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Radar scattering of linear dunes and mega-yardangs: Application to Titan

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ABSTRACT

The Ku-band (13.8 GHz – 2.2 cm) RADAR instrument onboard the Cassini-Huygens spacecraft has revealed the richness of the surface of Titan, as numerous seas, lakes, rivers, cryo-volcanic flows and vast dune fields have been discovered. Linear dunes are a major geomorphological feature present on Titan, covering up to 17% of its surface, mainly in equatorial regions. However, the resolution of the RADAR instrument is not good enough to allow a detailed study of the morphology of these features. In addition, other linear wind-related landforms, such as mega-yardangs (linear wind-abraded ridges formed in cohesive rocks), are likely to present a comparable radar signature that could be confused with the one of dunes. We conducted a comparative study of the radar radiometry of both linear dunes and mega-yardangs, based on representative terrestrial analogues: the linear dunes located in the Great Sand Sea in western Egypt and in the Namib Desert in Namibia, and the mega-yardangs observed in the Lut Desert in eastern Iran and in the Borkou Desert in northern Chad. We analysed the radar scattering of both terrestrial linear dunes and mega-yardangs, using high-resolution radar images acquired by the X-band (9.6 GHz – 3.1 cm) sensor of the TerraSAR-X satellite. Variations seen in the radar response of dunes are the result of a contrast between the dune and interdune scattering, while for mega-yardangs these variations are the result of a contrast between ridges and erosion valleys. We tested a simple surface scattering model, with parameters derived from the local topography and surface roughness estimates, to accurately reproduce the radar signal variations for both landforms. It appears that we can discriminate between two types of dunes – bare interdunes as in Egypt and sand-covered interdunes as in Namibia, and between two types of mega-yardangs – young yardangs as in Iran and older ones as in Chad. We applied our understanding of the radar scattering to the analysis of Cassini RADAR T8 acquisitions over the Belet Sand Sea on Titan, and show that the linear dunes encountered there are likely to be of both Egyptian and Namibian type. We also show that the radar-bright linear features observed in Cassini RADAR T64 and T83 acquisitions are very likely to be mega-yardangs, possible remnants of ancient lake basins at mid-latitude, formed when Titan's climate was different.

1. Introduction

The Cassini-Huygens mission has been in orbit around Saturn since June 2004. The Ku-band (13.8 GHz – 2.2 cm) RADAR instrument onboard the Cassini spacecraft is a combined radiometer/alti meter/scatterometer/imaging radar that has revealed a various and rich surface of Titan through its optically-opaque atmosphere (Elachi et al., 2004). RADAR has allowed the discovery of numerous seas, lakes, rivers, cryo-volcanic structures and vast dune fields (Elachi et al., 2005; Lopes et al., 2007; Lorenz et al., 2006; Radebaugh et al., 2007; Stofan et al., 2007). Dunes are in particular a major landform on the surface of Titan, since large dune fields cover more than 10 million km^2 in equatorial regions. They are typically 1–2 km wide, with 1–4 km spacing, up to 150 m-high, and can reach more than 100 km in length, being mainly east–west oriented and aligned parallel with time-averaged equatorial winds (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Le Gall et al., 2011). Dunes on Titan are the linear type as observed on Earth, the latter ones being used as analogues to infer Titan's dunes morphology (Neish et al., 2010; Radebaugh et al., 2010; Paillou et al., 2014).

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The RADAR instrument shows Titan's dune fields as dark linear features separated by brighter linear features. Different qualitative interpretations have been proposed for this radar signature: (1) dark lines are sand covered interdunes with brighter features caused by specular reflection over dunes' crests, as for the linear dunes observed in the Namib Desert (Neish et al., 2010), or (2) dark lines are the smooth dunes with brighter linear features caused by rougher interdunes, where bedrock is exposed, as observed in the Great Sand Sea in Egypt (Paillou et al., 2014). Besides linear dunes, other natural wind-related structures on Earth show a comparable morphology: mega-yardangs are wind-abraded landforms which develop in Earth's drylands (Sahara, Middle-East, Central Asia), where winds tend to be unimodal in direction (Goudie, 2007). Mega-yardangs are composed of alternating linear ridges and valleys created by wind erosion and sediment deflation, and are often associated with soft deposits of desiccated lake beds. As for linear dunes, radar images of mega-yardang structures show alternating dark linear features (the erosion valleys) and brighter linear features (the ridges): confusing radar images of linear dunes and mega-yardangs is then quite possible, especially at the 300 m resolution of the RADAR instrument.

Comparative planetology is a powerful approach to help understand the geology of remote planetary surfaces. We conducted a comparative study of the radar scattering of both linear dunes and mega-yardangs, based on representative terrestrial analogues. We considered the linear dunes located in the Great Sand Sea in western Egypt and in the Namib Desert in Namibia, and the mega-yardangs located in the Lut Desert in eastern Iran and in the Borkou Desert in northern Chad. We analysed and modelled the radar signatures of both linear structures using high-resolution (18 m) radar images acquired by the X-band (9.6 GHz – 3.1 cm) radar of the TerraSAR-X satellite. We used a simple surface scattering model, whose parameters were derived from the local topography (ASTER Global Digital Elevation Map – GDEM, and Shuttle Radar Topography Mission – SRTM data) and from surface roughness estimates (Bayesian inversion), which accurately reproduces the radar signature for both landforms. We were able to discriminate between two types of dunes: those with bare interdunes in Egypt vs. those with sand-covered interdunes in Namibia; and between two types of mega-yardangs: young ones in Iran vs. older ones in Chad.

