Oulu University - B.Sc. Thesis
Lakes and Seas of Titan

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Contents

Used in this thesis

K - Kelvin

kg - Kilogram

W - Watt

m - Meter

s - Second

Astronomical unit (Earth-Sun distance) [AU] $1AU = 149\ 597\ 871\ km$

Atomic mass unit [amu] $1u = 1.66053904 * 10^{-27} kg$

Solar constant $F_{Solar} = 1370\ Wm^{-2}$ [1][p.132]

Gravitational constant $G = 6.67408 * 10^{-11} m^3\ kg^{-1}\ s^{-2}$

Boltzmann constant $k = 1.38064852 * 10^{-23} m^2\ kg\ s^{-2}\ K^{-1}$

Stefan-Boltzmann constant $\sigma = 5.670400 * 10^{-8} W\ m^{-2}\ K^{-4}$

Titan's mass $M = 1.3457 * 10^{23} kg$ [2][Table 1.5]

Titan's radius $R_{Titan} = 2575\ km$ [2][Table 1.5]

Semi-major axis of Saturn's orbit $a_{Saturn} = 9.542\ AU$ [2][Table 1.1]

Eccentricity of Saturn's orbit e = 0.0555 [2][Table 1.1]

Methane's molecular mass $m_{CH_4} \approx 16.043\ u$ [3]

Nitrogen's molecular mass $m_{N_2} \approx 28.014\ u$ [4]

Other quantities are given within sections when needed.

1. Introduction

Among the satellites in the solar system, Titan is unique due to its thick atmosphere - seen in Figure 1 $^{[5][p.13]}$. Studies conducted with data obtained by the Cassini-Huygens mission show that there are liquid hydrocarbon pools on Titan $^{[5][p.275-277]}$. The main purpose of this thesis is to describe these liquid pools of Titan.

First, conditions on the surface of Titan are estimated to validate if stable liquid pools can form. Surface equilibrium temperature, the required pressure for methane and nitrogen to exist in liquid form, origin of the thick atmosphere and Titan's ability to hold the atmosphere gravitationally are the subjects covered in section 2.

This is followed by section 3 where descriptions of devices that have been used to study Titan are given. Reviews of the Voyager mission, Earth-based studies with telescopes and the Cassini-Huygens mission are featured.

Studies concerning the liquid pools are considered in section 4. The first confirmation of liquid on Titan's surface and features of the pools are described, followed by results on composition from bathymetric analysis. Results from models that study wind, tide and thermally driven liquid currents and waves are reviewed. Lastly, Titan's habitability for life is considered.

The first subsection of section 5 describes a region in one of Titan's seas that is appearing and disappearing in Cassini's images. Secondly, the Titan Submarine project is reviewed with swimming module that could explore the liquid pools and study the currents, composition and evolution of Titan.

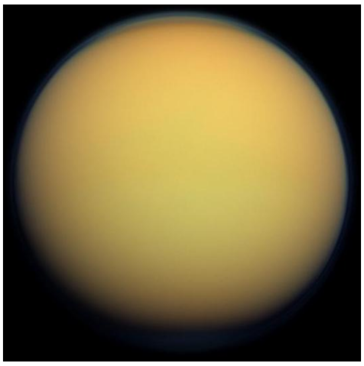


Figure 1: Titan with its atmosphere as seen by Cassini's ISS-instrument in optical light.
NASA/JPL/Space Science Institute
https://photojournal.jpl.nasa.gov/catalog/PIA06183

2. Saturn's moon Titan

This section's goal is to give a basic idea of the conditions on Titan with the focus on the equilibrium surface temperature and the required pressure for methane and nitrogen to exist in liquid phase. Additionally, the origin of the optically opaque [6][p.104] atmosphere is considered.

2.1 Surface equilibrium temperature on Titan

In this subsection, Titan's surface equilibrium temperature is determined through the equilibrium between incoming and outgoing radiation. Titan's atmosphere's effects are added without explicit calculation.

Sun's flux at some distance can be determined with the simple equation [7][p.59]:

$$F = \frac{L_\odot}{4\pi r_\odot^2}, \tag{1}$$

where $L_\odot$ is the luminosity of the Sun and $r_\odot$ is the distance to the Sun. At Earth's radial distance (1 AU) the result for the formula (1) is F_{Earth}. In Saturn's case its semi-major axis value (a_{Saturn}) is used to determine the flux F_{Saturn}. These can then be compared:

$$\frac{F_{Saturn}}{F_{Earth}} = \frac{(1.0AU)^2}{(9.542AU)^2} = 0.01098. \tag{2}$$

The value for the flux at 1 AU (F_{Earth}) is equal to the solar constant F_{Solar}, so the energy flux at Saturn's distance is about 1% of the solar constant:

$$F_{Saturn} = \frac{L_\odot}{4\pi(a_{Saturn})^2} = 0.01098 * F_{Solar} \tag{3}$$

The solar incident side of a body receives radiation given by the equation [7][p.60]:

$$L_{in} = (1 - A_b)\frac{L_\odot}{4\pi r_\odot^2}\pi R^2, \tag{4}$$

where A_b is the bond albedo - the energy fraction which is scattered and reflected back from a body as radiation. In the case of Titan, the $\frac{L_\odot}{4\pi r_\odot^2}$ part is the result from formula (3) and πR^2 is the projected area of Titan ($R = R_{Titan}$). The received energy is absorbed by the target area which in turn emits some energy back as thermal emission; Fast rotation gives the approximation that the whole surface area emits outwards [7][p.60]:

$$L_{out} = 4\pi R^2 \epsilon\sigma T^4, \tag{5}$$

where ϵ is the emissivity of the surface, σ is the Stefan-Boltzmann constant and T is the temperature of the emitter.

In the case of a slow rotation, the result from the formula (5) would be halved as one side of the target is illuminated constantly. Titan's orbital period of 16 days matches its rotation period around Saturn making it tidally locked towards Saturn [2][Tables 1.4 and 1.5], but to obtain a first order approximation one continues to use formula (5), motivated by the fact that, owing to the atmosphere, the surface temperature on Titan has only a very small diurnal variation. Namely, the atmosphere stores heat and redistributes it by convection and radiation around the whole surface of Titan making the temperature difference between day and night side about 1.5K - depending on the latitude and season [8],[9] . Therefore, the result from the formula (5) is not halved because of the atmosphere's effect.

Formulas (4) and (5) must be in equilibrium and the equilibrium temperature T_{eq} is the formerly mentioned temperature of the emitter from (5); The result is:

$$T_{eq} = \sqrt[4]{\frac{F(1-A_b)}{4\epsilon\sigma}}, \tag{6}$$

where the flux in the case of Titan is the result from (3). The bond albedo A_b is 0.20 [6][Table 4.2] and the emissivity ϵ is 0.9 in the case of infrared radiation [7][p.60]. The result is $T_{eq} = 87.6K$, which is approximately -185.5 degrees in Celsius. In the case of the emissivity being 1.0 the surface equilibrium would be approximately 85K [6][Table 4.2] - this value is used in the following estimations.

There is a greenhouse effect happening in the atmosphere of Titan which warms the satellite by 21K, whereas the haze-layer decreases the warming by 9K by blocking off shorter wavelengths [6][p.82]. The case of equilibrium temperature being 85K is therefore used, and with the atmosphere's net warming of 12K the final result for the surface equilibrium temperature is 97K.

It should be noted that the flux (1) changes over one Saturnian year due to the eccentric orbit of Saturn. With the following formula one can calculate the radial distance r at any point of the orbit [10][p.22]:

$$r = \frac{a(1-e^2)}{1+e\cos(f)}, \tag{7}$$

where a is the semi-major axis of Saturn's orbit, e the eccentricity and f the true anomaly which is the angle (in degrees) from perihelion - closest distance to the Sun - to Saturn's location on the orbit. As different values for the radial distance are solved from formula (7), formula (6) gives the corresponding surface equilibrium temperature. The surface equilibrium temperatures during one Saturnian year are given in Figure 2 with the atmosphere's net warming of 12K added. Notably, the minimum temperature is around 94.7K and the maximum is at 99.5K.

Titan's atmosphere's effect on temperature's evolution also varies with Titan's seasons but this evolution is not included in this case.

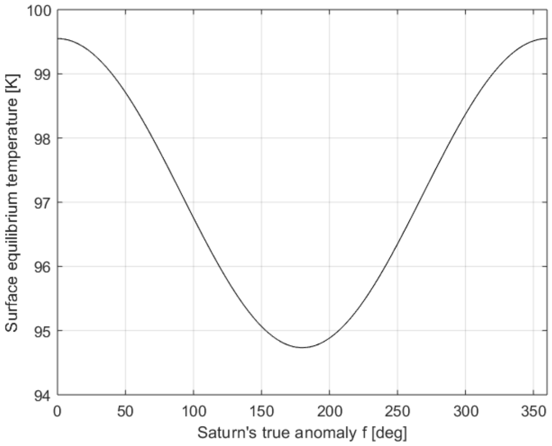


Figure 2: Titan's equilibrium temperature at different points of Saturn's orbit with the atmospheric net warming of 12K included.

2.2 Vapor pressures and Titan's overall atmosphere

Methane was detected in Titan's atmosphere early on, and nitrogen was confirmed later by the Voyager-mission [6][p.93] . This led to the question if these substances can exist in liquid form on Titan's surface. In this subsection, methane's and nitrogen's vapor pressures are approximated separately. For a specific temperature, vapor pressure indicates the needed pressure for the substance to change phases between liquid and vapor [11] . Also, Titan's ability to hold the atmosphere is considered briefly.

The Antoine equation is used for the evaluation of the vapor pressure [11] :

$$log_{10}p = A - \frac{B}{C+T} \tag{8}$$

where p is the vapor pressure of the studied substance in bar unit, A, B and C are the Antoine coefficients for this specific compound and T is the temperature of the system in Kelvin. For a sample containing just methane at a temperature of 97K the Antoine coefficients are $A = 3.9895$, $B = 443.028$ and $C = -0.49$ [12],[13] with the result vapor pressure being 0.3 bar. At the same temperature Antoine coefficients of nitrogen are $A = 3.7362$, $B = 264.651$ and $C = -6.788$ [14],[15] , and the result is a vapor pressure value of 6.3 bar. It follows, that Titan's atmospheric pressure on its surface must be estimated to further evaluate if either of these substances can exist in liquid form on Titan's surface.

Measurements for the surface pressure on Titan has been conducted by studying non-uniform broadening of spectrum line-widths [16] . In general, substances emit or absorb radiation at specific wavelengths given by transitions between energy levels of the molecules [7][p.65]. When Titan's spectrum is measured, the excess or absence of intensity at different wavelength values is seen [5][p.15, Figure 1.8]. The emission or absorption will never appear as strict lines in the spectrum as there will always be some broadening due to the Heisenberg's uncertainty principle and the Doppler shift - caused by the thermal motion of the particles [6][p.86].

