SCIENTIFIC OBJECTIVES AND ENGINEERING CONSTRAINTS OF TITAN LANDING SITES

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ABSTRACT

The surface of Titan is highly diverse with a remarkable landscape including dunes, streambeds, and presently liquid-filled lakes, as well as mountain ridges, depressions, and rare, eroded impact structures. The geology is characterized by both smooth and rough surfaces with height variations (slopes) on short scales. Radar altimetry suggests the overall height variation is low, typically no more than 150 meters. However, occasional elevation changes of 500 meters have been discovered and Titan has mountains that sometimes reach several hundred meters to more than 1 kilometer in height.

The process of identifying potential landing sites on Titan is based on the analyses of science cases, the definition of candidate sites, and engineering considerations. Regions for in-situ observations are the atmosphere, the surface, including both solid and liquid surfaces, and the subsurface. Concerning the surface solid areas as well as liquid zones must be considered. The most critical engineering constraints are atmospheric density and composition, temperature, surface hardness, roughness, inclination, sub-surface hardness, mechanical uniformity, composition, layering depths, and wind and seismic levels. The most promising sites are wet polar regions or dry equatorial regions because of their high compositional diversity and the mobility of material.

1. INTRODUCTION

One of the mission proposals envisaging *in situ* exploration of Titan is the Titan Saturn System Mission (TSSM) which was studied by ESA and NASA in 2008 and prioritized to launch second in the Outer Planets Flagship Mission Programme [1]. The TSSM *in situ* elements were designed in order to respond to the following major two science questions:

How does Titan function as a system? How do we explain the similarities and differences between Titan and other solar system *bodies in the context of the complex interplay of the geology, hydrology, meteorology, and aeronomy present in the Titan system?*

What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its putative subsurface water ocean and how does this inventory differ *from known abiotic organic material in meteorites and therefore contribute to our understanding of the origin of life in the solar system?*

Titan *in situ* elements as defined in TSSM, but also in several other Titan exploration studies, comprise a hot-air balloon (montgolfière), a short-lived probe which will land in a lake or sea at northern latitudes and a long-lived probe to land near the equator on solid ground. The lake lander is generally preferred over the solid surface lander as it clearly provides easier access to the surface material for chemical analysis and also because it allows scientists to explore a medium different from the one investigated by Huygens in 2005 [2]. Additional long-term (2-Titan days, possibly more) investigations relevant to geophysical aspects of Titan's surface could be performed using an instrumented heat shield which would carry a geophysical package allowing for a number of additional investigations to be performed, including: measurements of 1) the induced and inducing magnetic fields of Titan and their variation as Titan orbits Saturn with a magnetometer, providing clues on the magnetic environment and possibly on the location and thickness of Titan's internal ocean; 2) the tidally-induced solid crustal displacements and forced librations of the outer ice shell through the radio science equipment; 3) the level of seismic activity on the surface, the structure of the outer ice shell and hence the internal ocean with a micro-seismometer; 4) the environment through an acoustic experiment. Thus, two *in situ* elements currently considered will operate in synergy to achieve the scientific objectives.

Primary scientific objectives and investigations for the *in situ* elements studied in TSSM and with the provisional model payload include

- Perform chemical analysis, both in the atmosphere and in the liquid of the lake, the latter to determine the kinds of chemical species that accumulate on the surface, to describe how far such complex reactions have advanced and define the rich inventory of complex organic molecules that are known or suspected to be present at the surface.
- Analyze the composition of the surface, in particular the liquid material and in context, the ice content in the surrounding areas.
- Study the forces that shape Titan's diverse landscape. This objective benefits from detailed investigation at a range of locations, a demanding requirement anywhere else, but that is uniquely straightforward at Titan with the montgolfière high-resolution cameras and subsurface-probing radar.

The Huygens probe carried by the Cassini spacecraft was the first human-made robot to ever land so far away from the Sun. In spite of its enormous success [2], returning to Titan with two additional *in situ* elements such as an equatorial montogolfière and the northern latitudes lake lander, carrying a whole new and more complete set of instrumentation, would allow us to improve the science return more than significantly [3].

