FINAL REPORT

AKAL

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Code: AKAL-GMV-FRe

Version: 1.1

Date: 23/05/2018

Internal code: GMV 21717/18 V2/18

ESA STUDY CONTRACT REPORT		
ESA Contract No: **4000119960/16/NL/AS**	SUBJECT: **EGEP ID103 – AKAL: Accurate Calibration of Multisystem/Multi-Frequency GNSS Receiver Chains**	CONTRACTOR: **GMV Innovating Solutions Sp zoo, Poland**
ESA CR() No:	No. of Volumes: **1** This is Volume No: **1**	CONTRACTOR'S REFERENCE: GMV 21717/18 V2/18

ABSTRACT:

The Final Report describes in a comprehensive way all work done in the framework of a mutli-frequency multi-constellation absolute calibration campaign of GNSS receiver chains. This project focus in high accuracy, absolute calibration of considerably broad range of GNSS signals (GPS, Galileo and GLONASS). The results are presented for different receivers and antennas, highlighting critical results for absolute calibration campaigns.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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DOCUMENT STATUS SHEET

Version	Date	Pages	Section	Changes
1.0	11/04/2018	28		First version of the document for FR milestone.
1.1	23/05/2018	33	5.5	Table with validation differences added.
			5.6	Table with satellites DCBs added.
			7	AKAL general recommendations added.
			Annex A	Short description of Technical Notes and Software deliverables added.

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LIST OF TABLES AND FIGURES

1. INTRODUCTION

This document is prepared as the Final Report of the AKAL project.

1.1. PURPOSE

The Final Report describes in a comprehensive way all work performed under the AKAL contract. The Technical Notes produced in this contract (see Reference Documents below) complement it to the largest possible extent, and can be considered as annexes to the Final Report. The Final Report is intended for publication, and it is delivered together with the Final Review data package.

1.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-1 Acronyms

Acronym	Definition
1PPS	One Pulse Per Second
APC	Antenna Phase Center
ARP	Antenna Reference Point
BIPM	Bureau International de Poids et Mesures
BGD	Broadcast Group Delay
CATR	Compact Antenna Test Range (at ESTEC)
CGGTTS	CCTF Group on GNSS Time Transfer Standards
CNES	Centre National d'Études Spatiales
EGEP	European GNSS Evolution Programme
ESA	European Space Agency
FR	Final Review
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GST	Galileo System Time
ORB	Royal Observatory of Belgium
PDR	Preliminary Definition Review
PTF	Precise Timing Facility
PTB	Physikalisch-Technische Bundesanstalt
RINEX	Receiver INdependent EXchange format
SiS	Signal in Space
SoW	Statement of Work
TAI	Temps Atomique International (International Atomic Time)
TCR	Test Campaign Review
TIC	Time Interval Counter
TRR	Test Readiness Review
TVF	Time Validation Facility
TVR	Test Validation Review
UTC	Universal Time Coordinated
VNA	Vector Network Analyser
WP	Work Package

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	EGEP Management Requirements	GNSS-SYST-REQ-ESA-X-0001	3.1	10/02/2016
[AD.2]	Invitation to Tender - Accurate calibration of multi-system/multi-frequency GNSS receiver chain	AO/1-8705/16/NL/MM	--	16/06/2016
[AD.3]	Appendix 1 to [AD02] – Statement of Work	TEC-ETE/2015.194/PW	0.0	17/01/2016
[AD.4]	Appendix 2 to [AD02] - Draft Contract	AO/1-8705/16/NL/MM	--	16/06/2016
[AD.5]	Appendix 3 to [AD02] - Special Conditions of Tender	AO/1-8705/16/NL/MM	--	16/06/2016

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.1]	REVIEW AND TRADE-OFFS REPORT – TN01	AKAL-GMV-TN-01	1.1	22/06/2017
[RD.2]	AKAL As-Run procedures	AKAL-GMV-As-run PRC1	1.2	16/05/2018
[RD.3]	PROCEDURE FOR THE ACCURATE CALIBRATION OF MULTI- SYSTEM/MULTI-FREQUENCY GNSS RECEIVER CHAINS – TN02	AKAL-GMV-TN-02	2.1	14/02/2018
[RD.4]	PROCEDURE VERIFICATION AND VALIDATION DESCRIPTION – TN03	AKAL-ORB-TN-03	1.2	23/10/2017
[RD.5]	VALIDATION OF THE PROCEDURE FOR THE ACCURATE CALIBRATION OF MULTI-SYSTEM/MULTI-FREQUENCY GNSS RECEIVER CHAINS – TN04	AKAL-ORB-TN-04	2.1	03/05/2018
[RD.6]	Report of Absolute Calibration of PolaRX5	-	-	27/02/2018
[RD.7]	Report of Absolute Calibration of GTR51	-	-	27/02/2018

3. AKAL EXECUTIVE SUMMARY

The use of Global Navigation Satellite Systems (GNSS) is a well-established time-transfer technique employed by national timing laboratories and time service providers worldwide. In particular, GNSS is one of the two technologies endorsed by the Bureau International des Poids et Mesures (BIPM) for the realization of the international TAI and UTC timescales.

One of the key contributors in uncertainty budget of this method is the receiver chain calibration (including the GNSS receiver, cable and antenna). The operational method in use today for GNSS receiver chain calibration in the timing community is defined and maintained by the BIPM, and is based on a hierarchical relative calibration scheme with a travelling "golden" receiver. This method is currently limited to GPS P1-P2 with a level of uncertainty arbitrarily set to 2.5 ns (for stations in agreement with the BIPM guidelines for GNSS equipment calibration). One possible way to decrease the uncertainty level and mitigate errors introduced by traveling stations, is to perform absolute calibration of the receiver chain.

Absolute calibration consists on characterizing the electrical delay of each element of the reception chain by means of simulated signals. These signals allow us to neglect the errors introduced by the satellite, the signal propagation and multipath effects found in real life conditions, and thus provides a calibration uncertainty lower than the differential technique. On the other hand, it is important to make sure that the simulated signal is representative of the real signal in space.

In the development of the AKAL project, further research and studies were done to explore possible applications and improvements, corresponding to the absolute calibration method. As a result, independent absolute calibration procedures were defined and validated, tailored to the facilities and equipment available at ESTEC. With the novel step-by-step absolute calibration procedures, ESA is capable of providing absolute calibration services for in-house equipment, and third party customers, of in-operation timing receiver chains. On top of the procedures, two complete receiver chains were absolutely calibrated for the validation and to be used by ESA in the near future. The new "golden" receiver is a travelling station, available at ESTEC and can be used as a reference for the relative calibration of Galileo signals (E1, E5a, E5b, E5altBOC, E6).

In the procedures of absolute receiver chain calibration, the receiver is calibrated using GNSS signals generated by means of a GNSS simulator. The antenna calibration is done by means of a Vector Network Analyser (VNA) inside an anechoic chamber available at ESTEC. The delay of the antenna cable is also measured using a VNA, which generates continuous sinusoidal wave. The results of the absolute calibration technique have shown that obtained accuracy around 1ns, with 1-sigma coverage, for the complete chain (receiver, antenna, and antenna cable), can be achieved.

The AKAL generated procedures are divided into three separate activities: receiver, antenna and cable calibration.

- Receiver calibration is divided in two parts: simulator calibration and receiver calibration. Each of them uses simulated GNSS signals, considering satellites at geostationary positions. The analysis of the simulator calibration is done using a newly developed correlation software, and the receiver calibration with a dedicated script to process measurements in Rinex 3.01 file format. As the results, calibrated delays are obtained for each system, frequency and signal, independently. Estimated uncertainty of the procedure is between 0.5 and 1 ns, based on the signal.
- Antenna calibration is performed in the anechoic chamber located at ESTEC Compact Antenna Test Range facility. Antenna procedure also has two separate steps: first is characterization of the facility and transmitter antenna, by measuring the delay of two identical Standard Gain Horn (SGH) antenna. The second step is the calibration of the geodetic antenna mounted on the robotic arm. Based on the initial tests, the final calibration values are characterized only for elevation angles dependency. The variations of the antenna group delay against different angle are then introduced in the uncertainty calculations. As a final value, only one group delay value is reported for each analysed frequency, and its associated bandwidth. Delays are reported in reference to the Antenna Reference Point (ARP), but easy conversion to Antenna Phase Center (APC) is described in the TN [RD.3]. Estimated uncertainty of the procedure is of 0.5 ns for all the signals.
- Cable calibration is done using artificial sinusoidal signal generated by the VNA. Because of the non-dispersive character of the antenna cable, delay is defined as one value, valid for each analysed frequency. Estimated uncertainty of the procedure is around 0.2 ns, based on the quality and length of the link.

The total run-time of the calibration procedure is estimated to be one day, except if Glonass calibration is desired, which require calibration of each frequency slot separately, and it will increase the time of the calibration up to two days. As the result of the calibration, delays are reported for signals L1C, L1P, L2P, L5Q, E1C, E5Q, E7Q, E8Q, E6C, G1C, G1P, G2C, G2P (Rinex naming convention). These values can be applied to commonly used CGGTTS format and utilized in standard time-transfer procedures.

As a part of AKAL project, the validation of executed calibration activities was performed. Two absolutely calibrated reception chains were installed in several common clock configurations:

- Comparison with BIMP Group 1/Group 2 stations,
- Comparison with two absolutely calibrated, in scope of AKAL project, receivers chains
- Comparison with receiver chain calibrated with different absolute calibration procedures

The validation activities focused only on GPS and Galileo signals.

Based on the several test cases and measurements performed in three different timing labs (ESTEC, ORB and PTB), the combined uncertainty of the calibrated delay was assessed and is shown in Table 3-1. These values corresponds to the trade-off between uncertainty obtained during the calibration and the results achieved in validation, using real signals.

