Correction of the Impact of Refraction due to Environmental Conditions in High Resolution SAR

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***Abstract*— SAR signal processing is based on the evolution of the time delay between the emission of the pulse and the reception of the echo during the illumination time. During processing, it is assumed that the wave travels through an homogeneous medium with constant dielectric characteristics and thus that the optical path corresponds to the straight line between sensor and target. In reality, waves travel through different media, like clouds, forest canopies, walls, which have a different dielectric constant. Refraction through those different media will impact the measured time delay and so lead to an incorrect estimation of the range of the different targets. Ignoring this effect during processing will cause a degradation of the image quality. It is possible to correct this effect when all parameters (thickness and dielectric constant) of the different media are well known. This paper proposes to analyze the possibilities to estimate the value of those parameters from the SAR data.**

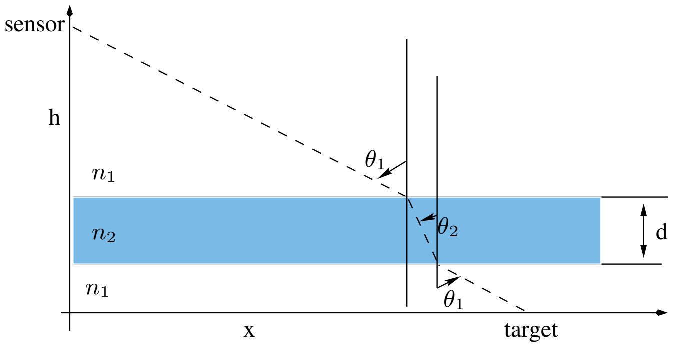

Fig. 1. Canopy refraction model

I. INTRODUCTION

In several SAR applications, the medium situated between the sensor and the target is not an homogeneous medium from dielectric point of view. FOPEN applications [5],[3] are interested in ”seeing” through forest canopies. FOPEN applications often use the polarimetric and/or interferometric aspects of SAR data and one specific model of forest canopies, the Random Volume over Ground (RVoG) model [8] is used to describe the polarimetric behavior of the canopies. This model doesn’t take into account a possibly different dielectric constant of the canopy due to its higher water content.

One main advantage of radar is its ability to ”see” through clouds and rain. Clouds are characterized by a very high relative humidity and so the radar wave will be refracted by the cloud. The thicker the canopy cloud, the more important the refraction.

Through the wall applications [1] are applications where sensor and targets are separated by at least one wall. Depending on the material used, this wall can show a dielectric constant that can easily reach values 10 times higher than the dielectric constant of the air.

In all the cases described above, refraction of the radar wave will occur. This refraction will have an impact on the processed image quality if the refraction is not taken into account during processing. As described in [7], the degradation will become more important as the thickness of the medium (cloud, wall,...) increases, as the dielectric constant becomes higher or as the resolution of the SAR system becomes finer. The impact of the refraction on the image quality and the problem statement are described in section II. In section III, we will shortly describe the possibilities for correction of the refraction effects. Section IV will then be dedicated to the analysis of the possibilities for determining the parameters of the medium from the SAR data. Finally, section V will give the conclusions on this present work.

II. PROBLEM STATEMENT

The additional delay added by the propagation through a different medium than the atmosphere is due to the dielectric properties of that medium. From a dielectric point of view, we model that medium as an horizontal homogeneous layer with a dielectric constant value which differs from the atmosphere. If we neglect attenuation and dispersion, we can apply the optical law of refraction on the wave going through that layer, as depicted on figure 1.

The optical path follows the Snell-Descartes law [2].

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

where n_1 and n_2 are the refraction indexes of respectively the atmosphere and the considered canopy and θ_1 and θ_2 the incidence angles represented on figure 1. In the canopy the wave velocity v_2 is given by the Huygens-Fresnel law [2].

$$v_2 = \frac{c}{n_2} \tag{2}$$

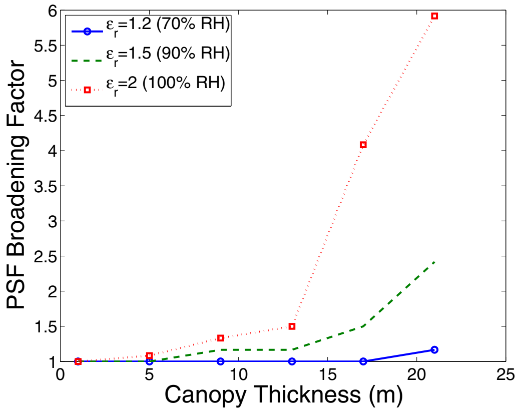

Fig. 2. 3 dB-width degradation for an airborne L-band system with azimuth resolution of 45 cm (RH=relative humidity

where c is the speed of light.

