GPS/Galileo Time Transfer with Absolutely Calibrated Receivers

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60th CGSIC - Timing Subcommittee
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Introduction

- GPS is the de-facto standard for global access to precise time and time transfer
- Other GNSS are now in the air
- Multi-constellation / multi-frequency receivers are available

  → improved robustness

  → improved performance

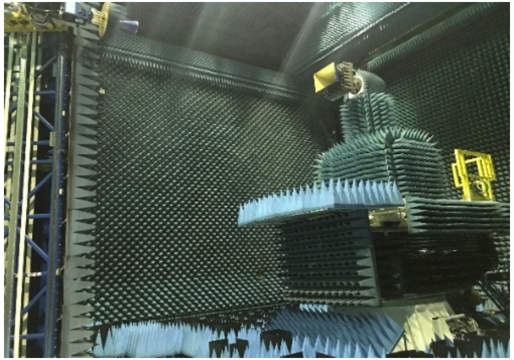
- But: inter-system biases need to be estimated accurately

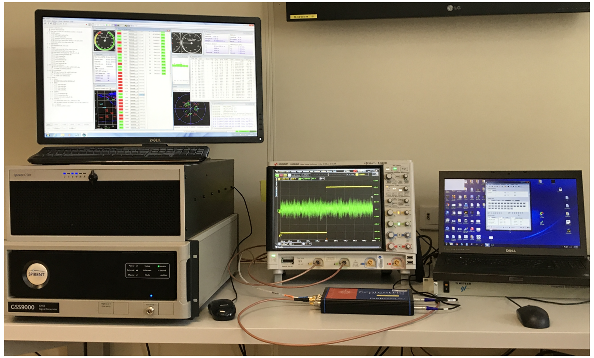
  → HW delays in the receiver chain (Antenna, Receiver…)

- Absolute calibration method was developed for the accurate estimation of HW delays
- Several test campaigns were executed and consistency of results accurately checked

Absolute Calibration

- Accuracy at sub-ns level
- Hardware delays are estimated using simulated signals
  - → Antenna: anechoic chamber + VNA
  - → Antenna cable: VNA
  - → Receiver: GNSS simulator + scope + SDR correlator + PR differences



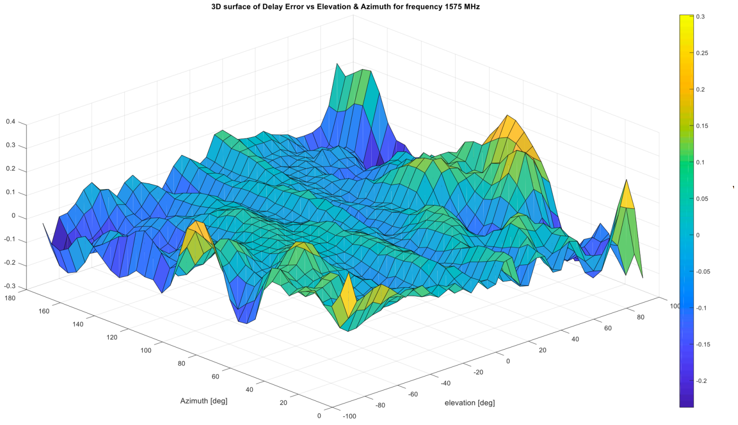


E. Garbin, P. Defraigne, P. Krystek, R. Piriz, B. Bertrand, P. Waller, "Absolute calibration of GNSS timing stations and its applicability to real signals" 2019, *Metrologia* **56** 015010

Absolute Calibration Results

Antenna

- Several test campaigns executed at ESTEC
- 1 antenna also measured independently by CNES, using smaller anechoic chamber

