Design and Optimization of a C-Band Lens Horn for Scatterometer Calibration

Fernando Rodríguez Varela, José Luis Besada San Martín, Belén Galocha Iragüen
frodriguezv@gr.ssr.upm.es, besada@gr.ssr.upm.es, belen@gr.ssr.upm.es
Dpto. de Señales, Sistemas y Radiocomunicaciones, Universidad Politécnica de Madrid
Av. Complutense 30, Ciudad Universitaria, 28040, Madrid

***Abstract*- In this paper the design and optimization process of a scatterometer calibration antenna is presented. The solution consists in a septum polarizer and a high gain Potter horn with exceptionally low axial ratio (0.2 dB) and low SLL at 5.3 GHz. To obtain a compact design, the horn length has been reduced and a dielectric lens has been designed to correct the horn phase error. Several types of lenses are presented and analyzed, and their effects on the radiation pattern and aperture fields are discussed. The discontinuity in electric permeability produced by the lens degrades the horn adaptation. To solve this issue, impedance matching transformers are designed and simulated in order to fulfill the mentioned specifications.**

I. INTRODUCTION

The Eumesat Advanced Scatterometer (ASCAT) is an on-board satellite radar instrument designed to measure wind fields over the oceans [1]. It operates by transmitting a microwave pulse towards Earth's surface and measuring the reflected pulse. Geophysical inversion algorithms are used to derive wind speed and direction from these radar backscattering cross-section measurements.

ASCAT measurements require high precision and gain stability (less than 0.15 dB variations), so periodic calibration [2] must be performed by means of an Earth transponder unit that relays the transmitted pulses back to the scatterometer in order to perform system gain measurements. Basically, the transponder acts as a known and constant RCS object. In Fig. 1 the block diagram of the ASCAT transponder is depicted. It consists of a horn with a polarizer that decomposes an incoming linear polarization field into two circular components. This is done because the polarization transmitted by the satellite (H or V) is a priori unknown and must be determined by the transponder. Therefore, the LHC component is the one processed and retransmitted back to satellite, while the RHC component is only used to determine the original polarization of the received pulse at the antenna, by comparing the relative phase between the two components.

For these types of transponders, horn antennas with gains between 23 and 30 dBi are used. In this paper the design and optimization process of a 27 dBi horn and its polarizer for the ASCAT transponder is presented. The most relevant parameters and requirements of this antenna are listed below:

- Frequency bands: 5.255 GHz $\pm$ 1MHz and 5.355 GHz $\pm$1MHz for the Tx and Rx functions respectively.
- Antenna: smooth-walled horn Potter with 27 dBi gain.
- Circular polarization with axial ratio below 0.2 dB.
- Tx/Rx calibration port: LHC.
- Return loss < 20 dB.
- Isolation between RHC and LHC channels ≥ 20 dB.
- Side lobe level below ITU-R S.465-6 recommendation.
- Compact design: horn length around 60 cm.

In addition, the antenna should operate at outdoor conditions so resilience to moisture and UV radiation is required.

The limiting element in the system compactness is the horn. Due to its high gain, a conventional horn design requires a low aperture phase error [3] and has an impractical size. For example, a 27 dBi antenna meeting the mentioned ITU-R SLL recommendation needs an error phase below 0.2. This results in an antenna of 52 cm of diameter and around 2.5 m of length. The length cannot be reduced by increasing the flare angle, because this produces big aperture phase errors, thereby reducing the gain and increasing de SLL. However, the spherical phase front responsible of the phase error can be corrected using a dielectric lens in the aperture. This approach, used in this paper, allows increasing the flare angle in order to reduce the axial length significantly.

This paper is organized as follows. Section II deals with the design and optimization of the polarizer, section III shows the design of the Potter horn and some theory regarding its lens design and adaptation. In section IV several considerations regarding the combined system and its simulation results are presented. Finally, in section V some conclusions are drawn.

