High accuracy testing of Interferometric Antenna

ESR

Executive Summary

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1 Introduction

This document is issued in the frame of ESA TRP “High accuracy testing of interferometric antenna with large baseline”. It consists in the executive summary of the work performed and includes test range trade-off and analysis as well as the test results of the test campaign conducted on the Thales Alenia Space Toulouse Planar Near Field Test Range in first quarter 2023.

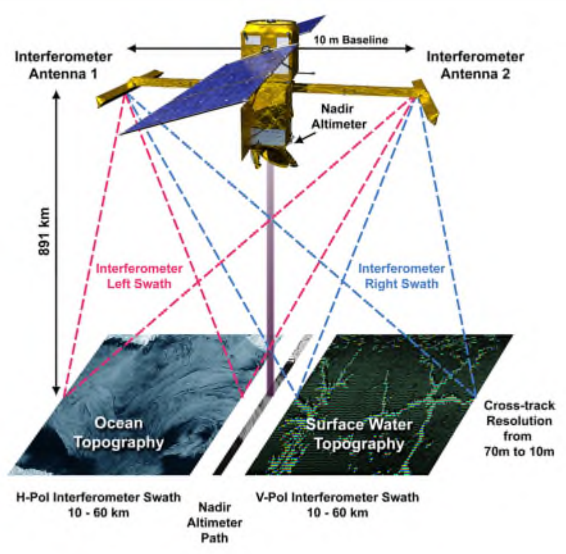
In the past years, several studies and projects have been funded with the common objective to provide improved ocean topographic maps that can be used by the scientific community. In particular, interferometric concepts have been developed in the recent years. A radar interferometer comprises, at least, two antennas working together to form an interferometric antenna subsystem. Interferometry consists in measuring accurately the phase difference between a radar echo as seen from the two antennas. This phase difference is called the interferometric phase. The vector between the two antennas is referred to as the interferometric baseline, or in short “baseline”.

The interferometric phase can be converted using the geometry into an angle of arrival of the echo, for across-track interferometry, allowing Earth surface or Ocean surface topography measurements. This is the configuration for CRYOSAT/CRISTAL and SWOT and for the future swath altimeter missions for Copernicus as studied in ESA Sentinel 3 New Generation Topography phase A/B1. Alternatively, if the baseline is oriented parallel to the satellite velocity vector, the target radial velocity (*i.e.* ocean surface currents) can be determined.

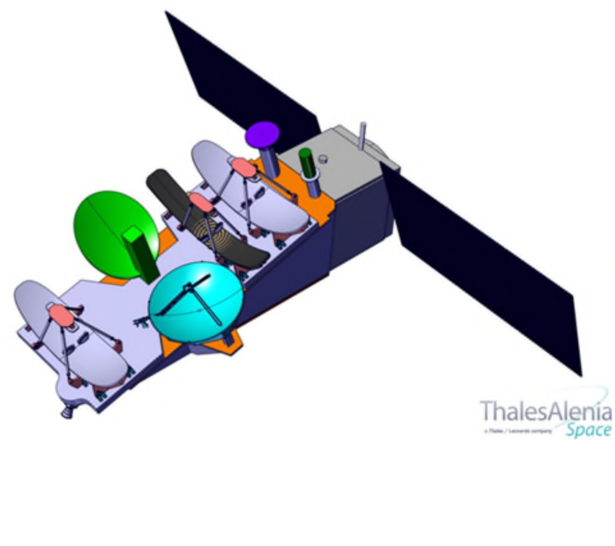
The conversion from interferometric phase to topography or to velocity requires an accurate antenna subsystem characterization and an accurate knowledge of its orientation. Recently, new class of interferometric systems with large baseline (higher than 10 meters) have emerged. The objective of the TRP was to study and identify test setup that is suitable for on-ground characterisation of interferometric antennas with large baseline.

2 Test requirements

Several interferometric systems were gathered with their high level requirements and main antenna characteristics. These inputs were used to derive a set of antenna test requirements for interferometric antennas with large baseline. Notably, Sentinel 3 NG and SWOT missions embark an across track interferometric system in Ka-band with a baseline of 10 meters for SWOT and 3 meters for S3NG.



SWOT principle (from https://swot.jpl.nasa.gov/gallery)



Satellite concept for a swath altimeter with 3 fixed Cassegrain antenna (Swath altimetry study)

Figure 2-1: Across track interferometric system example

For along-track interferometry, Wavemill uses an antenna spanning on 22 meters.

