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TECHNICAL NOTE

Absolute Calibration Report of GNSS Chains for the BIPM

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EXECUTIVE SUMMARY

As part of an agreement between the BIPM and ESA, an absolute calibration campaign of two GNSS receiver chains was executed at ESA/ESTEC over the period December 2018 to February 2019. This campaign was based on methods and tools developed and facilities available at ESA/ESTEC. Calibration included GPS, Galileo, Glonass and Beidou observables. Both chains include a GNSS Antenna, an RF antenna cable and a GNSS Receiver.

The tables below report the obtained final calibration results and associated 1-sigma uncertainties (in ns) for all calibrated GNSS observables.

Chain #1 ("BIPM Chain")

		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

Chain #2 ("NIST Chain")

		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

Note: the above estimated uncertainty values relate to the absolute calibration measurements, i.e. using "perfect" simulated signals (CW and GNSS). As indicated in RD02, when using real signals, those values shall be increased typically by one to two ns, depending on the GNSS signal.

1 INTRODUCTION

This document reports the results of the absolute calibration campaign executed in December 2018 to February 2019 on two GNSS receiver chains in the frame of an agreement between ESA/ESTEC and the BIPM.

These calibrations were performed in the ESA/ESTEC Laboratory facilities by ESA personnel using methods and tools initially developed and validated in the frame of an R&D contract under the ESA/EGEP Programme with the company GMV and the Royal Observatory of Belgium. These methods rely on the individual measurements of the absolute delays in the 3 elements of the receiver chain (antenna, antenna cable and receiver) for GPS, Galileo, Glonass and Beidou signals.

This report summarises the measurement method and associated data processing (section 3), derives the uncertainty budget (section 4), presents the GNSS chains that have been calibrated (section 5), and finally presents the measurement results (section 6).

2 REFERENCES

2.1 Applicable Documents

AD01 "ESA-BIPM collaboration to foster the use of Galileo in UTC", Feb 2019

2.2 Reference Documents

RD01 AKAL Final Report - AKAL-GMV-FRe, 23/05/2018

RD02 "Absolute calibration of GNSS timing stations and its applicability to real signals", E.Garbin *et al* 2019 *Metrologia* **56** 015010

RD03 "Cross-calibrations of multi-GNSS Receiver Chains", P.Waller et al, 2019, EFTF-IFCS.

RD04 "Absolute group delay characterization of GNSS antennas for reference receiver chains", E.Garbin et al. 2018, ION-PTTI

RD05 RINEX, The Receiver Independent Exchange Format, v3.03, 14/07/2015

RD06 "Zero-doppler pseudorange biases", JM.Sleewagen et al., 2018, ION-PTTI

RD07 "Guidelines on the Evaluation of Vector Network Analysers (VNA)", Euramet Calibration Guide No.12, V3.0, 2018

2.3 Acronyms

AGC	Automatic Gain Control
APC	Antenna Phase Centre
ARP	Antenna Reference Point
BIPM	Bureau International des Poids et Mesures
CATR	Compact Antenna Test Range
CW	Continuous Wave
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
GNSS	Global Navigation Satellite System
HERTZ	Hybrid European RF and antenna Test Zone
IGS	International GNSS Service
NIST	National Institute of Standard and Technologies
PCV	Phase Centre Variation
PSD	Power Spectral Density
RF	Radio-Frequency
SGH	Standard Gain Horn
VNA	Vector Network Analyser

2.4 Definitions

In this report, the term "GNSS Signal" refers to the combination code-frequency of a given GNSS signal (e.g. P-code on L1 frequency for GPS or B,C-code on E1 frequency for Galileo).

3 MEASUREMENT METHODS

The absolute calibration is based on piece-wise measurements of the electrical delays in the three elements of the GNSS chain (antenna, antenna cable and receiver) using representative artificial signals. CW signals are used for the antenna and antenna cable measurements, simulated GNSS signals are used for the receiver measurement. The basic measurement method and associated tools were developed under a prior activity (RD01, RD02), and have been further improved and validated (RD03) as part of several additional test campaigns.

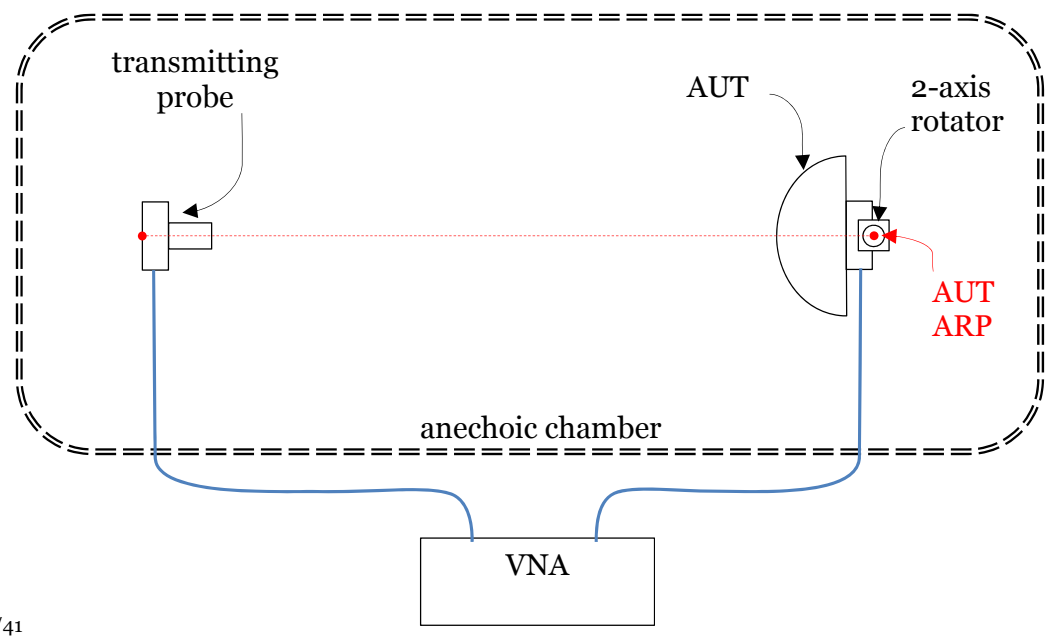
3.1 Antenna

The antenna calibration is performed in the ESTEC HERTZ facility, a 25m x 16m x 11m anechoic chamber equipped with spherical near-field measurement system and guaranteeing reduced room scattering and reflections.

The antenna under test is mounted on a numerically-controlled 2-axis rotator allowing for full 4π steradian scan centred on the Antenna Reference Point. The rotator is equipped with two rotary joints to avoid the motion of cables during azimuth and elevation scans.

The antenna under test is illuminated by a dual polarised transmitting probe whose radiation pattern is dominated by first-order spherical mode. Laser tracker is used to align the probe-to-antenna axis and measure the geometrical distance between their respective reference points. The antenna under test is positioned so that its ARP coincides with the spherical near-field scanning centre of the transmitting probe, which is also the origin of the measurement coordinate system.

The transmitting probe and the antenna under test are connected through phase-stable coaxial RF cables to the two ports of a Vector Network Analyser. A bias-T is introduced on the cable to the antenna under test to supply its internal low-noise amplifier. A simplified diagram of the measurement set-up is depicted below.



In a first step, the AUT is replaced by a high directivity Standard Gain Horn (SGH) antenna whose boresight phase characteristics over the frequency band of interest has already been measured (RD04). VNA transmission (S12) measurements are then recorded (for both vertical and horizontal polarizations) over the carrier frequency band of interest as the SGH is rotated over the full sphere. These spherical near-field measurements are then mathematically transformed to far-field measurements (also taking into account probe correction and SGH phase insertion), thereby guaranteeing full far-field conditions at the AUT locations.

In a second step, the SGH is replaced by the antenna under test and VNA S12 measurements are recorded over the carrier frequency bands of interest as the AUT is rotated in azimuth and elevation. The contribution of the AUT is then obtained by subtracting from these new measurements the ones obtained at the end of the first step.

The group delay of the AUT for each GNSS signal and for each elevation/azimuth point is then computed as a weighted average over the signal frequency band, with a weight corresponding to the ideal normalised PSD of that specific GNSS signal. Finally, the single group delay value for each GNSS signal is obtained by uniform average over azimuth and elevation with a 10° masking angle.

It must be noted that the so-obtained antenna group delays are defined from the AUT connector to the ARP, while in GNSS time transfer, antenna group delays are instead referred to the Antenna Phase Centre (APC).

The coordinates of the APC at a given frequency and in a reference frame centred on the ARP are therefore computed from the VNA measurements as the centre of the sphere that minimises its difference to the measured equiphase contour. The group delays referred to the APC are then computed by applying the geometrical correction from ARP to APC.

3.2 Antenna Cable

The antenna cable calibration is performed in the ESTEC Microwave Laboratory.

The group delays of the cable under test are measured by conventional Vector Network Analyser technique, using either transmission (S12 or S21) or reflection (S11 or S22) modes. In both cases, the cable is kept rolled.

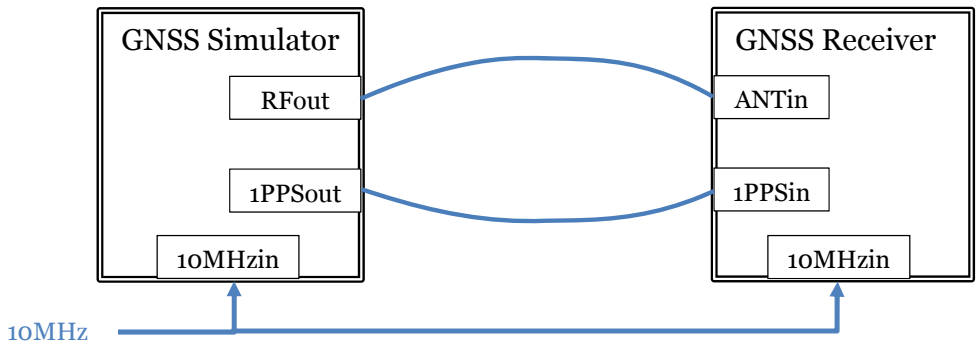
Following the conventional technique, the VNA system is calibrated using calibration kit over the frequency range of interest prior to the cable measurement. Amplitude and Phase measurements with the cable under test are then collected over the frequency range of interest.

Group delays are then computed as an average over the full measured frequency band. Due to the high quality and very low dispersion of the cables used, the averaging over the individual GNSS signal bandwidth (possibly weighted by the normalised PSD of the signal) is not significantly different from the averaging over the full frequency band and therefore this correction is not applied.

Note: the antenna cable group delays can also be determined using simulated GNSS signals when combined with the receiver measurement (see next section). The agreement between the results obtained with both methods has demonstrated to be below the combined measurement uncertainties.

3.3 Receiver

The receiver calibration is performed in the ESTEC Radio-Navigation Laboratory. It is based on the use of simulated signals generated by a GNSS Simulator using the set-up depicted in the figure below.



The GNSS simulator and receiver under test are both connected to the same external frequency reference signal. The antenna port of the receiver is connected to the RF signal generated by the GNSS simulator through high quality coaxial cable. Likewise, the 1pps input of the receiver is connected to the 1pps generated by the GNSS simulator with similar coaxial cable. The GNSS simulator is configured to activate all GNSS satellites and all GNSS signals simultaneously, with no ionosphere, no troposphere and on-board clock errors set to zero.