The process of defining landing sites is based on analyzing of science cases (e.g based on geological spectral units as defined by the Cassini orbiter instruments) and deriving viable candidates.

The science categories, which may apply to more than one region, include: meteorology, geology/geophysics and astrobiology. Regions for *in situ* investigations should thus combine – atmosphere, surface, near sub-surface, and deep interior observations. The importance of these is their potential ability to provide new science; allow confirmation and extension of orbital information by direct measurements; provide greater precision to orbital measurements; and improve interpretation of more distant and remote orbital measurements.

It would also be desirable, as much as possible to land on a site which would combine a variety of geological aspects that would simultaneously be attached to the atmospheric processes. Some such sites, with a potntial for being active, like Hotei Regio or Tui Regio, have been identified from current Cassini VIMS and RADAR observations near the equator [4]. The liquid extents at the pole are another privileged site to investigate the ground but also surface-atmosphere interactions.

Engineering considerations at these *in situ* regions need to be put forward for each individual location and include: illumination levels; atmospheric density and composition; temperature; surface hardness, roughness, inclination; sub-surface hardness, mechanical uniformity, composition, layering depths; wind and seismic levels.

2. SCIENCE CASES

Based on the spectral signatures in the infrared methane windows and radar features three major geological units can be distinguished [5-11]: whitish material mainly distributed in the topographically high areas; bluish material adjacent to the bright-to-dark boundaries, and brownish material that correlates with dunes.

Bright materials may consist of precipitated aerosol dust composed of methane-derived organics [e.g. 7, 11, 12] superimposed on water-ice bedrock. The bluish component might mainly contain water ice as its defining feature [e.g. 7, 11, 12].

Stereo analysis of the dendritic region at the Huygens landing site indicates an elevation of 50–200m relative to the large darker plain [13]. In the rugged surface of Xanadu, mountain heights can reach 2000m, with slopes approaching 45°in a few cases [11, 14, 15]. Stereo analysis of radar images near the largest north polar lakes indicates elevation variations ≤1200 m and slopes over 10 km baselines generally less than 5°. Steep-sided depressions, some of which contain smaller lakes , have depths as great as 600m [16].

Requested landing site measurements for geological objectives are:

- geological context by descent imaging and in-situ panorama stereo imaging;
- elemental chemistry by mass spectroscopy, tele-Raman spectroscopy and xrf/xrd spectroscopy;
- mineralogy by infrared spectroscopy and tele-Raman
- physical properties (e.g. particle sizes, porosity, permeability, heat flow
- subsurface access (e.g. mole)

with the following desirable surface materials to be sampled:

- dune material (is this erosive or solid form of precipate material? what material is under the dunes, and how deep does the surface dune material go?)
- lake liquid material (precipated, or from sub-surface reservoirs ?)
- surface fluvial material (washed down or precipate, eroded). As this may represent a collection of material from a very wide distance(10's-100km it may represent a significant sample. Is the fluvial material composed of a mixture of dune and highland material or is it different? What lies beneath the surface fluvial material, and how deep does it go (also in the lakebeds).
- other materials (need to avoid sampling contaminant precipitative materials, e.g. by

sub-surface sampling, or choosing a sloping run-off area ?)

There are important astrobiological interests in selecting the surface location such as surface organic chemistry, sub-surface organic chemistry and potential habitability and life in the subsurface liquids

Organic chemistry on Titan's surface is expected to occur in lakes that are filled with a cryogenic solvent : methane + ethane + dissolved N_2 and with a large variety of solutes, including all minor volatile atmospheric organic species, with, for most of them, concentrated higher or much higher than in the atmosphere, some volatile inorganics (noble gases, water, ammonia, H_2S), the soluble parts of the aerosols, mainly condensates and a small fraction of the polymer, some minor compounds produced by the chemical evolution of the main constituents induced by high energy cosmic rays reaching Titan's surface: such as diazomethane, azides and additional polymeric material. For most of these minor species, saturation may be reached and, probably the non-soluble part of the aerosols may be floating, if fluffy enough.

