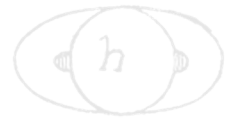


HUYGENS PROBE

The European Space Agency (ESA) Huygens Probe was an entry probe designed to study the atmosphere and the surface of Saturn's largest moon, Titan. Huygens was delivered to Titan by the Cassini Orbiter in January 2005 after a seven-year interplanetary cruise. The Huygens scientific objectives were to carry out detailed in situ measurements of the physical properties, the chemical composition and the dynamics of the atmosphere and to provide a local characterization of the surface near the landing site. Titan's Earth-like surface was revealed in images taken during the probe's descent to the surface.

Huygens was a highly sophisticated robotic laboratory equipped with six scientific instruments including: 1) Aerosol Collector Pyrolyser (ACP), 2) Descent Imager and Spectral Radiometer (DISR), 3) Doppler Wind Experiment (DWE), 4) Gas Chromatograph and Mass Spectrometer (GCMS), 5) Huygens Atmospheric Structure Instrument (HASI), and 6) Surface Science Package (SSP). Additionally, an engineering system, the Radar Altimeter, provided some scientific information about the structure along the ground track. The Doppler signature of the transmitted Huygens radio signal was directly detected by the two largest radio telescopes that were included in a network of 17 telescopes that were part of the very long baseline interferometry (VLBI) project put together a couple years before Huygens' release. These instruments allowed the Huygens probe to investigate Titan's atmospheric composition and dynamics, formation and evolution, to study Titan's meteorology, to investigate Titan's organic haze and to examine Titan's surface characteristics and to infer information about Titan's internal structure. The Huygens science team successfully addressed all the Huygens mission science objectives.



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EXECUTIVE SUMMARY

The Cassini-Huygens mission comprising the NASA Saturn Orbiter and the ESA Huygens Probe, arrived at Saturn in late June 2004. Following the separation of the Huygens probe from the Cassini Orbiter on December 25, 2004, Huygens arrived at Titan on January 14, 2005. Following entry protected by its heatshield, Huygens descended under two sequentially deployed parachutes to Titan's surface where it landed safely. It continued to fully operate on Titan's surface for several hours, until its batteries were depleted. Huygens findings and discoveries include new and improved understanding of Titan's atmospheric structure and chemical composition, distribution and composition of atmospheric aerosols, morphology and composition of the surface at the Huygens landing site, the altitude profile of zonal and near-surface winds along the Huygens descent trajectory, and atmospheric electrical properties. The data set collected by Huygens provided significant contribution to the understanding of the origin and evolution of Titan [Lebreton et al. 2009]. Furthermore, Huygens data set also served as the ground truth for several orbiter atmosphere and surface observations, proving the complementarity of in situ and remote sensing observations of a newly explored world.

In situ (accelerometry) measurements were made from about 1400 km altitude under the heatshield configuration. They revealed a very wavy atmospheric temperature/density profile attributed to atmospheric gravity waves. Direct in situ measurements of various atmospheric parameters started after parachute deployment (and heatshield release) at an altitude of about 150 km. During the latter stages of the descent, below about 50–60 km altitude above the surface, clear images of the surface were obtained by DISR, revealing a remarkably Earth-like world, showing strong evidence for erosion due to past epochs of flowing liquids, possibly methane. The Huygens descent trajectory carried the probe across a boundary between a bright, icy, rugged terrain and into a darker flat area where Huygens landed. Measured profiles of pressure and temperature below 150 km by HASI were found to be close to those expected based on Voyager observations. At the landing site, the surface temperature and pressure measured by Huygens were 93.7 K and 1,470 mbar, respectively. Reflectance spectra taken during descent show that the surface is primarily composed of dirty water-ice, and images of the landing site from the surface show a scattering of water-ice cobbles up to several centimeters in diameter. The SSP penetrometer found the surface to be unconsolidated, with the consistency of damp sand.

During the latter stages of the descent, below about 50–60 km altitude above the surface, clear images of the surface were obtained by DISR, revealing a remarkably Earth-like world, showing strong evidence for erosion due to past epochs of flowing liquids, possibly methane.

Atmospheric winds measured by Doppler tracking of the Huygens probe were found to blow predominantly in the direction of Titan's rotation (prograde: west–east) with speeds of about



125 m/s (~450 km/hr) detected above an altitude of 120 km. Although the winds diminished with decreasing altitude as expected from both Voyager and ground-based observations, a somewhat unexpected weakening of the winds was found between 100 km and 60 km. In the planetary boundary layer near the surface, the direction of the winds changed to include a significant north-south component.

Haze was detected from the top of the atmosphere to the surface with no evidence of the haze-free atmosphere predicted below 60 km. At an altitude of about 60 km, an ionosphere-like layer likely produced by galactic cosmic rays predicted by models was characterized, but at an altitude slightly lower than predicted by models [Whitten et al. 2007] was characterized, but at an altitude slightly lower than predicted by models.

The GCMS and ACP measurements of Titan's atmospheric composition and aerosols confirmed the presence of a complex organic chemistry in both the gas and the solid phase, and vertical abundance profiles were obtained for the more abundant species. Although primordial argon ^{36}Ar and radiogenic argon ^{40}Ar were detected, there was no detection of either xenon or krypton. Isotopic ratios of carbon, nitrogen, and deuterium to hydrogen (D/H) were measured, helping to further constrain formation scenarios for Titan's atmosphere [Niemann et al. 2010].

Composition measurements made by GCMS from the surface material vaporized after landing included detection of ^{40}Ar . The time profile of the composition of surface vapors indicated the Huygens probe landed on a surface damp with methane which subsequently evaporated as the cold regolith was heated by the GCMS inlet and the DISR lamp. Compounds such as C_6H_6 , C_2N_2 , and CO_2 were detected in the gas from the surface material.

Huygens Science Assessment

The Huygens science objectives were defined in the ESA's Announcement of Opportunity (AO), 1989.

Table HUYGENS-1. Huygens Science Assessment.

Fully/Mostly Accomplished:		Partially Accomplished:	
H1 Titan Atmosphere Formation and Evolution: Determine Abundance of atmospheric constituents (including noble gases); establish isotope ratios for abundant elements; constrain scenarios of formation and evolution of Titan and its atmosphere.			
Huygens Objectives	Status	Instrument	Notes
H1.1		GCMS	CH_4 mole fraction $5.65 \pm 0.18\%$ and CH_4 relative humidity near surface ~50%.
H1.2		GCMS	Measured isotopes of H (D/H), C, N, Ar
H1.3		GCMS	Detected extremely low quantities of ^{36}Ar which rules out primary origin of N_2 and argues N_2 as secondary like on Earth; Measured isotopic ratios of C, N, and D/H helps constrain atmospheric formation & evolution scenarios; Radiogenic ^{40}Ar measured to constrain Titan outgassing history.



