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Modeling microwave backscatter and thermal emission from linear dune fields: Application to Titan

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ABSTRACT

We present an electromagnetic model that relates the microwave backscatter and thermal emission from linear dune fields to their compositional, physical (roughness, subsurface porosity/heterogeneity) and geometrical (slope, orientation) properties. This model shows the value of exploring these highly directional and geometrical features in light of both their backscattering cross-section and emissivity. Compared to Cassini concurrent radar and radiometry data acquired from October 2004 to June 2011 over Titan's dune fields, it provides clues to understand variations among dune regions on the largest Saturn's moon. In particular, it brings a formal support to the idea first advanced in Le Gall et al. (Le Gall, A., Janssen, M.A., Wye, L.C., Hayes, A.G., Radebaugh, J., Savage, C., Zebker, H., Lorenz, R.D., Lunine, J.I., Kirk, R.L., Lopes, R.M.C., Wall, S., Callahan, P., Stofan, E.R., Farr, T. and the Cassini Radar Team [2011]. Icarus 213, 608–624) that the size of the interdune valleys (relative to that of the dunes) varies across Titan as well as the diffuse scattering properties of these interdune areas due to different thickness of sand cover (i.e. bedrock contribution) or degree of compaction/heterogeneity of the sand cover. The Fensal and Belet dune fields, in particular, are quite different in terms of these properties. The comparison between the model and Cassini data also reveals the potential presence of structures, possibly small-superposed dunes, oriented perpendicular to the dune crests in the Aztlan region.

1. Introduction

Where they occur in the Solar System i.e. on Earth, Venus, Mars and Titan (see Bourke et al., 2010 for a review), dunes point to the mobility and processing of sediments – they are the signatures of wind at work. As such, their observation (distribution, pattern, morphology, size, orientation, migration, etc.) can disclose fundamental information about the sedimentary environments and climates in which they have formed and evolved.

On Earth, the value of the observation of dunes by radars has been pointed out by several authors (e.g. Blom and Elachi, 1981, 1987; Blom, 1988; Qong, 2000; Stephen and Long, 2005a). The measured radar return (i.e. the normalized backscattering cross-section in the cases of synthetic aperture radar (SAR) or scatterometer) can help constrain the surface composition, texture and the degree of volume scattering within or at the base of the dunes as well as the geometry of the aeolian features. Ground penetration radars (GPR) surveys that measure reflected power from the subsurface are also commonly conducted to map dune internal structure thus revealing different episodes of formation and migration related to changing wind regimes (Bristow et al., 2000). On Mars, the stratigraphy of the north polar-layered deposits (NPLD) provided by the radar sounder SHARAD on board MRO (Mars Reconnaissance Orbiter) has shown that the central spiral troughs were created and shaped primarily by wind; as such they can be regarded as mega-dunes made of water ice and offer new constrains on the paleo-climate of this area (Smith and Holt, 2010). The venusian and titanian dune fields were discovered thanks to radar, the only remote sensing instrument able to examine surfaces masked by an opaque atmosphere. On Venus, the presence of possible asymmetric microdunes was even inferred from the backscattering anisotropy observed on Magellan SAR images acquired under different viewing geometries (Weitz et al., 1994). On Titan, SAR images as well as scatterometry and altimetry observations of dune fields have proved to be very helpful to understand the sedimentary and climatic environment of Saturn's largest moon (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Le Gall et al., 2011, 2012).

Less commonly used in the frame of planetary missions, microwave radiometers, which passively measure the surface thermal emission, are also key instruments in the study of deserts and

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aeolian bedforms (Prigent et al., 1999; Stephen and Long, 2005b). In particular, radiometry independently addresses the dielectric composition, surface and subsurface scattering properties, and has already proved to be helpful in diagnosing the relative roles of these properties in the radar appearance of different terrains (Paganelli et al., 2007; Janssen et al., 2011).

The abundance of radar and radiometry data collected over Titan's linear dune fields over the past 9 years in the frame of the ongoing Cassini mission thus offers a unique opportunity to further understand these dominant geological features on the saturnian moon. Indeed, at each flyby, the backscatter and thermal emission from Titan's surface are simultaneously measured at the wavelength of 2 cm. In this paper, we will show that even when Cassini Radar active and passive (radiometry) data do not resolve individual dunes, they contain crucial information on the compositional (dielectric constant), physical (roughness, subsurface heterogeneity/porosity) and geometrical (slope, orientation) properties of Titan's dunes.

The paper is organized as follows. Section 2 is dedicated to the description of the forward electromagnetic model developed to relate the microwave backscatter and emission from linear dune fields to their compositional, physical and geometrical properties. Dunes being highly directional features; the geometrical effects resulting from different azimuth and incidence angles need to be carefully considered. The model is then applied to the case of Titan in Section 3 using all relevant information in literature. Compared to the active and passive measurements collected at closest approach by the Cassini Radar over Titan's dune fields from flyby TA (October 2004) through T77 (June 2011), this model leads to a better understanding of dune variability on the Moon as shown in Section 4. Our results support the conclusions of Le Gall et al. (2011, 2012) that explore the regional variations among dune regions on Titan and can be used for further detailed investigation of these aeolian features.

