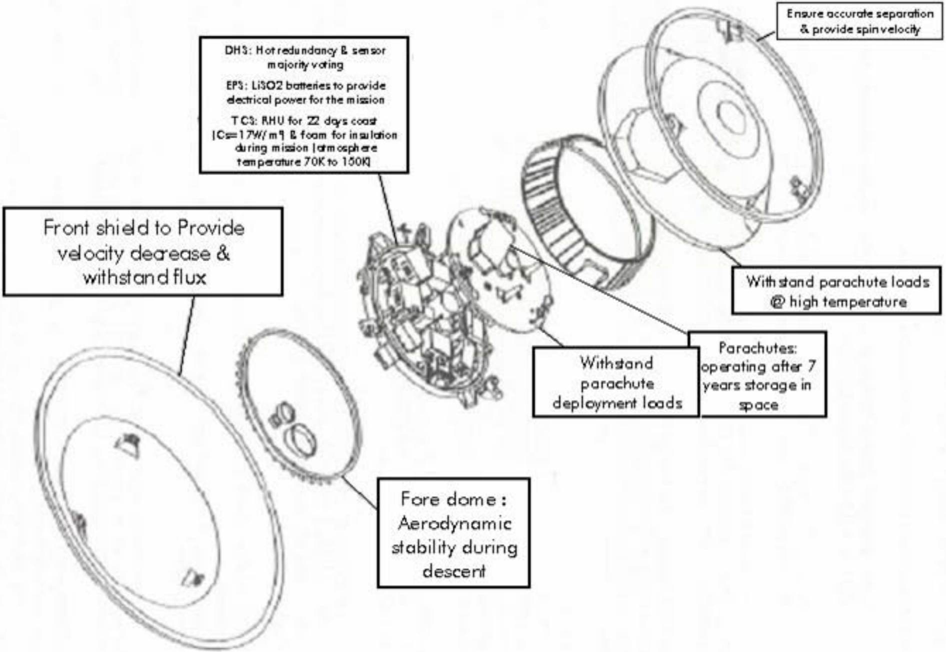
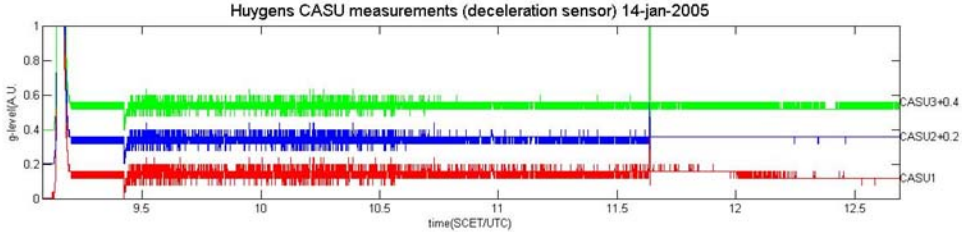
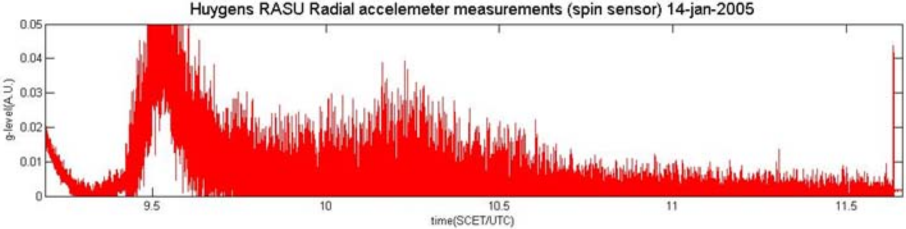