The chemical analysis of the lake will be a way to detect - in one sample - many species present together, the concentration of which is too low in the atmosphere or as a condensate on the aerosols.

Lakebeds, fluvial deposits and streambeds can be considered as analogues in composition to the lakes, but without the solvent. Thus the concentration of most minor species must be increased drastically compared to the lake content.

Similar to dunes, except embedded in sediment, provides an optimized site to allow investigations of material from potentially a very large collection area of perhaps several hundred square kilometres including run-off precipitates and eroded material, as well as potentially denser concentrated sedimentary material accumulated at the bottom of liquid zone from e.g. a shallow lake bed or from a period of flooding in a fluvial plain. Such sedimentary material could include heavy organics or deceased portions of astrobiological material denser than the surrounding medium.

Also of interest here would be the identification of chemical species; mechanical information of layering and particle sizes/mineralogy, and sub-surface temperatures.

Although impact craters are rare on Titan, the few proven impact craters are of great astrobiological interest: since these locations may have experienced liquid water – in a relatively recent time scale - allowing an efficient chemical evolution of the organics (both volatile and refractory) coming from the atmosphere, as described above for the dunes.

Sites containing cryovolcanic deposits are probably the most interesting for the astrobiological perspectives because they may have also experienced episodes of liquid water, eventually with some ammonia: conditions allowing a fruitful chemical evolution towards complex organics.

Cryovolcanic deposits locations may also provide information on potential organic chemistry occuring in Titan's subsurface [4]. By carrying up to the surface some of the materials of the sub-surface, these locations may also provide information on the chemical composition of the sub-surface, and the possible nature of organics synthesized in the hot, deep interior of Titan

Materials coming from the sub-surface also may include some biosignatures, indicating the presence of biological activity in the internal ocean such as molecular organic biosignatures (peptides, polynucleotides, sulfur- and phosphorus-containing organics, lipidic compounds, homochirality), isotopic biosignatures (enrichment in ^{12}C, ^{14}N, ^{32}S), mineral biosignatures (silica, sulfides/sulfates, etc) and micro-structures**.** However, it should be emphasized that the identification of potential biological activity requires the detection of several of these indices, and not only one!

The requirement for the measurements of tidal displacements and induced magnetic field are mainly determined by the interaction between Titan and Saturn and are independent on the surface geology and of surface units. Equatorial locations would be more favourable for tidal displacement and induced magnetic field measurements. The highest tidal fluctuation of surface elevation expected in the equatorial region preferentially near the sub-Saturnian and anti-Saturnian points (~25-30 m). Smaller but still high fluctuations expected at the poles (~20 m). Preferred location for the detection of an induced magnetic field is the equatorial region near 270° longitude.

Detections of seismic signal require geologically active region (cryovolcanic and/or tectonic regions). However, only limited geophysical measurements can be done by a floating lander on a lake filled with liquids. An optimal geophysical landing site could be a dune field in the equatorial region near a tectonic/cryovolcanic region to investigate the

- present-day interior structure: rocky core and liquid water/ice shells
- tidally-induced deformation and related seismicity
- intrinsic and induced magnetic field
- heat sources, cryovolcanism and eruptive processes
- early Titan's internal evolution, crust and atmosphere formation

3. CANDIDATE LANDING SITES

In what follows, locations (A) to (F) are the main targets that cover most of the different science requirements discussed above. Figures 1 to 5 show the candidate landing sites A-F including landing ellipses in different Cassini data sets.

(A) Xanadu broadly defined as 'bright terrain' (can be hit by a 45x30 (2000x1300km) landing ellipse). Coordinates: 110°W 12°S (center of ellipse);

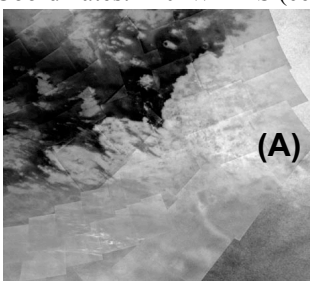

Fig. 1: Xanadu (Cassini ISS-data ~2km/px), Orbit

(B) Distinct blue alluvial units, e.g Chusuk Planitia (landing ellipse of about 200x100km requires delivery accuracy of 100km or better?). Coordinates: 30°W 7°S center of ellipse).

