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An overview of the descent and landing of the Huygens probe on Titan

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Titan, Saturn's largest moon, is the only Solar System planetary body other than Earth with a thick nitrogen atmosphere. The Voyager spacecraft confirmed that methane was the second-most abundant atmospheric constituent in Titan's atmosphere, and revealed a rich organic chemistry, but its cameras could not see through the thick organic haze. After a seven-year interplanetary journey on board the Cassini orbiter, the Huygens probe was released on 25 December 2004. It reached the upper layer of Titan's atmosphere on 14 January and landed softly after a parachute descent of almost 2.5 hours. Here we report an overview of the Huygens mission, which enabled studies of the atmosphere and surface, including *in situ* sampling of the organic chemistry, and revealed an Earth-like landscape. The probe descended over the boundary between a bright icy terrain eroded by fluvial activity—probably due to methane—and a darker area that looked like a river- or lake-bed. Post-landing images showed centimetre-sized surface details.

Titan is the second-largest moon in the Solar System, after Jupiter's Ganymede, and is assumed to have formed in the Saturn subnebula about 4.5 billion years ago. One of its great mysteries is the origin of the methane in the atmosphere. With a lifetime of just 20 million years, methane must be regularly resupplied to the atmosphere to be as abundant as it is today. The surface of Titan remained hidden to the Voyager cameras, which led to speculation on its appearance and processes. The surface pressure on Titan is about 1.5 times that on Earth and the surface temperature is about minus 180 °C. At such a low temperature, it was postulated that liquid methane might be present on Titan's surface or in underground reservoirs. Although the images returned by the Voyager spacecraft were featureless, the richness of the detected organic compounds confirmed that Titan was indeed worthy of being revisited and explored in detail.

The distinct orange appearance of Titan's atmosphere, as observed by the Voyagers in the early 1980s, comes from the methane-induced organic chemistry. Complex hydrocarbons and carbon-nitrogen-based compounds form high in the atmosphere, which is irradiated by solar ultraviolet rays and bombarded by energetic particles from Saturn's space environment. Methane converts to ethane, acetylene, ethylene, and so on, and when combined with nitrogen forms hydrogen cyanide and more complex nitrogen-bearing carbon and hydrocarbon compounds. These organic compounds float slowly downward in the atmosphere, condense in the stratosphere, and form the aerosols that give the well-known orange colour to Titan's hazy atmosphere. The aerosols eventually rain to the surface, where they accumulate.

Images of Titan's surface at various resolutions were obtained by the Hubble Space Telescope[1,2] and ground-based observatories[3,4]. Early images of Titan's surface obtained by the Cassini orbiter[5] were almost as baffling as those obtained from Earth. Bright and dark patches were clearly visible on the surface. Albedo patterns suggested a heterogeneous active surface, perhaps with some fluvial processes. No direct evidence of surface liquid was found before the Huygens probe, although ground-based radar observations were interpreted as indicative of the presence of liquid surfaces[6] near the equator.

The scientific objectives established for the Cassini-Huygens mission at Titan[7,8] were to: (1) determine atmospheric composition; (2) investigate energy sources for atmospheric chemistry; (3) study aerosol properties and cloud physics; (4) measure winds and global temperatures; (5) determine properties of the surface and infer internal structure; and (6) investigate the upper atmosphere and ionosphere. The Huygens probe performed detailed *in situ* observations along the descent path and on the surface, while in mid-2004 the Cassini orbiter started to carry out the global mapping planned during its 45 Titan fly-bys. The Huygens probe's scientific payload includes six experiments: (1) HASI (Huygens Atmospheric Structure Instrument)[9]; (2) the DWE (Doppler Wind Experiment)[10]; (3) the ACP (Aerosol Collector and Pyrolyzer)[11]; (4) the GCMS (Gas Chromatograph and Mass Spectrometer)[12]; (5) the SSP (Surface Science Package)[13]; (6) the DISR (Descent Imager and Spectral Radiometer)[14]. The main characteristics of the payload are given in the Supplementary Information. The payload accommodation is illustrated in Fig. 1.

The entire Huygens mission was designed to be carried out during a 2.5-hour descent through the atmosphere and possibly a few more minutes on the surface[7]. The probe was not guaranteed to survive its impact on what was unknown terrain. The coordinates of the predicted Huygens landing site were uncertain by several hundred kilometres because there were large uncertainties in how far the winds would carry the probe laterally during its descent under parachute.

