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Titan and the Huygens Mission

Editorial

The human eyes progressively lose power to accommodate when the phase of biological necessities is over. Seneca, himself plagued by the loss of vision, described the use of a globe of water helping to see the letters enlarged and hence more clearly. The Arab scientist Ibn al-Haitam is said to have proposed the use of solid transparent material of suitable shape to support the vision. European monks of the 13th century translated his oeuvre in Latin. Not required to fulfil biological, but rather intellectual necessities, they were strongly interested in his ideas and in 1267 Roger Bacon, a Franciscan friar of Oxford, showed, that small letters can be magnified by specially shaped pieces of crystals, from which his colleagues then made the first reading stones to be shifted carefully from one letter to the next.

This promising business opportunity was discovered by the glassblowers of Murano in the early 14th century, who were able to fabricate the best material for eyeglasses. The new product successfully penetrated the market, but at the same time challenged craftsmen all over Europe to grasp their share also. Of course, scientists became an important customer segment; they used the lenses not only for reading letters, but for additional purposes as well, be it for looking at objects very close or very far. It was Hans Lippershey, a Dutch lens maker, who demonstrated the first refracting telescope in 1608 for military use. Galileo Galilei introduced the instrument in the science community: he constructed his first telescope in July 1609, and turned an improved instrument to the heavens in November. With this telescope, he observed the Moon and found the rings of Saturn. Isaac Newton improved his design by replacing the first lens by a mirror, to produce what is now called the Newtonian telescope. Due to technical limitations of the manufacturing process, increased magnification had to be achieved by increasing the focal length. While the Galilean telescope had a handy length of 2 m, the Dutch Christiaan Huygens half a century later came up with an astronomical telescope of 7 m. New methods for grinding and polishing glass allowed him to make a quantum leap in telescope technology and to discover Titan, the largest moon of Saturn in 1655.

It is here that our story begins, the story of a marvellous space mission to land a probe on Titan. We are indebted to Professor Nicolas Thomas of the Physikalisches Institut of the Universität Bern for his kind permission to present our readers herewith a revised version of his fascinating lecture on the ESA Huygens mission to Titan.

Hansjörg Schlaepfer
Zürich, November 2005

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Front cover
An artist's view of the moon Titan and the Saturnian ring system. (Credits: see figure 7)

Titan and the Huygens Mission[1]

Introduction

The fourteenth day of January 2005 was one of mankind's major milestones, which, like most milestones probably, passed unnoticed by the vast majority. On this day, at 11:30 UTC a spacecraft from planet Earth landed on the surface of Titan, after a journey of more than 3,000,000,000 km. There, the probe remained busy for its short lifetime of a mere seventy minutes before it fell into an eternal sleep.

Why was Titan chosen from all the numerous heavenly bodies populating our solar system? Titan, the largest moon of Saturn, was discovered by Christiaan Huygens[2] in 1655. In 1908, the Spanish astronomer Comas Sola stipulated that Titan must have an atmosphere, which was an outstanding finding as no other moon of the solar system is covered by a gaseous shell. It was in 1944, when the Dutch Gerard Kuiper[3] detected the 6,190 Å methane absorption line in Titan's atmosphere. This again was a revolutionary result: at least on Earth, methane is associated with biological activity. In the fifties, much was hypothesized about the evolution of life on Earth. These discussions challenged the American student, Stanley Miller in 1953 to execute a simple experiment: he put some water in a large laboratory bottle, added methane and nitrogen which were thought to be the main constituents of the primordial Earth atmosphere before life developed. He simulated the effects of the Sun by ultraviolet radiation and lightning by means of electrical discharges in the bottle and then went quietly to dinner. During the whole night, his experiment was running. When he came back the next morning, he found the gas mixed with a stunning wealth of complex organic molecules including amino acids, the very building blocks of life. Was that the key to understanding the evolution of life on Earth?

Thirty years later, the two US spacecraft Voyager 1 and 2 were underway to probe the outer solar system[4] and passed by Saturn and Titan. They not only confirmed the presence of methane but also of many heavier organic molecules.

These were the results that prompted the European scientific community in the early eighties to propose to ESA a space mission to Titan. However, landing on a moon in the outer solar system is not a Sunday morning's walk: the distances are enormous: while the Earth circles the Sun at a radius of approximately 150 million km, the diameter of the Saturn orbit measures roughly 1.5 billion km making a journey to Saturn a lengthy endeavour. ESA therefore joined forces with the US space agency NASA and planned a mission to Saturn called Cassini[5], in honour of the discoverer of the Saturnian ring system. An inter-agency agreement was concluded whereby NASA was to provide the launch and the mother ship Cassini, on which the ESA Titan probe Huygens was attached to ride to Saturn. In addition, Cassini was to act as relay station for the Huygens radio signals over its entire mission duration.

The present issue of Spatium is devoted to this outstanding mission and to the scientific results gained so far.

Figure 1: A self-made telescope enabled the Dutch scientist Christiaan Huygens to discover Titan in 1655.

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[1] Lecture by Prof. Nicolas Thomas for Pro ISSI on 22 March 2005

[2] Christiaan Huygens, 1629–1695, Dutch scientist

[3] Gerard Kuiper, 1905–1973, Dutch-American astronomer

[4] It is interesting to note, that both these spacecraft launched in 1977 are still functioning: they have left now the outer limits of the solar system and continue to send back information from distances of 94 AU (14 billion km) for Voyager 1 and 75 AU (11 billion km) for Voyager 2.

[5] Jean-Dominique Cassini (1625–1712), Italian astronomer

Titan, the Mysterious Moon

Saturn's giant moon Titan **(figure 2)** is the second largest in the solar system, larger than planet Mercury, and the only planetary body, other than the Earth, to have a substantial nitrogen-based atmosphere. Many exotic chemical reactions, driven by solar radiation and the high energy particles of Saturn's magnetosphere, result in an atmosphere with primitive organic compounds, which eventually rain down onto the surface.