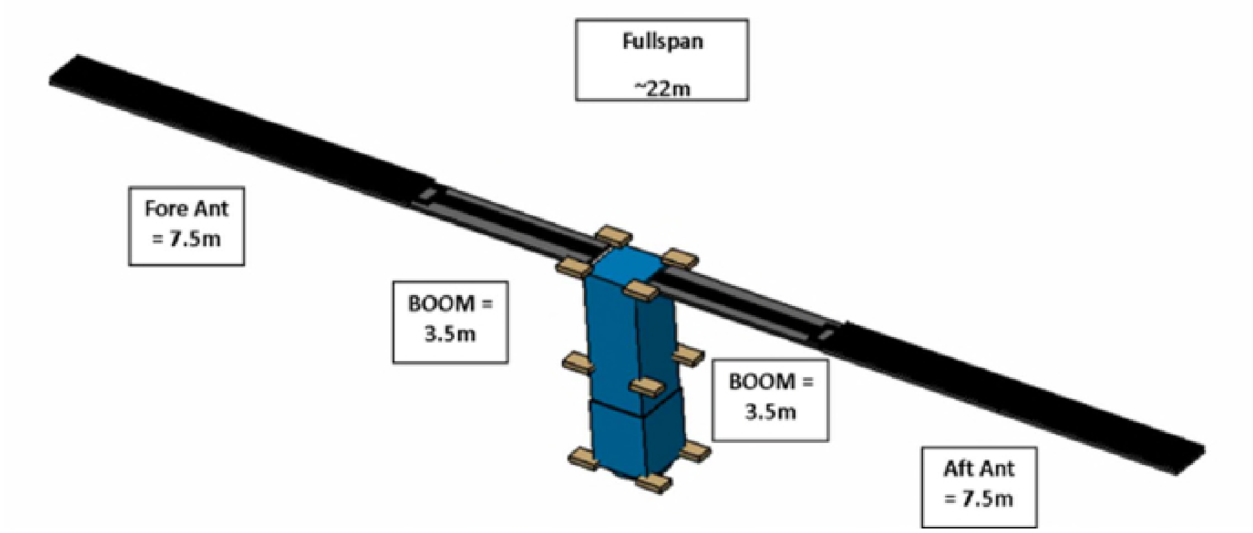


Figure 2-2: Wavemill antenna dimensions from *Wavemill leaky wave antenna for javelin concept, "37 ESA antenna workshop on large deployable antennas"*

The typical characteristics for the interferometric antennas for these instruments are given in the next table.

	SWOT	SAOO	KaSAR	WaveMill	SeaStar
Frequency bandwidth	200 MHz	200 MHz	500 MHz	100MHz	100MHz
Polarization	H and V	H or V	Dual linear	Linear VV	Linear VV
Peak gain	49 dBi	46 dBi	55 dBi	41 dBi	Unknown
Boresigth direction	Az=0° 2 beams (one for each swath)	Az=0° 2 to 8 beams ranging from -5 to 5°	Az=0° El=25°-30 ° 56 beams	Az=[-45°, 45°] El=[-30° , 30°]	Az=[-45° , 0°, 45°] El=[-30° , 30°]
Azimuth HPBW	0.12°	0.26°	0.23°	Unknown	Unknown
Elevation HPBW	3°	1 to 3° depending on the number of beams	0.267°	Unknown	Unknown
Overall scan range in elevation	±4°	±4.7°	25°-30 °	20°-36.6°	20°-36.6°
Beam Coalignment	Beam overlap better than 90%	Beam overlap better than 90%	Beam overlap better than 90%	Beam overlap better than 90%	Beam overlap better than 90%
Baseline length	10m	3m – 6m	20 m	15 m	15 m
Aperture dimensions	0.3 m x 4.5 m	0.5 m x 2.1 m	2 m x 2m	Unknown	Unknown

Table 2-1: Main antenna characteristic implying large baseline instrument

All these antenna are working in the Earth observation Ka-band, 35.5 – 36 GHz.

The interferometric phase knowledge of the antenna subsystem at the time of acquisition is critical for each application. The antenna system is represented by a baseline vector $\vec{B}$ linking the two reference points of each antenna, usually the vertex the parabola (it is not necessarily the phase center of each antenna). This baseline vector is defined in a reference frame to one point of the interferometric antenna structure.

For across track interferometry, the interferometric phase, *i.e.* the difference of phase at the two antenna ports for a plane wave coming from direction $\vec{D}$ can be expressed with following equation. We consider here that transmission is performed with one antenna and that the echo is acquired simultaneously on the two Rx antennas.

$$\Delta\varphi_{geo} = 2\,.\,\pi\,.\frac{\vec{B}\,.\,\vec{D}}{\lambda}$$

The interferometric phase allows to estimate the angle between the direction of arrival and the baseline vector $\vec{B}$.

For along track interferometry, we consider the case where one acquisition per antenna is performed each antenna operating in Tx and Rx mode. These two acquisitions are separated by a small time Δτ. In that case the interferometric phase can be written as follows.

$$\Delta\varphi_{geo} = 4.\pi\,.\frac{\left(\vec{B} - \Delta\tau.\overrightarrow{Vsat}\right).\ \vec{D} + \Delta r}{\lambda}$$

If the baseline orientation and the time shift are such that the ant2 comes to the location of ant1 after a time Δτ then the interferometric phase is directly link to the radial displacement of the target.

$$.\Delta\varphi_{geo} = 4.\pi\,.\frac{\Delta r}{\lambda} \qquad \text{If } \vec{B} = \Delta\tau.\overrightarrow{Vsat}$$

Moreover, the RF harnesses of the two antennas can endure dissymmetrical perturbation causing an interferometric phase error and the two antenna complex radiation pattern dissymmetry also causes an interferometric phase error (refer as phase screen). The total interferometric phase is given hereafter for the across track interferometry:

$$\Delta\varphi_{obs} = 2\,.\,\pi\,.\frac{\vec{B}\,.\,\vec{D}}{\lambda} + \Delta\varphi_{guided} + \Delta\varphi_{a1a2}\left(\vec{D}\right)$$

The along track interferometric phase is given hereafter for the across track interferometry:

$$\Delta\varphi_{obs} = 4.\pi\,.\frac{\left(-\Delta\tau.\overrightarrow{Vsat}\right).\ \vec{D} + \Delta r}{\lambda} + 4\,.\,\pi\,.\frac{\vec{B}\,.\,\vec{D}}{\lambda} + 2.\Delta\varphi_{guided} + 2.\Delta\varphi_{a1a2}\left(\vec{D}\right)$$

All the point of antenna characterization is to know the baseline vector $\vec{B}$, the offset coming from the harness and the phase screen in order to apply the adequate instrument post-treatment on the measured (observed) interferometric phase in orbit. An measurement accuracy was derived for each of these terms.