The round-trip time of the wave, as represented on figure 1 will be longer than expected in the absence of the specific medium because of the longer optical distance, compared to the physical distance between target and sensor, but also because of the smaller velocity in medium. As SAR signal processing uses this round-trip time to evaluate the range evolution of the target during illumination time, a higher round-trip time will lead to an overestimation of the range of the target.

One obvious effect of that range error is a displacement in range of the target image. As all ground targets in the scene would be displaced, that effect would not be very disturbing for further image processing, even if the displacement is a function of range. The second more disturbing effect is the fact that the range error during illumination will cause a phase error in the azimuthal phase history of the target making the azimuth compression less efficient. The consequence will be a degradation of the azimuthal Point Spread Function (PSF) that can be measured and described by the 3-dB width of the main lobe of the PSF.

Figure 2 represents the PSF broadening in the case of a fine-resolution airborne L-Band system as a function of the canopy thickness and the relative dielectric constant of the medium. As can be seen on figure 2, a broadening of the PSF with a factor 5 can occur.

III. CORRECTIVE METHODS

The refraction effects on the image processing are a range displacement of the targets and a broadening of the azimuthal PSF. In the ideal case, both effects have to be perfectly corrected. In [4], it is effectly shown that it is the refraction through a dispersive layer that must be accounted for in order to obtain a focused image. A theoretical imaging operator that takes the refraction inti account is also defined in [4] considering continuous signals. The following sections are presenting the numerical implementation of several solutions to correct the refraction.

SAR processing algorithms use the explicit hyperbolic expression of the range evolution that in some cases (low squint, limited apertures) can be approximated by a parabolic expression [6] given in equation (3).

$$R(\eta) = \sqrt{R_0^2 + V_r^2\eta^2} \approx R_0 + \frac{V_r^2\eta^2}{2R_0} \tag{3}$$

where R_0 is the range of closest approach, V_r is the effective radar velocity and η is the azimuth time relative to the time of closest approach. This relatively simple expression allows fast and effective SAR reconstruction algorithms, for instance the Range-Doppler Algorithm [6].

In the presence of a dielectric medium between sensor and target, that hyperbolic expression is no longer valid and should be adapted taking the real round-trip time into account. To compute the real round-trip time by considering the acquisition geometry of figure 1 and equations (1) and (2), the correct values of the medium parameters (thickness and dielectric constant) have to be known. This limitation classifies the corrective methods in two groups as a function of the availability of those values.

A. *Corrective Methods with Known Parameters*

1) 2-D Matched Filtering: In the RDA algorithm, 2 one-dimensional matched-filters are used. First a one-dimensional matched filtering in the range direction for range compression. And after the Range Cell Migration Correction (RCMC), a one-dimensional matched filtering in the azimuth direction for azimuthal correction. Both matched filterings are easy to implement and relatively fast computed in the spectral domain. In the presence of a refractive medium, the expression of the matched filter changes for each data bin. Matched filtering is still possible but the correct filter has to be computed for each data point making this method very time consuming. But the main advantage of this method is that both effects of the refraction are perfectly corrected.

2) Adapted RDA: As an alternative to the very time-consuming 2-D matched filtering, [7] proposed to adapt the azimuthal compression in the RDA algorithm to correct the azimuthal PSF. There is then no correction of the range displacement of the targets. The difference in range curvature of a target because of the medium is negligeable when performing the RCMC which allows an almost perfect recovery of the azimuthal PSF.

Figure 3 illustrates the ability of this adapted RDA to recover the azimuthal PSF in the scenario described above and with a 20-meter-thick medium with a relative dielectric constant equal to 2.