Table 3-1 Final AKAL uncertainties

Signal	Uncertainty
L1C	1.8 ns
L1P	0.7 ns
L2P	1.5 ns
E1C	1.1 ns
E5Q (E5a)	1.1 ns
E7Q (E5b)	0.6 ns
E8Q (AltBOC)	0.6 ns

Based on the final uncertainty results, we can confirm that AKAL project produced a novel absolute calibration procedures, which decrease the uncertainty to the level around 1 ns for nearly all analysed signals. It is believed that this level of uncertainty make this method suitable for accurate calibration of time transfer stations.

4. ABSOLUTE CALIBRATION

4.1. INTRODUCTION

As a system providing timing services, Galileo has to provide the user with an accurate prediction of the offset between its own timescale (Galileo System Time, GST) and Coordinated Universal Time (UTC). Similarly, in order to guarantee interoperability with GPS (and other GNSS in the future), the user has to be provided with an accurate estimation of the offset between GST and the GPS (or other GNSS) timescales.

Furthermore, Galileo distributes time information over different navigation messages (INAV, FNAV and GNAV), making use of different signals and different frequencies. The different navigation messages are created in three separated dual-frequency processes (E1- E5a, E1-E5b and E1-E6A). To ensure consistency between these combinations, the calibration of the inter-frequency code biases at the Precise Time Facility (PTF) is of decisive importance.

One of the key contributors in this estimation is the receiver chain (including the GNSS receiver, antenna cable and antenna). The operational method in use today for GNSS receiver chain calibration in the timing community is defined and maintained by the BIPM, and is based on a hierarchical relative calibration scheme with a travelling "golden" receiver. This method is limited to GPS P1-P2 with a level of uncertainty arbitrarily set to 2.5 ns.

Along with the availability of the new GNSS signals (especially Galileo), the need of a new calibration method arose. The AKAL project was proposed to define novel procedures for the absolute calibration of a time transfer receiver chain with a special attention to Galileo E1, E5 and E6 signals. With new step-by-step procedures available at ESTEC, it is possible to estimate the absolute delays of GNSS equipment with an uncertainty level of 1ns.

4.2. TIME-TRANSFER RECEIVER CHAIN

The time-transfer receiver chain consists of three main parts: antenna, cable and GNSS receiver. In aims of completeness in the context of absolute calibration of GNSS receivers, we present hereafter the different elements of the receiver chain, as well as the associated delays with each one of them. In Figure 4-1 we can observe the three main elements of the chain with a detailed description.

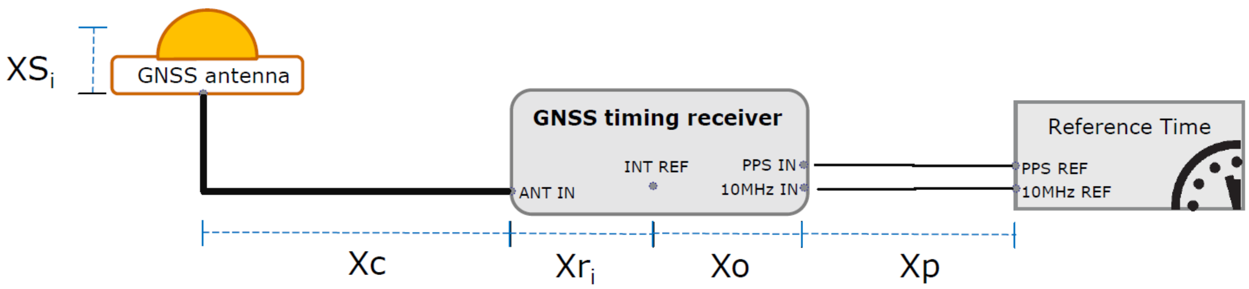


Figure 4-1 Delays in the GNSS receiver chain

The delays affecting the measured pseudorange are the following:

- **XS_i**: delay due to the propagation of the RF signal through the antenna
- **Xc**: delay due to the propagation of the RF signal through the antenna cable
- **Xr_i**: delay inside the receiver itself, from its antenna connector to the receiver internal reference point (or "latching" point); this delay is due partly to RF propagation and partly to code processing
- **Xo**: delay between the receiver 1PPS input connector and the receiver internal reference point (this delay is independent of GNSS signals)
- **Xp**: delay between the external clock and the receiver 1PPS input connector (this delay is independent of GNSS signals)

In the frame of the AKAL project, the procedures for calibration of XS_i, Xc and Xr_i were defined. The definitions of other delays (Xo and Xp) are already well defined in available publications, and these elements were not of particular interest for the study. In the next sections the concise report of the main activities performed during AKAL project will be introduced. This final report along all related Technical Notes represent a comprehensive study on the topic of absolute calibration of time-transfer receiver chains.

4.3. RECEIVER CALIBRATION

The calibration of the receiver is based on the artificial signals generated by the GNSS simulator. In our approach, one satellite is simulated at geostationary orbit, for each GNSS. All atmospheric effects (mainly ionospheric and tropospheric) are disabled in the simulation and does not affect the signal. This approach simplifies the procedures and makes easier the computations of the final delays.

The receiver group delay will be the difference between the simulated and the obtained pseudorange by the receiver. To be able to compare the two values, the simulator and cable delays need to be subtracted from the pseudorange difference. Then the receiver delay value $\mathbf{Xr_i}$, is computed as:

$$\mathbf{Xr_i} = \frac{\mathbf{PR_i} - \boldsymbol{\rho}}{\boldsymbol{c}} + (\boldsymbol{X_{RF_i}} - \boldsymbol{X_{PPS}}) \qquad (1)$$

Where:

- $\mathbf{PR_i}$ is the pseudorange measured by the receiver. It is dependent on the signal i.
- $\boldsymbol{\rho}$: is the "true" range generated by the simulator. Could vary based on the allocated transmission channel.
- $(\boldsymbol{X_{RF_i}} - \boldsymbol{X_{PPS}})$: is the delay between RF signal from the simulator at the end of the cable and the 1PPS signal transmitted from the simulator. This difference is defined in the simulator calibration, denoted as **SD**.

Another element in the receiver chain calibration will be the so called X_0, which indicates the delay between the 1PPS IN connector of the receiver and its latching point. For the AKAL project, the value of X_0 on both used receivers can be autocalibrated, so the value of X_0 will be zero, with a related uncertainty reported in the manufacturer specifications. The value of X_0 will be critical to consider if a calibration is performed for a receiver that does not auto-calibrate its internal latching (e.g. the PolaRx4), and it will be measured once the receiver is installed and running.

4.3.1. SIMULATOR CALIBRATION

For the receiver calibration, the delays of the simulator and cable need to be defined and removed from the total delay.

Figure 4-2 Visualisation of example reading from the Oscilloscope.

In the AKAL project, a newly developed correlation software is able to process the RF data coming from the simulator. The RF data are captured using an oscilloscope and post-processed. In comparison to the manual observation of the "ditch" in oscilloscope readings, higher accuracy can be achieved by means of a correlation software, and it is possible to distinguish each individual signal in every frequency, including longer codes like the P ones.

With the use of the Keysight Infiniium Oscilloscope (available at Estec laboratories) it is possible to log up to 5 ms of data in two channels, one for the RF signal and one for the 1PPS generated by the simulator. To maintain synchronization of the longer codes (e.g. P-code), the simulation is started always at the beginning of the GNSS week, or TOW equals to zero. In Figure 4-2 we can observe the available oscilloscope, with a visualisation of typical log of simulator RF and 1PPS data. The jump of the power level in the RF data (green) can be easily noticed, and thus confirm the beginning of the simulation. The trigger value is set to the RF data, and the voltage level will depend on the oscilloscope and simulator configuration. In the figure the trigger is set at 2.1 mV for the Single Spirent simulator.

The correlation software is used for processing the data collected by the oscilloscope, in order to measure the delay of each individual signal at the end of the cables. The new correlation software was developed in Matlab, with capabilities to calibrate all signals currently available from the Spirent simulator: L1C, L1P, L2P, L5Q, E1C, E5Q, E7Q, E8Q, E6C, G1C, G1P, G2C, G2P (Rinex naming convention). The block scheme of the software is presented in Figure 4-3.

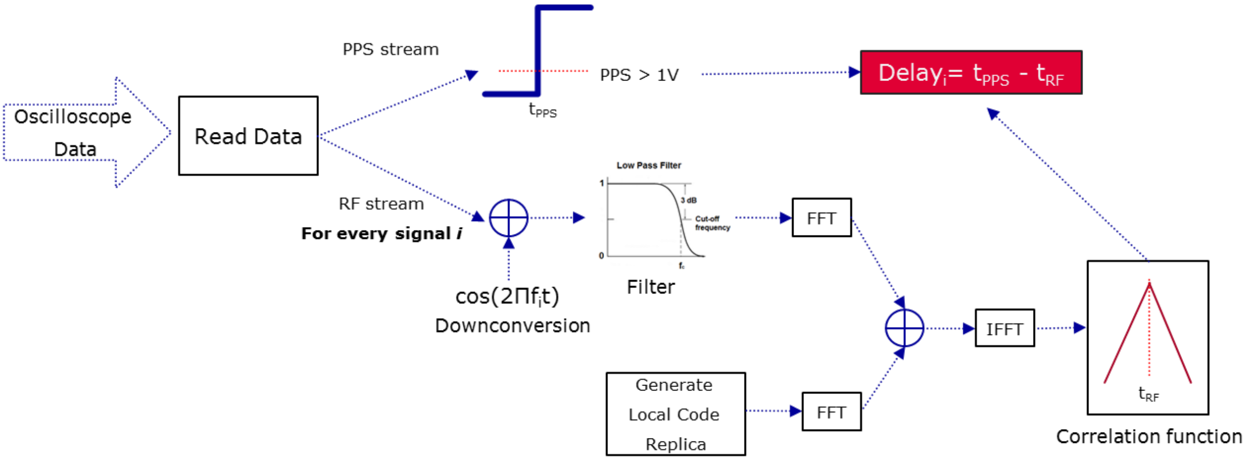


Figure 4-3 Block diagram of the correlation software for simulator calibration

The data from the oscilloscope is read in two different data streams, the PPS signal and the RF signal. The PPS signal is used to find the transition time, and in this way the calibration will not be dependent on the oscilloscope trigger level. For every signal that will be processed, the RF data is then down-converted to baseband, filtered with a tailored bandpass filter, transformed into the Fourier domain, multiplied with a local code replica and inverted to the time domain in order to observe the correlation function peak. Finding this peak, we can obtain the time of the beginning of the code, and the difference with the PPS signal, will be the delay of the simulator, **SD**, at the two ends of the cables connected to the receiver.

