POTENTIALLY ACTIVE REGIONS ON TITAN: PROMISING LANDING SITES

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ABSTRACT

The highly successful Cassini-Huygens mission to the Saturnian system provided us with valuable scientific Titan data and has unveiled a complex world where Earth-like phenomena occur. One of the highlights of the mission was the landing near the equator of the Huygens probe. Based on the Cassini-Huygens findings on surface properties and complexity, the need for a return mission, with enhanced in situ capability, is of high priority in the space exploration program [1]. Responding to NASA and ESA calls for studies of large (Flagship) class missions to the outer planets [2], the Titan Saturn System Mission (TSSM) was proposed for the exploration of Saturn and two of its moons, Titan and Enceladus [3]. One of the mission's goals is to achieve a safe and successful landing on a Titan location that will combine a variety of geological aspects that could be investigated and which are simultaneously attached to atmospheric processes on which information could be inferred. In this study we present two candidate active regions on Titan [4] that present multivariable geomorphology [5], Tui and Hotei Regio and argue as to why these regions would be good landing candidates for a future mission to Titan.

1. INTRODUCTION

Due to its complex surface composition, in combination with unique geological features, Titan is a prime candidate for geological, internal and surface *in situ* investigation. Multiple flybys of NASA/ESA's Cassini-Huygens spacecraft, which is still in commission, brought into light surficial expressions and Earth-like figures, that were not expected to be observed on an icy surface. Data retrieved from the Cassini Visual and Infrared Mapping Spectrometer (VIMS) [6], the Synthetic Aperture Radar (SAR) [7] and the Imaging Science Subsystem (ISS) [8] aboard Cassini supplied information regarding Titan's atmosphere, surface composition and structure. This first approach of Titan's geological environment with Cassini/Huygens has classified it as extremely interesting because of the diversity of surface formational mechanisms, including potential cryovolcanism at Tui Regio (20°S, 130°W) and Hotei Regio (26°S, 78°W) [5].

Tui Regio is a large, lobate, 5-μm-bright region, which lacks the erosion channel features that mark other highland regions on Titan, suggesting it may be geologically young. Data acquired from both VIMS and ISS indicate that the area may be a flow field resembling terrestrial lava flows and volcanic edifices. Hence, this area could be a good candidate for current volcanic activity [9]. Another enigmatic possible cryovolcanic candidate is Hotei Regio, which is an area of extremely complex geology [10]. Both VIMS and SAR data show it to be an area anomalously bright at 5μm with diverse roughness. Hotei Regio includes a basin filled with structures similar to those found on Earth, like lava flows and caldera-like features, mountainous terrain, dark blue patches and possibly alluvial deposits. In addition, the Southern margin of Hotei Regio, a bright arc named Hotei Arcus ("The smile"), may be a heavily eroded crater [11]. Furthermore, as episodic outgassing events have been suggested to explain the mystery of Titan's atmospheric methane replenishment [12], the candidacy of Tui Regio and Hotei Regio for landing sites is strongly endorsed due to their possible cryovolcanic origin. In this work, we focus on data concerning these sites taken with the first two aforementioned instruments.

The two cameras of Cassini/VIMS have observed the surface of both candidate areas Tui Regio and Hotei Regio at visible and infrared wavelengths, giving details about their composition. Furthermore, the Cassini/Radar acquires topographic pictures using microwaves, trying to penetrate Titan's hazy thick atmosphere. In particular, investigations of Hotei Regio suggest that both instruments are in agreement and that a variety of geological processes have occurred in the past [10] or recently [13], indicating cryovolcanism. Indeed, data analysis derived by the first two instruments provided us with images never seen previously. However, Titan's dense nitrogen-methane atmosphere produces a strong contribution in the data under investigation here and specifically the problem of atmospheric haze scattering and particle absorption needs to be dealt with before recovering reliable surface images. Thus, when processing VIMS and SAR data, corrections for atmospheric effects and photometry are applied, as well as filtering in order to produce constraints on the surficial chemical composition and morphology. The need to explore more thoroughly and *in situ* interesting areas like Tui Regio and Hotei Regio as it will be shown hereafter, makes the case for a future mission to Titan, like the Titan Saturn System Mission [2, 3, 14].