(C) Distinct crater surrounding unit, e.g Sinlap (landing of ellipse about 100x100km; requires delivery accuracy <100km). Ccoordinates: 14°W 7°N (center of ellipse)

Units (B) and (C) meets most geological objectives with different materials and processes but small landing ellipses

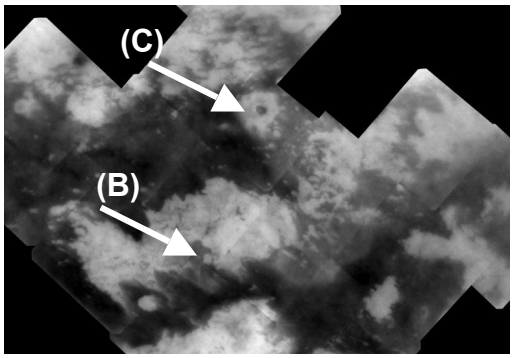

Fig. 2. Chusuk Planitia and Sinlap crater (Cassini ISS-data (PIA08352) 700 m/px)

(D) Brownish dune units e.g. Belet dunefield (can be hit by a 15x40° (600x1600km) landing ellipse). Coordinates: 255°W 5°S (center of ellipse); Dunefields fit most of engineering requirements and addresses most science objectives.

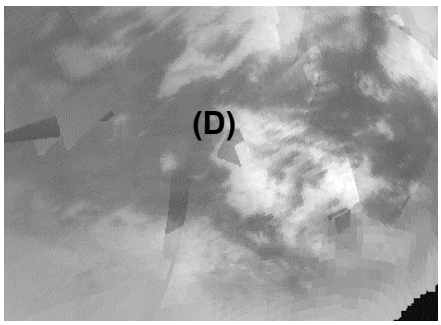

Fig. 3. Belet dune filed (Cassini ISS –data)

(E) North Polar Lakes above >72°N (200km circular delivery error can be accommodated in Ligeia Mare; Kraken Mare can probably accommodate ~400km circular delivery zone) coordinates: > 72°.

Lakes can satisfy the most exiting science goals of Titan's methanological cycle and productions of organics because chemical and isotopic composition changes of the lake liquids over time constrain diurnal and seasonal variations in atmospheric photochemistry and precipitation. An extraordinarily important goal of any return to Titan would be to constrain its climatic history, and one of the best ways to do that would be to analyze the chemical and isotopic composition of the lake sediments. An analysis of lake sediments will also inform us about both the sedimentation characteristics of atmospheric particles, as well as the role of wind and fluvial erosion processes on Titan. There are undoubtedly many other problems that could be addresses by analyzing lake contents and sediments, and this must be one of the highest priority goals of any return to Titan with landers.

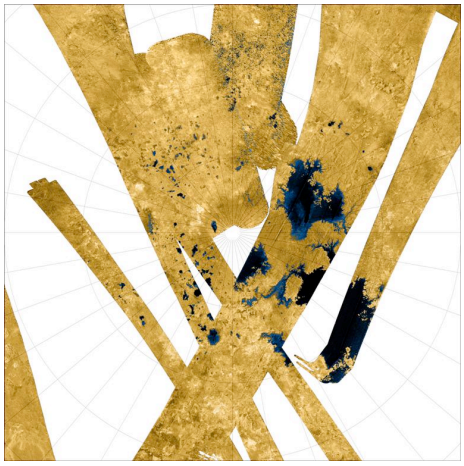

Fig. 4. North polar lakes (Cassini Radar-data)

(F) Anomalous spectral region e.g. Tui Region (~80% fit by 7x18° landing ellipse (300x800km) ~100% fit by 5x12° ellipse (200x500km)). Coordinates: 130°W 20°S (center of ellipse).