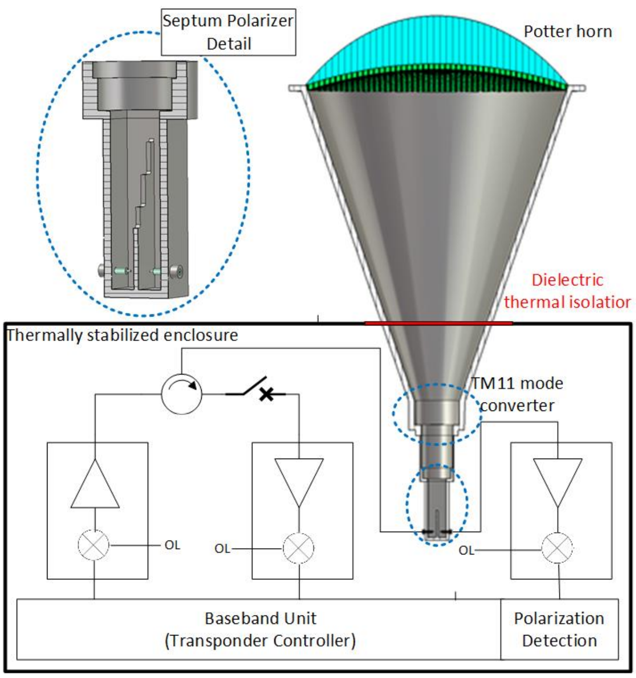

Fig. 1 Block diagram of the ASCAT radar echo calibrator

II. SEPTUM POLARIZER

The scatterometer sends either H or V polarization, which is a priori unknown to the Earth transponder. As previously stated, this uncertainty is solved using RHC and LHC polarizations in the transponder antenna. A square waveguide stepped septum polarizer [4] is used to decompose the linear polarization sent by the scatterometer into two circular polarizations. The LHC is the one used for calibration purposes, whereas the RHC is only used to determine if the original polarization is vertical or horizontal by comparing the relative phase to the LHC (0º for H and 180º for V).

Due to the extremely low axial ratio specification, special attention has been paid to the posterior septum manufacturing process. For example, the step edges have been rounded to include in the simulation the effects of the mechanization by a 4 mm drill and a tolerance test has been carried out performing simulations applying ±50µm variations at random to the different septum dimensions. Fig. 2 depicts the worst cases obtained in this test along with the optimized case where it can be appreciated that the specification is met. Therefore, it can be concluded that a 50 µm precision manufacturing process (which is achievable by any modern drilling machine) is enough to meet the axial ratio specification.

The designed septum is depicted in Fig 1. It consists of four steps and has input coaxial ports. At the septum end, a single step circular quarter wavelength transformer is attached to connect with the circular waveguide horn. The simulated reflection and isolation coefficients of the polarizer (with the transition attached) are below -25 dB in the whole bandwidth.

III. LENS AND POTTER HORN

Potter horns [5] have long been used due to its low cross polarization and side lobe level characteristics. For the ASCAT transponder a compact design is needed, so the horn length has been reduced considerably. This has the undesirable effect of increasing the phase error thus deteriorating the gain and side lobe level. To solve this problem, a microwave lens has been used to correct the phase error.

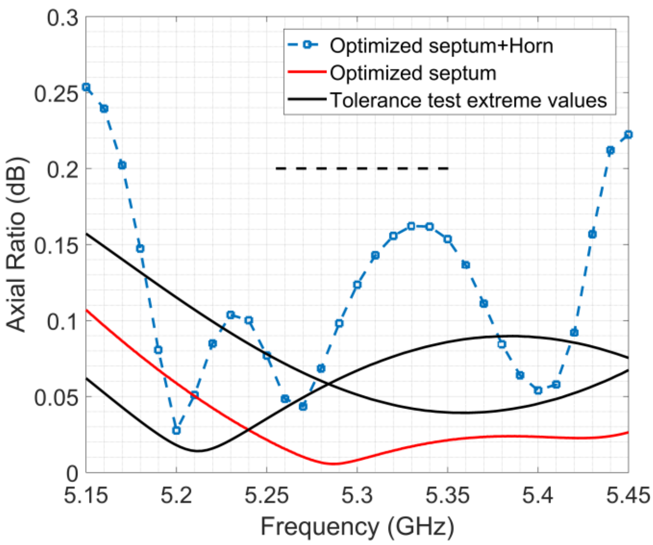

Fig. 2 Axial Ratios of the optimized septum, worst cases of the tolerance test and complete antenna