The software includes the possibility to perform coherent and non-coherent summations to increase performance and sensitivity. It is important to use the same pair of cables during the receiver calibration or have them thoroughly characterized, as changing the cables after simulation calibration and not carefully adjusting for the different delays can easily void the validity of the procedure.

4.3.2. RECEIVER CALIBRATION

Once the simulator delays are defined, the same simulation scenario is retransmitted to the receiver. One run of the calibration lasts around sixty minutes, in order to collect valid statistics and give time to the receiver to stabilize the measurements, and it will include one geostationary satellite per constellation, which will be the ones used for the calibration.

The RINEX files containing the recorded pseudoranges are then compared with the one reported by the simulator by means of a dedicated Python script. Combining the results from the pseudorange comparison and the simulator calibration, the receiver delays for the different signals are calculated according to the equation (1).

4.3.3. FURTHER STUDIES

During the execution of the AKAL project, several additional tests and verifications were made in order to adopt the procedures and define a level of uncertainty. The detailed description of the tests as well as the initial validation of the accuracy can be found in [RD.3]. Novel results are presented hereafter in a condensed form. During the tests we confirmed that:

- Delays between tracking channels in the GNSS receiver are usually a small number, thus negligible in final calibration value. This statement was tested on Septentrio PolaRx4 and PolaRx5 receivers, as well as Dicom GTR51. For other receivers, additional tests might need to be performed, although no big changes between tracking channels are expected.
- There is a bias in the pseudorange calculation of the receivers for shorter GNSS codes, due to the use of zero Doppler measurements generated by the simulated geostationary satellites. This bias is dependent on the code (PRN), length and rate, and it is dominant in shorter codes, like L1C. The results indicates that the maximum bias can be up to 1 ns, and that if we are going to use geostationary satellites for the calibration, the final value should be the average of several different PRN numbers, due to the PRN bias being PRN dependent and uncorrelated between satellites. Figure 4-4 and Figure 4-5 presents the bias observed during tests.

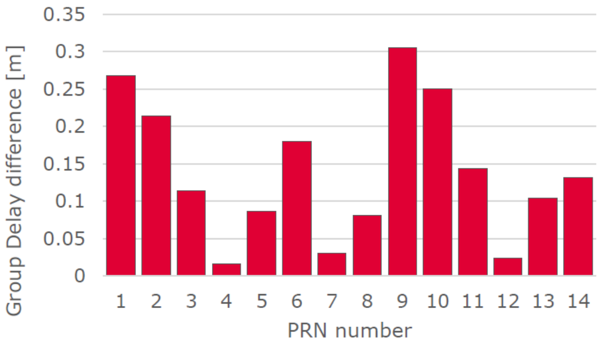


Figure 4-4 Obtained Group delay variations for different PRNs and signal L1C

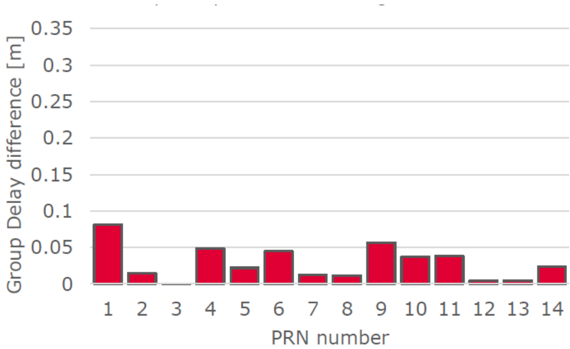


Figure 4-5 Obtained Group delay variations for different PRNs and signal E1C

- The filtering of the signal is necessary in order to obtain good repeatability of the results, once the RF data is down-converted to baseband. If the filter is not included, aliasing effects of higher frequencies distort the correlation function and can affect the peak position, and produce errors up to several nanoseconds in the obtained group delay. Figure 4-6 shows the shape of the correlation function with different filter bandwidth, and it is easy to observe the effect of the filter. During the studies, the conclusion was to use a wider filter than strictly necessary (>20 MHz) in order to avoid translation of the peak, and to have a narrower peak making it easy to identify the true maximum.

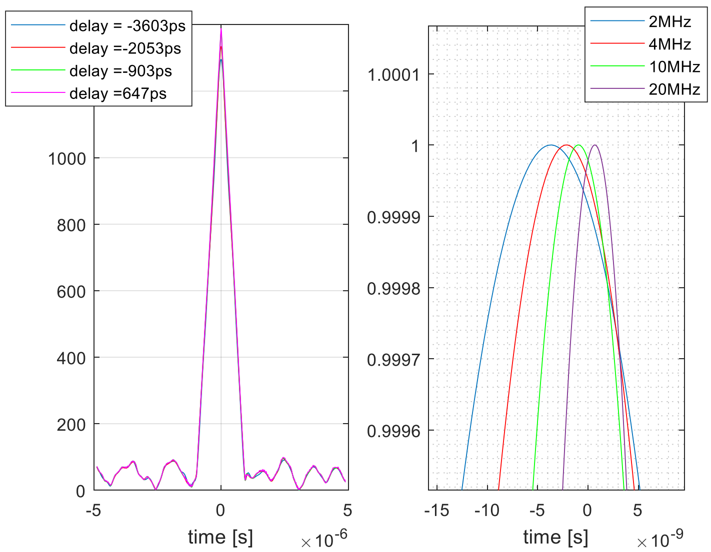
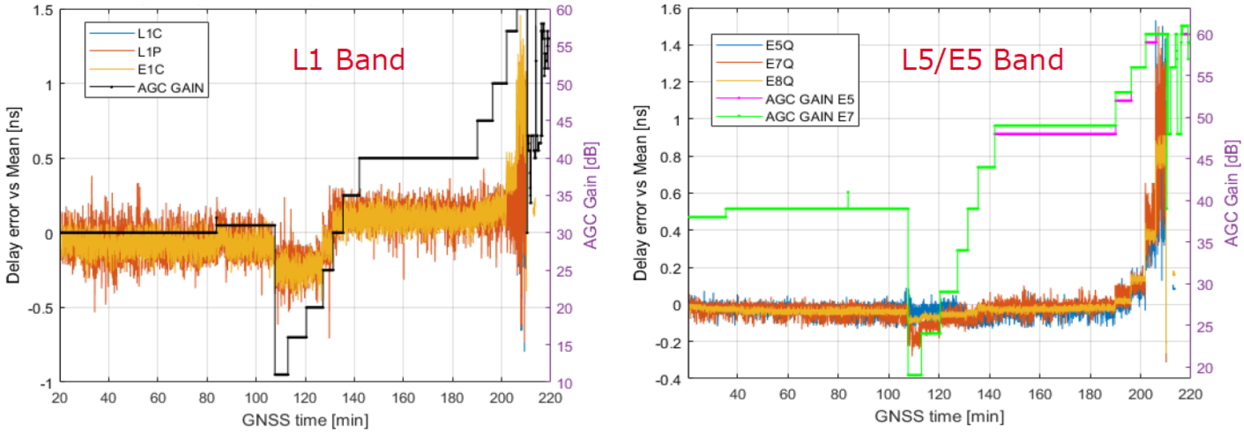


Figure 4-6 Comparison of different filter bandwidth for signal L1C

- Changing the power of simulated signal may have an effect in the pseudorange computed by the receiver. This effects can be caused by the Front-End of the receiver, and will be unique for each receiver model and brand. The front-end has an Automatic Gain Control (AGC) element, which is in charge of adjusting the dynamics of the input signal to the dynamic range of the analogue to digital converter. This means that changing the power of the incoming signal will change the gain value of the AGC, and thus might change the group delay value of the component. Figure 4-7 presents the results of performed tests, and we can observe how for the top and bottom values of the AGC gain, the effects on the delay are much more accentuated. The drawn advice is to check the linear region of the AGC and adjust the simulated power to fit it. In that way we expect to have variations only in the order of 100 ps.



(a) (b)

Figure 4-7 Group delay changes with respective AGC values for L1/E1 (a), and for L5/E5 (b) signals

- The receiver delay variations due to temperature changes are not very significant. As timing receivers are usually working in temperature-stable environment, it is advised to perform calibration in the same temperature as the one used in time laboratory. During the characterization of the temperature, the maximum temperature slope for all signals was around 100 ps/C. Figure 4-8 presents the temperature slopes for Septentrio PolaRx5 receiver and GPS signals.

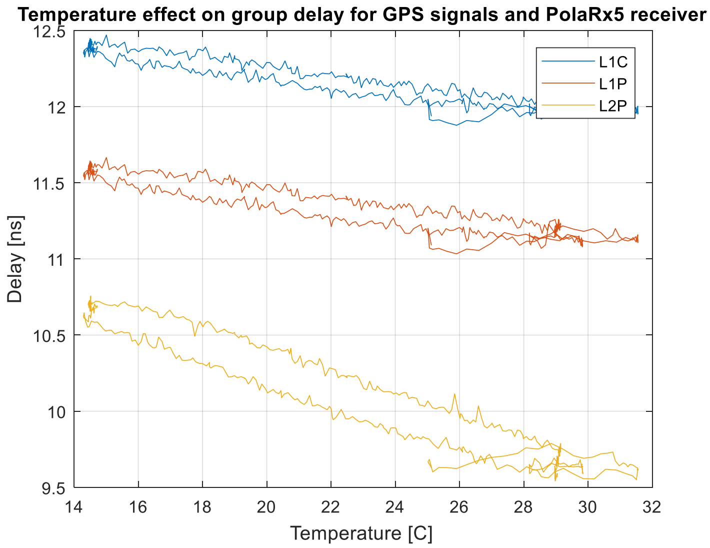


Figure 4-8 Temperature sensitivity for GPS signals and PolaRx5 receiver

4.3.4. RECEIVER CALIBRATION UNCERTAINTY

Table 4-1 presents maximal uncertainty defined based on the performed tests. The values corresponds to the worst case scenario. In the final calibration reports, the final uncertainties will be reported individually for each signal.

