Research Networking Programmes

Short Visit Grant ☒ or Exchange Visit Grant ☐

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Scientific Report

The scientific report (WORD or PDF file – maximum of eight A4 pages) should be submitted online within one month of the event. It will be published on the ESF website.

Proposal Title: Experimental Validation of New Phaseless Radiating Systems Characterization Techniques Based on Indirect Holography at Millimeter and Sub-Millimeter Wave Bands

Application Reference N°: 7157

1) Purpose of the visit

Antenna and radiation systems characterization becomes a very challenging process at millmeter/ sub-millimeter wave frequency bands because of the high requirements of the measurement systems regarding thermal stability, positioners accuracy, facilities size, etc., making necessary to resort to near-field phaseless acquisition systems due to their lower cost and complexity.

Off-axis or indirect holography is one of the most remarkable phase retrieval techniques. Based on interferometry, it combines the radiated field from the antenna under test (AUT), with a reference field that has to be previously characterized. The use of syhthesized reference waves or mechanical shifts for the case of the reference signal have improved the performance of off-axis holography, allowing to accurately retrieve the phase of the AUT. Nevertheless, implementation of these setups generally require the use of additional components such as diectional couplers, phase shifters or power combiners,increasing the system complexity.

The grantee has been working in colaboration with the host center in two modified indirect holography setups that allow for: a) Broadband antenna characterization from just one phaseless acquistion. b) Use of mirror reflection in substitution of the phase shifter and combiner, to increase the separation of the hologram terms in the spatial frequency domain and more easily filter the desired hologram component.

2) Description of the work carried out during the visit

The developed algorithms are based on the conventional off-axis holography setup, although data processing and applications are completely different for each of them. The first developed setup can be applied to the broadband characterization of antennas (in the entire working frequency band), while the second one is suitable for the characterization of non-directive radiating systems at one specific frequency.

The basis of the conventional indirect holography setup and the modifications introduced in the development of the herein proposed algorithms will be explained in the current section, while the results of the experimental validation carried out in the host center will be shown in section 3).

a) Conventional Off-Axis Setup:

In conventional off-axis holography, Fig. 1 (a), an interference pattern is created between the AUT and a secondary reference antenna, whose amplitude and phase are previously known, so that the following power hologram is measured:

$$\mathrm{H}(\vec{\mathrm{r}}) = |\mathrm{E}_{\mathrm{aut}}(\vec{\mathrm{r}}) + \mathrm{E}_{\mathrm{ref}}(\vec{\mathrm{r}})|^2 = |\mathrm{E}_{\mathrm{aut}}(\vec{\mathrm{r}})|^2 + |\mathrm{E}_{\mathrm{ref}}(\vec{\mathrm{r}})|^2 + \mathrm{E}_{\mathrm{aut}}(\vec{\mathrm{r}})\mathrm{E}^*_{ref}(\vec{\mathrm{r}}) + \mathrm{E}^*_{aut}(\vec{\mathrm{r}})\mathrm{E}_{\mathrm{ref}}(\vec{\mathrm{r}}) \tag{1}$$

Wherein $\vec{\mathrm{r}}$ is the position vector defining the position of the probe antenna, the term ()* indicates the complex conjugate, $\mathrm{E}_{\mathrm{aut}}$ is the field radiated by the AUT and $\mathrm{E}_{\mathrm{ref}}$ is the field radiated by the reference antenna, noting that both $\mathrm{E}_{\mathrm{aut}}$ and $\mathrm{E}_{\mathrm{ref}}$ refer to the field component received by the probe antenna. The acquisition process can be repeated for each component of the field without modifications. Since the square amplitude of the AUT and reference antenna can be easily measured with minimum changes of the setup in Fig. 1, this hologram can be modified as follows:

$$\mathrm{H}_m(\vec{\mathrm{r}}) = \mathrm{H}(\vec{\mathrm{r}}) - |\mathrm{E}_{\mathrm{aut}}(\vec{\mathrm{r}})|^2 - |\mathrm{E}_{\mathrm{ref}}(\vec{\mathrm{r}})|^2 = \mathrm{E}_{\mathrm{aut}}(\vec{\mathrm{r}})\mathrm{E}^*_{ref}(\vec{\mathrm{r}}) + \mathrm{E}^*_{aut}(\vec{\mathrm{r}})\mathrm{E}_{\mathrm{ref}}(\vec{\mathrm{r}}) \tag{2}$$