Particle collisions also influence the broadening as particles' geometries change during collisions. Different spectral lines can start to overlap due to the broadening of the lines with the result being one broadened spectral line. With low frequencies the broadening of this line is not equal towards lower and higher frequencies and this asymmetry gives a way to determine the atmospheric pressure; Collision frequency forms the atmospheric pressure and with increased atmospheric pressure the asymmetry of the broadened spectral line also increases. [6][p.87]

A measurement from Titan's spectrum has given estimates for the surface pressure of about 1.3 bar [16] , which at 97K temperature is over the vapor pressure limit for methane (0.3 bar) but under nitrogen's limit (6.3 bar). Therefore, at the approximate surface temperature of 97K, methane can possibly exist in the liquid phase on Titan's surface but nitrogen cannot.

Already, the simple estimate from section 2.1 is suggestive of a very mild seasonal change of surface temperature on Titan over one Saturnian year, in the range of 95-100K. The temperature range is marked in Figure 3 as well as methane's triple point (90.67K, 0.117bar) [17],[18] , the approximate condition on Titan's surface (97K, 1.3bar) and the boiling curve - values of vapor pressure at different temperatures. Titan's surface temperatures lie well above the triple point temperature; Based on these simple estimates it is therefore likely that methane on Titan can exist in the liquid phase. The melting curve - phase change between solid and liquid - is not included in this simple consideration, but it is implied that the melting curve will not prevent liquid methane from occurring on Titan [19] - the credibility of the reference's phase diagram is hard to determine as there are no sources or methods given that describe how the phase diagram was created.

Last thing to discuss is Titan's ability to hold the atmosphere gravitationally. If the thermal velocity of a gas molecule exceeds the escape velocity then the particle will escape from a gravity well. The formula for the escape velocity on Titan is as follows [1][p.224]:

$$v_e = \sqrt{\frac{2GM}{R_{Titan}}} \approx 2640 m/s, \tag{9}$$

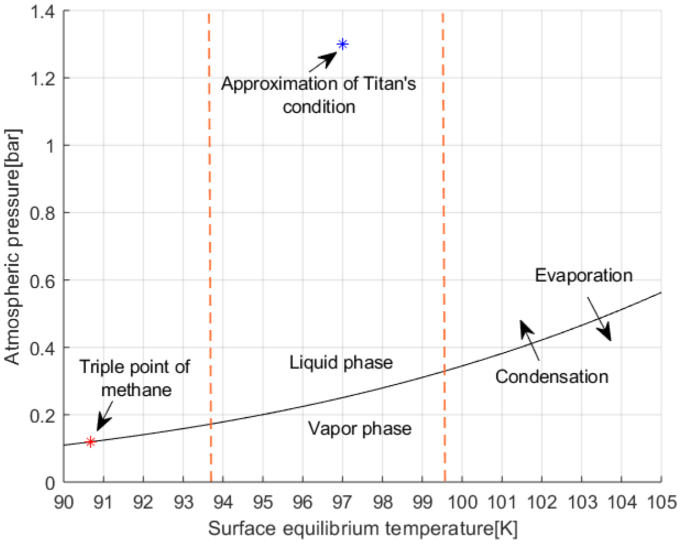


Figure 3: Simplified phase diagram of methane - Orange lines depict the variation limits for the surface equilibrium temperature on Titan expected during one Saturnian year. The black curve corresponds to the boiling curve, red dot is the triple point of methane (90.67K, 0.117bar) [17],[18] , and the blue dot the approximated condition on Titan at a radial distance of 9.542AU from the Sun (97K, 1.3 bar).

where G is the gravitational constant, M the mass of Titan and R_{Titan} the radius of Titan. The average thermal velocity is [1][p.224]:

$$< v_T >= \sqrt{\frac{3kT}{m_{particle}}}, \tag{10}$$

with the Boltzmann constant k, the mass of the studied particle $m_{particle}$ and Titan's exobase's temperature (T=149K) [6][Table 4.2]. For methane the result is approximately 481 m/s, and 364 m/s with nitrogen. The average thermal velocities for both methane and nitrogen are greatly lower than the needed escape velocity meaning that Titan's gravitational hold is strong enough to keep the atmosphere - some particles may still escape from the exobase, with velocities in the tail of the Maxwell distribution [1][p.224] .

2.3 Origin of the substances found in Titan's atmosphere

As stated formerly, Titan is the only satellite in the Saturnian system with a notable atmosphere [5][p.13]. This subsection features only a brief look on the subject of Titan's atmosphere's origin as the theory of Solar System formation is currently still highly debated subject [2][p.18−19] .

When looking back to the beginning of the Solar system, icy materials such as methane (CH_4), water (H_2O), ammonia (NH_3) and carbon dioxide (CO_2) could exist in the solid phase at the outer regions of the Solar System where the temperature would be low enough [2][p.19]. Combined with some rock-forming elements, these would start forming planetesimals which in turn would combine to planets and satellites [2][p.19]. Densities of Saturnian moons are mainly low (densities under 1 gram per cubic centimeter), but few of them, including Titan, stand out (1.88 grams per cubic centimeters with Titan) [2][Table 1.5]. A possible reason for this difference is an early bombardment of Titan's crust which would have removed some of the more volatile components [20][p.544–545], which in turn increased the overall percentage of rock-based materials in Titan. With a suitable mass of the projectile the icy materials such as methane could have been released from the crust but not ejected out of Titan's atmosphere increasing the overall abundance of methane in the atmosphere. The sub-surface gases could also be transported to the surface through small cracks in a long time scale [5][p.327].

A stable atmosphere with an atmospheric pressure of around 1.3 bar, and a surface temperature of around 97K is suggestive of liquid methane occurring on Titan. This assertion could be confirmed by direct observation of liquid hydrocarbons on Titan. This was achieved by sending a spacecraft to the Saturnian system.

3. Titan exploration from Earth and space

This section's agenda is to describe the former space missions to the Saturnian system - Voyager and Cassini-Huygens. Additionally, observations have been carried out from Earth.

3.1 The Voyager mission

Humanity has had telescopes far longer than spacecrafts, and the discovery of Titan was done far before the Voyager mission - by an astronomer from Netherlands, Christiaan Huygens, in 1655 [5][p.2] . It would take just under 300 years until Titan turned from just another satellite in the Solar System to something actually noteworthy, as methane was discovered in its atmosphere by Gerard Kuiper in 1944 [5][p.13] . Spectroscopic analysis had shown methane absorption lines in Titan's atmosphere, and further studies started to estimate the surface pressure on Titan's surface and the abundance of methane [5][p.14–15] . Temperature and pressure estimates ranged from low estimates of about 80K and millibar scale pressures to high estimates of 200K and 20 bar pressure [5][p.15] . As the Pioneer probes passed Saturn's system in 1979, it was at the time closest to Titan humanity had ever been, but Titan was not studied notably during these flybys [5][p.16–17].

In the 1970s, the Voyager program got the green light to manufacture two spacecraft. Voyager 2 was launched first, during August of 1977, and it took the long route by visiting all the giant planets in the Solar System, while Voyager 1 (launched during September 1977) would use Jupiter as a gravitational catapult and head straight to Saturnian system to study Titan. Voyager 2 passed through the Saturnian system in 1981 but it did not come close enough to Titan to study it notably. Voyager 1 had plunged deeper into the Saturnian system during November of 1980 and crossed the orbital plane of Saturn from north to south with the minimum distance from Titan being around 7000 kilometers, which only enabled it to take measurements of Titan's atmosphere. [5][p.17–19]

The Voyager probes had identical instruments on board and for the study of Titan four of the eleven instruments were used [5][p.19] , but none could directly detect lakes or seas on Titan [5][p.35].

The Infrared Interferometer Spectrometer (IRIS) was able to study Titan's atmosphere within the infrared wavenumber range of 200 cm^{-1} to 1500 cm^{-1} with the resolution of 4.3 cm^{-1} [5][p.28] . The Ultraviolet Spectrometer (UVS) was used to study Titan's higher atmosphere around 1000km [5][p.25] . The Wide angle cameras took images, and the radio antennae could be used as a radio telescope system with the technical ability to measure the temperature profile from the surface up until 200km when used together with IRIS [5][p.25]. In practice, fitting of the expected temperature profile from the abundance of substances was more reliable [5][p.25] .

Titan's surface temperature and pressure were determined with radio occultation method where Voyager's radio pulse is refracted by Titan's atmosphere on the way to Earth. The result was a surface temperature average of 94K with an error estimation of 1.4K, and a pressure of about 1.5 bar. [5][p.22]

The estimated surface equilibrium temperature from section 2.1 was 97K which is quite close to Voyager's measurement of 94K. Earth based measurement of the surface pressure gave the result of 1.3 bar [16] which is also near Voyager's measurement. If Voyager's measurement of 94K and 1.5 bar is set to methane phase diagram in Figure 3, the point would again imply a stable liquid phase.

IRIS and UVS of Voyager 1 had a major role when determining the abundance of substances in the atmosphere of Titan. Spectral analysis was mentioned in section 2.2 when discussing pressure and by studying the width of the lines as well as the overall intensity one can determine the overall amount of a substance [6][p.83–84]. UVS confirmed that Titan's atmosphere consists 95% of molecular nitrogen [5][p.22] while IRIS measured the near-surface abundance of methane to be between 4 to 8 percent [5][p.22]. Complex hydrocarbons, hydrogen, nitriles and carbon dioxide were also detected with IRIS [5][p.22].

For Titan's overall climate and formation of clouds and rain, the vertical temperature gradient is important [6][p.100−101]. The tropopause in Earth's atmosphere appears colder than the surrounding altitudes [6][p.79, Figure 4.1a], and this was also detected on Titan by Voyager [5][p.24, Figure 2.5]. Similar temperature profile measurement was also done with the Huygens lander (Figure 4).

Voyager's temperature profile did not match well with methane rich atmosphere and the best fit was more in terms of dry nitrogen model meaning that methane based rain was unlikely. Ethane, which boils at 184K temperature in Earth's atmospheric pressure [21] , was deemed more probable to form clouds and rain. But as the data was still sparse, the possibility of methane based clouds could not be completely dismissed. [5][p.24−25]

No instrument on Voyager 1 could take images of Titan's surface as none had the capability to work at near infrared range where the surface would have been visible [5][p.35], so a second mission to Titan was needed to study the surface further.

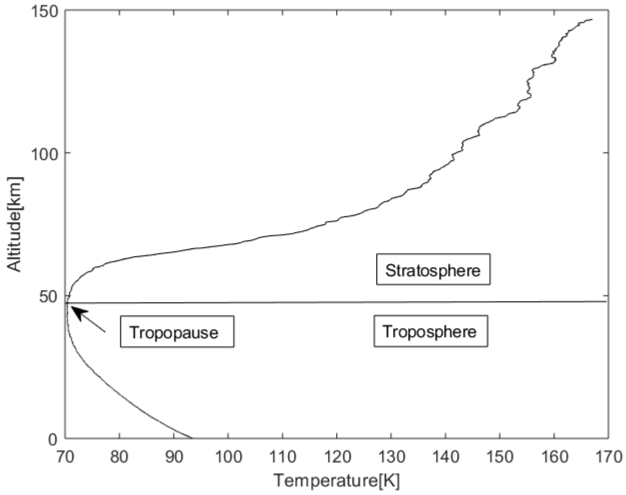


Figure 4: Titan's temperature profile measured by Huygens' HASI-instrument. Data provided by ESA Planetary Science Archive https://www.cosmos.esa.int/web/psa/huygens

3.2 Earth based studies of Titan

Before and after the launch of Cassini-Huygens - which happened in 1997 - Titan has been studied by Earth based telescopes and satellites. This subsection discusses some of these studies.

