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Multi-model radiometric slope correction of SAR images of complex terrain using a two-stage semi-empirical approach

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ABSTRACT

Practical approaches for the implementation of terrain type dependent radiometric slope correction for SAR data are introduced. Radiometric slope effects are modelled as the products of two models. The first is a simple physical model based on the assumption of a uniform opaque layer of isotropic scatterers, which is independent of terrain type, frequency and polarization. It accounts for the slope-induced variation in the number of scatterers per resolution cell. The second is a semi-empirical model, which accounts for the variation in scattering mechanisms, dependent on terrain type, frequency and polarization. PALSAR FBD (L-band, HH- and HV-polarization) data are used at two test sites in Brazil and Fiji. Results for the Brazilian area, which has slopes up to 25°, show that remaining slope effects for the multi-model case are much smaller than 0.1 dB, for all land cover types. This is much better than the best single-model approach where remaining slope effects can be very small for forests but be as large as 1.77 dB for woodland in HH-polarization. Results for the Fiji area, which has different vegetation types, are very similar. The potential large improvement, using this multi-model approach, in the accuracy of biomass estimation for transparent or open canopies is discussed. It is also shown that biomass change on slopes can be systematically under- or overestimated because of associated change in scattering mechanism.

1. Introduction

Steep slopes in SAR images are notoriously difficult to handle. Even when an accurate DEM (Digital Elevation Model) is available and a proper orthorectification has been achieved, slopes are still visible. Slopes modulate the radar backscatter level in a complex way depending on slope steepness, slope aspect, land cover type, radar observation geometry, radar frequency band and polarization. Many applications of radar monitoring require a proper handling of slope effects. For forests, for example, this is the case because a large fraction of the remaining pristine forests are located on steep slopes. For agricultural crop monitoring, for example, this is the case because dense time series are required and images from different look directions and incidence angles need to be combined. For accurate biomass estimation proper handling of slope effects is critical since slope effects, or remaining slope effects, can be of similar magnitude as the biomass induced backscatter modulation.

Slope effects are mentioned by many authors as they affect applications such as bio-physical parameter estimation (biomass, soil moisture), land cover classification and complicate the combination of ascending and descending images and multi-sensor analysis, including Atwood, Small, and Gens (2012), Franklin et al. (1995), Castel et al. (2001), Luckman (1998), Goering, Chen, Hinzman, and Kane (1995), Stussi, Beaudoin, Castel, and Gigord (1995) and Sun, Ranson, and Kharuk (2002). These authors also provide approaches to handle the slope effects. Several categories of approaches may be distinguished, such as (a) simple physical models, (b) empirical models and (c) terrain type dependent or tunable models.

Simple physical models with exact solutions were introduced by Hoekman (1990) and Ulander (1996). These models compensate for slope induced variation in the amount of scatterers in a resolution cell and will be described in more detail in Section 2. Both models assume uniform isotropic scattering. In Hoekman (1990) the terrain is described as an opaque volume scatterer and in Ulander (1996) as a surface scatterer, which leads to different expressions. The opaque isotropic volume scatterer model was validated for tropical forests in Hoekman, van der Sanden, and Bijker (1994) and often successfully applied for large-scale application in areas with dense vegetation such as in Hoekman, Vissers, and Wielaard (2010). Both models have a limited range of applicability, however are independent of frequency and polarization.

In Ulander (1996) it is noted that alternative equations can be found in literature but that these are only approximations of the exact solution presented in Ulander (1996), such as Holecz, Meier, Piesbergen, Nuesch, and Moreira (1994), based on local incidence angle, and Van Zyl, Chapman, Dubois, and Shi (1993) and Goering et al. (1995), based on slope tilt angles.

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Many empirical models, many of which may be regarded as approximate solutions of Ulander (1996), have been proposed. These empirical models have a limited range of applicability as they depend on terrain type, frequency and polarization, however, may perform satisfactorily when tuned properly for the (dominating) terrain type and the sensor used. The models introduced by Hinse, Gwyn, and Bonn (1988), Franklin et al. (1995) and Stussi et al. (1995) can be regarded as approximate solutions of Ulander (1996), based on the use of the local incidence angle. In Kellndorfer, Pierce, Dobson, and Ulaby (1998) another empirical solution based on the local incidence angle is proposed. Sun et al. (2002) compares the model of Kellndorfer et al. (1998) and several other simple empirical models and concludes that none of these models provides a close approximation of the real scattering behaviour. Sun et al. (2002) states that terrain slope changes the local radar incidence angle, as well as the forest structure perceived by the radar and, consequently, the dependence of radar backscattering on slope steepness and slope direction is very complex.

More recently Löw and Mauser (2007) applied the model of Ulander (1996) and concluded that it worked well for a test site in Germany. Akatsuka, Takeuchi, Rakwatin, and Sawada (2009) applied a simple empirical model for PALSAR data. Shimada (2010) applied an empirical for PALSAR and concluded that it did not perform well on steep slopes. Small (2011) applied a slope normalization model for ASAR and PALSAR. In Atwood et al. (2012) polarimetric PALSAR data are normalized for slope effects by applying the same normalization factor to each element of the coherency matrix. However, it is noted that this method presupposes that each scatter mechanism is equally affected by slope while, in fact, the proportions of surface, volume and double bounce, scattering are affected by slope and, moreover, these proportions are polarization dependent. Therefore, future developments should address the complex interplay between look angle, topography and land cover. Atwood et al. (2012) also states that such an approach would entail an a priori knowledge of the land cover classification.