The lens loaded Potter horn design includes the following steps:

1. Design of the horn alone: Using SABOR [6] analytical models, the horn diameter (48 cm) is selected to be the same of a zero phase error 27 dBi horn. Then, the desired length (60 cm) is imposed. This will produce a given phase error to be corrected by the lens. These dimensions yield a flare angle of 18.9º and a phase error of 0.72. Despite the phase correcting lens, this phase error and flare angle cannot be arbitrarily high, as they increase the final SLL [7].
2. Optimization of the horn alone: with the flare diameter and length defined in the previous step, the dimensions of the horn TM11 mode converter (see Fig. 1) are optimized in order to obtain a good adaptation and TE11/TM11 amplitude and phase proper equalization [5] at the aperture, which will be reflected in a low cross polarization radiation level. Lenses tend to increase return loss, so a very low value is desired for this design step.
3. Lens design: a dielectric microwave lens is designed to correct the aperture phase error. This allows to increase the gain to the level of the zero error phase horn used as reference in the first step.
4. Lens matching and optimization: As the lens itself degrades de return loss, impedance transformers must be added, as it will be explained in the following sections. Finally, an optimization of some of the lens parameters is performed to improve the return loss and cross polarization characteristic.

The design and optimization of a Potter horn is a simple process dealt in numerous publications. However, the lens design poses some difficulties. In the next sections, some guidelines are given on how to in practice perform steps 3 and 4.

A. *Lens design*

The lens shape is determined so that it produces a constant phase front over its aperture. Ray tracing techniques have been used to derive the equations that describe the lens surface [8]. Figure 3 depicts the two most used types of lenses with the equations of their refracting surfaces. In the plane-convex lens, this surface is a hyperbola while in the meniscus lens is an ellipse. The non-refracting surface has no effect on the wave front, as the rays are normal to it. Plane-convex lens tend to concentrate the rays at the aperture center, producing a more tapered field distribution while the meniscus lens causes the opposite effect. This can be quantified using the amplitude correction factor [8], which represents the aperture power distribution over a lens illuminated by an isotropic source.

Any dielectric can be used to implement a lens. The higher the dielectric permittivity constant is, the thinner the lens will become. For this application, Teflon ($\varepsilon_r = 2.1$) has been selected due to its good properties in terms of water absorption (hydrophobic material) and UV radiation resilience. In addition, it presents a very low dissipation factor (loss tangent) (0.0002) at C-band frequencies.

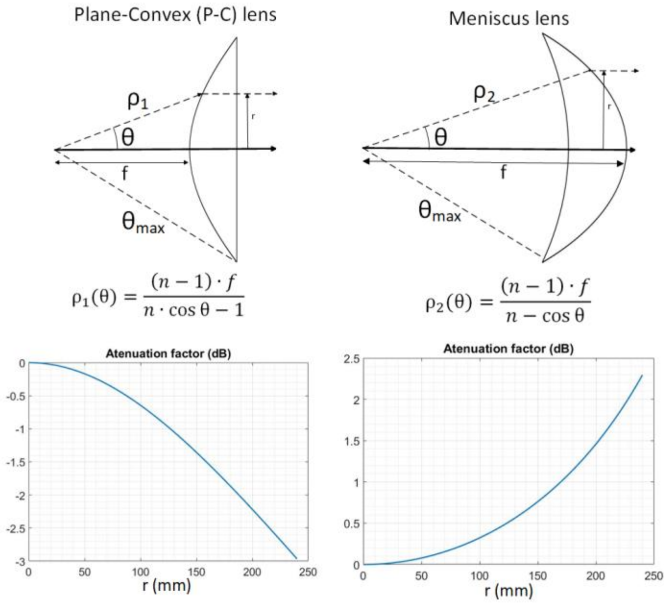

Fig. 3 Geometry of the plane-convex and meniscus lens and their corresponding amplitude correction factors

The two types of lenses described have been designed and simulated with the Potter horn obtained in step 2. In addition to the far field radiation, aperture fields have been computed in order to check the agreement with the formulation. In Fig. 4 it can be seen how the parabolic phase response of the Potter horn is practically equalized by the lens in both cases. The amplitude taper has increased in the plane-convex lens, whereas the meniscus lens exhibits a more planar response, which agrees with the attenuation factors presented in Fig. 3.