H2 Titan Atmosphere Composition and Distribution: Observe vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photochemistry of the stratosphere; study formation and composition of aerosols.

	Huygens Objectives	Status	Instrument	Notes
H2.1	Observe vertical distribution (profile) of trace gases		GCMS, DISR	DISR: low altitudes; GCMS: Vertical distribution of CH ₄ and H mole fractions
H2.2	Search for more complex organic molecules		GCMS	Found evidence of heavy organic molecules
H2.3	Investigate energy sources for atmospheric chemistry		DISR, HASI	DISR measured light absorption vs altitude; HASI detected cosmic ray ionization
H2.4	Model the photochemistry of the stratosphere		GCMS, ACP	Data used in multiple photochemical models
H2.5	Study formation and composition of aerosols		GCMS, ACP	Low mass of ACP sample transferred to GCMS limited the results to simple species, rather than complex hydrocarbon hazes

H3 Titan Meteorology: Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning discharges.

	Huygens Objectives	Status	Instrument	Notes
H3.1	Measure winds and global temperatures		DWE, HASI, DISR	DISR: Wind drift near surface via feature tracking; PBL detected at ~7 km; Measurements provided ground truth for global Cassini remote sensing measurements.
H3.2	Investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere		DWE, DISR	Huygens measurements provided ground truth for Cassini global remote sensing studies for seasonal effects.
H3.3	Search for lightning discharges		DISR, HASI	Schumann Resonance seen by HASI PWA, but not linked to lightning activity. No optical or RF signature of lightning found.

H4 Titan Surface Characteristics and Internal Structure: Determine the physical state, topography and the composition of the surface; infer the internal structure of the satellite.

	Huygens Objectives	Status	Instrument	Notes
H4.1	Determine the physical state, topography and the composition of the surface		SSP, HASI, DISR, GCMS	DISR: Imaging of surface topography show drainage basins, dry riverbeds, dunes; IR reflectance spectroscopy. GCMS: Trace organic species found in surface measurements. HASI: Surface permittivity SSP: Acoustic Sounding; Surface penetrometry and accelerometry. Radar altimeter: surface topography and reflectivity.
H4.2	Infer the internal structure of the satellite;		HASI	HASI PWA: Measurement of Schumann resonance within ionosphere / subsurface ocean waveguide.

H5 Titan Upper Atmosphere: Investigate the upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

	Huygens Objectives	Status	Instrument	Notes
H5.1	Investigate upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn		DISR, HASI	DISR: Hydrocarbon haze number density in upper atmosphere. HASI PWA: Measurement of Schumann resonance within ionosphere / subsurface ocean waveguide.



HUYGENS MISSION OVERVIEW

The Huygens probe was the ESA contribution to the NASA/ESA/ASI Cassini-Huygens mission. The Cassini-Huygens spacecraft arrived in the Saturnian system on June 30, 2004, following a seven-year cruise, and performed a perfect Saturn Orbit Insertion maneuver to initiate a long series of orbits around Saturn that included frequent regular flybys of Titan. For the first three Titan flybys, Cassini was still carrying the Huygens probe. Following the third Titan encounter on December 13, 2004, the Cassini orbiter main engine was fired on December 17 to bring the orbiter and Huygens probe, still attached, onto a collision trajectory with Titan. Small onboard jets were fired on December 23, 2004, to fine-tune the flight path of Cassini-Huygens to align the spacecraft on a trajectory that would target Huygens to the desired entry location, and on December 25, 2004, at 02:00 UTC the Spin/Eject Device separated Huygens from Cassini with a relative speed of approximately 0.35 m/s and a spin rate of 7.5 revolutions per minute. The Huygens probe was targeted for a low southern-latitude site on the dayside of Titan. Constrained by the heat shield design performance and radio visibility conditions between the probe and the orbiter during the descent, the probe entry flight path angle into the atmosphere was set to -65° (25° from the local vertical) with a tolerance of three degrees. The relative position of Cassini, Huygens, and Titan enabled a theoretical maximum telecommunications link between Huygens and Cassini of 4 hours 30 minutes. Huygens and Cassini were effectively in radio contact from the start of the radio transmission after parachute deployment until after about 72 minutes after landing. Two Earth radio telescopes, first Green Bank in West Virginia, and then Parkes in Australia, detected directly the Huygens radio signal (carrier).

The relative position of Cassini, Huygens, and Titan enabled a theoretical maximum telecommunications link between Huygens and Cassini of 4 hours 30 minutes.

Prior to arrival at the atmospheric entry interface point on January 14, 2005, at 11:04 UTC [Lebreton et al. 2005], the Huygens coast timer woke up Huygens. Four and a half hours later, the Huygens probe encountered the Titan atmosphere at an altitude of about 1500 km above the surface, causing the 300 kg probe to aerobrake from its approaching velocity of around 21,600 km/h (6 km/s) to less than 1,400 km/h at 150 km altitude. During entry, Huygens experienced aerodynamic forces up to 12 g (measurements saturated at 10 g by design) and an estimated entry temperature of $12,000^\circ\text{C}$ ($21,600^\circ\text{F}$) in the shock that formed in front of the probe, leading to an expected heat shield temperature of $1,800^\circ\text{C}$. After the entry, speed had decreased to about Mach 1.4 (290 km/h at about 160 km altitude). The pilot chute was deployed and the backshell of the heat shield was pulled away by the pilot chute and deployed, within less than 2 seconds the 8.3-meter (diameter) main parachute. The heat shield was released 30 seconds later. Following 15 minutes of descent, the main parachute was discarded and replaced at about 110 km altitude by a smaller 3-meter (diameter) parachute to ensure that the probe would reach the surface at least 30 minutes before the orbiter would pass below the horizon as seen from the



landing site. The descent from atmospheric entry to landing took 2 hours 27 minutes 50 seconds. The radio contact between Huygens and Cassini was operational until the orbiter passed below the horizon 72 minutes after landing.

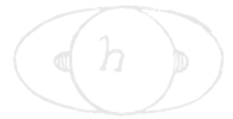
The light level on the surface of Titan was roughly 1,000 times less than experienced on Earth by day, but 500 times brighter than the light of the full moon.