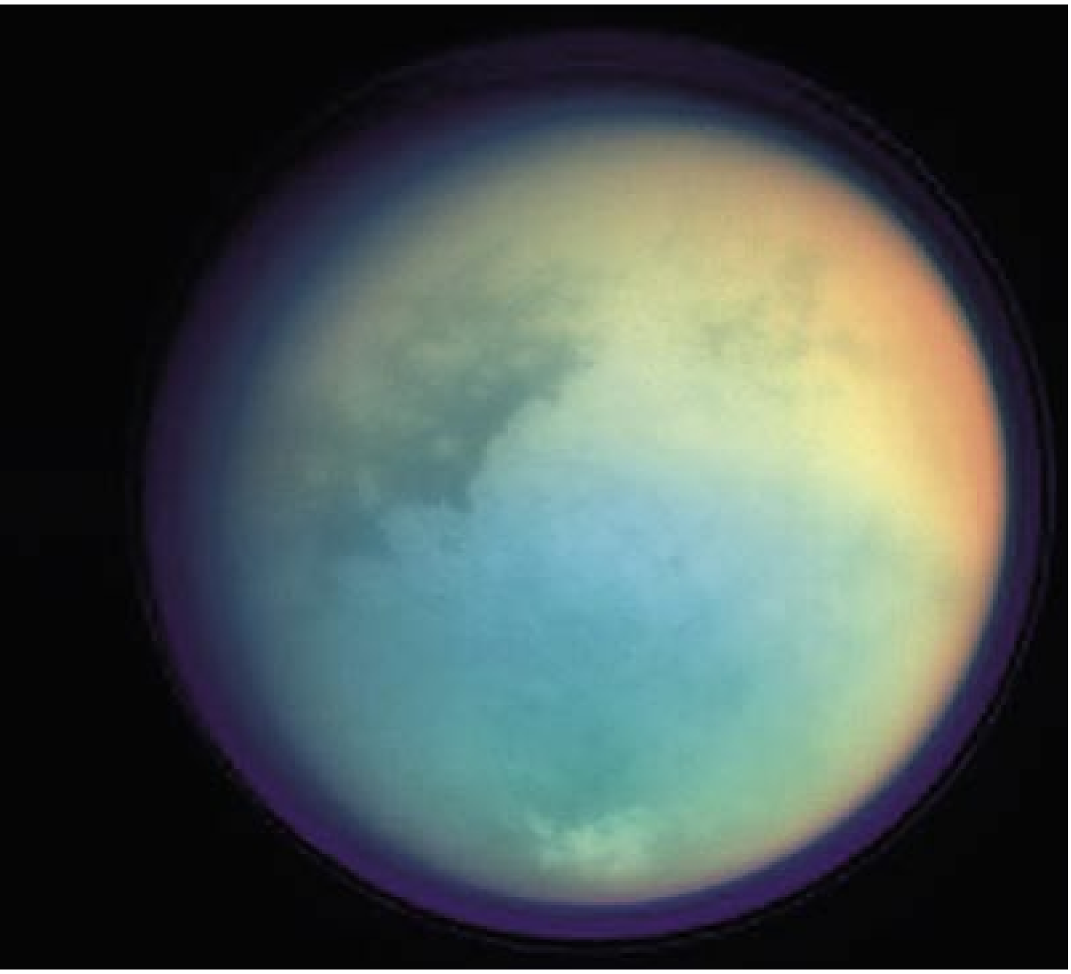


Figure 2: A close-up view of Titan recorded as the Cassini spacecraft approached its first close fly-by of Saturn's smog-shrouded moon on 26 October 2004. Here, red and green colors represent specific infrared wavelengths absorbed by Titan's atmospheric methane while bright and dark surface areas are revealed in a more penetrating infrared band. Ultraviolet data showing the extensive upper atmosphere and haze layers are seen as blue. Sprawling across the 5,000 km wide moon, the bright continent-sized feature known as Xanadu Regio is near picture center, bordered at the left by contrasting dark terrain. (Credits: Cassini Imaging Team, SSI, JPL, ESA, NASA)

What makes Titan so fascinating is that many processes that occur on the Earth are thought to have analogues on Titan albeit at much colder temperatures as it is ten times farther away from the Sun. These processes include not only chemical reactions, but also weather including rain, erosion by winds and liquids, a greenhouse effect and possibly volcanism. Titan's key parameters are compared to those of the Earth in the table on page 5.

On Earth, the water cycle drives many important phenomena: it condenses to form clouds in the atmosphere, rains down to the surface to cause fluvial erosions from the bedrock creating surface structures like rivers with complex tributary systems. On Titan, it is too cold for water to exist in liquid form, but methane plays a similar role there. While, however, the water cycle on Earth is closed, this is not the case with the methane cycle on Titan: photons of the solar irradiation and the energy electrons from the Saturnian radiation belt dissociate the methane molecule leaving a CH_3 or CH_2 radical, which quickly reacts to ethane, ethylene and so forth. It is estimated that within a mere 10 million years, the equivalent of the complete atmospheric content of methane is destroyed by these mechanisms, which raises the question regarding the fresh supply of methane. On Earth, it is life which refreshes the methane reservoir, as methane is a by-product of the metabolism of many organisms. But all known forms of life require the presence

	Earth	Titan
Atmospheric composition	78% N_2, 21% O_2, <1% H_2O	98% N_2, 2%CH_4
Surface pressure	1 bar	1.5 bar
Atmospheric thickness (top of stratosphere)	50 km	300 km
Clouds/rain	H_2O	CH_4
Radius	6,371 km	2,575 km
Axial tilt	23.5°	26.7°
Distance from Sun	1 AU	9.5 AU
Solar irradiance	1,368 W/m^2	15 W/m^2

of liquid water which can not exist on the frosty Titan: the source of fresh methane remains one of the many secrets which Titan continues to keep even after the intense probing by Huygens and Cassini.

The Interior

The Voyager 1 and 2 spacecraft first determined the average density of Titan by measuring the radius and the mass derived from the gravitational pull experienced by the spacecraft. The result was 1,881 kg·m^{-3}, which corresponds to roughly 30% of the density of the Earth. No magnetic field was detected suggesting that no molten iron core is present.

The Surface

The handful of Voyager images of Titan revealed little, as they were unable to penetrate Titan's thick atmosphere. The Hubble Space Telescope acquired a series of infrared images in the 1990's showing some patterns on the moon's surface, but it was not clear, whether these indicated solid continents in oceans of liquid methane or whether the surface was entirely solid.

The Atmosphere

The most intriguing feature of Titan is the thick atmosphere completely hiding the surface in the visible spectrum. The moon's dry cold atmosphere causes a 300 km thick layer of smog to build up, which is the result of complex chemical interactions between the atmospheric hydrocarbons driven by the sunlight and the high energy particles of Saturn's radiation belt.

The Objectives for the Huygens Mission

Based on the knowledge of Titan in the late eighties, the goals for the Huygens mission were set at understanding the complex processes shaping this distant celestial body, which in many respects mirror those on our home planet Earth especially during its prebiotic phase. The main areas of scientific interest were:

- abundance of atmospheric constituents; isotope ratios for abundant elements; scenarios of formation and evolution of Titan and its atmosphere

- vertical and horizontal distributions of trace gases; range of complex organic molecules; energy sources for atmospheric chemistry; photo-chemistry of the stratosphere; formation and composition of aerosols

- winds and global temperatures; cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges

- physical state, topography and composition of the surface; internal structure of the moon

The Cassini-Huygens Mission

Space science missions have always been attractive as they push available technologies to achieve performance never reached before. The Cassini-Huygens mission is no exception. The distances involved are enormous and the uncertainties about the physical parameters governing descent and landing on Titan were so great that the mission planners faced a whole host of challenges:

The Challenges

Orbit: Saturn orbits the Sun at approximately 10 Astronomical Units (AU), i.e. at about 1.5 billion km. To reach such a distant target in a reasonable time frame, advanced celestial mechanics are to be used as present day launchers are not able to provide a 5,600 kg spacecraft with the required thrust. The trajectory included four swing-bys, one of the Earth, two of Venus and the last of Jupiter, see **figure 3.** A swing-by is a manoeuvre, whereby the spacecraft passes near a planet. When the spacecraft enters the gravitational field of the planet, it is accelerated; when it leaves the planet, it is decelerated again. As seen from the planet, there is no exchange of energy, but in the Sun's inertial system, the spacecraft gains some additional speed at the expense of the planet's motion. As its mass is many times larger than the

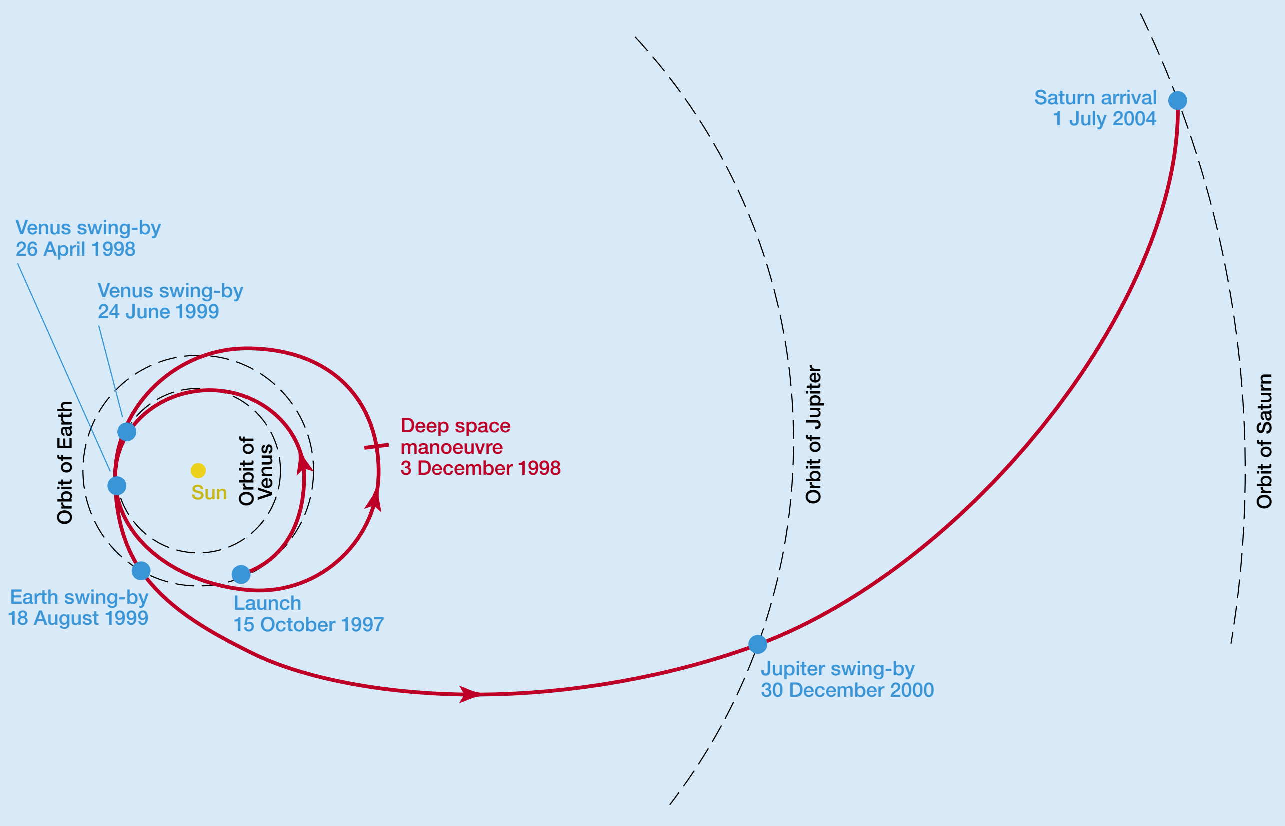


Figure 3: The complex trajectory of Cassini-Huygens in a simplified form: Launch was on 15 October 1997. The first swing-by occurred at Venus on 26 April 1998, the second on 26 April 1998, while the Earth swing-by was on 18 August 1999. After this phase the Cassini-Huygens spacecraft left the terrestrial planets and headed towards the giant planet Jupiter, which it passed on 30 December 2000 to arrive at Saturn on 1 July 2004.

spacecraft's mass, the net change of speed of the planet can be neglected, while the increase of the spacecraft's speed is essential for the mission.