Table 4-1 Uncertainty budget for the receiver delay measurement U(Xr)

Uncertainty Source	Type	Origin of the value	PolaRx5 U(*) [ps]	PolaRx4 U(*) [ps]	GTR51 U(*)
Pseudorange measurements	*A/B*	*$U(PR_i)$*	*530*	*535*	*560*
Correlation software	*A/B*	*$U(X_{RFi} - X_{pps})$*	*180*	*180*	*180*
PPS latching	*A/B*	*U(Xo)*	*115*	*170*	*115*
Maximum uncertainty for receiver calibration U(Xr)			***571****	***589****	***600****

**The final uncertainties obtained for each signal is reported in the calibration reports [RD.6] and [RD.7].*

4.4. ANTENNA CALIBRATION

The antenna calibration consists on estimating the time delay due to the signal propagation through the antenna. It is therefore necessary to determine the input and output ports of the device. An antenna allows the transition of the electromagnetic wave between a guided environment (cable) and a free environment (air). One of the access ports is defined by the physical connector of the cable, named CONN (antenna/cable)., while the other port can be defined arbitrarily. It is customary to choose the position of the Antenna Phase Centre (APC) which is a mathematically descripted point, assumed to be the interface point between the guided environment and the free space because is the point for minimum phase variations versus elevation angle.

Given that for time transfer applications, we are not using the phase information of the signal, we are not forced to choose the APC point. AKAL procedures chose a physical point in the antenna, that we can easily measure with a laser pointer, and reference all the measurements to this physical point instead of the APC. This choice slightly decreases the uncertainty of the measurements, as well as making the calibration procedures much simpler than they have been traditionally. The proposed physical point is the Antenna Reference Point (ARP), which is a well-defined point for each GNSS antenna model and can be retrieved by looking at the antenna description files.

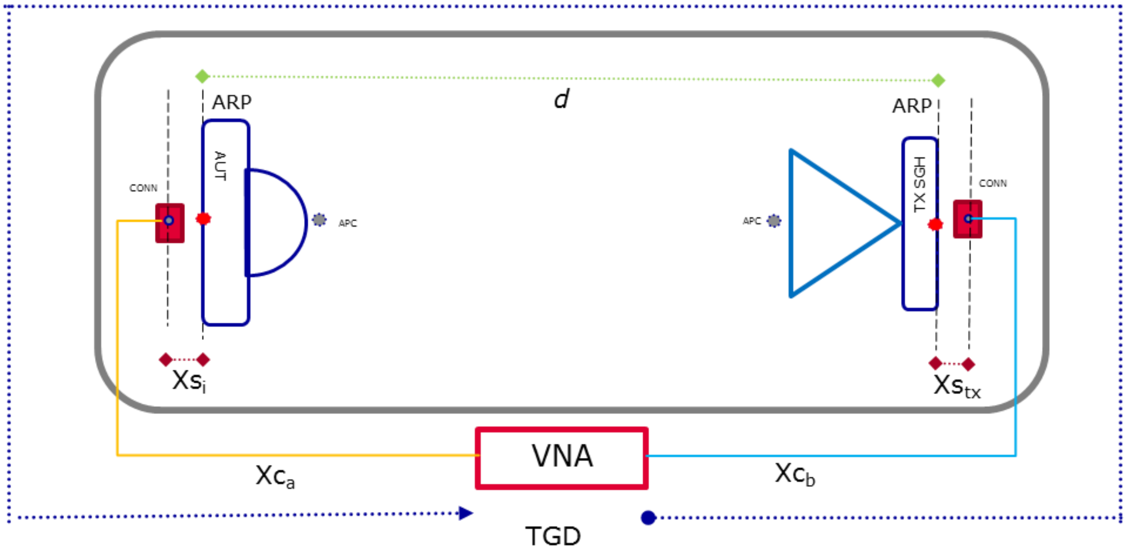


Figure 4-9 Antenna Calibration setup

In the calibration procedures, the antenna under test (AUT) is placed inside an anechoic chamber, in order to reduce the effects of multipath signals and other interferences, and the measurement of the total group delay is obtained by means of a VNA as observed in see Figure 4-9.

It is important to make sure that the physical distance between the two antennas satisfy the criteria of the far-field region. E.g., for an antenna with a diameter of 32 cm like the one used for the AKAL project, the far-field region limit is around 80 cm. This distance is maintained at ease in all directions inside the CATR facility located in ESTEC.

Using the setup shown in Figure 4-9, the Antenna group delay values can be obtained as:

$$XS_i = TGD - Xs_{Tx} - d/c \quad (2)$$

Where:

- XS_i : Internal delay of the AUT
- TGD : Total group delay measured by the VNA
- Xs_{Tx} : Internal delay of transmitting antenna (previously calibrated)
- d/c: Delay due to the signal propagation in the air. It is computed based on distance between the ARPs, measured by the laser tracker.
- The VNA has to be calibrated at the end of the cables, to measure correctly the two CONN ports of the antennas.

Prior to the calibration of the GNSS antennas, the group delay of the transmitting antenna needs to be defined. In our procedures, Standard Gain Horn (SGH) antennas are used as the transmitting ones. The SGH are built in a very standardized and repeatable way, with no cables or electronics inside, obtaining very good repeatability of Gain and APC between twin antennas. These characteristics make the SGHs ideal for the transmission of reference signal. Additionally, SGHs have a good directivity and gain (around 12 dBi), which decrease the reflections of the signals in the walls of the chamber. The SGH antenna, as is used for calibration, is shown in Figure 4-10.

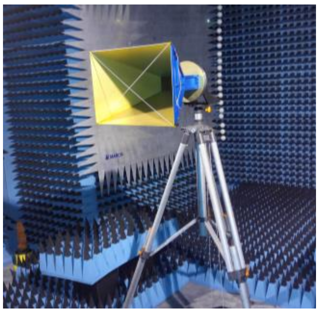


Figure 4-10. SGH used during the initial calibration test campaign

4.4.1. FURTHER STUDIES

During the AKAL project, the use of the CATR facility, as well as possible tests and configurations for the group delay characterization were thoroughly investigated. The detailed description of the tests as well as the initial validation of the accuracy can be found in [RD.3].

A brief summary of the main findings is:

- GNSS choke ring antennas calibrated during the project are symmetric and do not show significant variations versus azimuth angles. The main variations (up to 300 ps) are elevation dependant. Figure 4-11 presents the group delay grid versus azimuth and zenith angle for the Leica AR20 and we can observe that variations are mainly along the zenith angle axis. As similar behaviour is expected for other kind of choke ring antennas, the AKAL procedure measures only group delay variations versus elevation (zenith) angle. In case of calibrating different type of antenna, this statement need to be confirmed by measurements in both rotations.

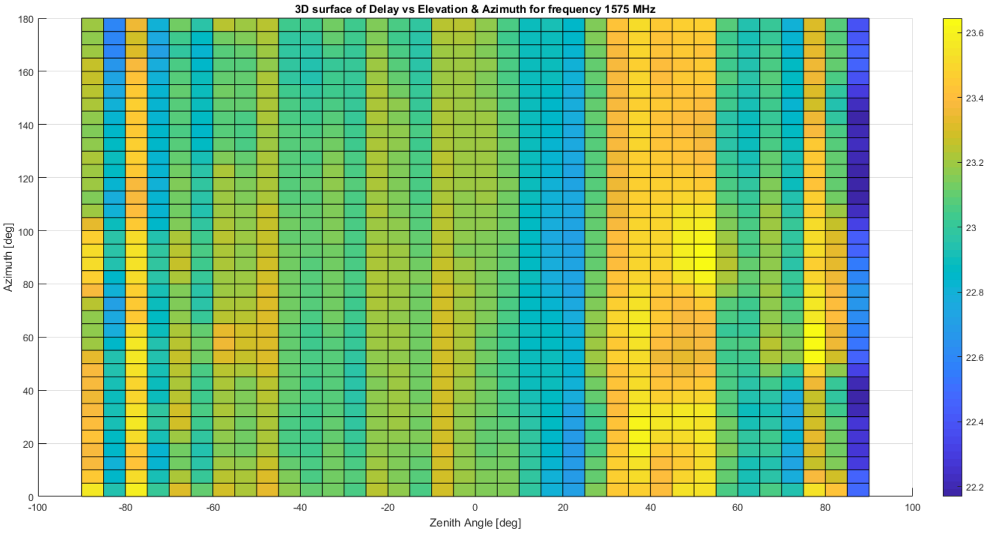


Figure 4-11. Group delay grid versus Azimuth and Elevation. Change of azimuth angle is not producing significant variation (columns)

- For delays referenced to the ARP, a slightly different computation approach needs to be implemented to translate the measurements to more common conventions. Figure 4-12 highlights the differences between both methods, but the final computed delay will be equivalent, whichever method you decide to use. The values of Xs_0 and Xs_1 are referring to the specific calibrated group delay value for given azimuth and elevation angles.