The aperture field distribution affects directly to the radiation patterns (see Fig. 5). Both lenses focus the radiation pattern narrowing the main lobe and increasing the gain. Due to the tapered aperture field, the plane-convex lens has a very low side lobe level, but widens considerably the main lobe which translates into a 1 dB gain loss (respect to the theoretical reference horn). In the opposite case, the meniscus lens exhibits a narrower beam width and higher SLL. Regarding the cross-polar radiation, lenses have little effect on the CP/XP level, since they only affect the amplitude and phase of the fields, regardless of the polarization.

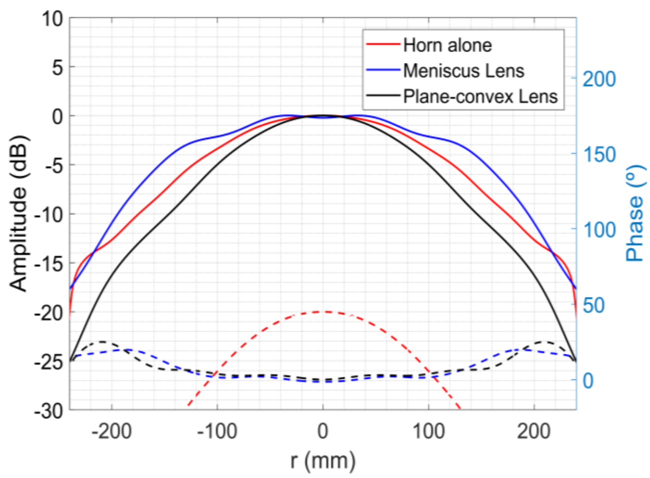

Fig. 4 Aperture field amplitude (continuous trace) and phase (dotted) of the horn with and without lens

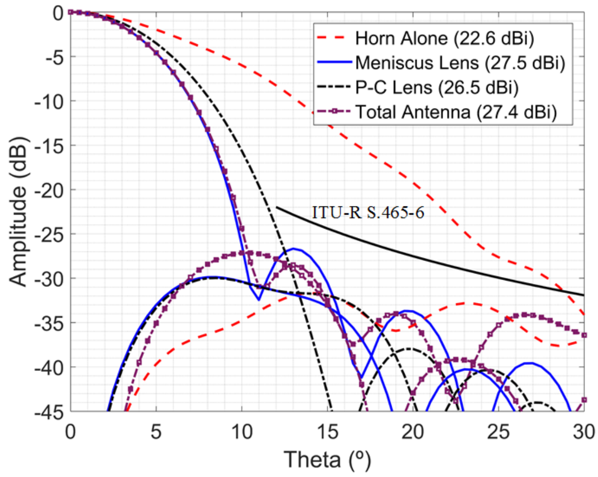

Fig. 5. Phi=45° cut radiation pattern for the horn with and without lens, and for the complete antenna

Figure 5 also shows the ITU-R S.465-6 recommendation. It can be seen that the meniscus lens presents enough margin. This fact and the higher aperture efficiency make the meniscus lens the most suitable choice, so it will be the one used for the final design.

B. Lens adaptation

The dielectric difference between the air ($\varepsilon_r = 1$) and lens ($\varepsilon_r = 2.1$) produces a discontinuity, which results in a reflection coefficient that can be approximated by the plane wave normal incidence equation:

$$\rho = \frac{\eta_1 - \eta_2}{\eta_1 + \eta_2} = -14\ dB \qquad (1)$$

This reflection coefficient is added to the horn return loss, which results in a value above the requirements. Therefore, matching techniques must be applied. The most common way is adding adaptation layers working as quarter wave impedance transformers at the desired frequency.