Prior to the receiver measurement, the GNSS simulator system is calibrated. It consists in measuring, for each GNSS signal, the delays between the rising edge of the first chip of the signal and the rising edge of the 1pps signal, both measured at the end of the cables that will be connected to the receiver. To do so, these two ends of the cables are connected to a wideband – high sampling rate digital oscilloscope that records simultaneously the RF and 1pps signals. While the rising edge of the 1pps signal is easily identified in the data records, a dedicated correlator tool is used to identify the maximum correlation peak of all individual GNSS signals (corresponding to the rising edge of the first chip).

After the GNSS simulator has been calibrated, the two ends of the cables are connected to the receiver and pseudoranges are being collected and recorded. The receiver delays for each GNSS signal is then computed by subtracting to the so-obtained pseudoranges the geometrical range and the simulator calibration values, and by adding the delay of the external 1pps signal to the receiver clock ("latching delay").

In practice, all GNSS satellites and signals are generated by the simulator simultaneously but to simplify the correlation process, one satellite (PRN) per GNSS is set to geostationary orbit so that their signals are measured with zero-Doppler. To mitigate the possible effects of PRN-dependant biases due to zero-Doppler signals (RD06), the receiver delays are averaged over 14 runs with difference PRNs (14 is also the minimum number of runs to cover all Glonass frequencies). Each run has a duration of one hour and only the last 40min are used to guarantee stabilisation of receiver operation.

4 UNCERTAINTY BUDGETS

In general, the uncertainties related to VNA measurements are computed from the uncertainties in phase measurement reported in the VNA datasheets (taking into account the actual frequency, power received, IF bandwidth and averaging factor values) according to the formula $\Delta\Phi(°)/360/\Delta f$, where $\Delta\Phi(°)$ is the specified uncertainty on phase measurement and Δf is the frequency resolution of the measurement. It is considered to include both the systematic and statistical uncertainties of the VNA measurement.

All reported uncertainties refer to the 1-sigma value.

4.1 Antenna Measurements

The sources of error in the antenna measurements are:

(1) VNA measurements during spherical near-field data acquisition (step1). There are two sets of measurements (horizontal and vertical polarisations). The uncertainty in the near-field to far-field transformation is considered negligible.

(2) VNA measurements during AUT data acquisition (step1). There are two sets of measurements (horizontal and vertical polarisations).

(3) SGH measurements as reported in RD02.

(4) Spurious reflections (on the wall, antenna set-up, mismatches…). This is estimated as the maximum measured group delay differences as the probe-to-antenna distance is varied over 1 carrier wavelength. Such characterization was reported in RD02 for a similar set-up under worse conditions (smaller anechoic chamber, poorer absorber set-up…). This is therefore considered a very conservative value in the present situation.

(5) Temperature effects: all measurements were performed in a stable environment (20°C ± 1°C, 45% ± 10%) but no sensitivity to temperature was measured. A conservative value of 100ps is assumed.

(6) Probe-to-antenna distance and alignment measurement with a laser tracker, with typical distance error below 1mm and alignment error below 0.1°.

(7) Group delay averaging over azimuth and elevation. This is signal dependant and lie in the range of 100ps to 300ps.

(8) Error on APC estimation (only valid for Group Delays referred to APC). Comparisons with values reported in antex files agree to within few cm. A conservative value is 10ps.

The uncertainty budget for antenna measurement is summarised in the table below.

Antenna	Type	Description	Typ. Value
	A/B	VNA measurement during step 1 (H+V pol)	140ps
	A/B	VNA measurement during step 2 (H+V pol)	140ps
	B	SGH group delay	132ps
	B	Spurious reflections	300ps
	B	Temperature effects	100ps
	B	Probe-to-antenna distance/alignment	4ps
	B	Averaging over azimuth/elevation	100ps to 300ps
	B	APC estimation	10ps
		TOTAL	**410ps to 500ps**

4.2 Antenna Cable Measurements

The sources of error in the antenna cable measurements are:

(1) VNA measurements during cable characterization, depends on the test conditions and is extracted from VNA datasheet.

(2) Effects due to cable deformation. Tests were performed for similar type and length of cables in RD01, leading to a conservative value of 150ps.

(3) Temperature effects: group delay sensitivity to temperature was characterized in RD01 for similar cable type and length over a temperature range of -15°C +45°C. A conservative value of 10ps is allocated to this effect.

(4) Connectors/Adapters. Some cable measurements included intermediate steps to measure the delays of connector adapters. A conservative value of 200ps is estimated.

The uncertainty budget for antenna cable measurement is summarised in the table below:

Cable	Type	Description	Typ. Value
	A/B	VNA measurement	100ps to 200ps
	B	Cable deformation	150ps
	B	Temperature effects	10ps
	B	Connector/Adapters	200ps
		TOTAL:	**270ps to 320ps**

4.3 Receiver Measurements

The receiver delay measurements is a combination of simulator delay measurements, pseudorange measurements and latching delay measurements. Errors affecting those measurements are summarised below.

Simulator delays measurements

(1) Measurement noise. It is computed as the maximum over the 14 runs of the standard deviation to the mean of the 3 simulator delay measurements.

(2) Oscilloscope resolution. A sampling rate of 10GSps leads to a value of 100ps.

(3) Trigger error. The waveform of the 1pps trigger signal and the oscilloscope leads to a conservative value of 13ps.

(4) Correlator low-pass filter effects. Tests and characterization using the same oscilloscope have demonstrated a possible variation on the position of the correlation peak due to low-pass filter design of up to 100ps.

(5) Simulator configuration/RF power. When calibrating the simulator, the output power of the GEO satellite is increased to ease the cross-correlation process. Tests have demonstrated that sensitivity to power level can reach a maximum of 100ps.

Pseudorange measurements

(1) Pseudorange noise and variations during the measurement run. It is computed as the maximum over the 14 pseudorange measurement runs of the standard deviation to the mean of the run.

(2) Receiver inter-channel biases. A conservative value of 10ps is set based on measurements on a receiver of the same type.

(3) Thermal sensitivity. Temperature sensitivity measured on a receiver of the same type (~80ps/°C) and a control of the room temperature at the level of +/-1°C lead to a conservative value of 200ps.

(4) AGC gain level. A conservative value of 100ps is set based on measurements on a receiver of the same type.

(5) PRN-dependant biases. This is computed as the standard deviation to the mean over the 14 pseudorange measurement runs.

Latching delay measurements

(1) Measurement Noise. It is estimated as the 1 sigma over 14 runs of the auto-calibrated latching delay.

(2) Auto-calibration error. This is the maximum offset over several runs of the offset between the auto-calibrated delay and the delay measured with a TIC (SR620).
(3) TIC measurement error: this is the error on the TIC reading during latching delay measurement.
(4) Auxiliary cable delay error: this is the error on the delay of the auxiliary cable used for the latching delay measurement.

Element	Type	Description	Typ. Value
Simulator			
(1)	A	Measurement noise (std over 14 runs)	60ps to 500ps
(2)	B	Oscilloscope resolution (setting: 10GSps)	100ps
(3)	B	Oscilloscope trigger error (datasheet)	13ps
(4)	B	Correlator low-pass filter effects (tests)	100ps
(5)	B	Simulator configuration/RF-power (test)	100ps
Pseudorange			
(1)	A	Pseudorange Noise (max std over the 14 runs)	60ps to 700ps
(2)	B	Inter-channel biases (test)	10ps
(3)	B	Thermal sensitivity (test)	200ps
(4)	B	AGC-level (test)	100ps
(5)	B	PRN-dependant biases (std over the 14 runs)	100ps to 1.3ns
“Latching delay”			
(1)	A	Measurement noise	40ps
(2)	B	Auto-calibration error	300ps
(3)	B	TIC measurement error	100ps
(4)	B	Auxiliary cable delay error	100ps

5 GNSS CHAINS

The tables below include all details of the two calibrated chains.

5.1 BIPM Chain

BIPM Antenna	
Manufacturer	Septentrio BV
Type	PolaNt Choke Ring B3/E6
IGS Name	SEPCHOKE_B3E6
Serial Number	5253
Weight / Diameter	5kg / 376mm
Thread	5/8”
Connector	N-Type Female
Input Voltage	+10V
BIPM Antenna Cable	
Manufacturer	Times Microwave systems
Type	LMR-195
Approximate length	~34m
Attenuation(Total Length)	16.22 (1500MHz)
Diameter (outer)	4.95 mm
Connectors	N-Type Female (adapter) - TNC
Impedance	50 Ohm
v/c	80%
BIPM Receiver	
Manufacturer	Septentrio BV
Type	PolaRx5 TR
BIPM Label	BP21
Serial Number	4701229
SSID	PolaRx5TR-3022484
rxfullid	SN17323022484
Firmware version	5.1.2
os version	2.3.2

5.2 NIST Chain

NIST Antenna	
Manufacturer	Novatel
Type	GNSS-750
IGS Name	NOV750.R4
Serial Number	01017982 (HW Rev: 4.01)
Weight / Diameter	7.6kg / 380mm
Thread	5/8”
Connector	N-Type Female
Input Voltage	3.3V to 12V (100mA typ.)
NIST Cable	
Manufacturer	Heliax
Type	LDF2-50
Approximate length	~80m
Attenuation(Total Length)	3.00 (1250MHz), 3.32 (1500MHz)
Diameter (outer)	11.176 mm
Connectors	N-Type Female (adapter) - TNC
Impedance	50 Ohm
v/c	88%
NIST Receiver	
Manufacturer	Septentrio BV
Type	PolaRx5 TR
NIST Label	none
Serial Number	DEMO_6135
SSID	PolaRx5TR-3034704
rxfullid	SN18223034704
Firmware version	5.2.0
os version	5.0.0

6 MEASUREMENT RESULTS

All reported uncertainties are the 1-sigma values.

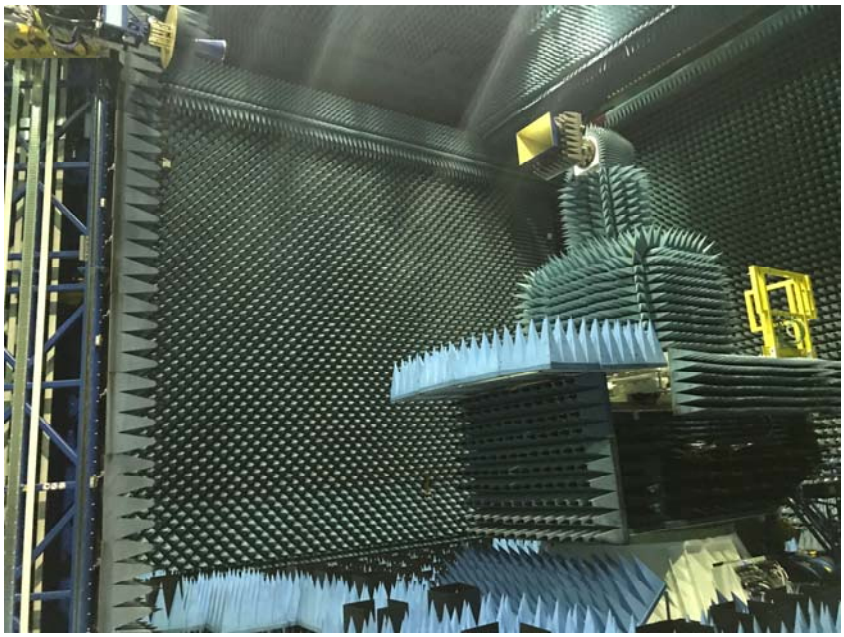
6.1 Antenna

6.1.1 Test Conditions

The antenna test equipment and configuration is summarised in the table below.