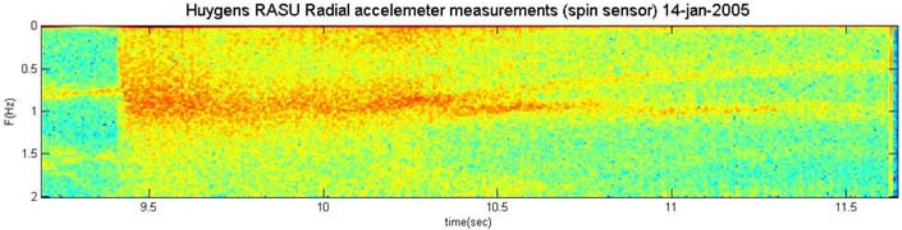
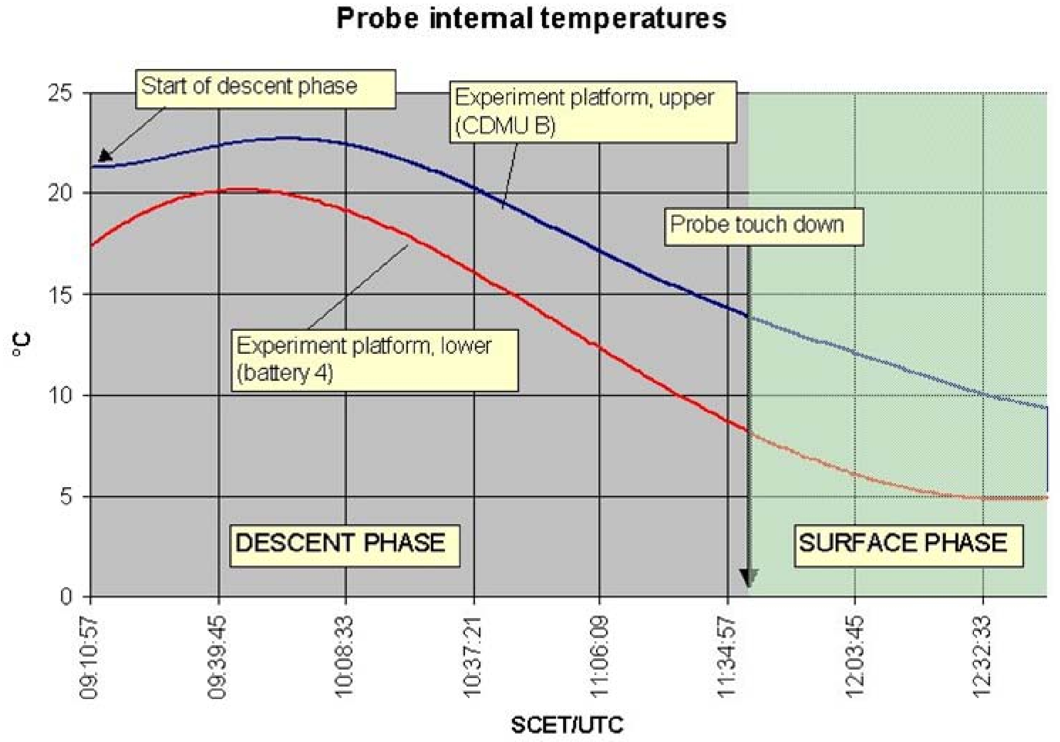
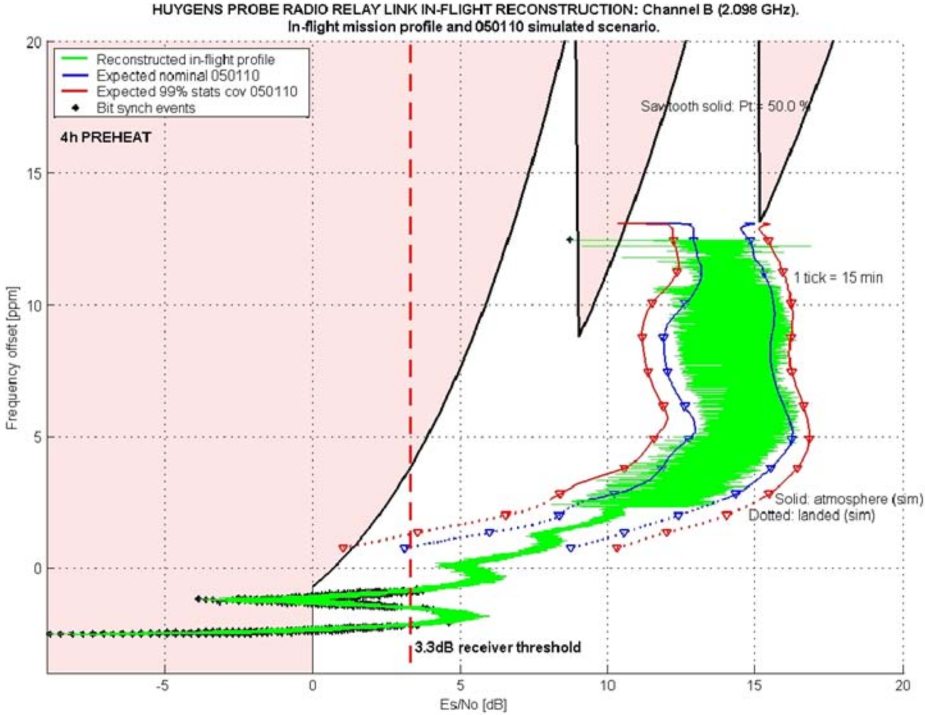