Theoretical models had predicted an ocean on Titan consisting mainly of methane or ethane depending on the temperature [5][p.55]. With a colder surface temperature of 92 kelvin, the ocean would mainly contain photolysis products of methane like ethane and propane; For a warmer variant of 101 kelvin, the result would be reversed and methane would dominate [5][p.55, Table 3.1]. The depth of this ocean would range from 500 meters to almost 10 kilometers depending on the model [5][p.55] .

Earth based radars started scanning Titan in 1991. The surface of Titan appeared quite bright in the radar images in contradiction to the deep ocean model, as a deep sea would greatly absorb the signal. It was concluded that Titan is partly covered by some signal darkening material or smaller scale liquid pools were dampening the radar signal. [5][p.56]

Imaging and spectroscopy in near-infrared by the *Hubble Space Telescope* (HST) and ESO's *Very Large Telescope* with Adaptive Optics-system (NACO) showed asymmetry in brightness when comparing the pole regions, as seen in Figure 5 [5][p.66–69]. One explanation for the brightness asymmetry was solid methane existing on mountain ranges as higher altitude with lower temperature allows solid methane to form [5][p.69–71] . Another idea was that the darker areas were covered by something highly absorbing in infrared and Titan's rains could remove this material making that area appear brighter [5][p.69–71]. Spectroscopic study of substances that absorb in the infrared wavelength range of 1 to 2.5 micrometers confirmed that there could be water-ice on the surface with some other substance that absorbs closer to 1 micrometer [5][p.62–64]. Organic compounds were considered to be responsible for the absorption [5][p.64] .

To summarize, Earth based observations by radio- and infrared-methods appeared to support small-scale methane covered regions on Titan. Methane around those regions could be in the liquid phase as the surface temperature and the atmospheric pressure were measured to be suitable.

3.3 The Cassini-Huygens mission

Most of the data reviewed in this thesis were obtained with the Cassini-Huygens mission conducted by ESA and NASA [5][p.72] . An introduction to the mission is given in this subsection.

The target for the mission was the whole Saturnian system, where some of the instruments were especially designed for Titan exploration - notably the Huygens lander-probe was prepared for the study of Titan [5][p.72–73]. Huygens was dropped off to land on Titan while Cassini served as a transmitter for the scientific data obtained by the lander [5][p.86] . This came with a time limit as Cassini would move behind Titan's horizon which would cut communication between the

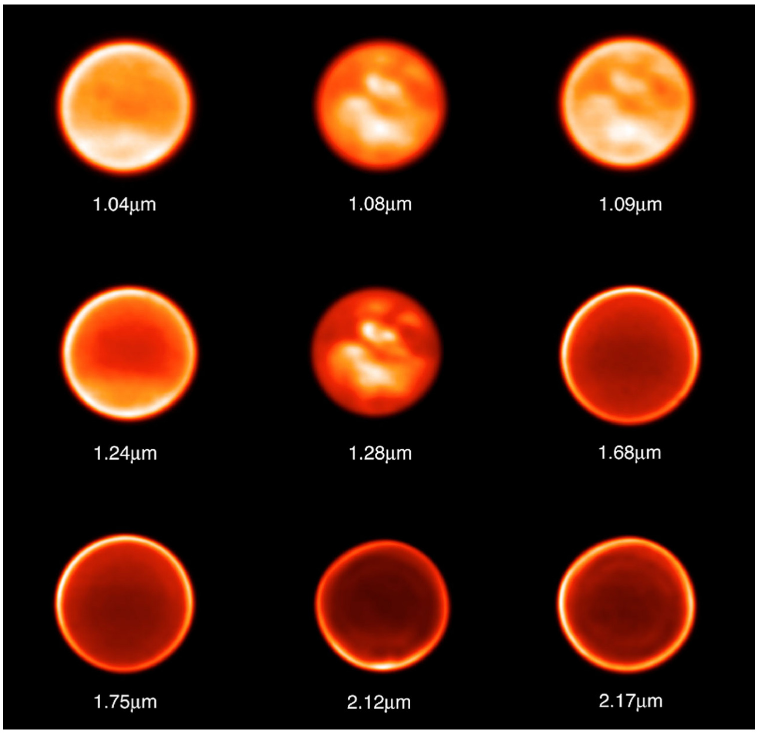


Figure 5: Titan imaged at nine infrared-filters by the Very Large Telescope with NACO-adaptive optics system (2002) - Note the southern hemisphere in 1.04 micrometer measurement appearing brighter than the northern hemisphere.
ESO
https://www.eso.org/public/images/eso0408b/

probe and the orbiter. The lifetime of Huygens was also limited due to its limited battery and Titan's cold atmosphere freezing the probe [5][p.87].

In order to maximize the usable time for studies, the main parachute of Huygens was detached quickly after the first deceleration phase followed by the opening of a smaller parachute [5][p.87] . The smaller parachute made the fall more stable and Huygens could begin to carry out its measurements already at high velocity after the entry to the upper atmosphere [5][p.87] .

Huygens was carrying six main instruments to study the atmosphere and the surface of Titan, which are described below.

The Aerosol Collector Pyrolyser (ACP) prepared aerosol particles during the descent by heating and vaporising particles sending the products to a mass spectrometer for analysis. [5][p.100]

The Gas Chromatograph/Mass Spectrometer (GCMS) could analyze Titan's atmosphere by detecting its particles in a mass range of 2 to 146 amu. First, it separated chemically different particles in the gas chromatograph portion. The particles were then ionized and driven through a magnetic field which separated the ionized particles by mass. [5][p.104–105]

The Doppler Wind Experiment (DWE) estimated the wind speed during the descent and also monitored the orientation of the probe. [5][p.103–104]

The Huygens Atmospheric Structure Instrument (HASI) performed temperature and pressure measurements. It also had the capability to constrain electrical properties of the atmosphere and was important in the study of thunder and lighting on Titan - Figure 4 depicts HASI's measurement of Titan's thermal profile. [5][p.105–106]

The Descent Imager/Spectral Radiometer (DISR) included a silicon photodiode system, a silicon CCD (charge-coupled device), two linear array detectors for infrared detection, fibre optics for both optical and infrared spectroscopy set on top and bottom of Huygens, as well as cameras. The task was to study light scattering at different altitudes of the atmosphere while the cameras had the opportunity to capture images of the surface in search of notable topography. [5][p.101–103]

The Surface Science Package (SSP) was a combination of multiple instruments responsible for the study of landing area's properties like the sound velocity, scanning for the condition of the landing site's ground, plus accelerometer and penetrometer to study the surface material upon impact. SSP was also able to study liquid material if Huygens had happened to land on a liquid pool. [5][p.106]

Cassini's mission continued after Huygens stopped sending out data. Flybys by Titan were necessary for Cassini since the gravity assist of Titan enabled the orbiter to reach different objects of Saturnian system, and Titan was studied during each flyby [5][p.107]. During the flybys Cassini used the following five instruments to study Titan:

The Imaging Science System (ISS) included a Narrow Angle Camera (NAC) with a resolution of 0.35° × 0.35° and spectral range of 200-1100 nanometers (near-ultraviolet to near-infrared), and a Wide Angle Camera (WAC) with a resolution of 3.5° × 3.5° with a spectral range of 380-1100 nanometers (optical to near-infrared) [22][p.434–435]. With Voyager, technology was at the point of using vacuum-tubes [5][p.89–91], but the Cassini-Huygens mission had upgraded to CCD's of 1024 × 1024 pixel size giving ISS more sensitivity [22][p.418] . ISS studied Titan's haze-layer properties, such as opacity [23] , but also topography and terrain types of the surface [24] .

The Composite Infrared Spectrometer (CIRS) was a direct upgrade from the Voyagers' IRIS instrument (section 3.1). Two interferometers covering mid- and far-infrared wavenumbers from 10 to $1400cm^{-1}$ with resolution of $0.5cm^{-1}$ gave Cassini better performance when compared to IRIS (section 3.1). The finer details of the spectrum became visible, so the separation of molecules became easier and additionally one could now probe deeper parts of the atmosphere. [5][p.91–94]

The Ultraviolet Imaging Spectrograph (UVIS) did spectroscopy both in extreme ultraviolet and far ultraviolet totaling a range of 55 to 190 nanometers. It was not important in the study of the surface, but it detected substances in Titan's atmosphere making it important in the study of Titan's chemistry. [5][p.94–95]

The Visual and Infrared Mapping Spectrometer (VIMS) with a wavelength range of 0.6 to 5 micrometers extended CIRS's range which had a lower limit of about 7 micrometers. For example, this instrument was used to study the reflected light from the atmosphere, and on the night side of Titan it could detect signs of atmospheric lightning. In infrared, VIMS could probe deeper parts of the atmosphere and even see thermal emission of cryovolcanoes on the surface. [5][p.95]

Radar was a crucial instrument as its signals could pass through the atmosphere with 13.78 gigahertz frequency and probe the surface for topography [5][p.96]. Basically, a signal passes through the atmosphere, gets reflected from the surface and is received back by the antenna [5][p.96] . The time until the echo is received is measured. The same antenna was used to send all the obtained data to Earth [5][p.96] . Additionally, SAR (Synthetic Aperture Radar) technology was used [5][p.96] , where the antenna sends pulses rapidly as the orbiter moves, and a whole region gets mapped out which forms an image [25] .

As there are windows in the infrared region where methane, nitrogen or other vapor do not absorb electromagnetic radiation, Titan's surface could be seen with CIRS and VIMS [26][p.66,Table 7b]. UVIS was the key instrument for the study of Titan's atmosphere's chemistry, but it was not designed to study the surface [5][p.94]. Radar created topography maps of Titan's surface revealing topography and possible liquid pools [27] . As scientific data was collected from the year 2004 until Cassini's destruction in Fall of 2017, a clear case was building up for the presence of liquid pools on the surface of Titan.

4. Seas and lakes - Maria and lacūs

In the summer of 2009, Cassini's VIMS instrument pointed at Titan and detected a specular reflection (Figure 6) on the northern hemisphere. It was confirmed to be from a liquid pool [28] . This section focuses on the first confirmation of liquid on Titan between 2006 and 2008 with reviews of studies that were conducted before and after the confirmation.

4.1 Liquid pool confirmation and transfer of liquid between Titan's hemispheres

As Cassini was passing by Titan in 2006, it was observing Titan with Radar in SAR mode by mapping out a slice of surface from the northern latitudes [29] . The

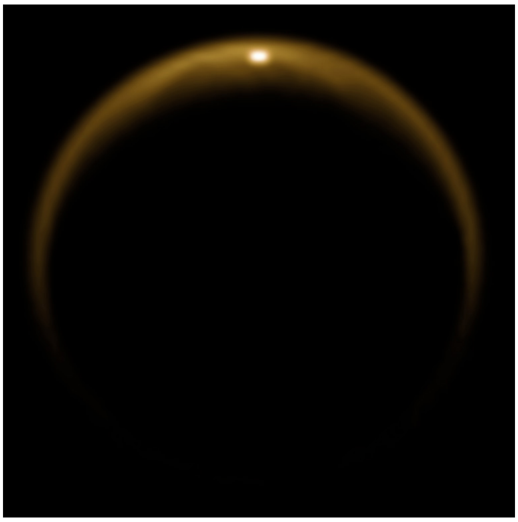


Figure 6: Specular reflection seen on Titan's northern hemisphere by VIMS in 2009.
NASA/JPL/University of Arizona/DLR
https://photojournal.jpl.nasa.gov/catalog/PIA12481

resulting image is seen in Figure 7 which shows darker spots corresponding to lower radar reflectivity [29] . These areas were believed to be liquid filled depressions as there were no apparent wind driven features on them [29] . This subsection focuses on these dark areas and how the distribution of the areas suggests a liquid transfer between Titan's hemispheres.

