

Resolving the Cassini/Huygens Relay Radio Anomaly*

Dr. Leslie J. Deutsch
Chief Technologist (Acting)
Jet Propulsion Laboratory
California Institute of Technology
(818) 354-3845
leslie.j.Deutsch@jpl.nasa.gov

Abstract—NASA's Cassini mission to Saturn carries the European Space Agencies (ESA's) Huygens probe, which it will release shortly before an encounter with Saturn's moon, Titan, a possible location for extraterrestrial life within our Solar System. As it parachutes towards Titan's surface, Huygens will acquire scientific information which will be relayed to Earth through Cassini. Comprehensive testing of this relay radio link was not performed prior to Cassini launch and cannot be done during cruise. A test using NASA's Deep Space Network (DSN) to mimic the probe's signal was performed in 2000 and uncovered an anomaly that, unchecked, would result in nearly complete loss of the Huygens mission. An international team of experts from NASA and ESA was assembled to solve this problem: the Huygens Recovery Task Force (HRTF.) This team, co-chaired by the author, performed extensive testing, modeling, and simulation to understand the failure mechanism. Each Huygens science team determined mission impacts for various scenarios based on these results. This led to a suggested modification to the Cassini trajectory that will result in nearly complete data return for Huygens with minimal impact on Cassini.

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1. INTRODUCTION

NASA's Cassini [1] spacecraft is currently about three years away from beginning its primary mission exploring the Saturnian system. It carries ESA's Huygens probe which it will release shortly before an encounter with Saturn's moon, Titan (see Figure 1.)

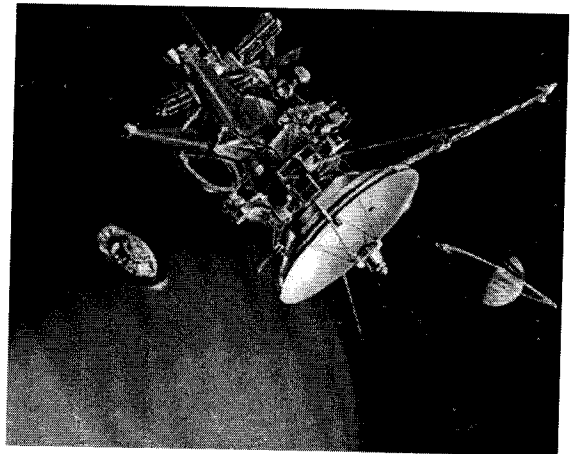


Figure 1 – Cassini releasing Huygens probe at Titan

Huygens is equipped with a suite of instruments for studying the atmosphere and surface of Titan, which is a possible location for extraterrestrial life within our Solar System (see Figure 2.)

Huygens has no propulsion system and will therefore have a ballistic trajectory toward Titan. At various times during the descent, Huygens will deploy a series of parachutes and eject an aeroshell. It will then acquire scientific information as it drifts toward the surface. If it survives on the surface (if indeed there is a hard surface!) it will continue to acquire information.

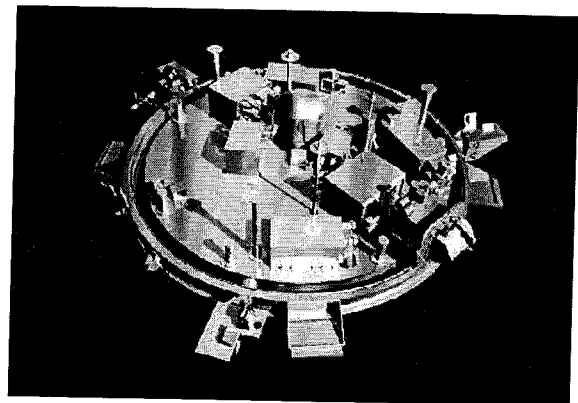


Figure 2 – Huygens Probe

* The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

The information gathered by Huygens will be relayed to Earth through a special dedicated radio on Cassini. This relay link will begin just after the aeroshell is ejected and end when Cassini passes Titan and loses sight of Huygens. The duration of the link is expected to be approximately three hours, depending on various error sources including the direction and magnitude of Titan's wind.