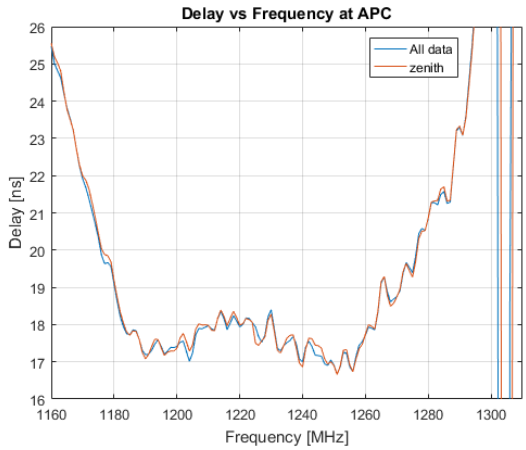
Parameter	Value
VNA Model	Keysight N5225A PNA
Frequency span	1160MHz to 1310MHz 1520MHz to 1620MHz
Frequency resolution	1MHz
IF Bandwidth (IFBW)	100Hz
Output power	20dBm
Average samples	1 (no averaging)
Smoothing	OFF
Runs	1
LNA supply voltage	10V
SGH type / Serial Number	MVG-Satimo SGH112 / 32
Probe type / Serial Number	MVG-Satimo SP1100 / 01
Uncertainty on alignment/distance	< 0.1°, < 1mm
Room temperature, humidity	20°C ± 1°C, 45% ± 10%

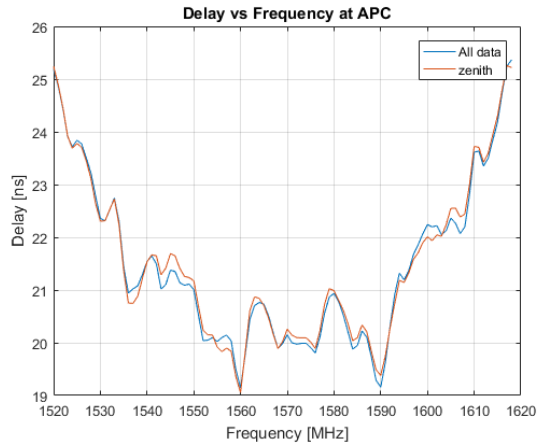
The antenna measurements campaign took place in December 2018. The set-up is depicted in the picture below (upper left corner: transmitting probe, right: SGH mounted on the 2-axis rotator).



6.1.2 Septentrio PolaNt Choke Ring (BIPM Antenna)

The plots below show the measured group delays referred to APC over frequency, both at zenith and averaged over azimuth and elevation (10° mask). Associated azimuth-vs-elevation plots are included in Annex.



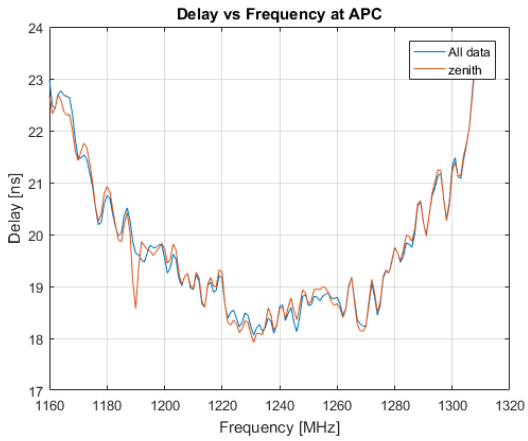


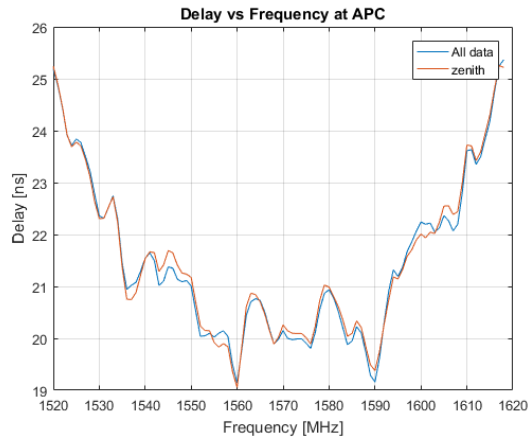
The table below summarises the group delays values per GNSS signal.

	GNSS signal	PolaNt Choke Ring Mean group delay (ns)			
		@ ARP		@ APC	
		Value	Uncertainty	Value	Uncertainty
GPS	L1 C/A	20.52	0.47	20.89	0.54
	L1 P	20.51	0.46	20.88	0.53
	L2 P	17.55	0.49	17.93	0.43
	L5	19.83	0.57	20.22	0.53
Galileo	E1 BC	20.53	0.47	20.90	0.54
	E6 BC	20.27	0.43	20.65	0.48
	E5a	19.91	0.55	20.30	0.51
	E5b	17.37	0.44	17.75	0.49
	E5 (AltBOC)	17.67	0.42	18.06	0.41
GLO	G1 C (centre)	21.04	0.49	21.41	0.53
	G1 P (centre)	21.03	0.49	21.40	0.53
	G2 C (centre)	16.85	0.49	17.23	0.55
	G2 P (centre)	16.85	0.49	17.23	0.55
BD	B1	19.56	0.51	19.93	0.44
	B2	17.46	0.46	17.85	0.51

6.1.3 Novatel GNSS-750 (NIST Antenna)

The plots below show the measured group delays referred to APC over frequency, both at zenith and averaged over azimuth and elevation (10° mask). Associated azimuth-vs-elevation plots are included in Annex.





The table below summarises the group delays values per GNSS signal.

	GNSS signal	GNSS-750 Mean group delay (ns)			
		@ ARP		@ APC	
		Value	Uncertainty	Value	Uncertainty
GPS	L1 C/A	19.61	0.47	19.98	0.44
	L1 P	19.64	0.46	20.01	0.43
	L2 P	17.98	0.47	18.36	0.43
	L5	20.35	0.44	20.74	0.46
Galileo	E1 BC	19.61	0.48	19.98	0.44
	E6 BC	19.00	0.42	19.38	0.45
	E5a	20.39	0.42	20.78	0.44
	E5b	18.79	0.42	19.18	0.46
	E5 (AltBOC)	19.58	0.41	19.97	0.42
GLO	G1 C (centre)	21.81	0.50	22.18	0.46
	G1 P (centre)	21.82	0.51	22.19	0.46
	G2 C (centre)	17.94	0.51	18.32	0.59
	G2 P (centre)	17.92	0.51	18.31	0.59
BD	B1	19.30	0.51	19.67	0.44
	B2	18.74	0.44	19.13	0.48

6.2 Antenna Cable Measurements

6.2.1 Test Conditions

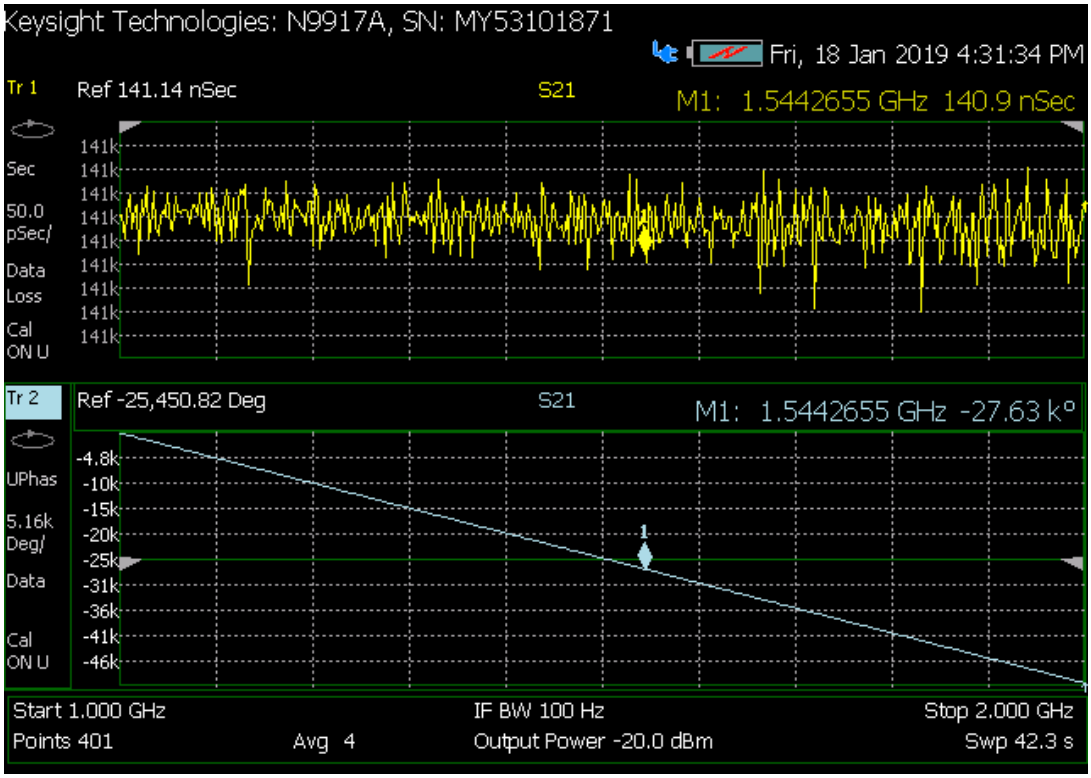
The antenna cable test equipment and configuration is summarised in the table below.

Parameter	Value
VNA (calibration date)	FieldFox N9917A (10.08.2018)
VNA calibration kit	Mechanic Calibration Module 85518A
Frequency span	1 GHz to 2 GHz
Resolution	401
IF Bandwidth (IFBW)	100 Hz
Output power	-20 dBm
S-parameter	S21
Average samples	4 (point averaging)
Smoothing	OFF
Runs	1
Room temperature, humidity	21°C ± 1°C, 45% ± 10%

The antenna cable test campaign took place in January 2019. Here below an example of the test set-up with the NIST antenna cable.

6.2.2 Times Microwave LMR-195 (BIPM Cable)

The plot below shows the cable group delay and relative phase over the measured frequency band.