Mission duration: Notwithstanding the complex trajectory, the flight time to Saturn amounted to seven years. In addition, Cassini is scheduled to explore the Saturnian system for another four years, which brings the mission duration to 11 years. During this time frame the spacecraft requires electrical power to keep the thermal control system active, the electronics running, the scientific instruments working when needed, the telecommunication system operational to generate the radio signals carrying data back to Earth and to receive the commands from ground control. On an Earth-like orbit, the electrical energy is generated by solar cells converting the sunlight into electrical current. At Saturn's distance from the Sun, the solar irradiation is a mere one percent of its value around the Earth, which makes solar energy generators unfeasible. More attractive, but also much more complex, is the energy generation from the heat of the decay of plutonium dioxide radioisotopes. Three thermoelectric generators provide Cassini with 300 W at the beginning of the mission in 1998 and 210 W in 2009.

Of course, the Earth swing-by on 18 August 1999 caused major concerns in the public as the plutonium could have caused radioactive pollution if the spacecraft would have entered the Earth's atmosphere. However, the orbit parameters were extremely well-known, so there was never any danger.

Mission control: Radio signals, although propagating with the speed of light of 300,000 $\mathrm{km \cdot s^{-1}}$, require over eighty minutes to reaching the Saturnian system. Any real time mission control activity is therefore not possible. If the spacecraft were to experience an immediate problem any necessary corrective commands would reach the spacecraft at least 2.5 hours after the critical situation occurred. All the mission sequence steps including the entire landing sequence had to be executed in a fully automatic mode. With today's technology this would pose no major problem under the known parameters of the Earth. On Titan, however, where no probe had ever been before, this was an extraordinary challenge to be met with technologies available in the early nineties.

Ultimately, the successful landing of Huygens on Titan has demonstrated that the assumptions of the scientists were very accurate and the performance of the spacecraft as designed by the engineers was practically nominal: after a flight time of seven years landing occurred a mere 14 minutes later than expected. The separation speed of Huygens away from Cassini as well as its spin rate were exactly in the middle of the allowed tolerance. The Huygens probe was operational for 70 minutes after landing, much more than the initially expected two or three minutes. Unfortunately though, some information was lost, due to a command error on one of two redundant data channels linking Huygens with Cassini. But finally, taking into account all the challenges met, the mission has been an outstanding success, not only on technical and scientific grounds, but also regarding the successful co-operation between the two space agencies ESA and NASA, with their radically different corporate cultures.

The Technical Solutions

The Huygens Spacecraft

The Cassini-Huygens spacecraft **(figure 4)** was one of the largest, heaviest and most complex interplanetary vehicles ever built. The main body of the Cassini orbiter consisted of a cylindrical stack with a lower equipment module, a propulsion module and an upper equipment module. It was topped by the fixed, four-meter diameter high-gain antenna securing the link to the Earth. Cassini was equipped with a suite of instruments, cameras and other remote sensing instruments. The Huygens probe was mounted on the side of the Cassini spacecraft from where it was jettisoned by the spin and eject device.

The Huygens probe's structural system consisted of several subunits: the central experiment platform contained the six scientific experiments. The front shield protected the instruments during entry in the atmosphere and slowed the spacecraft as it entered the atmosphere at supersonic speed.

Figure 4: The Huygens probe (centre) is mated to the large body of the Cassini spacecraft. (Credits: NASA)

The specific shape of the front shield together with the axial spin assured stability during the entry phase. Aerodynamic friction at this time heated the protective tiles of the front shield to 1,200 °C and radio contact to Cassini was lost. On top of the experiment platform a secondary platform with additional instruments was mounted. The after cone connected the experiment platforms to the back cover, which itself was linked to Cassini via the circular spin and eject device. This mechanism provided Huygens a spin rate of 7.5 revolutions per minute and an axial velocity of 0.35 metres per second.

It is interesting to be noted here, that the Swiss space industry contributed major subsystems to the Huygens probe: the front shield and the spin and eject device were developed and built by Contraves Space of Zurich, while the back cover was built by APCO Technologies of Vevey **(figure 5).**

The temperature control system was responsible for maintaining the temperature of the spacecraft within the specified range. The complex trajectory to Saturn exposed the spacecraft to extreme variations in its thermal environment: in the vicinity of Venus, the solar heating is nearly three times greater than near the Earth and the probe's electronics and instruments required active cooling. On the other hand at Saturn, solar irradiance is hundred times less, which required the probe's heaters to be turned on. The Huygens telecommunication system provided the link between the probe and Cassini after separation until the end of the Huygens mission. As Huygens could not carry a high gain antenna allowing direct contact with ground control due to mass constraints, Cassini acted as a relay station to send the Huygens data back to Earth.

The Huygens payload consisted of six complex instruments addressing many scientific questions:

- The Huygens Atmospheric Structure Instrument HASI was a multi-sensor package designed to measure the physical properties of Titan's atmosphere such as temperature, pressure, turbulence and atmospheric conductivity. In addition, it searched for lightning. The sensors consisted of a 3-axis accelerometer, a temperature sensor, a multi-range pressure sensor, a microphone, and an electric field sensor array.

Figure 5: Installation of the Multi-Layer Insulation (MLI) blankets on Huygens' front shield and back cover. The intense aerodynamic heating during entry rapidly vaporised the MLI, and the 20 mm thick sponge-textured brown tiles insulated the carbon fibre internal structure and the descent module from the intense radiation of the hypersonic shock wave.

- The Gas Chromatograph and Mass Spectrometer GCMS measured the chemical composition of Titan's atmosphere from 170 km altitude down to the surface. It determined the isotope ratios of the major gaseous constituents. GCMS also analysed the gas samples from the Aerosol Collector Pyrolyser (ACP) and investigated the composition of several candidate surface materials.

- The Aerosol Collector and Pyrolyser ACP deployed a filter out in front of the probe to sample the aerosols during the descent and prepared the collected matter (by evaporation, pyrolysis and gas product transfer) for analysis by the Gas Chromatograph/Mass Chromatograph (GCMS). Two samples were collected: one from the top of the descent down to the tropopause (160–40 km) and the second sample in the cloud layer (23–17 km). At the end of each collection period, the filter was retracted into a pyrolysis furnace, where the effluent from the captured aerosols was analysed, first at ambient temperature (about 0 °C), subsequently heated to 250 °C and then to 600 °C in order to conduct a step-wise pyrolysis. The pyrolysed products were flushed into GCMS for analysis.

- The Doppler Wind Experiment DWE was a high-precision tracking investigation to determine wind direction and magnitudes in Titan's atmosphere. DWE measured the Doppler shift of the probe relay link signal from the Huygens probe to the Cassini orbiter. The DWE-proper hardware consisted of two ultra-stable oscillators, one on the probe and one on the orbiter. A height profile of wind velocity should have been derived from the residual Doppler shift of Huygens radio relay signal as received by Cassini. Unfortunately all these data were lost due to a command error on one of the two communication channels between Huygens and Cassini.

- The Surface Science Package SSP was a suite of sensors for determining the physical properties of the surface at the impact site, and for providing information on the composition of the surface material. The instrument included a force transducer for measuring the impact deceleration and sensors to measure the refraction index, temperature and thermal conductivity of the surface material. It included an acoustic sounder for sounding the atmosphere's bottom layer and the surface's physical properties before impact. If the probe would have landed in a liquid, the sounder was to be used to probe the liquid depth. A tilt sensor was included to indicate the probe's attitude after impact.

