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# Non specular reflection and depolarisation due to walls under oblique incidence

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## 1. Introduction

Bi static radar remote sensing has became a large source of data intended to analyse the composition and the behaviour of targets placed very far away from the sensor. The possibility of determining the nature of the surface in which the electromagnetic waves have impacted, and have been reflected by, is directly correlated to the knowledge of high precision scattering models. In most of the situations, the Fresnel coefficients for reflection have been the only procedure used to obtain the electromagnetic characteristics of the target material from the reflection this surface induced in the propagating wave. That electromagnetic characterisation is quite important in remote sensing techniques, as it depends on the frequency and, so that, it could help in defining the spectral signature of each target material.

Historically, several models have been proposed in order to improve the performance of the simple Fresnel coefficients to obtain the dielectric constant of an obstacle. The aim of such models is to define the outcomes of the incidence of a propagating wave on a constructive surface (Balanis, 1989; Burnside & Burgener, 1983; Correia & Françês, 1995; Sato et al., 1997). When the reflective phenomenon is limited to the specular direction, it is commonly known as specular reflection; whereas when several directions are taken into account, the reflection concept (or, in general terms, scattering) is extended to all directions in the incidence region. Any obstacle generates its own reflection pattern, which depends on the electromagnetic characteristics of the material, the surface roughness, the frequency, and the angle of incidence. Published measured results show that there may be several scattering directions as significant as the main specular reflection one. This result leads to conclude that the received power in the specular direction could not represent the main contribution among the reflections on the surface under study. Thus, computing the dielectric constant of the surface material from just the data reflected towards the specular direction could lead to large mistakes.

The specular reflection on flat or almost flat obstacles can be considered as a well studied propagation mechanism, and several models have been enunciated to describe its performance. The interest of specular direction resides in the need of exact models and fast algorithms that are used in the radio electric planning tools. The non-specular or general reflection, although less taken into account in practice, is also a topic that focuses several works (Beckmann & Spizzichino, 1963-1987; Cuiñas et al., 2007). These results have capital importance when the application is remote sensing and the objective is to detect and even to identify possible targets by means of their scattering patterns.

A phenomenon associated to reflection, the depolarisation that could be generated when a wave beats a flat obstacle, appears to be not so fine defined and modelled. The reason of this lack of interest is probably because the typical application of reflection models has been the radio planning tools. These tools were designed for frequencies bellow millimetric bands, assigned to cellular phone or television broadcasting, and the typical obstacles (walls) are electrically flat enough to provide strong specular reflections at these frequencies. At higher frequencies, the electrical size of a given obstacle becomes larger, and the specular reflections could not be so dominant among the complete scattering arc angles.

Although there are different published research works on depolarisation, they are commonly centred at lower frequencies, and they often treat on complete radio channels, instead of the analysis of isolated obstacles. Several of these works reports the polarisation diversity gain measured at indoor radio channels: up to 15 dB at UHF band (Sánchez & Sánchez, 2000), and from 4 to 10.5 dB at 2.05 GHz (Dietrich et al., 2001); or even in outdoor environments: between 11 to 5.2 dB at 1800 MHz (Turkmani et al., 1995), depending on the type of environment: urban, suburban or rural. The contents of this chapter are not comparable to the previous work, as they are oriented to analyse the radio channel, including multipath propagation, whereas the aim of the presented work is the study of isolated flat obstacles.

This chapter summarises the theoretical approaches to the study of scattering and depolarisation generated by flat isolated obstacles, and it also outlines measurement results obtained by the authors at 5.8 GHz, involving three different constructive materials and taking into account two orthogonal polarisations for the incident wave, which comes from several angles of incidence to the obstacle.

The chapter is organised as follows. The contents of the section 2 are the theoretical basis of this work: an overview of specular reflection models, which are used to extract the electromagnetic parameters of each considered material, and the exposition of the Physical Optics model used to compute the reflection patterns.

The depolarisation indexes computation procedure is introduced in section 3. This section contains the discussion of a methodology to determine the amount of cross-polarised wave that could be generated by reflection on the surface of an obstacle in the radio channel. The proposed matrix formulation, which is inspired in the polarimetric matrix (Mott, 1986), allows the separation between the depolarisation due to the antennas and that produced by the obstacle. The depolarisation indexes indicate the fraction of the signal power that is depolarised after beating the obstacle.

The section 4 shows the results, comparing the behaviour of the Physical Optics model application when it simulates reflection patterns in similar geometrical conditions that previously measured. Finally, the section 5 contains the conclusions.