Ensure accurate separation & provide spin velocity
DHS: Hot redundancy & sensor majority voting
EPS: LiSO2 batteries to provide electrical power for the mission
TCS: RHU for 22 days coast (Cs=17W/m^2) & foam for insulation during mission (atmosphere temperature 70K to 150K)
Front shield to Provide velocity decrease & withstand flux
Withstand parachute loads @ high temperature
Parachutes: operating after 7 years storage in space
Withstand parachute deployment loads
Fore dome : Aerodynamic stability during descent

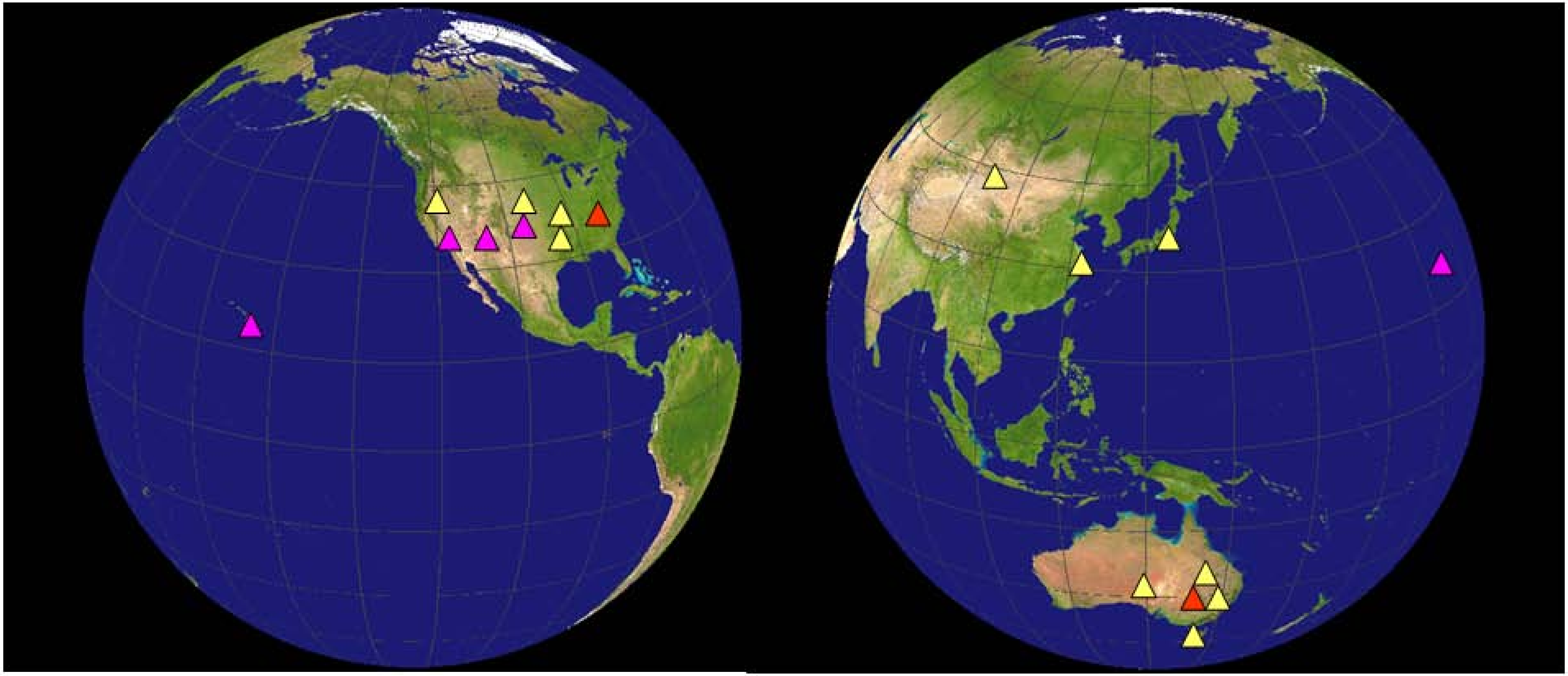

Huygens CASU measurements (deceleration sensor) 14-jan-2005
g-level(A.U.)
0
0.2
0.4
0.6
0.8
1
9.5
10
10.5
11
11.5
12
12.5
time(SCET/UTC)
CASU3+0.4
CASU2+0.2
CASU1

