HUYGENS RADIO LINK IN-FLIGHT PERFORMANCE

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ABSTRACT

Huygens is the ESA-provided element of the joint NASA/ESA/ASI Cassini/Huygens mission to Saturn and its largest moon Titan. The spacecraft, delivered to the interface altitude of 1270 km above the surface by NASA/JPL, dived into the dense atmosphere of Titan on 14th January 2005 and landed on the surface after a nominal descent of 2.5 hours. The scientific and housekeeping data was continuously transmitted after the heat shield release to Cassini and relayed back to Earth in a later retransmission through the Deep Space Network.

Probably the most challenging activity after launch was the identification and recovery from a design flaw in the communications system that, if not corrected, would have led to major loss of scientific data, accounting up to 80 - 90% of the complete dataset.

It was February 2000 and the first in-flight test of the Probe relay link was executed. Although results confirmed the expected carrier level performance, unexpected behavior was observed at data-stream level: in particular, the receiver showed anomalous behavior when working at the mission Doppler. The Huygens Recovery Task Force (HRTF), a joint ESA/NASA task force, was established in January 2001 to understand the link anomaly and define alternative scenarios to recover the mission. An in-depth modeling of the link was performed, aiming at a 0.5 dB accuracy prediction in power, and sub-ppm in received frequency.

The Huygens Implementation Team (HIT) was established in July 2001 with the task of implementing the Recovery mission, based on a Cassini-Huygens change of geometry in the relay period to reduce the Doppler, and a four hour pre-entry warming of the probe to take advantage of the thermal variation of the frequency of the clock that drove the data stream.

In this paper we describe the latest estimated performances before the Huygens descent into Titan on 14th January, that claimed a 100% data return for the nominal mission time. The reconstructed link performance based on in-flight mission measurements is also presented, to highlight the excellent behavior of the relay link, and the success of the recovery mission predictions. Real mission profiles will be compared to predicted ones, showing the remarkable match achieved.

Additional aspects of the relay link will also be discussed, for both the descent and the surface phase. In the atmospheric phase, the establishment of the link and the attitude influence under the different parachutes will be assessed. In the surface phase, the touchdown signature, multi-path and ground interference with the soil, and a possible grazing of the rays due to atmospheric refraction before the orbiter fell below the horizon, will be analyzed.

1. INTRODUCTION

1.1. The Huygens mission

On 14th January 2005, the Huygens probe plunged in the hazy atmosphere of Titan (Lebreton et al, 2005). Huygens is the ESA contributed element to Cassini/Huygens, the joint NASA/ESA/ASI dual-craft mission for the exploration of the Saturn's system and its largest moon, Titan.

The Probe Data Relay Subsystem (PDRS) was in charge of returning all science and engineering data back to Earth (Jones and Giovagnoli, 1997). The data was continuously transmitted via 2 redundant S-band channels at 8 kbps, after the back cover and heat shield release. During this phase the PTAs (Probe Transmitting Antenna) had direct line of sight to the Orbiter, and the instruments a direct access to Titan's environment. The data was received in the PSA equipment (Probe Support Avionics) on board Cassini and stored for a later retransmission to Earth through the Deep Space Network.

1.2. The anomaly: the Huygens Recovery Task Force

A first in-flight test of the Probe relay link (Probe Relay Test, PRT#1) was planned and executed on 3 & 4 February 2000 to characterize the Huygens receiver behavior, with particular emphasis to signal and data detection thresholds.

Although results confirmed the expected carrier level performance, unexpected behavior was observed at data-stream level: in particular, the receiver performed nominally at zero-Doppler, but showed anomalous behavior (data loss) when simulated mission Doppler (~5.6 km/s) was applied to carrier, sub-carrier and data.

The data acquired in PRT#1 were only partially helpful in understanding the failure mechanism. In particular, it was possible to demonstrate that many frames had been shifted by a single bit in either temporal direction (since PRT#1 included tests of either positive or negative Doppler). Some doubly-shifted frames were also observed. Single shifts were expected and the Frame Synchronizer could tolerate them without declaring a loss of synchronization. Many frames appeared to be completely corrupted. At the time, the frequency offset applied was only including the Doppler offset contribution (~19 ppm). Ulterior characterization of the transmitter clocks showed an additional clock drift of ~5-6 ppm, placing the nominal mission at ~24 ppm.

The joint ESA/NASA Huygens Recovery Task Force (HRTF) was established in January 2001 by the ESA Director of Science and the NASA Associate Administrator for Space Science. The goal was an in-depth understanding of the anomaly and the definition of alternative scenarios to recover the mission. The HRTF studies successfully finished in July 2001 with the definition of the mission recovery plan. JPL's Cassini program had to accommodate changes to the Cassini trajectory in support of the HRTF outcome. In particular, the firsts orbits of the Cassini tour were re-planned in order to reduce the Doppler shift between the Orbiter and the Probe during the data relay period (HRTF, 2001).

1.3. The Huygens Implementation Team

The Huygens Implementation Team (HIT) was established in July 2001 with the task of implementing the Recovery mission. The team was set up by ESA / JPL-NASA top programme management. Industry support was essential. For this purpose, ESA had to re-establish a Huygens Mission Team (HMT). The work started in September 2001 and was presented for review and accepted in the Delta Flight Acceptance Review (ΔFAR), held in early 2004.