The darkest and largest areas in the SAR images are called seas (maria) and smaller dark regions are called lakes (lacūs). Some regions are morphologically similar to the dark regions but have the same brightness as the surrounding environment. These bright regions were deemed to be empty basins. [30]

It was also discovered that some of Titan's northern hemisphere's markings had shores and river like features [30] . This gave a clue that the liquid may be transported between lakes and seas, and as Titan progresses through seasons, with changing amount of sunlight, the liquid could also evaporate [30] .

Titan's poles contain about 650 dark basins, but the southern pole has mostly empty bright basins. The exception is one major dark region named Ontario Lacus which shows reseeding shorelines - the liquid is moving. Since the equatorial region of Titan does not show many prominent marks of liquid, it is assumed that the liquid cycles between the polar regions through evaporation and rain. [31]

This exchange has been explained in terms of the seasons of Titan and the long-term evolution of orbital parameters of Saturn and Titan [32] . In Earth's case seasons are caused by the tilt of the planet compared to the ecliptic plane;

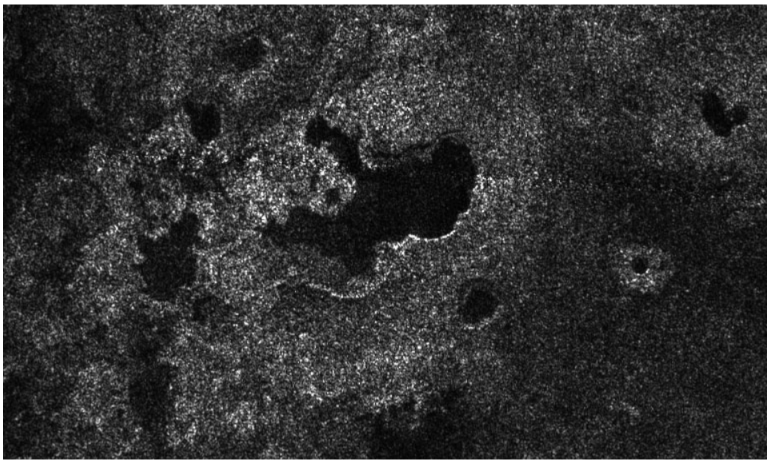


Figure 7: T16 Radar swath of northern hemisphere of Titan showing highly absorbing areas as the darker regions.
Cassini RADAR Team, NASA
https://pirlwww.lpl.arizona.edu/p̃erry/RADAR/#T16

During northern hemisphere's summer the north pole is tilted towards the Sun by 23.5 degrees which increases the intensity and duration of sunlight at the northern hemisphere and decreases these at the southern hemisphere which is facing 23.5 degrees away from the Sun [33] . The tilt stays the same as Earth revolves around the Sun, and after half an year the south is facing towards the Sun by the 23.5 degrees causing the seasons to switch between Earth's hemispheres from the aforementioned case . Earth's orbital parameters - like eccentricity, axial tilt and longitude of perihelion - change on long time scales causing a phenomenon called Croll-Milankovich cycle where the overall climate changes on a timescale of hundreds of thousands of years [34] .

At present times, Titan revolves around Saturn nearly in Saturn's equatorial plane, which keeps a fixed orientation in inertial space when Saturn revolves around the Sun. Therefore, Titan's seasons arise from the orbital motion of Saturn. Titan's southern summers are intense as Saturn is at perihelion then. During Titan's northern summer Saturn has already moved further away from the Sun. [32]

More radiation leads to increased evaporation, so Titan's southern liquid pools have evaporated and volatile substances condense more easily in the northern hemisphere. As Saturn's orbital elements evolve, at some point the procedure reverses and liquid is moved back to the southern hemisphere. The whole liquid cycle from a hemisphere to another and back would take about 60 000 years. Currently Titan's northern polar region yields most of the liquid, and the southern hemisphere has been supplying it for at least 14 000 years. [35]

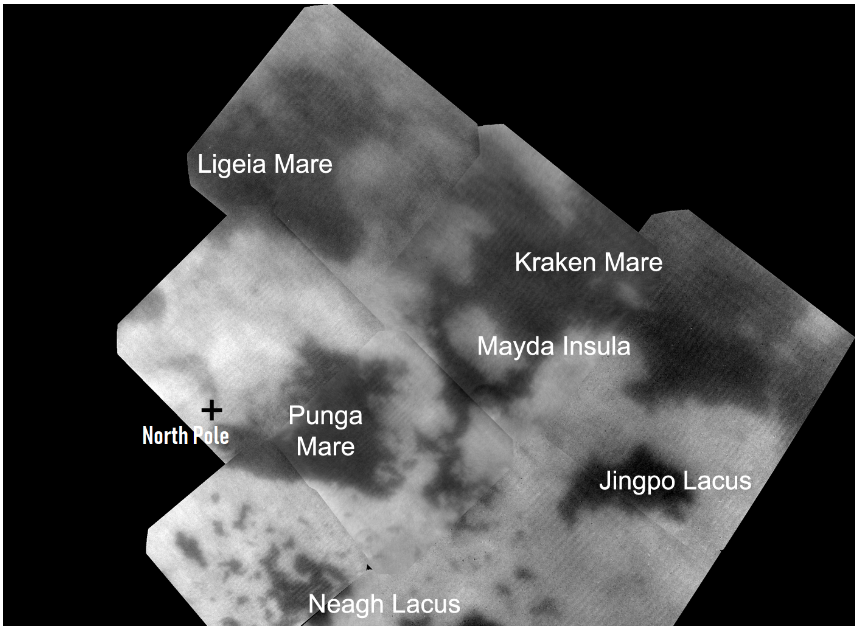


Figure 8: Near-infrared image of Titan's northern hemisphere's seas (PIA 17473). NASA / JPL-Caltech / Space Science Institute
http://www.ciclops.org/view/7732/Birds-Eye-View-of-the-Land-of-Lakes

4.2 Surface area and other features of the major liquid pools

Main properties of Titan's seas and the major lake of the southern hemisphere are given in this subsection, as well as a brief look into the interaction between the liquid pools.

Ontario Lacus (Figure 9) on the southern hemisphere of Titan has an area of $1.6 * 10^4 km^2$ [36] . The largest pools (seas) of Titan are on its northern hemisphere (Figure 8), and the names of the seas are Kraken Mare, Ligeia Mare and Punga Mare with areas of $5.0 * 10^5 km^2$, $1.3 * 10^5 km^2$ and $6.1 * 10^4 km^2$ [26][p.60]. Ligeia and Kraken seas are connected, and all three seas reside locally at the lowest points on the surface with an elevation difference of 8 to 50 meters between each other [26][p.60] .

SAR, altimetry, and stereo photogrammetry - comparison of multiple images of the same region - show that if empty basins exist near a liquid filled pool, the empty depressions are always at a higher elevation [26][p.60, Figure 5], . The formation and evolution of these lakes are hard to model, as some of the empty lakes appear to be hundreds of meters deep. Dissolution erosion - removal of solid matter by liquid induced chemical processes - or sublimation of volatile compounds could possibly explain the excavation holes. These processes have to move large quantity of material through subsurface or to atmosphere to form the deep depressions.

Similar Earth based depressions are comparatively smaller which brings up the question if Titan's conditions are adequate for the excavation. Still, this process does give a hint how the high altitude basins are emptied as the solvent at higher altitude basin could move through subsurface to the lower altitude basins. [37]

Shorelines and river channels were mentioned in section 4.1 but there are also other features around the lakes and seas. For instance, there are signs of dried out deltas on Ontario Lacus where sediment has formed ridges visible in SAR-mosaic images (Figure 9) [38] . Large dried out valleys in the southern hemisphere are indicators of former seas [39] , and as the northern hemisphere received the liquid in a rapid manner, rivers and seas were overflown hiding and removing topography [29] . There are islands (insulae) in the liquid pools such as the Mayda Insula as seen in Figure 8 as well as bays (sinūs) [40] . There also seems to be a region in Ligeia Mare which appears and disappears when observed throughout the years (Figure 14) [41] . This is further discussed in section 5.1.

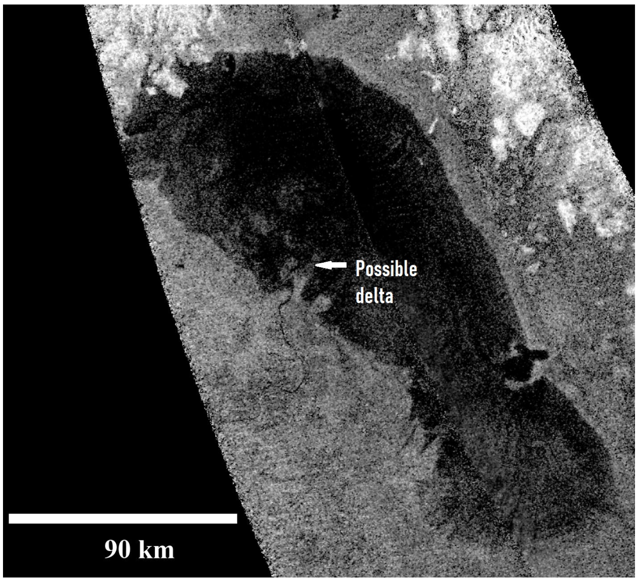


Figure 9: Ontario Lacus imaged with Radar showing a possible delta feature.
NASA/JPL-Caltech
https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA13172

4.3 Depth profiles and chemical composition

The study of the liquid composition of some liquid pools of Titan was conducted with Cassini's Radar. The data obtained with Radar was also used to determine depth profiles of the liquid pools - known as bathymetry. These subjects are discussed in this subsection with Ligeia Mare functioning as an example of a target that has been studied with bathymetry.