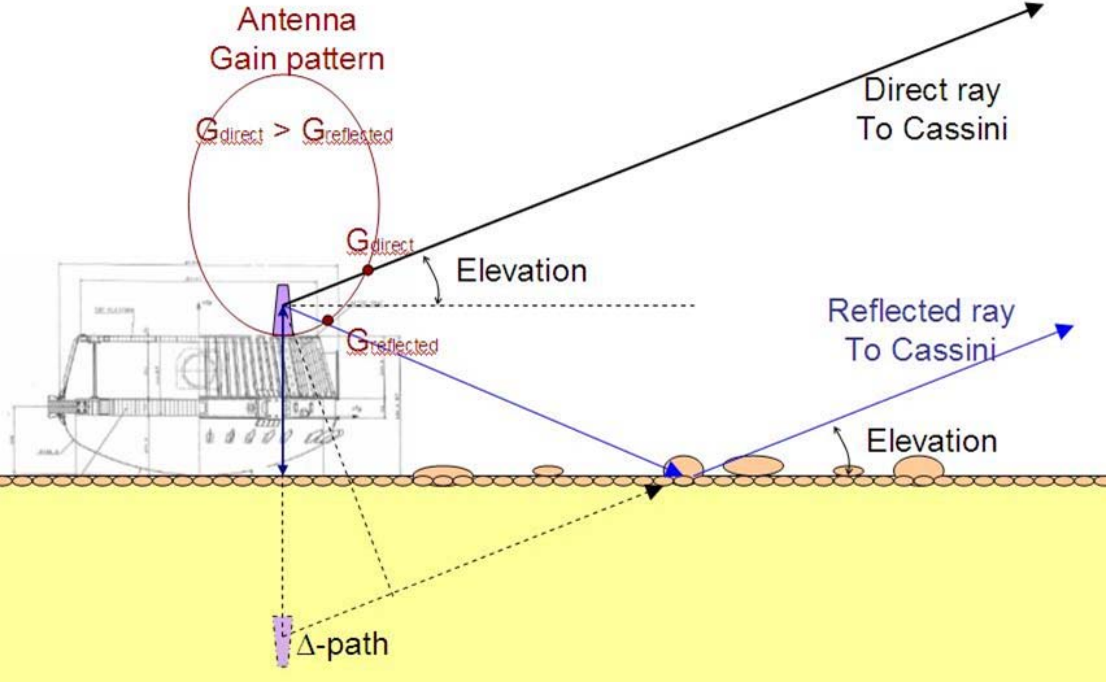

Huygens RASU Radial accelemeter measurements (spin sensor) 14-jan-2005
g-level(A.U.)
0
0.01
0.02
0.03
0.04
0.05
9.5
10
10.5
11
11.5
time(SCET/UTC)


Huygens RASU Radial accelemeter measurements (spin sensor) 14-jan-2005
F(Hz)
0
0.5
1
1.5
2
9.5
10
10.5
11
11.5
time(sec)


Probe internal temperatures
Start of descent phase
Experiment platform, upper (CDMU B)
Experiment platform, lower (battery 4)
Probe touch down
DESCENT PHASE
SURFACE PHASE
°C
25
20
15
10
5
0
09:10:57
09:39:45
10:08:33
10:37:21
11:06:09
11:34:57
12:03:45
12:32:33
SCET/UTC


HUYGENS PROBE RADIO RELAY LINK IN-FLIGHT RECONSTRUCTION: Channel B (2.098 GHz).
In-flight mission profile and 050110 simulated scenario.
Reconstructed in-flight profile
Expected nominal 050110
Expected 99% stats cov 050110
Bit synch events
4h PREHEAT
Sawtooth solid: Pt = 50.0 %
1 tick = 15 min
Solid: atmosphere (sim)
Dotted: landed (sim)
3.3dB receiver threshold
Frequency offset [ppm]
Es/No [dB]
20
15
10
5
0
-5
0
5
10
15
20




Antenna
Gain pattern
$G_{direct} > G_{reflected}$
Direct ray
To Cassini
G_{direct}
Elevation
Reflected ray
To Cassini
$G_{reflected}$
Elevation
Δ-path

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

Supplementary table 1: The Huygens payload

Experiment	Principal Investigator	Scientific Objectives
ACP (Aerosol Collector Pyrolyser)	G. Israel Service d'Aéronomie/CNRS Verrières le Buisson, France	Aerosol sampling of two layers, pyrolysis and injection to the GCMS instrument.
GCMS (Gas Chromatograph and Mass spectrometer)	H. B. Niemann NASA/GSFC Greenbelt, MD, USA	Atmospheric composition profile. Aerosol pyrolysis products analysis.
DISR (Descent Imager/Spectral Radiometer	M. Tomasko University of Arizona, Tucson, AZ, USA	Atmosphere composition and cloud structure. Aerosol properties. Atmosphere energy budget. Surface Imaging.
DWE (Doppler Wind Experiment)	M. Bird University of Bonn, Germany	Probe Doppler tracking from the orbiter and Earth for zonal wind profile measurement.
SSP	J. C. Zarnecki	Titan state and composition at

(Surface Science Package)	Open University Milton Keynes, UK	landing site. Atmospheric measurements.
HASI (Huygens Atmospheric Structure Instrument)	M. Fulchignoni Obs. Paris-Meudon & University Paris 7, France	Atmospheric temperature and pressure profile, winds and turbulence. Atmospheric conductivity. Search for lightning. Surface permittivity and radar reflectivity.