B. *Corrective Methods with Unknown Parameters*

The methods described here above do need the knowledge of the exact parameters of the medium. In the case of through the wall imaging, it might be reasonable to admit that the wall thickness can easily be measured. Measuring the dielectric constant of the wall might be more difficult on the field. In the case of clouds or forest canopies, it is a lot more difficult to get

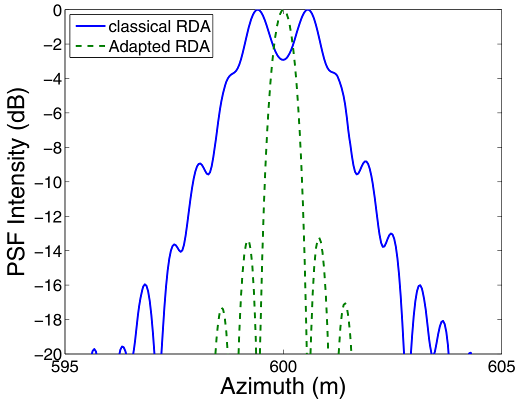

Fig. 3. Comparison of the azimuthal PSF obtained with a classical or an adapted RDA in the presence of a 20-meter-thick medium with ϵ_r=2

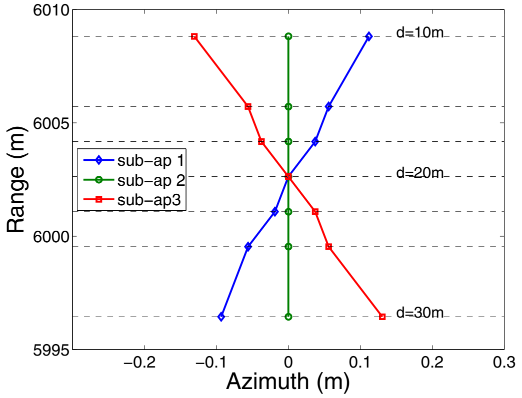

Fig. 4. Loci of a focussed point target using different data subsets and different estimated values for the thickness of the medium

the right values of those parameters, even if some estimation is available.

One way to avoid the need for those parameter values is to rely on a kind of algorithm able to correct phase errors, for instance autofocus algorithms.

It is possible to correct the azimuthal PSF by blindly processing the data with a classical RDA algorithm followed by an autofocus algorithm as the Phase Gradient Autofocus (PGA) [9]. The main advantage of this method is that it doesn't need any knowledge at all of the medium parameters (thickness and dielectric constant). The disadvantages of the method are determined by the limitations of the PGA algorithm in the case of complex or extended scenes.

IV. ESTIMATION OF THE MEDIUM PARAMETERS : INVERSE PROBLEM

The performance of the adapted RDA or the 2-D matched filtering doesn't depend on the data or on the observed scene, making those algorithms more robust and more reliable than the PGA. But the non negligeable condition is the availability of the right values of medium parameters. In [4], the possibility to retrieve the value of the permittivity had been left for the future.

If we can retrieve the parameter values from the SAR data itself and use those values with an adapted RDA for example, we will combine the reliability of the algorithm with the independance of any a priori knowledge of the environmental conditions.

We propose to study the possibility to retrieve the value of one parameter from the data, knowing the other or even more to retrieve both parameters from the data.

A. *Retrieving the Thickness*

In a first step we will attempt to recover the thickness of the medium assuming the dielectric constant is known. In [10], a method to resolve the wall thickness is presented in the case of beamforming for through-the-wall imaging. We propose to adapt this method to SAR processing.

The full aperture is divided into at least 2 smaller apertures to get data sets having different squint angles. Each data subset is processed with the adapted RDA taking different values of the unknown parameter into account. A point target in the scene will then be focused at different positions. The result of the different simulations is depicted on figure 4 showing the locus of the focussed point target for each subset. The different loci will intersect in a point corresponding to the right parameter value. This value can then be used for a high accuracy processing of the full data set.

Apparently, this method would need the presence of point targets in the image, comparably to the PGA algorithm. One possibility to generalise the method for a situation without point targets is to correlate the different images to retrieve similar curves as on figure 4.

B. *Retrieving the dielectric constant*

In a second step we will attempt to recover the value of the dielectric constant of the medium assuming the thickness of the layer is known.

Similarly to the former section we divide the data set into at least 2 subsets that are processed with the adapted RDA taking different values of the dielectric constant into account. The results of the different simulations are depicted on figure 5 where the locus of the focussed point target for each subset is represented. The instersection of the resulting curves corresponds to the right value of the dielectric constant.