1.4. Pre-entry predictions

The communications link modeling and robustness predictions were fully accepted in the Mission Readiness Review (MRR) in Dec'04. Final fine tuning simulations were carried out on Jan 10th, 2005, 4 days prior the entry on Titan, taking into account some last-minute updates: link modeling, data stream clock frequency refinements, updated mission analysis tool, JPL/NAV trajectory, atmosphere model and aerodynamic database.

2. HUYGENS DATA LINK DESCRIPTION

2.1. Data relay configuration

The Probe Data Relay Subsystem is the Huygens telecom system. Science and housekeeping data were continuously transmitted at 8 kbps via 2 hot redundant S-band channels (A & B), through 2 circular polarized Probe Transmitting Antennas (PTA). Using its High Gain Antenna (HGA) for reception, the data was acquired in the Probe Support Avionics equipment (PSA) onboard Cassini and stored for later re-transmission to Earth through the Deep Space Network

The one-way radio links consisted of a classic BPSK/PM modulation scheme, at 2040 MHz LHCP (chain A, Left-Hand Circular Polarization) and 2080 MHz RHCP (chain B, Right-Hand Circular Polarization). This residual carrier was phase modulated (PM) by a 131072 Hz subcarrier, in turn BPSK modulated (Binary Phase Shift Keying) by the symbol stream. The BPSK phase ambiguity is avoided by a differential scheme. Reed Solomon (RS) and Convolutional coding 2:1 were implemented. The on-the-air symbol rate is therefore 16ksps.

2.2. Telemetry format

The Huygens telemetry follows the Packet Telemetry Standard (ESA PSS-04-106). *Transfer Frame* is the basic Probe transmitted data block (1 kbyte). Created every one second by the Command & Data Management Units, it encapsulates science and HK source packets polled over a 16 seconds long major cycle, along with a Header, the RS code word and the synch marker. These frames are convolutional and differentially encoded.

Once radioed and received in the PSA aboard Cassini, a *Super Packet* is created by decoding and removing the synch marker, and adding an Orbiter header and a time stamp. A Super Packet is the basic data block for storage in Cassini and retransmission to Earth. If the incoming Probe Transfer Frame fails to arrive, a Dump

Super Packet is sent instead, containing PSA memory dump data. Additionally, housekeeping telemetries from the Huygens receivers are sent as PSA HK Packets, independently of the link establishment.

3. IN-FLIGHT PERFORMANCE OVERVIEW AND LINK RECONSTRUCTION

The Huygens Probe performed a successful entry, descent and landing onto Titan on 14 Jan 2005. All times hereafter will be referred (unless specified) to the T0 time, 09:10:20.3 SCET/UTC, 14th Jan 2005, corresponding to the first (pilot) parachute deployment.

3.1. The excellent performance of ChB

The performance of the link chain B is presented in **Fig. 1**, in terms of RS error corrections to the incoming Probe Super Packets.

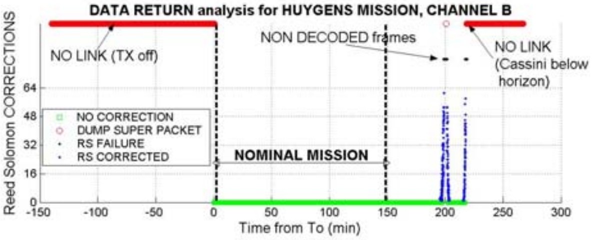

Fig. 1. Huygens in-flight performance: on-ground Reed Solomon corrections, Chain B. Dots below the 64 corrections level are packets correctly received on Earth. Nominal mission achieved a 100% data packet return, with a 70 min of extra data on the surface.

The number of corrections applied to the packets is shown in the graph. All packets with less than 64 errors were correctly received on Earth. The 'NON DECODED frames' correspond to RS failure, packets with Probe data but too corrupted to be decoded. The 'NO LINK' lines correspond to periods of Dump Super Packet generation, basically two: 1) from the PSA switched on by the Cassini sequence until the Probe transmitters were switched on by the descent sequence; 2) after the link was lost until PSAs were turned off by the Cassini sequence. Please note that although no Probe data is available in these periods, PSA HK telemetries were anyway delivered to Earth, so the receiver status was monitored during the complete mission interval. In the **nominal mission** (from link-start to 3 min after touchdown), a **100%** of the Transfer Packets generated in the Probe chain B were **received** on ground[1].

3.2. PSA Receiver B status analysis

3.2.1. Receiver start-up

The start-up of the link was nominal. The PSA locked right after the HPA were on, in around 2 seconds about 09:11:07 SCET/UTC. Light time between Cassini and Huygens was around ¼ sec.

The PSAs started listening more than 2 hours before the first signals were transmitted. The receiver initially alternates between the AGC (Automatic Control Gain) normalization state and signal detection state (S1). Once the first radio energy arrived to Cassini (~46sec after T0), the analysis of a 512-point FFT indicated the power threshold was surpassed, and the receiver moved to a carrier frequency detection status (S2) based on this rough FFT frequency estimation. In 6 CUTs (Counter Unit Time, equivalent to 125ms) the frequency was acquired in an AFC (Automatic Frequency Control) loop. Next, the signal phase was searched in a Carrier phase acquisition estate (S3), and the subcarrier locked (S4). All this took 1 CUT, after which the receiver finally stayed in signal tracking estate (S5).