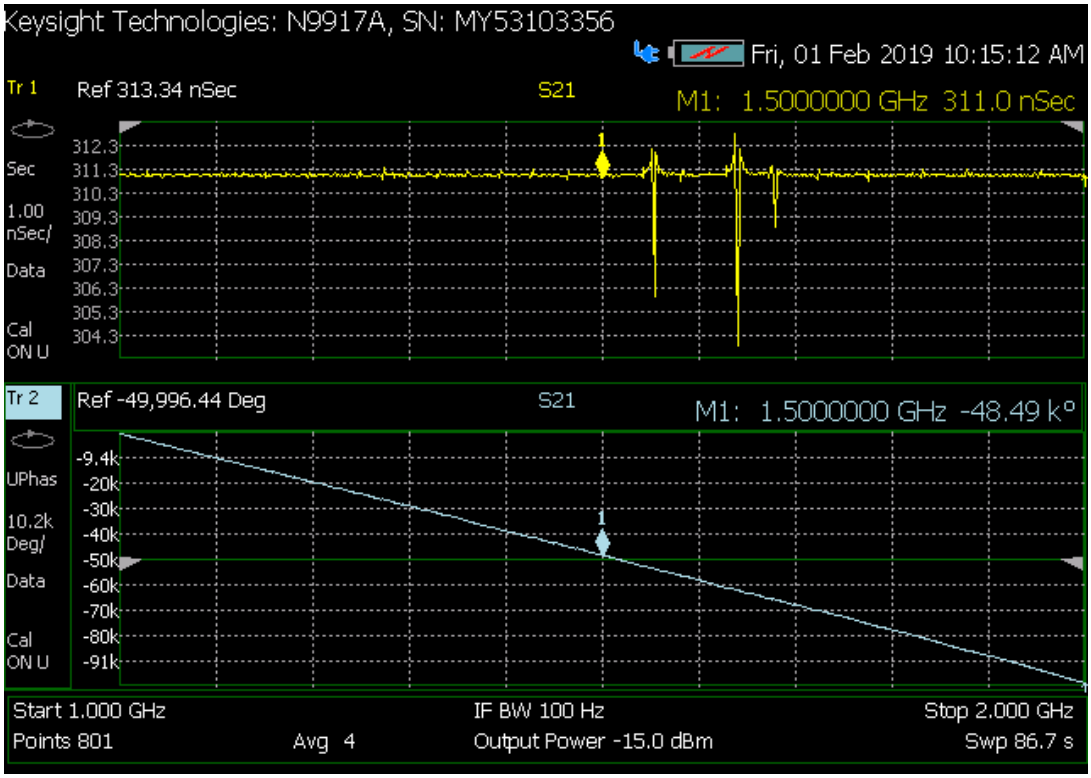


After averaging over the sub-frequency bands of interest, and removing the effect of the N to TNC adapter, the following group delays are obtained:

	LMR-195 Mean Group Delay (ns)	
Frequency Band	**Value**	**Uncertainty**
1160MHz to 1310MHz	140.76	0.25
1520MHz to 1620MHz	140.75	0.26

6.2.3 Heliax LDF2-50 (NIST Cable)

The plot below shows the cable group delay and relative phase over the measured frequency band.



The above plots indicate instabilities in group delays in the frequency bands: 1.54MHz - 1.56MHz and above 1.62MHz, which remained present and stationary when the cable was softly moved or the test equipment/conditions were changed. Inspection of cable and connectors did not show any visual damages. Such instabilities are expected to be due to internal defects in the cable.

Since there are no GNSS signals in these bands, those instabilities have been removed from the data set to compute the group delays. It is however recommended to use another cable.

	LDF2-50 Mean Group Delay (ns)	
Frequency Band	**Value**	**Uncertainty**
1160MHz to 1310MHz	311.28	0.31
1520MHz to 1620MHz	311.28	0.33

6.3 Receiver Measurements

6.3.1 Test Conditions

The receiver test equipment and configuration is summarised in the table below.

Parameter	Value
Simulator Type	Dual Spirent TS1140
Simulator Item #	117201 and 117200
Simulator FW	V6.03.00
Rise Time of Simulator 1pps output	3ns (tbc)
Oscilloscope Type	Keysight DSOS404A (4GHz, 20GSps)
Oscilloscope SN	MY55510163
Oscilloscope trigger level	1V
Oscilloscope samples duration	4ms
Receiver scenario duration	40min
Room temperature, humidity	22°C ± 1°C, 40% ± 10%

The receiver test campaign took place in February 2019. Here below an example of the test set-up.

6.3.2 Septentrio PolaRx5TR (SN 4701229)

The table below summarises the BIPM receiver delays values per GNSS signal.

	GNSS Signal	Value	Uncertainty
GPS	L1 C/A	9.48	0.74
	L1 P	9.38	0.52
	L2 P	10.28	0.53
	L5	10.66	0.46
Galileo	E1 BC	9.75	0.47
	E6 BC	7.99	0.55
	E5a	10.58	0.48
	E5b	6.89	0.79
	E5 (AltBOC)	8.59	0.48
GLO	G1 C (centre)	6.26	0.78
	G1 P (centre)	6.90	0.55
	G2 C (centre)	11.38	1.34
	G2 P (centre)	10.29	0.60
BD	B1	5.95	0.62
	B2	6.81	0.59

6.3.3 Septentrio PolaRx5TR (SN 4701229)

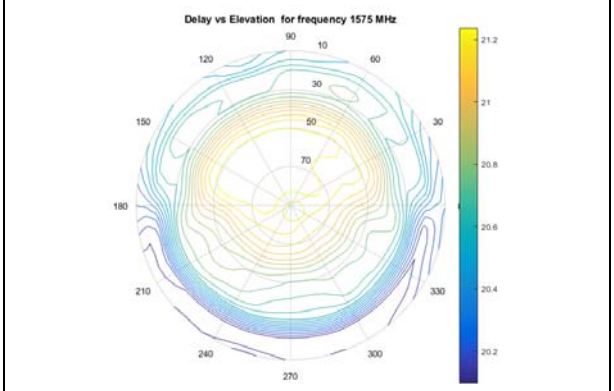
The table below summarises the BIPM receiver delays values per GNSS signal.

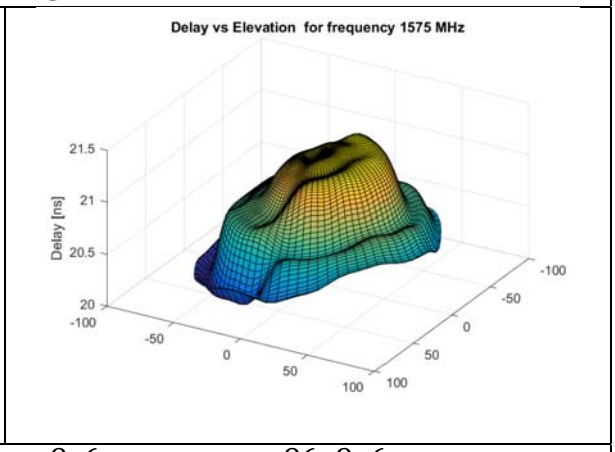
	GNSS Signal	Value	Uncertainty
GPS	L1 C/A	11.70	0.64
	L1 P	11.22	0.49
	L2 P	11.20	0.50
	L5	11.96	0.47
Galileo	E1 BC	11.86	0.45
	E6 BC	9.83	0.57
	E5a	11.87	0.47
	E5b	7.68	0.75
	E5 (AltBOC)	9.56	0.46
GLO	G1 C (centre)	5.32	0.91
	G1 P (centre)	6.23	0.78
	G2 C (centre)	12.71	1.46
	G2 P (centre)	11.24	0.92
BD	B1	4.51	0.61
	B2	7.63	0.56

ANNEX: ANGULAR DEPENDANCY OF ANTENNA GROUP DELAYS

Septentrio PolaNt Choke Ring (BIPM Antenna)

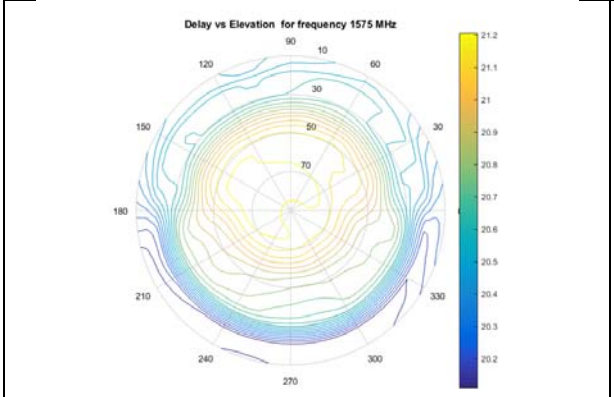
GPS L1 CA

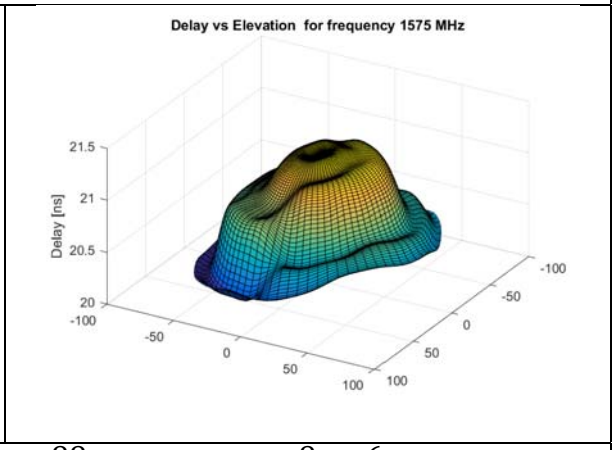




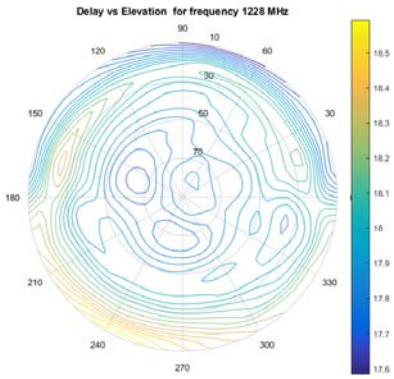
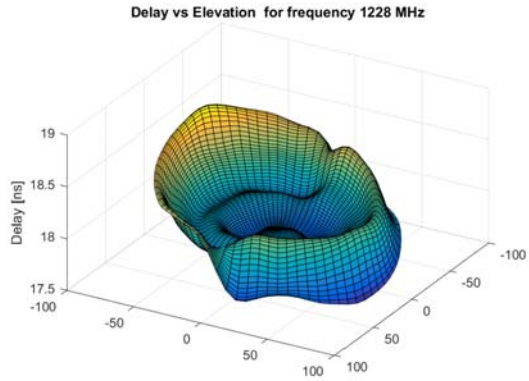
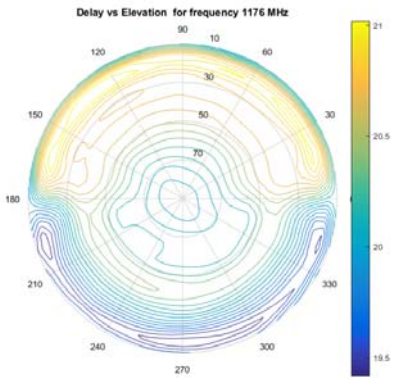
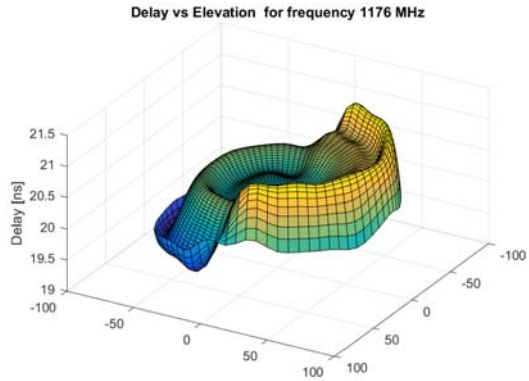
ARP: mean: 20.520650, std: 0.239369, min: 19.856550, max: 20.864826
APC: mean: 20.890108, std: 0.358689, min: 20.037102, max: 21.298457
Zenith, ARP: 20.665184
Zenith, APC: 21.070702