The antenna gain and pointing pattern characterization are as demanding as classical antenna measurement (typical gain accuracy of 0.25 dB and pointing accuracy of 0.02 deg). However, phase measurement accuracy are far more challenging. Two particular requirements were set to characterize the interferometric phase: Delta Phase Pattern Error which is the measurement error on the global phase offset between the two antennas (independent of the angle of arrival) corresponding to the $\Delta\varphi_{guided}$ and Relative Phase Pattern Variation accuracy which is the measurement error of the interferometric phase for each far field point over the half power beam width corresponding to $\Delta\varphi_{a1a2}\left(\vec{D}\right)$. The test requirement for the offset is 0.3 deg and for the phase screen is +/-0.05 deg.

It can be demonstrated that these phase measurement errors permit also to retrieve the baseline vector of the antenna with enough accuracy. Indeed, the baseline vector is not directly measured by extracted from the measurements using the above formula and knowing the vector **D** for each measured interferometric phase.

The antenna test requirements given in the next table are compatible with SeaStar, Wavemill and KaSAR applications.

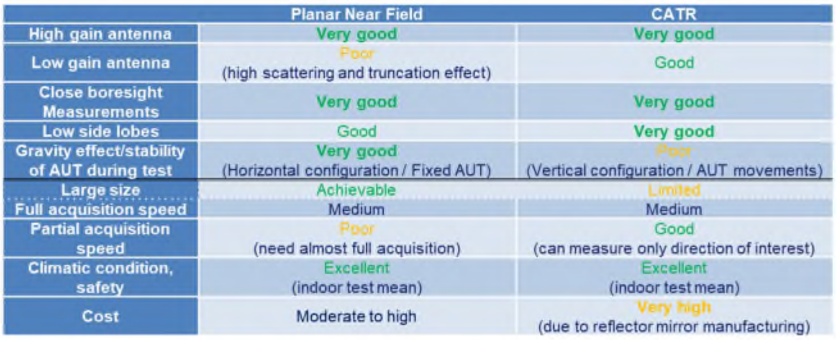
	Specification
Req. 1. : The operational frequency shall be:	35.5 GHz – 36 GHz
Req. 2 : The polarization shall be:	Linear
Req. 3 : The generated beams number shall be:	2
Req. 4 : The two beam pointing shall be (like across track system):	+/- 5 deg
Req. 5 : The minimum physical baseline length shall be:	16 m
Req.6 : The peak gain shall be:	> 40 dBi
Req. 9: The test frequency	35.5 GHz – 36 GHz
Req. 10: The polarization	H or V
Req. 11: Co-Alignment Beam Pointing Accuracy	0.02
Req. 12: Absolute Peak Gain accuracy	+/- 0.25 dB
Req. 13: Angular Range	+/- 40deg El / Az for along track interferometry +/- 10deg El / Az for across track interferometry
Req. 14: Measurement Error level	< -40 dB
Req. 15: Phase centre Location error	< 2 mm
Req. 16: Delta Phase Pattern Error	< 0.3 deg
Req. 17: Physical Baseline length Measurement Error:	< 1.5 mm
Req. 18: Relative Phase Pattern Variation Accuracy	0.05 deg

Table 2-2: Antenna test requirements

3 Test setup trade-off and analysis

A high trade-off were performed between Planar Near Field Test Range (P-NFTR) and Compact Antenna Test Range (CATR). In P-NFTR, the near field is sampled close to the antenna on a known surface and the far field is computed by applying Fourier transform. The antenna under test is fixed and the probe performs the scan. Its typical dimension is from 5 to 10 meters. For CATR, a plane wave is produced by a reflectors system and the antenna under test is put on a positioner in the middle of the plane wave and is rotating to characterize the antenna in each direction. This test mean was used in the past for CRYOSAT interferometric antenna measurement. The bigger CATR found is of 6 meters.

High level trade-off is summarize in next Table. As at first order the two test mean can be suited an accurate phase measurement, the choice was based on antenna size dimension. Scalability of CATR is limited and very costly and it is not reasonable to envision such test mean for large baseline antenna.



	Planar Near Field	CATR
High gain antenna	Very good	Very good
Low gain antenna	Poor (high scattering and truncation effect)	Good
Close boresight Measurements	Very good	Very good
Low side lobes	Good	Very good
Gravity effect/stability of AUT during test	Very good (Horizontal configuration / Fixed AUT)	Poor (Vertical configuration / AUT movements)
Large size	Achievable	Limited
Full acquisition speed	Medium	Medium
Partial acquisition speed	Poor (need almost full acquisition)	Good (can measure only direction of interest)
Climatic condition, safety	Excellent (indoor test mean)	Excellent (indoor test mean)
Cost	Moderate to high	Very high (due to reflector mirror manufacturing)

Figure 3-1: High level trade-off between P-NFTR and CATR

The expected accuracy for P-NFTR was analyzed through GRASP and Matlab analysis by injected phase errors on planar near field simulation and computed their impact in far field. The most impactful error is the one coming from the coaxial cable in the P-NFTR scanner. The way it has been assessed is the following. During the scan in the P-NFTR, the coaxial cables linked the receiver to the probe in winding and unwinding for each direction. It has be considered an phase drift of 1 deg between the edge of the scanner as well as a sinusoidal variation of 1 deg peak peak along the scan.