After a seven-year interplanetary journey and two orbits around Saturn aboard the Cassini orbiter, the Huygens probe was released during the third orbit on 25 December 2004. On 14 January 2005 it

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reached the upper layers of Titan's atmosphere with a speed of 6 km s^{-1}. Analysis of the accelerometer measurements obtained during the entry produced an atmospheric structure profile from an altitude of 1,400 km down to 155 km (ref. 15). The Huygens probe revealed much structure above 200 km and the high-altitude densities were slightly more than predicted. The Huygens probe decelerated to 400 m s^{-1} in less than 5 min. The main parachute was then deployed at a speed of approximately mach 1.5 (400 m s^{-1}), at an altitude of about 155 km. Within one minute after the parachute deployment, the Huygens payload was fully operational and data were being transmitted to Cassini via two redundant radio-link channels[16]. After a descent of 2 h 28 min, the probe landed softly at 11:38:11 UTC (Coordinated Universal Time) with a speed slightly less than 5 m s^{-1} on a surface that appeared solid, with no apparent surface liquid, although some evaporated methane was detected soon after the impact. Cassini received data from the Huygens probe until 12:50 UTC (1 h 12 min after touchdown) when it passed below the probe's horizon. At that moment, the probe was still operating and broadcasting from the surface. One of the two carrier frequencies was received by an array of Earth-based radio telescopes[17] (see the Supplementary Information), which provided wind measurements[18].

Clear images of the surface were obtained below about 40 km altitude. The Huygens probe revealed an extraordinary world, resembling Earth in many respects, especially in meteorology, geomorphology and fluvial activity. The images show strong evidence for erosion due to liquid flows, possibly methane, on Titan. The probe trajectory carried it across a boundary between a bright, icy, rugged terrain and a darker flat area[19]. The Huygens probe landed in the dark area. The measured pressure and temperature profiles[15] below 150 km are close to those expected on the basis of Voyager observations. The measured surface temperature and pressure at the landing site were ~93.7 K and ~1,470 mbar respectively. At the landing site, the surface is relatively flat and solid. Reflectance spectra show that it is mostly composed of dirty water-ice[19]. Water-ice pebbles up to a few centimetres in diameter were scattered near the landing site. The Huygens Surface Science Package penetrometer found the surface here to be unconsolidated[20], with the consistency of loose wet sand.

Winds were found to blow predominantly in the direction of Titan's rotation[18]. West–east winds up to 450 km h^{-1} were detected above an altitude of 120 km. The winds decreased with decreasing altitude. An unexpected layer of high wind-shear was encountered between altitudes of 100 and 60 km. Perhaps unrelated but worth noting, an ionosphere-like layer produced by galactic cosmic rays was discovered at an altitude of about 60 km (ref. 15). The winds, with speeds of metres per second, reversed direction below 8 km (refs 18, 19). Haze was detected all the way down to the surface[19], contrary to the predictions of pre-Huygens models. It was predicted that the atmosphere would be clear of haze in the lower stratosphere, below around 60 km. Fortunately, the haze was transparent enough for good images of the surface to be obtained below 40 km.

In situ composition measurements of Titan's atmosphere[21] and of the aerosols[22] below 150 km confirmed the presence of a complex organic chemistry in both the gas and the solid phase. Vertical profiles were obtained for the more abundant species. So far no new organic compound has been detected in the atmosphere, except that the presence of ^{40}Ar, already detected in the upper atmosphere by INMS[23], was confirmed. Primordial argon, ^{36}Ar, was detected, to our knowledge for the first time, but not xenon and krypton. The non-detection of these noble gases, a surprising finding, will fuel theories of the origin and evolution of Titan's atmosphere. The C, N and H/D isotopic ratios were measured. This will make it possible to constrain formation scenarios for Titan's atmosphere.