In order to match the lens to the air, usually two adaptation layers are placed in the inner and outer lens faces. In [7] analytical formulas are given to determine the depth and dielectric constant required for the adaptation layers. The value of this dielectric constant depends on the polarization and incidence angle of the wave coming to the lens. However, for small incidence angles (α) the dielectric constant can be approximated by:

$$\varepsilon_x \approx \sqrt{\varepsilon_{lens}} \qquad (2)$$

And the depth:

$$d = \frac{\lambda}{4\sqrt{\varepsilon_x - \sin^2\alpha}} \qquad (3)$$

Due to the lenses geometries, equation (2) is more accurate in the meniscus lens, as incidence angles are considerably smaller than in the plane-convex case. In addition, it is particularly good for circular polarization.

Fig. 6 (a) shows these dielectric impedance transformers in a meniscus lens. The obtained return loss is depicted in Fig. 7, showing a reflection coefficient below -23 dB over the whole bandwidth. In practice, adaptation layers are usually implemented using the same material as the lens, but applying to it some perforations to obtain the desired effective dielectric constant. In [9] several ways of implementing these perforations are studied, such as slots and cylindrical holes.

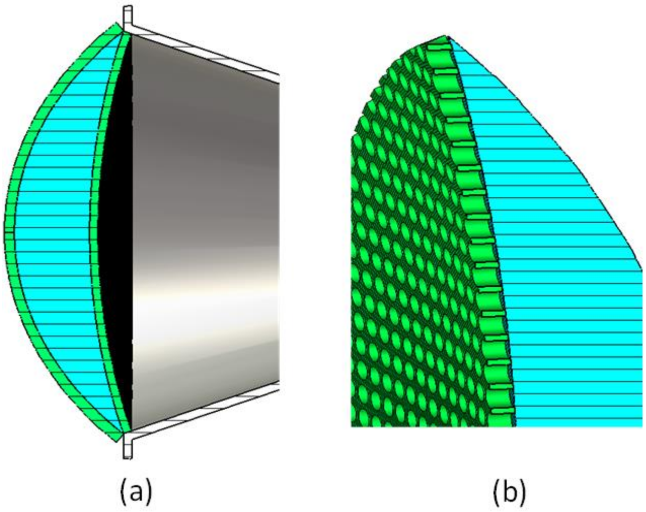

Fig. 6 Sectional views of a horn: (a) with two dielectric adaptation layers and (b) final optimized lens

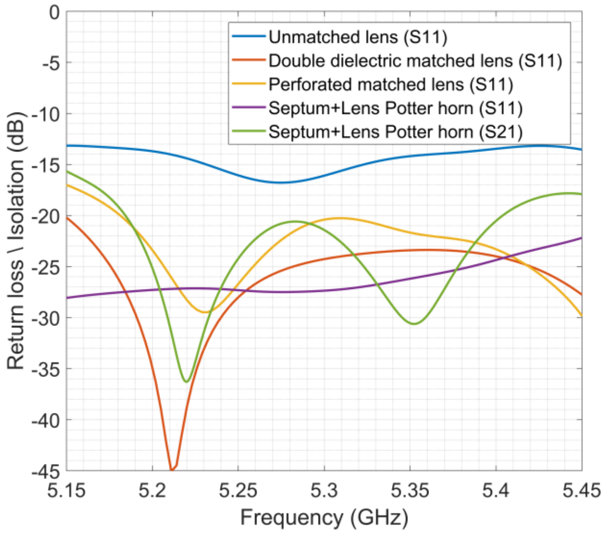

Fig. 7 Return loss and isolation for several meniscus lens matching configurations and for the complete antenna

Kildal [7] analyzed thoroughly the cylindrical holes and gave more accurate formulation for determining their dimensions. Cylindrical corrugations are also possible, as they present the advantage of resulting in a lens easier to manufacture with a milling machine. However, they present a less homogenous medium, thus degrading the cross polarization characteristic.