The hologram $\mathrm{H}_m(\vec{\mathrm{r}})$ is then Fourier transformed to k-domain (spatial frequency) resulting in:

$$\mathrm{h}_m(\vec{k}) = \mathrm{e}_{\mathrm{aut}}(\vec{\mathrm{k}}) \otimes \mathrm{e}^*_{ref}(\vec{\mathrm{k}}) + \mathrm{e}^*_{aut}(\vec{\mathrm{k}}) \otimes \mathrm{e}_{ref}(\vec{\mathrm{k}}) \tag{3}$$

wherein $\otimes$ denotes a convolution between both signals and $\mathrm{e}_{\mathrm{aut}}$ and $\mathrm{e}_{\mathrm{ref}}$ denote the Fourier Transform (FT) of the radiated fields. The modified hologram in the spatial frequency domain is composed by the so-called cross-correlation terms (Fig. 1 (b)). By appropriately choosing the position of the reference antenna and the sampling rate, the position of the cross-correlation terms can be modified, up to a certain point, to reduce overlapping and filter one of them out.

Finally, by means of an inverse Fourier Transform (iFT), it is possible to obtain the value of the filtered cross-correlation term back in the spatial domain eq. (4) and retrieve the amplitude and phase of the AUT by numerically removing the effect of the reference antenna, eq. (5):

$$\mathrm{H}_{m\,filtered}(\vec{r}) = \mathrm{FT}^{-1}\{\mathrm{h}_{m\,filtered}(\vec{k})\} \simeq \mathrm{FT}^{-1}\{\mathrm{e}_{\mathrm{aut}}(\vec{k}) \otimes \mathrm{e}^{*}_{ref}(\vec{k})\} \simeq \mathrm{E}_{\mathrm{aut}}(\vec{r})\, \mathrm{E}^{*}_{ref}(\vec{r}) \tag{4}$$

$$\mathrm{E}_{\mathrm{aut}}(\vec{r}) = \mathrm{H}_{m\,filtered}(\vec{r}) / \mathrm{E}^{*}_{ref}(\vec{r}) \tag{5}$$

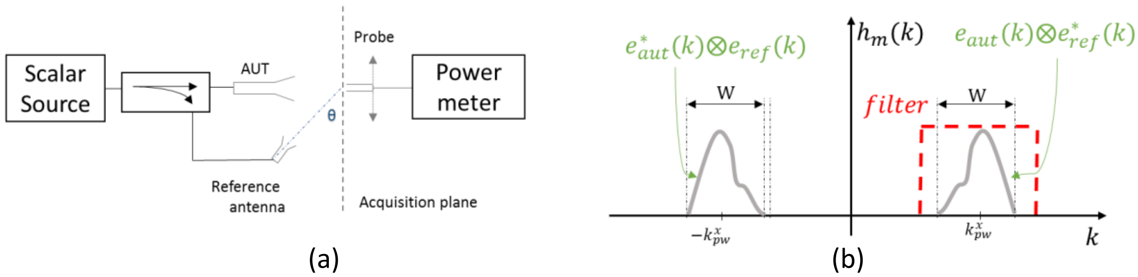


Fig. 1 (a) Conventional off-axis holography setup. (b) Spectrum of the modified Hologram

a) Proposed setup 1: Broadband Phaseless Antenna Characterization Setup

For the proposed technique, the physical arrangement of the elements is identical to the one in the previous scheme (Fig. 1 (a)). At each point of the acquisition plane, the field is acquired along a set of equally spaced frequencies giving an interferometric signal. The modified hologram can be obtained after subtracting the square amplitude of the AUT and the reference antenna to the previous interferometric signal:

$$\mathrm{H}_m(\vec{r}, w) = \mathrm{H}(\vec{r}, w) - |\mathrm{E}_{\mathrm{aut}}(\vec{r}, w)|^2 - |\mathrm{E}_{\mathrm{ref}}(\vec{r}, w)|^2 = \mathrm{E}_{\mathrm{aut}}(\vec{r}, w)\mathrm{E}^{*}_{ref}(\vec{r}, w) + \mathrm{E}^{*}_{aut}(\vec{r}, w)\mathrm{E}_{\mathrm{ref}}(\vec{r}, w) \tag{6}$$

being w the angular frequency. The inverse FT of the modified hologram produces the following signal in the time domain (TD):

$$\mathrm{h}_m(\vec{r}, t) = \mathrm{e}_{\mathrm{aut}}(\vec{r}, t) \otimes \mathrm{e}^{*}_{ref}(\vec{r}, t) + \mathrm{e}^{*}_{aut}(\vec{r}, t) \otimes \mathrm{e}_{ref}(\vec{r}, t) \tag{7}$$

A schematic representation of the modified hologram in the TD is shown in Fig. 2. The hologram is composed of the two cross-correlation terms. Thus, to retrieve the amplitude and phase of the AUT, it is necessary to filter the term corresponding to the convolution of $\mathrm{e}_{\mathrm{aut}}(\vec{r}, t) \otimes \mathrm{e}^{*}_{ref}(\vec{r}, t)$ in eq. (7) providing no time overlap is present. The parameter constraints that allow performing a correct filtering will be discussed next.

Once the signal has been filtered in the TD, last step, as in the conventional off-axis approach, is the removal of the effect of the reference antenna back in the Frequency Domain (FD).

The error of the phase retrieval algorithm will depend mostly of the separation of the cross-correlation terms in the TD. This separation is determined by the starting times of the signals coming from the AUT and the reference antenna, t_{aut} and t_{ref}, as it can be seen in Fig. 2. The type and length of the filter used also influences the retrieval process, thus several types and lengths of filters have been analyzed in the simulations.

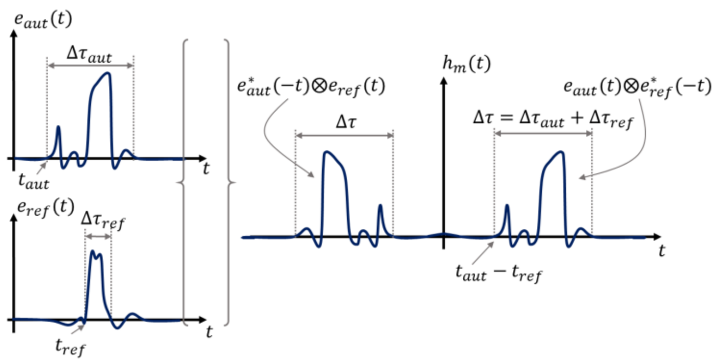


Fig. 2. Time Domain Modified Hologram Scheme

Time overlap can be avoided if $t_{aut}>t_{ref.}$ In practice, due to the setup layout this condition cannot be satisfied. To overcome this problem, a delay in the reference signal branch has to be included in order to be able to swap both cross-correlation terms. In the measurement examples presented in next section, a mirror is used to reflect the reference signal in order to enlarge the path from the reference antenna to the acquisition plane. Second constrain affects the sampling rate. In order to correctly retrieve the phase of the AUT, frequency sampling must satisfy the Nyquist criterion as defined in equation (8).

$$\Delta \mathrm{f} = \frac{1}{2B} = 1/2(\Delta \mathrm{t} + t_{aut} + t_{ref}) \tag{8}$$

b) Proposed setup 2: Hologram Cross-Correlation Terms Displacement by Means of Phase-Shifted Holograms Combination

In order to reduce the error of the conventional off-axis holography, some authors have introduced the so-called synthesized reference signal. This modification of the conventional setup substitutes the reference antenna with a sample of the source, whose phase is modified by means of a phase shifter and then combined with the signal acquired in the probe antenna (Fig. 3 (a)).