## 2. Scattering coefficients

The specular reflection is just a simplification of the complete, and complex, effect of walls over propagating waves. When a wave beats a wall, a scattering phenomenon is generated towards all space directions, defining a reflection pattern. However, specular reflection

models are very useful to obtain an initial approach to the characteristic parameters, as permittivity and conductivity, which drive the electromagnetic behaviour of the material. These parameters could be used as input data to those more complex scattering models.
The scattering due to surfaces of any kind is a classical area of study that has its biggest impetus with the advent of radar, in the middle of 20th century. There are several models to predict the behaviour of a surface when an incident wave beats it (Ruck et al., 1970). The strategy to model their effects on the propagating wave depends on the type of roughness.
Besides, the scattering by perfectly conductive surfaces is a problem analysed by several reflector antenna methods. These problems are tried to be solved by employing high frequency methods, which are valid when the reflector size (in our case, the obstacle size) is large in terms of wavelength (Scott, 1990). A combination of both radar ideas and antenna analysis methods has been applied in the work summarised at this chapter to model the reflection due to constructive walls. The formulation, based on Physical Optics, is intended to compute scattering patterns due to flat and rough surfaces, both dielectric and conductive.

### 2.1 Specular reflection coefficients

The behaviour of a wave when it beats an obstacle mainly depends on its permittivity. This behaviour has been modelled by different methods (Landron et al., 1993, 1997; Lähteenmäki &Karttavi, 1996; Cuiñas et al., 2001), most of them based on classical Fresnel formulation. This Fresnel theory works consistently when the obstacle thickness is electrically large and/or the material losses are huge. Typical walls are not infinite thickness, and this is the reason because several models have been enunciated to take into account this situation. Among the models based on Fresnel method, the internal successive reflections (ISR) model must be mentioned: it tries to explain transmission and reflection phenomena as a result of the coherent sum of several multipath components, generated in both boundaries between the obstacle and the free space (Burnside & Burgener, 1983). Although this model assumes that the slab surface is infinite, the results are adequate if the material sample is wide enough to contain the first Fresnel ellipsoid of the radio link.

### 2.2 Physical Optics model

A good characterisation of scattering due to rough or slightly rough surfaces must include all-direction effects. The Physical Optics formulation fits this condition, and it is a classical method to characterise conductive surfaces (Beckmann & Spizzichino, 1963-1987).
The electric field strength, as well as its derivative respect to surface normal, could be estimated by using Kirchhoff approximations. Thus, it can be assumed that the total field in a point on the surface is the same as in a tangent plane to the surface at the same point. The larger the roughness curvature radius is, the better the approximation is.
Assuming an electrically large obstacle, the Physical Optics model leads to a single equation to define the reflection coefficient, the general formulation of the scattering coefficient.

$$\rho = \frac{1}{4L\cos\theta_i}\int_{-L}^{L}(a\xi' - b)\cdot e^{jv_x x + jv_z \xi}\,dx \tag{1}$$

There is no general, exact and explicit solution for finite conductivity surfaces, but some approximations can be applied, which performance is better when the rough surface presents soft slopes, or large radii of curvature: in other words, when we manage rough, but smooth enough surfaces.

As a general conclusion, it can be said that scattering due to non-conductive surfaces is affected by finite conductivity only when local reflection coefficients are more influenced by its local incident angle, than by the electromagnetic properties of the scatterer.

### 2.3 Application of the model

The application of this formulation is suggested for three different strategies. Successive proposals have growing computational cost and complexity, but they give better concordance to actual situations (Cuiñas et al., 2007). Figure 1 depicts the three strategies.