At an altitude of 60 km, the surface-sensing radar was turned on to provide altitude information to the onboard computers, which then broadcast the altitude to the instruments to allow the instruments to adapt their measurement sequence to the measured, rather than to the predicted altitude. Accurate altitude information was in fact provided only below 20 km. DISR, HASI and SSP adapted their measurement sequence to the measured altitude information provided by the onboard computer. This tuning allowed the Huygens surface lamp to be activated at 700 m altitude and the SSP instrument to activate its high-time

resolution impact detection measurement mode while approaching the surface. The light level on the surface of Titan was roughly 1,000 times less than experienced on Earth by day, but 500 times brighter than the light of the full moon. Although the natural lighting by the Sun was sufficient to illuminate the landing site, the surface lamp enabled high signal-to-noise multispectral measurements of surface reflectivity.

Due largely to the thick atmosphere and the excellent performance of the parachutes, the surface impact speed was slightly less than 5 m/s (about 18 km/h). Once on the surface, Huygens' five batteries lasted much longer than expected, allowing the probe to continue functioning several hours after landing, providing time for the orbiter to collect surface data for 1 hour 12 minutes before disappearing below the horizon. The Earth-based radio telescope received the Huygens signal for more than 3 hours after landing, until 16:00 GMT, corresponding to the end of the window assigned to that observation.

More than 350 images and numerous spectra were returned by the DISR camera during descent, while four other probe instruments, the HASI, ACP, GCMS, and the SSP sampled Titan's atmosphere to help determine its composition and structure, and to characterize the aerosols. To retrieve the altitude profile of zonal winds, the DWE was designed to provide Doppler tracking of the probe throughout descent. Once on the surface, the SSP, HASI, GCMS, and DISR continued to acquire data (ACP turned off as planned below 10 km). The Huygens probe was also tracked by a VLBI network of 17 radio telescopes, as part of an experimental project put in place about one year before Huygens landing. Two of the VLBI radio telescopes, the Green Bank Telescope and Parkes were equipped with highly sensitive radio receivers provided by the JPL radio science team. They collected the most accurate Doppler information during the descent, as this information could not be retrieved from the channel of the Huygens radio link equipped with ultra-Stable Oscillators as the receiver onboard Cassini was not activated properly due to a programming error. Limited Doppler information was however retrieved from the



second channel of the Huygens-to-Cassini radio link which itself was equipped with less stable crystal oscillators.

The Huygens science data was relayed to the Cassini orbiter at a rate of 8 kilobits per second and stored in solid-state memory on the orbiter. Although the data were transmitted on two nearly redundant channels, A and B, a programming error in the channel A receiver resulted in no data collected through that channel. In the end, because of the redundancy philosophy applied to the Huygens design, almost all of the measurements were recovered. In particular, the exceedingly weak signal from Huygens was captured by two of the Earth-based radio telescopes, Green Bank and then Parkes, both equipped with highly sensitive radio receivers provided by the JPL radio science team, in effect providing a channel C to Doppler-track the probe throughout descent and enabling the DWE to retrieve the Titan zonal wind profile. In the end, radio telescopes on Earth received 5 hours 42 minutes of Huygens data, including 3 hours 14 minutes from the surface. The probe survived the landing and continued transmitting from the surface for a much longer time than expected because Huygens touched down on a relatively soft solid surface. Once the Cassini orbiter flew beyond the horizon as seen from Huygens, the probe continued transmitting for several hours. The Huygens signal was still detected when Parkes stopped tracking it at 16:00 UTC. Flight performance of the probe allowed an estimate that the batteries became depleted about 20–25 minutes later. [Huygens Flight Performance Report, Huygens data set archive, Lorenz 2017].

TOP TEN HUYGENS FINDINGS

The top 10 Huygens discoveries at Titan are listed below and can be found at ESA website <http://sci.esa.int/cassini-huygens/55221-huygens-titan-science-highlights/>, [ESA 2017].

On 14 January 2005, at 13:34 CET (12:34 UTC), ESA's Huygens probe entered the history books by descending to the surface of Titan, Saturn's largest moon. This was humanity's first successful attempt to land a probe on another world in the outer solar system.

Huygens hitched a ride to the Saturn system during an epic, seven-year voyage attached to NASA's Cassini spacecraft. The final chapter of the interplanetary trek was a 21-day solo cruise toward the haze-shrouded moon. Plunging into Titan's atmosphere, the probe survived the hazardous 2-hour 27 minute descent to touch down safely on Titan's frozen surface.

Huygens continued to transmit back to Earth for another 72 minutes before contact was lost with Cassini as it dipped below the horizon. The stream of data provided a unique treasure trove of in situ measurements from the planet-sized satellite which scientists are still mining today. In the following articles we present 10 important results from the pioneering mission.

1. Profiling the Atmosphere of Titan

The HASI made the first in situ measurements of Titan's atmosphere. HASI determined the atmospheric temperature, pressure, and density from an altitude of 1400 km down to the surface.

Long before ESA's Huygens probe arrived at Titan, scientists knew that the moon's dense atmosphere was mainly composed of nitrogen, with some methane, but the atmosphere's structure—its temperature and pressure at different altitudes—was poorly understood.

By monitoring the probe's rate of deceleration as it plunged into the atmosphere, the HASI instrument directly determined the density of the upper atmosphere. The temperature was derived from models of how it should change with density and altitude. In the lower atmosphere (below 160 km) and on the surface of Titan, HASI directly measured the pressure and temperature, as well as electrical properties such as permittivity and the distribution of ions.

HASI data showed that the upper atmosphere (the thermosphere) was generally warmer and more dense than expected. Titan's atmosphere was also found to be highly stratified.

Above 500 km, the average temperature was about -100°C but strong variations of $10\text{-}20^{\circ}\text{C}$ were detected due to inversion layers and other phenomena, such as, gravity waves and tides. The mesosphere was virtually absent, in contrast with theoretical predictions.

Below 500 km, the temperature increased quite rapidly, reaching a maximum of -87°C at the top of the stratosphere, at an altitude of 250 km. The temperature then decreased steadily throughout the stratosphere, reaching a minimum of -203°C at an altitude of 44 km. This marked the boundary between the stratosphere and the troposphere.

The temperature increased again as the probe neared the surface, rising to a chilly -180°C at the landing site. The surface pressure was 1.47 times that on Earth.