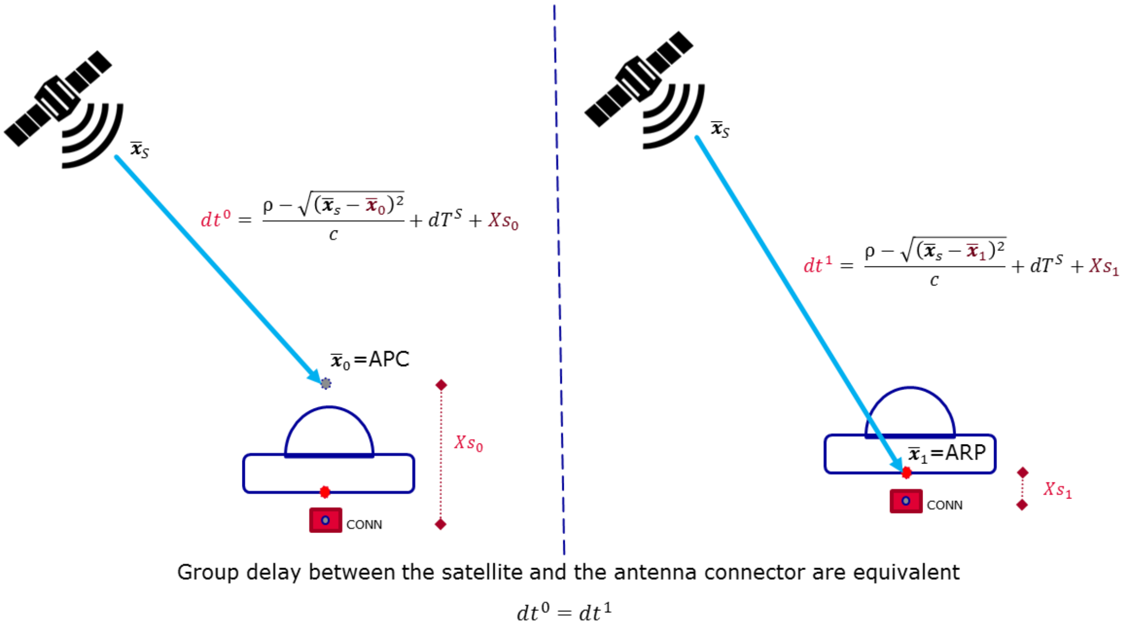


Figure 4-12 Graphical representation of the group delay calculation.

- As traditionally the APC has been used as the reference position for the GNSS antenna calibration, the calibration value between the APC and the connector, is reported in the CGGTTS format and included inside the INTDLY. To make the calibration compatible with current version of CGGTTS, the method of transformation between ARP and APC reference is defined and used.
- Averaging method of group delay bandwidth can have significant impact on the calibration value. Each individual signal group delay value was obtained by averaging the measurements in a specific shape, based on the real modulation of such signal. The effects of the different modulations averaging can be observed in Figure 4-13, for Leica (a) and Novatel (b) antennas. It is believed that this way of averaging signal bandwidth group delay is the most representative.

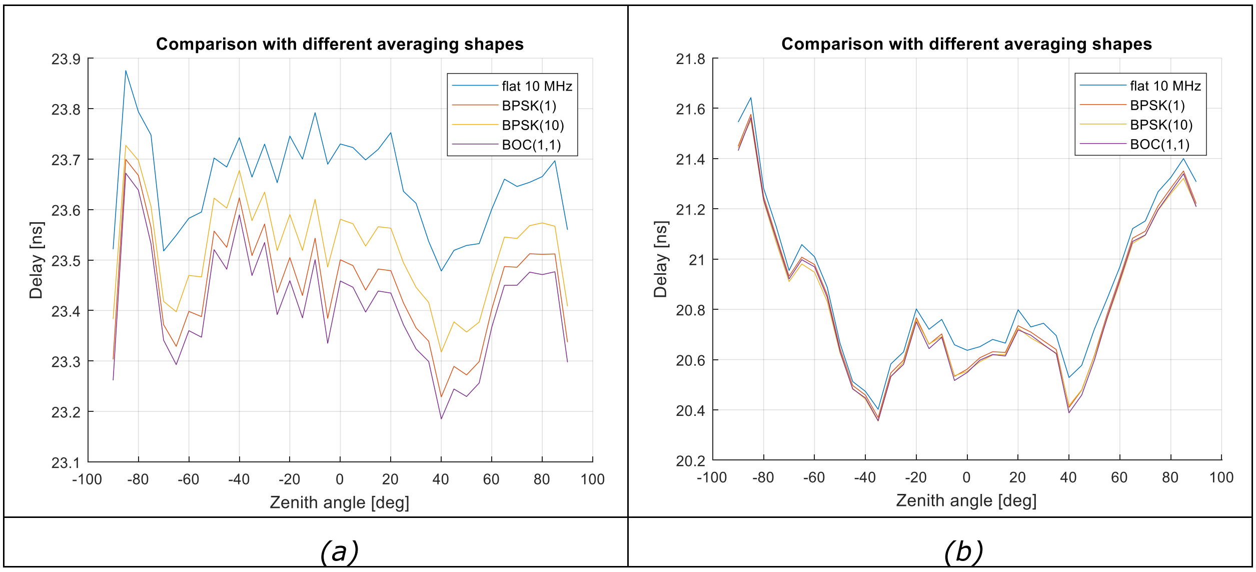


Figure 4-13. Effect of different averaging shapes based on GNSS modulations, for LEICA (a) and NOVATEL (b) antennas

4.4.2. ANTENNA CALIBRATION UNCERTAINTY

Table 4-2 presents the uncertainty defined based on the performed tests. The values corresponds to the worst case scenario, especially for room scattering and angular dependency.

Table 4-2.Uncertainty estimation of the group delay value of the antenna

Uncertainty Source	Type	Origin of the value	U(*) 1-sigma [ps]
Measurement	A/B	VNA – Measurements S12. Value from specifications	200
Facility Characterization	A/B	Assessed by multi-position acquisition of the two SGHs antennas	132
Room scattering	A	Max variations of values at different positions	300
Angular dependency	A	Std. of variation over Azimuth and Elevations	300
Antenna group delay U(XS_i)			**487**

4.5. CABLE CALIBRATION

The cable delay (Xc) is defined as the transit time of the signal between of the two ends of the cable In general, the group delay is a function of frequency, but in non-dispersive devices, such as cables, group delay will be mainly constant for the whole frequency span. Discrepancies are mainly caused by imperfections on the cable and measurements equipment.

The cable calibration is performed by means of a VNA, which transmit a signal to the DUT and is able to measure the scattering parameters (see Figure 4-14). These measurements include reflection and transmission coefficients of a device, including both amplitude and phase variations induced by it. The phase variations can be easily transformed into group delay values.

Figure 4-14 Graphical representation of S-parameters (S_{out-in}; out – port which analyse the output from the DUT, in – port which transmit signal into the DUT).

AKAL procedures focused on two measurement techniques for the cable delay: reflection and transmission. Depending on the cable installation either technique can be used to accurately define its group delay.

4.5.1. FURTHER STUDIES

Several additional tests and verifications were made in order to adopt the procedures and define reliable uncertainty. The detailed description of the tests, as well as the initial validation of the accuracy can be found in [RD.3]. As the results of the performed tests we obtained that:

- VNA measurements of 50 m cables, especially the ones performed using the reflection technique, might be affected by high ripples, which period can be larger than the configured frequency span. Figure 4-15 presents the group delay versus frequency for reflection technique. Due to these effects, three approaches of final group delay calculation were chosen to analyse during tests: average, linear regression and slope between extreme frequency data points. The results showed that averaging over the whole frequency span is the most reliable cable delay definition.

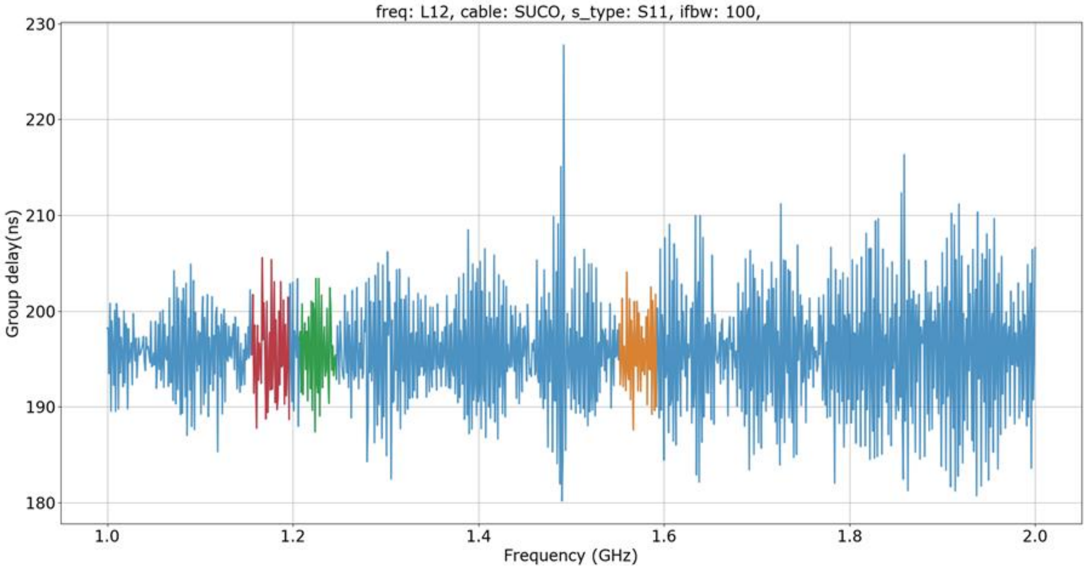


Figure 4-15 Group delay for SUCO cable. Frequency span 1GHz, reflection technique. In Red we have L5 frequency, L2 is depicted in green and L1 in yellow.

- Deformation of the rigid cable has an impact on the overall group delay of the cable. Figure 4-16 presents the changes of the group delay of the cable in reference to different rolls of the cable. In this test, we analysed several radius of the cable, and observed that up to 150ps variations are obtained in the group delay. Due to this, it is advised to perform calibration using reflection technique on the installed cable.