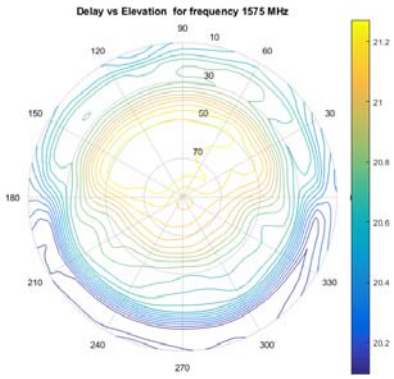
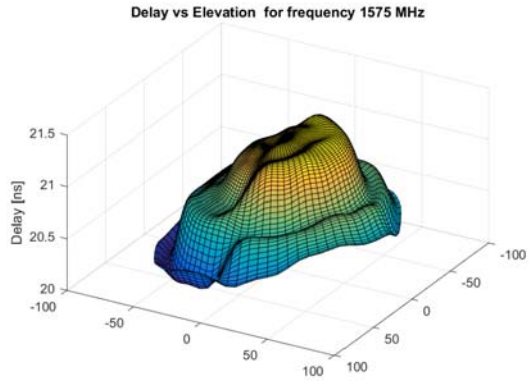
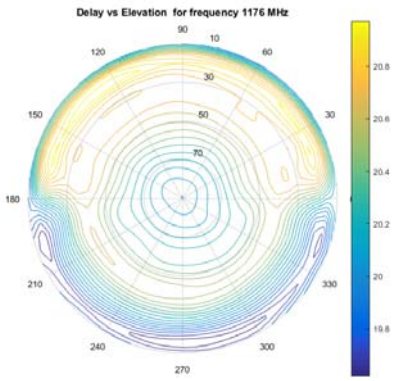
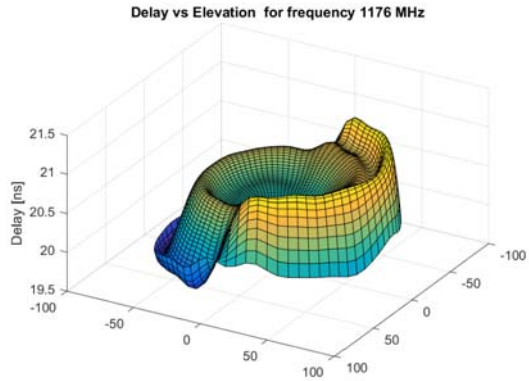
GPS L1 P



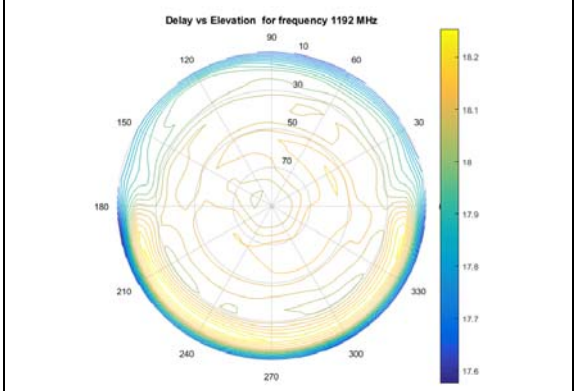


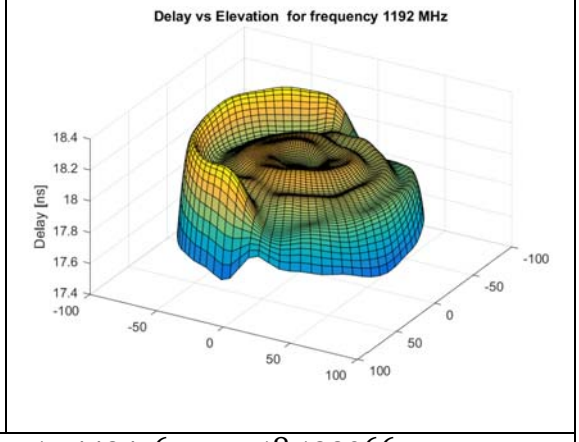
ARP: mean: 20.506238, std: 0.226340, min: 19.887743, max: 20.784456
APC: mean: 20.875696, std: 0.353645, min: 20.049009, max: 21.265800
Zenith, ARP: 20.644096
Zenith, APC: 21.049614

GPS L2 P	
	
ARP: mean: 17.549703, std: 0.287364, min: 17.157566, max: 18.552072 APC: mean: 17.933595, std: 0.172641, min: 17.530285, max: 18.647587 Zenith, ARP: 17.420464 Zenith, APC: 17.841824	
GPS L5	
	
ARP: mean: 19.831689, std: 0.405042, min: 19.165710, max: 20.915574 APC: mean: 20.224893, std: 0.354195, min: 19.311526, max: 21.108264 Zenith, ARP: 19.962434 Zenith, APC: 20.394016	

GAL E1 BC	
	
ARP: mean: 20.526650, std: 0.245816, min: 19.850824, max: 20.901959 APC: mean: 20.896108, std: 0.359441, min: 20.031877, max: 21.335591 Zenith, ARP: 20.671267 Zenith, APC: 21.076785	
GAL E5 A	
	
ARP: mean: 19.905027, std: 0.376771, min: 19.381999, max: 20.856086 APC: mean: 20.298231, std: 0.319347, min: 19.527815, max: 21.048776 Zenith, ARP: 20.050104 Zenith, APC: 20.481686	

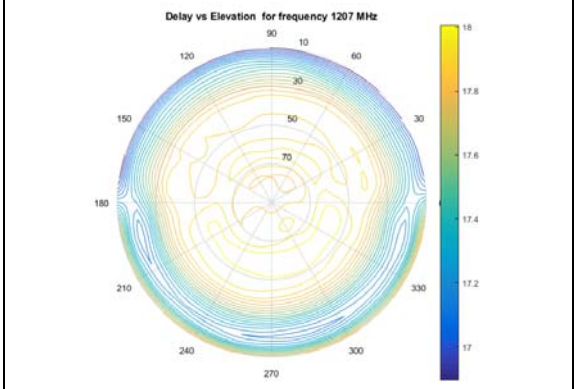
GAL E5 ALTBOC

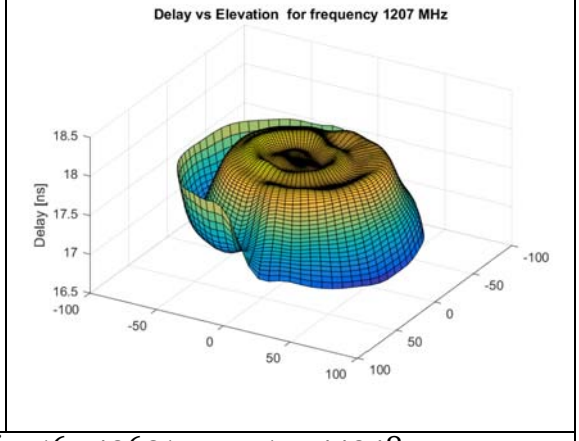




ARP: mean: 17.673787, std: 0.130458, min: 17.443476, max: 18.103966
APC: mean: 18.063964, std: 0.114764, min: 17.540554, max: 18.295174
Zenith, ARP: 17.667043
Zenith, APC: 18.095303

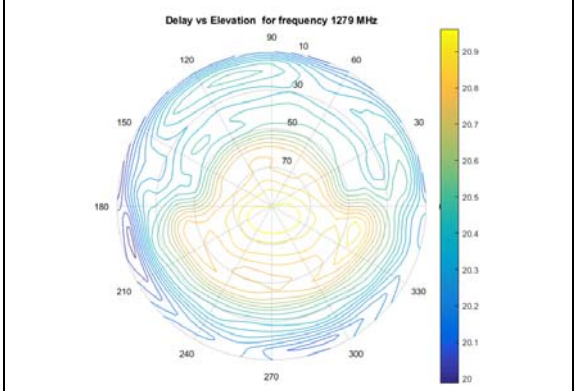
GAL E5 B

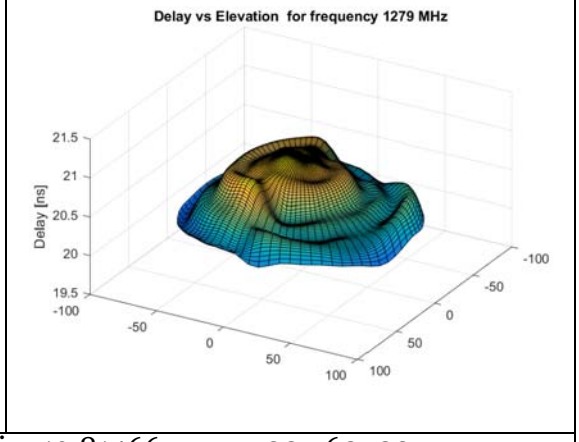




ARP: mean: 17.366085, std: 0.188795, min: 16.740601, max: 17.744048
APC: mean: 17.754168, std: 0.279501, min: 16.837158, max: 18.066753
Zenith, ARP: 17.478471
Zenith, APC: 17.904431