Supplementary table 2: Huygens radio astronomy network

	Telescope	Institute, country	Diameter [m]	Observing time (ERT/UTC)	
				Start	Stop
1.	Green Bank (GBT)	NRAO, USA	100	09:31:10	12:15:00
2.	VLBA North Liberty	NRAO, USA	25	09:31:10	13:15:00
3.	VLBA Fort Davis	NRAO, USA	25	09:31:10	13:45:00
4.	VLBA Los Alamos	NRAO, USA	25	09:31:10	14:00:00
5.	VLBA Pie Town	NRAO, USA	25	09:31:10	14:15:04
6.	VLBA Kitt Peak	NRAO, USA	25	09:31:10	14:15:00
7.	VLBA Owens	NRAO, USA	25	09:30:09	14:49:14

	Valley				
8.	VLBA Brewster	NRAO, USA	25	09:31:10	14:48:00
9.	VLBA Mauna Kea	NRAO, USA	25	09:31:10	16:00:00
10.	Kashima	NIICT, Japan	34	09:31:10	16:00:00
11.	Sheshan (Shanghai)	NAOC &ShAO, China	25	10:01:10	16:00:00
12.	ATCA	Australia	6x25	10:01:10	16:00:00
13.	Nanshan (Urumqi)	NAOC, China	25	11:31:10	16:00:00
14.	Mopra	ATNF, Australia	22	10:10:10	16:00:00
15.	Parkes	ATNF, Australia	64	12:26:23	16:00:00
16.	Hobart	U Tasmania, Australia	26	11:13:10	16:00:00
17.	Ceduna	U Tasmania Australia	30	10:13:10	16:00:00

Figure captions – supplementary information

Supplementary figure S1: Exploded view, which shows the main elements of the Probe (Refer to text for further details)

Supplementary figure S2: Engineering accelerometer measurements. Top panel: line plots of the three Central Accelerometer Sensor Units (CASU). Middle panel: line plot of one of the two Radial Accelerometer Sensor Unit (RASU). Bottom panel: Fast Fourier Transform analysis of the RASU measurements.

Supplementary figure S3: Probe internal temperature measurements performed at two representative locations inside the Probe. The upper platform measurements were made near the on-board computer; the lower platform measurements were performed near one of the batteries (battery#4). At the start of the descent, the upper platform is slightly warmer than the lower platform. The temperature difference between the two platforms increases during the last part of the descent when convection increases. The rate of temperature decrease on the upper platform changes only slightly on the surface while it decreases significantly on the lower platform indicating that the lower platform temperature was more sensitive to convection during the descent than the upper one.

Supplementary figure S4: This figure illustrates the overall variation of the communication radio link parameter during the mission. Time proceeds from top to bottom in the curves (15 minute-ticks marks). The line plots show the signal strength variation. The region shaded in pink are the forbidden areas where the receiver does not lock properly due to a design flaw (refer to text for further details). The recovery mission criterion was to place the signal strength in the white area. The green curve displays the flight measurements. The performance of the receiver is no longer nominal below the E_s/N_0 threshold of 3.3 dB. Data (frame) losses occurred only when the signal was close or below this level.

Supplementary figure S5: Configuration of the Earth-based radio telescopes as seen from Titan at the beginning (left panel) and at the end (right panel) of the observation. The observation began about half an hour before Huygens signal arrived at Earth and stopped at 16:00 UTC (~14:53 SCET/UTC). All 17 radio telescopes participated in the VLBI observation. 6 of the telescopes participated in parallel to the Doppler Tracking experiment. Among them, two telescopes, shown in red colour, the NRAO R.C. Byrd Green Bank Telescope and CSIRO Parkes Telescope, were equipped, in addition to the VLBI data acquisition system, with NASA's DSN Radio Science Receiver (RSR) with real-time detection capability provided by the Radio Science Group of the Jet Propulsion Laboratory. The four NRAO VLBA telescopes shown in purple (Pie Town, Kitt Peak, Owens Valley and Mauna Kea), were also part of the Doppler Tracking experiment.

Supplementary figure S6: Illustration of the radio ray paths after probe landing. As viewed from the probe on the surface, Cassini is low on the horizon and its elevation decreases with time. The relative strengths of both the direct and the ground-reflected signals combine to form an interference pattern that produces the characteristic variations seen in Supplementary Figure S4.

Supplementary discussion

Test of the Cassini-Huygens communication link

The Probe-to-Orbiter radio link was exercised through an umbilical during cruise. In order to test the radio link in mission mode, special Probe Relay Tests, designed to execute in-flight end-to-end performance tests of the receiving elements of this link, were introduced during the cruise phase. In these tests, the Huygens mission team used a NASA Deep Space Network antenna to transmit a radio signal to the Huygens receivers on board Cassini. The signal was programmed in frequency and amplitude to mimic the one expected from Huygens during its actual descent.