2. GEOLOGY: TUI REGIO - HOTEI REGIO

In general, Titan's surface appears to host diverse types of both smooth and rough areas of various altitudes, which include volcanic-like features and impact craters that are intermittently filled by possible atmospheric precipitations [15; 16]. In addition, Titan exhibits topographic features such as rims and ridges and tectonic features filled with material, probably resulting from thermodynamic processes [17]. Chronologically, the surficial geological features are young and complex, a unique case for a celestial satellite [18].

The data acquired from VIMS and SAR onboard Cassini spacecraft indicate that the geological terrains Tui Regio and Hotei Regio, which are potentially cryovolcanic and have multivariable geomorphology, are interesting candidates for future landing sites. Not only have the data revealed the uniqueness of both areas in terms of morphological aspects, but also depicted the variability in the composition [10]. Moreover, candidate regions for *in situ* investigations should combine atmospheric, surficial, near sub-surficial and deep internal investigations [19]. If the cryovolcanic origin of Tui Regio and Hotei Regio is confirmed, they will stand as study case areas for all of the aforementioned investigations.

a) Tui Regio

During the processing of the Cassini data, many different theories have arisen, suggesting possible paths of formation for Tui Regio and Hotei Regio. In spite of these theoretical diversities, the main view is that Tui Regio (Fig. 1a,b) and especially Hotei Regio (Fig. 2a,b) were formed and survived through several dynamic processes. These processes could have been endogenic and/or exogenic. Both areas present geological terrains that possibly endured cryovolcanism, tectonics, impacts, hydrodynamics and fluvial activity. The observed geological surficial expressions like calderas, ejecta deposits, alluvial terrains, flows, the low basin and more, depict the imprints of these activities [20]. Thus, both extensive observation and detailed examination of these structures are required in order to identify whether the aforementioned theories satisfy the observations. Such an identification would open new horizons in Titan's science as well as icy moons geology in general. In particular, Tui Regio is one of the areas, which was observed as anomalously bright at the 5 μm wavelength (Fig. 1b), and therefore constitutes a reliable evidence concerning cryovolcanism on Titan's surface. It is circa 150 km wide, extends 1500 km in an east-west direction and is situated near 130° W 20°S [9]. The region was observed by VIMS on four occasions (13/12/04, 27/10/05, 15/01/06, 18/03/ 06 during the Tb, T8, T10 and T12 Cassini flybys respectively). Color images were constructed from the image cubes at three bands (R = 2.78 μm, G = 2.01 μm, B = 1.59 μm). Nelson et al. (2009b) reported infrared spectrophotometric variability on Xanadu within the Tui Regio area from VIMS data. The changes occurred between 27/10/05 and 15/01/06. The area presented higher reflectance with time [4] and is considered active because once it changed, it did not return to its initial state, which suggests that fog is not a possible reason for these transformations [13]. Topographically also the area is at relatively low latitudes, where not much cloud activity has been reported. Even though an aeolian deposition could have affected the area [21], no evidence of dunes, the most accurate expression of aeolian activity, has been noted in that region. Eventually, Nelson et al., (2009b) suggested that cryovolcanism is the most likely interpretation for the observed variability in Tui Regio, a hypothesis also supported by Hayne et al. (2008).

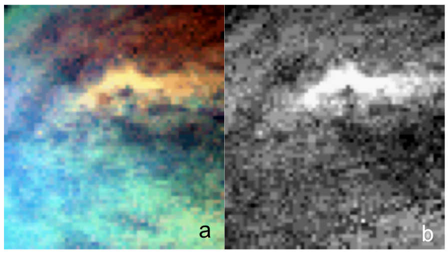

Fig. 1. Tui Regio in false colors R: 5μm G: 2μm B: 1.08μm (a) and at 5μm (b).