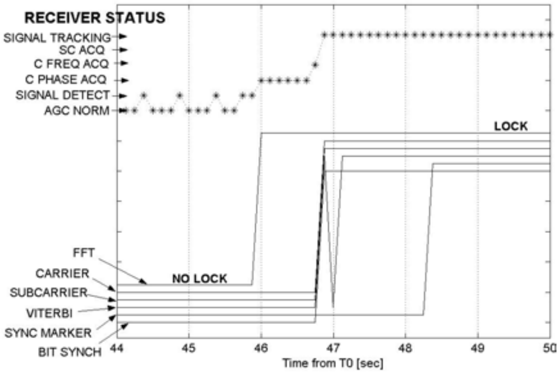

Fig. 2. Link start-up telemetries and receiver status. The signal was nominally locked and tracked within 2 sec. after the transmitters were switched one (~46sec).

At this moment, with the subcarrier locked, the bit synchronization is enabled and achieved. The Viterbi decoder[2] took 2 more CUTs to stabilise, probably due to an initial displacement of the 2 symbols that encode a bit, in the 3-symbol quantization word. Once the bit stream was finally in-sync, the decoder found the synchronization marker of the incoming frame, and hence the first packet was properly decoded and returned to Earth. It remarkably remained in the S5 state up to 50 min after landing.

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[1] *No data could be recovered in the redundant chain A due to a flight operations error (Lebreton et al., 2005).*

[2] *The Viterbi algorithm is a common maximum-likelihood decoding procedure for convolutional codes.*

3.2.2. Nominal mission

All the PSA link and receiver status telemetries were 'green' during the nominal mission, even during parachute exchange and impact.

3.2.3. First loss period

The first data loss period (**Fig. 1**) occurred from 196 to 203 min in the mission, after a stunning **50.7 min** on the surface, when the signal to noise ratio E_s/N_0 approached the 3.3dB threshold of the receiver. With such faint signal strength, the identification of the individual symbols becomes ambiguous, and the bit synchronizer starts to fail. In the worst case, if the frame header is not recognisable, the PSA rejects the Transfer Frame, and delivers instead a Dump Super Packet with no Probe information. On ground, the Reed Solomon (RS 223/255) code capability started to correct these errors. With a maximum correction capability of 63 bytes per Transfer Frame (interleave depth=4), if the errors exceed 63, the frame is not decodable any more, and a RS failure happens. In this 8 min period, 168 RS failures (~3 min of data) occurred, and only one Dump Super Packet was reported.

3.2.4. Second loss period and End of link

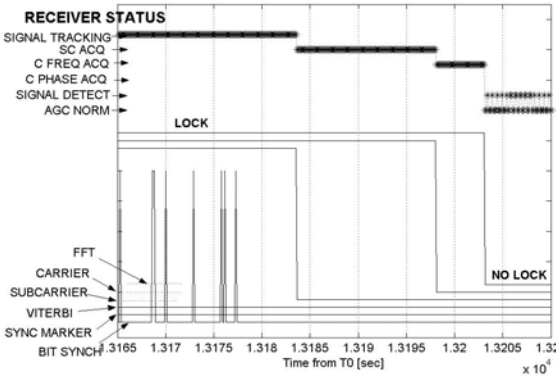

Fig. 3. End of link telemetries and receiver status. The faint signal prevented the bit synchronization and frame identification, until the carrier was lost at 12:50:20 (SCET).

The link surprisingly recovered for a last 15 min period of loss-free science return. But inevitably, at 216 min (when E_s/N_0 reached again 3.3 dB) bit-synch events resumed and on-ground RS corrections became more frequent. 83 Super Packets could not be decoded in this period. At 218 min sync marker was lost, leading to Dump Super Packets. From this moment on (**Fig. 3**), no more Probe packets were received. Signal strength continued to degrade, and the carrier was lost at 220 min. Remarkably, the radio link lasted for $3^h\ 40^{min}$ until Cassini set beneath Titan's horizon, approximately at 12:50:20 SCET/UTC.

Ulterior enhanced offline processing of the RS Failure frames allowed the recovery of 8 packets.

3.3. Finger-plot link reconstruction and comparison to predictions

The reconstructed chain B radio link performance is shown in **Fig. 4** in the frequency-offset versus E_S/N_0 domain.

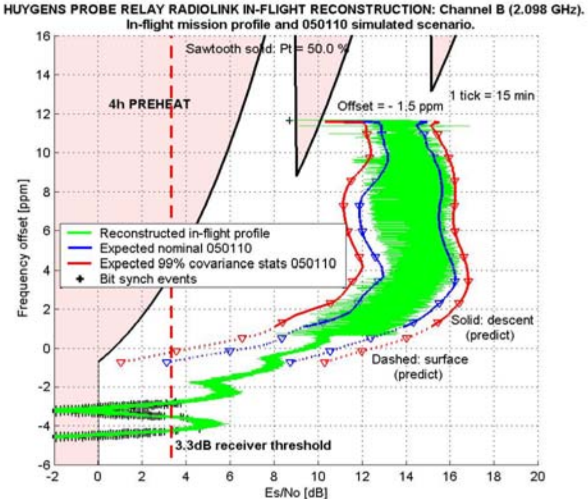

Fig. 4. The reconstructed in-flight E_s/N_0 – freq. offset profile in the fingerplots and pre-flight simulations.