Huygens Probe Description

The Huygens Probe System consisted of the Probe itself (a 319 kg module) and the Probe Support Equipment (PSE). The Probe was attached to the Orbiter via a spring-loaded Spin and Eject Device that was designed to provide a nominal relative separation velocity of 33 cm/s and a nominal spin of 7.5 rpm at separation. The probe was released from the orbiter upon firing a set of pyrotechnic devices and, following a three-week ballistic flight, entered Titan’s atmosphere. The PSE, which remained attached to the orbiter, included the avionics equipment necessary to track and recover data transmitted by the Probe during its descent and to process this data for recording on the Orbiter solid-state recorders, for later transmission to Earth. The Probe itself was designed as a descent module cocooned in a shell consisting of a 2.75 m diameter heat shield and a back cover. The heat shield and the back cover protected the enclosed Descent Module from the radiative and convective heat fluxes generated during the entry into Titan's methane-rich, nitrogen atmosphere. An exploded view of the Probe is shown in Supplementary Figure 1. The heat shield was jettisoned early on during the parachute deployment sequence to fall under the Descent Module suspended under the main parachute. The Descent Module consisted of an aluminium inner shell containing the scientific instruments and servicing subsystems. The instruments and all the Probe electronic equipment were distributed on two platforms: the main platform on which most of the instruments were mounted, and the top platform that supported the mortar that deployed the pilot chute and that, in turn, removed the back cover. The top platform also supported the container for both the main and the stabilizer chutes, and the Probe radio transmission antennae. The inner structure was coated with thick foam blankets to minimize convective cooling during the Probe descent. The foredome of the Descent Module was instrumented with a set of 36 spin vanes that forced the Probe to spin during the descent thanks to aerodynamic interaction with the gas flow. While it was attached to Cassini during cruise, the Probe Descent Module was electrically connected via dedicated Orbiter power lines. After its separation from Cassini, the Probe relied on 5 non-rechargeable LiSO2 batteries (7Ah, 70V), a Power Conditioning and Distribution Unit (28V, 600W) and a Pyro Unit supplying 2 redundant sets of pyrotechnic devices for the activation of the various deployment and ejection mechanisms.

The Probe System avionics was organized in two branches, Channel A and Channel B. They operated in "hot" / active redundancy in handling payload data acquisition and formatting, and in the reception and recording of the data on board the Orbiter. This architecture was designed for robustness. It was both single-failure tolerant in the transmission of the acquired telemetry (including the science data), and in controlling the pre-entry, entry and descent activities.

Each of the two branches consisted of: i) one Command and Data Management Unit (CDMU) on the Probe, containing the on-board software which collected and formatted the telemetry, housekeeping and science data, and autonomously controlled the mission activities according to the programmed timeline, and processed sensor (entry and spin measurement accelerometers, radar altimeters) data to support the Probe autonomy and the operation of the science instruments during the entry and descent.

ii) one S-band (either 2040 or 2098 MHz) , 12W RF transmitter connected to a low gain helical antenna which transmitted the Huygens telemetry to Cassini. The telemetry rate of each branch was 8192 bps. On Channel A, the RF signal frequency was controlled by an ultrastable oscillator that was part of the Doppler Wind Experiment.

iii) one digital receiver in the PSE, which amplified and coherently demodulated the Probe signal, and passed the data to the Orbiter's Command and Data System via a MIL 1553 data Bus. During the cruise phase, when the Probe was attached to the Orbiter, the RF signal was passed to the Orbiter via the umbilical connection. During the mission, the Probe RF signal was received via the Cassini High Gain Antenna, which was pointed toward the predicted position of Huygens on Titan's surface.

Critical functions were implemented using triple redundancy: these are essentially the Probe wake-up function, performed by three Mission Timer Units, and the measurement of deceleration during Titan atmospheric entry, monitored by three Central Acceleration Sensor Units. This approach allowed a safe detection of the threshold of 10

m/s^2 on the falling edge of the deceleration profile, which triggered the parachute sequence deployment and defined the mission event time "t_0". To further increase the robustness of the mission, these critical functions were backed up by G(gravity)-switches and a software time-out function. All entry detection methods performed nominally. Thus, although they functioned properly, the G-switches and the software time-out function were not used by the on-board computers to trigger the parachute deployment sequence.

Overall Probe performance

About 130 Mbits of scientific and engineering data were returned by Huygens. The analysis performed at the time of this writing indicates that the overall probe engineering performance is within the initial expectations. However several aspects will require further analysis once the atmosphere conditions have been established from the evaluation of the scientific data. The descent lasted slightly under 2^h28^m, just within the predicted descent time envelope of $2^h15^m \pm 15^m$. A detailed iterative analysis of the atmosphere conditions and of the descent parameters under those conditions is needed in order to validate the aerodynamic performance of the parachute under the Titan atmospheric conditions encountered the day of the descent. The spin reversal after 10 minutes will also require further analysis once the atmospheric conditions have been established. The effect of convection inside the open instrument (in particular the SSP "Top Hat" structure) will also require further analysis in order to be able to fully explain the thermal behaviour during the descent. The Probe attitude profile during the descent and the repose attitude and probe orientation on the surface are expected to be reconstructed from the correlated analysis of the whole scientific and engineering data set. This is a rather complex task which is beyond the scope of the work described in the set of early Huygens papers published in this issue.