We applied our understanding of the radar scattering to the analysis of radar images obtained during the Cassini T8 flyby over the Belet Sand Sea on Titan: we show that the linear dunes there are likely to be of both Egyptian and Namibian types, contradicting previous studies which proposed single-type dune scenarios. We also show that the bright linear structures observed in radar acquisitions during Cassini T64 and T83 flybys are very likely to be mega-yardangs, possible remnants of lake beds at mid-latitude (around 40°N).

2. Linear dunes and mega-yardangs on Earth

Linear dunes on Earth are mainly located in arid equatorial regions, and constitute more than half of terrestrial dunes (Rubin and Hesp, 2009). They are formed in a context of moderate sand supply, with bimodal wind regimes associated with seasonal changes, producing quasi-symmetrical and linear dunes in a direction parallel to the one of average annual wind (Bristow et al., 2000). Linear dunes can reach hundreds of kilometres in length, and more than a hundred metres in height, with an interdune separation of the order of a couple of kilometres (Besler, 2008). Such results of sedimentary transport and deposition processes have been observed on all bodies of the Solar System that have an atmosphere: Venus, Earth, Mars and Titan (Zimbelman et al., 2013).

Also belonging to the "wind-related linear features" family, are yardangs (or mega-yardangs at a regional scale), made of parallel ridges separated by narrow valleys. The latter are formed by the wind abrasion of cohesive rocks (Goudie, 2007). Mega-yardangs are also mainly located in hyperarid regions on Earth, and form under the condition of a strong unimodal wind, that transports sand and gravel eroding soft sediments on a time scale of a million years (Gabriel, 1938; Ehsani and Quiel, 2008). A favourable condition for yardangs formation is the presence of soft deposits over a harder bedrock, typically observed in areas of ancient lake basins. Mega-yardangs were observed on Mars (De Silva et al., 2010) and might also be present on Venus (Greeley, 1999).

We selected four terrestrial sites to study radar scattering of linear dunes and mega-yardangs. For linear dunes, we considered the Egyptian side of the Great Sand Sea, a large dune field covering 300×700 km in eastern Libya and western Egypt (Besler, 2008). The typical length, width and height of dunes in the Great Sand Sea are in the range of values proposed for Titan, the interdune being most of the time uncovered and exposing the underlying bedrock. Egyptian dunes are mainly composed of pure silicate, with a low dielectric constant close to the values reported for Titan's surface materials (Paillou et al., 2008). They have been used as terrestrial analogues to develop a scattering model that was applied to the study of the radar response of Titan's dunes (Paillou et al., 2014). The Namib Desert in Namibia (Lancaster, 1989; Bristow et al., 2000) was also considered for its linear dune fields. It is an arid area which borders the southwestern African coast over hundreds of kilometres, with mostly linear sand dunes presenting sand-covered interdunes, and also comparable in size and morphology to those on Titan. These dunes have been used as a training model for radarclinometry (reconstruction of the topography from the radar signature), with results applied to the study of Titan's dunes (Neish et al., 2010).

As regards mega-yardangs, we considered the young structures of the Lut Desert in eastern Iran, firstly described by Gabriel (1938) and later studied by Ehsani and Quiel (2008). The region corresponds to a Pleistocene basin with fill deposits (silty clay, gypsiferous sands) and is about 150 km long by 50 km wide, with ridges reaching heights of 100 m (Goudie, 2007). We also considered the older mega-yardangs of the Borkou Desert in northern Chad, formed by erosion of sandstone of Paleozoic age (Mainguet, 1968). This is a region located between the Tibesti and Ennedi mountains, in a corridor of very strong unimodal wind oriented to the northeast. Eroded valleys between sandstone ridges are mostly filled with aeolian sand and present an average depth around 50 m (McHone et al., 1996).

We acquired radar scenes of the four study sites using the X-band radar of the TerraSAR-X satellite, launched in 2007 (Pitz and Miller, 2010). The TerraSAR-X sensor presents two interesting characteristics for our study: (1) X-band is the shortest wavelength (3.1 cm) among available orbital radars for Earth observation, close enough to the Cassini RADAR (2.2 cm) and thus sensitive to the same surface roughness range and (2) its high-resolution (18 m) allows the detailed study of the radar signatures of landforms. We used the TerraSAR-X ScanSAR mode, in HH polarisation, to cover 100×150 km areas at an average resolution of 18 m (multi-look images resampled to 8.25 m), with a varying incidence angle from the near to the far range of the image. Acquisition parameters of the four TerraSAR-X scenes are summarized in Table 1.

The TerraSAR-X radar scenes are shown in Fig. 1, with relevant full resolution extracts presented in Fig. 2. Both linear dunes of the Great Sand Sea and Namib Desert are roughly north–south oriented and are comparable in size, but they show a different radar signature mainly due to the interdune properties: the bare interdune in Egypt (Fig. 1a) appears brighter than the sand-covered