Comprehensive testing of this relay radio link was not performed prior to Cassini launch. Since Huygens cannot send radio signals to Cassini while it is bolted to the side of the mother craft, there is now no way to test the link using Huygens. Fortunately, ESA designed a test that used NASA's Deep Space Network (DSN) to mimic the probe's signal from Earth, including signal strength and Doppler. Unfortunately, this test uncovered an anomaly that, unchecked, would result in nearly complete loss of the Huygens mission. The relay radio was not capable of tracking the expected Doppler profile of the Huygens radio signal during its descent through Titan's atmosphere. Sadly, the relay radio had been designed so that it cannot be reconfigured in flight.

An international team of experts from NASA and ESA was assembled to resolve this anomaly: the Huygens Recovery Task Force (HRTF.) The HRTF was chaired by Kai Clausen of ESA and co-chaired by the author. This team performed extensive ground and flight-testing, modeling, and simulation to understand the failure mechanism in the relay radio. Each subsystem in the relay link was analyzed, modeled, and the results verified by a testing campaign. Tests were performed using a complete engineering model of the relay radio system at the European Space Operations Center (ESOC) as well as additional in-flight tests using the DSN.

The models were used to predict the corruption of science data under various scenarios. These predictions were given to each Huygens science team to determine mission impacts for the various scenarios. This led to a suggested modification to the Cassini trajectory that will result in complete data return for Huygens while having minimal impact on the Cassini orbital mission.

This paper describes the anomaly, the testing process, the failure mechanism, and the proposed new mission design for Huygens.

2. THE HUYGENS LINK DESIGN

A top level block diagram of the Huygens communication system is shown in Figure 3. Data from the five on-board Huygens instruments are assembled into fixed length packets by the individual instrument subsystems. These packets are gathered by the Probe Software, which adds its own housekeeping packets (also the same length.) The packets are assembled into fixed length telemetry frames, each containing seven packets according to a pre-defined

allocation algorithm managed by the probe software. A standard Consultative Committee for Space Data Systems (CCSDS) format [2] is used for the frame headers and synchronization words. The frames are passed through a standard CCSDS coding system [3], including a (255, 223) Reed-Solomon encoder and a (7, 1/2) convolutional encoder, and placed in two buffers for transmission to Cassini on the two S-band radio channels.

As is customary in the field of deep space communications, the digital data before encoding is said to consist of "bits" while the encoded data stream consists of "symbols." By using this convention, there is less confusion in the discussion that follows.

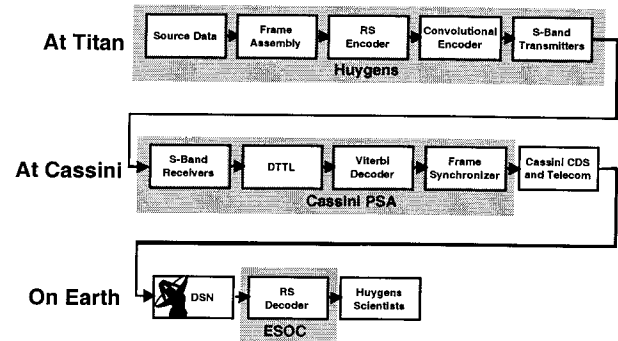


Figure 3 – Huygens Telecommunications System

Two radio frequency (RF) channels (at slightly different S-band frequencies) are used to send the frames to Cassini using a standard Binary Phase Shift Keying (BPSK) modulation scheme [4] with a sinusoidal subcarrier. There is no pre-compensation for the expected Doppler on the signals caused by the relative acceleration of Huygens and Cassini. The signals are received on Cassini's high gain antenna. There is substantial signal margin on this link in the baseline Huygens mission design so there should be almost no degradation due to the RF link.

On Cassini, a dedicated radio receiver is used to detect and decode the Huygens signal. The receiver is a portion of the Probe Support Avionics (PSA) subsystem on Cassini. The PSA uses conventional Costas loop [5] carrier and subcarrier tracking. The PSA also has the capability of using a Fast Fourier Transform (FFT) algorithm for fast signal acquisition.