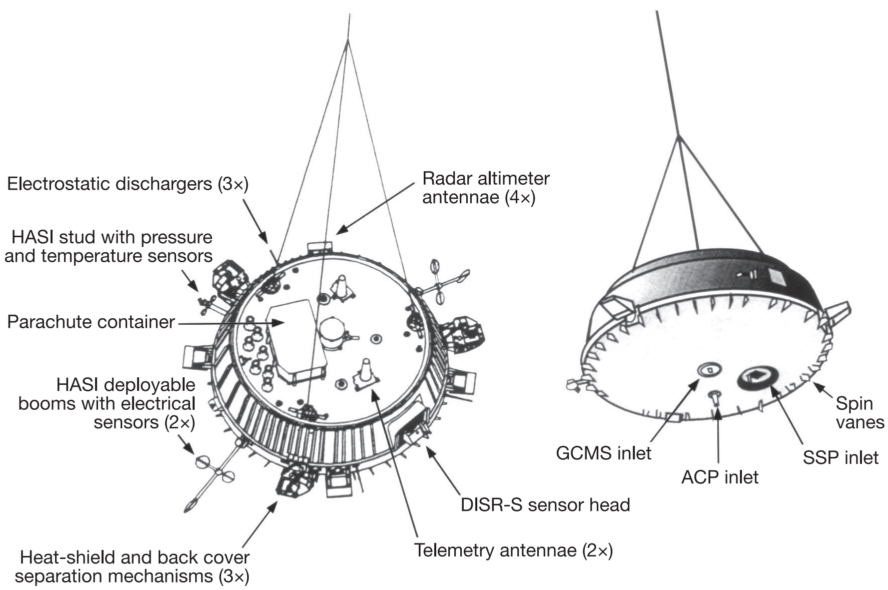

Figure 1 | Accommodation of the payload seen from two different perspectives. The external units of the probe are labelled. Five of the instruments required direct access to the gas flow and/or a clear field of view. The inlet ports of both the GCMS[12] and the ACP[11] were mounted close to the nose (apex) of the probe. The SSP[13] also required direct access of the sensors in its 'Top Hat' structure to the gas—and eventually to a fluid if the Huygens probe had landed on a liquid surface. The judiciously designed SSP impact sensor protruded in front of the 'Top Hat' to allow direct detection of the impact a few milliseconds before the probe body itself reached the surface. The pressure and temperature sensors of the HASI[9] were located on a fix stub and the electric properties sensors on two booms that were deployed immediately after the heat shield was released. The HASI microphone was mounted on the outer ring. HASI included a sensitive accelerometer located near the centre of gravity of the probe in the entry configuration. The DISR[14] sensor head was mounted on the outer rim of the probe ring so that it provided a clear field of view of almost 180 degrees from zenith to nadir. Probe spin allowed panoramic observations that took advantage of the probe rotation under the parachute. The Doppler Wind Experiment[10] (DWE) included two ultra-stable oscillators designed to stabilize the transmitted carrier frequency and the corresponding receiver on one of the two radio links. The probe altitude was measured by a set of two radar altimeters that were switched on at an altitude of about 60 km, but started to provide useful measurements at an altitude of 45 km.

Composition measurements were made on the surface. ^{40}Ar was detected on it. Its presence indicates that Titan has experienced in the past, and is probably still experiencing today, internal geologic activity. The time profile of the composition of surface vapours obtained by GCMS shows that the Huygens probe landed on a surface wet with methane, which evaporated as the cold soil was heated by the warmer probe. Compounds not seen in the atmosphere, such as C_6H_6, C_2N_2 and CO_2, were nevertheless detected in the gas from the surface material. Those measurements, which have not yet been fully analysed, appear to indicate complex chemical processes occurring on or in Titan's surface, as well as in the atmosphere.

The Huygens observations are presented and discussed in more detail in the accompanying papers[15,18–22]. We now aim to put the Huygens mission operations into perspective.

The Huygens mission

Launch and flight to Saturn. The Cassini-Huygens spacecraft was launched from Cape Canaveral complex in Florida on 15 October 1997, with the probe mated onto the side of the orbiter. In this configuration, the orbiter provided electrical power to the probe through an umbilical connection. Commands and data were also exchanged by this route. During the seven-year journey to Saturn, the Huygens probe was subjected to 16 in-flight checkouts to monitor the health of its subsystems and scientific instruments[16]. During these in-flight tests, maintenance was performed and calibration data were obtained in preparation for the mission at Titan. The special in-flight tests designed to characterize the communication radio link between the probe and the orbiter were especially important (see the Supplementary Information).

In the first link test in 2000, a flaw was discovered in the design of the Huygens telemetry receiver on board the orbiter that would have resulted in the loss of a large fraction of the Huygens probe's scientific data during the actual mission at Titan. Originally the Huygens mission was planned to be executed at the end of the first orbit around Saturn. As a remedy to the radio receiver flaw, the first two orbits of the original mission were redesigned[7,8] into three shorter orbits that enabled the Huygens mission to be carried out on the third orbit. The re-designed orbiter trajectory during the probe relay is shown in Fig. 2. This trajectory provided a Doppler shift on the probe–orbiter radio link that was compatible with the well-characterized receiver performance and it also smoothly reconnected with the already-designed post-Huygens orbiter four-year trajectory[8].

As a bonus, the new trajectory allowed early orbiter observations of Titan's upper atmosphere in order to validate the so-called Titan atmosphere engineering model[7] well before the Huygens probe release. It led to improvements in our knowledge of the structure and the composition of the upper atmosphere; in particular, it provided better constraints on the argon concentration and indicated that methane was not present in sufficient quantity to affect the probe entry adversely (that is, via excessive radiative heating). Indeed, the new mission scenario led to the Huygens mission being completely successful. This achievement was the culmination of more than 20 years of work and shows that the in-flight rework of the mission was necessary and was successfully implemented.