In the graph, the saw-tooth line marks the area above which bit desynchronization start to build up in the receiver, leading to bit slips in the received data stream and eventually frame rejection/loss. The latest predicted nominal profiles (4 days prior to entry, Jan 10th, 2005) are shown in the inner envelope (triangular marks). The outer envelope outlines a 99% confidence power statistics, including the uncertainties in the probe targeting, atmosphere and wind profiles, aerodynamics and link budget. Its frequency corresponds to the minimum in the considered uncertainty range ±1.5ppm for the pre-flight robustness analysis (Pérez-Ayúcar, 2004). The reconstructed in-flight profile lies within. It remained in the designed boundaries, so the forbidden areas were avoided and therefore an outstanding 100% of the nominal mission data was safely returned to Earth. Mission time proceeds from top to bottom in the curves (15 minute-ticks added for illustration). The analysis highlights the excellent behaviour of the relay link, and the success of the recovery mission design.

3.3.1. Signal strength reconstruction

The received signal strength reconstruction, shown in **Fig. 5**, is based on the AGC telemetry, the control word of the coherent AGC loop in the digital part of the receiver. There is also another AGC loop (non-coherent wide-band) before the input of the digital part, but it is not, unfortunately, telemetered. The AGC data has been calibrated in-flight, based on the PRT#4 analysis, for conversion to signal-to-noise-ratio (E_s/N_0).

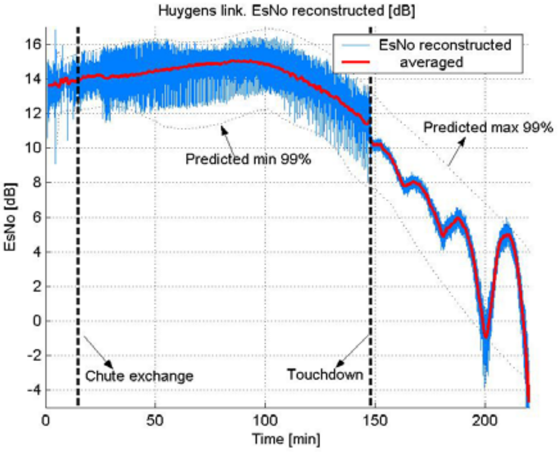

Fig. 5. Reconstructed in-flight E_s/N_0 profile.

The 3-4 dB band was expected: the non-symmetric PTA radiation pattern was scanned in every rotation while the probe spun down the surface. Spin cycles are clearly distinguishable in the raw signal, playing a key role for attitude reconstruction and confirming a spin reversal anomaly. Probe touchdown is marked by the 'flat line' occurrence at 2h 27.8min after T0, as spin stops. All relay link functions survived this event and continued working nominally.

3.3.2. Frequency offset reconstruction

The frequency drift in the PSA has been reconstructed as described in (Couzin, 2003). The method is based on the FDI Start telemetry (Frame Data Interruption), which precisely corresponds to the time difference between the arrival of a frame at the PSA (Synch Marker detection) and the Cassini RTI (Real Time Interruption), which frequency drift is very well characterised. So the FDI derivative, corrected with the RTI drift, provides the total frequency drift of the data stream. A comparison between the in-flight measured profile and the predictions is shown in **Fig. 6**. The main contributors to the frequency offset are the geometric Doppler and the thermal drift of the CDMU quartz clock driving the data stream generation (Pérez-Ayúcar, 2004).

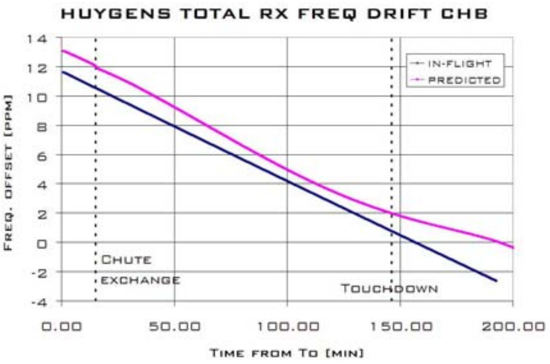

Fig. 6. Reconstructed frequency offset profile and pre-flight simulation.

One can observe that the actual offset is lower than nominally anticipated. Since the distance Cassini-Huygens is well known during the descent (sub-ppm precision), the warmer temperature (see **Fig. 7**) experienced by the CDMU seems the best explanation. The 'beneficial' effect brought the profile down by ~1.5 ppm in the early descent, the critical part, as shown in **Fig. 8**.