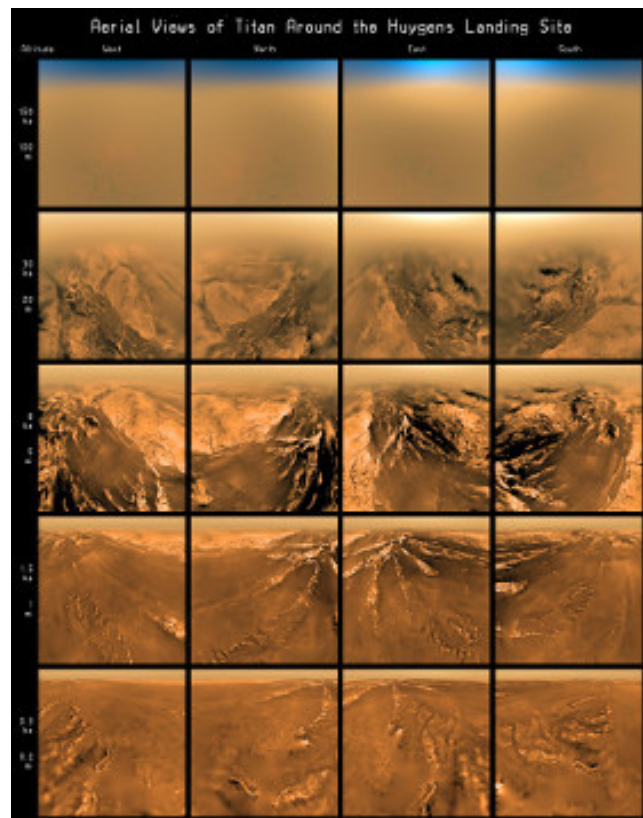
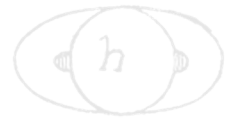


Figure HUYGENS-1. Huygens' view of Titan from five altitudes. Credit: ESA/NASA/JPL/University of Arizona.



2. Titan's Super-rotating Winds

Although spacecraft observations had indicated that strong zonal (east-west) winds may exist in Titan's atmosphere, the first direct measurements were made by the Doppler Wind Experiment on ESA's Huygens probe.

By measuring the Doppler shift of the radio signal from Huygens and studying panoramic mosaics from the onboard imager to work out the descent trajectory, it was possible to create a high resolution vertical profile of Titan's winds, with an estimated accuracy of better than 1 m/s.

Huygens found that the zonal winds were prograde (the same direction as the Moon's rotation) during most of the atmospheric descent. The probe generally drifted east, driven by remarkably strong westerly winds which peaked at roughly 120 m/s (430 km/h) at an altitude of about 120 km.

Down to a height of 60 km, large variations in the Doppler measurements were observed—evidence that Huygens endured a rough ride as the result of significant vertical wind shear. Wind speeds then decreased toward the surface, dropping from 30 m/s (108 km/h) at an altitude of 55 km to 10 m/s (36 km/h) at a height of 30 km, eventually slowing to 4 m/s (14 km/h) at 20 km. The winds dropped to zero and then reversed direction at around 7 km.

The large prograde wind speeds measured between 45 km and 70 km altitude and above 85 km were much faster than Titan's equatorial rotation speed. It was the first in situ confirmation of the predicted super-rotation of the moon's atmosphere, even though the speed observed was slightly lower than expected.

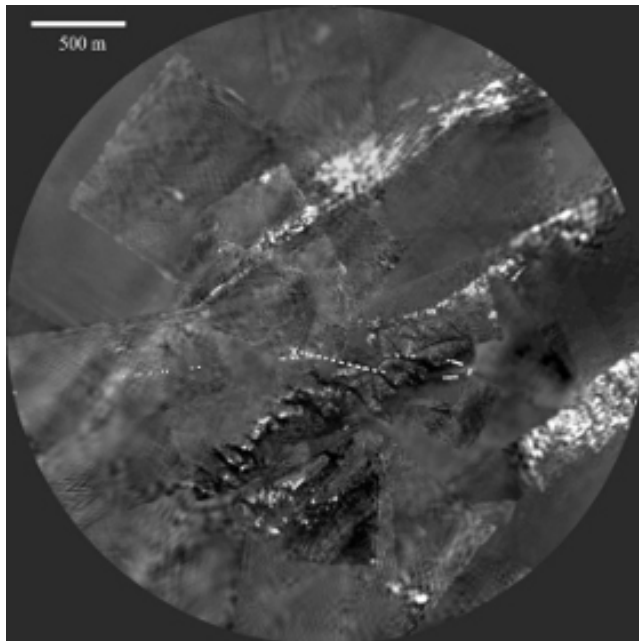


Figure HUYGENS-2. The ground track of Huygens is marked on this aerial view of Titan. Credit: ESA/NASA/JPL/University of Arizona.

A layer with surprisingly slow wind, where the sideways velocity decreased to near zero, was detected at altitudes between 60 km and 100 km.

During the last 15 minutes of the descent, Huygens headed west-northwest at a speed of approximately 1 m/s. The wind speed on the surface was between 0.3 m/s and 1 m/s.

Over the duration of the descent, the probe drifted eastward a distance of 165.8 km with respect to the surface of Titan.

3. Methane Mystery

ESA's Huygens probe made the first direct measurements of the composition of Titan's lower atmosphere. Data returned by the GCMS on Huygens included altitude profiles of the gaseous constituents, isotopic ratios and trace gases (including organic compounds).

Two of the key questions about Titan are the origin of the nitrogen and methane in its atmosphere, and the mechanisms by which methane levels are maintained. Since sunlight destroys methane irreversibly on Titan, its lifetime in the atmosphere is only tens of millions of years. Somehow the methane must be continually or periodically replenished.

The primary constituents of Titan's atmosphere were confirmed to be nitrogen and methane. In the stratosphere, levels of methane were found to be fairly low and the gas was uniformly mixed. Then, at an altitude of 40 km, in the upper troposphere, the relative amount of methane began to increase gradually until approximately 7 km, when it reached 100% relative humidity (saturation level).