- The Descent Imager and Spectral Radiometer DISR was the optical remote sensing instrument aboard Huygens. It included a set of upward and downward looking photometers, visible and IR spectrometers, a solar aureole sensor,

Figure 6: A demanding mission like Huygens-Cassini was of course planned to gather as much information en route to its destination. This image shows Phoebe, one of Saturn's many moons taken by Cassini during its close encounter on 11 June 2004. Phoebe's irregular shape and retrograde orbit suggest a Kuiper belt origin. (Credits: Cassini Imaging Team, SSI, JPL, ESA, NASA)

a side-looking imager and two down-looking imagers: a medium-resolution and a high-resolution imager. There was also a Sun sensor that measured the spin rate. DISR spectral sensitivity covered the range of 0.3 to 1.7 µm, i.e. the visible and the near-infrared wavelengths.

The Trajectory

Launch took place on 15 October 1997 from Cape Canaveral in Florida by means of a Titan IV-B/Centaur launcher. After 143 s, the spacecraft detached from the launcher at a speed of 7,000 $\mathrm{km \cdot h^{-1}}$. 40 minutes later, the spacecraft established the first radio contact with NASA's Deep Space Network tracking complex near Canberra, Australia. The launcher boosted the spacecraft into a Venus–Venus–Earth–Jupiter swing-by trajectory toward its final destination of Saturn, **see figure 3.**

After the long interplanetary cruise, Cassini made its first measurement in the Saturn system with a close fly-by of Phoebe on 11 June 2004, see **figure 6.** Phoebe is a small moon with a diameter of only 220 kilometres. Its inclined and retrograde orbit around Saturn suggests that it may have been a Kuiper belt object captured by the Saturn gravity field. Following the fly-by, a trajectory correction manoeuvre was made on 16 June 2004 to place the Cassini-Huygens spacecraft on a precise intercept course with Saturn. On 1 July 2004 Cassini arrived at Saturn and performed a major engine burn to bring it into orbit. One day after, Cassini had a first, albeit distant, encounter with Titan (339,000 km) which provided the first opportunity to study the moon's South polar region with its radar.

The spacecraft crossed through the large gap between the F ring and G ring, **see figure 7.** For this phase, the spacecraft oriented its high gain antenna forward to use it as a shield against the incoming dust particles in the ring plane. The main engine burn began shortly after it crossed above the ring plane on 1 July 2004 at 01:12 UTC and ended 97 minutes later in order to slow down the spacecraft sufficiently to be captured by Saturn's gravity field. Cassini-Huygens' closest approach to Saturn occurred during this burn; its distance from Saturn was then a mere 20,000 km, only $^{1}/_{6}$ of its diameter.

Cassini made its first close Titan encounter on 26 October 2004 at a distance of 1,200 km, i.e. $^{1}/_{4}$ of the moon's diameter. A second close encounter followed on 13 December 2004. This trajectory, if uncorrected, would have led to a subsequent fly-by at an altitude of about 4,600 km. A targeting manoeuvre was required, therefore, to achieve the desired intercept course for the Huygens probe. Once released there was no way to change its trajectory. This manoeuvre was executed on 17 December 2004 and placed Cassini-Huygens on a direct impact trajectory with Titan.

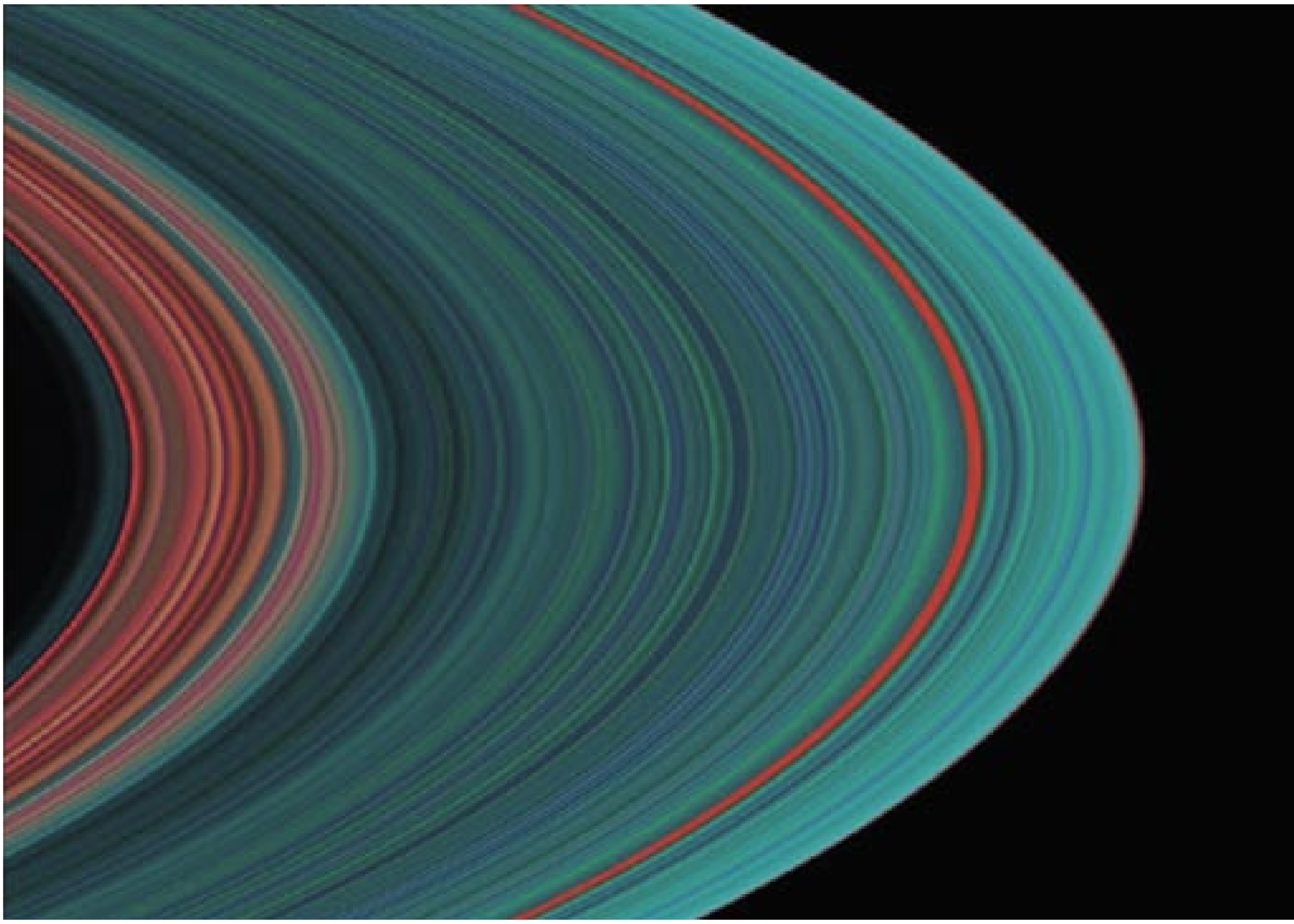


Figure 7: False colours help to highlight subtle differences like for example in this wonderful image of the Saturnian ring system. The bluer an area appears, the richer it is in water ice, conversely, the redder an area appears, the richer it is in some sort of dirt. The exact composition of dirt remains unknown, however. This and other images show that inner rings have more dirt than outer rings. This dirt/ice trend could be an important clue to the ring's origin. The thin red band in the otherwise blue A ring is the Encke Gap. (Credits: UVIS, U. Colorado, ESA, NASA)

On Christmas Day, at 02:00 UTC, the Cassini onboard computer generated the signals that activated the spring and eject device which had firmly held the Huygens probe for the past seven years and now provided the probe with exactly the required spin and velocity toward its final destination, Titan, **see figure 8.** After release, Huygens coasted towards Titan for a distance of 4 million km and reached the outer limits of its atmosphere on 14 January 2005. At the same time, Cassini passed Titan at a distance of 60,000 km with its high gain antenna directed towards the Huygens probe for the entire descent, landing and surface phase. Later, Cassini pointed its antenna towards the Earth to relay the Huygens data back to Earth. The relative position of Cassini, Huygens and Titan allowed a theoretical maximum coverage of 4 hours 30 minutes after landing.