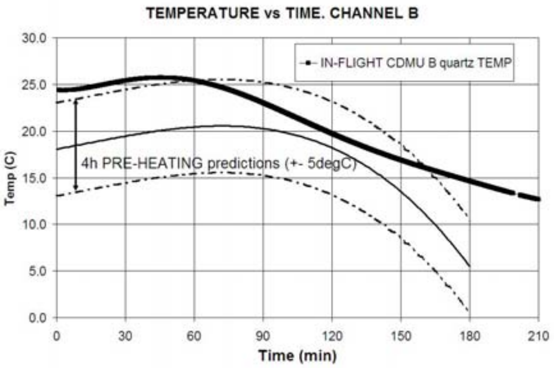

Fig. 7. In-flight CDMU/quartz temperature and comparison to pre-flight simulations. The actual temperature was warmer than anticipated.

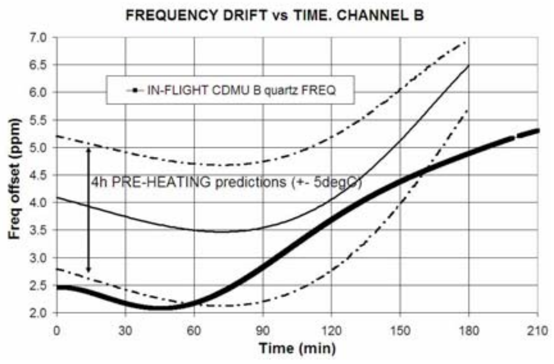

Fig. 8. Reconstructed CDMU clock frequency offset contribution and comparison to pre-flight simulations. The offset is lower (better) than expected due to the higher temperature of the oscillator.

4. SCIENTIFIC AND SYSTEM IMPLICATIONS DERIVED FROM THE LINK TELEMETRIES

The Probe Data Relay Subsystem has been also studied and used beyond the operational engineering service it is normally intended for. From the housekeeping telemetries, some additional system performance has been inferred and will help the scientific teams to better analyse their data. And surprisingly, some scientific results have been obtained. They are introduced in this chapter.

4.1. Initial localised large power fluctuations

Several large E_s/N_0 variations (up to 7dB) under the main chute are observed in the AGC telemetry data. Two explanations are plausible: 1) a large swing/attitude disturbance, or 2) a line-of-sight radio blockage by the metallic parts of the parachute (swivel and legs attachment ring).

1) Mapping the PTA gain pattern, a variation of 7dB can only be achieved by a 70deg swing (full angle) or higher of the Descent Module. These localized attitude disturbances have not been observed by any other instrument onboard so far.

2) The PAA (Probe Aspect Angle, the angle between the Huygens vertical and the Probe-Cassini vector) at the time of the fluctuations is minima (around 25 deg). A combination of a relatively small angular swing from the local vertical (less than 20 deg), with a particular positioning of the antennas within the spin period (the antennas have a lateral offset from the symmetry axis), would permit occasional line-of-sights blockages. The RF blockage is therefore the most probable explanation. The study, in preparation at the time of writing, might constrain the link and chute design of future parachute missions.

4.2. Azimuth and spin rate reconstruction

The spin rate of the Probe has been accurately reconstructed based on the AGC telemetry (Pérez-Ayúcar et al., 2005). The Probe Transmitting Antennas (PTA) are not ideal but present an azimuthal asymmetry. As Huygens spun down the surface (Parachute-DM line assumed vertical), the received power in Cassini showed periodic variations every rotation. The PTA gain pattern was measured before launch in a representative mock-up, so by comparison one can estimate the absolute Orbiter azimuth in a Probe body-fixed frame. A geometric conversion is then applied to obtain absolute azimuth on Titan's frame. Spin rate is computed as the derivative of the azimuth, except in the spin reversal interval, where AGC is not useful as the Probe stops spinning. Here it is extracted from the RASU telemetry. The rotation sign is explained in section 4.3. Based on this data, the Huygens Probe completed 24 rotations in the counter clockwise direction, followed by a spin reversal, and 330 rotations in the clockwise direction, before landing on Titan's surface.

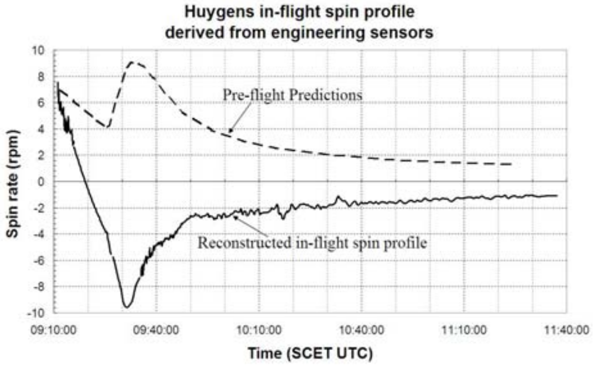

Fig. 9. Reconstructed Huygens spin rate profile (in Lebreton et al., 2005) and comparison to pre-flight predictions. Positive values mean counter-clock-wise as seen in the speed direction. The spin inversion is clearly seen.

4.3. Spin reversal anomaly

Preliminary interpretation [Bashar Ritz, personal communication] of the images acquired by the Science camera on board Huygens (DISR) suggested a reversal in the spin direction around 10min in the mission, under the main chute. The analysis of the radio link patterns is used to confirm this anomaly, and to indicate in addition the absolute direction of rotation. The PAA evolution is shown in **Fig. 10**.