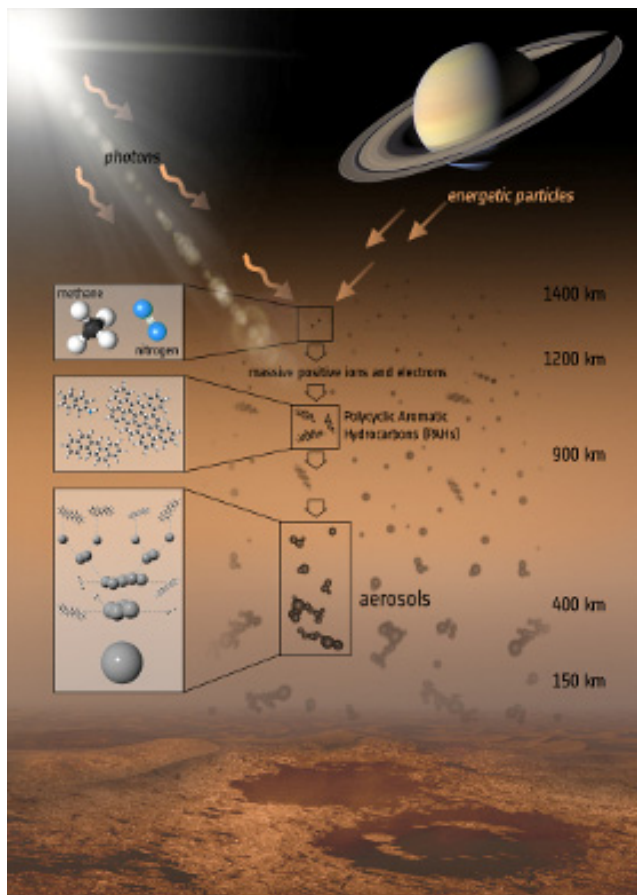


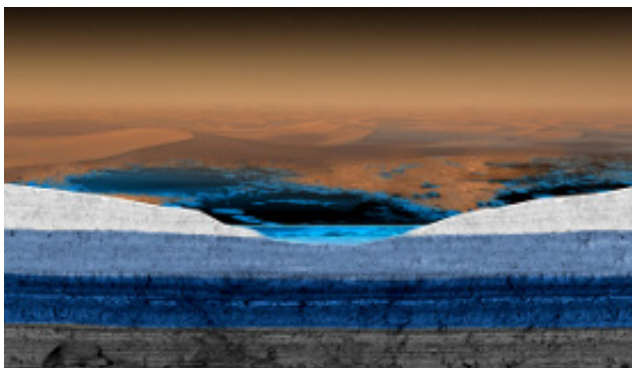
Figure HUYGENS-3. Chemistry in Titan's atmosphere.
Credit: ESA/ATG medialab.

For the last part of the descent, methane amounts remained relatively constant until the probe touched down on the surface. A sudden, 40% increase in the methane signal after landing, while the nitrogen count rate remained constant, suggested the presence of liquid methane on the surface. This may have been due to the spacecraft heating the surface material. This increased value for methane remained nearly constant for about one hour, with a hint of a very slight decrease in the level toward the end of this period.

Measurements of the carbon isotopes in the methane provide no support for suggestions that it is generated by active micro-organisms on Titan. The methane was probably accreted by Titan during the moon's formation, and large quantities of liquid methane are now trapped in ices beneath the surface, possibly reaching the surface through some form of cryovolcanism. (Surface features



associated with possible cryovolcanism have been observed by Cassini. See Science highlights from Huygens: #5. Radioactive decay and cryovolcanism [ESA 2019a].) This activity would replace the methane that is lost as a result of photochemistry in the atmosphere.



The spectra taken on the surface also showed signatures characteristic of more complex hydrocarbons, such as ethane, cyanogen and benzene.

Figure HUYGENS-4. Titan's subsurface reservoirs contain hydrocarbons, including methane. Credit: ESA/ATG medialab.

4. The Origin of Titan's Nitrogen Atmosphere

Titan and Earth are the only worlds in our solar system that have thick nitrogen atmospheres. Although data from the Voyager Mission had implied that nitrogen (N₂) was the main atmospheric gas, the GCMS on ESA's Huygens probe made the first direct identification of bulk atmospheric nitrogen and its abundance. Other GCMS atmospheric measurements provided clues about where this atmosphere came from.

During its descent to the surface, the GCMS measured isotopic ratios and trace species in the atmosphere. One of the objectives for the GCMS was to search for heavy, noble gases such as argon-36 (³⁶Ar), argon-38 (³⁸Ar), krypton (Kr), and xenon (Xe). These primordial gases have been detected and measured in meteorites, in the atmospheres of Earth, Mars, Venus (to some extent), and Jupiter. Differing patterns of relative abundances and isotopic ratios of the gases provide insights into the origin and evolution of these objects. As a result, their measurements in the atmosphere of Titan were eagerly anticipated.

Scientists had theorised that these noble gases were present throughout the solar nebula, and should therefore have been incorporated into both Saturn and Titan during the early stages of planet formation. In the context of the origin of nitrogen, ³⁶Ar is of particular importance, and the GCMS found that the ratio of ³⁶Ar to nitrogen was about one million times less than is found in the Sun.

Direct condensation of gases in the young Titan would have resulted in the capture of ³⁶Ar, as well as nitrogen, in solar proportions. However, the depleted ratio detected by the GCMS on Huygens implies that the nitrogen was captured as ammonia (NH₃) or in other nitrogen-bearing compounds.

The rarity of noble gases on Earth has long been viewed as strong support for the atmosphere having been formed by the impacts of gas-rich planetesimals, and the near absence of noble gases from Titan provides more support for this hypothesis.

5. Radioactive Decay and Cryovolcanism

One of the trace gases detected by the GCMS on ESA's Huygens probe was radiogenic argon-40 (^{40}Ar). This isotope offers a window to the interior of the giant moon.

Radiogenic argon was detected by the GCMS below 18 km. This detection was important because ^{40}Ar originates solely from the decay of potassium-40 (^{40}K), a radioactive isotope of potassium found in rocks. The only possible source of this ^{40}Ar is rocks which exist deep in Titan's interior, below the satellite's mantle of hydrocarbon and water ice.

Since the radioactive half-life of ^{40}K is about 1.3 billion years, much shorter than the lifetime of Titan, the small amount of ^{40}Ar in the atmosphere provides an important indicator of how much outgassing has occurred from the deep interior.

If the rocky component of Titan's interior has the same composition as that of Earth and has outgassed to the same extent, ^{40}Ar should be about ten times more abundant than measured by Huygens, comprising approximately 0.05% of the atmosphere. If the interior was warm enough in the past for a liquid water or water-ammonia mantle to have reached all the way down to the moon's rocky core, potassium could have seeped into the liquid. The radiogenic ^{40}Ar could then have outgassed to the surface.