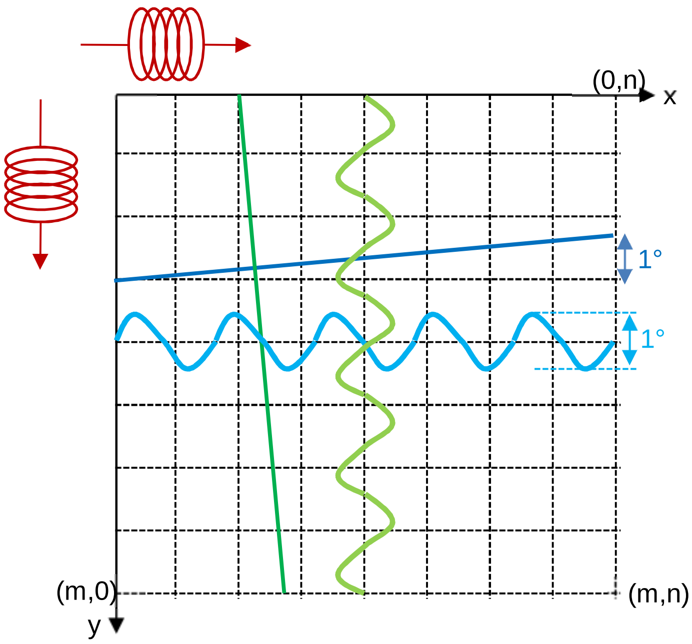


Figure 3-2: Phase error model due to the coaxial cables

The phase error in the far field due to this effect can go beyond 1 degree. The associated baseline error is 16 µm (note: it shows that phase measurement accuracy is far more stringent than baseline length knowledge accuracy).

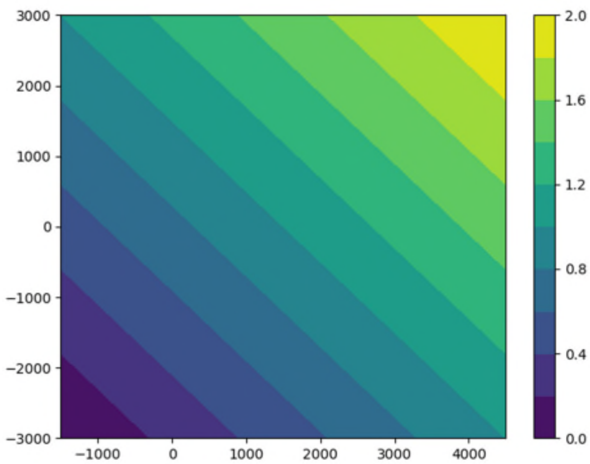


Figure 3-3: Simulated phase error due to cable movement

Besides this cable error, the overall budget was established and the expected accuracy is 0.42 deg for phase offset and +/-0.11 deg for phase screen. The overall budget is detailed in the following table. It shall be noted that the first source errors in the list do not produce interferometric phase error as they are identical for both antennas. The error 14 corresponding to the cables was not considered in the current summation.

ERR#	Error topic	FF error [°]	Baseline length error [mm]	Roll-angle error ['']
ERR1	Probe relative pattern	-	-	-
ERR2	Probe polarization ratio	-	-	-
ERR3	Probe or SGH gain measurement	-	-	-
ERR4	Probe alignment error	-	-	-
ERR5	Normalization constant	-	-	-
ERR6	Impedance mismatch error	-	-	-
ERR7	AUT alignment error	-	-	-
ERR8	Data point spacing (aliasing)	-	-	-
ERR9	Measurement area truncation	Negligible in HPBW		
ERR10	Probe XY position errors	0.02	0.02	0.02
ERR11	Probe Z position error	**0.02**		
ERR12	Mutual coupling (Probe/AUT) (4z/2z)	**< 0.25 (req. 16)** **< 0.1 (req. 18)**		
ERR13	Receiver amplitude linearity	**< 0.25 (req. 16)** **< 0.01 (req. 18)**	0.02	0.40
ERR14	System phase error	1.30*	*0.06*	*2.10*
ERR15	Receiver dynamic range	< 0.03 (req. 16) < 0.01 (req. 18)	0.02	0.03
ERR16	Room scattering(4z/2z)			
ERR17	Leakage and crosstalk			
ERR18	Random amplitude/phase errors	< 0.1 (req. 16) < 0.04 (req. 18)	0.10	0.18
	Total	**0.42 (req 16)** **0.11 (req 18)**		

Table 3-1: Planar near field phase error budget in Ka-band

It was then decided to have a strong focus on cable characterization during the test campaign.

4 Breadboard and test

4.1 Breadboard

The breadboard consists of a feed in single linear polarisation in front of an offset circular reflector of 2.05 meter. The feed is defocused in order to create a dissymmetric antenna pattern to be more representative of interferometric antennas. The antenna radiating pattern is then the following:

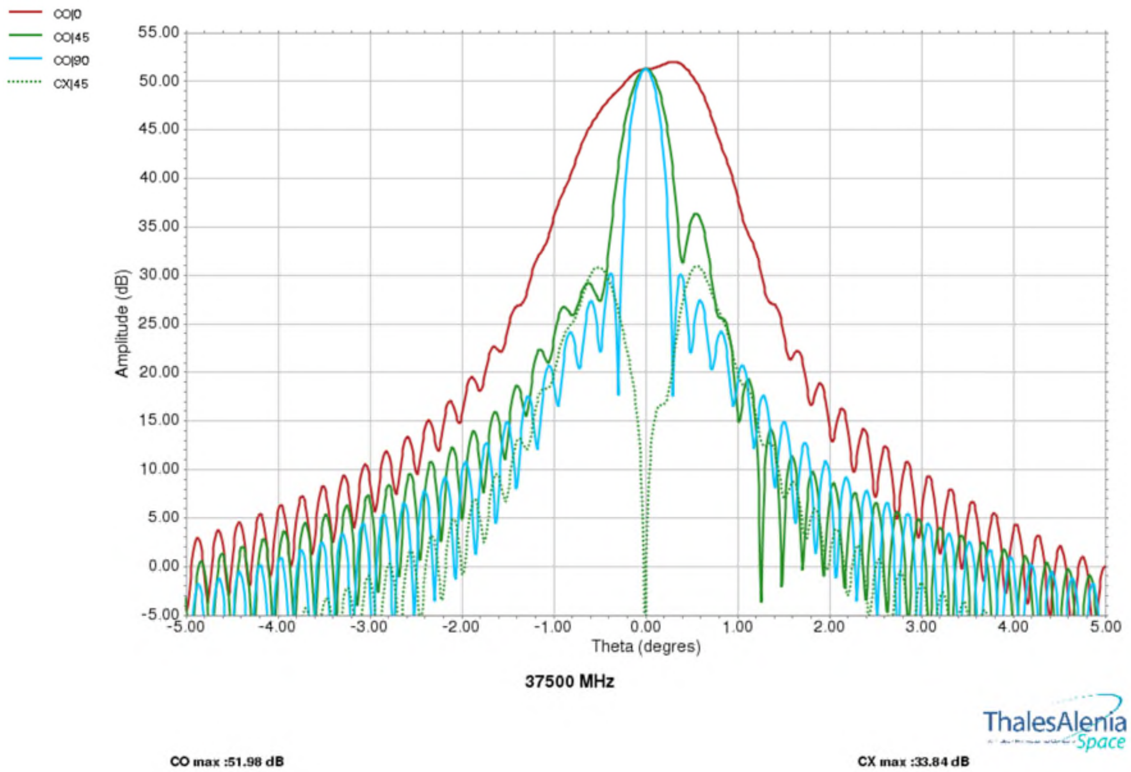


Figure 4-1 Radiation pattern of the simulated antenna that will be used for test measurement.

The test campaign was divided into two different phases. The first one are done at the test range level itself. There are tests to verify the stability of the probe and receiver signal in time, to characterize the scanner cables, to check the impact of the mixer on the phase response.

The second phase are tests done with the antenna. It was not possible to have two different antennas in the test range and to directly perform an interferometric phase measurement. Instead, there is a horn reference used for all measurements and different geometrical configurations of the reflector are successively put in place. The purpose of the tests is to retrieve in the RF measurements the impact of the geometrical displacement.

The first configuration is the reference configuration. The reflector is installed in its nominal configuration and geometrically characterized. The second configuration consists to slightly move the reflector with respect to the reference position (few µm). A new alignment measurement is performed to know exactly where the reflector is. The third configuration consists to impose a slight deformation on the reflector surface through the testing tool. The surface is characterized before RF test.

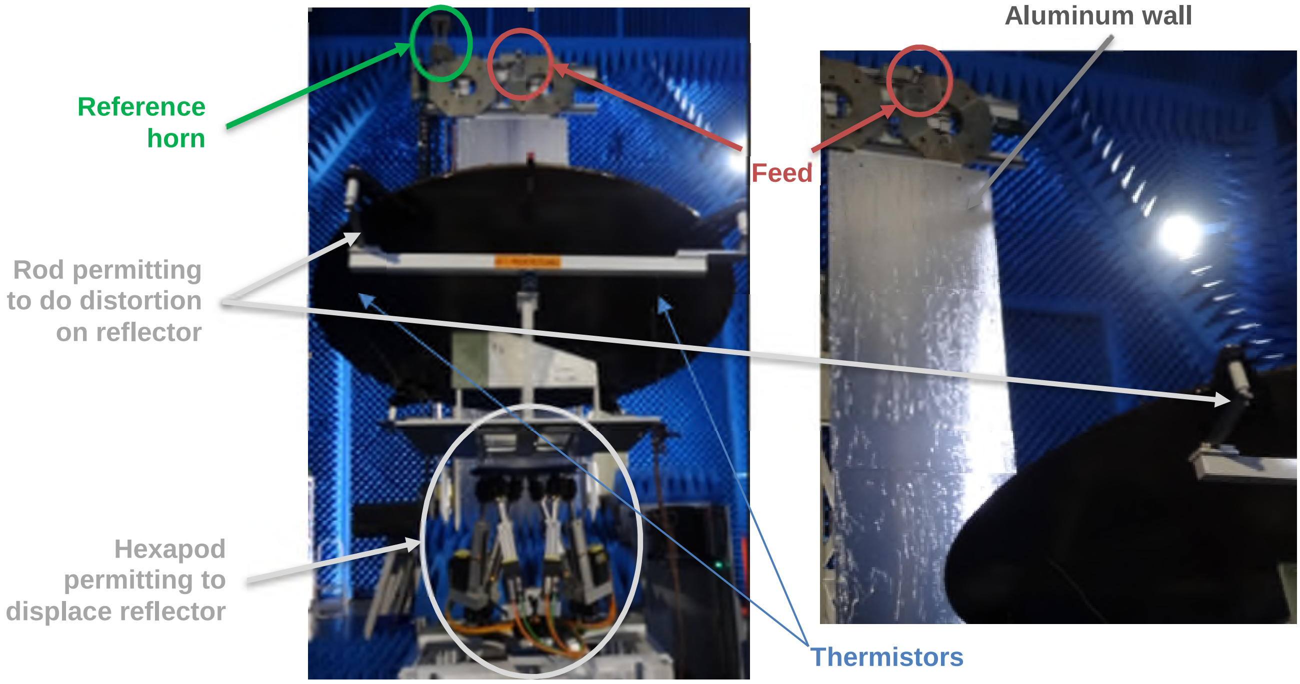


Figure 4-2: Test setup configuration

4.2 Tests

Before the test campaign, the stability of the test setup was checked in terms of temperature, RF chain stability (including receiver, LNA, mixers) and geometrical stability (microvibration). All these tests have demonstrated a stability well better than the required accuracy.