A Data Transition tracking Loop (DTTL) [6] is used to detect the symbols which are then passed to a Viterbi decoder to undo the convolutional coding.

At this point (since the Reed Solomon code is transparent) the frame header information is available and bit stream is passed to a frame synchronizer which detects and tracks the CCSDS frame synchronization word at the beginning of each frame.

When the PSA has locked on all aspects of the incoming signal (carrier, subcarrier, symbols, and frames) it passes the detected frames to the Cassini Command and Data System (CDS) for subsequent transmission to Earth on the normal Cassini downlink. If the PSA is not locked on the frames, the data is not passed to the CDS and data loss can occur. This was not expected to occur in the baseline Huygens mission design.

After the frames are received on Earth at the DSN, they are sent to ESOC for Reed-Solomon decoding and dispersion of the science packets to the instrument Principal Investigators (PIs.)

3. TESTING THE LINK

Cassini is currently in cruise, about halfway on its journey to Saturn. Huygens is bolted to the side of Cassini and there is no way to radiate signals from Huygens to Cassini. There is a tether between the two that allows digital communications.

Because there was no comprehensive test of the Huygens link before launch (i.e. a test that simulated the complete Huygens signal dynamics) ESA devised a method by which the non-Huygens portions of the link could be tested in flight. This method uses NASA's DSN to send S-band signals to Cassini that mimic the expected signal strength, Doppler, and format of a signal from Huygens.

In order to accomplish this, ESA developed a personal computer-based ground support system to generate Huygens-like telemetry streams and control DSN modulators and transmitters. This equipment was placed in the basement of DSS-24, a 34m beam waveguide antenna [7] at the DSN Goldstone complex. Telemetry from Cassini, including the received frames from the test, was received later (after the round-trip light time delay) at DSS-24 and sent on to ESOC for analysis. A block diagram of the test setup is shown in Figure 4.

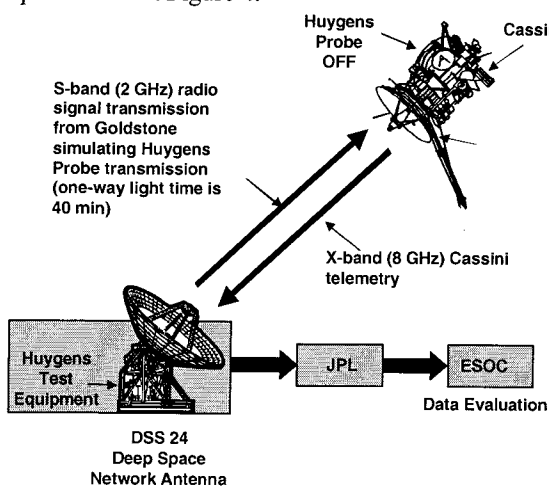


Figure 4 – Probe Relay Test (PRT) configuration

The first of these tests, Probe Relay Test #1 (PRT#1) was accomplished in February, 2000. The expected range of signal strengths and Doppler shifts was exercised and it was expected that almost all the transmitted frames would be recovered at ESOC.

In fact, almost all the frames were lost. Analysis of the housekeeping telemetry from the PSA showed that the DTTL was not locking on the symbols as predicted.

Since the PRT testing required precious DSN tracking resources, additional testing to determine the range of the DTTL failures was accomplished using the Huygens engineering model located at ESOC. Since the DTTL was then believed to be the likely problem, three parameters were varied during these tests to understand the extent of the anomalous behavior:

- Frequency offset, or Doppler (Δf)
- Signal strength (E_s/N_0)
- Transition density in the data stream (P_t)

The last of these is important because the DTTL requires symbol transitions (0-1 or 1-0) in the symbol stream in order to perform well. The more bit transitions, the better the DTTL will tend to work.

All the test results were commensurate with the hypothesis that the DTTL was at fault and that it had likely been built with incorrect loop bandwidths for the expected signal dynamics. In other words, the DTTL could not keep up with the changes in frequency caused by the Doppler acceleration expected in the Huygens mission.