The Huygens probe reached Titan with a relative speed of 18,000 $\mathrm{km \cdot h^{-1}}$. Aerodynamic friction caused the probe to slow to a velocity of 1,400 $\mathrm{km \cdot h^{-1}}$. A sequence of parachutes was then

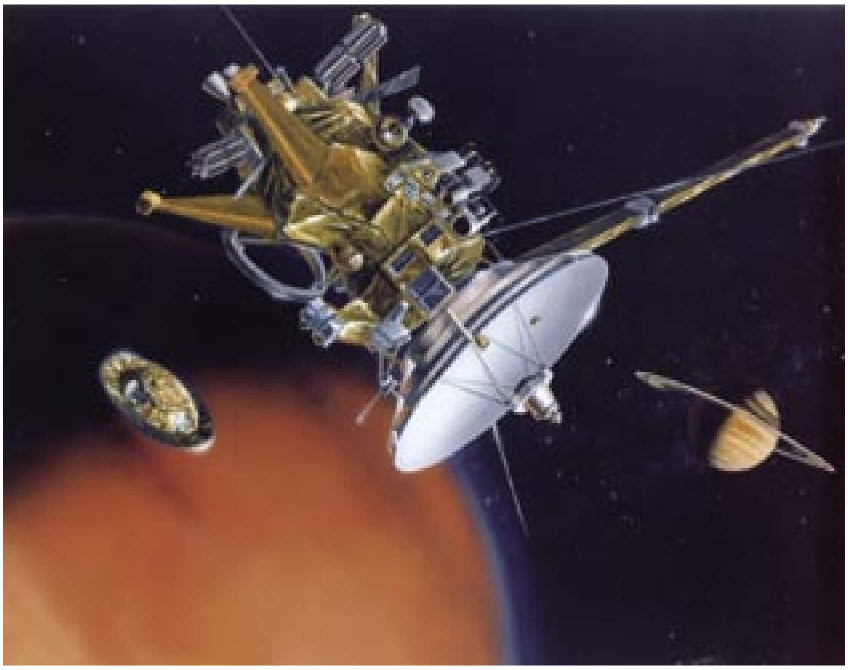
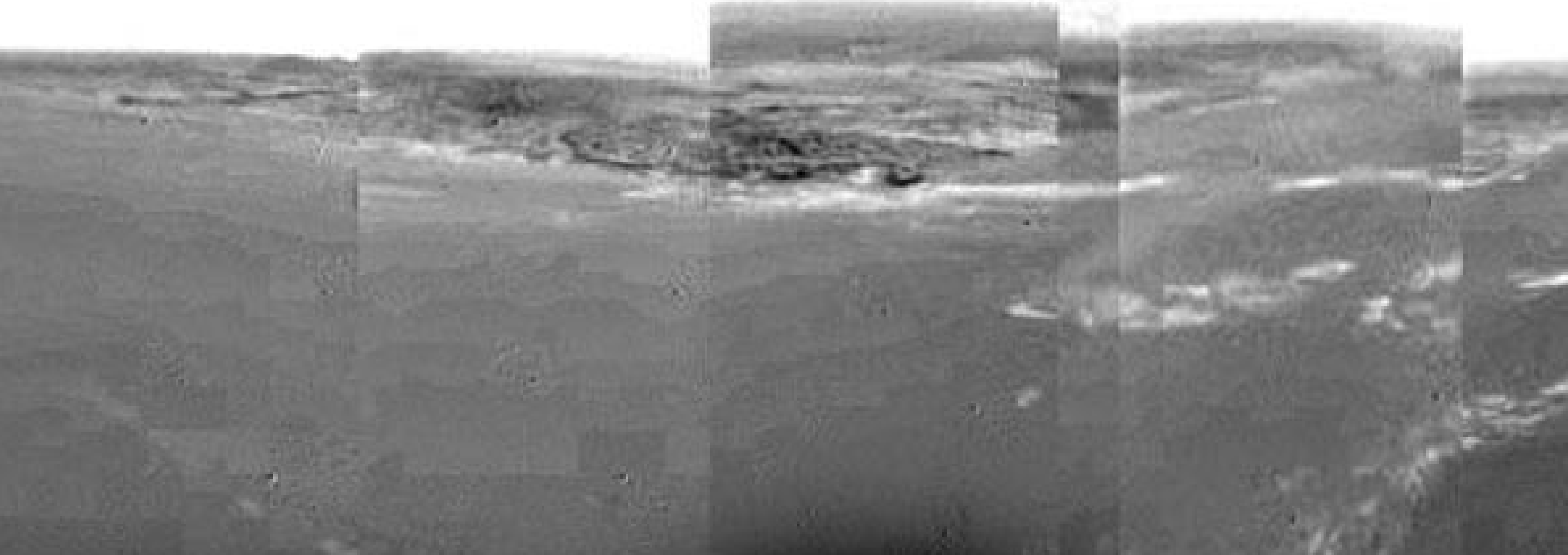


Figure 8: Artist's concept of the Cassini-Huygens orbiter shows the Huygens probe immediately after separation from Cassini. The probe drifted for about three weeks until reaching the upper layers of Titan's atmosphere. (Credits: NASA/JPL/Caltech)

deployed to further brake the probe to $300\ \text{km}\cdot\text{h}^{-1}$ **(figure 9).** The back cover and the front shield were jettisoned so that the scientific instruments became exposed to Titan's atmosphere at a height of 160 km above ground. At that moment, Huygens started to transmit the first radio signals to Cassini. These reached not only Cassini, but about 67 minutes later also the Green Bank Telescope in West Virginia, USA. They were, as expected, far too faint to carry any useful information, their very appearance, however, was a great sensation as they confirmed that Huygens had executed its entry sequence perfectly.

The flight through the upper atmosphere was a bumpy ride, as the probe rocked far more than expected. In the high-altitude haze, it swung at least 10 to 20 degrees from the vertical; while in the lower layers the probe was much more stable, tilting less than 3 degrees. In this phase, the probe decelerated to approximately $5.4\ \text{m}\cdot\text{s}^{-1}$, and drifted sideways at about $1.5\ \text{m}\cdot\text{s}^{-1}$. It came as a great surprise that during this descent phase the probe's spin reversed; a fact which is still unexplained today.

At an altitude of 700 m above the surface the descent lamp of the DISR instrument was activated. The purpose of this lamp was to provide a light source with known spectral properties to enable scientists to determine accurately the reflectivity of the surface. At 11:30 UTC the Huygens probe touched