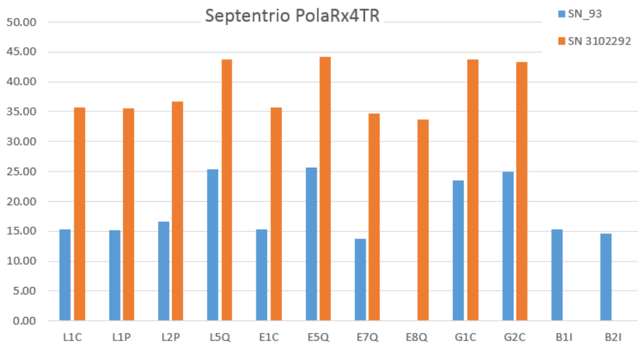


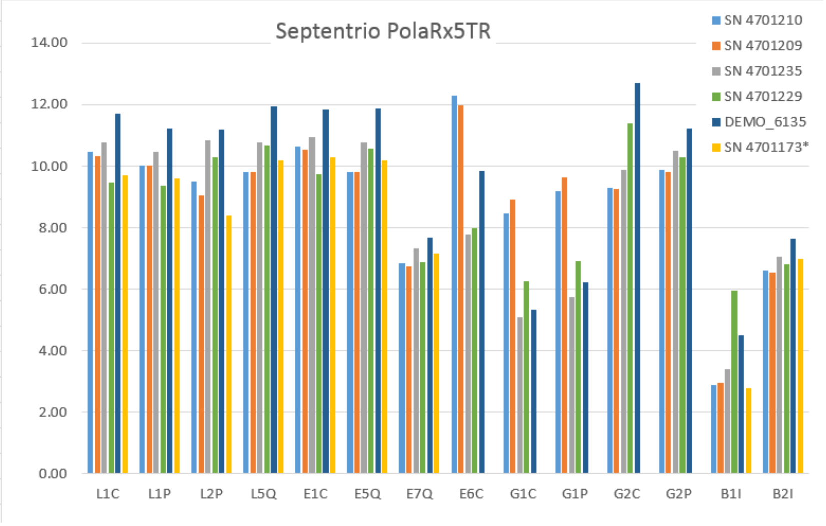
	CNES-ESA (ns)	
	delay difference	combined uncertainty (1 σ)
L1C	0.28	0.66
L1P	0.24	0.68
L2P	0.32	0.54
L5	-0.51	0.54
E1	0.23	0.58
E5a	-0.56	0.55
E5b	0.19	0.54

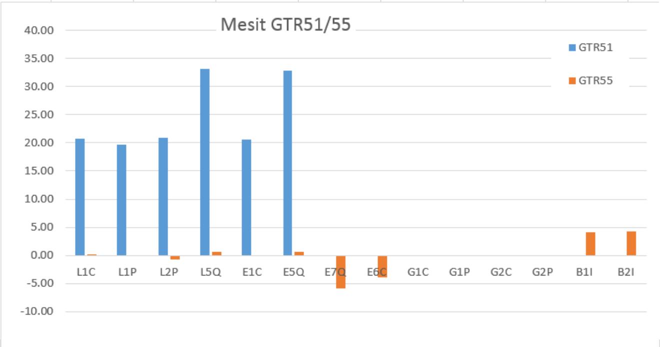
Absolute Calibration Results

Receivers

- Several test campaigns executed at ESTEC on several types of timing receivers







Absolute Calibration Results

Receivers

- One receiver also tested independently by CNES

	CNES-ESA (ns)	
	delay difference	combined uncertainty (1 σ)
L1C	-0.71	0.70
L1P	-0.52	0.70
L2P	-1.01	0.35
L5	-1.09	0.42
E1	-0.38	0.51
E5a	-1.1	0.29

Absolute Calibration

- Absolutely calibrated chains are operating continuously at ESA/ESTEC
- Two full chains were calibrated for the BIPM using the ESA/ESTEC procedure:

BP21

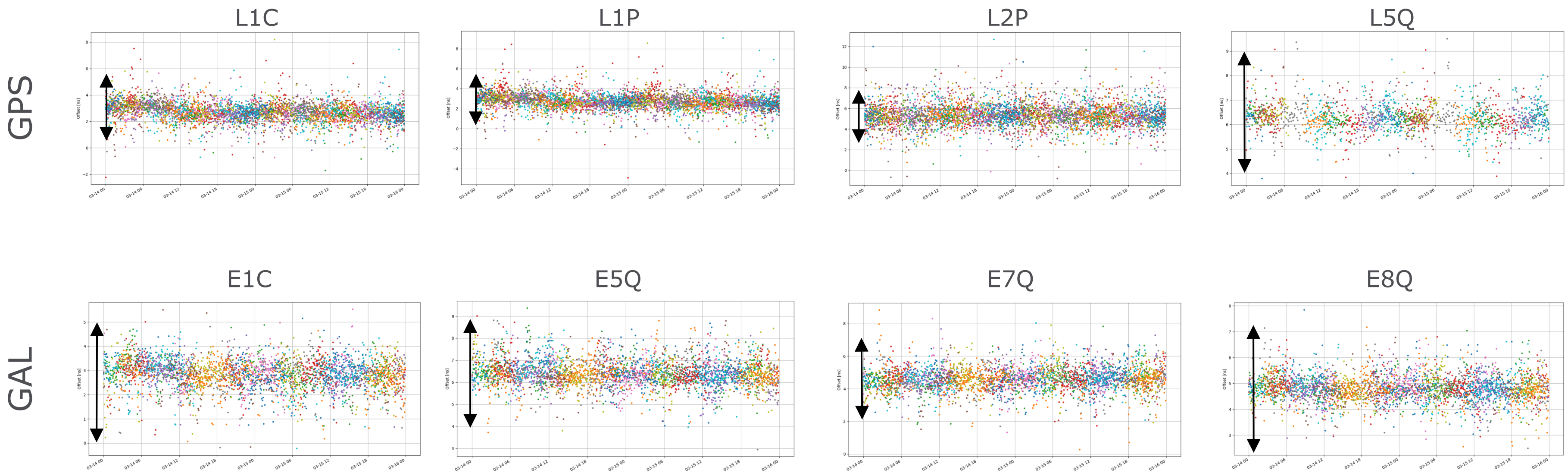
		Antenna APC		Cable		Receiver		TOTAL	
	GNSS Signal	Value	Uncer.	Value	Uncer.	Value	Uncer.	Value	Uncer.
GPS	L1 C/A	20.89	0.54	140.75	0.26	9.48	0.74	171.12	0.95
	L1 P	20.88	0.53	140.75	0.26	9.38	0.52	171.01	0.79
	L2 P	17.93	0.43	140.76	0.25	10.28	0.53	168.97	0.73
	L5	20.22	0.53	140.76	0.25	10.66	0.46	171.64	0.74
Galileo	E1 BC	20.90	0.54	140.75	0.26	9.75	0.47	171.40	0.76
	E6 BC	20.65	0.48	140.76	0.25	7.99	0.55	169.40	0.77
	E5a	20.30	0.51	140.76	0.25	10.58	0.48	171.64	0.74
	E5b	17.75	0.49	140.76	0.25	6.89	0.79	165.40	0.96
	E5 (AltBOC)	18.06	0.41	140.76	0.25	8.59	0.48	167.41	0.68
GLO	G1 C (centre)	21.41	0.53	140.75	0.26	6.26	0.78	168.42	0.98
	G1 P (centre)	21.40	0.53	140.75	0.26	6.90	0.55	169.05	0.81
	G2 C (centre)	17.23	0.55	140.76	0.25	11.38	1.34	169.37	1.47
	G2 P (centre)	17.23	0.55	140.76	0.25	10.29	0.60	168.28	0.85
BD	B1	19.93	0.44	140.75	0.26	5.95	0.62	166.63	0.80
	B2	17.85	0.51	140.76	0.25	6.81	0.59	165.42	0.82

NISG

		Antenna APC		Cable		Receiver		TOTAL	
	GNSS Signal	Value	Uncer.	Value	Uncer.	Value	Uncer.	Value	Uncer.
GPS	L1 C/A	19.98	0.44	311.28	0.33	11.70	0.64	342.96	0.84
	L1 P	20.01	0.43	311.28	0.33	11.22	0.49	342.51	0.73
	L2 P	18.36	0.43	311.28	0.31	11.20	0.50	340.84	0.73
	L5	20.74	0.46	311.28	0.31	11.96	0.47	343.98	0.73
Galileo	E1 BC	19.98	0.44	311.28	0.33	11.86	0.45	343.12	0.71
	E6 BC	19.38	0.45	311.28	0.31	9.83	0.57	340.49	0.79
	E5a	20.78	0.44	311.28	0.31	11.87	0.47	343.93	0.71
	E5b	19.18	0.46	311.28	0.31	7.68	0.75	338.14	0.93
	E5 (AltBOC)	19.97	0.42	311.28	0.31	9.56	0.46	340.81	0.70
GLO	G1 C (centre)	22.18	0.46	311.28	0.33	5.32	0.91	338.78	1.07
	G1 P (centre)	22.19	0.46	311.28	0.33	6.23	0.78	339.70	0.96
	G2 C (centre)	18.32	0.59	311.28	0.31	12.71	1.46	342.31	1.60
	G2 P (centre)	18.31	0.59	311.28	0.31	11.24	0.92	340.83	1.14
BD	B1	19.67	0.44	311.28	0.33	4.51	0.61	335.46	0.82
	B2	19.13	0.48	311.28	0.31	7.63	0.56	338.04	0.80

Operation with real signals

- Operation of multiple absolutely calibrated receivers in common clock (common antenna)
- Compare geometrically-corrected pseudorange difference with absolute delay difference (including antenna, antenna cable and REFDLY)
- Focused on GPS and Galileo