The plot below shows the stability over time of the RF signal through the complete setup with the scanner in a fixed configuration. The short term error is less than 0.05deg and the medium/long term drift is corrected during measurement thanks to a reference measurement done every 15 minutes. The temperature stability over tens of hours is better than +/-0.2°C.

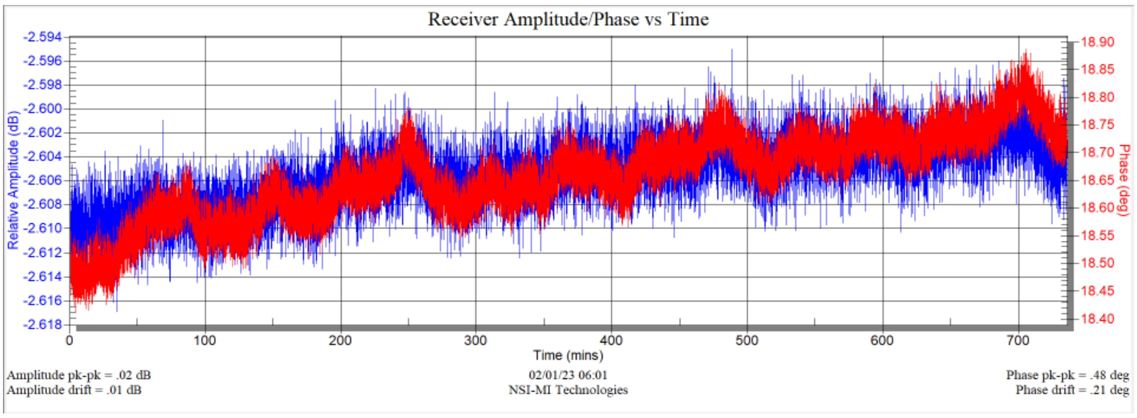


Figure 4-3: Phase stability over time of the whole P-NFTR RF chain

The coaxial cables have then be characterized through different technics. None of them were perfectly conclusive and another test setup was proposed at the end of the study for further implementation. Nonetheless, the results are in line with expectation, with an inhomogeneity of +/-2deg over the full scan.

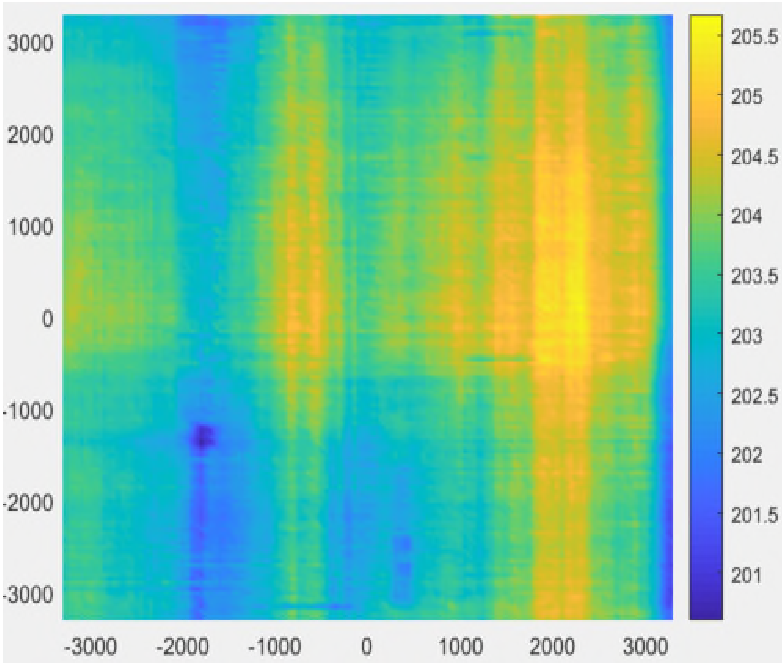


Figure 4-4: P-NFTR coaxial cables signature over the scan

Translating this signature to the far field, it corresponds to an offset error between 0.7 deg and 1 deg and a phase screen error of +/-0.07 deg. This emphasis the need of very stable cables and to think of a possible correction of cable signature in the measurements to improve the far field measurement accuracy.