Whenever the DTTL did not “keep up” with the signal’s frequency shifting, it slipped cycles – and in doing so would drop symbols (0s and 1s) from the encoded data stream.

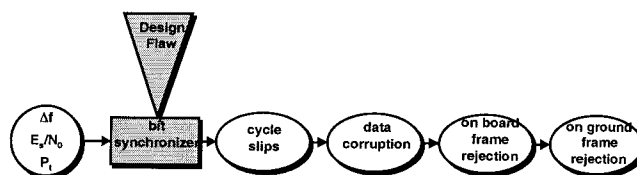


Figure 5 – Huygens failure mechanism

This led to an understanding of the basic failure mechanism for the Huygens link as shown in Figure 5. A design flaw in the DTTL would, under certain combinations of the three relevant signal parameters, cause cycle slips to occur. This would, in turn, cause corruption of the received symbol stream (bits,) rejection of frames on-board Cassini, and additional loss of frames on Earth.

4. CYCLE SLIPPING

All the test results were commensurate with the hypothesis that the DTTL was at fault and that it had likely been built with incorrect loop bandwidths for the expected signal dynamics. In order to corroborate this hypothesis, a complete dynamic model of the DTTL's performance was developed by Luitjens Popken of ESA. Dr. Popken's model was used to predict the performance of the DTTL as a function of the three relevant parameters. Some of these results are shown in Figure 6.

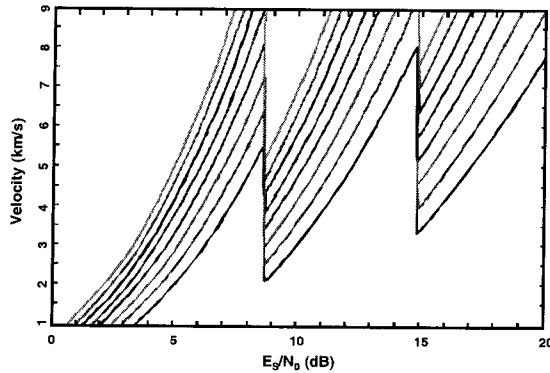


Figure 6 – Results of DTTL modeling

In this Figure, the vertical scale is measured in km/s and is equivalent to frequency offset. The contours in the plot represent various values of transition density from the lowest curve with $P_t = 50\%$ (random data) to the highest curve with $P_t = 100\%$. (Clearly, the 100% case is not very useful as there would be no information conveyed on the link!) Whenever the DTTL is operated below a contour, it should track perfectly. Whenever it is above a contour, there is a predictable rate of cycle slipping.

This model was compared to test data from both the engineering model and the PRT tests (conducted with the actual Cassini PSA.) In all cases, the model and empirical data agreed with a high degree of confidence. An example of these comparisons is shown in Figure 7.

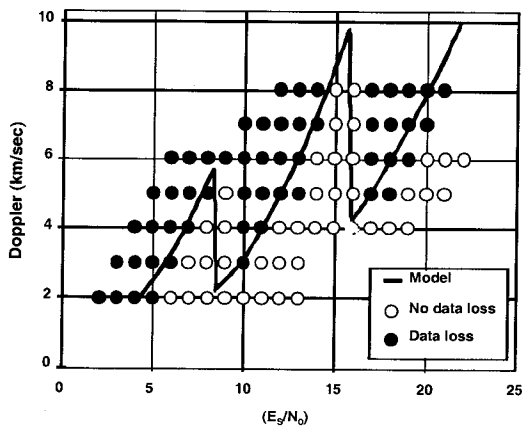


Figure 7 – Test data vs. modeling of DTTL

5. THE FAILURE MECHANISM

Now that the cause of the failure was understood, it was necessary to model the effect of these cycle slips on the actual science data stream. This required a thorough analysis of the subsequent elements of the link: particularly the Viterbi decoder and frame synchronizer.

Although there had been a large volume of test data accumulated by this point, there was not sufficient data acquired at particular combinations of Δf , E_g/N_0 , and P_t to observe the kinds of long error sequences produced by the Viterbi decoder and frame synchronizer. In other words, while it was possible to observe regular patterns of cycle slips with only a few thousand symbols of data, it would take hundreds of thousands of symbols to see their effect on the frames.