=5ns

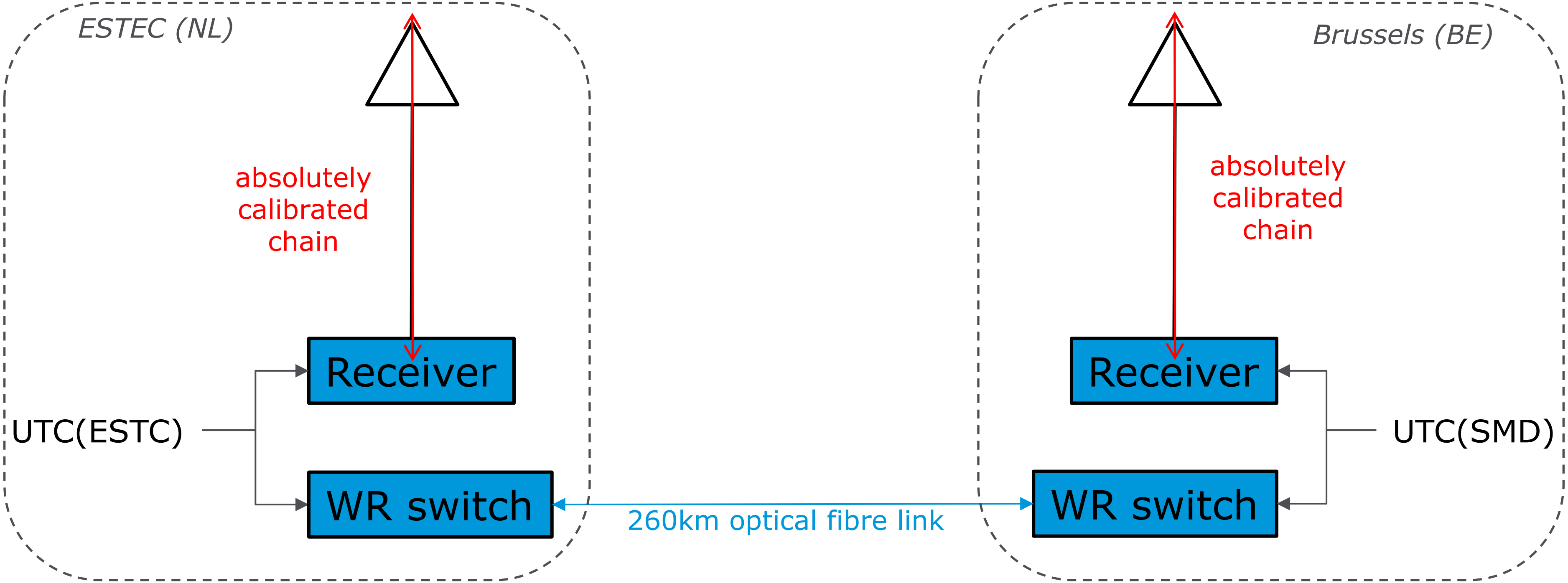
Operation with real signals

- Local common-clock measurements
- Absolute delay difference – pseudorange difference:

GNSS Signal	PolaRx5 – PolaRx5 common antenna (ns)	PolaRx5 – PolaRx5 different antennas (ns)	PolaRx5 – GTR51 common antenna (ns)
L1C	0.11	0.21	1.45
L1P	0.24	-0.16	-0.9
L2P	0.12	-0.34	-0.96
L5Q	0.14	-0.77	-1.34
E1C	-0.08	0.17	0.34
E5Q	0.12	-0.68	-0.62
E7Q	-0.05	-0.98	
E8Q	0.11	-0.59	
E6C	0.03	-0.35	