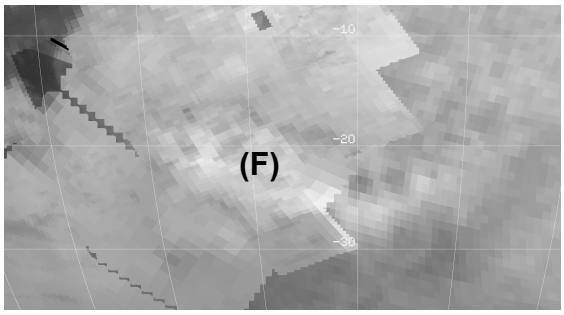

Fig. 5. Tui Region (Cassini ISS-data)

4. ENGINEERIN CONSUDERATIONS

Enabling a safe touchdown of a landing element at a candidate site requires a detailed analysis and engineering assessment of surface features over small scales, i.e. surface relief in terms of e.g. height variations, slopes, boulder coverage etc.

The major Engineering criteria for landing are summarized as follows.

Safety: Terrain relief/slopes: 'free' area over size of landing ellipse (~1000km needed (no steep slopes, large rocks, rugged surface (canyons, craters, channels, etc.)); uniformity in major surface features, i.e. no change between solid and liquid surface on smaller scales than size of landing ellipse. A strong constraint in this respect is mainly the limited resolution of available VIMS and ISS datasets. It is therefore difficult to assess.

Design constraints: depending on the surface relief of the selected landing site, the lander (EDLS, outer shell,..) must be designed to meet uncertainties, e.g. crushable shell, sufficiently sized airbags, lander must have the capability to land in every orientation, the unfold mechanism must rotate the lander into desired orientation if toppling over occurs, instrument deployment systems (seismometer, heat flow probe etc.) must be designed to cope with inclined position)

Latitude and elevation: Elevation plays a role w.r.t. the EDLS design. In Titan's thick atmosphere a system approach will favour a soft landing using parachutes rather than an active landing system. Parachutes need an adequate atmospheric density column to provide enough drag and consequently enough time to allow completion of all events needed for a safe landing. No problems concerning this constraint are expected on Titan due to the dense atmosphere.

Landing Ellipse/Warning track: ~1000 km (preliminary estimation), dispersion from winds during parachute descent needs to be considered radar altimeter can be spoofed by long-wavelength terrain features up to several km away from the predicted landing site. Since touchdown may occur at the edge of the ellipse, the radar view includes area up and down track of the potential landing ellipse, in a region referred to as the "warning track" (size from the center of the ellipse along either end of its major axis tbd) => calls for slope constraint that applies to this region outside of the nominal landing ellipse.

Terrain relief/slopes: Assumption: a Doppler velocimeter/altimeter on the carrier module will be used (e.g. to control time of airbag inflation): These systems use multiple radar antennas to measure the distance to the surface and the descent velocity (both vertical and horizontal components). The first measurement is usually taken while still on the parachute before backshell separation, with continuous measurements up to lander release. Over the range of the landers's trajectory during this time, slopes at various length scales may alter the measured altitude of the spacecraft above ground level, with potential adverse effects on control and lander safety. For certain classes of errors, the EDL system will be more directly sensitive to maximum terrain relief (i.e., minimum to maximum or valley-to-peak height variation) over a range of length scales rather than slope. This places constraints on maximum terrain relief values. The above relief and slope constraints could be evaluated by using Cassini data at kilometer length scales. Although not all of the landing ellipse must meet all of the slope requirements, the more area that exceeds them, the less likely the site would meet all the safety criteria thereby increasing the chances for failure.

Atmospheric Parameters: due to Titan's dense atmosphere no difficulties with EDL are expected. Criterion is only listed for completeness. The influence of horizontal and vertical winds should be considered during sizing of the landing ellipse.

Radar reflectivity: The surface material at the landing site must: i) be radar reflective (sufficient radar backscatter cross-section) to enable measurement of altitude and velocity during descent, ii) bear the load of the lander at landing, iii) experience a range of temperatures within the limits of the lander design. These requirements constrain the radar and thermophysical properties of the surface materials, including albedo, thermal inertia (and bulk density, through the latter), radar backscatter cross-section and reflectivity (and inferred bulk density).