Hence, when the HRTF designed a second PRT to be performed in late January, 2001, several "long dwell" tests were included specifically to observe these effects on frames.

In fact, patterns of frame behavior were evident immediately from these long dwell tests. In Figure 8, data from the PSA's housekeeping telemetry as shown as a function of time during a small portion of one of these tests. The numbers on the x-axis refer to frame numbers measured from an arbitrary point in the data stream. The housekeeping data is sampled eight times for each frame, or approximately once for each packet.

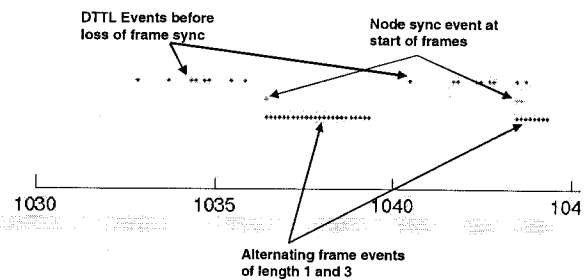


Figure 8 – Patterns of frame errors

The top line of dots corresponds to PSA-detected errors in frame synchronization. The middle line of dots shows PSA-detected problems in the Viterbi decoder. The bottom row of dots corresponds to PSA detected problems in the DTTL.

It is clear, though unexpected at first, that the Viterbi decoder synchronization failures align with frame synchronizer problems. Also, there is a clear pattern of frame synchronization problems: alternating sequences of one and three problematic frames.

It turns out that all of these effects can be explained by a careful analysis of the frame synchronization algorithm and the parameters used in the specification of the Viterbi

decoder method for obtaining node synchronization (i.e. which of the pair of symbols generated for each but is “first.”) An overall model of this behavior was developed by Dr. Kenneth Andrews of JPL.

In fact, depending on Δf , E_s/N_0 , and P_t , the patterns of frame errors change – and they are all explained by the model developed by the HRTF.

Frames that are returned to Earth will fall into one of four categories: good frames (no errors caused by this anomaly,) dropped frames (when the PSA does not send the frames to the CDS,) bit-slipped frames (these will occur periodically when the DTTL is failing,) and corrupted frames. There is clearly no hope of recovering the dropped frames.

6. MITIGATION STRATEGIES

There are basically two ways to go about resolving this anomaly.

First, to the extent possible the Huygens communication system needs to be changed so that it is less likely to lose frames while keeping everything else (Δf , E_s/N_0 , and P_t) constant. Since the PSA cannot be modified from the ground, this requires making changes either to the Huygens probe software or to the Earth elements of the system. It is not feasible to modify the Huygens end of the link without the ability to modify the PSA – except for changes to the Reed-Solomon code or frame assembly. The HRTF considered each of these but eventually rejected these ideas.

Another possibility of this type is to modify the ESOC Reed-Solomon decoders to do a better job of recovering corrupted frames that are received on the ground. This method has merit and is likely to be implemented. As an example, any bit-slipped frame that is returned to Earth can be recovered in this way. Also, by using the erasure correcting capability of the Reed-Solomon code [8] it may be possible to recover a fraction of the corrupted frames that are returned to Earth.

The second way to improve the link is to modify the parameters Δf , E_s/N_0 , and P_t by one of a number of methods. This is illustrated in Figure 9. A given Huygens mission design (including its trajectory relative to Cassini) can be represented as a trace in the (Δf , E_s/N_0) plane as shown. The performance is indicated (to first approximation) by the relative position of this trace to the corresponding contour for P_t , shown for a value of 50% in this Figure.