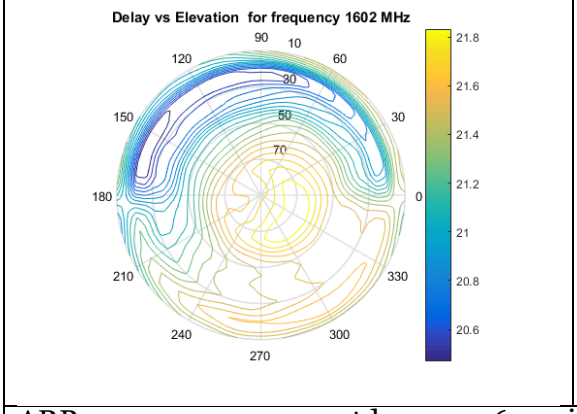
GAL E6 BC

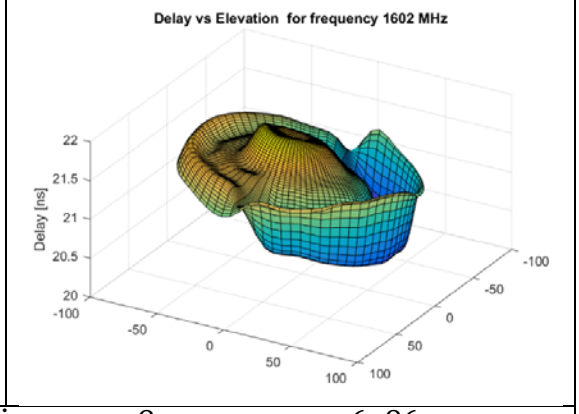




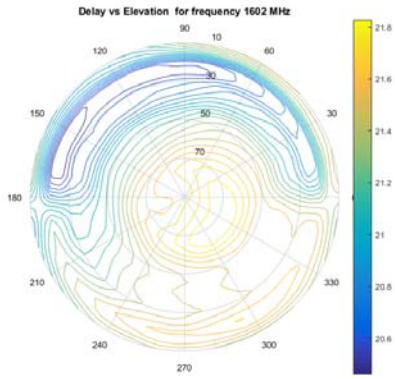
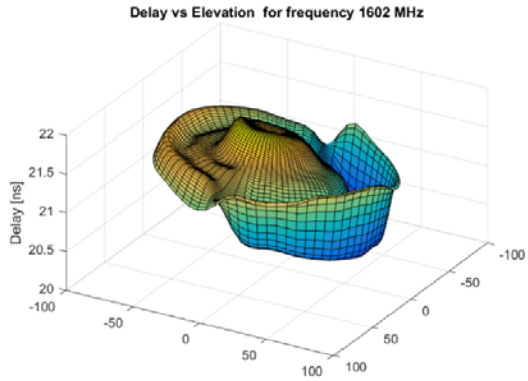
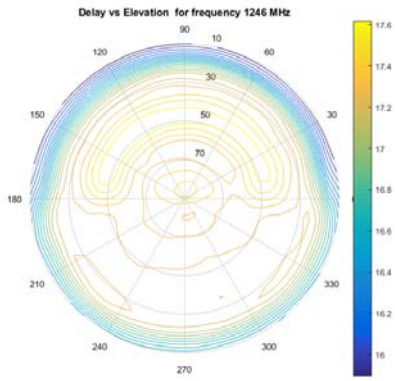
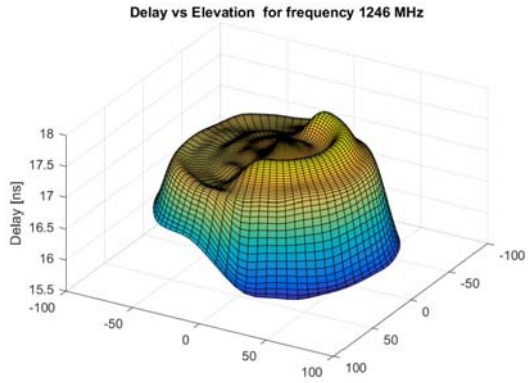
ARP: mean: 20.269831, std: 0.147289, min: 19.814667, max: 20.560502
APC: mean: 20.648601, std: 0.272857, min: 19.935783, max: 21.014704
Zenith, ARP: 20.200159
Zenith, APC: 20.615898

GLO G1 C

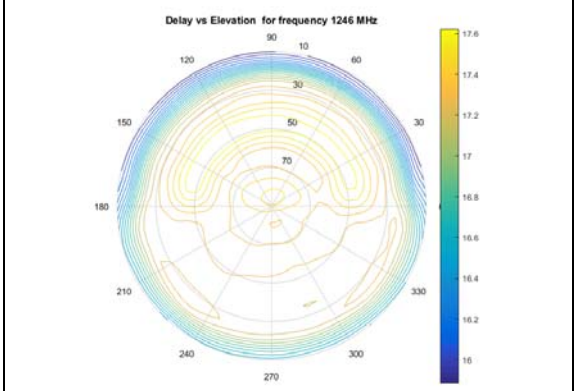


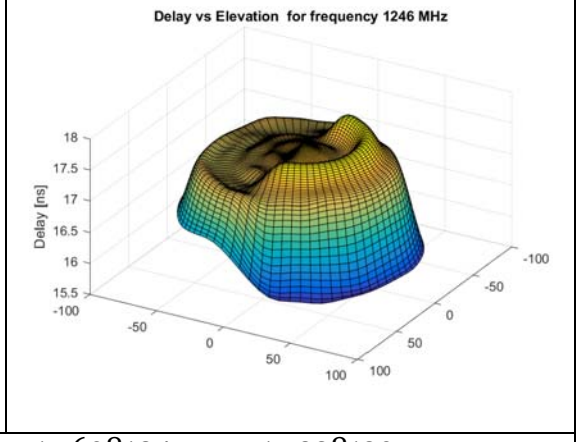


ARP: mean: 21.037499, std: 0.290465, min: 20.207839, max: 21.506986
APC: mean: 21.407655, std: 0.351799, min: 20.389235, max: 21.907347
Zenith, ARP: 20.728178
Zenith, APC: 21.134463

GLO G1 P	
	
ARP: mean: 21.033449, std: 0.291839, min: 20.199050, max: 21.508565 APC: mean: 21.403605, std: 0.352676, min: 20.380446, max: 21.904751 Zenith, ARP: 20.721533 Zenith, APC: 21.127817	
GPS G2 C	
	
ARP: mean: 16.847983, std: 0.283064, min: 15.709462, max: 17.322429 APC: mean: 17.231642, std: 0.381713, min: 15.804918, max: 17.711135 Zenith, ARP: 17.028163 Zenith, APC: 17.449268	

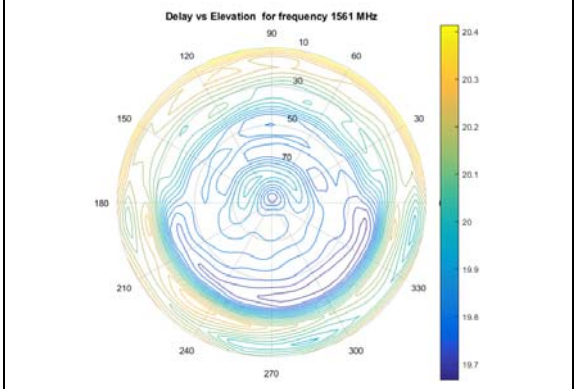
GLO G2 P

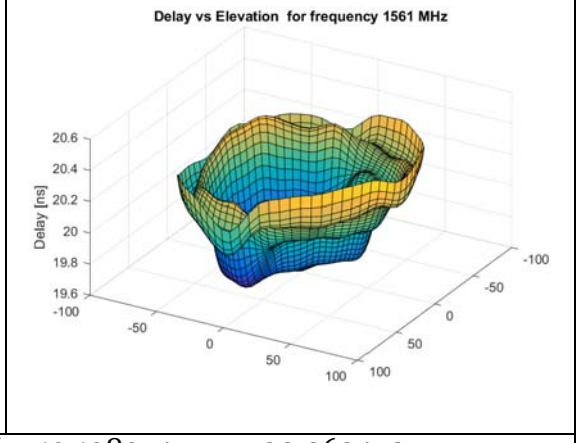




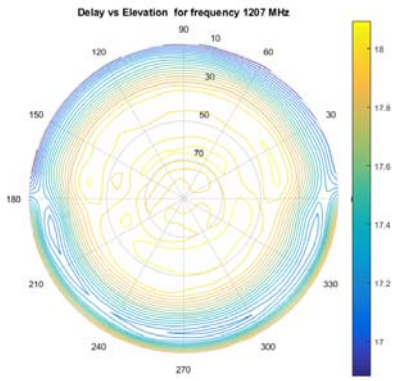
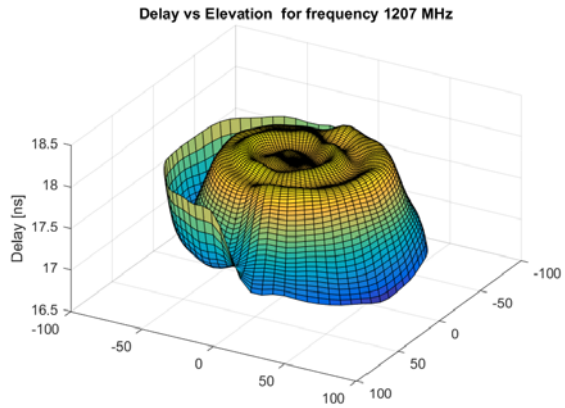
ARP: mean: 16.849750, std: 0.286117, min: 15.698104, max: 17.328129
APC: mean: 17.233409, std: 0.384995, min: 15.793561, max: 17.716835
Zenith, ARP: 17.032439
Zenith, APC: 17.453545

BDS B1 I

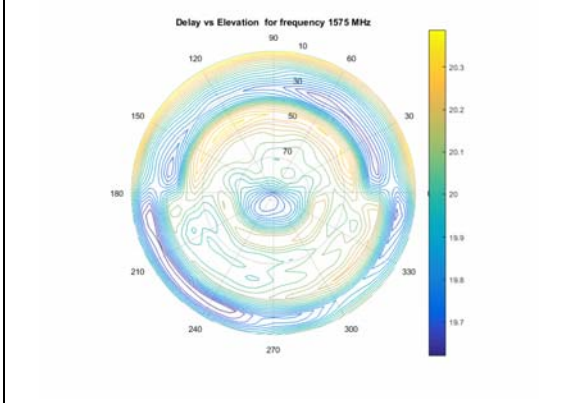
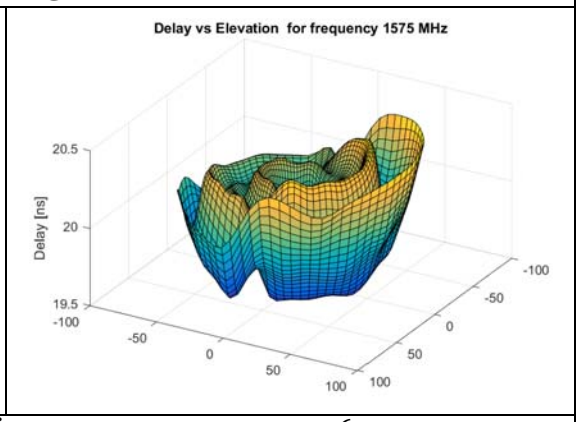
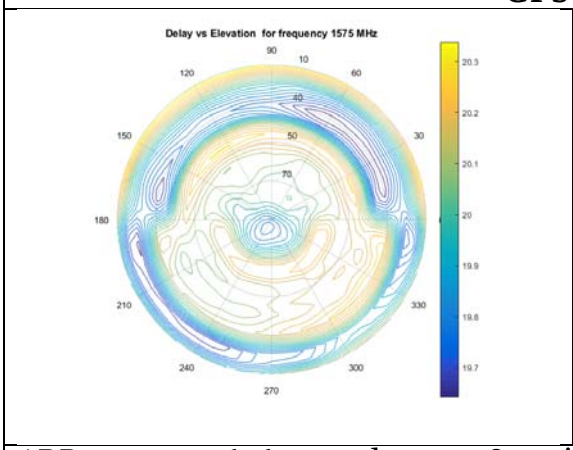
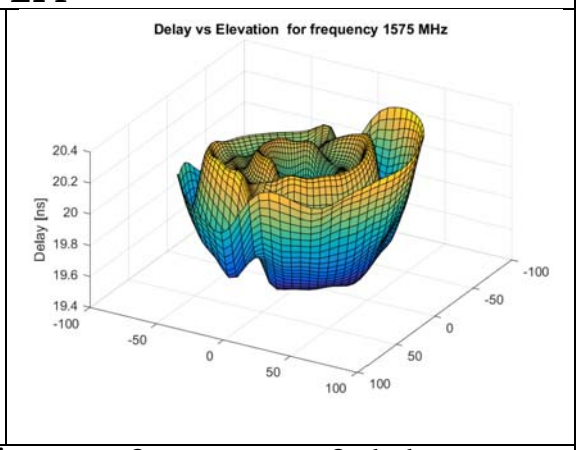