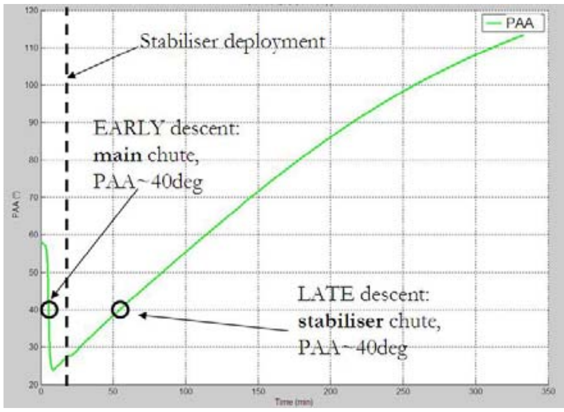

Fig. 10. Predicted Probe Aspect Angle for the Huygens mission. The rapid decrease at the beginning is attributed to the verticalization of the Probe as the main chute kills the initial large lateral velocity. The slow increase after that (Probe almost vertical) is due to Cassini sky-track.

Comparing the AGC pattern at similar PAA values in times before and after the suggested inversion, we should confirm or not if the spin was reversed. Luckily, the PAA evolution presents a minimum close to this time. After a visual inspection of the AGC signal, we choose a PAA ~40deg where the effect is best visible. A zoom of 3-4 rotations is shown in **Fig. 11**, for the early descent (main chute, 1min in the mission). A similar plot is displayed in **Fig. 12** for the mid descent (stab chute, 50 min in the mission), with time scale (x axis) reversed. Both patterns correlate well only if **one** is **time-reversed**.

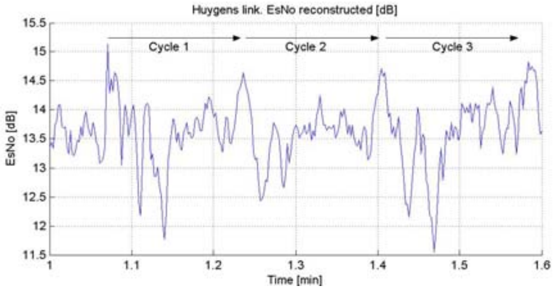

Fig. 11. In-flight E_s/N_0 around 1 min.

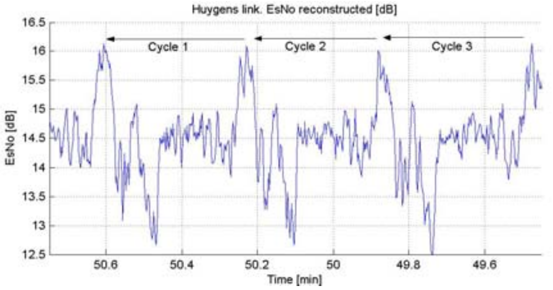

Fig. 12. In-flight E_s/N_0 around 50 min. Time is REVERSED.

Furthermore, these two patterns match well to the predicted AGC pattern (**Fig. 13**) which assumes ideal spin-only motion. The differences are attributed to the uncertainties in the measured PTA Gain pattern, noise in the AGC, and pitch-yaw movements of the Probe.

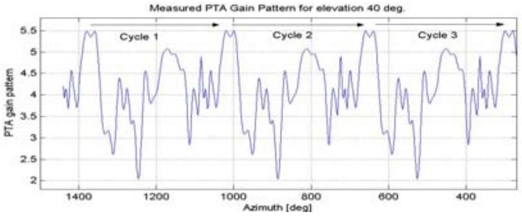

Fig. 13. Simulated PTA Gain at PAA=40° (4 complete cycles are shown).

As a result, the Huygens in-flight spin direction is estimated as:

- *Counter-clockwise* (as seen from above) for the *early part of the descent* (consistent with the spin imparted by the separation from Cassini), i.e. the first ten minutes under the main parachute.

- *Clockwise* for the last 5 minutes under the main parachute and the whole stabilizer chute phase.

4.4. The touchdown event

Probe touchdown (see **Fig. 14**) is marked, in the RF power domain, by the 'flat line' occurrence in the AGC signal at 8873.5 sec after T0, as spin stops. All relay link functions survived this event and continued working nominally. Touchdown is defined by SSP dedicated sensors to happen 8870 sec (2^h 27.8^{min}) after T0, but the AGC signal stabilization is reached 3.5 seconds later. A transitory phase or bouncing might be the explanation.

In the frequency domain, a fast glitch at 8872 sec is observed in the NCO telemetry that could be related to touchdown event. Reconciliation with SSP time is on-going at the time of writing. After it, the frequency changes by ~10.5 Hz, a value consistent with a vertical Δv extinction of 4.5 to 5 m/s. NCO frequency is based on TCXO clocks (not USO), but it should be stable enough for this short period. A detailed study is made by DWE in (Dzierma, 2005).

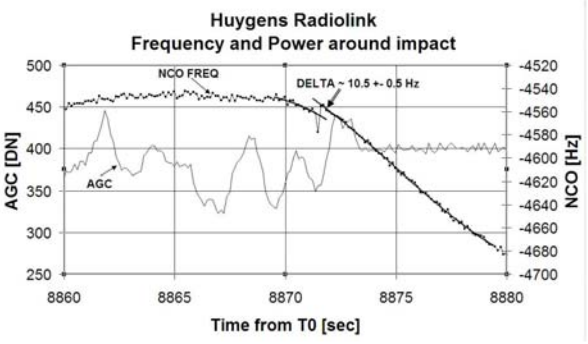

Fig. 14. Huygens radio frequency and power change around impact.