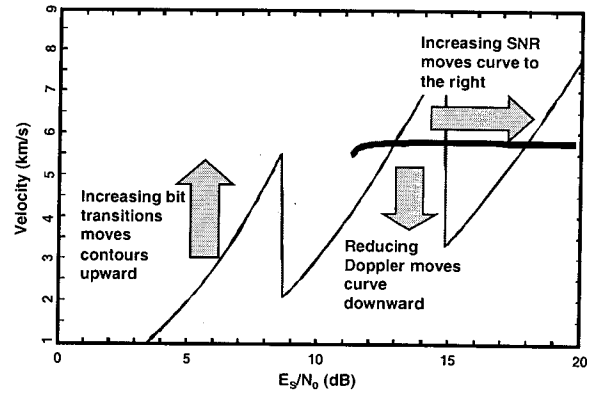


Figure 9 – Effect of modifying parameters

If Δf is reduced, then the trace effectively moves downward, increasing the overall performance.

It is possible to make small changes to the frequency of the Huygens oscillator that is used to generate the S-band signals. By heating the oscillator, for example, Δf can be reduced slightly.

The Δf can also be changed by changing the trajectory of Huygens relative to Cassini. This can cause a dramatic increase in performance – but often at the expense of the Cassini orbital (non-Huygens) science.

Increasing E_s/N_0 will also increase the performance. This could be effected, for example, by using a better pointing algorithm for Cassini’s high gain antenna. The HRTF considered several such methods, including an implementation of “conscan” [9], a general algorithm for closed loop antenna pointing.

Another way to increase E_s/N_0 is to reduce the time by which the Cassini spacecraft lags behind Huygens as the two approach Titan. This lag time is called the *Orbiter Delay Time*, or *ODT*. In the baseline mission, the ODT is planned to be about four hours.

Finally, increasing P_t raises the contour in the Figure, thus increasing performance. Since all the Huygens instruments produce random-looking data (with $P_t \approx 50\%$) this requires modification of the data stream on-board Huygens. Two methods were considered.

First, it is possible to pre-code the Huygens science data so that there are more symbol transitions. This is accomplished at the expense of data bandwidth. As an example, the HRTF discovered a code that could produce a stream with $P_t \approx 70\%$, but with only 1/2 of the science data being transmitted.

Second, some science packets can be replaced with packets consisting of all zeros. Since streams of all zero bits are encoded to alternating symbols of zeros and ones, this has the effect of increasing the average value of P_t . Once again, this happens at the expense of science bandwidth.

In fact, the cost in lost science packets is nearly the same for the two methods. Since the zero packet method is much easier to implement, it is preferred by the HRTF.

7. SCIENCE ANALYSIS

Based on the DTTL and failure mechanism models described in the Sections 4 and 5, a simulation was developed that takes, as input, a Huygens trajectory and gives, as output, a statistical prediction of which science packets will be lost due to the anomaly. In order to accomplish this, Dr. Ralph Lorenz, of the University of Arizona, developed a method to map lost frames into individual lost science instrument packets based on the Huygens allocation algorithm mentioned in Section 2.

The simulation provides a series of catalogs of which packets will be lost to which instruments. This comprehensive error simulation comes from the combined models of Dr. Popken, Dr. Andrews, Dr. Lorenz.

These catalogs were provided to each Huygens science team in order to evaluate the overall performance of several possible scenarios. Each team used their own representative science data and tools to understand the effect of each of these scenarios on accomplishing their science goals for the Huygens mission.

8. RECOVERY OPTIONS

Several options were considered, including (as a baseline) a “no-change” option that keeps the current mission as already defined. This option was estimated to return less than 10% of the science data and accomplish essentially none of the science goals.

A series of options were considered that leave the Huygens and Cassini trajectories unchanged. In this way, no other aspects of the Cassini mission are effected. This option included preheating the Huygens oscillator by turning Huygens electronics on sooner than planned. It also included changing the relative delay between Huygens and Cassini, thus reducing their distance from each other (ODT) and increasing E_s/N_0 . Finally, enough zero packets were inserted to bring frame performance up to a reasonable amount. This case still returned significantly less than 50% of the science frames. For some instruments, particularly the imager, loss of this many frames results in essentially a total mission failure.