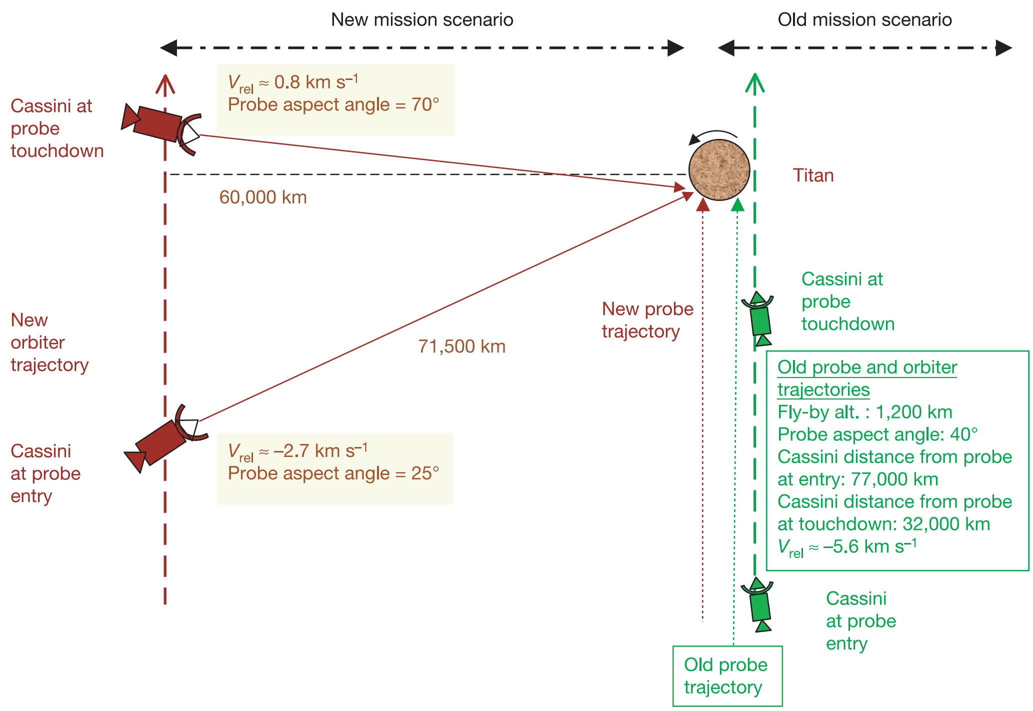

Figure 2 | Orbiter trajectory during the probe mission. This trajectory was implemented after a flaw was discovered in 2000 in the design of the Huygens telemetry receiver aboard Cassini. As originally designed, its telemetry demodulator was not able to receive and properly decode the transmissions at the expected frequency shift of about 25 p.p.m. (parts per million). The relative orbiter–probe velocity (Doppler shift)would have contributed 19 p.p.m., while the thermal frequency drift of the oscillator clocking the data stream would have contributed an additional 5–6 p.p.m. After full characterization of the receiver performance, a new mission scenario was designed to work around the constraints imposed by the receiver. The new design was developed in 2001 and was implemented during 2002–2004 (refs 7, 8, 16). The solution required a combination of the following measures: (1) A new Cassini trajectory that minimized the relative probe–orbiter velocity. This changed the geometry of the Titan encounter by Cassini during the probe mission. It required the probe mission, initially planned to be conducted on the first orbit around Saturn, to be delayed until the third orbit. This trajectory change decreased the Doppler shift by 10–15 p.p.m. For reference, the old baseline trajectory is also indicated. (2) Pre-heating the Huygens probe before its arrival at Titan, by programming its wake-up four hours earlier than planned. As a result of the on-board oscillator that clocked the data stream frequency being warmer, the frequency of the data stream was further decreased (up to 3–4 p.p.m.). The pre-heating was implemented by appropriate changes in the on-board software of both the probe and the scientific instruments. It provided the robustness needed for the new mission.