C. *Retrieving both parameters*

The method described in the last 2 sections allows the computation of one parameter with the knowledge of the second one. Nevertheless we are still looking for a method to retrieve the value of both parameters.

It is not possible to combine in an iterative way the derivation of the thickness with a known value of the dielectric constant and the derivation of the dielectric constant with a known value of the thickness to find the good pair of values. Indeed, if we started from an underestimated value of the dielectric constant ϵ_{under}, the computation of the thickness with the method using different apertures would give us a greater value than the real one, d_{over}. The computation of the dielectric constant starting from the thickness d_{over} would, in

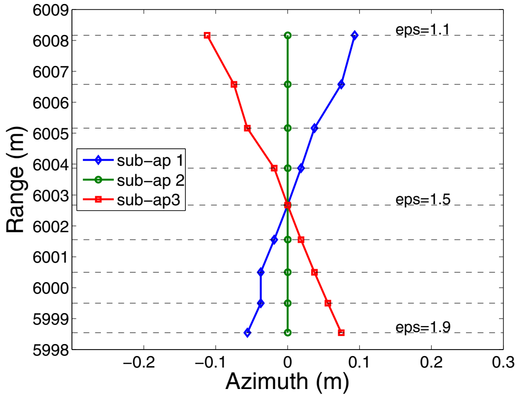

Fig. 5. Loci of a focussed point target using different data subsets and different estimated values for the dielectric constant of the medium

turn, result in ϵ_{under}, which cancels immediately any iteration attempt.

The application of the method with different apertures to different point targets at different azimuth or range positions does not allow to determine if we are in the case of underestimation, overestimation or correct estimation of the thickness (and a forteriori of the dielectric constant). Indeed, the used pixel size does not allow to see any difference in the computation of the thickness corresponding to a wrong estimated dielectric constant for different point target positions.

So far, it doesn't seem that the method with different apertures allows the separation of the effects of the thickness and of the dielectric constant, which means it does not allow the correct estimation of both parameters.

D. Effect of an incorrect estimation of the values of the parameters

Let us give a look at the effect on the image quality of an incorrect pair of values for thickness and dielectric constant. An incorrect pair of values means from now on that one parameter has been arbitrarely chosen or roughly estimated starting from any kind of a priori knowledge and that the other parameter has been computed by the method with different apertures using the rough estimate of the first parameter.

Starting from simulated data of a point target in the presence of a layer with known parameters, we can apply the derivation of the thickness, for example, starting from different values of the dielectric constant. The result is then different pairs of values from which only one corresponds to the parameters used to simulate the data. Figure 6 shows different pairs of values we can obtain with this method starting from simulated data with a thickness of the layer $d = 20$ m and a dielectric constant $\epsilon = 1.7$.

The next step is to analyse in which way an incorrect pair of values obtained as described hereabove can correct the data. The data is processed with the adapted RDA for each of the obtained pairs and the obtained PSF in each image is compared to the others on figure 7.

As can be seen on figure 6, any combination of values obtained as described above is able to correct the PSF and to retrieve the expected theoretical azimuthal resolution. The pairs of values represented at figure 6 have been obtained by applying the method of multiple apertures to a point target situated at a specific range (here R=6003 m). The PSF correction obtained with those pairs of values and represented on figure 7 corresponds to a target at that same range. But the same effective correction is obtained at all ranges, as can be seen on figure 8 showing the results of the adapted RDA for a target situated at a longer range and on figure 9 showing the results for a target situated at a shorter range.

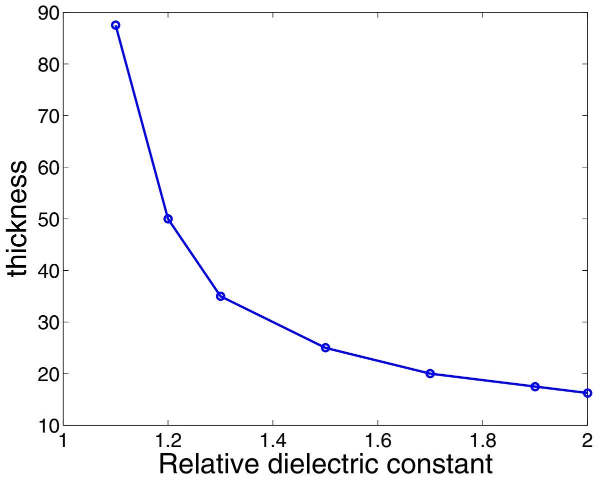

Fig. 6. Pairs of values obtained for simulated data with $d = 20$m and $\epsilon = 1.7$