The echo mapping by Radar was done by listening to the signal's echo from the liquid's surface and from the bottom of the pool and measuring the time difference between the two echoes. As Cassini moved across the target liquid pool, multiple bursts of signal were sent to get depth values across the area. By combining the results, a bathymetric map - a liquid depth figure - is formed. Echoes also lose some energy due to absorption by the liquid and that knowledge can be used to determine the chemical composition of the lakes as absorption strength depends on the liquid composition. [42]

The study of Ligeia Mare's depth [42] included data processing techniques such as extrapolation of the received bandwidth from 4.25 megahertz to 9.0 megahertz to increase the sharpness of Radar's resolution - surface-subsurface peak maxima became more localized and distinguishable from the noise level. Waveform altering methods such as the Kaiser-Bessel window were also used to further increase the quality of the data at shallow parts of the sea. Figure 10 shows one burst of altimeter signals with the liquid surface echo as the highest reaching peak and the seafloor echo's peak at 18 microseconds. Figure 11 depicts the result from multiple bursts which formed the depth profile of Ligeia Mare as latitude's function. Figure 11 indicates that the lowest point is at approximately 160 meters from the surface and that there is a third-order correspondence for the shape of the seafloor through that flightpath. [42]

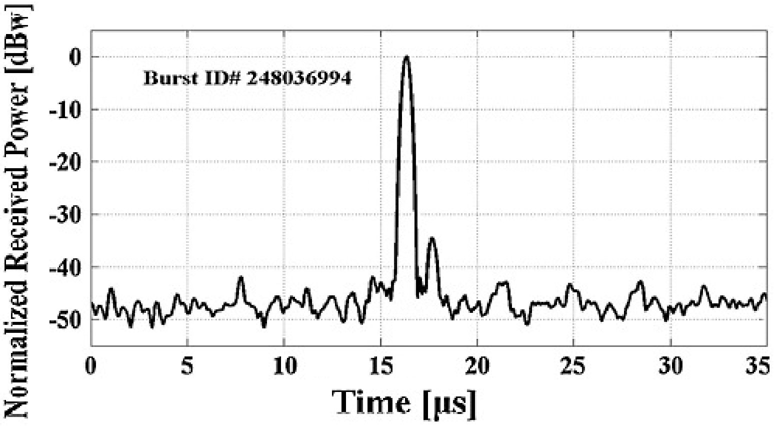


Figure 10: Single radar measurement over Ligeia Mare with echoes received after different delay times. The highest reaching peak at $16\mu s$ is from the liquid surface, and the echo from the seafloor is the peak around $18\mu s$.
Figure from reference [42] [Used with permission through Rightslink]

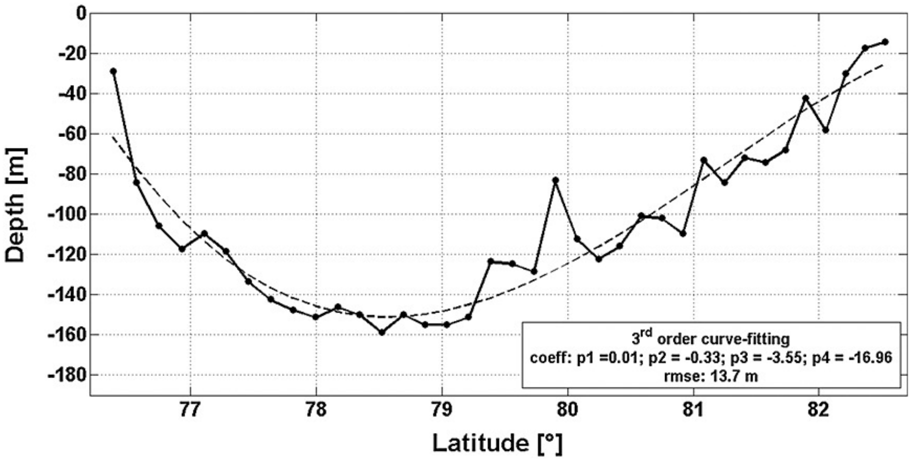


Figure 11: Bathymetric map of Ligeia Mare.
Figure from reference [42] [Used with permission through Rightslink]

Still, it is highly probable that Ligeia Mare is deeper at some other spot as the aforementioned flightpath gave only one bathymetric map [42] . One depth measurement of Kraken Mare did not even yield a seafloor echo [27] . It is concluded that the seas can be even so deep that Radar could not measure the depth.

Simulations can be used with different liquid parameter combinations to fit simulated waveforms to the obtained Radar data. The best fitting waveform gives an estimate for certain parameters, like the loss-tangent value. [43]

The loss-tangent determines the loss of a signal's energy when the signal passes through a liquid [43] . It changes depending on the liquid's composition and therefore one can put constraints on composition when measuring it. Different mixtures are tested in laboratories to find a combination that yields a similar loss-tangent as the one measured from Titan's liquid pool. [44]

The study by Mastrogiuseppe et al. [43] , showed that the loss-tangent was somewhat different for the northern and southern parts of Ligeia Mare - meaning that the composition may vary within one liquid pool. The average loss-tangent in Ligeia Mare was $4.4 \pm 0.9 * 10^{-5}$ [43] . Table 1 has loss tangent values and the estimated methane, ethane and nitrogen fractions for some of the liquid pools of Titan.

Notably, methane and ethane percentages seem to vary between regions featured in Table 1. Ontario Lacus in the southern hemisphere has notably less methane than the other areas which all are in the northern hemisphere - Baffin Sinus is a bay in the northern hemisphere of Titan [45] . Ontario Lacus also has a higher ethane concentration. This indicates that more volatile components, such as methane, have begun to be transported out of Ontario Lacus by evaporation, increasing ethane concentration [45] . The set of locations is quite limited in the

Table 1: Loss tangents and chemical mole fractions of liquid pool areas on Titan (errors in 1-sigma) [27],[43],[45]

Area	Loss-tangent	Methane [mol-%]	Ethane [mol-%]	Nitrogen [mol-%]
Ligeia Mare	$4.4 \pm 0.9 * 10^{-5}$	71	12	17
Punga Mare	$3 \pm 1 * 10^{-5}$	80	≈0	20
Baffin Sinus	$3^{+1}_{-2} * 10^{-5}$	80	≈0	20
Ontario Lacus	$7 \pm 3 * 10^{-5}$	59	28	13

table as most of the liquid pools of Titan are yet to be studied in this manner.

In principle, Cassini's VIMS-instrument could also be used to constrain the composition of the lakes but infrared light that passes through Titan's atmosphere is efficiently absorbed by liquid methane and ethane [46] . Therefore, precise composition estimations of Titan's lakes are hard to make with infrared based instruments. For one to accurately study Titan's lakes with an instrument such as VIMS, the pools need to be either shallow or contain a layer of sunlight reflecting particles so that some infrared photons scatter towards the orbiting instrument before being fully absorbed [26][*p*.70], [47] .

4.4 Liquid currents on Titan driven by tidal forces

Liquid water in the seas of Earth show movement caused by multiple different sources such as the Coriolis effect, wind, convection induced by temperature and salinity differences as well as tidal forces of the Moon and the Sun [48] . The following three subsections handle the subject of Titan's liquid currents mostly through description of simulations and model results.

As Titan's orbit is slightly eccentric [2][Table 1.4], Saturn's gravitational force is varying slightly which affects the seas and lakes [49] . With the use of the Bergen Ocean Model which describes circulation of oceans, and with parameters such as viscosity of methane and ethane, liquid densities and changing solar heating due to seasons, Tokano [49] made simulations of tidal currents of Kraken Mare and Ontario Lacus.

As Titan goes through different orbital phases around Saturn - perikron and apokron -, the vector of tide-generating force moves counter-clockwise [49] . It is not uncommon on Earth that water moves clockwise in lakes when the vector of tidal force moves counter-clockwise [49] , and this is also seen in the tide simulations of Titan's Kraken Mare [49] . The northern parts of Kraken Mare experience the largest tidal variability of 4 meters in the model [49] . Tides cause liquid height change of 2 to 5 centimeters in the Baltic Sea on Earth [49] , so the greatest tides of Titan are notable.

The same model also predicts that tidal currents of Ontario Lacus do not rotate but move back and forth, a motion that is estimated to be caused by the elongated shape of the lake; Other smaller and elongated lakes of Titan are estimated to act like Ontario Lacus [49] . Still, further studies with newer models predicted that Ontario Lacus would also experience the clock-wise movement of liquid with the southern region effected mostly by the tides - with the maximum liquid surface change of 0.56m [50] .

Velocities of the currents were predicted to be few centimeters per second to even tens of centimeters per second in tight areas such as straits, but by taking into account Titan's crust's influence on the liquid, the actual velocity would be closer to 0.2 centimeters per second [49],[51] . On Earth, Nova Scotia's tidal currents have velocities of around 1m/s [52] , so Titan's tidal currents are comparatively slower.

4.5 Liquid currents driven by wind drag

If tidal forces, evaporation and temperature gradients are not included, then the Bergen Ocean model can be used to model liquid movement caused by surface winds' drag force [53] . The results of such model's usage with Titan is described in this subsection.

The surface wind's effect on liquid pools containing 40% of methane, 40% of ethane and 20% of nitrogen has been modeled by Tokano et al. [53] . The surface wind data was obtained from Tokano's former model of hydrostatic general circulation [54] . Surrounding topography of the liquid pools were not considered for simplicity. The surrounding topography would cause more local wind systems to form that in turn bring more variables into the simulation [53] .

The model's wind velocities did not exceed 1 m/s and the wind current tended to follow a spiral pattern during Titan's summer solstice, as seen in Figure 12a. Liquid does not follow the wind's direction, as seen when comparing Figure 12a and Figure 12b, due to the Coriolis force on Titan [53] . Combination of the Coriolis effect and wind forcing forms an Ekman spiral in a liquid [48] .

The Ekman spiral is formed when the surface layer of liquid is deflected sideways away from the wind's direction by the Coriolis effect. The movement of the surface layer causes a drag force on the layer below it making that layer move towards the same direction as the top layer but with reduced velocity. Every layer is affected by the Coriolis effect, so the second layer is also deflected sideways. The continuation of this forms a spiral with every layer moving slower than the one above. The net current of this is towards the side of the surface wind's direction, and this explains the difference between wind's direction and the surface liquid's direction between Figures 12a and 12b. [48]

The Ekman spiral causes an overall current from the eastern side of Ligeia

Mare all the way to the southern end of Kraken Mare (Figure 12b) - the current gets deflected and slowed down by islands and shores along the way [53] . The velocity of the sea surface would be around 3 cm/s [53] . If the surface wind is weaker during different seasons, the flow of liquid becomes more random and the overall current disappears [53] .

Sea depths vary within and between each sea of Titan causing the seafloor currents to become weaker and more randomly orientated [53] ; An exception is at the connection point of Ligeia Mare and Kraken Mare, where the velocity of the current is larger and directed towards Kraken Mare [53][Figure 9] . This is explained by the different altitudes of Ligeia Mare and Kraken Mare [53] . Liquid flows from the higher basin to the lower one without the wind affecting the movement notably [53] . If the seafloor currents move at several centimeters per second pace, the currents could move gravel particles [55] . The conclusion from Tokano's model [53] is that the currents can move micrometer scaled sand particles as the seafloor velocities of the current would be only some millimeters per second.

4.6 Liquid currents driven by temperature differences and rain

In this subsection, both thermally and rain driven current models are reviewed.

