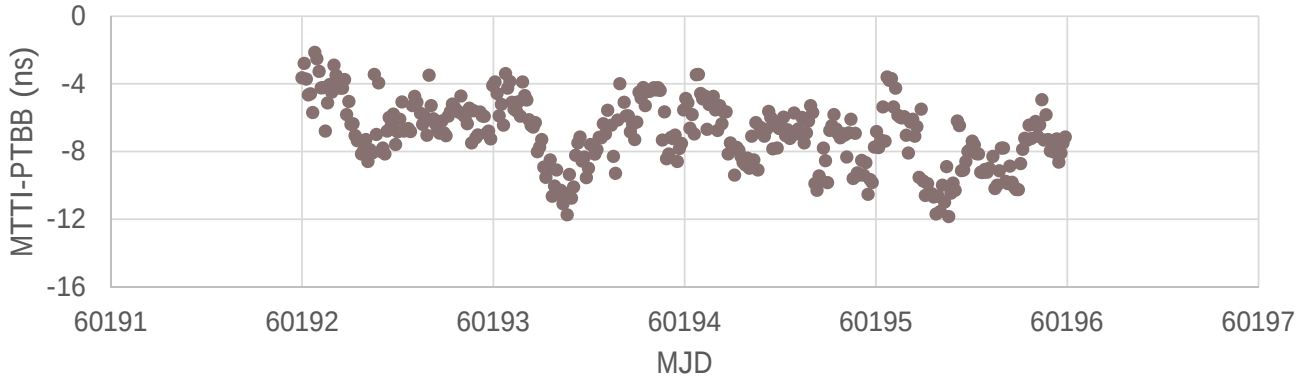
Link	Type	Equipment	Cal_ID1/Cal_ID2	uStb/ns	uCal/ns	uAg/ns	Al/ns	YYMM
AGGO/PTB	GPS P3	TC_2	/PT13	1014-2021/1001-2020	0.7	2.7	1.1	
AOS /PTB	GPSPPP	AO_4	/PT13	1014-2018/1001-2020	0.3	3.2	2.1	
APL /PTB	GPSPPP	AP04	/PT13	NC /1001-2020	0.3	20.0		
AUS /PTB	GPSPPP	AU04	/PT13	1015-2021/1001-2020	0.3	2.7	1.1	
BEV /PTB	GPSPPP	BE1_	/PT13	1016-2021/1001-2020	0.3	2.7	1.1	
BFKH/PTB	GPS MC	MK01	/PT13	NC /1001-2020	1.5	20.0		
BIM /PTB	GPSPPP	BM51	/PT13	2007-2019/1001-2020	0.3	7.3	1.9	
BIRM/PTB	GPSPPP	BI41	/PT13	1016-2018/1001-2020	0.5	3.1	1.9	
BY /PTB	GPS MC	BY46	/PT13	1020-2021/1001-2020	1.5	2.9	1.1	
CAO /PTB	GPS MC	CA__	/PT13	NC /1001-2020	1.5	20.0		
CNES/PTB	GPSPPP	CS23	/PT13	1012-2021/1001-2020	0.3	2.7	1.1	
CNM /PTB	GPS MC	CN00	/PT13	NA_Al /1001-2020	1.5	4.1	2.5	-27.3 0804
CNMP/PTB	GPSPPP	MP1_	/PT13	1011-2017/1001-2020	0.3	5.3	2.5	
DFM /PTB	GPSPPP	DK01	/PT13	1017-2022/1001-2020	0.3	2.7	1.1	
DFNT/PTB	GPS P3	DN__	/PT13	NC_Al /1001-2020	0.7	20.0	10.3	1507
DLR /PTB	NL							
DMDM/PTB	GPSPPP	ZM68	/PT13	1011-2016/1001-2020	0.3	3.7	2.7	
DTAG/PTB	GPSPPP	DT05	/PT13	1012-2019/1001-2020	0.3	3.1	1.7	
ESA /PTB	GPSPPP	ES07	/PT13	1014-2022/1001-2020	0.3	2.7	1.1	
HKO /PTB	GPSPPP	HKO1	/PT13	1011-2018/1001-2020	0.5	3.3	2.2	
IBM /PTB	GPS MC	BO__	/PT13	2005-2016/1001-2020	4.0	7.5	2.6	
ICE /PTB	GPS MC	CE1_	/PT13	NA_Al /1001-2020	3.5	7.3	1.8	-16.5 2111
IDN /PTB	GPSPPP	KI01	/PT13	1017-2018/1001-2020	0.3	3.2	2.0	
IFAG/PTB	GPSPPP	IF20	/PT13	1014-2020/1001-2020	0.3	2.8	1.3	
IGNA/PTB	GPSPPP	IG02	/PT13	NC_Al /1001-2020	0.3	20.0	-7.0	2106
IMBH/PTB	GPSPPP	BH02	/PT13	1013-2022/1001-2020	0.3	2.7	1.1	
INCP/PTB	GPS MC	CP__	/PT13	NC /1001-2020	5.0	20.0		
INM /PTB	GPS MC	IC__	/PT13	NC /1001-2020	2.5	20.0		
INPL/PTB	GPSPPP	IL06	/PT13	2003-2016/1001-2020	0.3	7.5	2.6	
INTI/PTB	GPSPPP	INTI	/PT13	1014-2021/1001-2020	0.3	3.1	1.1	
INXE/PTB	GPSPPP	NXRA	/PT13	1012-2020/1001-2020	0.3	2.9	1.5	
IPQ /PTB	GPSPPP	IP05	/PT13	1017-2021/1001-2020	0.3	2.7	1.1	
JATC/PTB	GPSPPP	JA01	/PT13	1201-2018/1001-2020	0.3	3.3	2.1	
JV /PTB	GPSPPP	JV02	/PT13	1101-2017/1001-2020	0.3	4.6	2.3	
KRIS/PTB	GPSPPP	KRP1	/PT13	1015-2021/1001-2020	0.3	2.7	1.1	
KZ /PTB	GPS P3	KZ04	/PT13	1202-2021/1001-2020	0.7	4.2	1.1	
LRTE/PTB	GPS P3	LRRC	/PT13	NC /1001-2020	0.7	20.0		
LT	NL							
LUX /PTB	GPSPPP	LU02	/PT13	1014-2023/1001-2020	0.3	2.7	1.1	
MASM/PTB	GPSPPP	MN__	/PT13	1019-2018/1001-2020	0.3	3.2	2.0	
MBM /PTB	GPSPPP	ME01	/PT13	NC /1001-2020	0.3	20.0		
MIKE/PTB	GPSPPP	MI04	/PT13	1016-2019/1001-2020	0.3	3.0	1.6	
MSL /PTB	GPS P3	MS01	/PT13	1015-2021/1001-2020	0.7	2.7	1.1	
MTC /PTB	GPS P3	MC02	/PT13	NA_Al /1001-2020	1.0	7.8	3.4	32.6 1411
NAO /PTB	GPS MC	NAT2	/PT13	NC /1001-2020	2.0	20.0		
NICT/PTB	GPSPPP	NC4S	/PT13	1001-2020/1001-2020	0.3	2.0	1.4	
NIM /PTB	GPSPPP	IM15	/PT13	1001-2020/1001-2020	0.5	2.0	1.3	
NIMB/PTB	GPS MC	MB02	/PT13	2001-2015/1001-2020	1.5	7.6	3.0	
NIMT/PTB	GPSPPP	MTTI	/PT13	1016-2022/1001-2020	0.3	2.7	1.1	
NIS /PTB	GPSPPP	IS_5	/PT13	2001-2021/1001-2020	0.4	7.1	1.1	
NMIJ/PTB	GPSPPP	NM0D	/PT13	1015-2022/1001-2020	0.3	2.7	1.1	
NMLS/PTB	GPSPPP	LSM2	/PT13	1011-2023/1001-2020	0.3	1.9	1.1	

