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Titan dune heights retrieval by using Cassini Radar Altimeter

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ABSTRACT

The Cassini Radar is a Ku band multimode instrument capable of providing topographic and mapping information. During several of the 93 Titan fly-bys performed by Cassini, the radar collected a large amount of data observing many dune fields in multiple modes such as SAR, Altimeter, Scatterometer and Radiometer. Understanding dune characteristics, such as shape and height, will reveal important clues on Titan's climatic and geological history providing a better understanding of aeolian processes on Earth. Dunes are believed to be sculpted by the action of the wind, weak at the surface but still able to activate the process of sand-sized particle transport. This work aims to estimate dunes height by modeling the shape of the real Cassini Radar Altimeter echoes. Joint processing of SAR/Altimeter data has been adopted to localize the altimeter footprints overlapping dune fields excluding non-dune features. The height of the dunes was estimated by applying Maximum Likelihood Estimation along with a non-coherent electromagnetic (EM) echo model, thus comparing the real averaged waveform with the theoretical curves. Such analysis has been performed over the Fensal dune field observed during the T30 flyby (May 2007). As a result we found that the estimated dunes' peak to trough heights difference was in the order of 60–120 m. Estimation accuracy and robustness of the MLE for different complex scenarios was assessed via radar simulations and Monte-Carlo approach. We simulated dunes–interdunes different composition and roughness for a large set of values verifying that, in the range of possible Titan environment conditions, these two surface parameters have weak effects on our estimates of standard dune heights deviation.

Results presented here are the first part of a study that will cover all Titan's sand seas.

1. Introduction

Dune fields are arousing a great interest among scientists representing one of the most interesting geological features present on Titan. They are located around the equatorial area (±30°) covering about 15% of the whole surface (Le Gall et al., 2011), their shape is believed to be the result of a general eastward transport of cohesive organic solids (Lorenz et al., 2006) and their morphology similar to the terrestrial dunes seen in Namib, Sahara and Arabian deserts (Radebaugh et al., 2008). Furthermore, they represent a real challenge for the complexity in retrieving information connected to single dune height due to the high resolution required by the remote sensing instruments. Since single SAR image is not adequate for an immediate retrieval of dunes' topography information (i.e. the height of dunes), radargrammetry techniques such as SAR-Stereo (Toutin, 1996) or radarclinometry (La Prade and Leonardo, 1969) are needed. Radarclinometry (Neish et al., 2010) was used to evaluate dunes heights on Titan (Lorenz et al., 2006). This method was successfully applied over three regions of Titan leading to a dunes' height estimation in the order of 45–180 m and dunes' spacing between the of 2.3–3.3 km. However, the results of this method depend on the EM models adopted and can be distorted by the change in surface reflectivity (Jaumann et al., 2009).

Estimation of dunes topography was obtained even by means of Stereo data analysis of Cassini SAR images which allowed a partial characterization of Belet dunes. Therein, dunes were estimated to be about 3 km wide with a peak to trough elevation difference in order of 100–200 m (Kirk et al., 2012). As mentioned by the author, this method leads to good results only when the pair of Stereo images are acquired under optimal geometric condition.

Dunes' height was also estimated by means of photoclinometry technique applied to VIMS data, leading to an estimation of the Belet dunes ranging from 30 to 70 m (Barnes et al., 2008).

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By processing the radar altimeter data we were able to provide Titan topographic profiles estimating the time delay of the echoes received from the surface. Additional information about Titan surface characteristics such as dunes' height, can be obtained by an accurate modeling of the magnitude and shape of the altimeter echoes (Zebker et al., 2009).

In this work, we used SAR images to localize altimeter tracks overlying dunes fields and we retrieved Fensal dune heights by applying the Maximum Likelihood Estimator (MLE) over the shape of the Cassini altimeter received echoes using a dedicate EM model (Montefredini et al., 1995).

First, we illustrate the nadir and near-nadir Cassini impulse response model adopted in this work. Second, we present signal simulation in order to evaluate the retrieval errors. Finally, we review the results obtained by applying, over Fensal dunes, the above described method.

2. Dataset

The Cassini Radar Altimeter has operated for more than nine years obtaining topographic detail of Titan, Saturn's largest moon. When operating in high resolution mode (between 4000 km and 9000 km nominal altitude), the radar altimeter uses its nadir-pointed central antenna beam in order to transmit and receive 15 chirped signals every 3.333 s (Elachi et al., 2004) (Table 1). By means of range compression and incoherent average processing of the Cassini burst signals (Alberti et al., 2007) it is possible to obtain a vertical range resolution in order of 35 m and a ground swath horizontal resolution ranging from 55 to 6 km depending on the spacecraft altitude (Montefredini et al., 1995; Zebker et al., 2009).