4.5. Cassini grazing geometry on the surface

The precise determination of the Huygens landing site coordinates is a high priority objective of the mission. The link analysis may shed light on the estimated position performed by the Descent Trajectory Working Group (Kazeminejad et al., 2005) and others instrument teams (DWE and DISR).

The Cassini position in Titan's sky is shown in **Fig. 15**. At the time of touchdown, the Orbiter elevation was around 20° over the horizon, as computed from the JPL/NAV Spice kernels[3].

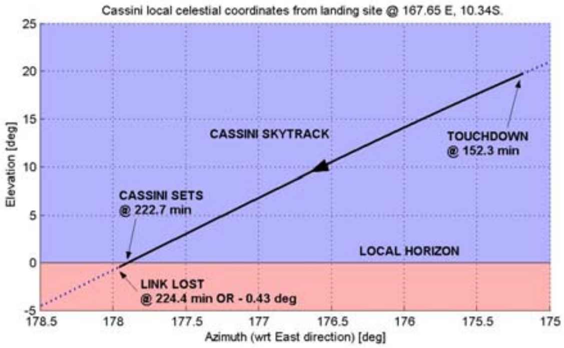

Fig. 15. Cassini position in Titan's sky, as seen from 167.65E 10.34S position on Titan surface. In an equant projection, Cassini would set nearly vertical.

The Cassini set time is highly dependent on the coordinates of the landing site, with a sensitivity of 4 minutes per LON°, and a negligible LAT° dependence, as illustrated in **Fig. 16**. Assuming the DTWG landing coordinates and a flat horizon, the end of link time would be 106 seconds after the Orbiter optical set time, or -0.43° in local elevation.

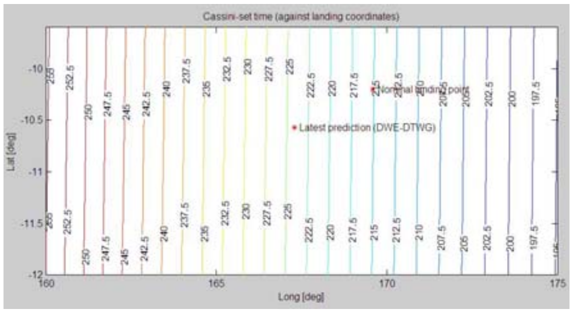

Fig. 16. Cassini set time as a function of the landing coordinates, in a perfect Titan sphere. Its sensitivity is 4 min/LON°, and negligible for LAT°.

Updated predictions of the refraction effects in the thick atmosphere have been performed based on the method described in (Bird, 1997). The newest recommended atmospheric model (the so-called TAMWG post-Ta atm_a model (Yelle, personal communication) was used. Simulations estimate a maximum bending of 1.03° for the grazing ray, with an associated defocusing loss of 0.6 dB, as illustrated in **Fig. 17**. A Huygens trans-horizon transmission is therefore observed, but the power loss on these grazing rays due to terrain undulation, diffraction and defocusing loss might have forced the radio link to be lost before the maximum theoretical elevation of -1.03°.

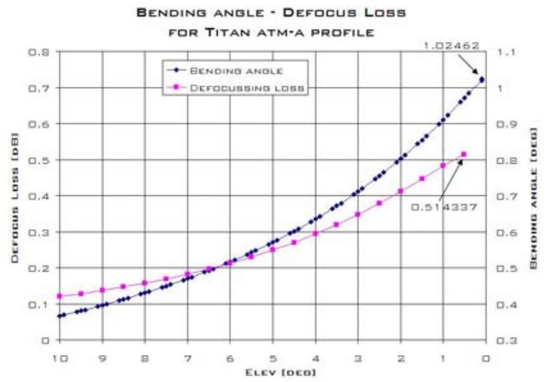

Fig. 17. Theoretical ray bending and defocusing loss from the surface of Titan, assuming the TAMWG Post-Ta atmospheric model.

As a result, the current estimates from DTWG are well in accordance with the link estimates.

4.6. Multi-path on the surface

One of the most interesting phenomena in the link analysis is the slow and steep variations in received power observed on the surface (thick 'noisy' curve in **Fig. 18**). A simple scanning of the antenna gain pattern (simulated in the dark straight lines, for different initial azimuths) due to the Orbiter movement in Titan's sky cannot explain these large oscillations.

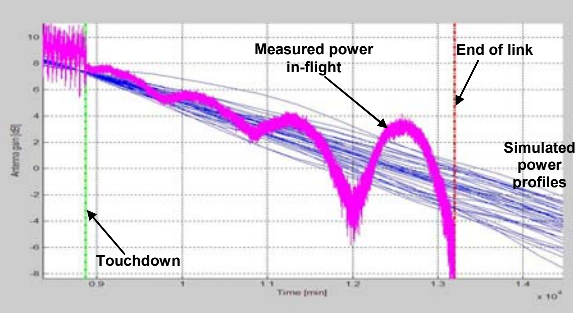

Fig. 18. Surface link simulation WITHOUT multi-path effects (dark lines) and comparison to in-flight measurements (noisy thick line). The predictions cannot be explained the observed large oscillations.