b) Hotei Regio

As far as Hotei Regio (78° W, 26° S) (Fig. 2a,b) is concerned, VIMS and SAR data showed it to be another bright spot, lying at the south of the equator. Hotei Regio is a 700 km-wide area, probably of volcanic origin. The VIMS images show that the area is a low basin surrounded by higher terrains with possible calderas, fault structures and extensive cryovolcanic flows [10]. By analyzing VIMS data, Nelson et al., (2009b) reported evidence for photometric variability in Hotei Regio. Also, a change in the morphology of a specific region within Hotei Regio, in addition to the brightness change, between different epochs was observed. The latter region is the southern margin of Hotei Regio called Hotei Arcus. Nelson et al. (2009a) compared result images from three flybys T5 (16/04/05), T47 (19/11/08) and T48 (05/12/08). The reflectance of the area increased by a factor of two between July 2004 and March–April 2005 (Nelson et al., 2009a). A contrario, there are theories suggesting that the VIMS observations to date do not provide compelling evidence for actual ongoing volcanic activity in Hotei Regio [10].

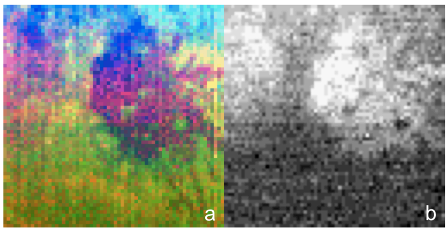

Fig. 2. Hotei Regio at false colors R: 5μm G: 2μm B: 1.08μm (a) and at 5μm (b).

Processing of Radar images showed that Hotei Regio is a low basin depression, (as expected in a volcanic terrain) 1-km deep [10]. It is filled with terrestrial volcanic-like flows that are 100-200-km thick [10]. The peripheral area lying at higher altitudes has rough, as well as smooth, texture. This means that the surrounded formations are probably alluvial deposits [10]. These alluvial materials could have been carried in suspension in a river or stream of liquid methane, curved on the slope of high landed masses deposited as the velocity of the current decreases. The observations suggest the deposition is localized in the outer margins of the basin. The ring-fault-like structures seen within the basin present possibly caldera-like features. The number of these forms, in addition to their topography, implies the possible existence of a zone of weakness within the tectonic plates underneath the icy crust. This is consistent with the possibility that the area formed due to a massive impact.

3. IMAGE PROCESSING

In order to understand Titan's geology and evolution, it is critical to investigate and identify the chemical composition of the areas of interest. Cassini/VIMS acquired many spectral images from several flybys useful for chemical composition analysis. Many images were taken within the so-called “methane windows” (centered at 0.93, 1.08, 1.27, 1.59, 2.03, 2.8 and 5μm), where the methane absorption is weak, and therefore captured parts of the surface. However, the fact that Titan possesses an extended, hazy and dense atmosphere needs to be taken into account and its contribution (haze scattering, aerosol absorption, cloud opacity, etc) removed before accurate results on surface composition can be retrieved. As mentioned earlier for our study case, observations from VIMS at 5μm have showed Tui Regio and Hotei Regio to be anomalously bright areas.

Our goal is to obtain relatively clear surface images without the interference of the atmospheric contribution. Thus, we have used empirical methods to correct the atmospheric effects and photometric analysis that decrease the constraint factor on the surficial chemical composition. The first empirical method applied is the subtraction of the atmospheric component (Fig. 4b,f) from the images acquired in the centre of the atmospheric methane windows (Fig. 4a,e) where we expect the surface contribution to be predominant, though nevertheless hampered by the atmospheric interference [24]. This method has managed to reduce the effect of the contribution of the atmosphere within the atmospheric methane windows (Fig. 4c,g). Following this, we have used selections of isolated areas after applying the Principal Component Analysis (PCA) statistical method on raw data (Fig. 3a,b). Using the statistical method of Principal Component Analysis we have found that the areas seen as bright in the original data and suggested as cryovolcanic in origin, present high I/F values (Fig. 4 d, h), especially at long wavelengths. On the contrary, the surrounded dark areas present low I/F values at all wavelengths. The diversity of I/F values suggests significant alterations in the surface composition. Finally, we have constrained the chemical composition of these areas of interest by studying their contrast evolution with “differential spectroscopy”. This method allows us to compensate for most of the atmospheric contribution while focusing on the real discrepancies in surface composition.