Illumination: Variation of illumination geometry is maximum at low altitudes (e.g. for phase function studies). Illumination is strong (high light level, but small shadows) in polar summer (=South, late 2020s/early 2030s). Illumination is weak (scattered light plus Saturn shine) in polar winter (=North, late 2020s/early 2030s).

Power: The negligible available solar power on Titan's surface requires implementation of radioisotopic devices for electrical power generation

Communication/tracking: Low-latitude landing sites will 'see' Earth and Sun ~1/3 of the time – elevation changes continuously. High latitude (summer) landing site will see Earth and Sun 50-100% of the time, with rather constant (but low) elevation

Delivery: Trade/off: soft landers do not have to withstand high deceleration impacts, but are more restrictive in landing locations. Delivery accuracy will depend on entry angle. Allowable entry angles will depend on entry speed (from Titan orbit? From Saturn orbit? From arrival hyperbola?) In order to evaluate these aspects overall mission needs to be better defined. From the engineering point of view, safety is the highest order criterion with respect to identifying candidate landing sites, taking precedence over any other scientific or engineering constraint. Consequently, a candidate target site shall be a 'safe'

site, i.e. a site for which higher resolution data (at least down to ~300m/px) are available and indicate a flat, contiguous surface over at least the size of the landing ellipse. Hazards, such as boulders, gullies or steep slopes should be limited. Based on the 2007 Titan Explorer study data and recent mission design discussions [1] one could expect a 720 km by 220 km (3-sigma) landing footprint as a good estimate. The long axis of the ellipse should be in the direction of winds. A smaller ellipse would likely require a delivery from an aerial vehicle or an actively controlled entry vehicle. Furthermore, latitude and elevation have to be considered with respect to communication and tracking of the landed element. High latitude landing sites may require shallow entry angles, enlarging the size of the landing ellipse. Apart from general safety considerations the Titan terrain targeted for landing determines the technical grade of complexity of the EDL approach and/or lander design.

5. SUMMARY

The most promising sites are wet polar regions or dry equatorial regions because of their high compositional diversity and the mobility of material. North Polar Lakes above >72°N (200km circular delivery error can be accommodated in Ligeia Mare; Kraken Mare can probably accommodate ~400km circular delivery zone). These areas fit address the most exiting science goals of the methanological cycle and the productions of organics. In particular, beach regions, with close contact to liquids, of are a primary target because: (1) (1) We must try to determine as best we can, the chemical and isotopic composition of the lake liquids over time to constrain diurnal and seasonal variations in atmospheric photochemistry and precipitation. (2) An extraordinarily important goal of any return to Titan would be to constrain its climatic history, and one of the best ways to do that would be to analyze the chemical and isotopic composition of the lake sediments. To that end, we should analyze the stratigraphic sequence of the lake sediments, combined with age dating using 14C techniques, among others, to determine both long-term (climatic), versus short term (seasonal) changes in the isotopic and chemical composition of the lake sediments. (3) An analysis of lake sediments will also tell us about both the sedimentation characteristics of atmospheric particles, as well as the role of wind and fluvial erosion processes on Titan. The chemical and isotopic composition of lake liquids can be determined over time to constrain diurnal and seasonal variations in atmospheric photochemistry and precipitation and to detect many less abundant atmospheric species much as they would become more concentrated in the lake than in the atmosphere. (2) An extraordinarily important goal of any return to Titan would be to constrain its climatic history, and one of the best ways to do that would be to analyze the chemical and isotopic composition of lake sediments combined with age dating using ^{14}C techniques, among others, This will allow to determine both long-term (climatic), versus short term (seasonal) changes. (3) An analysis of sediments suspended in the lake sediments will also identify both the sedimentation characteristics of atmospheric particles, as well as the role of wind and fluvial erosion processes on Titan. However, the engineering requirements for such zones are hard to meet.