The remaining options all involved changes to the Cassini and Huygens trajectories. The basic idea of all of these options was to reduce the relative Doppler between Huygens and Cassini while maintaining sufficient signal strength for a good link. In addition, several constraints exist due to science objectives and spacecraft design. For example, the S-band antennas on Huygens are not useful beyond about 80° from their zenith. This angle is known as the *Probe Aspect Angle*, or *PAA*. The Huygens camera

requires a certain amount of illumination from the Sun during descent, which forces a constraint on how Huygens must enter Titan’s atmosphere. Also, the Huygens radio science experiment (to measure Titan’s winds by tracking Huygens’ Doppler as it descends through the atmosphere) further constrains the trajectory.

Another major consideration in designing a new trajectory is minimizing the effect on the remainder of the Cassini mission. Two major effects exist:

First, any change to the Cassini trajectory required to put Huygens in its new position can result in changes to the planned Saturn orbital tour. Huygens should be released at the beginning of the tour since it currently blocks some Cassini instruments and it adds mass to the spacecraft. The best solutions that the HRTF could design for these modified Huygens trajectories put Cassini back on its planned orbital tour after only a few additional Saturn orbits.

Second, any change to the Cassini trajectory requires the use of propellant. Propellant is a precious commodity on deep space missions. By using propellant early in the Saturn tour to place Huygens in a better place, there is less propellant left to handle unforeseen problems with Cassini, to target special scientific discoveries, or to run an extended Cassini mission.

9. RECOMMENDED SOLUTION

The option recommended by the HRTF involves making a change to the Cassini trajectory. The geometry of this option is shown in Figure 10.

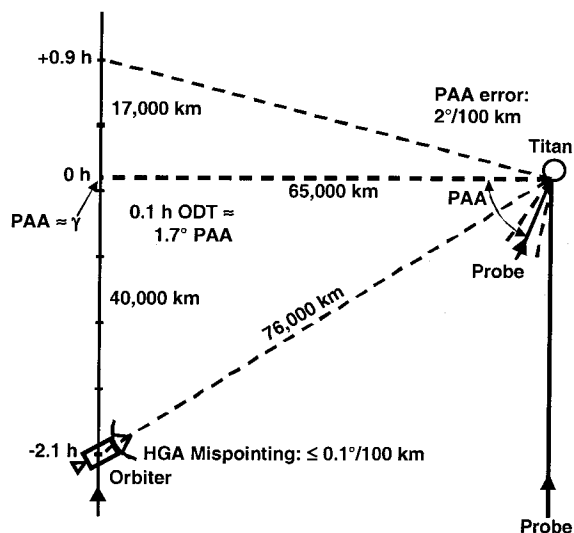


Figure 10 – Recommended Huygens trajectory

Cassini would fly by Titan at 65,000 km rather than the 1,200 km planned for the baseline mission. This reduces the Doppler to the point that the PSA can track the Huygens signal during the descent.

In order to maximize the signal strength, communications would continue after Cassini passes Titan. In fact, the HRTF recommendation is to push such communications as far as possible, constrained only by the PAA as shown. The PAA constraint allows such communications up to 0.9 hours after closest approach to Titan.

The HRTF recommendation places the approach on the opposite side of Titan from the baseline mission. By flying by on this side, less propellant is required to place Cassini in the right place. The total extra propellant required to implement this recommendation is estimated to be less than 95 m/s, which leaves a significant amount of propellant for other purposes. Cassini would resume the currently planned orbital tour after an additional three Saturn orbits (at the point of the original third Titan encounter.)

The recommendation includes preheating the Huygens oscillator for four hours by switching Huygens on earlier than currently planned. There is enough battery margin to accomplish this without danger to the rest of the Huygens mission.

Figure 11 shows the recommended solution in (Δf , E_s/N_0) space. The saw-tooth line indicates the boundary below which there will be no cycle slips. The two dark curves show the simulated best and worst case performance of the recommended option. The simulations take into account many statistical parameters such as Titan's winds, errors in the Huygens entry point to the atmosphere, and spinning of Huygens under its parachute.