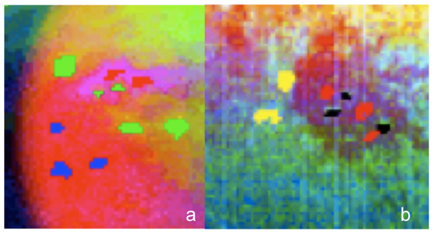

Figure 3: PCA on Tui Regio (a) and Hotei Regio (b). R: 1st PC, G: 2nd PC, B: 3rd PC. The isolated areas are selections of bright, dark and semi-dark areas (red, green, blue for Tui Regio and red, black, yellow for Hotei Regio respectively).

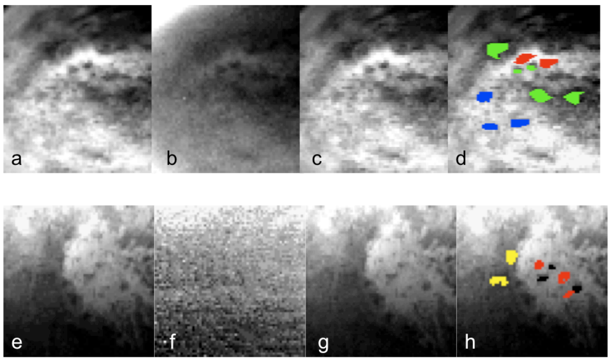

Figure 4: “Surface” (a & e) and “atmosphere” (b & f) references used to compute unaffected surface images (c & g). Figure 2d and 2h present the isolated areas using PCA color alterations as seen in Figs 1(a) and (b).

The applied methods are based on simple mathematical models. A VIMS spectrum of Titan is a measurement of I/F, whose dependence on the surface true albedo A is roughly modulated by the atmospheric absorption α

and the aerosol diffusion δ. It also depends on the wavelength λ, the latitude θ, the longitude φ, the incident angle i_i, the emergent angle i_e, the phase angle i_{ph}, and the time t (for seasonal/diurnal changes), as in Eq. 1. Instead of the geometric albedo, the contrast analysis can reduce such dependencies, given a few sensible conditions: when two regions from the same hyperspectral image are close to each other (ideally within 60° of the nadir, and with observational parameters no different than 10-20°), the contrast can be simplified as in Eq. 2. The only model- dependent parameter to remain is the additive contribution by the aerosols δ, which we have extracted from [25]:

$$s(\lambda,\theta,\varphi,i_i,i_e,i_{ph},t) = \alpha(\lambda,\theta,\varphi,i_i,i_e,i_{ph},t) \times [A(\lambda,\theta,\varphi) + \delta(\lambda,\theta,\varphi,i_i,i_e,i_{ph},t)] \quad (1)$$

$$C_{1,2}(\lambda,t) = \frac{s_1(\lambda,\theta_1,\varphi_1,i_{i1},i_{e1},i_{ph1},t)}{s_2(\lambda,\theta_2,\varphi_2,i_{i2},i_{e2},i_{ph2},t)} \approx \frac{A_1(\lambda,\theta_1,\varphi_1) + \delta(\lambda,t)}{A_2(\lambda,\theta_2,\varphi_2) + \delta(\lambda,t)} \quad (2)$$

4. FUTURE EXPLORATION – THE TSSM CONCEPT

Undoubtedly, the Cassini-Huygens mission has provided us with valuable data that have expanded our knowledge. However, there are still aspects, especially regarding the surface that are not yet covered, along with several unanswered questions. A full description of the nature of Titan's surface will be a key asset in unveiling the atmosphere and the interior, but also a major contribution to our better understanding of the icy moons. Therefore, the significance of a future mission, like the Titan Saturn System Mission (TSSM), focusing on this Earth-like world [2,3] is obvious. Indeed, the TSSM concept, consisting of an orbiter, a lake lander and a montgolfière (hot-air balloon), is designed to carry the essential instrumentation in order to study the surface as well as the subsurface. After having analyzed data from the Huygens mission, it is clear that it is important to acquire direct sampling of the surface and have mobility in the near-surface environment. With TSSM, we will have the opportunity to move around the equator with the balloon and to land in a lake to make direct measurements.