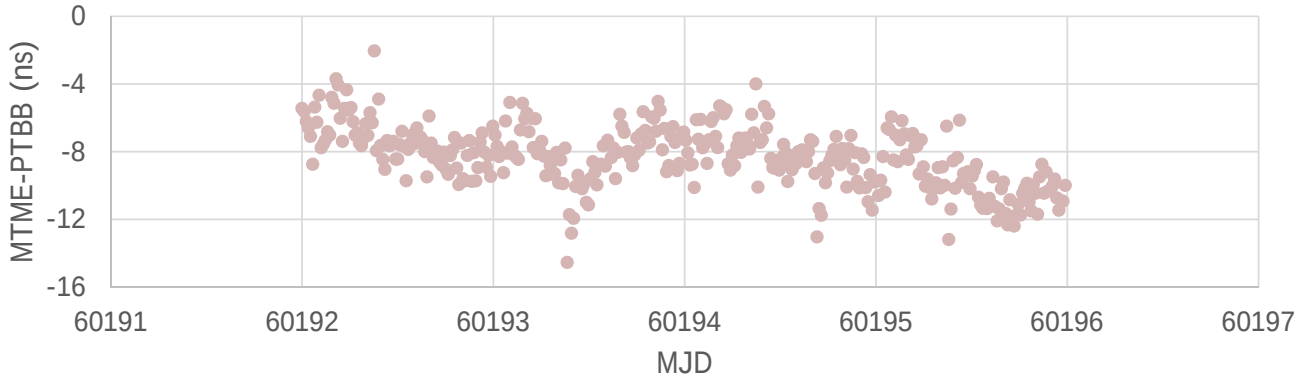
Results comparisons with PTBB (CV)