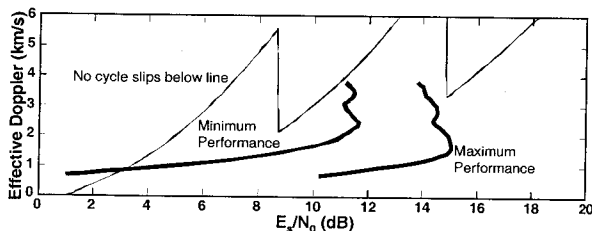


Figure 11 – Performance of recommended solution

It is extremely likely that this solution will return 100% of the Huygens science data. However, the HRTF recommended that the ability to place zero packets in the Huygens data stream be implemented. In this way, the Huygens operations team will be ready in case new information comes to light over the next three years to indicate that additional performance is required.

10. CONCLUSIONS/LESSONS LEARNED

The HRTF was able to develop a solution for the Huygens radio relay anomaly. With the current understanding of the situation and the current spacecraft performance, 100% of the Huygens science data will be recovered. The

solution was only evident after gaining a thorough understanding of the failure mechanism.

In the course of resolving this anomaly, the HRTF identified several important lessons to be learned from this experience.

Spacecraft subsystems must be tested to all of their requirements before launch

If the PSA had been subjected to a communication test that mimicked the expected signal levels and Doppler, this problem would have been identified and fixed before launch. At that time, the solution would have entailed a minor change in a software table.

Keep engineering model and flight spares operational throughout the mission

Because the Huygens engineering model was operational, extensive testing could occur to completely characterize the anomaly. These results were used to target the testing of the flight unit and reduce the required DSN tracking time to a manageable amount.

Documentation of Spacecraft Hardware and testing

This is particularly a problem on long duration deep space missions. It is important to keep proper documentation of all tests so that this information is available when something goes wrong. In the case of this investigation, it was difficult to recover many pre-launch test results because some of the people involved had retired.

Never intentionally throw away data in a deep space mission

The design of the PSA results in intentional destruction of science data in the case where the PSA believes it has not achieved sufficient synchronization. In fact, if this data could be sent to Earth, it would be possible to glean a significant portion of its scientific value.

Deep space communication systems should always be designed to insure the return of science data to Earth. Data should only be destroyed on a spacecraft after it has been successfully recovered on Earth, and the confirmation is sent to the spacecraft.

Spacecraft systems need to have an appropriate level of reconfigurability in flight

This anomaly would have been easy to solve if there had been even a modest amount of reconfigurability in the PSA.

The HRTF recognized that there is much debate in the space community about reconfiguring spacecraft in flight.

This anomaly should serve as a lesson because it is an example of being too restrictive in this regard.

Subsystems such as the PSA should at least be programmable at a parameter level. If the PSA had a table to define its loop bandwidths, data rates, and synchronization thresholds, there would have been many possible solutions to this problem that would not have required changes to the Cassini trajectory or changes to Huygens.

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Dr. Leslie J. Deutsch received his Ph.D. in Mathematics from Caltech in 1980, the year he came to the Jet Propulsion Laboratory. He developed techniques for communicating with the Voyager 2 spacecraft at Neptune and Uranus and also developed microelectronics to enable advanced communications systems to be placed on spacecraft. Dr. Deutsch received the IEEE Judith Resnick Medal in 1991 "for contributions to the theory and practice of deep-space telecommunications and information processing." In 1995, Dr. Deutsch co-led the team that redesigned the Galileo mission to Jupiter after the spacecraft's high-gain antenna failed to deploy.



For this work, he received the NASA Outstanding Leadership Medal in 1996. This work led eventually to a meeting between Dr. Deutsch and Pope John Paul II at the Vatican in 1997.

Dr. Deutsch has managed JPL's Signal Processing Research Group, Communications Systems Research Section, and Telecommunications and Mission operations Technology Program. He is currently the acting JPL Chief Technologist and oversees all of the Laboratories technology activities. He holds 28 patents in the fields of communication and electronic music and has written more than 40 technical papers in communications, microelectronics, space systems, and ground station design.

Dr. Deutsch spends his spare time working as a professional musician and composer. He has given organ recitals in Europe and Japan and has served as Caltech's organist since 1973. He performs with several jazz bands and has traveled extensively in North America and Europe playing the piano, trumpet, and tuba.