The Cassini SAR operative mode is able to map the surface of Titan at the highest resolution of 350 m (Elachi et al., 2005), with incidence angles ranging from around 15° to 40°. SAR images show that dunes are typically 1–2 km wide and 1–4 km spaced (Radebaugh et al., 2008).

During Fly-By T28, on April 10th 2007, Cassini Radar observed the Fensal dunes field (15°S to 23.7°N and 22.1°W to 40.2°W) operating in SAR mode. The SAR image mapping was performed at the nominal SAR mode spacecraft altitude (4000–1000 km) with an incidence angle ranging from 7.4° to 22.3°, thus allowing the radar imaging of Fensal dunes with a pixel resolution ranging from 1.7 km to 350 m (Le Gall et al., 2011).

During Fly-By T30, on May 12th 2007, Cassini Radar observed the same field of dunes in Altimeter mode. The radar collected echoes by pointing the antenna to nadir direction at an altitude ranging from 16915 to 959 km, thus exceeding the nominal altimeter mode altitude (9000–4000 km). The collected data were processed obtaining a long altimetric in-bound profile across Fensal dunes (from 11.1°S and 27.6°W to 70.9°N and 354.7°W).

Table 1
Cassini Radar Altimeter main parameters.

Carrier frequency	13.78 GHz
Carrier wavelength (λ)	2.17 cm
Burst period (T)	3333 ms
Pulse width	150 µs
Pulse repetition frequency (PRF)	4700–5000 Hz
Antenna 3 dB beamwidth (θ_B)	0.35 deg
Chirp bandwidth (B)	4.25 MHz
Sample rate	10 MHz
Transmit time	1.4–1.8 ms
Peak transmitted power (PT)	48.084 W
Peak antenna gain (G0)	50.7 dB
Titan mean radius (RT)	2575 km
Vertical resolution (σ)	35 m

3. Models

In 1977, a paper by Gary S. Brown introduced a model of the average impulse response of a rough surface (Brown, 1977) that has been very successfully used for analytical description of radar altimeter echo received over ocean surfaces (Zeiger et al., 1991).

For the Cassini altimeter mode, a Brown-like electromagnetic (EM) model has been developed (Montefredini et al., 1995) based on the following assumptions:

- Rough surface with a Gaussian specular point heights probability density function.
- Gaussian antenna beam (circular symmetry).
- Surface composed by independent scattering elements.
- Completely non-coherent scattering mechanism.

In Montefredini et al. (1995) it is also demonstrated that the overall average power echo from a rough surface for a nadir pointing radar altimeter can be written in the following form:

$$i(\tau) = \sqrt{\frac{\pi}{2}} A\sigma^0 \exp\left[\frac{\delta^2}{2} - \frac{\delta\tau}{\sigma_{eq}}\right] \cdot \left[1 + \mathrm{Erf}\left(\frac{\tau}{\sqrt{2}\sigma_{eq}} - \frac{\delta}{\sqrt{2}}\right)\right] \tag{1}$$

where:

$$A = \pi H c \sigma \tag{1a}$$

$$\sigma_{eq} = \sqrt{\sigma^2 + \left(\frac{2\sigma_h}{c}\right)^2} \tag{1b}$$

$$\delta = \frac{A}{A_{eq}} \sqrt{1 + 2F} \tag{1c}$$

$$\sigma = 1/2B \tag{1d}$$

$$A_{eq} = \pi \left(\frac{H\theta_B}{\sqrt{2.8}}\right)^2 \tag{1e}$$

$$F = (2\sigma_h/c)^2/2\sigma^2 \tag{1f}$$

being c the speed of light, H the spacecraft altitude, τ the two-way incremental ranging time, A_{eq} the area of the beamwidth limited circle, A the area of the pulsewidth limited circle, σ^0 the backscattering coefficient, σ_{eq} a parameter related to both the root mean square (rms) of the surface heights (σ_h) and to the system vertical resolution (σ).

This model takes into account the beam limited (BL), as well as the pulse limited (PL), radar altimeter operating geometries, which are both met by the Cassini operational conditions.

Fig. 1 shows some examples of the normalized nadir model impulse response evaluated for several surface roughness conditions.

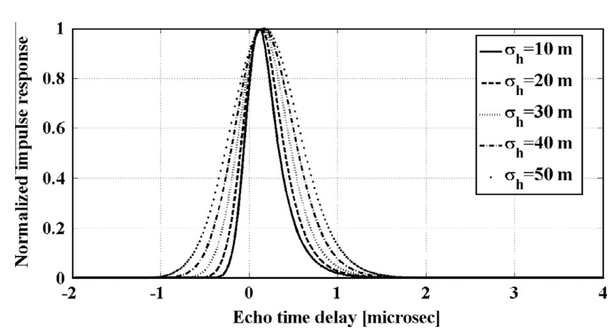

Fig. 1. Averaged and normalized nadir ($\xi = 0°$) impulse response model evaluated at different values of surface roughness σ_h and at $H = 5000$ km of S/C altitude.