Hydrocarbons show a density decrease as the temperature increases, meaning that as the seasons change on Titan, hydrocarbons could sink and rise causing vertical mixing. Between Titan's spring and summer, lakes heat up and the lake bottom stays at lower temperatures, warming up slowly. From autumn to winter the surface cools quickly and sinks because the liquid at the bottom is still warm and less dense. [56]

The horizontal currents depend on the power of the solar heating at different depths of the lakes. If the solar radiation causes heating only on the surface layers of the liquid, then no temperature differences are formed between horizontal regions - equilibrium stays and no currents form. But if the solar radiation warms deeper liquid layers, then the temperature at shallow shores increases and a difference forms between the shore and the center of a liquid pool - a current forms driven by the temperature gradient. The surface temperature of Titan varies with the seasons and so does the surface current's velocity. [56]

Tokano's model [56] features Kraken Mare as the study target. The surface current velocities there change with seasons by approximately 0.6 cm/s to 1.8 cm/s and at the seafloor 0.2 cm/s to 1.1 cm/s with a vertically isothermal model of the sea [57][Figure 8a] . In the case of a highly absorbing surface the current velocity is approximately between 0.1 cm/s to 1.0 cm/s and at the seafloor 0.5 cm/s to 0.8 cm/s [57][Figure 8b] . Figure 13 shows an example of the thermally driven currents

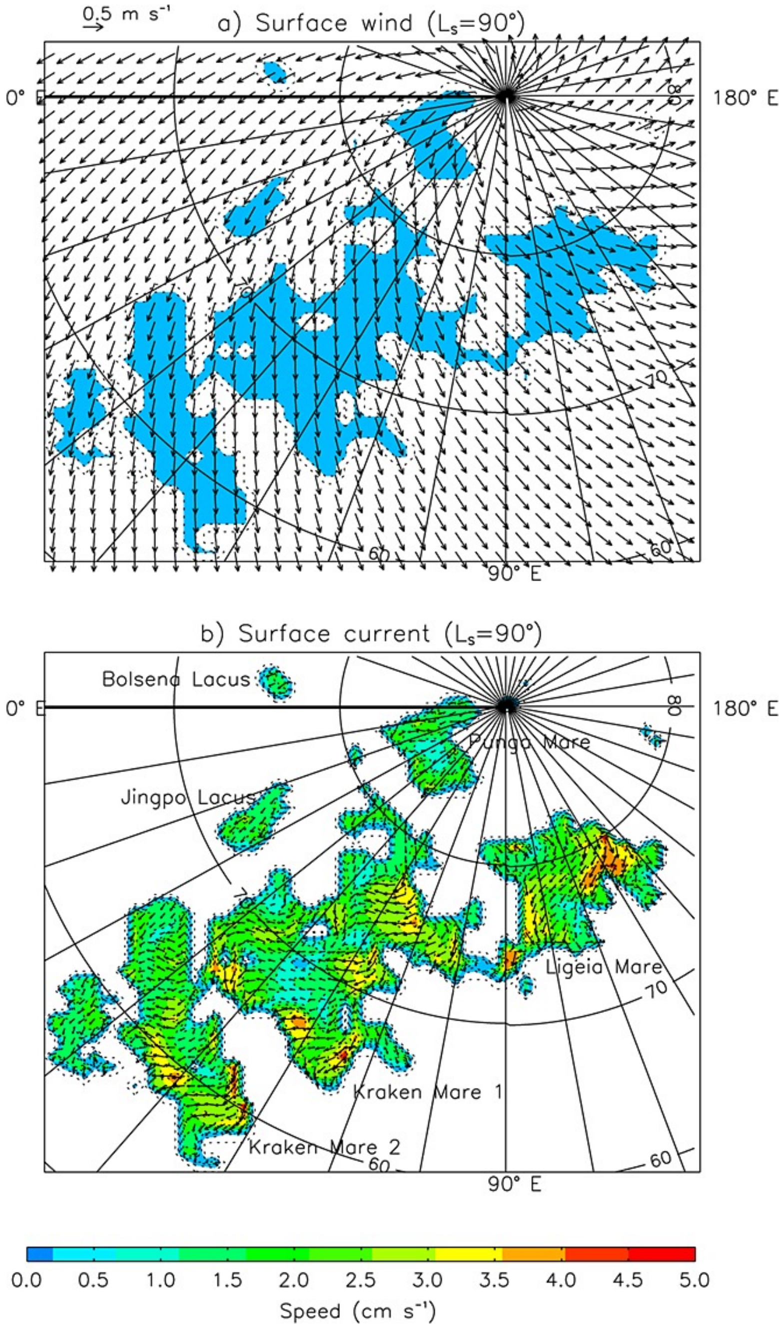


Figure 12: Wind driven liquid currents of Titan's northern regions.
a) Surface wind velocities and directions.
b) Liquid surface current velocities and directions.
Figure from reference [53][Used with permission through Rightslink]

during Titan's summer solstice. The currents represent a rotational motion due to the temperature gradient between shore and middle of a liquid pool and also because of the Coriolis effect [57],[58] . Additionally, surface currents are directed inward and seafloor currents outward due to the temperature gradient [57],[58] .

Methane evaporation and rains generate currents too. It is estimated that methane rainfall occurs more frequently at higher latitudes and the extra methane causes density differences between northern and southern parts of the seas. This difference would be balanced by moving the surface liquid layers southward and the liquid at the bottom towards north. [57]

With low amount of rain, the surface velocity of Kraken Mare is induced in this way to be between 0.1 cm/s and 1.2 cm/s and at the seafloor the range is 0.9 cm/s to 1.2 cm/s. This effect also forms an overall surface current from the east side of Ligeia Mare to Kraken Mare's southern parts during northern hemisphere's summer [57][Figure 14a] - like in the wind model as seen in Figure 12b.

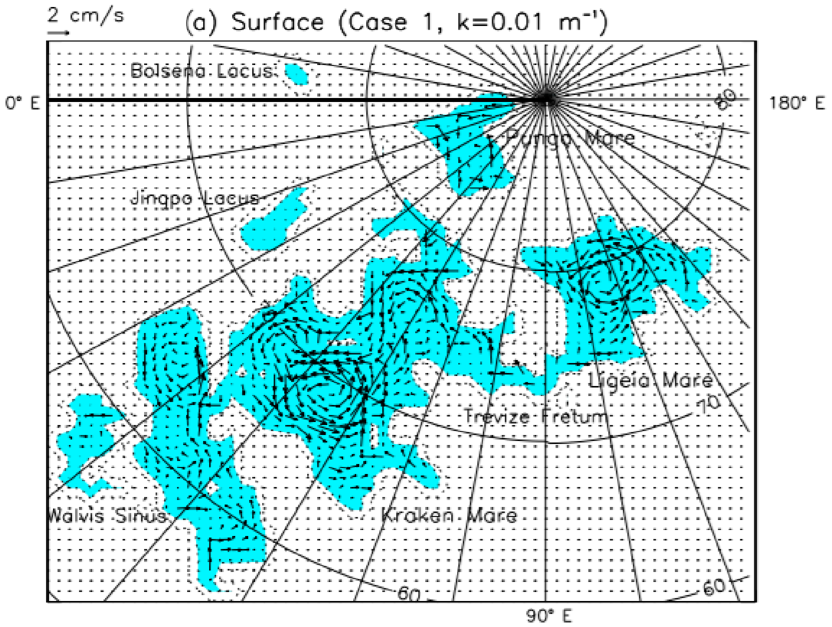
If there is abundant rainfall and the whole northern hemisphere has the same liquid surface density, no currents form between different liquid pools but there are still currents forming in each sea separately. With changing seasons, the model predicts that Kraken Mare's current velocity would vary between 0.2 cm/s to 1.2 cm/s and close to the seafloor current the velocity would be between 0.1 cm/s and 1.8 cm/s. During the summer, same sort of liquid surface movement is expected as in Figure 13 but it is considerably weaker and the seafloor currents are non-existent [57][Figure 15] .

The results from the models discussed in the previous three subsections should be considered as approximations to Titan's more complex current system. In reality, all the aforementioned driving forces act simultaneously on the lakes and seas.

4.7 Waves on the liquid surface

The above three subsections described that the surface liquid layers are in movement on Titan's liquid pools. This subsection focuses on the study of wave formation on Titan's sea surfaces.

Cassini's Radar has been used to study the sea surfaces of Titan to determine amplitudes and wavelengths of possible waves. This requires statistical analysis of the energy loss of echoes from the liquid surface; The analysis separates the signal into a coherent signal and an incoherent signal. With low liquid surface roughness the coherent signal is dominating, and with high roughness the power of incoherent signal increases as the perturbation of the liquid surface affects the pulse. Both echo types together yield information on the amplitude and the wavelength. [59]



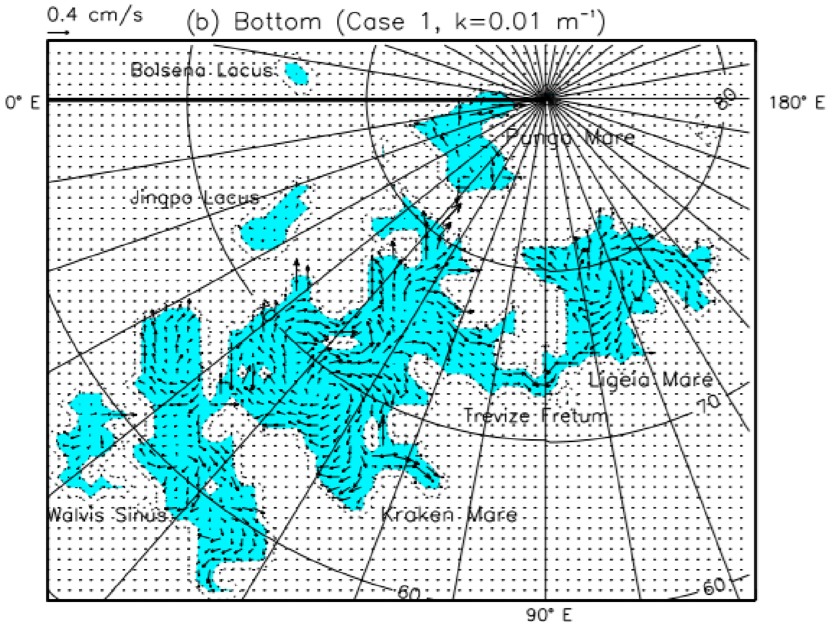


Figure 13: Figures of thermally driven currents in Titan's northern hemisphere in the case of the liquid being in thermal equilibrium vertically.
a) Surface liquid current velocities and directions.
b) Seafloor liquid current velocities and directions.
Figure from reference [57][Used with permission through Rightslink]

Composition of the lake surface does also affect the result as substance's permittivity affects the signal [59] . Laboratory tests have estimated the values of the relative permittivities for methane, ethane and nitrogen at Titan's conditions with ethane receiving the highest value of 2.0, nitrogen the lowest 1.5 and methane the middle-ground 1.73 [60] .