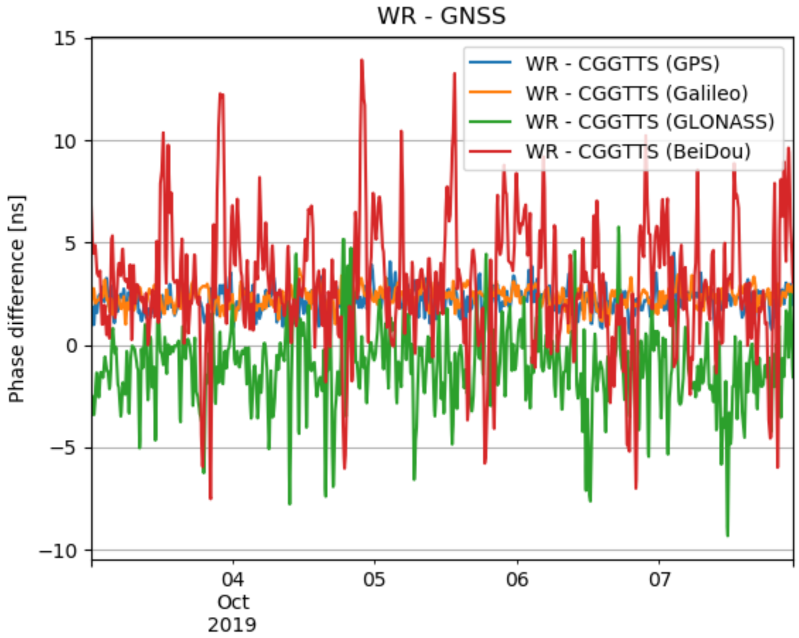
Operation with real signals

- Remote common-clock measurements, connected via White Rabbit link:



Operation with real signals

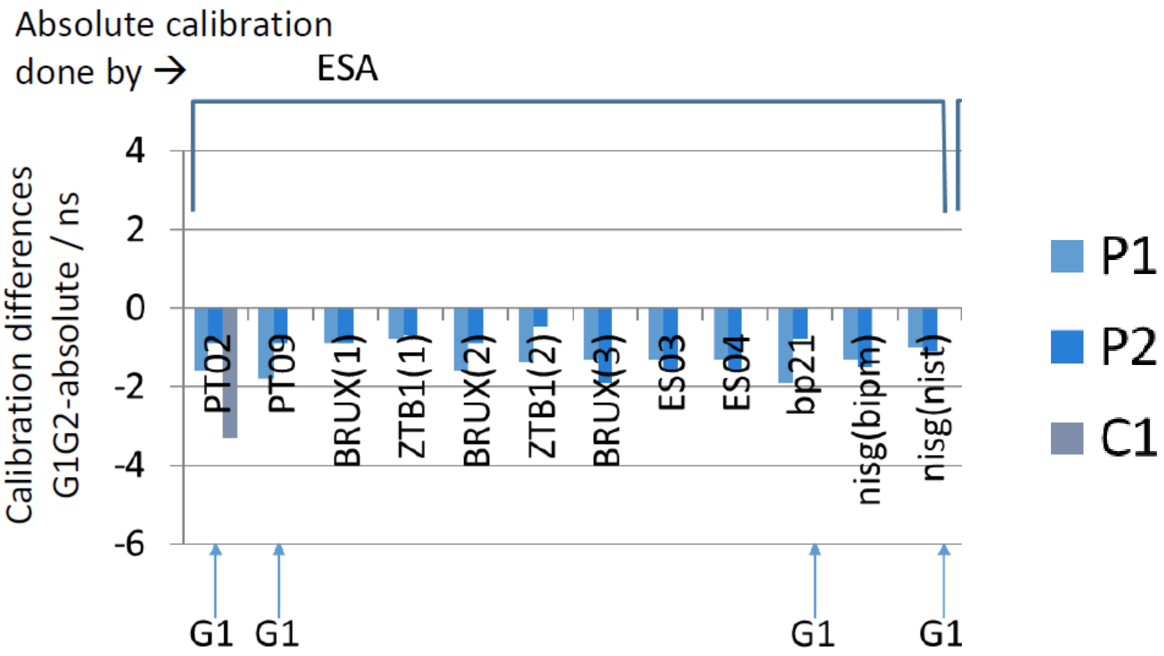
- Remote common-clock measurements, connected via White Rabbit link
- Absolute delay difference – pseudorange difference:



	WR - CGGTTS	
	mean (ns)	stdev (ns)
GPS	2.17	0.57
Galileo	2.35	0.44
Beidou	-1.08	1.82
Glonass	2.96	3.06

Operation with real signals

- Consistency with existing GPS standard



(courtesy: BIPM, G.Petit, P.Defraigne)

In summary

- A simple and accurate procedure for calibration of HW delays in GNSS receiver chains has been developed, executed and validated
- Delays with simulated signals:
    - Sub- to ns internal consistency
    - 1-2ns consistency with independent method (CNES)
- Comparison with real signals:
    - Sub- to ns consistency
- Comparison with existing GPS standard:
    - Few ns consistency

Outcomes

- On the basis of these results (and others), the BIPM CCTF Working Group on GNSS Time Transfer has decided to use the absolute calibration of the BP21 chain as standard for Galileo
- Standard already transferred to G1 laboratories in EURAMET and SIM, on-going for the other areas
- Future G1/G2 trips will include GPS + Galileo

- Note: a G1/G2 trip took place in ESTEC in July 2020. Comparison with absolutely operated chains confirm the reported level of consistency

Thank you

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