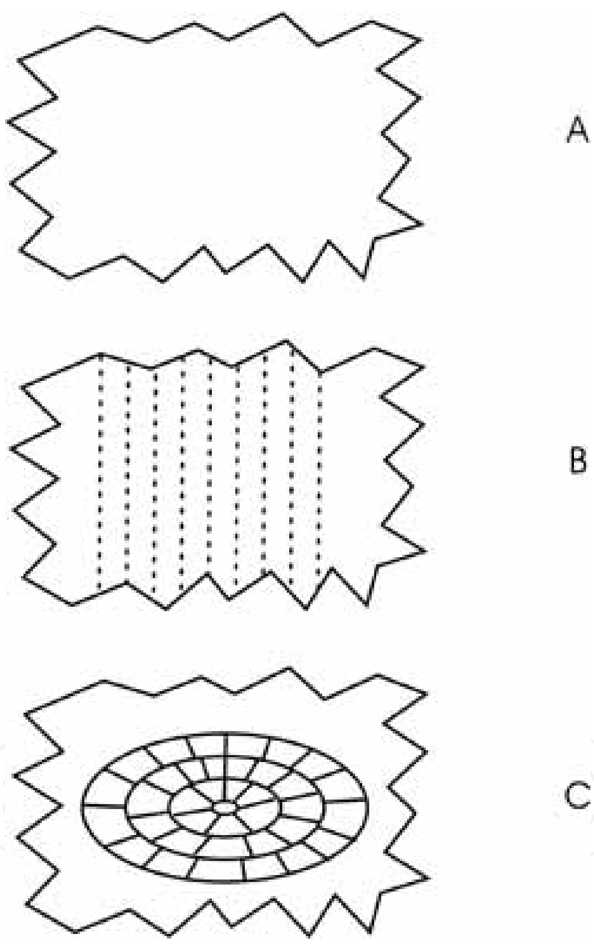


Fig. 1. Strategies to apply the Physical Optics formulation: A, direct; B, by segments; C, 3D

The first option focuses on the direct application of the Physical Optics formulation considering an incidence field on a flat surface, with an incidence angle determined by direct propagation path between the transmitter antenna and the centre of illumination. This case does not consider the radiation pattern of the antenna.

As the field strength over the illuminated area is not uniform, but varies with the angle from the centre of the beam according to the gain pattern of the antenna, a second option is

proposed. This strategy consists in dividing the surface into several parallel segments of the same width and assumed infinite length. The local angle of incidence at each segment is considered when applying Physical Optics method. Thus, part of the effect of the antenna radiation pattern can be considered, as local situations are taken into account. This method may be a good choice for flat or for one-dimensional rough or periodic surfaces.
The third option consists of determining the illuminated surface on the obstacle, taking into account the radiation pattern of the transmitter antenna. That radiation pattern determines a footprint on the obstacle surface, with elliptic shape. This footprint on the surface is divided into several patches. The Physical Optics formulation is applied on each patch, considering the local incidence angle at each of them. In this situation, the application of the algorithm needs a reformulation, as the local scattered electric field has to be computed at each patch, and then all these contributions have to be coherently combined to compute the complete scattered field at any scattering direction. This idea is based on antenna analysis techniques, as (Arias et al., 1996).

## 3. Depolarisation indexes

The depolarisation index, for any material, at any angle of incidence and any polarisation of the transmitted waves could be defined as the fraction of the power of this wave that is received in the orthogonal polarisation. From this definition, depolarisation indexes may be computed by means of a matrix procedure. The proposed method provides a set of depolarisation indexes that characterise the reflection mechanism generated when a wave reach an obstacle with oblique incidence (Cuiñas et al., 2009).
The definition of the matrix model begins in the characterisation of the radio channel following the Friis formula, but taking into account two orthogonal polarisations, considering the presence of an obstacle in the radio path, and assuming that both transmitting and receiving antennas are pointed to the same spot on the reflecting surface. Then, the transmitting antenna is illuminating the reflection point with its maximum gain, and the receiving antenna is getting the waves from the obstacle by its maximum gain direction. The free space attenuation coefficient could be computed by substitution of the obstacle by a perfectly conductive surface.
With the model equation, the definition of the obstacle behaviour is completely independent from the effect of the free space propagation in the open links between the transmitter and the obstacle, and between the obstacle and the receiver. The matrix $A^{OBS}$ contains the data corresponding to the obstacle effect on the complete radio channel. Figure 2 depicts the physical significance of each element in the matrix.

$$A^{OBS}\left(\theta_{inc},\theta_{obs}\right)=\begin{bmatrix} a_{VV}^{OBS}\left(\theta_{inc},\theta_{obs}\right) & a_{VH}^{OBS}\left(\theta_{inc},\theta_{obs}\right) \\ a_{HV}^{OBS}\left(\theta_{inc},\theta_{obs}\right) & a_{HH}^{OBS}\left(\theta_{inc},\theta_{obs}\right) \end{bmatrix} \tag{2}$$