Ideally, both inner and outer adaptation layers are required for an adequate matching. However, the matching of the non-refracting surface is the most critical, as the reflected rays in it return to the focal point in a constructive way. In the refracting surface, the reflected rays bounce back in different directions and their contribution to the total reflection is less significant. For this application, this allows removing the outer adaptation layers in the meniscus lens. This presents the advantage that, when the antenna is pointing to the satellite, there is no risk of external agents like water or dust getting into the holes and thus degrading its performance.

Once the meniscus lens and its perforated adaptation layer have been designed, a final optimization is done to improve its adaptation and cross polarization characteristics. This is done with small variations of the depth and size of the holes. The lens thickness can also be varied displacing the non-refracting surface to make lens work as half wavelength window. In Fig. 6 (b) a sectional view of the optimized lens is shown. The cylindrical holes part is depicted in a different color than the lens just for better visualization, since they are of the same material as the lens (Teflon), unlike in Fig. 6 (a). It presents 4 mm holes separated 10 mm of each other. The obtained return loss is depicted in Fig. 7.

IV. Combined Antenna: Septum+Horn

Once the septum and Potter horn have been designed, the last step is their assembly. As a circular polarization changes its rotation direction when reflected, the horn return loss does not contribute to the complete antenna adaptation, but to the channel isolation. This means that the complete system return loss will be the same as that of the septum, while the isolation will be a combination of the septum isolation and horn reflection coefficient, as it can be appreciated in Fig. 7. In addition, the polarization inversion has the effect of degrading the final axial ratio, as shown in Fig. 2.

V. Conclusions

A septum polarizer and a short Potter horn have been designed and simulated to be used in a scatterometer calibration transponder. The horn length has been reduced with the help of a Teflon meniscus lens that produces a quasi-planar aperture phase. The dielectric discontinuity produced by the lens is matched by means of an impedance transformer implemented performing holes in the inner lens surface. Adaptation and radiation results are given for the several proposed lens as well as for the horn and polarizer combined.

Acknowledgements

This work has been supported by Advanced Radar Technologies (ART), the Spanish National project ENABLING5G “Enabling Innovative Radio Technologies for 5G networks” (TEC2014-55735-C3-1-R), and the Madrid Region Government S2013/ICE-3000 (SPADERADAR-CM).

References

[1] R. V. Gelsthorpe, E. Schied, and J. J. W. Wilson, “ASCAT—Metop’s advanced scatterometer,” *ESA Bull.*, no. 102, pp. 19–27, May 2000.
[2] Wilson, J.J.W., Anderson, C., Baker, M.A., Bonekamp, H., Saldaña, J.F., Dyer, R.G., Lerch, J.A., Kayal, G., Gelsthorpe, R.V., Brown, M.A., Schied, E., Schutz-Munz, S., Rostan, F., Pritchard, E.W., Wright, N.G., King, D., Onel, U. (2010). Radiometric calibration of the advanced wind scatterometer carried onboard the Metop-A satellite. *IEEE Transactions in Geoscience and Remote Sensing*, 48(8), 3236-3255.
[3] Alan W. Rudge, “The Handbook of Antenna Design, Volumen 1”
[4] Zhong, W., B. Li, Q. Fan, and Z. Shen, "X-band compact septum polarizer design," *ICMTCE*, , 167-170, 2011.
[5] P.D. Potter. “A new horn antenna with suppressed sidelobes and equal beamwidths”. Microwave J., Vol VI, No. 6, pp. 71 – 78, June 1963.
[6] M. A. Campo, F. J. del Rey, J. L. Besada, L. de Haro, "SABOR: Description of the Methods Applied for a Fast Analysis of Horn and Reflector Antennas", IEEE Antennas and Propagation Magazine, vol. 40, no. 4, August 1998.
[7] P-S. Kildal, K. Jakobsen, K. S. Rao, "Meniscus lens-corrected corrugated horn: An efficient feed for a Cassegrain antenna", Proc. Inst. Elec. Eng., no. 6, pp. 390-394, 1984-Dec.
[8] Thomas A. Milligan, “Modern Antenna Design”, Second Edition, 447-451.
[9] T. Morita, S. B. Cohn, “Microwave lens matching by simulated quarter-wave transformers”, IEEE Trans. Antennas Propagat., vol. AP-4, pp. 33-39, Jan. 1956.