The notion that a single model is not sufficient is not new. Teillet, Guindon, Meunier, and Goodenough (1985), Hinse et al. (1988) and Bayer, Winter, and Schreier (1991) state that slope corrections must be class specific and introduced terrain type dependent correction functions. These simple and local incidence angle dependent corrections should be applied on pre-classified images. Stussi et al. (1995) remark that relationships are polarization and frequency dependent. Franklin et al. (1995) state that a single formulation is unlikely to adequately cover the whole range of topographic effects and that stratification may be needed. In Sun et al. (2002) several models were used, none of them capable of dealing with the whole range of variation. In Leclerc, Beaulieu, and Bonn (2001) a single semi-empirical model was used, however, it was noted that a single model is unlikely to cover all types of terrain. Separate models would be needed, for example for terrain behaving as a Lambertian surface or terrain with a specular surface.

A single semi-empirical model with diffuse-Lambertian and specular components was used by Goering et al. (1995) for ERS-1 scenes of an Arctic landscape. The reduction of slope effects was demonstrated by comparing ascending and descending passes. It was noted that the proportions of the two model components depend on terrain characteristics, thus suggesting a stratification of the area. A semi-empirical radiative transfer model with a single parameter describing the optical thickness that should be tuned to local conditions was introduced by Castel et al. (2001). Encouraging results were obtained except for very steep slopes and open canopies.

The effects of topography on backscatter mechanism change, and its dependence on frequency band and polarization, were discussed by many authors (Van Zyl et al., 1993; Luckman, 1998; Franklin et al., 1995).

In summary, there is a general consensus that a single model will not suffice to describe SAR radiometric slope effects. The need for a multi-model approach was mentioned frequently and sometimes the need for stratification or pre-classification was indicated. However, practical solutions for such an approach were never offered.

In this paper an approach is introduced that can handle a wide range of terrain and topographic conditions. Moreover, a practical solution for the implementation of the stratification is offered. Section 2 describes the observation geometry, derives the exact solutions for normalization according Hoekman (1990) and Ulander (1996), and shows their relation. Under certain conditions these normalizations may be sufficient. In Section 3 two small case studies are used to illustrate that certain land cover types and polarizations require additional corrections. A semi-empirical approach to accomplish this is introduced. The complete correction follows from successive application of the general applicable physical normalization model and the class and polarization dependent semi-empirical model. Section 4 discusses two approaches to implement the stratification. To illustrate its feasibility a fully multi-model corrected SAR image is shown. The large accuracy improvement obtained for biomass estimation of sparse vegetation cover is discussed.

2. Theory

2.1. Observation geometry and definitions

2.1.1. Radar geometry

The radar look direction can be described by *two angles*: the (nominal) incidence angle θ_i and the range (or look) direction ϕ_i. The incidence angle θ_i is defined as the angle between the flat earth's normal direction and backscatter direction, and increases with range distance. The range direction is the angle in the horizontal plane with respect to true North, and varies with latitude. For side-looking radar in near-polar orbit, the variation of ϕ_i near the equator is very small. For the PALSAR Fine-Beam Dual image of Guyana used here the incidence angle range is 36.6°–40.9°, while the look direction is East, closely around 78.1° with respect to North (for more details see Section 3.1).

2.1.2. Terrain geometry

The terrain geometry is modelled by a DEM, such as the SRTM DEM. It can be described by *two angles*: the slope steepness angle α_s and the slope aspect angle (uphill direction) ϕ_s relative to true North. Note that these values follow from the height values of a pixel and its neighbouring pixels by interpolation. Methods commonly used include cubic interpolation, cubic spline interpolation or Lanczos interpolation (Conejero, 2011).

2.1.3. Model geometry

To describe radar backscatter relative to the terrain these four angles can be reduced to three angles. These are the above-mentioned θ_i and α_s, and the slope direction relative to range (or look) direction ϕ_r:

$$\phi_r = \phi_i - \phi_s. \tag{1}$$

In addition two dependant angles should be defined (depending on α_s and ϕ_r), which are the slope steepness angle in range direction: $\alpha_r$which follows from

$$\tan(\alpha_r) = \tan(\alpha_s)\cos(\phi_r) \text{ or } \alpha_r = \arctan(\tan(\alpha_s)\cos(\phi_r)); \tag{2}$$

and the slope steepness angle in azimuth direction: α_{az}which follows from

$$\tan(\alpha_{az}) = \tan(\alpha_s)\sin(\phi_r) \text{ or } \alpha_{az} = \arctan(\tan(\alpha_s)\sin(\phi_r)). \tag{3}$$

Now, the local incidence angle θ_Δ, defined here as the angle between the backscatter direction and the (tilted) surface normal direction, can be described as:

$$\cos(\theta_\Delta) = \cos(\alpha_{az})\cos(\theta_i - \alpha_r). \tag{4}$$