Probe entry and descent performance

The entry deceleration profile was measured by the three Central Accelerometer Sensor Units (CASU), which saturated at 10 g (98.1 m/s^2) as expected by design. The Radial Accelerometer Sensor Units (RASU) measured the radial acceleration caused by the Probe spin. The raw signals recorded by both sets of accelerometers are displayed as line plots in Supplementary Figure 2. The signature of impact on Titan's surface is clearly detected. A spectrogram of the RASU signal shows a frequency at about 0.8 Hz under the main parachute and 1 Hz under the stabilizer chute which are close to the expected characteristic frequencies of the probe attitude motion. The level of "noise" on the accelerometer shows that the descent was rather stable under the main parachute but rougher for most of the descent under the stabilizer chute (although remaining within specification) until below an altitude of about 20 km when it became smoother. The achieved spin profile is displayed in the article in Figure 4. The Probe entered the atmosphere and went through the entry with the expected spin rate (about 7.5 rpm) in the counter-clockwise direction. The spin rate decreased more rapidly than predicted under the main parachute and unexpectedly reversed direction after 10 minutes. It continued to spin with the expected rate but in the clockwise direction for the rest of the descent. The reason for this behaviour was still under investigation at the time of this writing. 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.

Thermal performance

At the start of the descent, the inner Probe temperature was about 7°C warmer than predicted. This favourable thermal behaviour may be due to two reasons: i) a lower-than-expected decrease of the inner temperature during the 20 day coast; ii) a temperature increase higher than expected during the 4-hour preheating. The Descent Module was well protected inside the entry shell during the hot entry. During that phase, the heat shield and the back cover were predicted to reach up to 1700 °C and 275 °C respectively. However no heating effect was detected by the units mounted in the Descent Module as could be inferred from temperature measurements that were made only after parachute deployment, once the radio link was established. Detailed post-flight analysis is ongoing to reconcile the measurements and the predictions. During the descent, the internal Probe temperature increased for about 1 hour due to the internal power dissipation when the payload was fully operational (in the order of 250 W average) and low convective cooling. The convective cooling increased during the last part of the descent, as the cold atmosphere was getting thicker, and the internal temperature decreased (Supplementary Figure S3). Some instrument units seem to have been somewhat colder than expected. This is attributed to higher-than-expected cooling due to gas flow and underestimated heat leak rates. After impact, the cooling rate decreased significantly, as there was no more convective gas flow inside the Probe. The internal Probe temperature remained very benign for the 72-minute period during which telemetry was available from the surface. At the time of this writing, post-flight analysis indicates that it was still well within the operating conditions of the units at 15:10 SCET/UTC when the Probe is believed to have stopped working.

Radio link performance

The reconstructed link performance for the radio’s Channel B is shown in Supplementary Figure S4 in the frequency-offset versus signal-to-noise (E_S/N_0) domain. In the graph, the saw-toothed lines mark the areas (reddish) where bit de-synchronization starts to build up in the receiver, leading to bit slips in the received data stream and eventually frame rejection/loss. The recovery mission profile aimed at keeping the signal strength outside these “forbidden” areas. The predicted nominal profiles (latest pre-mission estimate made on 10 January 2005) are shown in blue lines. The red lines outline the 99% confidence statistics envelope that includes uncertainties in the Probe targeting, atmosphere and wind profiles, aerodynamic effects and link budget. The reconstructed in-flight profile, in green, always remained within the designed boundaries. The forbidden areas were avoided (except for brief periods which were too short to have a detrimental effect) and therefore a full 100% of the Channel B data was safely decoded on board Cassini when the link signal-to-noise level was above the 3.3 dB threshold. The received signal frequency offset was slightly lower (0.6 ppm) than anticipated, due to a warmer temperature of the quartz clock of the on-board computer driving the data stream generation. The graph highlights the excellent behaviour of the relay link, and the success of the recovery mission, designed and implemented during the period 2001-2004.

The observed 3-4 dB band variation was expected. It is due to the non-symmetric radiation pattern of the Probe Transmitting Antenna (PTA) that was seen from every rotation and aspect angle while the Probe spun under parachute. Spin cycles are clearly distinguishable in the raw signal and played a key role in the post-flight attitude reconstruction and in confirming the spin reversal anomaly. Probe touchdown is marked by the noisy ‘flat line’ occurrence at $2^h27^m50^s$ after “t_0”. Spin stops at this time. All relay link functions survived this event and continued working nominally after landing.

The slow and large amplitude variations in received power after landing are most likely caused by multi-path effects which led to a constructive and destructive interference pattern by both the direct and the surface reflected rays (Supplementary

Figure S6). A preliminary analysis of the signal after landing indicates that it may be possible to characterize the soil in terms of dielectric constant and roughness (M. Pérez-Ayúcar, private communication, 2005). The link started to degrade after about 200 min of transmission, when the signal level decreased below the 3.3 dB threshold of the receiver and symbol errors occurred (marked as black asterisks in Supplementary Figure S4). Remarkably, the radio link lasted for 3^h40^m until Cassini set beneath Titan's horizon, approximately at 12:50:24 SCET/UTC.