The periodic occurrence of maxima and minima suggests a radio interference phenomenon of reflected rays on the surface, and implies that surface reflections are above the detectability threshold. An idealized representation of the surface link geometry is depicted in **Fig. 19**.

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[3] *ftp://naif.jpl.nasa.gov/pub/naif/CASSINI/kernels*

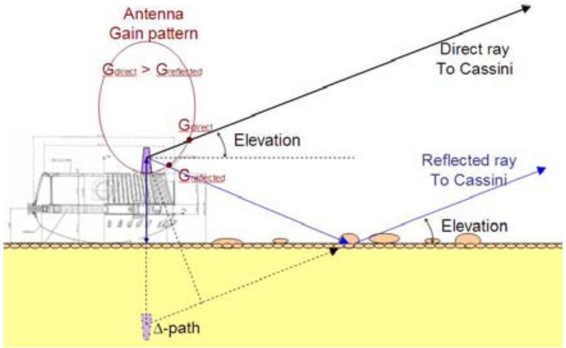

Fig. 19. Huygens idealized geometry on the surface, illustrating the multi-path phenomena.

This non-foreseen radio science experiment will help to characterize the soil in terms of dielectric constant and roughness, as well as to locate the PTA height. Preliminary simulations show a good match with the in-flight measurements, as illustrated in **Fig. 20**. Fine tuning of the parameters, namely soil dielectric constant and terrain roughness, is on-going at the time of this writing.

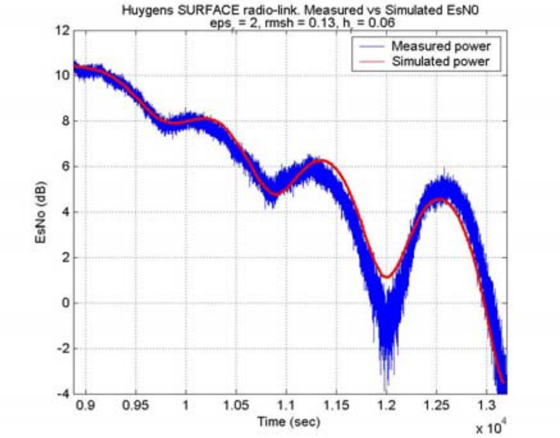

Fig. 20. Preliminary surface link simulation WITH multi-path effects and comparison to in-flight measurements. Interference patterns can better explain the measured profile.

5. CONCLUSIONS

The excellent performance of the Huygens ChB radio link has been presented. A full 100% of the nominal Probe transmitted data was returned back safely to Earth and, in addition, a stunning 71 min period on the surface of Titan, until Cassini set beneath Titan's local horizon. All the Recovery Mission efforts to solve the telecom problem discovered in 2000 were successful, and finally paid off.

Furthermore, due to its good quality, the link telemetries have been used for scientific purposes, beyond the regular engineering service the subsystem was intended for. As highlights:

- A spin reversal anomaly has been confirmed and characterized.
- The spin direction during the Huygens descent has been determined.
- Azimuth and spin rate profiles have been generated and will help the instrument teams to better interpret their measurements, both during the descent and surface phases.
- The predicted landing site coordinates from DTWG are in accordance with the link duration.
- The multi-path behaviour on the surface will also provide a local characterization of the soil properties for synergies with the lower resolution Cassini radar mapping of Titan.

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And the most special regards to you, Huygens Probe, now lonely resting in the coldness of Titan, hidden from our human eyes by its haze blanket. Thanks for such an outstanding job.

7. LIST OF ACRONYMS

ADRS:	Attitude Determination and Reconstruction Subgroup.
AFC:	Automatic Frequency Control.
AGC:	Automatic Gain Control.
ASI:	Agenzia Spaziale Italiana.
BPSK:	Binary Phase Shift Keying.
CDMU:	Command and Data Management Unit
SCET:	Space Craft Ephemeris Time
CUT:	Counter Unit Time
DISR:	Descent Imager and Spectra Radiometer.
DTWG:	Descent Trajectory Working Group.
DWE:	Doppler Wind Experiment.
ESA:	European Space Agency.
FDI:	Frame Data Interrupt.
FFT:	Fast Fourier Transform.
HGA:	High Gain Antenna.
HIT:	Huygens Implementation Team.
HMT:	Huygens Mission Team.
HK:	House Keeping.
JPL:	Jet Propulsion Laboratory.
LHCP:	Left Hand Circular Polarization
MRR:	Mission Readiness Review.
NASA:	National Aeronautics and Space Agency.
NCO:	Numerical Control Oscillator.
PAA:	Probe Aspect Angle
PDRS:	Probe Data Relay Subsystem.
PM:	Phase Modulation
PRT:	Probe Relay Test.
PSA:	Probe Support Avionics
PTA:	Probe Transmitting Antenna.
RF:	Radio Frequency
RHCP:	Right Hand Circular Polarization
RS:	Reed Solomon
RTI:	Real Time Interrupt.
TAMWG:	Titan Atmosphere Modelling Working Group.
TCXO:	Temperature Control Crystal Oscillator.
UTC:	Universal Time Coordinated.

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