Equatorial Dunefields (e.g. Belet can be hit by a 15x40° ellipse (600x1600km) at 255°W 5°S (center of ellipse)). Dune areas best fits engineering requirements while providing still a wide range of science goals due to the organic characteristics of the dune material and its close relationship to atmospheric processes. The macromolecular refractory organics constituting the nucleus of Titan's aerosol may, in the presence of water (ice), chemically evolve and produce a large variety of organics, including amino acids which that might be important to understand Titan's potential for habitable environments. Subsurface sounding, using sonar or radar techniques depending on the platform, will also provide key constraints on the sediment layering, and hence on Titan's climatic history. In case of solid landing, radio tracking and seismic investigations will also provide information on Titan's interior and tectonic activity.

6. REFERENCES

[1] TSSM report, 2008, ESA-SRE(2008)4.

[2] Brown, Lebreton, Waite (eds.) 2009, Titan from Cassini-Huygens, Springer, Dodrecht, Heidelber, London, New York.

[3] Coustenis et al., 2008, TandEM: Titan and Enceladus Mission, Experimental Astronomy, 23, 893-946, DOI 10.1007/s10686-008-9103-z

[4] Solomonidou, Coustenis et al., 2010, IPPW7, this issue

[5] Elachi et al., 2006, Titan Radar Mapper Observations from Cassini's T_a and T_3 Flybys, Nature, 441, 709–713, doi:10.1038/nature04786.

[6] Lorenz and Mitton, 2008, Titan Unveiled, Princeton University Press

[7] Soderblom et al., 2007, Correlations between Cassini VIMS spectra and RADAR SAR images: Implications for Titan's surface composition and the character of the Huygens probe landing site, Planet. Space Sci. 55, 2025–2036, doi:10.1016/j.pss.2007.04.014.

[8] Barnes et al., 2007, Global-scale surface spectral variations on Titan seen from Cassini/VIMS, Icarus, 186, 242–258, doi:10.1016/j.icarus.2006.08.021.

[9] Le Mouelic et al., 2008, Mapping and interpretation of Sinlap crater on Titan using Cassini VIMS and

RADAR data. J. Geophys. Res. 113, E04003, doi:10.1029/2007JE002965
[10] Jaumann et al., 2008, Fluvial erosion and post-erosional processes on Titan, Icarus, 197, 526-538
[11] Jaumann et al., 2009, Geology and surface processes on Titan: *In Titan from Cassini-Huygens*, R.H. Brown, J.-P. Lebreton, H. Waite (eds), 75-140, Springer, NY, 2009.
[12] Soderblom et al., 2009, Composition, in Titan from Cassini-Huygens: *In Titan from Cassini-Huygens*, R.H. Brown, J.-P. Lebreton, H. Waite (eds), 75-140, Springer, NY, 2009.
[13] Tomasko et al., 2005, Rain, winds and Haze During the Huygens Probe's Descent to Titan's Surface, Nature, 438(8), 765–778, doi:10.1038/nature04126.
[14] Radebough et al., 2007, Mountains on Titan observed by Cassini RADAR, Icarus 192 77-92, doi:10.1016/j.icarus.2007.06.020.
[15] Kirk et al., 2008, Digital topographic models of Titan produced by radar stereogrammetry with a rigorous sensor model, 39th Lunar and Planetary Lunar and Planetary Science Conference, Houston, abstract #2320.
[16] Stofan et al., 2007, The lakes of Titan, Natur 445, doi:10.1038/nature05438.