The modelling yields a decreasing roughness when the relative permittivity parameter is lowered from 2.0 to 1.5 - realistic relative permittivity of the sea surfaces should lie between 1.73 and 2.0. Lower roughness indicates lower wave heights and longer distances between waves. From the radar signal the estimate for Ligeia Mare's wave height was between 6.0 to 8.5 millimeters, and for Kraken Mare and Punga Mare 8.8 to 10.0 millimeters. [59]

Another way to quantify the size of the waves is to look at the effective slope which is the wave roughness value divided by the distance where two waves are identified as separate ones - approximately half of the wavelength of the liquid. This gave results of 0.5 to 2.3 degrees for Ligeia Mare, 1.1 to 2.4 degrees for Kraken Mare and 1.1 to 4.9 degrees for Punga Mare. The waves on Ligeia and Kraken seas are weaker when compared to Punga Mare's maximum of 4.9 degrees. [59]

Both wind and gravity generate waves, and on Titan's surface winds are estimated to create capillary waves with a wavelength of under 10 millimeters, while gravity would create waves with a wavelength of over 100 millimeters [61] . Punga Mare's wavelength varies between 60 to 100 millimeters meaning that the waves there could be generated by some other mechanism or combination of both the wind and gravitation. For Ligeia Mare and Kraken Mare, the wavelength mostly exceeds 100 millimeters, so gravity could be causing waves on these seas. [59]

The aforementioned results come with a problem of statistics. More extreme waves may have been included in the original data but these were lost in the study when statistical methods were used to determine the coherent and incoherent signals [59] . The data for the wave estimations was collected during northern Titan's early summer and the waves may differ between different seasons as Titan's surface temperature and winds evolve [59] .

4.8 Titan's potential for astrobiology

As discussed in the previous sections, liquid and organic compounds exist on Titan's surface. The focus of this subsection is to look at Titan's conditions and requirements for the formation of life.

On Earth, life depends on at least four main conditions. *A favorable temperature* is needed to keep water in the liquid phase and chemical bonds within and between molecules intact. Water also functions as a *solvent* which transports substances and allows those substances to interact chemically. For life, the interaction between molecules may be usable in *energy production* or in tasks that are driven by enzymes. Lastly, DNA (Deoxyribonucleic acid) is used to store genetic information, and for the reproduction of a lifeform the structure of DNA allows duplication of the information. [62]

Titan's surface conditions were estimated to be around 94K temperature and 1.5 bar pressure using data from the Cassini-Huygens mission [5][*p*.130, Table 5.1]. This is a problem for water based lifeforms as water is in the solid phase in Titan's conditions [63] . Not even tardigrades, which are extremely resilient to harsh conditions [64] , could survive on Titan. The method of survival in harsh conditions for creatures such as tardigrades is to lay dormant until conditions get better [65],[66] but if the requirement for life is to exchange energy with the environment and reproduce, then these microscopic creatures would not be alive on Titan.

It follows, that lifeforms need to replace water with something that is in liquid phase on Titan. Methane and ethane are fair candidates as these compounds can provide solubility for other components - such as cyanogen (C_2N_2) or carbon dioxide (CO_2) [62][p.3, Table 2]. Other compounds, like long hydrocarbons and nitriles, are formed in Titan's atmosphere through photolysis and these compounds could be dissolved into methane rain and transported to the lakes with the rain [5][*p*.54–55], [6][*p*.94] .

Some compounds, such as acetylene, can be deconstructed to release energy as methane rain brings these molecules to the lakes. An exothermic reaction for acetylene is as follows [62][p.3, Table 1]:

$$C_2H_2 + 3H_2 \rightarrow 2CH_4,$$

where acetylene (C_2H_2) is combined with three hydrogen molecules (H_2) - present in Titan's atmosphere [6][*p*.88, Table 4.4] - forming two methane molecules (CH_4). The reaction releases about 79 kilocalories per mole of energy [62][p.3, Table 1]. Photosynthesis produces glucose with a net energy of 117 kilocalories per mole on Earth [67] . The acetylene based reaction is not as efficient, but Titan's atmosphere also reduces illumination of the surface through absorption and scattering in the optical wavelength range [6][*p*.104]. Therefore, Earth based photosynthesis would not work efficiently on Titan as different chlorophyll variants function only in optical and short-infrared ranges [68] - although, Titan's atmosphere has a transparent window around the wavelength of 830 nanometers [5][*p*.59], which is in range of anoxygenic photosynthesis [68] .

Earth based lifeforms use enzymes to speed up chemical processes and to generally function [69] . Enzyme reactions in organic solvents have been studied, [70] but this does not guarantee that enzymes work in Titan's conditions - enzymes can barely function at temperatures lower than zero Celsius [71] . The enzymes on Earth also require elements such as iron, copper and zinc [62][p.4], and the availability of these elements on Titan is still an open question [62][p.4]. If there is a low abundance of metals in Titan's lakes, recycling of the sparse elements would be an option for the lifeforms, but water molecule clusters could also be used as a substitute compound for catalytic reactions [62][p.4] . For example, reduction-oxidation reaction can be driven by water clusters as electrons are transferred between other molecular structures with the assistance of the water clusters [72] .

To form molecular clusters, the thermal energy of a molecule must be lower than the binding energy between molecules. Presuming that the lakes are at the same temperature as the surface (94K), water molecules in the lakes would have a thermal energy of about 1 kilojoule per mole [62][p.4] . Hydrogen bonds have binding energies of 5 to 30 kilojoules per mole [62][p.4]. As the thermal energy of a water molecule in Titan's liquid pools would be lower than the hydrogen bond between water molecules, water could form clusters.

As for the genetic information, laboratory experiments using Titan like atmospheric properties have shown that chemical products of methane and nitrogen could be formed in the upper atmosphere through electron collisions [73] . High-velocity electrons break chemical bonds of methane and nitrogen molecules which then recombine to form more complex molecules [74] . The tests used plasma discharges which produced compounds such as adenine, 2,4-diaminopyridine, uracil, cytosine and isocytosine. For example, uracil and 2,4-diaminopyridine could form a base pair [73] - chains of base pairs form long molecules such as DNA [73] . Molecules 2,4-diaminopyridine and xanthine - which has been found in meteorites - could also form a base pair [73] .

In human DNA the connector between sections is the O-H-N (oxygen-hydrogen-nitrogen) bond relying on hydrogen bonds to hold together. But on Titan the N-H-N (nitrogen-hydrogen-nitrogen) variation may be more feasible - oxygen is not abundant in the atmosphere [6][p.88, Table 4.4]. As stated above, hydrogen bonds are strong enough at Titan's surface temperatures to hold, so this way the base pairs remain intact. [73]

The DNA of a Earth based lifeform consist of long chains of base pairs, and the sequence of base pairs holds information for the production of compounds such as proteins [75] . The base pair chains must be protected from the surrounding elements as these may break and change the chain which leads to incorrect production of compounds [62][p.8] . In practice, a membrane structure separates the life-sustaining molecules from the environment [76] . Human cells are made of phospholipids which function properly in water [62][p.8] but as Titan's lakes are not filled with water, an alternative structure is needed.

Acrylonitrile (CH_2CHCN) molecules on Titan have been detected with ALMA (Atacama Large Millimeter Array) [77] , and this molecule can form cell-like structures in Titan's conditions [62][p.8] . The membrane - azotosome - consist of short chains of the acrylonitrile with reinforcing structure made of methane [62][p.8] . As long as this structure allows for the exchange of important molecules through it - like acetylene for energy production - a system separated from the environment can function.

As a summary, a solvent in the form of methane is present, energy can be produced with exothermic deconstruction of acetylene, cell membranes can be produced in the cold temperatures by using acrylonitrile molecules and genetic information can be stored through compounds formed in the upper atmosphere. Currents in Titan's seas could also transport lifeforms to different environments with different conditions. This broadens biodiversity as lifeforms can find new resources - for example, in the form of seafloor thermal vents as these bring up usable elements from under the surface [78] .

5. Future study of Titan

Even though the Cassini-Huygens mission gathered a great amount of data about the lakes and seas of Titan, some questions remain open; One is the disappearing region seen in Ligeia Mare - mentioned at the end of section 4.2. This section describes that phenomenon. The remainder of the section is devoted to a possible future mission to Titan which could directly study the liquid pools by submerging into the liquid.

5.1 Magic islands - Changing region in Ligeia Mare

There is an area in Ligeia Mare appearing and disappearing with time as seen in Figure 14. Varying liquid height, currents, waves, floating material, and nitrogen bubbles under the liquid surface have been suggested as possible explanations so far, and this subsection reviews these hypotheses. [41]

Images of Ligeia Mare were taken by Cassini's Radar-instrument, and errors and artefacts should first be considered. One reason for artefacts could have been the ambiguity of the received signal [41] . If a sent signal does not return before a second pulse is emitted towards the next region, the radar system cannot distinguish the returning signals of the two pulses [79] . When the first signal arrives back to the radar system shortly after the second pulse is emitted, the second target area will appear to be at a higher altitude if the first pulse's return signal is seen as the second pulse's one [79] . If the radar system makes a mistake due to the ambiguity of the signals then the result is an incorrect approximation of the surface elevation which would appears as the transient feature in Ligeia Mare's case [41] . Still, this type of artefact was deemed unlikely [41] . A random dysfunc-

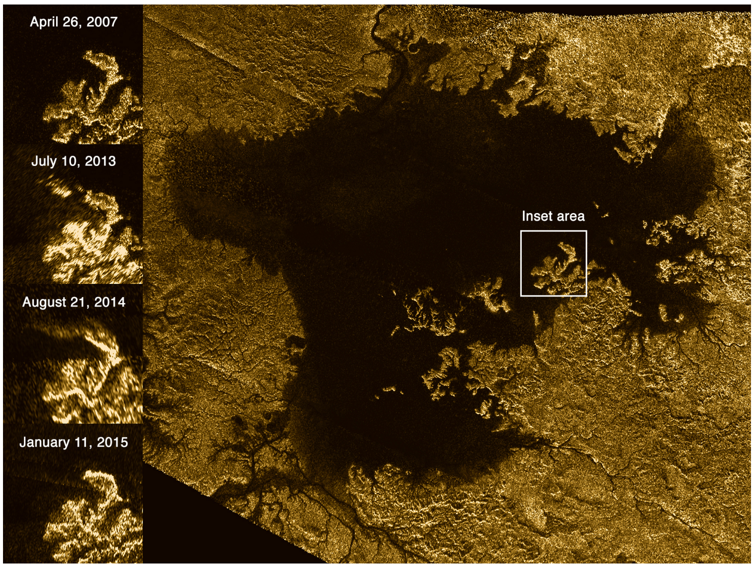


Figure 14: Appearing and disappearing feature in Ligeia Mare, imaged with Radar.
NASA/JPL-Caltech/ASI/Cornell
https://photojournal.jpl.nasa.gov/catalog/PIA20021

tion can also be excluded as the detection of the feature was done multiple times at the same spot with years between each scan [41] .

A permanent land structure surrounded by liquid has also been considered as the cause for the feature [80] . The average normalized radar cross section (NRCS) quantifies the received radar signal power over the power in the case of the signal being backscattered isotropically - equally to every direction [80] . If the feature area was a permanent geophysical structure, decreasing incident angle - flying closer to the targets zenith - would increase NRCS monotonically. Consequently, as the incident angle decreases the NRCS value must not decrease at any point. The monotonic increase of NRCS was not seen in the transient feature's case, as twice the area appeared brighter during a high incident angle flyby when compared to a lower incident angle's NRCS value [80] . It was concluded that the feature is not consistent with a permanent geophysical structure [80] .

Waves and currents could in principle explain the phenomenon [41] . The wave height at Ligeia Mare was approximated to be about 7 millimeters (section 4.7), but that may increase if the region's land topography forces the surface liquid to flow faster, as would happen at straits (section 4.4). Hofgartner et al. [80] deem waves the most likely cause for the phenomenon but currently available data cannot unambiguously confirm this.