Probe release. In preparation for releasing the probe, the Cassini-Huygens spacecraft had been set on a Titan-impact trajectory. Following its release, the Huygens probe had no manoeuvring capability and had to function autonomously. The Huygens release trajectory was achieved via a 'probe targeting manoeuvre' with a speed adjustment of 12 m s^{-1} on 17 December 2004, followed by a 'probe targeting clean-up manoeuvre' on 23 December 2004. After the separation of the Huygens probe on 25 December at 02:00 UTC, Cassini performed an 'orbiter deflection manoeuvre', so that it would not crash into Titan, and a 'clean-up manoeuvre' for final adjustment of its trajectory. These were on 28 December 2004 and 03 January 2005 respectively and placed Cassini on the correct trajectory for receiving data from the Huygens probe during the descent. The responsibilities for meeting the probe's trajectory requirements were shared between NASA/JPL and ESA. The targeting of the probe, the NASA/JPL responsibility, was specified at an altitude of 1,270 km, very close to the atmosphere's upper layer, above which no significant drag was expected. From this point onward ESA was responsible for the probe's trajectory.

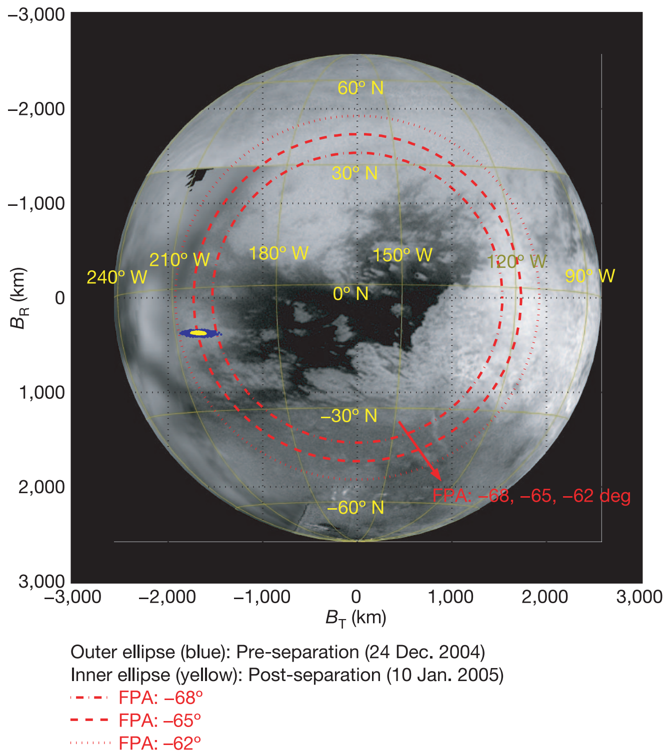

Figure 3 | Probe targeting as seen on a projection of the Titan disk. The surface image comes from the Cassini orbiter camera observation[5] during the Titan fly-by on 26 October 2004. The three red curves give the targeted uncertainty ellipse of the entry point at an altitude of 1,270 km, for an entry angle of $-62°$ (dotted line), $-65°$ (solid line), and $-68°$ (dashed line). (An entry angle of $-90°$ would have given an entry point right in the centre of the figure). The blue ellipse gives the dispersion of the entry point as computed before the Cassini-Huygens separation, while the yellow ellipse indicates a reduced dispersion, as computed four days before the entry. The achieved probe Flight Path Angle (FPA) (the angle between the probe velocity vector and the local horizon) at the 1,270 km interface altitude was $-65.4°$ with an uncertainty of $\pm0.85°$, compared to the requirement of $-65°$ with an uncertainty of $\pm3°$ (99% confidence level). The projection is shown in the Titan B-plane (impact plane), which is defined as the plane perpendicular to the asymptotic approach velocity and passing through Titan's centre. The T-axis is contained in Titan's equatorial plane, and the R-axis is perpendicular to it. The time uncertainty related to the arrival at 1,270 km altitude was reconstructed during the post-flight analysis as 5.8 s. Background image adapted from JPL's photojournal image PIA06201. Courtesy NASA/JPL Space Science Institute.

The spring-loaded Huygens separation mechanism, called the Spin Eject Device, had three points of attachment to the probe. It provided a speed increment relative to the orbiter of 33 cm s^{-1}. The Spin Eject Device also imparted to the probe an anti-clockwise spin of 7.5 r.p.m. (when viewed from the orbiter). This provided inertial stability during the ballistic trajectory and atmospheric entry.

Coast and probe 'wake up'. The Huygens probe was set on a ballistic trajectory that took a little over 20 days. During this time, the probe was dormant, with only three redundant timers counting down to a specific time programmed to end 4 h and 23 min before the predicted entry. At this time, battery power was turned on and the on-board computers, their sensors (accelerometers, and later in the descent the radar altimeters), and the scientific instruments were energized according to the pre-programmed sequence. The probe 'woke up' as planned, at 04:41:33 UTC on 14 January 2005. The Huygens probe's receivers on board the Cassini orbiter were powered on from 06:50:45 to 13:37:32 UTC. The Huygens probe arrived at the 1,270 km interface altitude on the predicted trajectory (Fig. 3) on 14 January 2005 at 09:05:53 UTC, just a few seconds before the expected time.