The geological objectives request landing site measurements of the *in situ* geological context, chemical composition by several types of spectroscopy, mineralogy provided by infrared data and petrological properties such as porosity, grain size, permeability and more [19]. The surface exploration payload could include instruments, not only on a surface element but also onboard the orbiter, such as a high spatial resolution imager and spectrometer that is capable to acquire spectra at 1–6μm (thus also extending the spectral range) and perform global mapping at 50 m/pixel in three colors. This kind of imaging resolution would enhance the science return from the acquired data, considering that the current resolution from images acquired at Tui Regio and Hotei Regio ranges from 12-18km/pixel. Another important part of the payload would be the Penetrating Radar and Altimeter instrument that could obtain global mapping of subsurface reflectors with 10 m altitude resolution in altimetry mode and more than 10 m depth resolution, with roughly 1 km x 10 km spatial resolution. Furthermore, a montgolfière with the capability of traveling over 10,000 km in linear distance is planned to image and map Titan's diverse landscapes at close range. The montgolfière will contain instrumentation such as a Balloon Imaging Spectrometer, a Visual Imaging System and also a Titan Radar Sounder (>150 MHz), and operate for at least 6 months. In addition to topography, the radars on both the orbiter and the montgolfière will provide information on the tectonics and stratigraphy of the crust with different and complementary resolution. Other than the described areas of interest we propose further investigations by spectrometers and radar instruments to focus on the dunes, the dendritic networks, the lakes and other surficial expressions. The accurate description of all geological aspects of Titan's surface is significantly important. Such holistic investigation will reveal the interdependence of all geological phenomena and will provide a global geological map as well as offer an interpretation of the internal and surficial geo-environment. TSSM is planned to have the ability to examine in detail the lakes and their surrounding environment through a probe entry, descent and landing.

A lake lander could also include efficient electronic equipment focusing on the study of the liquid itself, like with a MEMS (Micro-Electro-Mechanical Systems) instrumentation. The proposed MEMS is part of the science surface properties package on board of a future Lake Lander on Titan, and it could reinforce such kind of research [26; 27]. MEMS devices offer a low cost and reduced size of instrumentation [28; 29] in order to accomplish a 3D sounding of the liquid deposit and detect the presence of any biomarkers in a broader area. By dramatically reducing the production cost without decreasing the efficacy, these micro devices can execute scientific investigations in places and micro scales never imagined before.

5. LANDING SITES

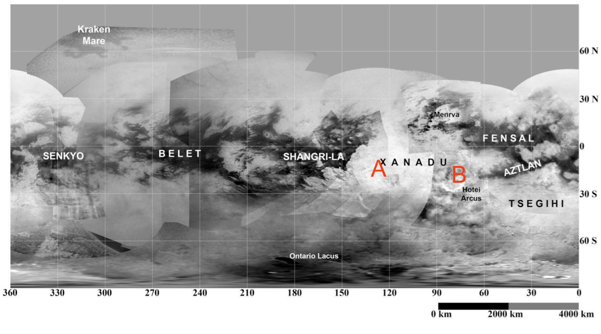

Figure 5. Map of Titan. Landing Sites: Tui Regio (A) and Hotei Regio (B).

Areas marked as (A) and (B) in Fig. 5 are proposed as the main targets.

(A) Tui Regio, which is a bright flow-like figure (150x1,500km) centered at 130° W 20°S.
(B) Hotei Regio, which is a volcanic-like terrain (700km) centered at 78° W 26°S.

The suggestion of Tui Regio and Hotei Regio as landing sites (Fig. 5) is based on their geomorphological variability as well as the expected compositional alterations of both areas. A crucial point of such a selection is the determination of intended investigation and sampling after landing. A potential lander, like the Huygens probe, should be capable of landing on solid surface and carry a fully instrumented robotic laboratory down to the surface.

The Titan Mare Explorer (TiME) concept is for a lander, similar to Huygens, that has been proposed as a tool to discover lakes and seas at Titan's northern hemisphere and confirm the expectation that liquid hydrocarbons exist [30]. In addition, TIME would have the ability to detect two distinct types of features, such as lakes and seas [30]. TiME could also investigate the methane/ethane ratio in the lakes, which is crucial in order to constrain the significance of the sources of methane [30]. Such determinations could help the cryovolcanic investigations since it is extremely important to know the percentage of methane that every surficial exogenic or endogenic process, yields in the atmosphere. Specifically, it will constrain the processes that are believed to provide methane to the atmosphere.