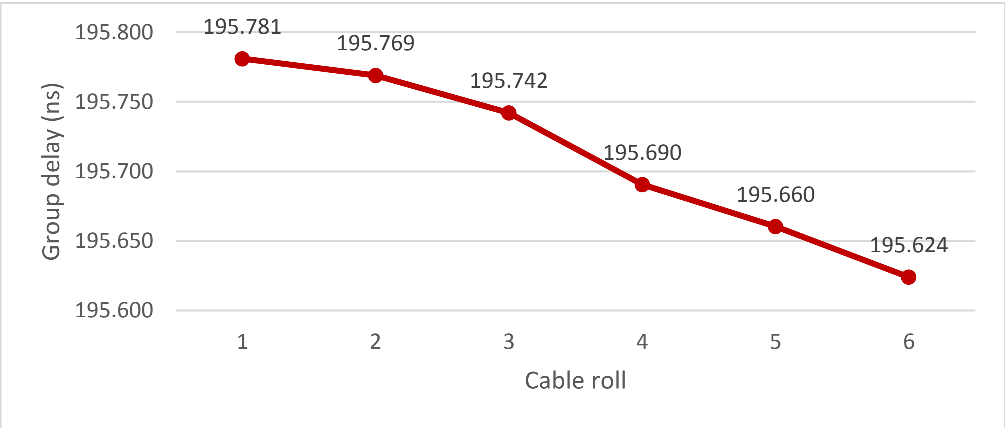


Figure 4-16 Cable deformation and the overall group delay.

- Impact of the external temperature of the cable is almost negligible in the group delay. Figure 4-17 presents the temperature slope of one of the measured cable during the tests. The temperature slope during tests was 1.6 ps/°C when the whole cable was inside the thermal chamber. In standard installation though, only few meters of the cable are outside the building and suffer from environmental factors, and in this case the temperature slope decreased to 0.2 ps/°C. Temperature variations of the cable are neglected from the uncertainty budget.

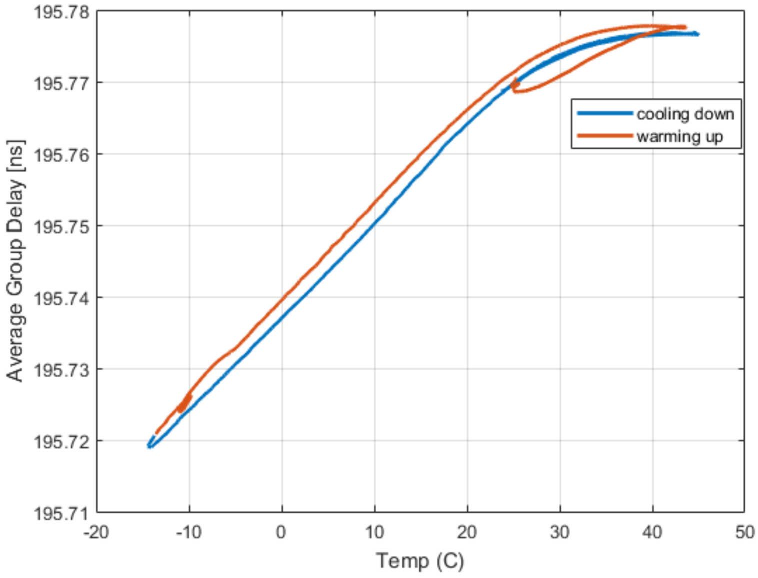


Figure 4-17 Group delay versus temperature – Suco_S21_whole

4.5.2. CABLE CALIBRATION UNCERTAINTY

Table 4-3 and Table 4-4 presents typical uncertainty defined based on the performed tests.

Table 4-3 Final transmission uncertainty.

Uncertainty Source	Type	Origin of the value	Cable U(*) [ps]
VNA measurements (average method)	A/B	Device specification	40
Thermal analyses	B	Thermal measurements (cable partially outside building)	10
Deformation	B	(Optional) Empirical test	(150)
Uncertainty for 50m SUCO cable calibration U(Xc)			**41 (156)**

Table 4-4 Final reflection uncertainty.

Uncertainty Source	Type	Origin of the value	Cable U(*) [ps]
VNA measurements (average method)	A/B	Device specification	124
Thermal analyses	B	Thermal measurements (cable partially outside building)	10
Uncertainty for 50m SUCO cable calibration U(Xc)			**124**

5. VALIDATION RESULTS

Validation of the calibration was done by the Royal Observatory of Belgium (ORB) to confirm the uncertainty level obtained during the calibration activities. The verification was performed by comparison of:

- Two AKAL absolutely calibrated chains in common clock and common antenna configuration,
- The GOLD chain with Group 1 / Group 2 stations of the BIPM in common clock configuration,
- Time Link between ESTEC and PTB,
- Two stations absolutely calibrated by different laboratories (AKAL and CNES).

In order to perform all necessary tests, the GOLD station was transported between three different time laboratories: ESTEC, ORB and PTB (as presented in Figure 5-1).

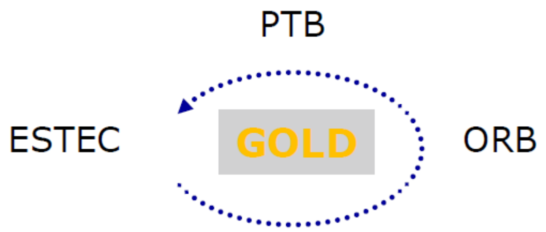


Figure 5-1 Scheme of the validation location

5.1. VALIDATION OF TWO ABSOLUTELY CALIBRATED CHAINS

The first validation was done at ESTEC, where the two calibrated chains were put in a common-clock setup. The goal of this setup was to provide an internal validation, as any systematic error in the measured hardware delays of the two absolutely calibrated stations is cancelled in the difference.

In order to isolate any possible errors from the receiver or antenna calibration, or an effect of antenna position, two different setups have been used: (1) the two complete calibrated chains were connected to a common clock, using each its calibrated antenna and calibrated receiver; and (2) the two receivers were connected to the same antenna using a splitter. Figure 5-2 presents the exemplary installation of the two separate receiver chains.

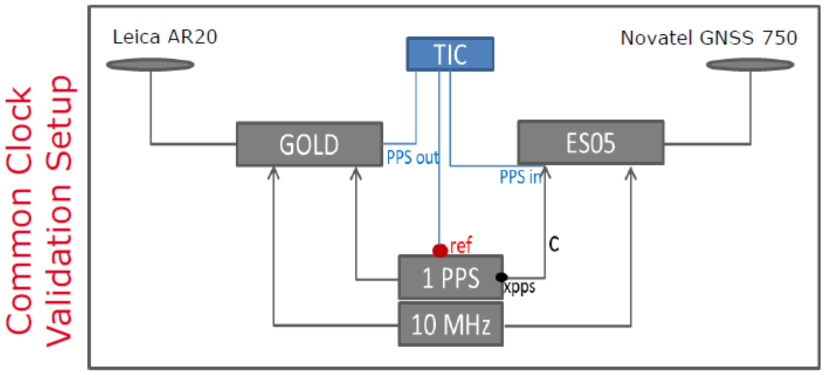


Figure 5-2 Diagram of the exemplary common clock installation.

The results of the common-clock validation are presented in Table 5-1. The differences are compared to the theoretical uncertainty defined during the calibration. Values coloured on red are within 3 sigma uncertainty, in orange are within 2 sigma and in green values within 1 sigma uncertainty. The discrepancies were the base for further investigations of the error source, and the details are found in [RD.5].

Table 5-1 Validation in Common-clock setup GOLD-ES05 using 5 days: 32-36/2018

	Average pseudorange differences (ns)	TOTDLY GOLD (ns)	TOTDLY ES05 (ns)	calibrated differences (ns) GOLD-ES05
C1	10.61	217.56	230.69	2.52
P1	11.06	217.33	228.68	0.29
P2	13.34	212.62	227.26	1.30
E1	12.06	217.72	230.31	0.53
E5a	23.84	217.03	241.66	0.79

5.1.1. INTER-SATELLITES CODE DIFFERENCES

After observing the differences show above, especially the one in P2 signal, an effort was placed towards observing these differences per satellite, and interesting results were found as shown in Figure 5-3.

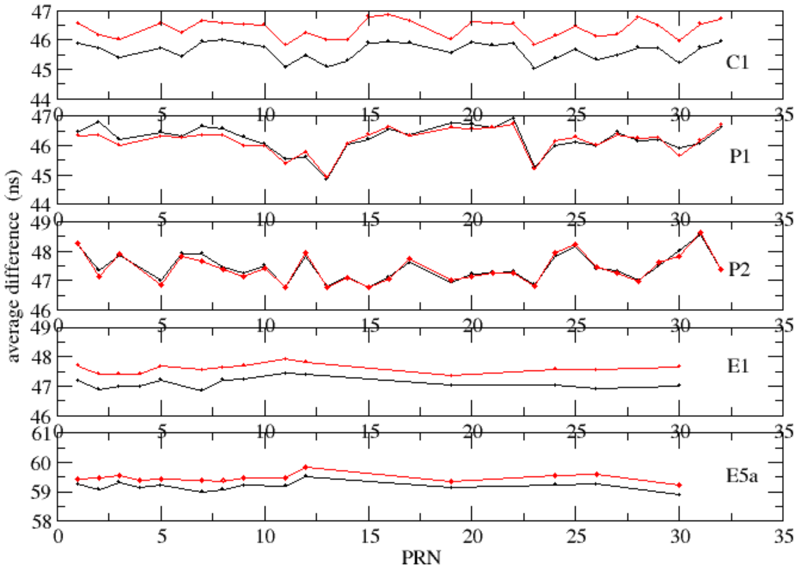


Figure 5-3 Mean pseudorange differences observed per satellite for the different GNSS signals. Black and Red lines indicated the multipath mitigation option turned ON and OFF, respectively

From the figure we can observed how the variations per satellite of P2 code are larger than for the other codes and its peak-to-peak variations are in the order of 2 ns, while for P1 and C1 is of 1 ns and for E1 and E5 is 0.5 ns. This also confirms that Galileo satellites pseudorange generation are more homogenous between satellites than the GPS ones.

The effect of the chip-shape of the satellites have been observed before, and with these results we are able to observe its impact on absolutely calibrated stations. Of course these variations are receiver-dependent and will be based on the techniques used to track each signal. It is important to state that this effect still does not explain the 2.5 ns differences observed for C1 code.

In Figure 5-3, two lines are present for each GNSS code. The black line shows the differences observed when the multipath mitigation of the PolaRx5 receiver is turned on and the red line represents the differences when the option is off. We can see that for P1 and P2 codes the option does not change the results at all, while for other signals a bias is created, hinting at a change in the tracking configuration of the receiver between the two cases. As we calibrated the receiver with the multipath mitigation option turned on, all further results are shown for this option.