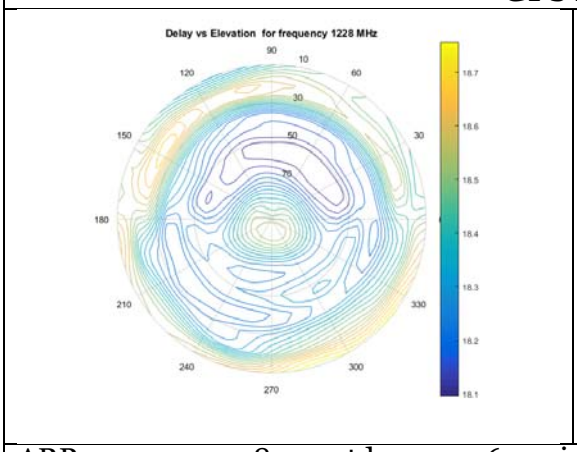
ARP: mean: 19.558125, std: 0.306570, min: 19.198974, max: 20.362450
APC: mean: 19.926186, std: 0.183432, min: 19.620023, max: 20.454026
Zenith, ARP: 19.437912
Zenith, APC: 19.841897

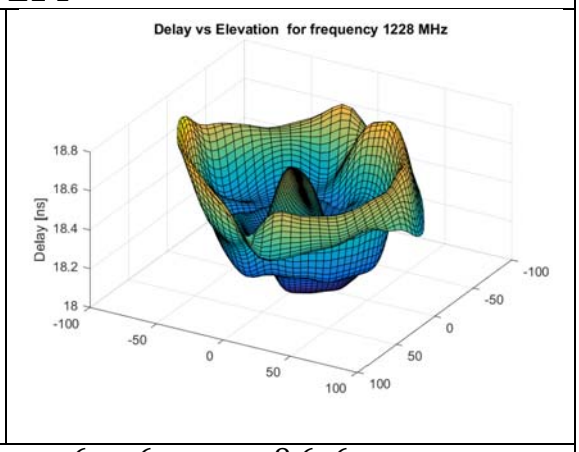
BDS B2 I	
	
ARP: mean: 17.462693, std: 0.218947, min: 16.720668, max: 17.844646 APC: mean: 17.850776, std: 0.313976, min: 16.817225, max: 18.161059 Zenith, ARP: 17.574327 Zenith, APC: 18.000287	

Novatel GNSS-750 (NIST Antenna)

GPS L1 CA	
	
ARP: mean: 19.613786, std: 0.243626, min: 19.130421, max: 20.336235 APC: mean: 19.983244, std: 0.184172, min: 19.576793, max: 20.428159 Zenith, ARP: 19.684670 Zenith, APC: 20.090188	
GPS L1 P	
	
ARP: mean: 19.636047, std: 0.221282, min: 19.239893, max: 20.283646 APC: mean: 20.005505, std: 0.170650, min: 19.600500, max: 20.375570 Zenith, ARP: 19.706032 Zenith, APC: 20.111550	

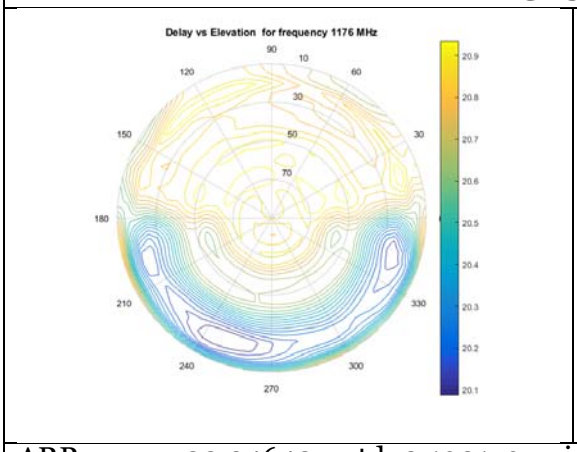
GPS L2 P

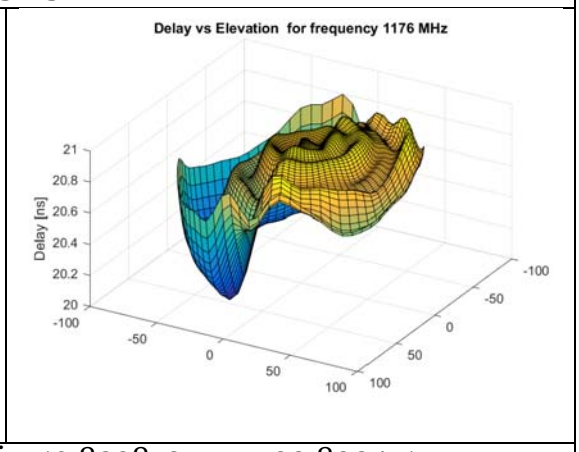




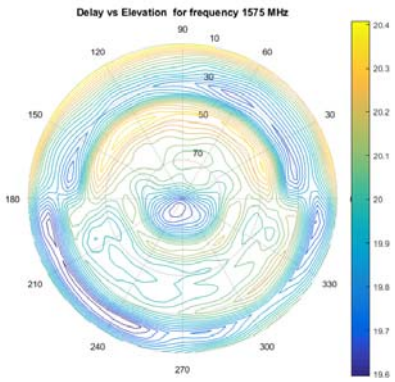
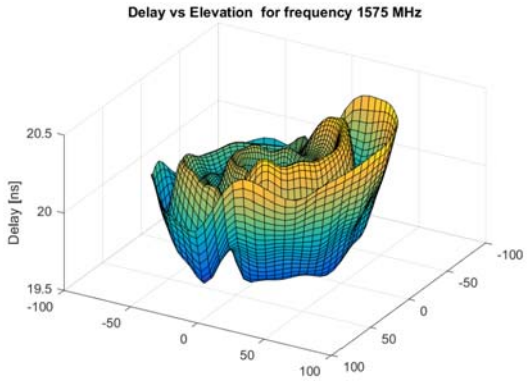
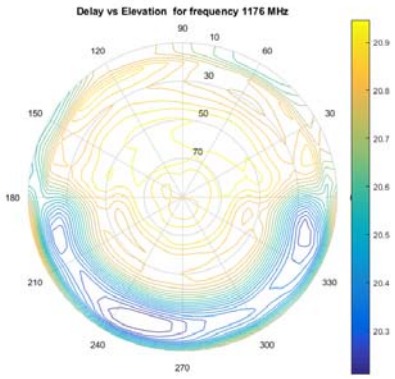
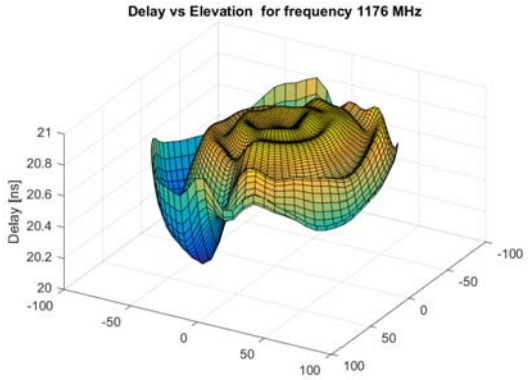
ARP: mean: 17.978375, std: 0.244967, min: 17.601469, max: 18.696535
APC: mean: 18.362266, std: 0.162077, min: 18.061164, max: 18.792050
Zenith, ARP: 17.816509
Zenith, APC: 18.237869

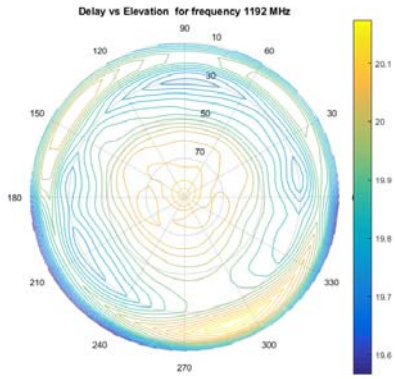
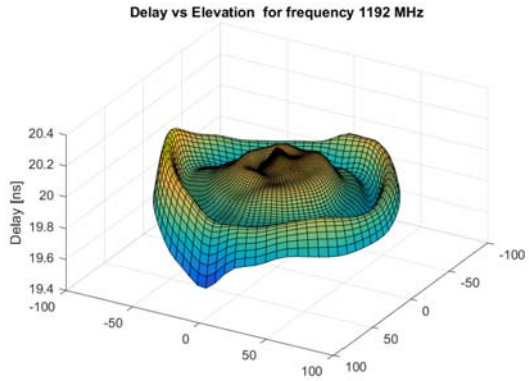
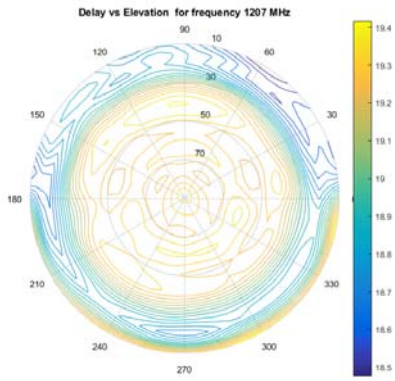
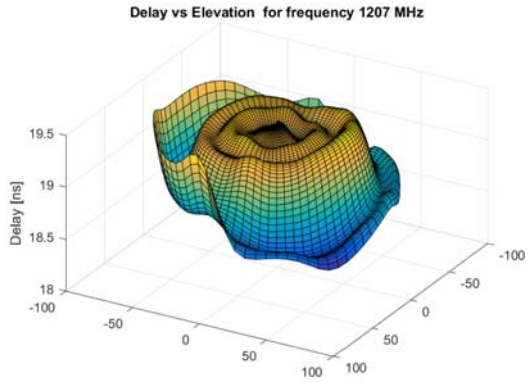
GPS L5



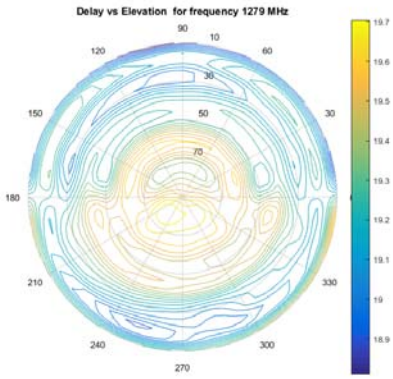


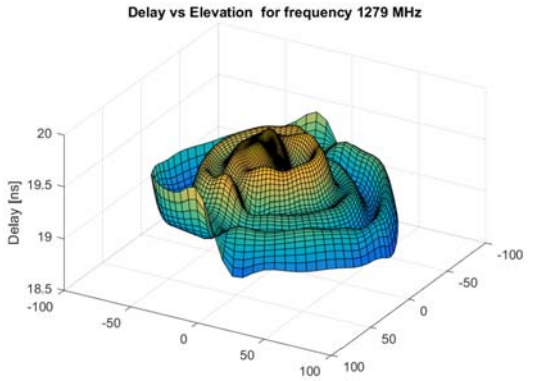
ARP: mean: 20.346407, std: 0.190179, min: 19.802870, max: 20.800451
APC: mean: 20.739611, std: 0.226721, min: 20.040969, max: 20.983735
Zenith, ARP: 20.380446
Zenith, APC: 20.812027