Entry, descent and landing. The Huygens scientific mission proper took place during the entry, descent, landing and post-landing phases. Table 1 shows the list of the main mission events. The descent of the probe through Titan's atmosphere was controlled by parachutes. The aerodynamic conditions under which the main parachute had to be deployed were critical. The correct instant for parachute deployment (mission time event, t_0) (the nomenclature t_0 is equivalent to T_0 in some of the accompanying papers)was determined by the probe on-board computers that processed the measurements from the accelerometers that monitored the probe's deceleration[16]. Pyrotechnic devices fired a mortar that pulled out a pilot chute, which in turn removed the probe's back cover and pulled out the main parachute. Then, 30 s later, the front shield was released. It was expected that, by this time, the probe would have stabilized under the main parachute. During the entry phase, telemetry could not be transmitted by the probe until its back cover was removed. Thus, a limited set of engineering housekeeping data and the HASI science accelerometer data[9] acquired during entry was stored on-board the probe for transmission to the orbiter after the radio link was established.

Post-flight data analysis showed that only one of the receivers (channel B) was phase-locked and functioned properly. Channel A had an anomaly that was later identified as being due to the

Table 1 | Huygens mission timeline on 14 January 2005

Activity	Time (h:min:s UTC)	Mission time, $t - t_0$ (h:min:s)
Probe power-on	04:41:18	−4:29:03
Probe support avionics power-on	06:50:45	−2:19:56
Arrival at interface altitude (1,270 km)	09:05:53	−0:04:28
t_0 (start of the descent sequence)	09:10:21	0:00:00
Main parachute deployment	09:10:23	0:00:02
Heat shield separation	09:10:53	0:00:32
Transmitter ON	09:11:06	0:00:45
GCMS inlet cap jettison	09:11:11	0:00:50
GCMS outlet cap jettison	09:11:19	0:00:58
HASI boom deployment (latest)	09:11:23	0:01:02
DISR cover jettison	09:11:27	0:01:06
ACP inlet cap jettison	09:12:51	0:01:30
Stabilizer parachute deployment	09:25:21	0:15:00
Radar altimeter power-on	09:42:17	0:31:56
DISR surface lamp on	11:36:06	2:25:45
Surface impact	11:38:11	2:27:50
End of Cassini–probe link	12:50:24	3:40:03
Probe support avionics power-off	13:37:32	4:27:11
Last channel A carrier signal reception by Earth-based radio telescopes	~14:53 16:00 (ERT)	5:42:39

The second column gives the time in UTC (for the probe), while the third column gives the time relative to t_0, where t_0 is the official start of the descent associated with the pilot chute deployment event. ERT, Earth Received Time.

unfortunate omission of the telecommand to apply power to the ultra-stable oscillator driving the channel A receiver (see Box 1 for further details). Subsequent on-board events were determined by the on-board software that initiated a set of commands at times all related to the moment the pilot chute was released. These commands included switching on other instruments and the replacement of the main parachute by a smaller 'stabiliser chute' after 15 min, to ensure that the probe would reach the surface of Titan within the designed duration of the mission (150 min maximum for the descent under parachute).

The actual duration of the descent following the t_0 event was 2 h 27 min 50 s. During the first part of the descent, the probe followed the nominal time-based sequence with the instrument operations defined by commands in the on-board mission timeline. The later part of the descent sequence was optimized by taking into account the altitude measurements provided by two redundant radar altimeters[7,16]. The altimeters were switched on 32 min after t_0, which corresponded to an altitude of around 60 km. They provided altitude measurements to the on-board computers, which filtered and compared the measurements to the predicted altitude, in order to exclude erratic measurements at high altitude and to provide reliable measured altitude information to the payload instruments. This allowed for optimization of the measurements during the last part of the descent. The DISR measurements sequence was adjusted to measured altitude below 10 km and its lamp was switched on at 700 m above the surface[19]. The HASI and SSP instruments were set to their proximity and surface modes[15,20] at low altitude above the surface.

The probe landed safely with a vertical speed of about 5 m s^{-1} and continued thereafter to transmit data for at least another 3 h 14 min, as determined by the detection and monitoring of the probe's 2.040-GHz carrier signal by the Earth-based radio telescopes. Throughout this time, Cassini was oriented to receive the two incoming radio signals from the probe by continuously pointing its high gain antenna to the predicted Huygens landing point. After listening for the longest possible duration of the Huygens probe's visibility, the orbiter was commanded to re-point its high gain antenna to Earth for transmission of the stored Huygens telemetry data. At that time, Cassini was at a distance of 1,207 million kilometres (8.07 AU) from the Earth (the one-way light-time was 67 min 6 s).