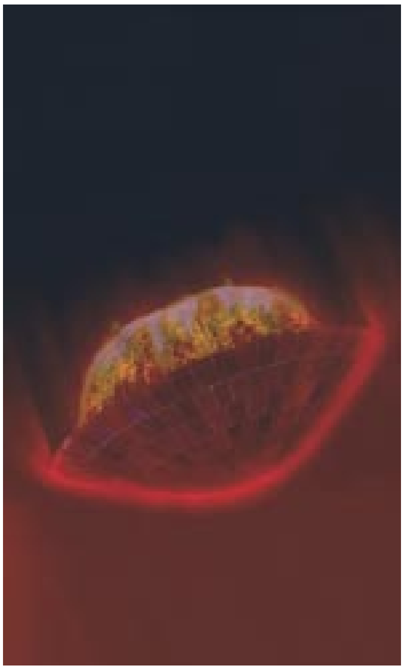


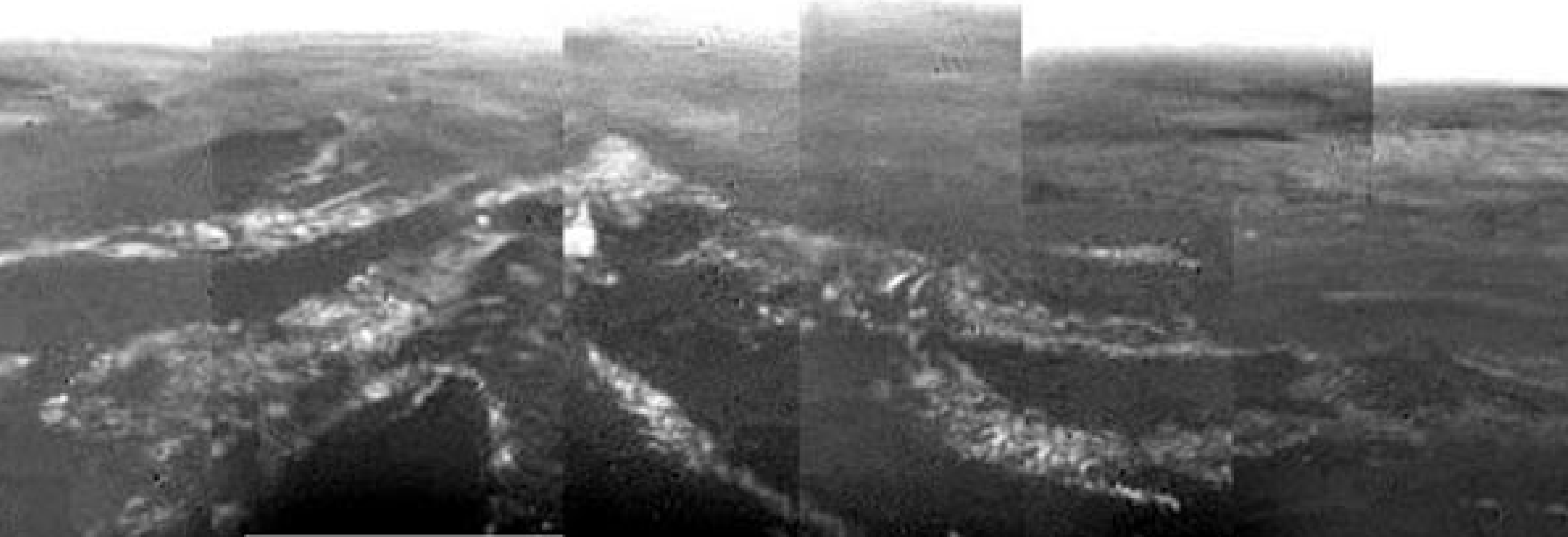
Figure 9: The Huygens probe during the hot phase of entry into Titan's atmosphere. The probe plunged into the upper layers of the atmosphere at a speed of 18,000 km·h^{-1}. The velocity was then reduced to about 1,400 km·h^{-1} in less than 2 minutes, thanks to the friction of the heat shield with the atmospheric gas. (Credits: ESA)

down on Titan. The first image reached the Earth two hours later, **see figure 11.** It confirmed the safe landing of Huygens in what seems to be a dry river bed with rounded pebbles.

One of the most stunning results of the Huygens mission is that during its descent through Titan's atmosphere, Earth-based radio-telescopes were able to pinpoint its position by tracking the extremely faint carrier radio signal. Connected together to implement Very Long Base Interferometry they were able to track the Huygens probe's path through the atmosphere with an accuracy of around 100 m, from which the directions and strengths of the winds as a function of the probe's altitude could be inferred. This came as an important and welcome redundancy for the lost communication channel carrying the Huygens Doppler Wind Experiment data. As a consequence, determination of a spacecraft's exact position by means of interferometry is now considered for the Agency's forthcoming BepiColombo mission to Mercury, where it is expected to allow pinpointing the spacecraft with an error of a few centimetres!

The surface phase of the mission lasted 70 minutes – considerably longer than anticipated as there was no failure on the batteries. Therefore, all five batteries could be used to power the probe while four would have been enough to complete a nominal mission. Furthermore, the landing on the surface was quite soft, so that no major damage was done to the probe and its instruments. After the end of battery power the probe became silent.

Figure 10 shows the view of Huyges from a height of 30 km. On the far left, a boundary seems to exist between some sort of smooth dark terrain and a type of choppier terrain in the distance. In the image center and on the left, white areas cover the image that might be a type of ground fog. The Huygens probe landed in the dark area of the far right. (Credits: ESA, NASA, Descent Imager/Spectral Radiometer Team)



Titan: the Results so Far

Titan continues to be an exciting celestial object even after the detailed analysis by Huygens and the continuing visits by Cassini. Space scientists all over the world are currently engaged in the analysis of the data received from Huygens and the information provided by Cassini. The main scientific results as of September 2005 are summarized below.

The Interior

It is thought that Titan consists basically of a rocky core of silicates overlaid by a crust mainly of water ice. At the temperatures prevailing on Titan, water ice plays the role of rocks on Earth. As Titan circles Saturn on a highly eccentric orbit,

Figure 11: The first scene recorded by the Huygens probe immediately after landing on Titan's frosty surface. Bathed in an eerie orange light at ground level, rocks strewn about the scene are thought to be composed of water and hydrocarbons frozen solid at an inhospitable temperature of –179 °C. The light-toned rock below and left of centre is only about 15 cm across and lies 85 cm away. The shapes of the pebbles indicate erosion processes either by water or by wind or both. After touching down at 4.5 meters per second, the probe is believed to have penetrated around 15 cm into a surface with the consistency of wet sand or clay. (Credits: ESA, NASA, Descent Imager/Spectral Radiometer Team, JPL)

strong tidal forces act on its interior causing local heating on top of the heat generated by the decay of radioactive material in its core, which may give rise to up-wells of material in the form of cryo-volcanoes in places which in turn may act as the source of methane – and other constituents – replenishing the moon's atmosphere. It must be remembered, however, that the term heating here is a relative: in the very cold environment of Titan the temperatures reached by these mechanisms remain in the order of a few 100 K.

The Surface

The moon's surface is being mapped globally by Cassini on its visits to Titan. The Cassini radar subsystem can penetrate the smoggy atmosphere undisturbed and its data are complemented locally by the ground truth information provided by the Huygens data.

The images of the surface taken by the Cassini radar show a complex terrain with large clear and dark areas. The Xanadu Regio, a continent-sized light area is the first to have received a name on Titan. The different albedos may stem from varying materials, textures, or different slopes of the surface.

Impact Craters

As any object, which would cause a crater smaller than roughly 20 km in diameter, would be burned during its entry into the thick atmosphere, no smaller, but many larger craters were expected. It came as a great surprise that only very few large impact craters have been identified so far, implying that the surface topography is of recent time, i.e. no more than 130–300 million years old in places. All large craters have a very weathered appearance suggesting that the moon's surface is continuously and intensively reworked by ongoing processes such as viscous sagging, tectonics, cryovolcanism, and erosion by wind and liquids. The icy pebbles imaged by Huygens on the surface **(figure 9)** show a rounded appearance consistent with strong erosional effects by winds or liquids.

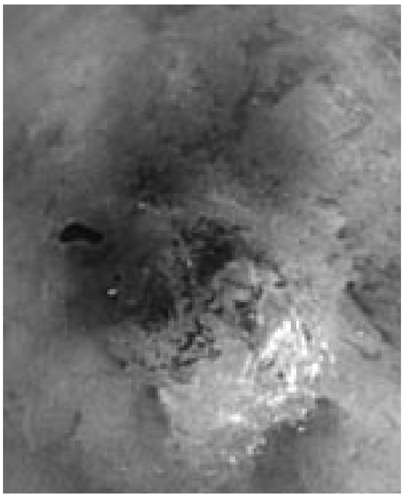


Figure 12: The dark patch is possibly one of the long awaited reservoirs of liquid methane on Titan's surface. It is situated in the South Polar region where currently the early summer season started causing strong meteorological activity, which may lead to temporary methane lakes. (Credits: NASA/JPL-Caltech/Space Science Institute)

Liquid Surfaces and Volcanoes

Again in contrast to the expectations, no ocean of liquid methane was found with the possible exception of a small lake in the vicinity of the South Pole, **see figure 12.** This, however, necessitates a new theory regarding the replenishment of the methane content in the atmosphere. One could be the out-gassing from cryo-volcanoes. A handful of surface features indicating the existence of volcanoes have been found, but their behaviour over time still needs to be observed in order to confirm this interpretation. The energy source feeding this mechanism could be either the tidal forces due to Titan's large eccentricity or decay of radioactive material in its interior.

Dunes, Tectonic Faults and Fluvial Systems

One salient feature of the moon's surface are thin dark structures extending over hundreds of kilometres. These may be caused by tectonic activity. Other features are more like rivers and may be caused by liquids flowing from higher parts of the surface (50–200 m elevation) down to lowlands. It is thought that the methane rain causes liquid to flow down-hill and to carve rivers into the "bedrock" of water ice. These flows carry other organic material washed out from the atmosphere, which in turn is deposited along the rivers, **see figure 13.** These channel-like features are the best evidence for the presence of liquids on the surface so far. At the South

Pole, where intense meteorological processes take place at present as the southern hemisphere enters summer time, an extensive system of channels has been identified. During its descent Huygens showed many such channels; all appear to have dark material in the valley surrounded by brighter material.

Other surface structures, mainly observed near the Equator, remind one of wind blown dunes on Earth. They show sharp western boundary lines together with extended eastern boundaries.