The computation of depolarisation indexes is difficult, in general terms, because of the separation between the depolarisation due to the obstacle and the depolarisation due to the antennas is needed. Nevertheless, this problem could avoided with the matrix formulation that has been commented, as the elements of the obstacle matrix ($A^{OBS}$) are only related to the obstacle, and they do not include other effects. The depolarisation indexes can be defined from the obstacle matrix elements as:

$$DI_H(\theta_{inc},\theta_{obs}) = \frac{a_{HV}^{OBS}(\theta_{inc},\theta_{obs})}{a_{HV}^{OBS}(\theta_{inc},\theta_{obs}) + a_{HH}^{OBS}(\theta_{inc},\theta_{obs})}$$
$$DI_V(\theta_{inc},\theta_{obs}) = \frac{a_{VH}^{OBS}(\theta_{inc},\theta_{obs})}{a_{VH}^{OBS}(\theta_{inc},\theta_{obs}) + a_{VV}^{OBS}(\theta_{inc},\theta_{obs})} \quad (3)$$

where the sub index indicates vertical or horizontal incidence (transmission). As these indexes are computed from $A^{OBS}$ elements, each pair of $\theta_{inc}$ and $\theta_{obs}$ would define their associated pair of depolarisation indexes.

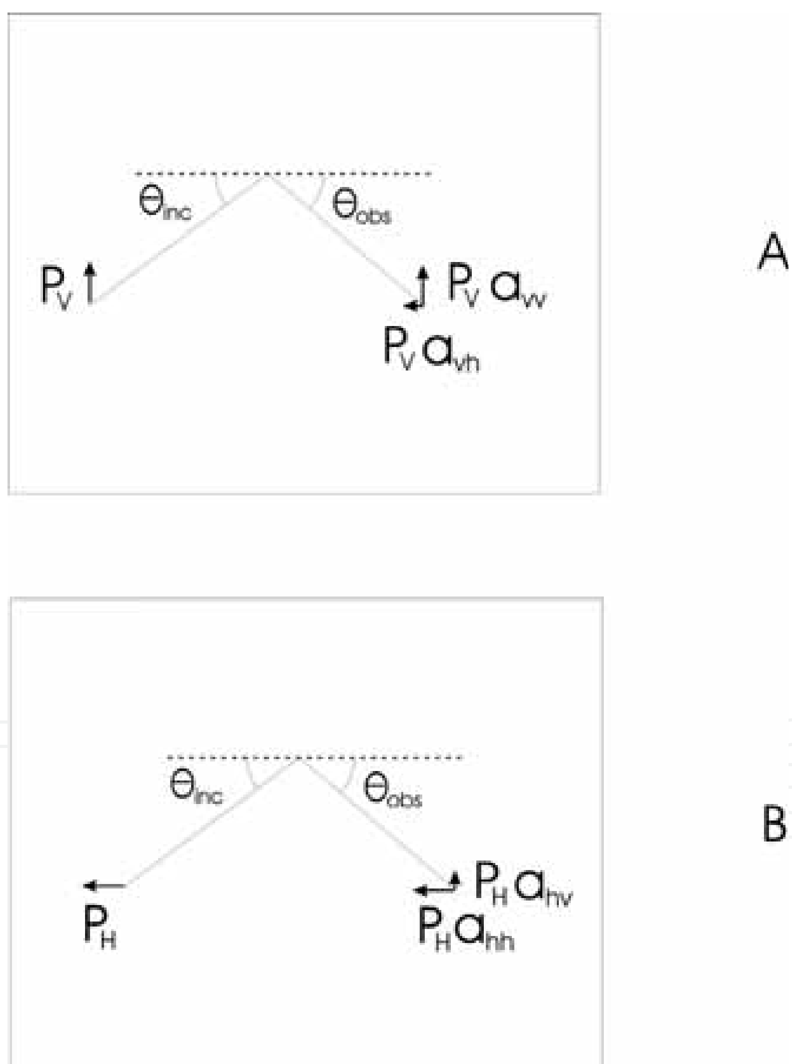


Fig. 2. Definition of matrix elements: A, vertical incidence; B: horizontal incidence

## 4. Results

The wellness of the proposed methods has been checked by comparing to measurement outcomes performed at 5.8 GHz (Cuiñas et al., 2007). The exposition of the results begins with the Physical Optics formulation: measured scattering patterns are compared with those computed by applying Physical Optics formulation, following the three described strategies. Then, the depolarisation indexes are computed.

### 4.1. Reflection pattern

The Physical Optics formulation has been applied following the three strategies previously mentioned. Direct application of the model provides reflection patterns with a very narrow main lobe and many smaller side lobes, clearly different from the measured patterns.

When the surface is perfectly conductive, the application of the Physical Optics model by segments leads to a simulation error (compared to measurement outcomes) similar to the direct use of Beckmann formulation, whereas the use of the elliptic patching (3D) model provides an improvement of around 57% in the simulated results.