5.2. COMPARISON WITH GROUP 1/ GROUP 2 BIPM STATION

Further analysis were made with traveling GOLD station at ESTEC, PTB and ORB. These validations were done for GPS codes only as those are the ones calibrated by the Group 1/Group 2 BIPM stations, and currently considered for the time links and computation of the International Atomic Time (TAI). Figure 5-4 presents the differences between absolutely calibrated GOLD station and Group 1/ Group 2 BIMP reference.

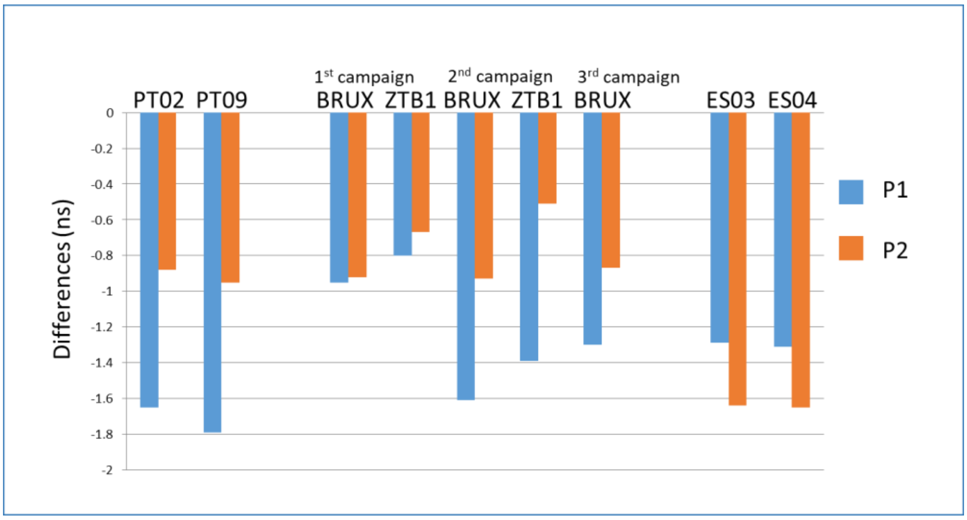


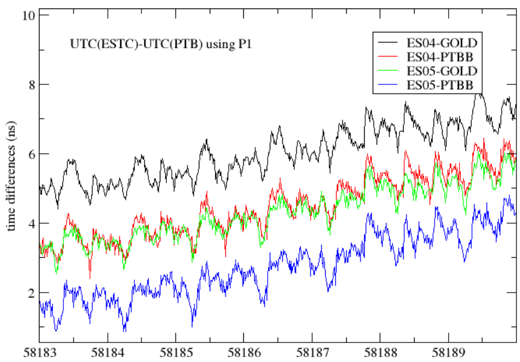
Figure 5-4 Calibrated pseudorange differences between GOLD and Group1/Group2 stations

There is a good agreement between the comparisons made in the same laboratory with two different stations. Indeed, the results for PT02 and PT09, BRUX and ZTB1 are all in good agreement, and the results for ES03 and ES04 are identical. However, from station to station we can observe some differences. From the values obtained in the comparisons, we can conclude that there is probably a bias of about -1 ns between the reference for the Group1/Group2 stations and the AKAL absolute calibration of the station GOLD, and on top of it, variations between different laboratories are within +/- 0.6 ns, which is believed to be a very good agreement.

5.3. TIME LINK BETWEEN ESTEC AND PTB

Once the GOLD station was located at PTB the time link comparison between ESTEC and PTB was performed, in which four station were used: GOLD and PTBB at PTB and ES05 and ES04 at ESTEC. The results are presented in Figure 5-5.

The results obtained in this validation confirmed the differences observed already in the common-clock validation at ESTEC and the comparisons of the GOLD station with the Group1/Group2 calibrated stations PTBB and ES04.



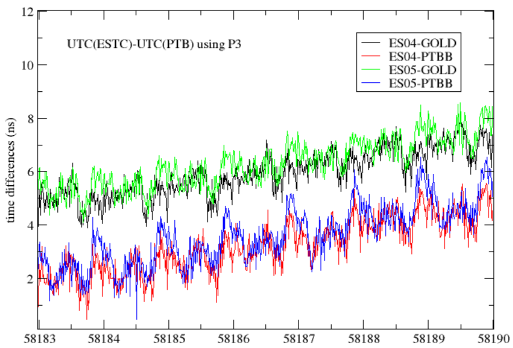


Figure 5-5 Time transfer between UTC(ESTC)-UTC(PTB) using difference receiver pairs.

5.4. COMPARISON WITH STATION ABSOLUTELY CALIBRATED BY DIFFERENT LABORATORY

The GOLD station was installed in common clock configuration with ORBA receiver chain, which have been previously calibrated in absolute by CNES. Two separate comparison campaigns were done. Figure 5-6 presents differences measured between the two stations.

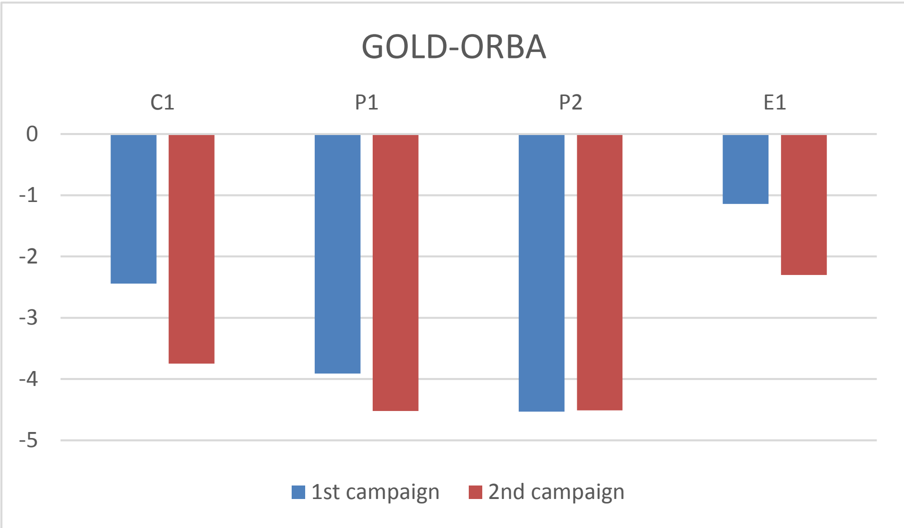


Figure 5-6 Differences (in ns) between ORBA and GOLD calibrations obtained from calibrated pseudoranges differences

We can directly observe that the differences of up to 4.5 ns are significantly above the uncertainty budget of the comparison, when considering the claimed uncertainties on the absolute calibration from both AKAL and CNES. It is currently difficult to explain these differences and further tests on both receiver chains are being performed in order to define the source of the discrepancies.

5.5. SUMMARY TABLE WITH VALIDATION DIFFERENCES

In the tables below, the results from validation activity are combined. In Table 5-2 the comparison between 3 absolutely calibrated stations is shown. GOLD and ES05 stations were calibrated in accordance to the AKAL procedures. The ORBA station delays were defined by CNES. Table 5-3 presents the validation against relatively calibrated BIPM group 1/ group 2 stations.

Table 5-2 Validation against other absolutely calibrated receiver chains.

Location	ESTEC				ORB		
Station 1	GOLD				GOLD		
Station 2	ES05				ORBA		
Installation	CC	CA	CA	Uncertainty	CC	CC	Uncertainty
Other	MM:ON	MM: OFF	MM: ON		MM: ON	MM: ON	
C1	2.52	3.12	2.37	1.16	-2.44	-3.75	1.13
P1	0.29	0.86	0.93	0.95	-3.91	-4.52	1.03
P2	1.30	2.04	2.07	0.99	-4.53	-4.51	1.06
E1	0.53	1.05	0.58	1.06	-1.14	-2.30	1.03
E5a	0.79	1.76	1.50	0.99	-	-	-
How computed ?	ES05.delay - GOLD.delay - pd				ORBA.delay - GOLD.delay - pd		

Table 5-3 Validation against BIPM group 1/ group 2 stations.

Location	BIMP Group 1/ Group 2 validation										
Station 1	GOLD										
Station 2	PT02	PT09	BRUX	ZTB1	BRUX	ZTB1	BRUX	ZTB1	ES03	ES04	
Installation	CC	CC	CC	CC	CC	CC	CC	CC	CC	CC	Uncertainty
Other	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	MM: ON	
C1	1.16	0.84	1st campaign		2nd campaign		3rd campaign		-	-	1.70
P1	-1.65	-1.79	-0.95	-0.80	-1.61	-1.39	-1.30	-	-1.29	-1.31	1.63
P2	-0.88	-0.95	-0.92	-0.67	-0.93	-0.51	-0.87	-	-1.64	-1.65	1.65
How computed ?	BIMP.delay - GOLD.delay - pd										

Abbreviation key:

CC- common clock

CA - common antenna

MM - multipath mitigation algorithms

pd - pseudorange difference

5.6. GALILEO DCBS VALUES

One of the side products of AKAL project are inter-frequency code biases of the satellites, which were computed using absolutely calibrated pseudoranges and an ionospheric corrections. The DCB so-obtained are presented in Table 5-4.

Table 5-4 Satellite DCBs computed from calibrated pseudoranges (ns)

	E1E5a		E1E5b	E1E6
PRN	GOLD	ES05	GOLD	GOLD
1	0.95	1.43	1.26	-2.55
2	2.03	2.45	2.60	-1.75
3	-1.42	-1.30	-1.22	0.92
4	3.51	3.79	3.69	0.41
5	-1.66	-1.25	-1.46	3.67
7	-2.93	-2.70	-2.63	1.40
8	3.99	4.30	4.32	-5.73
9	-0.25	0.17	0.15	-0.46
11	11.75	12.38	11.32	9.61
12	9.39	9.74	8.32	9.28
14	-	-28.91	-	-
18	-	-13.85	-	-
19	4.07	4.24	3.81	1.35
24	-36.77	-36.50	-36.27	24.19
26	-3.87	-3.82	-3.57	-1.90
30	-0.29	0.13	0.16	1.68

Considering the uncertainties on the hardware delays determined by absolute calibration and that the receiver signals delays have been determined without correlation, the final uncertainty on the computed DCBs from calibrated pseudoranges is around 1.0 ns.