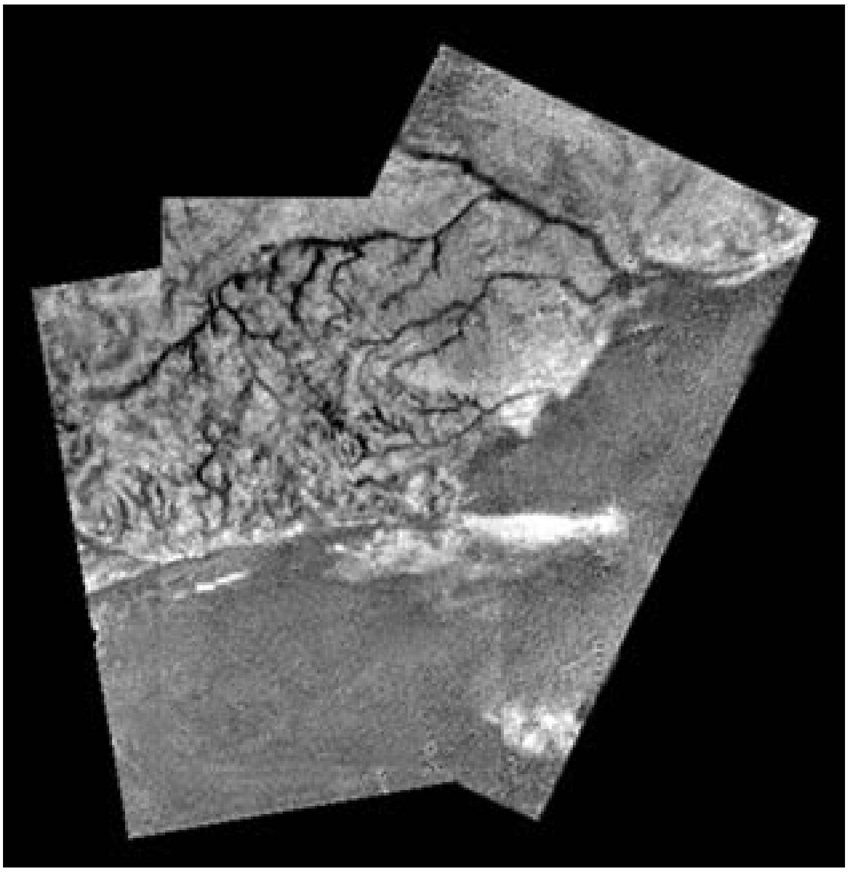


Figure 13: Methane clouds and rain, evaporating lakes, flowing rivers, and water ice-volcanoes all likely exist on Saturn's moon Titan, according to preliminary analyses of images taken by the Huygens lander. A snaking and branching riverbed is identified with the dark channel near the top of the above image, while a dark lakebed is identified across the image bottom. Both the riverbed and lakebed were thought to be dry at the time the image was taken but contained a flowing liquid – likely methane – in the recent past. Titan's surface was found to appear strangely similar to Earth even though it is so cold that water freezes into rock-hard ice. (Credits: ESA, NASA, Descent Imager/Spectral Radiometer Team [LPL])

Soil Reflectivity

During the descent, Huygens took many images of the surface with unprecedented detail. Due to the opacity of the atmosphere in the wavelengths of the DISR instrument, however, surface features could be identified only below a height of about 50 km. After landing, the surface reflection spectrum was measured from 480 nm to 1,600 nm and calibrated by means of the known emission spectrum of the DISR lamp, **see figure 14.** The peak reflectivity of about 0.18 occurs at 830 nm and decreases towards both sides. The red slope in the visible is consistent with organic material, such as tholins[6], but the infrared slope is still unexplained. Between 1,500 and 1,600 nm the reflectivity is low (0.06) and flat, consistent with water ice. Nevertheless, the decrease in reflectivity from 900 to 1,500 nm does not show the expected weak absorption bands of water ice near 1,000 and 1,200 nm, and the identity of the surface component responsible for this slope remains unknown. The entire set of DISR observations gives a new view of Titan, and reinforces the hypothesis that processes on Titan's surface are more similar to those on the surface of the Earth than anywhere else in the solar system.

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[6] Tholin is a hard, red-brownish substance made of complex organic compounds. Tholins don't exist naturally on Earth, because the present oxidizing atmosphere blocks their synthesis. However, tholins can be made in the laboratory by subjecting mixtures of methane, ammonia, and water vapour to simulated lightning discharges.

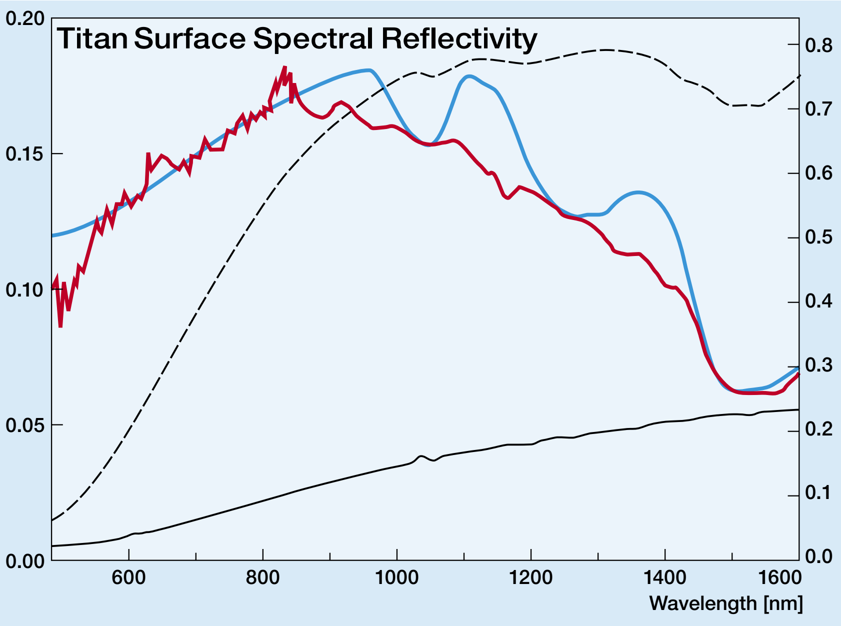


Figure 14 shows the surface reflectivity as measured after landing (red line). It is compared with a simulation (blue line) of a mixture of large grained low temperature water ice, yellow tholins, and an unknown component with a featureless slope between 850 and 1,500 nm. Spectra of two different organic tholins (yellow tholin: dashed line and dark tholin: solid black line) are also shown for comparison. Laboratory activity is ongoing in an attempt to identify or synthesize the missing blue material. (Credits: M. G. Tomakso and al. Rain, wind and haze; a close-up view from the descent to Titan's surface, Nature, to be published)

The Atmosphere

The Composition

The most striking feature of Titan's atmosphere are the various layers of haze, **see figure 15.** This haze is thought to be formed in a two stage-process: The atmospheric methane is dissociated by solar photons and high-energy electrons of Saturn's radiation belt. The remaining radicals then react and create larger organic molecules. Then, a first growth step may take place by accretion leading to small particles, roughly spherical monomers of 0.05 µm diameter. Due to their low mass, these particles remain at the altitude of their formation and it is thought that the outer haze layers are produced by this mechanism. Sedimentation and mixing begins then in a second step. Particles of about the same size stick together to form aggregates containing some tens of monomers up to several hundreds leading to very complex organic molecules and clusters. These cause the homogeneous orange haze in the lower atmosphere. In contrast to what was expected, Huygens has not found any clear part in the atmosphere. Rather, throughout the atmosphere there is a more or less dense haze much like a hazy day in Berne!

The near fly-by of Cassini in December 2004 at a distance of a mere 1,000 km from the surface allowed its mass spectrometers to detect gas from the upper atmosphere. An astonishingly complex array of short- and long-chain hydrocarbons and nitriles was detected, with atomic mass units of up to the instrument's maximum range of 100. The largest chains contained up to seven carbon atoms.

The mass spectrometers showed also that Titan's atmosphere is enriched in the heavy isotope of ^{15}N with respect to the more abundant light ^{14}N. The isotope ratio $^{15}N/^{14}N$ is much higher than on Earth. After insertion of Cassini in its orbit around Saturn its instruments detected the vast torus of gas orbiting Saturn along with Titan. As Titan lies within the magnetosphere of Saturn, it is constantly bombarded with high energy particles from Saturn's radiation belt. These particles collide with gas in Titan's atmosphere and cause gas to be ejected, forming the vast cloud of gas encircling Saturn. The loss of atmospheric matter by this process as well as the molecules' intrinsic thermal energy cause the enrichment of heavy isotopes because lighter isotopes move faster and therefore escape the Titan gravity field more easily than the heavier ones. In contrast, the heavy isotope of carbon is not enriched. The $^{13}C/^{12}C$ ratio is slightly lower than it is on Earth. This is consistent with the assumption of a methane replenishment process, which tends to keep the isotope ratio constant.