Certainly, the presence of the ^{40}Ar at the levels seen by Huygens is a strong indication of geological activity on Titan, and consistent with periodic replenishment of atmospheric methane (see Science highlights from Huygens: #3. Methane Mystery [ESA 2019b].) The apparent evidence for cryovolcanism observed by the Cassini orbiter—involving water or a mixture of water and ammonia—provides one possible process for release of both gases from the interior.

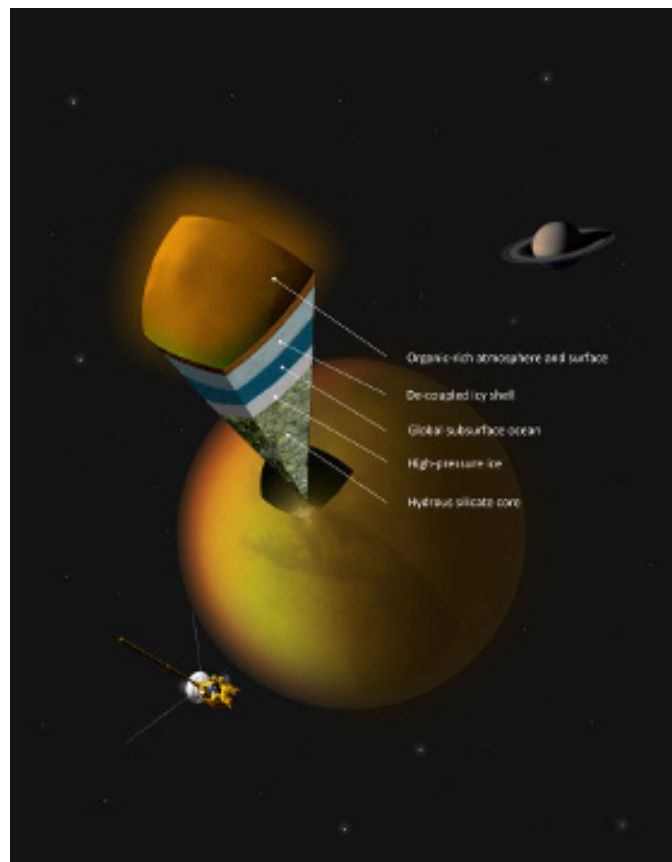


Figure HUYGENS-5. Concept sketch of the interior of Titan. Credit: Angelo Tavani.



6. Hazy Titan

One of the most noticeable features of Titan is the orange blanket of haze that hides its surface. However, no one knew whether the haze extended to the surface until ESA's Huygens probe landed on the icy moon.

The measurements of the DISR on the Huygens probe provided in situ information on the optical properties, size and density of the haze particles. The observations showed that there was a significant amount of haze at all altitudes throughout the descent, extending all the way down to the surface. With decreasing altitude, the haze particles became brighter, and the particle sizes increased, due to collisions which resulted in a 'snowball' effect, as well as condensation of methane, ethane and hydrogen cyanide gases onto small aerosol nuclei at lower levels.

Huygens detected three distinct haze regions (region I above 80 km, region II between 80 and 30 km, and region III between 30 km and the surface), based on the density and optical properties of the atmosphere.

Before the Huygens mission, it was generally believed that the tiny haze particles slowly sink through the stratosphere, eventually acting as condensation nuclei for lower-level clouds.

Some scientists theorized that the haze might clear below an altitude of 50 km to 70 km due to condensation of gases such as methane. However, the probe's DISR showed that Huygens began to emerge from the haze only in the troposphere, 30 km above the surface.

Another thin layer of methane haze was detected at an altitude of 21 km, where the local temperature was -197°C and the pressure was 450 mbar. This feature may be an indication of methane condensation. Indeed, the data suggest the presence of layered methane clouds in Titan's troposphere, at altitudes between 8 km and 30 km.

When combined with ground-based measurements, the data suggest an upper methane ice cloud (or haze) between approximately 20 km and 30 km and a liquid methane-nitrogen cloud layer between 8 km and 16 km, perhaps with a gap in between.

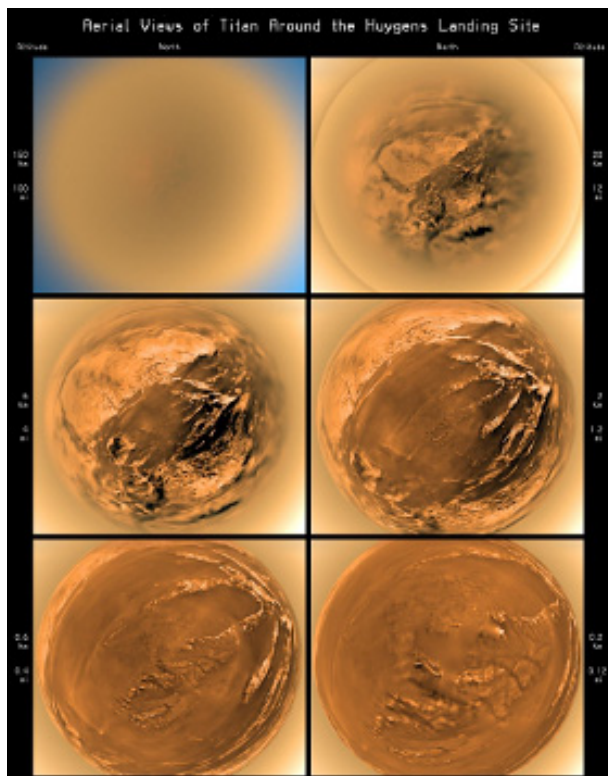


Figure HUYGENS-6. Six stereographic images of Titan's surface taken during Huygens's descent to Titan's surface, showing the haze clearing. Credit: ESA/NASA/JPL/University of Arizona.

7. Titan's Tiny Aerosols

Tiny particles (aerosols) in Titan's atmosphere have long been suspected to play an important role in determining its thermal structure and atmospheric processes. However, until the Huygens mission, no direct measurements had been made of the chemical composition of these particles.

One set of measurements was made by the GCMS and the ACP experiment. The collected aerosol particles were heated in the ACP oven in order to vaporize all volatile components, and the composition of the gases released by each sample was then analyzed by the GCMS.

Two atmospheric samples were obtained during the descent of Huygens. One was taken at 130-35 km (the middle stratosphere) and the other at 25-20 km (the middle troposphere). Ammonia (NH_3) and hydrogen cyanide (HCN) were identified as the main gases released in the oven, confirming that carbon and nitrogen are major constituents of the aerosols.