2. Electromagnetic modeling of linear dune fields

2.1. Modeling linear dune fields

Fields of linear dunes are modeled as sets of individual dunes separated by interdune areas or valleys. Each individual dune consists in two faces of equal slope, one on each side of a central ridge. Following Stephen and Long (2005a, 2005b), we account for slightly different orientation of the dunes within the dune field by assuming that the two sides of the dunes have a Gaussian probability distribution of slopes and azimuths. Interdune areas are considered to be normally distributed around the horizontal plane. The backscatter and emission from the dune faces and interdune valleys are modeled using Zebker et al. (2008) approach that takes into account volume scattering from the subsurface and surface large-scale roughness but neglects small-scale roughness. Volume scattering occurs when the subsurface is porous or inhomogeneous in composition; voids and inhomogeneities then diffuse the incident wave. The interdune areas are covered by a layer of sand whose thickness can vary. Where the sand cover is thin, contribution from the underlying substrate (i.e. the bedrock) must be considered. In this paper, for sake of simplicity, we only consider the two extreme cases where the interdune areas are either free of sand or covered by a layer of sediments thick enough to rule out contribution from the bedrock.

Fig. 1 illustrates the geometry and the main parameters of the model. A list of symbols is also given in the Appendix A. The indexes 0, 1 and 2 refer to the media air, sand and bedrock, respectively. The indexes d and i refer to the dune faces and interdune areas, respectively.

2.2. Modeling backscatter from linear dune fields

Radars report on the microwave surface reflectivity through the normalized backscattering cross-section σ^0, a non-dimensional quantity that describes the effective area that intercepts the transmitted power and scatters that power isotropically back to the receiver (Ulaby et al., 1982).

2.2.1. Backscatter model for dune faces

Let (θ,ϕ) be the direction of incidence of the ray and p its polarization. The total normalized backscattering cross-section $\sigma^0(\theta,\phi;p)$ of a typical rough surface can be separated in two terms: a quasi-specular and a diffuse term (Wye et al., 2007; Zebker et al., 2008). The response is generally independent of ϕ, which yields:

$$\sigma^0_d(\theta,\phi;p) = \sigma^0_d(\theta;p) = \sigma^0_{qs1}(\theta;p) + \sigma^0_{diff1}(\theta;p). \quad (1)$$

Following Zebker et al. (2008), the quasi-specular component for the dune faces can be modeled with a Gaussian law:

$$\sigma^0_{qs1}(\theta;p) = \frac{C_1 R_{01}(0;p)}{\cos^4\theta} e^{-C_1 \tan^2\theta}. \quad (2)$$

$R_{01}(0;p)$ is the Fresnel reflection coefficient at the surface of the dunes at normal incidence. By definition: $R_{01}(0;p) = \left|\frac{\sqrt{\varepsilon_1}-1}{\sqrt{\varepsilon_1}+1}\right|^2$ where ε_1 is the dielectric constant of the sand; $C_1 = \tan^{-2} s_1$ where s_1 is the rms (root-mean-square) surface slope of the dune faces.

Neglecting small-scale roughness i.e. considering that diffuse scatter only arises from volume scattering processes due to subsurface inhomogeneities or porosity. Zebker et al. (2008) establish that

$$\sigma^0_{diff1}(\theta;p) = \sigma^0_{vol1}(\theta;p) = (1 - R_{01}(\theta;p))^2 2f_1 \cos\theta \quad (3)$$

where $R_{01}(\theta;p)$ is the Fresnel reflection coefficient at the surface of the dunes in the polarization p and for the incidence angle θ and f_1 is the fraction of the energy transmitted to the subsurface that reemerges from the dune faces due to volume scattering. This model takes into account the coherent backscattering effect that might occur at high-order scattering (hence the coefficient 2) and assumes an isotropic scatter.

2.2.2. Backscatter model for interdune areas

For clear-of-sand interdune areas,

$$\sigma^0_i(\theta;p) = \sigma^0_{qs2}(\theta;p) + \sigma^0_{diff2}(\theta;p) \quad (4)$$

where σ^0_{qs2} and σ^0_{vol2} can be obtained by substituting the index 2 to 1 in Eqs. (2) and (3).

For interdune areas of thick sand cover, the backscatter follows the same law as the backscatter from the dune faces (i.e. Eq. (1)):

$$\sigma^0_i(\theta;p) = \sigma^0_d(\theta;p). \quad (5)$$

2.2.3. Backscatter model for dune fields

Because they are highly directional and geometrical features, the topography of the dune fields needs to be considered. Dune fields are modeled as composites of tilted rough surfaces. The unprimed coordinates are the reference frame. In other words, θ and ϕ are respectively the incidence angle and azimuth of the radar beam relative to the reference (i.e. horizontal) plane. Let the primed coordinates be the local frame for each rough surface face. The surface faces can be either the front side of an individual dune, its backside or an interdune valley. θ' and ϕ' are the incidence angle and azimuth relative to a local surface whose normal vector points at an angle u to the vertical and at azimuth v (see Fig. 1). The relationship between the local and reference coordinate systems is given in the appendix.