The main advantage of this type of setups is that a plane wave can be synthesized with the phase shifter. The position of the cross-correlation terms of the hologram, defined as the relation between the phase shift and the spatial sampling (Δφ/Δx), can be modified. The cross-correlation terms can be displaced to the non-visible part of the k-space and the overlapping is drastically reduced.

The main drawback of this setup is that the devices such as phase shifter and combiner working at millimeter and sub-millimeter wave bands are very expensive. Besides, it would be necessary to connect the output of the phase shifter, in the transmitter end, with one of the inputs of the combiner, in the receiver end and that would be almost impossible considering that the receiver end has to move along the acquisition plane and the connection would have to be made with waveguide sections.

Some variations have been introduced in the conventional off-axis holography setup (with no synthesized wave (Fig. 1 (a))), in order to avoid the use of the phase shifter and the combiner and still be able to modify the position of the spectral cross-correlation terms as it was done in the setup with synthesized reference signals.

A shift of 180º in the phase of the reference signal in the acquisition plane is introduced by combining the acquired hologram with the setup of Fig. 3 (b), with a second hologram, obtained after moving the mirror to a second position (mirror displacement of λ/2). The phase shifts of the reference signal are increased and the position of the cross-correlation terms of the hologram can be modified in a similar way than with the synthesized reference signals.

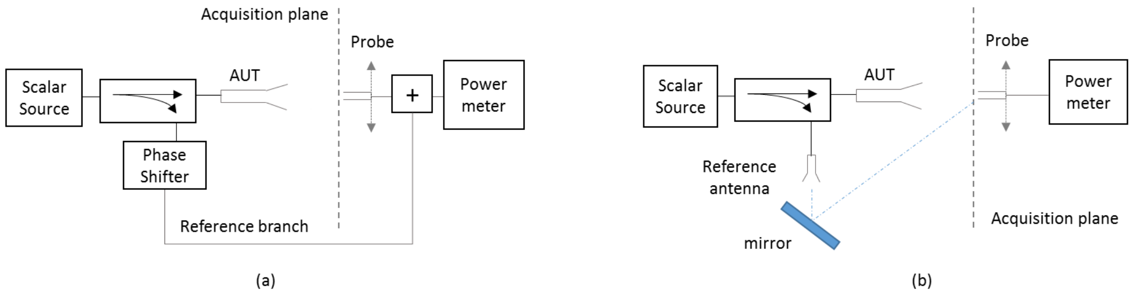


Fig. 3. Different types of synthesized reference wave setups. (a) Conventional setup, (b) Proposed setup

With the proposed setup, two different hologram acquisitions are required but with less dense sampling than the sampling required for the conventional holography setup. The two sets of data are combined by alternating columns of data from the two acquired holograms, so, in order to get a grid of λ/4 spaced points, two holograms with a grid of λ/2 spaced points have to be acquired. The two acquisitions are equivalent in number of points and required time, to the one acquisition done in the conventional setup.

The main drawback of this setup is that the combination of both holograms produces a high order frequency copy of the hologram, and depending on the introduced displacement of the cross-correlation terms and the spread of the terms of the hologram, this copy can overlap with the cross-correlation terms.

Nevertheless, simulation results reveal that the amplitude of this high frequency copy can be controlled with the position and tilt of the mirror, and the spread of its terms depends on the introduced phase shifts. With the correct selection of the position and tilt of the mirror, the effect of the copy can be reduced and the desired cross-correlation term can be filtered out.

After retrieving the phase of the AUT, the signal has to be low-pass filtered in order to eliminate the high frequency components. The error of the phase retrieval with this proposed setup is lower than the error obtained with the conventional setup when the position of the mirror is correctly selected. Furthermore, as the cross-correlation terms are displaced to the non-visible part of the k-space, this proposed method is more appropriated for characterizing non-directive antennas while the overlap of the spectrum with the conventional setup for these non-directive antennas can make not possible to correctly retrieve the phase.