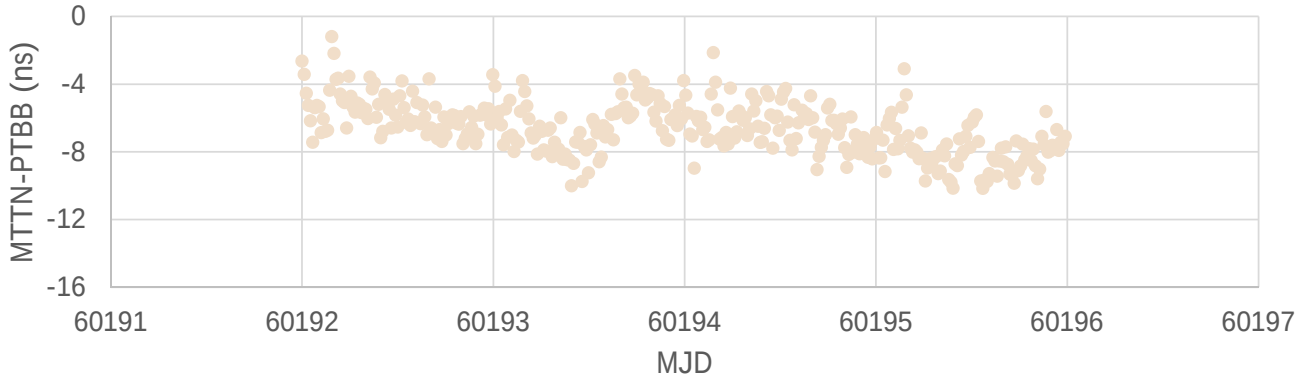
MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTTI	PTBB	-5.79	1.47	-8.60	-2.15	1	5	L3P
60193	MTTI	PTBB	-6.91	2.03	-11.75	-3.40	1	5	L3P
60194	MTTI	PTBB	-7.14	1.58	-10.53	-3.45	1	4	L3P
60195	MTTI	PTBB	-8.06	1.89	-11.85	-3.60	1	5	L3P
60196	MTTI	PTBB	-7.56	1.78	-11.40	-3.00	1	5	L3P

MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTME	PTBB	-7.31	1.50	-9.95	-2.05	1	5	L3P
60193	MTME	PTBB	-8.14	1.71	-14.55	-5.03	1	5	L3P
60194	MTME	PTBB	-8.18	1.54	-13.05	-4	1	5	L3P
60195	MTME	PTBB	-9.71	1.61	-13.20	-5.95	1	5	L3P
60196	MTME	PTBB	-9.20	1.64	-12.55	-5.33	1	5	L3P

MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60192	MTTN	PTBB	-5.58	1.23	-7.53	-1.20	1	5	L3P
60193	MTTN	PTBB	-6.44	1.47	-10.02	-3.50	1	5	L3P
60194	MTTN	PTBB	-6.48	1.26	-9.07	-2.15	1	5	L3P
60195	MTTN	PTBB	-7.98	1.27	-10.18	-3.10	1	5	L3P
60196	MTTN	PTBB	-7.09	1.37	-10.00	-3.37	1	5	L3P





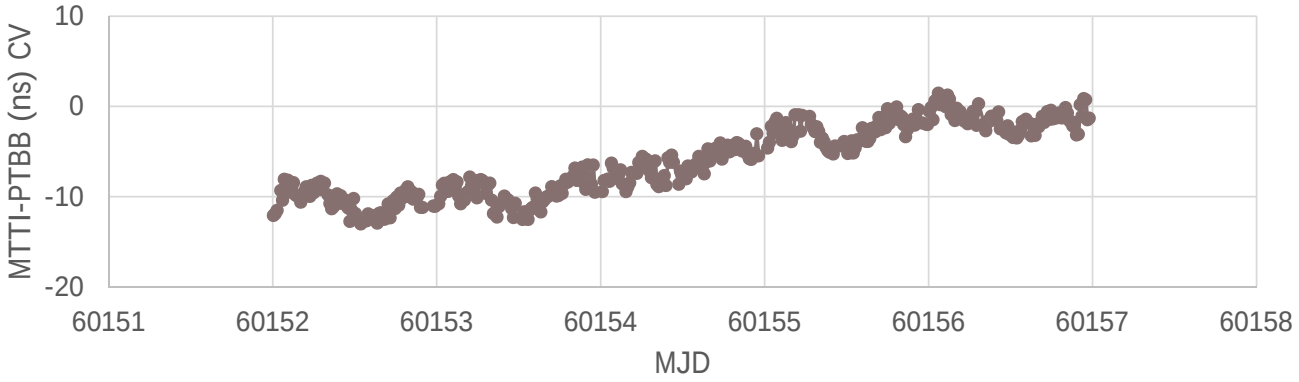


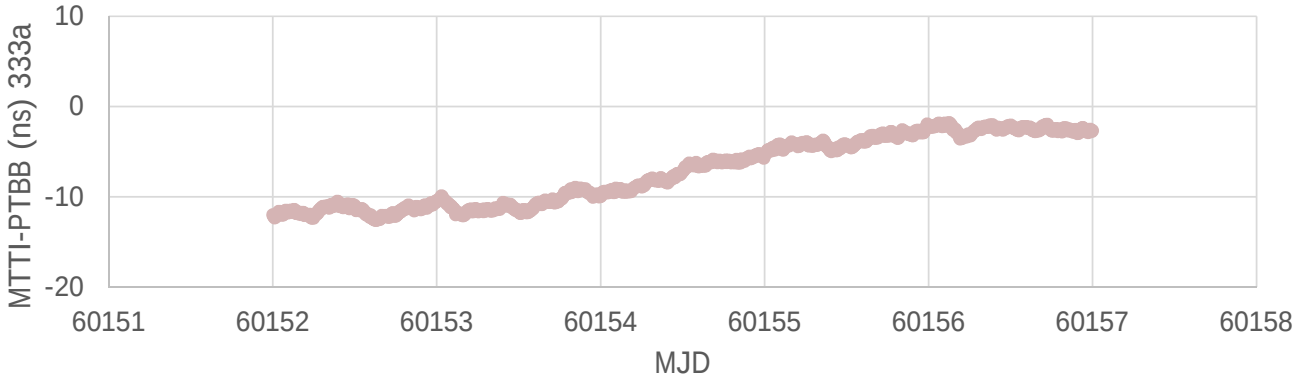
Results comparisons with PTBB(CV and PPP)