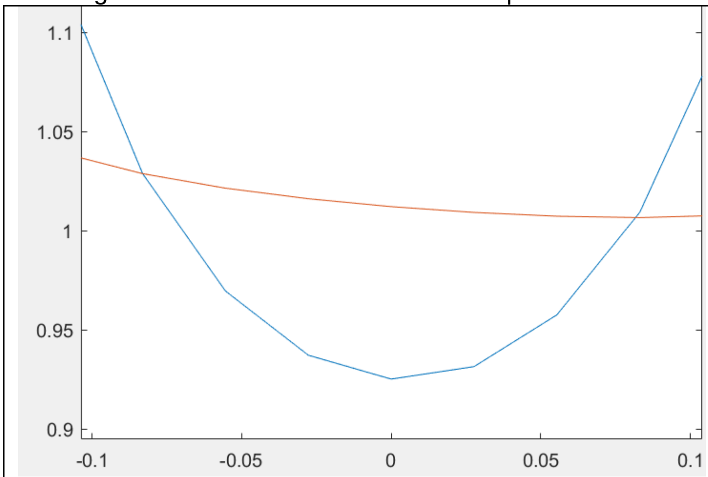
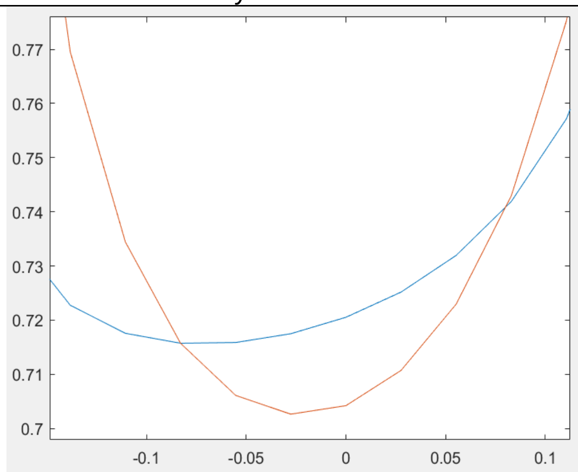
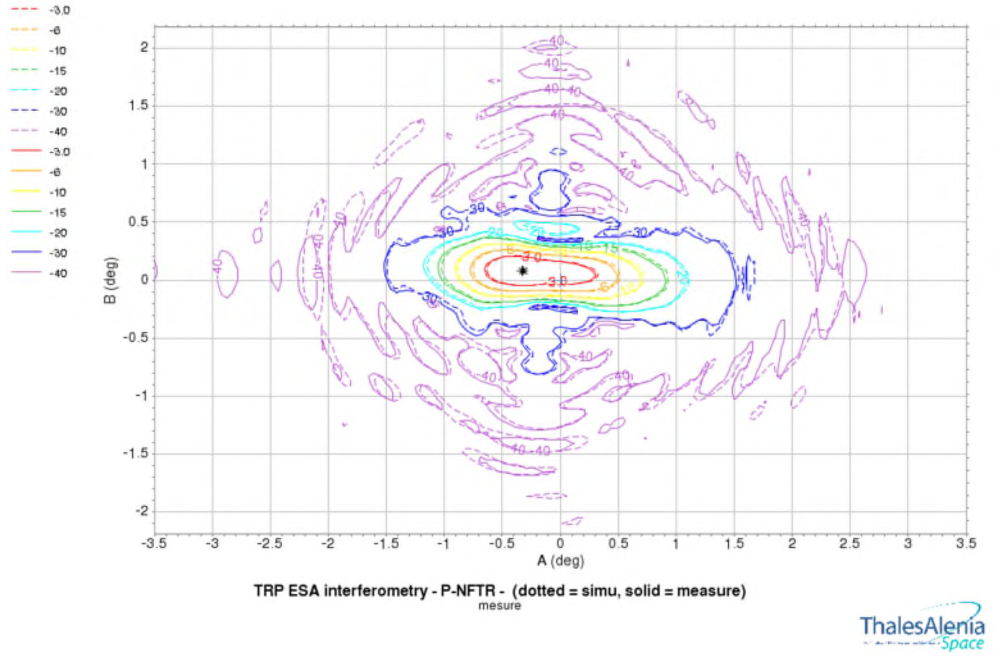
	
Far field phase error for uv cut planes for two antennas in PNFTR with baseline in X-direction	Far field phase error for uv cut planes for two antennas in PNFTR with baseline in Y-direction

Figure 4-5: Far Field phase error due to cables variation during scan

The antenna test for the three configurations has been done.

The reference measurement in amplitude shows satisfactory accuracy and in line with the requirement.



Regarding the far field phase, a difference up to 3deg in the half power beam width was seen between the measurement and the simulation. The slope is coming from alignment uncertainties and behavior of the coax cables in the scanner (the measured signature can create slope up to 2 deg in the HPBW).

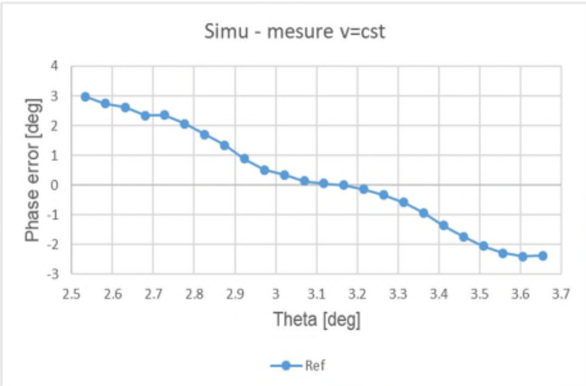


Figure 4-6: Phase difference between measurement and simulation for the reference breadboard position

The simulation / measurement comparison on the expected phase difference between the second (third) measurement and the reference measurement is performed. First, the comparison is done by normalizing the phase at the center of the beam, in order to see the impact in the Half Power Beam Width and assess the accuracy for the phase screen measurement accuracy.

Inside the HPBW, an accuracy on the phase screen of +/- 0.2deg is observed on 0deg cut plane and more than 6 deg in 90deg cut plane.