3) Description of the main results obtained

Many different test have been done in simulations before the experimental validation of both setups, nevertheless, they are going to be omited in this report due to the lack of space.

Experimental validation of the two proposed setups has been done at the host center facilities. The quality of the obtained results demonstrates the validity of both algorithms.

a) Experimental validation of the broadband phaseless antenna characterization setup

Measurements have been performed in the W-band in the planar measurement range in the host center. Spatial sampling of $\lambda/2$ at the highest frequency of the band (90 GHz) has been used and 61 equally spaced frequency points have been selected between 80 and 90 GHz.

The hologram will be processed in the time domain for each point of the spatial acquisition, this way, antenna characterization can be done for the 61 frequency points after just one spatial acquisition. Fig. 4 shows the setup for the characterization of a lens antenna using a horn as a reference antenna.

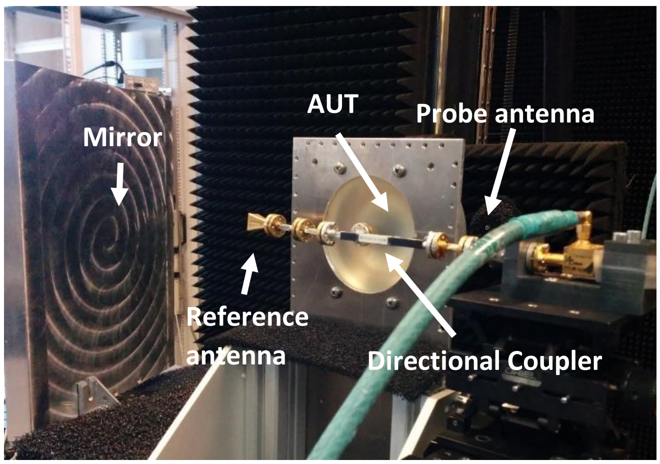
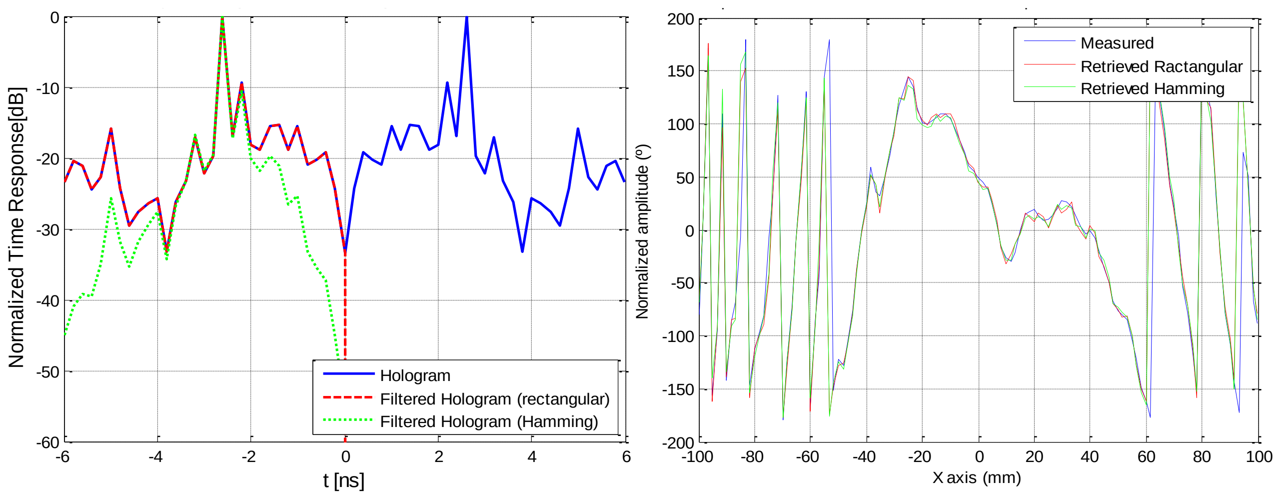