GAL E1 BC	
	
ARP: mean: 19.609435, std: 0.257112, min: 19.082880, max: 20.359700 APC: mean: 19.978893, std: 0.194131, min: 19.549941, max: 20.451623 Zenith, ARP: 19.679848 Zenith, APC: 20.085366	
GAL E5 A	
	
ARP: mean: 20.390740, std: 0.144833, min: 19.938307, max: 20.797783 APC: mean: 20.783943, std: 0.191116, min: 20.168578, max: 20.987282 Zenith, ARP: 20.454004 Zenith, APC: 20.885586	

Gal E5 ALTBOC	
	
ARP: mean: 19.579774, std: 0.103653, min: 19.429917, max: 20.018779 APC: mean: 19.969951, std: 0.130216, min: 19.534569, max: 20.209986 Zenith, ARP: 19.533751 Zenith, APC: 19.962011	
GAL E5 B	
	
ARP: mean: 18.789117, std: 0.148333, min: 18.330466, max: 19.370885 APC: mean: 19.177199, std: 0.228739, min: 18.427024, max: 19.467442 Zenith, ARP: 18.800776 Zenith, APC: 19.226736	

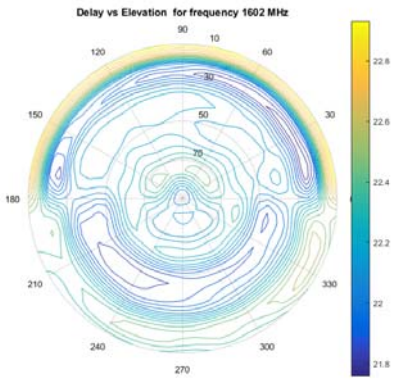
GAL E6 BC

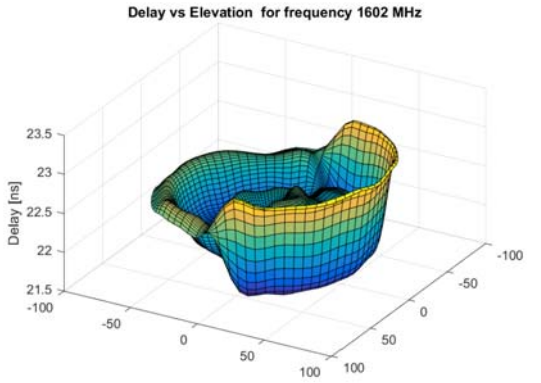




ARP: mean: 19.003164, std: 0.129778, min: 18.669524, max: 19.556107
APC: mean: 19.381934, std: 0.212389, min: 18.763765, max: 19.753902
Zenith, ARP: 18.980164
Zenith, APC: 19.395903

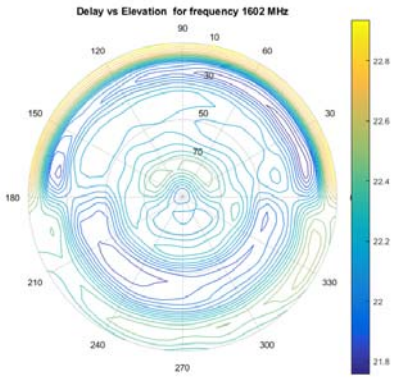
GLO G1 C

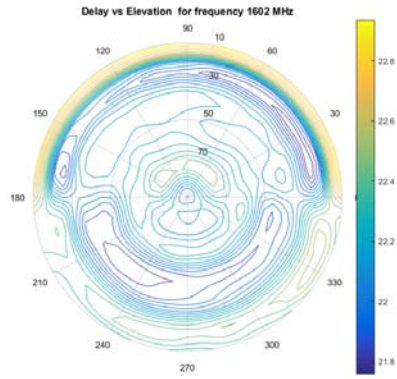




ARP: mean: 21.814803, std: 0.305469, min: 21.415334, max: 22.902508
APC: mean: 22.184959, std: 0.227760, min: 21.677489, max: 22.994606
Zenith, ARP: 21.609623
Zenith, APC: 22.015907

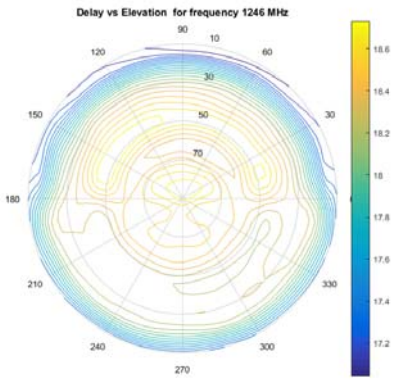
GLO G1 P

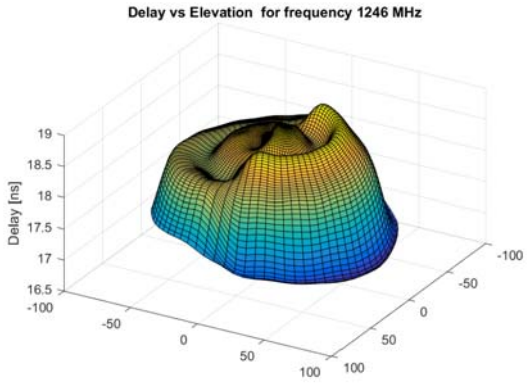




ARP: mean: 21.817180, std: 0.306708, min: 21.413701, max: 22.906558
APC: mean: 22.187337, std: 0.229736, min: 21.676026, max: 22.998655
Zenith, ARP: 21.608371
Zenith, APC: 22.014655

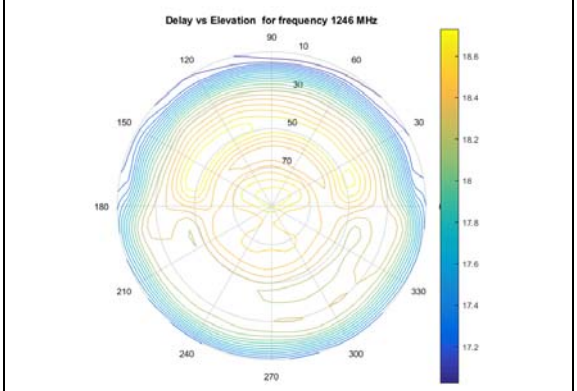
GLO G2 C

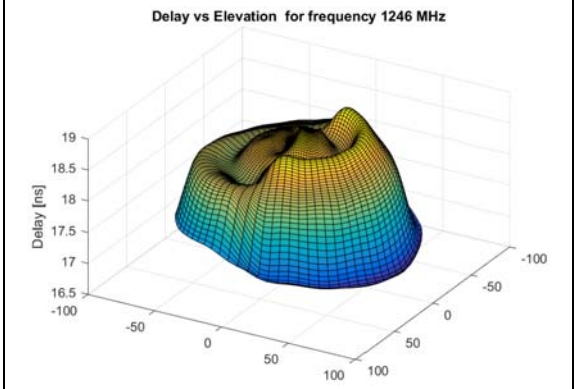




ARP: mean: 17.936436, std: 0.312402, min: 16.858811, max: 18.418770
APC: mean: 18.320095, std: 0.431597, min: 16.954267, max: 18.829389
Zenith, ARP: 18.096034
Zenith, APC: 18.517139

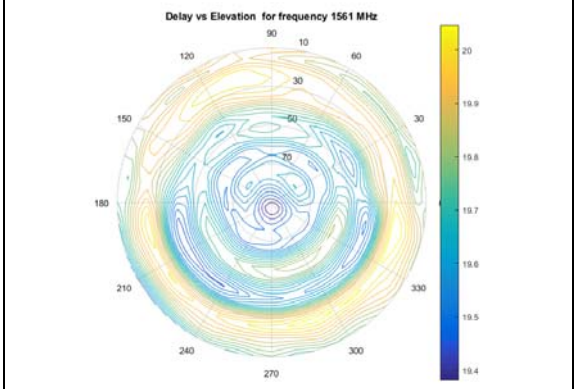
GLO G2 P

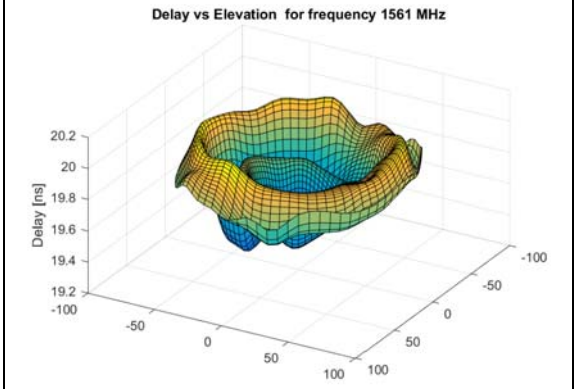




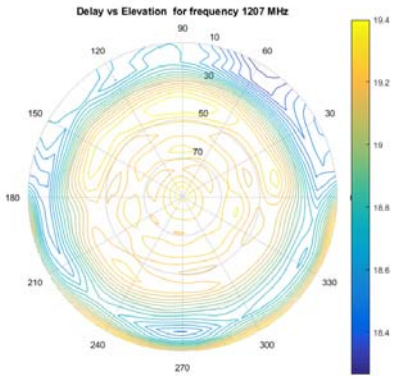
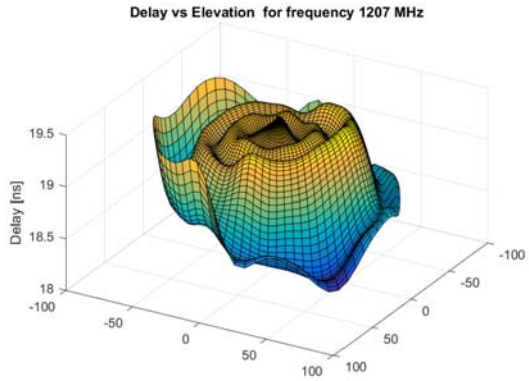
ARP: mean: 17.924210, std: 0.318710, min: 16.838393, max: 18.424532
APC: mean: 18.307869, std: 0.438067, min: 16.933849, max: 18.829600
Zenith, ARP: 18.090787
Zenith, APC: 18.511892

BDS B1 I





ARP: mean: 19.302131, std: 0.315607, min: 18.818405, max: 19.884398
APC: mean: 19.670192, std: 0.193611, min: 19.343763, max: 20.089205
Zenith, ARP: 19.248050
Zenith, APC: 19.652035

BDS B2 I	
	
ARP: mean: 18.742531, std: 0.180420, min: 18.108435, max: 19.303643 APC: mean: 19.130613, std: 0.274337, min: 18.204993, max: 19.464978 Zenith, ARP: 18.730456 Zenith, APC: 19.156416	