No substantial difference was found between the two samples, suggesting that the aerosols' composition was the same at both altitudes. This supports the idea that they have a common source in the upper atmosphere, where ultraviolet sunlight photochemically alters gases such as methane.

Meanwhile, the DISR characterized the optical properties of the photochemical aerosols from 150 km altitude to the surface. They were found to match the properties of 'tholins', materials created in laboratories by sending electrical discharges into mixtures of nitrogen and methane.

The aerosols' optical properties can be reproduced by the condensation of hydrogen cyanide close to 80 km, ethane condensation close to the tropopause (44 km), and methane condensation from the tropopause down to 8 km.

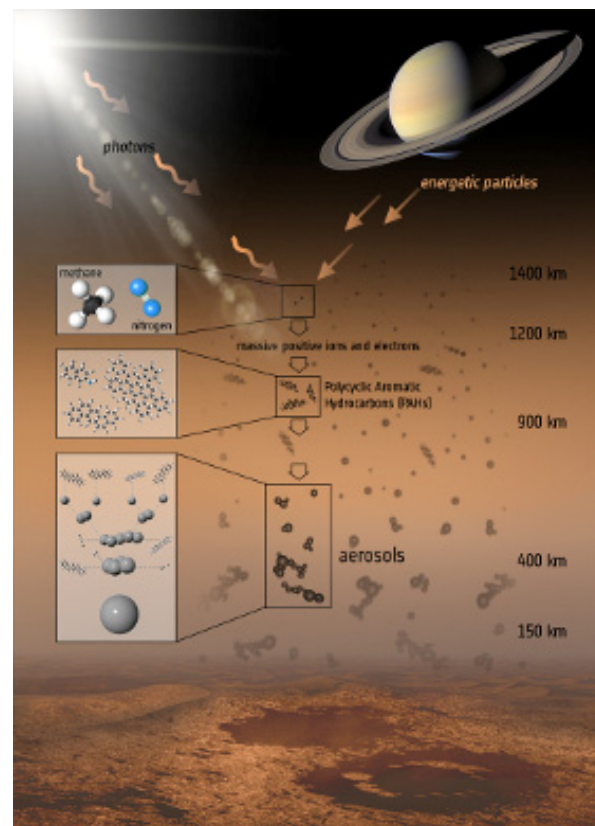


Figure HUYGENS-7. How aerosols form in Titan's haze. Credit: ESA / ATG medialab.



8. Dry River Beds and Lakes

Hidden beneath an all-embracing blanket of haze, Titan's surface remained a mystery until the DISR on ESA's Huygens probe sent back a series of unique, spectacular images.

The DISR took several hundred visible-light images with its three cameras during its 2 hour 27 minute descent, including several sets of stereo image pairs which enabled scientists to construct digital terrain models. See Huygens's descent to Titan's surface [ESA 2015] for further details and enhanced video.

The cameras revealed a plateau with a large number of dark channels cut into it, forming drainage networks which bore many similarities to those on Earth. The narrow channels converged into broad rivers, which drained into a broad, dark, lowland region. The ravines cut by the rivers were approximately 100 m deep and their valley slopes were very steep, which suggested rapid erosion due to sudden, violent flows.

No evidence of surface liquid was found at the time of the landing. However, it seems likely that, from time to time, the entire dark region is inundated by floods of liquid methane and ethane. If the darker region is a dry lakebed, it is too large to have been caused by the creeks and channels visible in the images. It may have been created by other larger river systems or some large-scale catastrophic event, which predates deposition by the rivers seen in the images.

Brighter regions north of the landing site displayed two different drainage patterns: 1) bright highlands with rough topography and deeply incised branching (dendritic) drainage networks with dark-floored valleys that indicated erosion by methane rainfall; and 2) short, stubby channels that followed linear fault patterns, forming canyon-like features suggestive of spring sapping by liquid methane.

The topographic data showed that the bright highland terrains are extremely rugged, often with slopes of up to 30 degrees. These drain into relatively flat, dark lowland terrains. The dark material that covers the plains may have been carried along by the flows and could be made up of photochemical deposits rained down from above.

The landing site itself resembled a dried-up riverbed. Rounded cobbles, 10 cm to 15 cm in diameter and probably made of hydrocarbons and water ice, rested on a darker granular surface.



Figure HUYGENS-8. Titan's surface viewed by DISR. Credit: ESA/NASA/JPL/ University of Arizona.

9. Schumann-like Resonances: Hints of a Subsurface Ocean

One of the most surprising discoveries of ESA's Huygens Mission was the detection of an unusual source of electrical excitation in Titan's atmosphere.

Scientists had wondered whether lightning might be generated in Titan's atmosphere, so Huygens was equipped with the permittivity, wave and altimetry (PWA) experiment to detect tell-tale radio signals.

On Earth, thousands of lightning flashes take place every second, and each bolt generates a radio 'crackle'. This means our atmosphere is continuously generating extremely low frequency (ELF) radio signals, known as Schumann resonances. These global electro-magnetic resonances, excited by lightning discharges, occur in the 'cavity' formed between Earth's surface and the ionosphere—a region of electrically charged particles in Earth's upper atmosphere.

Such a resonance is known only on Earth for being released by storm lightning and it had long been considered that its existence on other planets would make it possible to reveal the presence of both storm activity and a conductive ground.

Although no lightning or thunderstorms were detected in Titan's atmosphere, the PWA did detect an unusual ELF signal at a frequency of around 36 Hertz. Huygens also discovered a lower ionospheric layer between 140 km and 40 km, with electrical conductivity peaking near 60 km.

In order to explain the unique pattern of signals, scientists have proposed that Titan's atmosphere behaves like a giant electrical circuit. The electrical currents are generated in the ionosphere when it interacts with Saturn's magnetosphere. This results in a dynamo effect as plasma trapped in the magnetosphere co-rotates with the planet every 10 hours or so.

The lower boundary of Titan's 'cavity', which reflects the radio signals, is thought to be a conductive ocean of water and ammonia which is buried at a depth of 55–80 km below a non-conducting, icy crust.

Huygens' discovery of this unique Schumann resonance is seen as key supporting evidence for the existence of such a subsurface ocean, hidden far beneath the moon's frozen surface.