The results for dielectric obstacles seem to indicate better fitting when the application takes into account the geometry of the problem; i.e. when the illuminated surface is patched in concentric rings and local contributions at each patch are coherently added at each scattering direction. This appreciation is supported by the reduction percentage in the relative simulation error obtained by applying the Physical Optics theory by segments or by elliptic patching compared to that obtained by the direct application of the Physical Optics formulation. The 3D application of the integral equation led to an improvement of the relative error of 1.5% for a brick wall obstacle, and 67% for a highly reflective smooth chip wood panel, whereas the segment application improvements were 0.2% and 62%, respectively. This result confirms the visual appreciation: the more specularly reflective the material is, the better the improvement of Physical Optics 3D method is.

### 4.2. Depolarisation indexes

The difference between co polar and cross polar relative powers presents strong variations in measurement results: in the vicinity of the specular direction it is commonly larger than in other directions of observation, in which the cross polar component could be even stronger than the co polar. This appreciation confirms that the non-specular directions could not be ignored when planning the network.

The difference between co polar and cross polar received power, observed towards the specular direction could be up to 58 dB, for brick walls, 28 dB for chip wood panels, and 31 dB for stone walls, at 5.8 GHz (Cuiñas et al., 2009).

Once computed the depolarisation indexes, towards the specular direction, they resulted to be up to 0.75% for the brick wall, up to 9.8% for the chip wood panel, and up to 9.27% for the stone wall. This indicates that brick wall provides reduced depolarised waves compared to the co polar reflected waves in the specular direction.

But in a general case, all scattering directions have to be considered, and not just specular one, as the reflector could be randomly located and oriented. With this aim, median depolarisation indexes for each material could be useful, being 23% and 30% for brick wall, 18% and 18.5% for chip wood panel, and 4.5% and 4% for stone wall, in horizontally and vertically polarised incident wave, respectively, at 5.8 GHz. Once several angles of observation are introduced, not just the specular ones, the depolarisation indexes grow, and differences between incident polarisations appear in the brick wall case. The brick wall is the more non isotropic material among the considered, as it presents a clearly oriented structure, whereas the chip wood panel and the stone wall are the result of the solidification of a mass, which is expected to present a more isotropic behaviour. The large median values of depolarisation indexes indicate that high depolarised waves could be generated when several scatterers are present in an environment, which is the case of indoor scenarios.

## 5. Conclusions

Two methods to characterise an obstacle in terms of reflection and depolarisation, and the different strategies to apply these formulations, have been summarised along this chapter, providing the references to in depth study both formulation. The behaviour of such methods have been also compared to measurement results at 5.8 GHz, using three different flat obstacles, with more or less rough surfaces, and two orthogonal linear polarisations in the incident wave.

The modelling of scattering patterns generated by flat conductive and dielectric obstacles is proposed, based on the Physical Optics formulation. Among three possible strategies of implementation, that based on elliptic patching the illuminated area on the obstacle surface appears to provide more accurate results, since it is better adapted to the real problem: it defines the finite surface in a more precise way and it takes into account the radiation pattern of the antennas employed in the experimental work. The comparison between simulation results and actual situation measurements shows the good behaviour of the algorithm. The flatter and more conductive the material is, the better the algorithm works.

When observing the depolarisation, the measured results reflect differences between co polar and cross polar received powers from 17 to 58 dB in specular directions of observation, depending on the obstacle and the angle of incidence. But the most interesting observations are in the non-specular direction, in which the cross polar received power could be even stronger than the co polar, and with amplitudes that could not be ignored. These situations indicated that up to more than 50% of the incident wave could be scattered as a cross polarised wave.

The results of this experimental work were processed by means of a matrix model to compute the depolarisation indexes. Indexes up to 10 % have been obtained in the specular direction, and median values up to 30% are reached when considering the entire scattering region.

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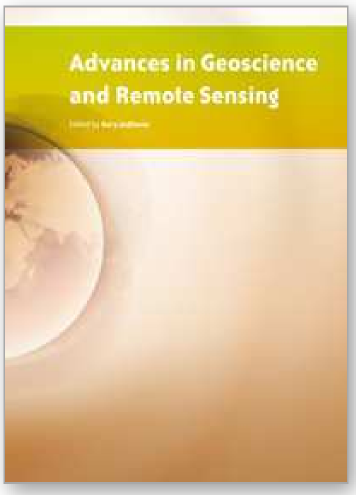


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Remote sensing is the acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s), that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Human existence is dependent on our ability to understand, utilize, manage and maintain the environment we live in - Geoscience is the science that seeks to achieve these goals. This book is a collection of contributions from world-class scientists, engineers and educators engaged in the fields of geoscience and remote sensing.