Fig. 4. Proposed indirect holography setup for broadband phaseless antenna characterization

Fig. 5 (a) shows the cross-correlation terms of the hologram for the worst case in the spatial acquisition main axis. Worst case is the positive extreme of the acquisition plane, which is closer to the reference antenna than to the AUT, which makes t_{aut}-t_{ref} maximum. Nevertheless, in this case t_{ref} is still higher than t_{aut} and no overlapping is observed. The filtered part of the spectrum is depicted in red for the case of using a rectangular window and in green for the case of using a Hamming window

As the amplitude of the AUT and the reference antenna have to be previously characterized in order to calculate the modified hologram, eq. (6), only the retrieved phase of the AUT is needed. The complex signal is then composed by combining the measured amplitude with the retrieved phase. The retrieved phase for the frequency of 83.5 GHz is shown in Fig. 5 (b) for the cases of using a Rectangular and a Hamming window. Both results are in very good agreement with the measured phase of the signal.

Finally, Fig. 6 shows the error of the phase retrieval algorithm for all the analyzed frequencies of the band. Mean error is 2.1 % in the whole band. The high value of the error at 80.33 GHz is due to a change of the source amplitude and could be compensated by software



(a) (b)

Fig. 5. Results of the proposed technique: (a) Modified hologram in the time domain for the positive axis extreme of the acquisition cut. (b) Retrieved phase of the AUT for f=83.5 GHz

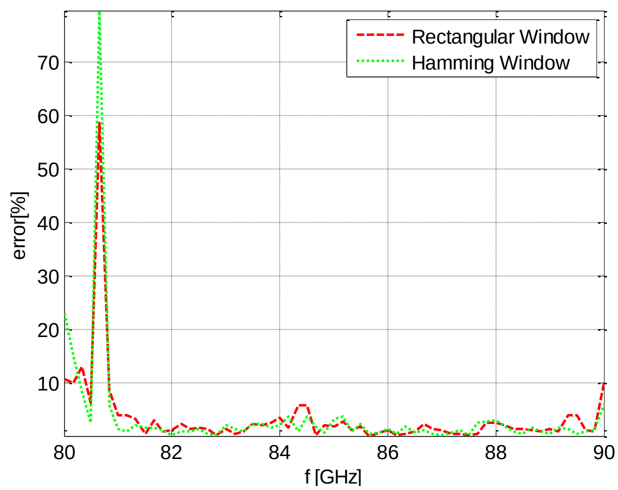
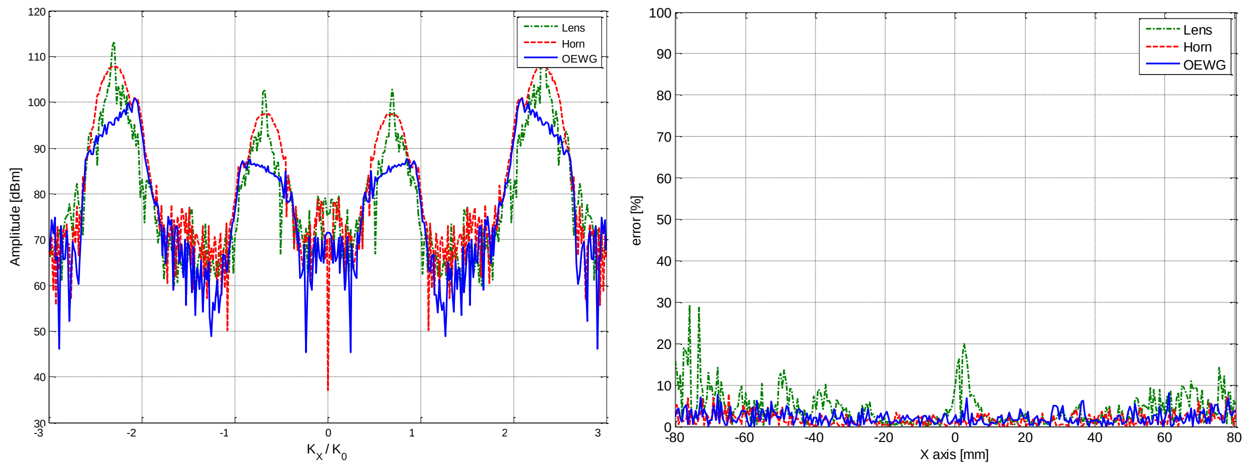