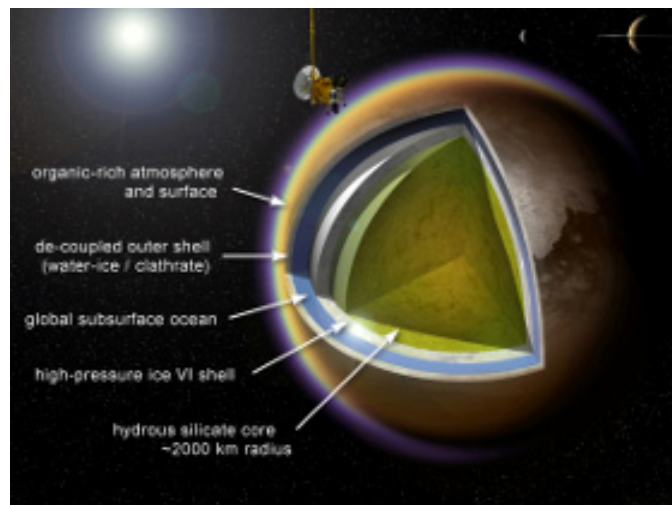


Figure HUYGENS-9. This artist's impression of a possible model for Titan's interior includes a global subsurface ocean. Credit: A. D. Fortes/UCL/STFC.



10. Elusive Dunes

To their surprise, scientists found that locating the Huygens landing site on images taken by the Cassini orbiter was much more difficult than expected.

Although the side-looking imager (SLI), part of the DISR on board ESA's Huygens probe, was able to image surface features located up to 450 km from the Huygens landing site, the images it sent back were hard to match with the synthetic aperture radar (SAR) images obtained by the Cassini orbiter. See Huygens's descent to Titan's surface [ESA 2015] for further details and enhanced video.

The area around the Huygens landing site turned out to be a huge plain of dirty water ice over which lay blankets of organic (carbon-bearing) deposits. These mantles of aerosol were invisible to radar waves, so Cassini SAR images only revealed the underlying water ice. As a result, the boundary between the bright highlands and dark plains that Huygens drifted over simply did not show up in the radar images.

The location of the landing site was only tied down after some time by the detection of two dark, longitudinal "sand" dunes, about 30 km north of the landing site. The elusive landforms were visible in both the SAR and Huygens images. Although dark, longitudinal dunes form vast "sand seas" throughout Titan's optically dark equatorial regions, Huygens descended over a region of bright and dark units that was free of the pervasive dune fields found elsewhere.

The dunes on Titan are probably composed of sand-sized hydrocarbon and/or nitrile grains mixed with lesser amounts of water ice. The particles rained down from above onto the surface and were subsequently eroded and moved by surface and aeolian processes, such as liquid methane runoff and wind erosion.

In order for the sand to migrate across the surface under the influence of Titan's weak surface winds, a process called saltation, scientists have concluded that the dune material must be between 100 microns and 300 microns in diameter.

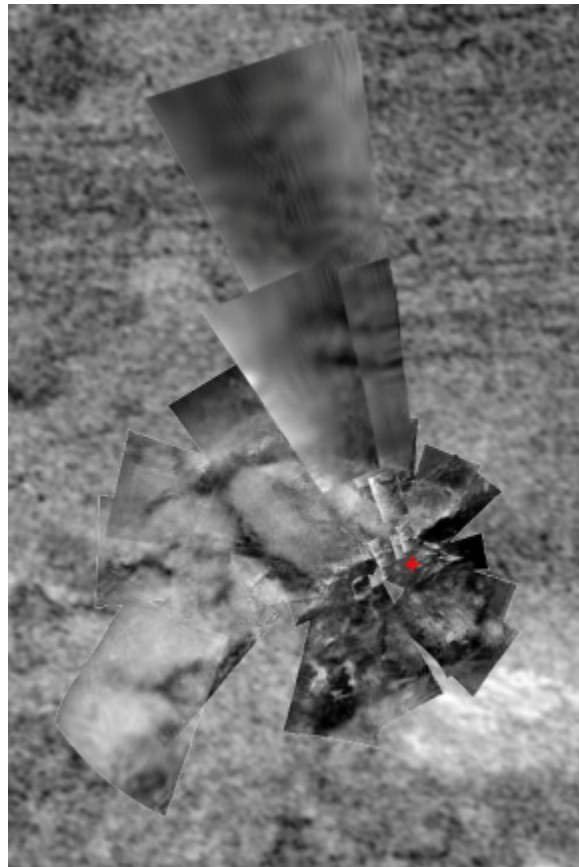


Figure HUYGENS-10. Huygens's landing site. Credit: ESA/NASA/JPL-Caltech/ University of Arizona/USGS.



ACRONYMS

Note: For a complete list of Acronyms, refer to Cassini Acronyms – Attachment A.

ACP	Aerosol Collector Pyrolyser
AO	Announcement of Opportunity
ASI	Italian Space Agency
AU	astronomical unit
CCD	charge coupled device
CIRS	Composite Infrared Spectrometer
CO	carbon monoxide
CSWG	Campaign Science Working Group
D/H	Deuterium to Hydrogen
DISR	Descent Imager and Spectral Radiometer
DWE	Doppler Wind Experiment
ELF	Extremely Low Frequency
ESA	European Space Agency
EUV	extreme ultraviolet
GC	gas chromatographic
GCM	general circulation models
GCMS	Gas Chromatograph and Mass Spectrometer
HASI	Huygens Atmospheric Structure Instrument
HCN	hydrogen cyanide
HST	Hubble Space Telescope
INMS	Ion and Neutral Mass Spectrometer
IRIS	infrared spectrometers
ISS	Imaging Science Subsystem
JPL	Jet Propulsion Laboratory
NH ₃	Ammonia
PWA	Permittivity Wave and Altimetry
SAR	Synthetic Aperture Radar
SLI	side-looking imager
SSP	Surface Science Package
TSSM	Titan Saturn System Mission
UTC	Coordinated Universal Time
UV	ultraviolet
VIMS	Visual and Infrared Imaging Spectrometer
VLBI	Very Long Baseline Interferometry



REFERENCES

***Disclaimer:** An extensive selection of Huygens references is provided here. For all other Cassini references, refer to the section entitled Other References and Papers, Attachment B – References & Bibliographies; Attachment C – Cassini Science Bibliographies; the sections entitled References contributed by individual Cassini instrument and discipline teams located in Volume 1 Sections 3.1 and 3.2 Science Results; and other resources outside of the Cassini Final Mission Report.*

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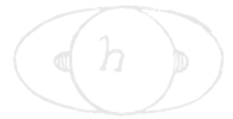
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