Radio astronomy segment of the mission

The Huygens Probe descent was monitored with a network of radio telescopes on Earth. Seventeen radio telescopes listed in Supplementary Table 2 took part in the observations on 14 January 2005. The telescopes were capable of receiving the Huygens Channel A carrier signal at the frequency of 2040 MHz driven by the DWE USO. This frequency is outside standard ranges of radio astronomy receivers at most of the observatories and special upgrades and modifications of some observatory hardware were required. The radio astronomy segment of the mission consisted of two types of observations:

i) VLBI observation: All seventeen radio telescopes listed in Supplementary Table 2 participated in Very Long Baseline Interferometry (VLBI) observations of the Huygens Probe during its parachute descent to and on the surface of Titan. The goal of these observations was to reconstruct the projection of the descent trajectory on the plane of sky. An assessment study conducted in 2003-2004 indicated that the expected linear accuracy of such measurements should be of the order of 1 km. The Huygens VLBI tracking project was led and coordinated by the Joint Institute for VLBI in Europe (The Netherlands) and involved a large international cooperation. The Huygens VLBI project included also the University of Bonn (Germany), Helsinki University of Technology

(Finland), ESA/ESTEC, European VLBI Network (EVN), Netherlands Foundation for Research in Astronomy (ASTRON, The Netherlands), MERLIN VLBI National Facility (UK), National Radio Astronomy Observatory and NASA Jet Propulsion Observatory (USA), CSIRO Australia Telescope National Facility and University of Tasmania (Australia), National Astronomical Observatories and Shanghai Astronomical Observatory (PR China), and National Institute for Information and Communication Technologies (Japan). The total amount of VLBI data recorded in the Huygens tracking amounts to ~27 Tbytes and covers about 340 minutes of the mission. Data processing was the responsibility of the EVN (European VLBI Network) Data Processing Centre at JIVE (Dwingeloo, The Netherlands).

ii) Doppler Tracking experiment: six telescopes of the network participated in the Doppler tracking experiment and operated in parallel with the VLBI instrumentation. The combination of the planned Doppler measurements on the probe-orbiter and probe-Earth links would have allowed the Doppler Wind Experiment team (Ref. 17) to generate a full two-dimensional characterization of the wind field during the probe descent. The ground-based Doppler measurements were led by the Jet propulsion laboratory. The two largest radio telescopes of the network, the NRAO R.C.Byrd Green Bank Telescope (GBT, West Virginia, USA) and the CSIRO Parkes Radio Telescope (ATNF, New South Wales, Australia), which were equipped with the NASA Deep Space Network Radio Science Receivers (RSR) operated by the Radio Science Group of the Jet Propulsion Laboratory, provided real-time detection of the Huygens carrier frequency. A subset of four NRAO VLBA telescopes listed in Supplementary Table 2, Pie Town, Kitt Peak, Owens Valley and Mauna Kea, was equipped with PC-based Digital Doppler Recorders (DDR), also provided by the Jet Propulsion Laboratory, which allowed recording the Doppler signature of the Huygens carrier signal.

The overall geographical configuration of the Huygens radio astronomy network is shown in Supplementary Figure S5. On 14 January 2005 GBT equipped with an RSR provided direct detection of the Huygens carrier signal at around 10:25 ERT/UTC, thus providing invaluable confirmation of the overall state of the mission some 6 hours before telemetry data could reach Earth via Cassini relay. The real time carrier signal detection indicated that (1) the back cover of Huygens had been ejected, (2) the main parachute had been deployed and (3) that the Probe had begun transmitting. This was the first indication that the Huygens mission was going to be successful. Parkes also provided direct detection of the Huygens carrier signal some two hours later and gave first evidence that the Probe had landed and continued to transmit after landing.

Due to the loss of the DWE data from the Channel A link, the Earth-based Doppler measurements constitute the entire data set of the Doppler Wind Experiment. The scientific outcome of these measurements largely mitigates the loss of DWE data from the original configuration.

Due to the weakness of the Huygens carrier signal (about 2.5 W), a phase-referencing scheme had to be adopted for the VLBI observation. This method required interleaving observations of reference and target sources with duty cycle shorter than typical timescale radio propagation inhomogeneities (usually – several minutes). To accommodate this mode of observation, most of the network telescopes nodded between Huygens and a nearby calibrator source. However, two of the VLBA telescopes equipped with DDR's, Pie Town and Owens Valley, were pointed on Huygens continuously to provide an uninterrupted set of direct Doppler measurements.

Preliminary results of VLBI data processing indicate that the goal of the experiment will be achieved. The radio interferometric response from the Huygens carrier signal (so called “VLBI fringes”) was detected on most baselines (pairs of telescopes). Radial velocity measurements, a by-product of VLBI data processing, are in perfect agreement with measurements obtained independently by RSR measurements and used for the wind profile reconstruction. The actual time, spectral and spatial resolution of the VLBI data is consistent with the results of the assessment study. Detailed results of Huygens VLBI tracking will be presented elsewhere.