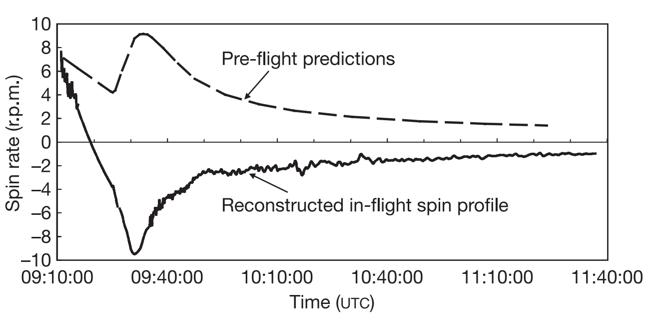

Figure 4 | Spin rate profile as a function of time. The solid curve displays the value derived from the radial accelerometer measurements and the spin phase variation of the automatic gain control of the probe-to-orbiter radio link. The probe entered the atmosphere and went through the entry with the expected spin rate (around 7.5 r.p.m.) in the anticlockwise direction. The spin rate decreased more rapidly than predicted under the main parachute and unexpectedly reversed direction after 10 min. It continued to spin with the expected rate but in the clockwise direction for the rest of the descent. The reason for this behaviour is under investigation. The post-flight verifications that could be made from design documentation do not show evidence for incorrect design or implementation of the spin vanes. Further detailed investigations of the aerodynamic interaction of the air flow with the probe under parachute may be required to explain this behaviour. The dashed line displays the predicted spin profile.

The data were received by the ground stations of the NASA Deep Space Network (DSN) and eventually delivered to the Huygens Probe Operations Centre (HPOC) in ESA's European Space Operation Centre (ESOC, Darmstadt, Germany) for science and engineering analysis. A 1-h margin was built into the orbiter sequence to cope with uncertainties as to when the orbiter would disappear below the horizon. As seen from the probe landing site, the orbiter actually set below the horizon at 12:50:24 UTC. The probe's channel A carrier signal was still being received on Earth by radio telescopes at the time of the planned completion of the observations, at 16:00 UTC (Earth received time), meaning that the probe was still operating at 14:53 UTC (Titan time). Post-flight analysis of the probe telemetry data indicates that the batteries probably became fully discharged at about 15:10 UTC, a mere 17 min after the Huygens radio signal was last verified on Earth. It is thought that the probe continued to function until the batteries were exhausted.

Trajectory reconstruction. The probe arrived at the 1,270 km interface altitude with the spin imparted at separation in the anticlockwise direction. No significant spin modification was observed during the entry. The spin decreased more than expected under the main parachute and unexpectedly changed direction after 10 min. The probe continued spinning in the unexpected direction (clockwise) for the rest of the descent as illustrated in Fig. 4. No explanation was found for this behaviour, which is still under investigation.

Figure 5 shows the probe entry and descent altitude and vertical velocity profiles. The methodology that was used for the reconstruction effort is described in more detail in refs 24–27. The determination of the landing site coordinates is a complex and iterative task and requires several assumptions. At present, the best estimate, based on the combined Descent Trajectory Working Group (DTWG), DISR and DWE reconstruction, is a latitude of 10.3° (±0.4°) south and a longitude of 167.7° (±0.5°) east.

Summary and discussion. The probe and its scientific payload performed close to and sometimes beyond expectations. The in-flight

Box 1 | Channel A anomaly

The mission had two probe–orbiter radio link channels, which we refer to as channels A and B. Both transmitters (on board the probe) and both receivers (on board Cassini) were equipped with a temperature-controlled crystal oscillator (TCXO) which provided sufficient frequency stability (~10^{-6}) for telemetry. One of the channels (channel A) was additionally equipped with ultra-stable oscillators (USOs) that were needed for the Doppler Wind Experiment (DWE)[10,18], which required a stable carrier frequency signal. As part of finalising the Huygens probe's configuration for its mission, it had been decided to use the channel A USOs instead of the TCXOs because the performance of the USOs had been very satisfactory during the seven-year cruise.

The command to power on the USO on the receiver side was unfortunately omitted. As a result, the Channel A receiver on board Cassini did not have a reference oscillator and was unable to lock onto the Huygens signal. Consequently, the frequency measurements for the Doppler Wind Experiment (DWE), together with the non-redundant telemetry data on Channel A, were lost.