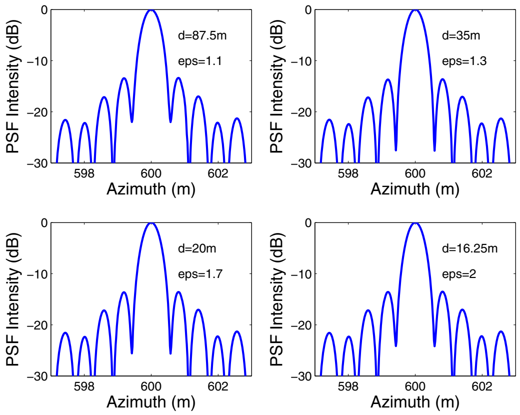

Fig. 7. PSF obtained with incorrect pairs of values for thickness and dielectric constant of the layer for a target at R=6000 m

V. CONCLUSIONS

Considering the trend to reach finer and finer resolutions in classical SAR applications but also in applications like through-the-wall imaging or FOPEN, the accuracy requirements will keep on increasing. Phenomenons or effects that could be neglected in the past and even still today will have to be taken into account.

The analysis of the possibilities to retrieve, from the data, the parameters describing the environmental conditions impact

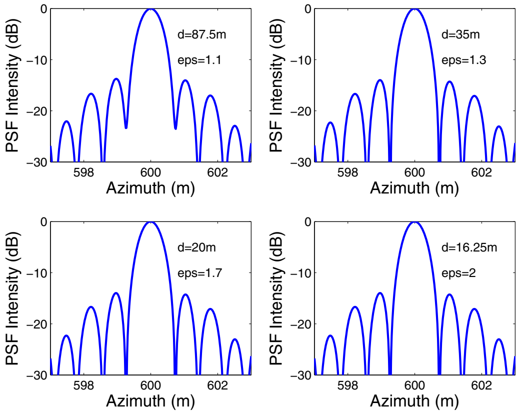

Fig. 8. PSF obtained with incorrect pairs of values for thickness and dielectric constant of the layerfor a target situated at R=7250 m

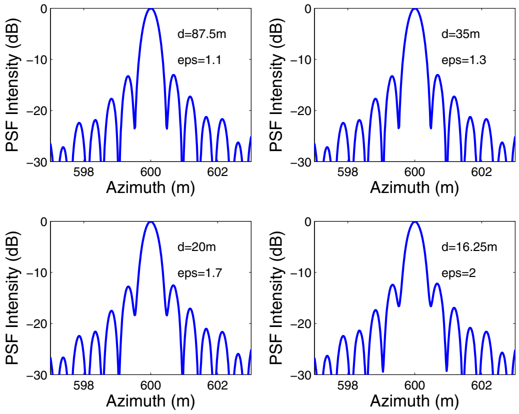

Fig. 9. PSF obtained with incorrect pairs of values for thickness and dielectric constant of the layerfor a target situated at R=5000 m

on the image quality, is achieved in the perspective of finding ways to prevent the degradation of the resolution in future SAR systems.

In this work we have introduced a simple model to describe the effect of refraction by another medium than air on SAR data. The well-known RDA algorithm has been adapted to correct the degradation caused by the refraction.

The disadvantage of the adapted RDA is the necessity to know the parameters of the layer, namely its thickness and its relative dielectric constant. As a priori knowledge is not often available, it is necessary to find ways to retrieve the values of those parameters from the data.

We proposed a method able to retrieve one parameter value from the data starting from the knowledge of the other parameter. As the proposed method is not able to estimate correctly both parameters, we have looked at the result obtained by this method starting from a wrongly estimated value of one parameter. We have shown that different pairs of values of both parameters have the same effect on the data and so have also the same capacity to correct data taken in the presence of a refractive layer, which means that we don't need the exact a priori knowledge of both parameters any more and not even the exact knowledge of one of the 2 parameters.

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