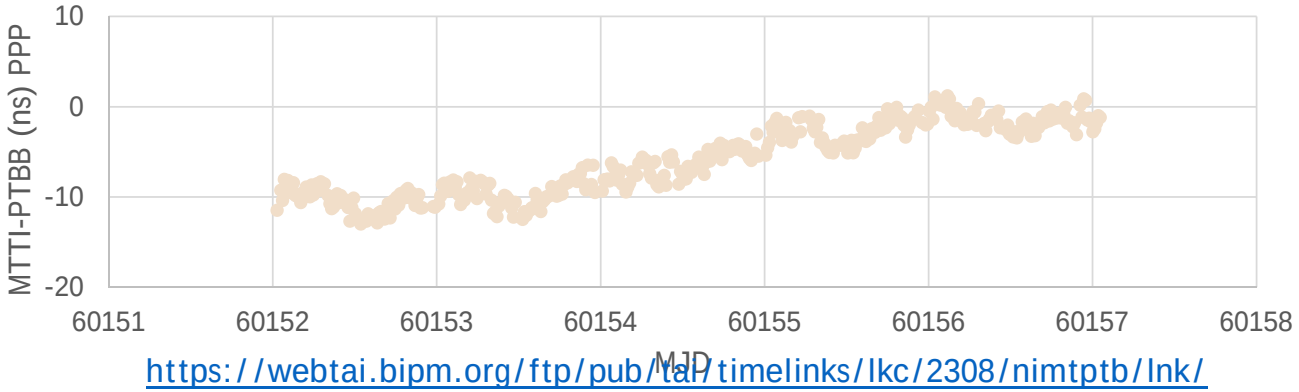
MJD	Rx 1	Rx 2	Mean	SD	Min	Max	Nsat (Min)	Nsat (Max)	Freq
60152	MTTI	PTBB	-10.2	1.68	-14.7	-6.25	1	4	L3P
60153	MTTI	PTBB	-9.64	1.84	-14.15	-4.95	1	4	L3P
60154	MTTI	PTBB	-6.34	2.19	-12.05	-1.65	1	4	L3P
60155	MTTI	PTBB	-2.23	1.86	-5.55	3.15	1	4	L3P
60156	MTTI	PTBB	-1.33	1.32	-4.25	2.00	1	4	L3P

MJD	Rx 1	Rx 2	Mean	SD	Min	Max
60152	MTTI	PTBB	-11.58	0.51	-12.62	-10.54
60153	MTTI	PTBB	-10.78	0.85	-12.12	-8.97
60154	MTTI	PTBB	-7.40	1.42	-9.97	-5.21
60155	MTTI	PTBB	-3.83	0.72	-5.71	-1.91
60156	MTTI	PTBB	-2.50	0.34	-3.61	-1.82

MJD	Rx 1	Rx 2	Mean	SD	Min	Max
60152	MTTI	PTBB	-10.50	1.29	-13.04	-8.09
60153	MTTI	PTBB	-9.63	1.45	-12.54	-6.50
60154	MTTI	PTBB	-6.48	1.52	-9.46	-3.05
60155	MTTI	PTBB	-2.75	1.37	-5.28	-0.06
60156	MTTI	PTBB	-1.38	1.17	-3.51	1.46







https://webtai.bipm.org/ftp/pub/tai/timelinks/lkc/2308/nimtptb/lnk/

Conclusions

- GNSS measurements are used for international and national time transfer to achieve the nanosecond level of accuracy
- GNSS receiver system needs to be regularly calibrated by the national metrology institute to follow the BIPM traceability system
- GNSS receiver, antenna and antenna cable have to be carefully selected and shall remain unchanged after the calibrated parameters are inserted

Thank you for your kind attentions

Acknowledgements: TL, PTB and NIMT