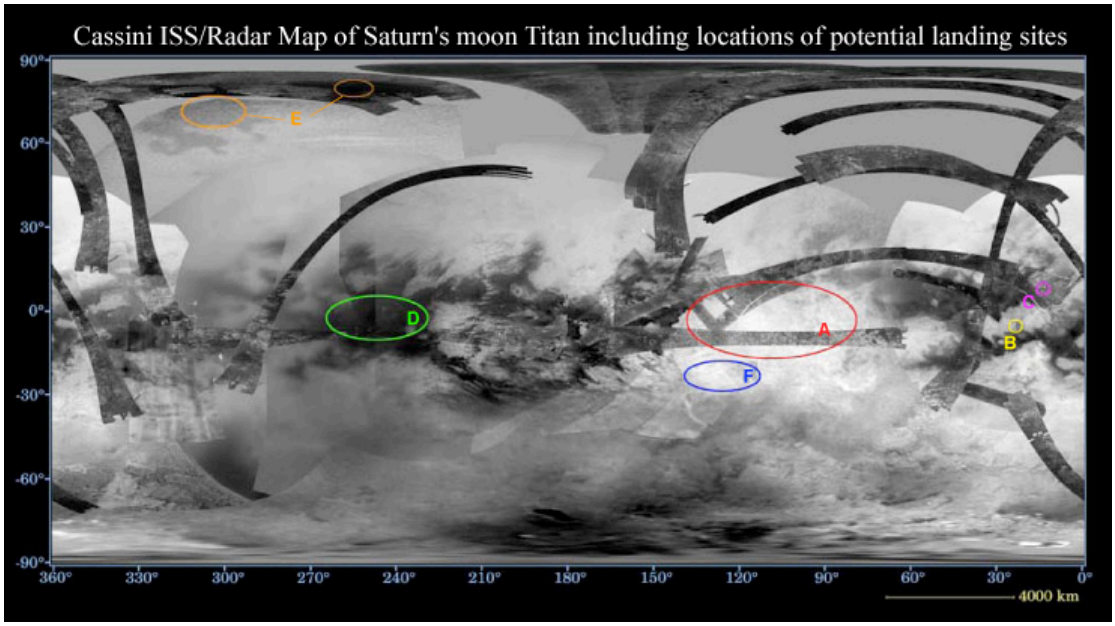

Fig. 6. Landing ellipses for target areas (A-F) on Cassini ISS and Radar data

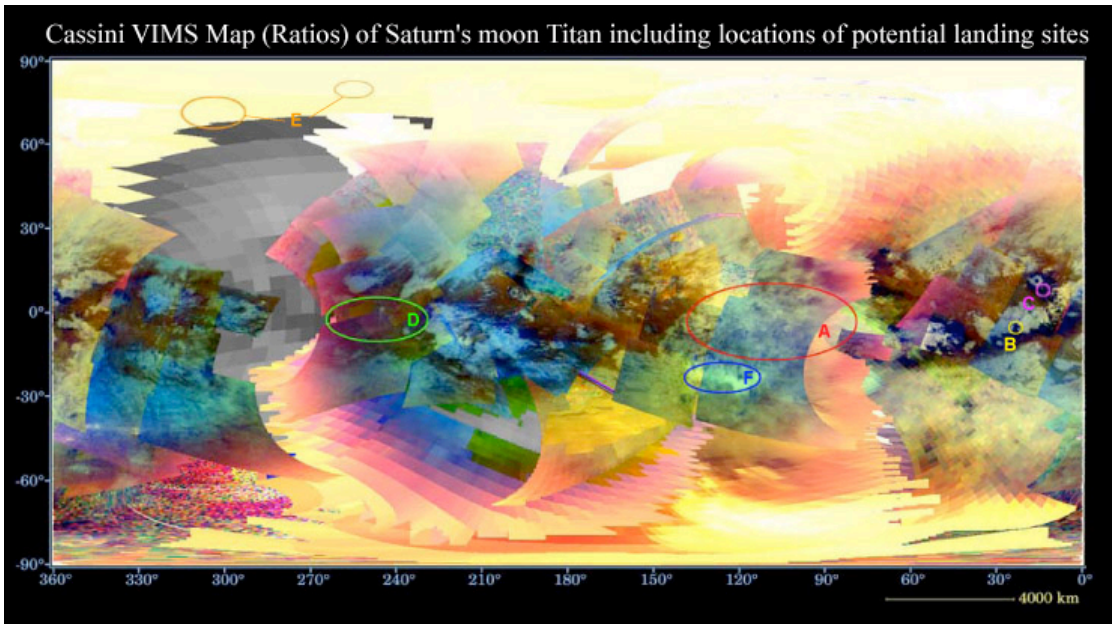

Fig. 7. Landing ellipses for target areas (A-F) on Cassini VIMS spectral ratio data (bright = mountainous regions; blue = plains (fluvial?); brown = dunes)