6. FINAL REPORT SUMMARY

In the AKAL project, we have expanded, updated and validated the procedures for the absolute calibration of GNSS timing receiver, as well as the related uncertainty budget.

For every part of the receiver chain we have analysed in-depth the procedure for performing the calibration of the group delay. Different tests have been performed in order to confirm previous results, to make ourselves used to the equipment and the measurements, as well as to investigate new topics that have not been previously presented.

For the antenna calibration, a novel procedure inside the Compact Antenna Test Range facility has been developed, and continuous discussions were being held with antenna experts in order to optimize the procedures and obtain the best possible accuracy for the antenna calibration. The characterization of GNSS antenna's group delay, by means of an anechoic chamber, is uncommon in time laboratories and represent the biggest overhead with respect to previous methods. There remains to explore further the possibilities to exploit the anechoic chamber capabilities and its unique features.

For the cable delay calibration, several different tests were performed in order to understand the best configuration for the VNA measurements. By means of these test we were able to identify the weak parts of the measurements, as well as the most accurate configuration based on the measuring method used. As the result, we identified the configuration parameters and the step-by-step procedures for accurate cable calibration.

For the receiver calibration multiple tests were done profiting of the available timing receivers in ESTEC's laboratories. We were then able to compare favourably the results obtained during the calibration to other previously published results. We also investigated the effect of the correlation software used for simulator delay, and the use of different simulators to obtain the best possible values. The inter-channel hardware delay was assessed, and confirmed that its effect is negligible in the overall receiver calibration, while the PRN dependency was observed and its impact mitigated.

Finally, the step by step procedure was put in place and two separate receiver chains were calibrated:

- "GOLD" station: PolaRx5, Leica AR20 and 50m SucoFeed ½' cable.
- "ES05" station: GTR51, Novatel 750 and 50m Heliax ½' cable.

The uncertainty level of the calibration was validated, modified and enhanced by ORB specialists during validation and verification tests. All above activities were documented in:

- AKAL_TN-02 – Procedure definition, initial tests and uncertainty definition,
- AKAL_TN-04 – Results from the validation campaigns,
- AKAL_As-run-PRC – step-by-step procedures developed in scope of AKAL project.

These documents complement the Final Report to the largest possible extent, and can be considered as annexes to it.

We believe that defined procedures and obtained uncertainty results, fulfil the requirements set at the beginning of AKAL project.

7. RECOMMENDATIONS

As in every research and study project, some solution become base knowledge after performing several dry runs and validation tests. Based on the lessons learnt during AKAL project, we propose domains in which further studies or developments might be performed in order to better understand the factors composing the absolute calibration and its uncertainty budget.

General recommendation on absolute calibration and time-transfer:

- Investigate the impact of real environment in the effectiveness of the antenna calibration.
- Extend the validation and verification against other BIMP group1/ group2 station or different absolute calibration procedures.
- From the AKAL activities, Galileo seems very advantageous for Time Transfer, due to the better consistency between receiver hardware delays of all the satellites with respect to GPS.
- Beidou absolute calibration should be considered for further activities.
- GLONASS calibration has been demonstrated, although with increased complexity due to the difference frequencies. As a results, its use for time transfer is strongly affected by the associated increased uncertainty.

In details, the AKAL procedures can be enhanced with the further studies in domains:

- Receiver calibration:
    - Perform receiver calibration with satellites' signals simulated in real Medium Earth Orbits (MEO).
    - Incorporate tracking loop (or Software Defined Receiver) into correlation software.
    - More thorough examination of GTR51 (access to Javad board) and other timing receiver brands.
    - As the temperature of the receiver can change due to the increased processor activity, thermal sensitivity tests with record of the receiver internal temperature are recommended.
    - Understand the impact of real satellite signals, and their differences with respect to the simulated ones.
- Cable calibration:
    - Investigate the impact of the cable integrity imperfections on the final group delay.
    - Flexibility of the cable and ease of installation is considered more important than very strict phase stability. It is recommended to perform further tests with low-loss flexible cable.
- Antenna calibration:
    - Full antenna pattern characterization, including calculation of APC for all new signals and frequencies.
    - Thermal sensitivity tests of the antenna and its impact in the group delay.
    - Further investigation about room scattering and environmental factors should be investigates with corresponding uncertainty.
    - Increase distance between antennas to reduce mutual coupling.

We believe that with further investigation of these topics, the uncertainty of the procedures can be decreased, although the minimum limit is believed to be not far from what obtained so far with AKAL procedures. It is advised to focus on these domains during a possible continuation of the AKAL project, as well as discussing on the impact of "real" signals and their differences with the simulated ones, which seem to be causing major impacts in the validation of the calibration

ANNEX A. TECHNICAL DATA PACKAGE DESCRIPTION

Technical data package consists of deliverable documents and software created during AKAL activity. Short description of them can be find below.

A.1. TECHNICAL NOTES

A.1.1. TN-01: REVIEW AND TRADE-OFFS REPORT.

Technical Note 01 summarizes the main findings after reviewing past and recent literature on absolute calibration of GNSS receivers, and makes a preliminary selection and description of the calibration methods chosen for the different elements of the receiver chain (antenna, antenna cable, and receiver).

A.1.2. TN-02: PROCEDURE FOR THE ACCURATE CALIBRATION OF MULTI SYSTEM/MULTI-FREQUENCY GNSS RECEIVER CHAINS.

In Technical Note 02, a detailed explanation of the procedures necessary for absolute calibration of GNSS receivers is described. It is divided into three main Sections, each focusing on a different part of the receiver chain. For antenna, receiver and cable calibrations, several tests results have been described, each highlighting the impact of a specific parameter or configuration in the final result of the calibration. The Technical Note 02 identify critical elements of the calibration, optimize the required configuration and estimate the final uncertainty.

A.1.3. TN-03: PROCEDURE VERIFICATION AND VALIDATION DESCRIPTION.

Technical Note 03 (TN-03) explains in details the validation strategies that were applied to verify the results of absolute calibration. This document was used as a guidelines for the validation activity.

A.1.4. TN-04: VALIDATION OF THE PROCEDURE FOR THE ACCURATE CALIBRATION OF MULTI-SYSTEM/MULTI-FREQUENCY GNSS RECEIVER CHAINS.

Technical Note 04 (TN-04) summarizes the validation of two receiver chains calibrated with AKAL absolute procedures. The validation was performed in three different time laboratories and compared with BIMP group 1/group 2 stations. In the conclusion, the reliable uncertainty of the AKAL procedures was estimated.

A.1.5. PRC: STEP-BY-STEP PROCEDURE FOR GNSS RECEIVER CHAINS.

Step-by-Step Procedure (PRC) is initial set of step-by-step instruction for absolute calibration of GNSS receiver chains. It is divided into three main Sections, each one focusing on a different part of the receiver chain. The initial procedures were prepared at the beginning of AKAL activity based on early dry-run results, thus presented approach is not optimized. As-run PRC document is an updated version of PRC and is suggested for further use.

A.1.6. AS-RUN PCR: AS-RUN STEP-BY-STEP PROCEDURE FOR GNSS RECEIVER CHAINS.

As-run Step-by-Step Procedure (As-run PRC) is a detailed guideline for absolute calibration of the GNSS receiver chain. The procedure were define based on the test results obtained during AKAL project. It is improved and enhanced version of the PRC document.

A.2. SOFTWARE

A.2.1. ANT_CAL

Matlab script, which analyses VNA phase observations, obtained during antenna calibration. Software calculates group delay values and average it with shape based on the modulation of specific signal. Delay is reported as single value for each GNSS signal.

Input:

- phase measurements data in .cut format.

Output:

- antenna group delay with graphs.

Main file of the script is 'ReadANTENNAdata.m'

A.2.2. CABLE_CAL

Python script, which analyses VNA phase and group delay observations, collected according to the AKAL procedures. The main aim of the software is to define cable delay. Software supports three different VNAs available at Estec: FieldFox N9917A, ENA E5061B and PNA N5224A.

The input data should contain two different traces: group delay and phase unwrap. Based on this data application calculates group delay with use of three different methods: average, regression and slope.

Input:

- VNA csv file

Output:

- Report_final - cable delay txt file with average, std dev
- Report_raw - raw delays calculated from the data files
- Report_raw_aperture - delays calculated from the data with different aperture
- graphs

Main file of the script is 'cable_cal_sw.py'

A.2.3. RX_CAL

To optimize the receiver calibration the scripts are organized in the standard template, which can be find in the Rx_cal folder ("test_template").

A.2.3.1. AKAL_RinexParser

Python script. Software calculates receiver delay based on the comparison between simulated geostationary pseudoranges and the one recorded by the receiver (Rinex v.3 format). The software and observation data should be put in the Rinex folder of the template. Inside the Python script, the PRN number of measured satellites need to be defined.

Input:

- Rinex observation file (v.3.x)

Output:

- Results folder – set of delay computed for each observation epoch and for each signal (to be used by correlation software)
- Avg report – report with average delay value with corresponding standard deviation

Main file of the script is 'Rx_parser.py'

A.2.3.2. AKAL_CorrelationSoftware

Matlab script. Based on the results from Python script and recordings made in oscilloscope, the final receiver delay is defined. The bin files collected from oscilloscope should by copied to "SimCal -> RFData" folder of the template. Inside the matlab script, the path to the data need to be defined.

Input:

- Oscilloscope observation in .bin format.
- Results from the AKAL_RinexParser.

Output:

- Combined receiver delay – report in .txt format with the final delay.

Main file of the script is 'MainC4C2.m'

END OF DOCUMENT