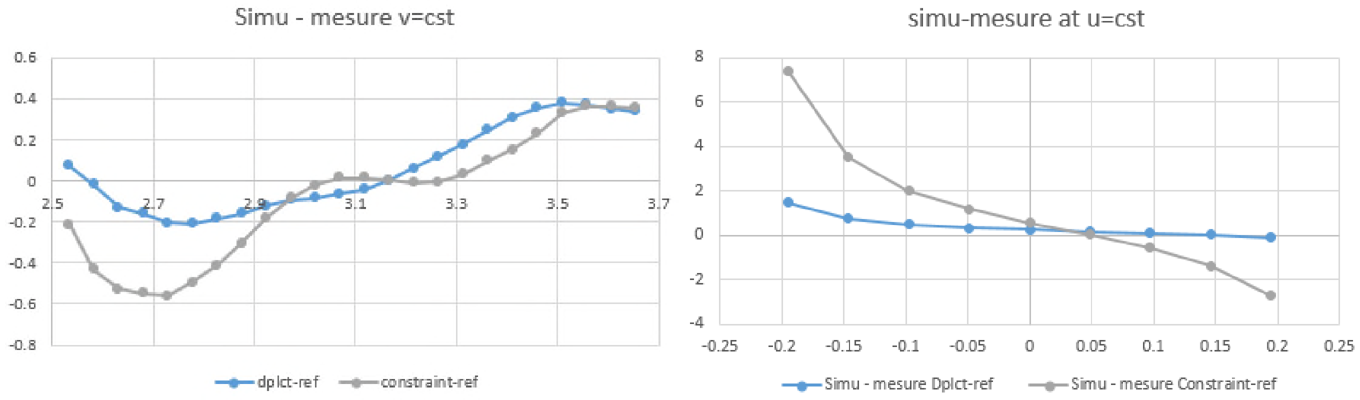


Figure 4-7: Comparison between simulation and measurement on expected phase screen

We conclude there is no overall test setup slippage otherwise the results would have been bad for both direction. It is almost certain that the Y-axis cable started to be damaged/broken introducing a higher slope error for successive scans. The retained value for phase screen accuracy is the one coming from v-plane.

Regarding the phase offset at beam center position, an error up to 4 deg was obtained. The offset was measured by using the reference horn to readjust phase offset between consecutive measurement. However, the reference horn is located on the edge of the scanner with a cable response different from the cables response in the center of the scanner. The cables variation behavior seen for the phase screen has also a big impact on the offset accuracy. We recall that the offset was assessed for two different measurements. For a real interferometric measurement done in one scan, the accuracy will only be linked to coaxial cable behavior and the stability of the test mean during the measurement.

The achieved phase accuracy in Ka-band is given in the next table. Ku-band tests were also performed with two horns in interferometric configuration to assess the achievable performances in Ku. In particular, it can be seen that the offset error is way better without the need to use an intermediate reference horn.

Ku achieved performance is indicated between (.) in the table.

Req. 16: Delta Phase Pattern Error	< 0.3 deg	~4 deg (0.4-0.8 deg in Ku)
Req. 18: Relative Phase Pattern Variation Accuracy	0.05 deg	~+/-0.5deg (+/- 0.1 to 0.2 deg in Ku)

The overall statement of compliance is given the next table. The requirements related to phase centre and baseline length are declared NA because baseline vector is retrieved through phase measurement and the desired accuracy is not critical. The reference frame is characterized geometrically with enough accuracy.

	Specification	Status
Req. 1. : The operational frequency shall be:	35.5 GHz – 36 GHz	C (test done at higher frequency)
Req. 2 : The polarization shall be:	Linear	C
Req. 3 : The generated beams number shall be:	2	C : Breadboard had only one beam but switch was used for reference horn so same setup is used for multi beam antennas
Req. 4 : The two beam pointing shall be (like across track system):	+/- 5 deg	PC : pointing of the breadboard was 3deg
Req. 5 : The minimum physical baseline length shall be:	16 m	NC with all current test ranges
Req.6 : The peak gain shall be:	> 40 dBi	C
Req. 9: The test frequency	35.5 GHz – 36 GHz	C – Test was done at higher frequency due to probe availability
Req. 10: The polarization	H or V	C
Req. 11: Co-Alignment Beam Pointing Accuracy	0.02	NC: Co-alignment could not be measurement with the breadboard Classical pointing error budget in Q-band for P-NFTR is 0.025deg with a bias of 0.005deg; co-alignment accuracy is then 0.03deg
Req. 12: Absolute Peak Gain accuracy	+/- 0.25 dB	C
Req. 13: Angular Range	+/- 40deg El / Az for along track interferometry +/- 10deg El / Az for across track interferometry	C : 40deg is at the limit for PNFTR
Req. 14: Measurement Error level	< -40 dB	PC – Between -39 and -41 dB
Req. 15: Phase centre Location error	< 2 mm	NA
Req. 16: Delta Phase Pattern Error	< 0.3 deg	**NC : ~4deg achieved**
Req. 17: Physical Baseline length Measurement Error:	< 1.5 mm	NA
Req. 18: Relative Phase Pattern Variation Accuracy	0.05 deg	**NC : ~+/- 0.5deg achieved in U-direction**

Table 4-1: Statement of Compliance to the antenna test requirements

Following this status, some recommendations were issued to further improve P-NFTR measurement for interferometric phase. In particular:

- Cable stability and knowledge is key for the P-NFTR measurement phase accuracy
- Cable error without correction are not compatible for offset accuracy better than 0.8deg in Ka-band, but is pretty satisfactory for the phase screen (below 0.05deg)
- A new test setup was proposed to allow a potential proper characterisation of the coaxial cables
- Measurement in Forward only
- Baseline length to be put on the X-axis (not the on-the-fly-direction)
- Different measurements can only be accurately compared by well knowing the probe origin, otherwise a slope is added to the measurement
- Perform two measurements with a rotation of 180deg to cancel out inhomogeneity in scanner response

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