The loss of the DWE data was, fortunately, largely mitigated by the radio astronomy segment of the mission consisting of a network of ground-based radio telescopes. The Channel A carrier signal, driven by the probe's USO, was received by 15 radio telescopes and tracked for post-flight data analysis. Real-time Doppler tracking information was obtained through the two largest telescopes of the network: the NRAO R. C. Byrd Green Bank Telescope (West Virginia, USA) and the CSIRO Parkes Radio Telescope (New South Wales, Australia). Both telescopes were equipped with NASA Deep Space Network's Radio Science Receivers (RSR) operated by the Radio Science Group of the Jet Propulsion Laboratory. In addition, the other 13 radio telescopes recorded the Channel A carrier signal for non-real-time Doppler and VLBI analysis.

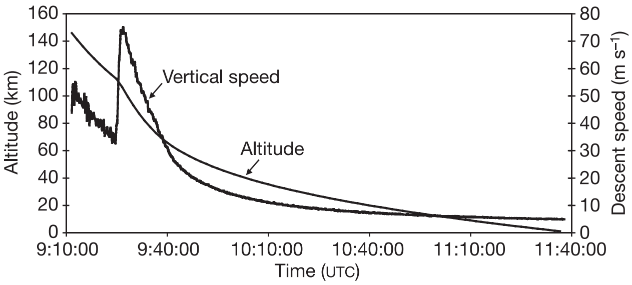

Figure 5 | Reconstructed altitude and descent speed as a function of mission time. **The entry trajectory reconstruction from the official NASA/ESA interface point and epoch to the initiation of the parachute sequence t_0 is based on the numerical integration of the probe's equations of motion, which requires as an input the initial state vector (provided by the Cassini Navigation Team), the (modelled) gravitational force of the planet, the (measured) aerodynamic deceleration, and an assumption of a high-altitude wind speed profile (that is, 90 m s^{-1} prograde was assumed). The descent-phase reconstruction is based on the altitude and descent-speed reconstruction from the measured HASI temperature and pressure profiles[15], the atmospheric mole fractions as measured by GCMS[21], the impact time as most accurately measured by the SSP[20] internal accelerometer (ACC-I), and the DWE-derived[18] zonal wind speed profile. Once the entry and descent trajectories were reconstructed independently from each other, a least-squares fitting algorithm was applied to adjust the probe initial conditions at the interface epoch and to ensure a smooth transition between the entry and descent trajectories.**

modifications of the Huygens part of the mission, to cope with the receiver design flaw detected in 2000, was highly successful. The loss of data on channel A, due to a telecommand omission, was largely compensated for by the flawless transmission on channel B, with not a single bit missing until the radio link signal-to-noise decreased below the design limit of 3.3 dB, in the last 10 min of surface transmission, and the fact that the DWE scientific objectives were largely recovered by using data from the Earth-based radio telescope observations.

Deceleration and load levels measured during the hypersonic entry were well within the expected limits and all prime systems worked well, with no need to have recourse to the two back-up systems (g-switches) that had also been activated. The parachute performance was within the expected envelope, although the descent time, at slightly less than 2 h 28 min, was only just within the predicted envelope of 2 h 15 min $\pm$ 15 min. The descent was rather smooth under the main parachute but rougher than anticipated during the first hour under the last parachute. A detailed profile of the atmosphere is being worked out from the scientific measurements to allow the parachute performance to be studied in detail.

An exciting scientific data set was returned by the Huygens probe, offering a new view of Titan, which appears to have an extraordinarily Earth-like meteorology, geology and fluvial activity (in which methane would play the role of water on Earth). While many of Earth's familiar geophysical processes appear to occur on Titan, the chemistry involved is quite different. Instead of liquid water, Titan has liquid methane. Instead of silicate rocks, Titan has frozen water ice. Instead of dirt, Titan has hydrocarbon particles settling out of the atmosphere. Titan is an extraordinary world having Earth-like geophysical processes operating on exotic materials under very alien conditions[28]. The Huygens data set provides the ground-truth reference for the interpretation of the remote observations of the Huygens landing site by orbiter instruments, and more generally the global observations of Titan. Future observations of the Huygens landing site by Cassini should allow us to place the local Huygens maps into their global context and are expected to tell us whether changes can be seen. Probe–orbiter synergistic studies are a key aspect for achieving the very ambitious Cassini-Huygens objectives at Titan.

Before the Huygens mission, it was thought that Titan could be a place of astro-biological interest[29,30]. The Huygens results summarized in this paper and detailed in the papers that follow reveal the uniqueness of Titan in the Solar System as a planetary-scale laboratory for studying pre-biotic chemistry, which confirms the astro-biological interest of Saturn's largest moon. The exploration of Titan has just begun.

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