Fig. 6. Error for the phase retrieval error in the working frequency band

b) Experimental validation of the Hologram Cross-Correlation Terms Displacement by Means of Phase-Shifted Holograms Combination Setup

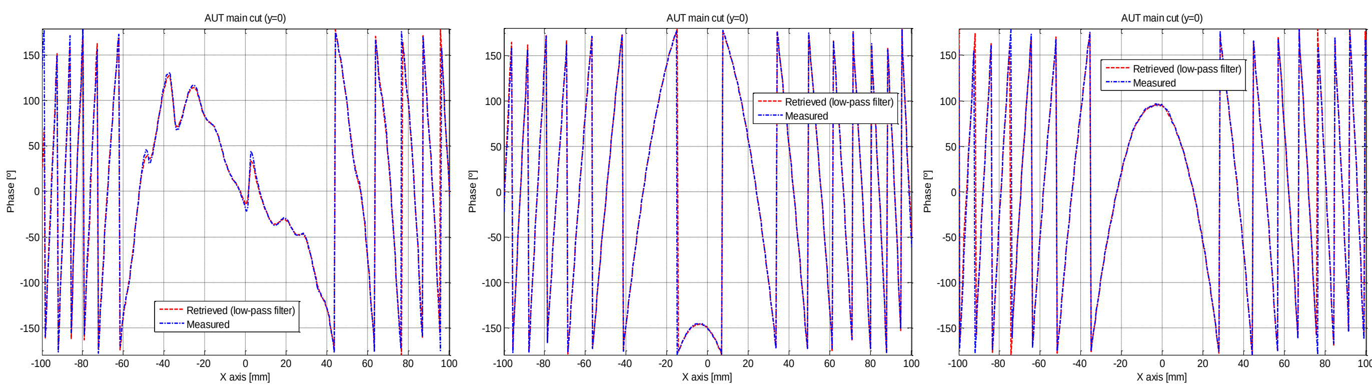
Same measurement setup has been used for the validation of this setup. A lens, a horn and an open-ended waveguide antenna have been characterized at 94 GHz in order to validate the proposed algorithm. The results herein presented correspond to an example in which the mirror is placed at 150 mm of the reference antenna with a tilt of 60º. The acquisition plane is at 125 mm of the AUT aperture and the depicted results correspond to a cut of the copolar component of the E plane of the antennas.

Fig. 8 (a) shows the spectrum of the hologram for the three antennas. The high order frequency copies are more than 10 dB below than the original cross-correlation terms and can be correctly filtered. Fig 8 (b) shows the error of the phase retrieval technique for the three antennas.



(a) (b)

Fig. 8. Results for the proposed algorithm. (a) Spectrum of the modified hologram for the three studied antennas. (b) Error of the phase retrieval for the three antennas. (Lens antenna in green, Horn antenna in red and Open-ended waveguide antenna in blue)



(a) (b) (c)

Fig. 7. Comparison of the retrieved and measured phase for the three studied antennas. (a) Lens antenna, (b) Horn antenna, (c) Open-ended waveguide antenna

4) Future collaboration with host institution (if applicable)

There are no specific collaboration actions defined for the time being, apart from the proposed algorithms final processing and the publication of the final results.

5) Projected publications / articles resulting or to result from the grant *(ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)*

At the moment, two articles are being wirtten for the publication of the developed algorithms and the exeperimental results.

6) *Other comments (if any)*