It was mentioned in section 4.6 that the densities of liquid hydrocarbons decrease when temperature increases. Sunken frozen material could start to rise and appear on the sea surface or free float in the liquid when the surrounding density increases. This solid material could then reflect radio signals and cause the phenomenon [41] . Still, the feature appears always at the same location which means that either the material only moves vertically, or it is continuously replenished. Currents were mentioned to be strong enough to move fine sand in section 4.5, so the free floating material should be transported also horizontally.

Hofgartner et al. [80] got NRCS values of the nearby land and the surrounding sea near the transient feature, and made models of the NRCS change as function of the incident angle. Couple of the NRCS values of the transient feature fit well with the land area's NRCS values which indicates that floating material on the sea surface could in principle have originated from the land and it is dry [80] . The remaining NRCS values from the transient feature fit well with the NRCS values from the seafloor which suggests that the seafloor also may be causing the phenomenon [80] .

Because the feature appears and disappears with time, this would imply that the sea floor is evolving. The seafloor would need to appear and disappear as the sea level changes to explain the transient feature. But the nearby land's shoreline would in this case also show a change. This was not detected, but it is possible that the edge of the seashore is steep and the change of sea level is therefore not noticeable. Also, the area of the transient feature could be shallow and a small sea level change could therefore be enough to make land appear at the transient feature's area. More information about the region's topography and bathymetry is needed to further evaluate if the sea elevation change is the reason for the transient feature. [80]

Another idea was that the seafloor's material and roughness could change with time. But as the feature appeared and disappeared, the roughness and material would also have to change between more scattering and less scattering variants which was assumed unlikely. Therefore, the seafloor of the transient region should not be causing the phenomenon. [80]

A nitrogen bubble based hypothesis has also been studied and deemed as a likely explanation. In the process of homogeneous nucleation gas exsolves in the liquid combining into bubbles. In the process of heterogeneous nucleation the bubble formation happens around a solid nucleus. With Titan's conditions in mind, the chance of the homogeneous nucleation occurring for nitrogen was presumed to be extremely unlikely as it would take billions of years to form one bubble. When considering the heterogeneous nucleation model, it was mentioned earlier that there could be solid matter floating in Ligeia Mare which could give nitrogen a surface to form bubbles on. The solid seafloor could also function as the nucleation surface. Therefore, the heterogeneous nucleation model could in principle work to form nitrogen bubbles. [81]

With a 8:2 ratio of methane and nitrogen liquid, the expected diameter for a single nitrogen bubble would be 1.4 centimeters. As a bubble rises through the liquid its diameter would increase to 3.6 centimeters due to decreasing pressure of the liquid. At that diameter, Cassini's Radar could detect the bubble as the signals sent by Radar had a wavelength of about 2.2 centimeters. [81]

Even millimeter sized bubbles can form centimeter sized ones by merging when rising through the liquid. This requires a concentration of one millimeter sized bubble per 10 cubic centimeters to reach a 1 centimeter end radius after rising for 100 meters. This formation could be even more efficient if hypothetically there were turbulence causing seafloor thermal vents in Titan's seas [81] - thermal vents being spots where hot liquid is released from beneath the seafloor surface [78] .

Bubbles should be seen in Radar data as weakening of the echo. The reflected flux was estimated with and without bubbles to get so called Bubble Radar Signal Amplification (BRSA) parameter. Fitting of different bubble density models to the resultant BRSA gave an estimate of 100 bubbles with one centimeter size within one cubic meter which was qualified to be the cause for the Magic island phenomenon. [81]

For now, the nitrogen bubble hypothesis, waves or floating solid material are the best explanations for the Magic island problem but future expeditions with nautical devices such as submarines could further shed light on this complex phenomenon.

5.2 Future mission concepts to Titan and the Titan Submarine

The Cassini-Huygens mission raised many new first order science questions about Titan - for example, what are the precise conditions under the liquid surface. A new spacecraft is mandatory for this, and this subsection focuses on one candidate which is already being developed - the Titan Submarine.

A serious concept for a Titan submarine was formed during 2014, but even before that there were other project ideas to further study Titan's lakes and seas. A combined effort of NASA and ESA formed a proposal between 2008 and 2009 for a three-device package called Titan Saturn System Mission (TSSM) [82][*p*.2] - also known as TandEM, the Titan and Enceladus mission [83] . The proposal featured an orbiter, a Montgolfier - a hot air balloon - and a lake lander [82][*p*.2] . The plan was to study compounds of the liquid pools and the evolution of Titan as a whole [82][*p*.2], but Europa-Jupiter System Mission was chosen over TSSM [83] . The technology for TSSM was to be further developed by NASA but the studies

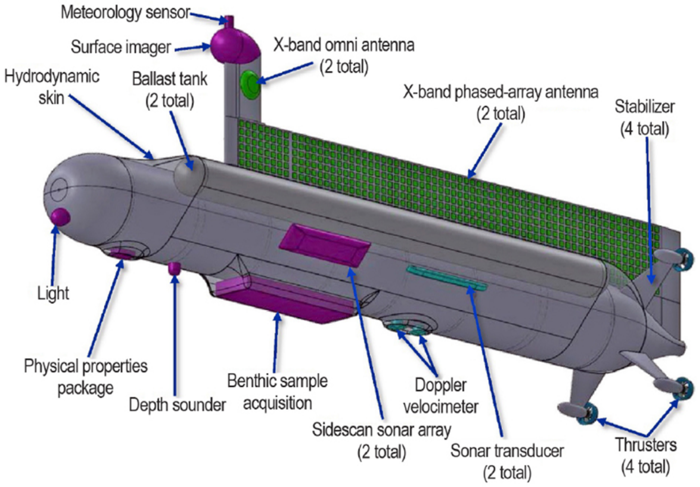


Figure 15: Titan Submarine's 3D-model with its instruments.
NASA
https://www.nasa.gov/feature/titan-submarine-exploring-the-depths-of-kraken-mare/

concerning TSSM are halted at least from the side of ESA [84] .

Another notable proposal was the Titan Mare Explorer (TiME) by NASA [82][p.2]. Ligeia Mare would be this mission's target with a list of studies concerning liquid movement and thermodynamical properties [82][p.2]. TiME was a candidate for a low cost NASA mission but the Mars Lander InSight was chosen over it [85] .

The aforementioned proposals had developed concepts which the scientific plan for the Titan Submarine mission was partly based on. The basic premise was to use TSSM's scientific targets of Titan's evolution and chemical composition, but also to investigate the seas by submerging and doing measurements under the liquid surface. [82][p.3–4]

Its scientific payload would contain the Depth Sounder (DS), the Sidescan Sonar (SS) and the Undersea Imager (UI) - these three were designed for the study of seabed morphology. On the liquid surface, the Surface Imager (SI) would be used in shoreline imaging and the Meteorology Package (MET) with the Navigation device (NAV) in meteorology studies. The Physical Properties Package (P3) would do the measurement of thermodynamical parameters and other liquid based measurements. [82][p.4]

After arrival to Titan, the submarine would begin by studying the connecting part of Ligeia Mare and Kraken Mare. It was described at the end of section 4.5 that the strait is expected to have currents which could be verified by the submarine. The overall goal for liquid current studies would be to understand the transport of methane throughout Kraken Mare's area. The other instruments would also conduct measurements throughout the submarine's operational time. [82][p.5]

The average speed of the submarine would be 0.3 m/s - with the maximum being 1.6 m/s. This would be obtained with a thrust generated by four 100 watt motors connected to propellers. The benefit with the four propeller-system is redundancy in a case of a motor failure and an overall good control of the submarine. To power the motors and other devices, two 430 watt Stirling Radioisotope Generators would be used. The generators would also keep the submarine at operational temperatures. [82][p.7,8,10]

The hull's shape would be a long cylinder as seen in Figure 15, coated with titanium, with a resistance to pressure set to 10 bar - the pressure at about 1 kilometer depth in Titan's sea. [82][p.10]

For communication, a microwave antenna would be installed on top of the submarine [82][p.8] . The antenna's energy consumption would be about 250 watts when in full use, and it would also cause drag because of its long form [82][p.8]. An orbiter is not necessary for the submarine to communicate with Earth but then Earth needs to be sufficiently high in Titan's sky [82][p.7] . As the seas of Titan are on the northern hemisphere, Earth will be too far south for direct communication around the year 2026 [82][p.3] . The next good launch window is around the year 2047 as communication between Earth and the submarine will then be possible and Titan's summer gives continuous lighted conditions to the northern region [82][p.7] . A second model of the mission does include an orbiter for flexibility concerning the communication with Earth [82][p.13] .

The whole package would cost 700 million dollars and as of year 2015, the project has obtained NASA's technology readiness stage of 6 [82][p.13] - meaning that prototypes are being tested in actual problems and used in existing systems. [86] Research for the project is still being conducted, and as an example, the effect of nitrogen bubbles on the scientific instruments of the submarine has been studied. [87]

The main challenge and also the broader benefit of this mission centers around the cryogenic circumstances it would be facing [82][p.13] . Notably, the development of better cryogenic engineering and methods to operate a faraway device reliably even when the device is submerged are important for the future Solar System exploration projects [82][p.13] . The liquid on Titan's surface is relatively easy to access, so this makes Titan a prime first target for a submerging spacecraft. Jupiter's Europa moon is believed to contain liquid water under its surface but reaching that liquid layer would require use of a drill [88] , which makes mission planning more complex. As the submarine is still in development, the earliest touch down on Titan's liquid pools would be around year 2047; Titan's northern summer is occurring then bringing better visibility on the surface, and communication to Earth would be possible [82][p.7] .

6. Conclusion

The basic estimates for the surface equilibrium temperature and limit pressures presented in section 2 already indicate that liquid methane can exist on Titan. Voyager 1 had indeed verified that the temperature and pressure on the surface were truly suitable. These results were refined by the Cassini-Huygens mission which also did detect the lakes with its instruments.

The data collected by Cassini VIMS and Radar showed that the composition of Titan's seas and lakes is mostly methane, nitrogen and ethane based. Methane was determined to be the main component of the northern seas but Ontario Lacus in the southern hemisphere showed an increased abundance of ethane and depleted methane. This loss of methane in the south was seen as a mark of overall transport of volatile components between the hemispheres on a long seasonal timescale, with most of the methane currently residing in the north.

The transport of liquid by currents within and between liquid pools was deemed plausible by the effect of tides, winds, thermal forcing and the density gradients in the liquid. This movement would also induce waves, though the sizes of the waves were estimated to be on a millimeter scale.

As no device to date has directly investigated the liquid pools on Titan's surface, several important scientific questions are still open. The specific thermodynamic properties of the hydrocarbon lakes are still only derived from models and fits to sparse data, and the quantification of currents is also based mostly on models. A movable device such as a submarine has the benefit of studying the liquid properties at different locations of the northern seas of Titan. It could also bring new data about the Magic island phenomenon and possibly even determine in situ if there exists lifeforms in Titan's seas.

Titan is nearing a point in time when communication to Earth from its seas will be difficult without an orbiter, so the future missions have to wait until the year 2047 when Titan is at the next optimal orbital phase. At that point, a successor for the Cassini-Huygens mission is hopefully ready to be sent to Titan.

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