The lander's principal function is to sample and analyze grains attributed from regions of the surface within the areas of interest that lie at the margins of alternative structures (*i.e.* the area where two geological edifices/plains conjunct). Since both areas are considered to be cryovolcanic in origin, the sampling process should be treated similarly as on terrestrial volcanic terrains. Tui Regio is possibly an accumulation of cryolava flows forming a massive flow. A theory on the formation of such structure suggests slow deposition of material from the vent with simultaneous formation of "pillow-lava" edifices. Such type of deposition follows a particular kind of material stratification, by placing the old and first deposited material at the bottom of the flow and the latter overlying the old one and so on. This means that the margins of the lava massive flow seeing in Tui Regio consist of the old and initial material while the central parts are the most recent materials coming from the most recent activity. Our theory is confirmed by image data processing [31]. Ideal sampling of Tui Regio area would comprise sampling from alternative regions by means of chemical composition and morphology. Such regions could be the main part of the flow, the margins, the "old terrain" which is the surface that covers the volcanic terrain and thought to be the initial ground and finally the "mixed terrain'', which possibly consists of material coming from the cryovolcanic activity mixed with initial surface grains. Since sampling of multiple areas, which are considerably distant from one another, is impossible, then the margin between the flow-like feature and the "old" spectrally dark terrain (Fig. 6a) could be a good compromise.

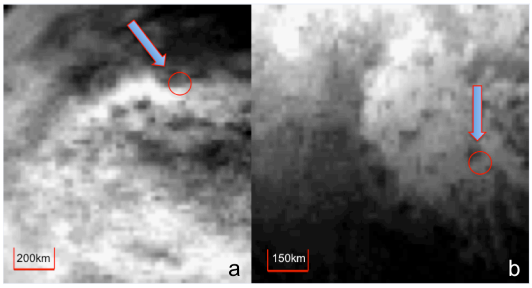

Figure 6. Areas of potential landing on Tui Regio (a) and Hotei Regio (b).

Hotei Regio presents a more complex geological terrain than Tui Regio. As mentioned before (Section 2), central Hotei Regio is a low basin consisting of caldera-like figure, flows, channels, and faults, with mountains surrounding it. The spectral images present dark, blue and extremely bright regions. As expected, data processing showed that the area suggested to be cryovolcanic distinguishes itself from the surrounding regions. Impressively the only figures that seem to compositionally combine the surrounded area and the volcanic field region are the caldera-like structures that probably consist of the primal surficial material (i.e the surrounded area) and the layer that resurfaced the area (i.e the cryomagma flows) [4]. This is compatible with terrestrial caldera structures that consist partially of primal surficial components, on which the volcano is being built, as well as of newly fresh material coming from the interior. Potential sampling and identification of the chemical composition of both the surrounded dark area and the material from the caldera-like structure could bring to light significant information regarding internal processing on Titan. Thus, the landing region proposed is the margin area lying between the biggest caldera within Hotei Regio's terrain and the bright component that surrounds the caldera (Fig. 6b).

5. SUMMARY

Titan's spectacular surficial terrain requires further and deeper investigation. The identification of ongoing processes on the surface will reveal the internal, sub-surficial and atmospheric processes as well, providing a holistic view of Titan's evolution. Tui Regio and Hotei Regio are Titan's distinguishable cryovolcanic candidates. The indications of multivariable processes occurring in both areas marks them as candidate landing sites for a lander that could measure the chemical composition as well as detect the petrological properties of each area. Thus, a future in situ mission could reveal not only cryovolcanic edifices but also the presence of both a subsurface liquid ocean and a rocky core. The aforementioned landing site candidates represent opportunities to answer some important scientific requirements for a future mission by presenting extremely interesting and variable geologic and topographic aspects. The Titan Saturn System Mission (TSSM) concept consisting of an orbiter, a lander and a montgolfière could provide all the necessary technology to achieve such investigation.

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