Figure 15: This image taken by the Cassini orbiter reveals Titan's complex layered haze structure. Two very distinct levels are discernible, while later images revealed as much as 12 separate layers above the main orange coloured haze. The haze tops roughly at an altitude of 500 km, which is much more than the Earth's stratosphere extending to about 30 km. (Credits: Cassini Imaging Team, SSI, JPL, ESA, NASA)

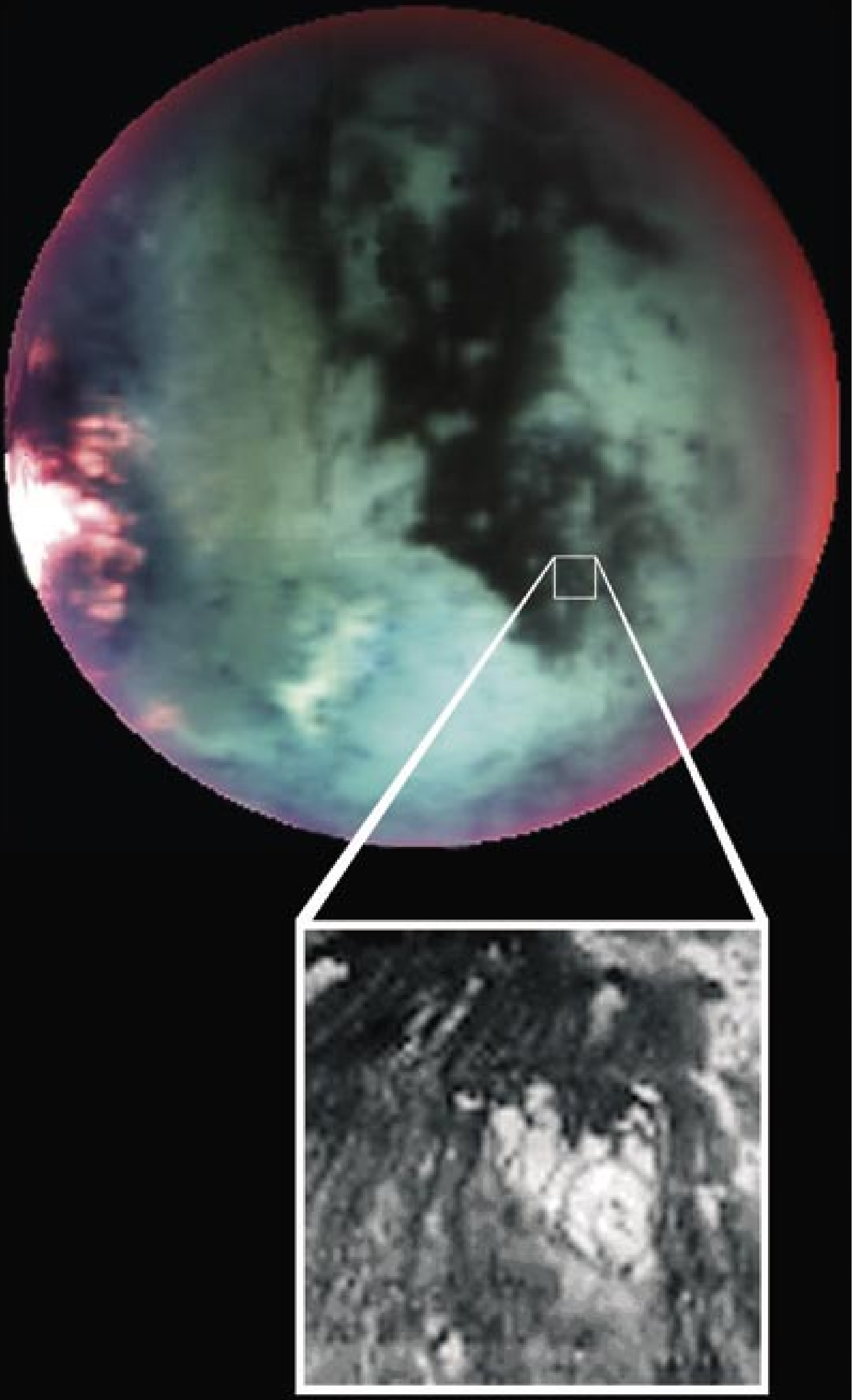
After landing on the surface, the Huygens DISR instrument indicated a methane abundance of 5% suggesting a relative humidity of methane of 50%, i.e. far from saturation. This observation together with the rivers carved out from the bedrock by fluids provide evidence for precipitation of methane with subsequent evaporation much like the rain on Earth.

Clouds and Atmospheric Dynamics

The Titan atmosphere shows signs of clouds, of which the largest concentrations have been found in the South Polar region, which is currently in early summer. The extra heat from the Sun is thought to create evaporation of methane from the surface. With the heated nitrogen, the methane is brought to higher altitudes in the atmosphere, where it condenses and forms cumulus clouds. From fly-by to fly-by these clouds vary significantly. It seems that the South Pole is a region of intense meteorological activity at present. Much fainter clouds were detected at mid latitudes. These lasted for only a few hours. Tracking these clouds allowed an estimate of the wind speed of 34 $\mathrm{m \cdot s^{-1}}$, faster than Titan rotates itself. This super-rotation of the Titan atmosphere had been predicted.

A third category of clouds take the form of east–west streaks hundreds of kilometres long. They seem to originate from fixed positions on the surface and one interpretation is that they are produced by surface processes and in fact may be gas vented from Titan's interior and then swept along by the super-rotating winds.

Figure 16: The domed feature detailed below is thought to be cryo-volcano, seen in infrared light. The lava welling up to form the volcanic mound would possibly be a slurry of methane, ammonia, and water ice combined with other ices and hydrocarbons. The circular feature is roughly thirty kilometers in diameter. (Credits: VIMS Team, U. Arizona, ESA, NASA)



Outlook

Titan has many similarities with the Earth. Its atmosphere is similar to the pre-biotic Earth atmosphere, and the surface processes strongly resemble their equivalents on the actual Earth. These facts make Titan an attractive object for scientific research as it may help to understand, how life developed on Earth 3.5 billion years ago. While it is a fascinating thought that understanding our past may require visiting such a distant object like Titan, its sheer distance from the Earth makes further missions in the near future very improbable especially in a time where the ESA science budget is squeezed. Clearly, the next logical step would be a sample return mission to Titan aiming at bringing back some material down to Earth. This, however, will remain a dream for the present generation of scientists to eventually become reality for their descendents…

The Author

Nicolas Gordon Morgan Thomas made his first lecture at his tender age of eight. Like his colleagues, he was asked to present a topic of interest; and as at that time Neil Armstrong just had set foot on the lunar surface, young Nicolas decided to give a presentation on the solar system. This laudable attempt, however, was stopped at Jupiter since his time allowance of two minutes was over at the giant planet. Notwithstanding this set-back planetary science continued to fascinate the youngster who later enrolled at the Polytechnic of Wolverhampton, and then focused on Experimental Space Physics at the University of Leicester, where he received a Masters Degree. Nicolas Thomas concluded his studies at the University of York with a thesis on the Jovian satellite, Io, which, as he confessed recently, continues to be his favourite celestial object.

The further path brought N. Thomas to the Max Planck Institute for Aeronomie (MPAe) of Lindau, where he worked on the analysis of data from the Halley Multicolour Camera aboard the Giotto spacecraft. A further post-doctoral fellowship allowed him to join the Space Science Department of ESA, and then he returned again to MPAe. During that time, he was also engaged as a visiting scientist at the Lunar and Planetary Laboratory at the University of Arizona, Tucson, and at the Queen's University of Belfast. In March 2003 he was elected Professor of Experimental Physics at the University of Bern.

Nicolas Thomas is the Principle Investigator for the Microscope on the Beagle 2 Lander and the Co-Principle Investigator of ESA's BepiColombo Laser Altimeter Experiment to Mercury. Over the years, Nicolas Thomas has published over 100 publications covering the fields of cometary, Jupiter and Mars science.

Nicolas Thomas is deeply fascinated by the beauties and miracles of our solar system, even, as he underlines, as a non-believer that there is life elsewhere in our solar system. But further out there? That is another story… We scientists ought to be honest, he confesses, and have to base our arguments on facts and not on fantasy. The solar system does not need fantastic hypotheses to fascinate people. Just tell them the truth. That's beautiful enough.