Findings, Recommendations and Conclusions

Report of the Huygens Communications System Inquiry Board

Signature page

Chairman

Link
D.C.R. Link

Members

J. C. Anne

A. Beretta

J. J. Dechezelles

K. J. Glutz

A. Jablonski

NASA observers

R.F. Draper
R.F. Draper

Richard L. Horttor
R.L. Horttor

Secretary

R. Bonnefoy

F C

Annex **Mission Overview**

1 INTRODUCTION

In February 2000, after the fifth in-flight cruise check-out of the Huygens Probe, a dedicated Probe Relay Link Test was performed, aimed at characterising the performance of the Probe Support Equipment (PSE) under realistic mission conditions. This test revealed some unexplained anomalies in the communication subsystem in terms of data recovery in the presence of Doppler at mission-representative levels.

An Investigation Team was therefore established in Spring 2000, with the participation of ESA, NASA/JPL and industry representatives, to investigate this matter further and assess its potential impact on the Huygens mission. Ground tests conducted at ESOC on the Huygens reference model (engineering and spare models) confirmed the non-optimal behaviour of the communication subsystem, which would have an adverse impact on data recovery during the Probe's descent at Titan.

The ESA Director General subsequently convened an independent Enquiry Board charged with:

- assessing the current status of the Huygens communication link
- recommending a course of action to be followed to safeguard the mission objectives and guarantee full scientific data return
- providing recommendations to ensure that such problems will not occur on future projects

The Board Members appointed by the Director General were:

D.C.R. Link	Board Chairman
K.J. Gluitz	Board Member
A. Jablonski	Board Member
J-J. Dechezelles	Board Member, representing Alcatel (formerly Aerospatiale), the Huygens Project Prime Contractor
A. Beretta	Board Member, representing Alenia Spazio, the Huygens Project Communication subsystem contractor
J-C. Anne	Board Member, from an Alcatel company.

The Board Members appointed by the NASA Administrator at the request of ESA's Director General were:

R.F. Draper	Former Cassini Deputy Program Manager
R.L. Horttor	NASA/JPL Communication Expert

The Board Secretary was R. Bonnefoy (ESA).

The Enquiry Board performed its tasks during November and December 2000, holding interviews and hearings with ESA, NASA and Industry project staff and experts. It decided to address the various issues within its terms of reference by means of five dedicated panels:

Panel 1 – J.J. Dechezelles: Requirements Traceability
Investigation of Doppler requirements flow from system to unit level.

Panel 2 - A. Jablonski: Test Requirements
Investigation of test requirements related to Doppler.

Panel 3 - K.J. Gluitz: Lessons Learnt for Future Projects
Investigation of how to avoid similar problems in future Projects.

Panel 4 – J.C. Anne: Investigation of the Reported Problem
Investigation of the causes of the problem.

Panel 5 – A. Beretta: Receiver Capabilities
Assessment of the performance limits of the receiver in relation to Doppler, and of potential solutions to the problem on the hardware side.

2 IDENTIFICATION OF THE PROBLEM

The Huygens Probe was launched on 15 October 1997 together with the Cassini Orbiter. The two spacecraft are now travelling towards Saturn, where they will arrive in 2004. The Huygens Probe will then be released and will descend through the atmosphere of Titan, Saturn largest moon, making a wide variety of scientific measurements, whilst the Cassini Orbiter overflies it.

The scientific data gathered will be transferred from the Huygens Probe Transmitting Terminal to the Receiving Terminal located on the Cassini Orbiter (Probe Support Avionics – PSA). From there the data will be relayed back to Earth from Cassini via NASA’s Deep Space Network (DSN).

A communication test was performed in February 2000 by transmitting a signal from NASA’s Goldstone DSN ground station to the Huygens PSA receiver on-board Cassini. The uploaded signal simulated mission-representative conditions for the Huygens PSA in order to verify the receiver’s ability to provide full data recovery. This test showed nominal receiver performance with no Doppler applied to the received signal, but unexpected behaviour when mission-simulated Doppler was applied to carrier, subcarrier and data rate. Further analysis performed by Alenia Spazio and ground tests conducted at ESOC confirmed that the Doppler shift effectively causes the data signal to fall outside the bandwidth of the receiver’s narrow-band bit-loop detector in the regions of the gain switching steps.

3 FINDINGS

The Board was unable to find any direct reference at any level of project requirements or subsequent design specifications regarding Doppler shift on the subcarrier or data rate in the received r.f. telemetry transmitted to Cassini from the Huygens Probe. This error of omission was perpetuated throughout the life of the project before launch with not a single recorded question raised on the subject in any ESA, NASA or independent review. Although there was a reference in a drawing showing a logical relationship between subcarrier and data stream this was not reflected in the wording of the requirement specification. The tolerance on frequency stability of the subcarrier is wide enough to cover the effects of frequency drift and Doppler shift but unfortunately the specified tolerance on the data stream clock rate is more limited and not wide enough to cover the Doppler frequency shift.

At the beginning of the project, one of the design drivers was the low r.f. signal from the Huygens Probe expected at the input to receiver on Cassini. The receiver was therefore designed for optimum performance at low signal to noise ratio to achieve a high sensitivity using a narrow bandwidth bit detector. However, before the end of Phase B, a decision was made to use the high-gain antenna on Cassini to receive the telemetry signal from the Huygens Probe rather than the medium gain antenna. At a stroke this solved the problem of the marginal r.f link, and if part of the increased margin had been released to the receiver this could have allowed the bandwidth of the bit synchronizer to be increased had there been any indication of the future problem. An increase of less than 1 Hz in the loop bandwidth of the bit detector would have been more than adequate to handle the Doppler shift in the data stream. A modification to the loop bandwidth is easy to incorporate on the ground by a small software change, but the software cannot be accessed in flight. The receiver on Huygens is derived from a digital technology development programme (ASTP) carried out between 1987 and 1991. The hardware/software design accommodates different requirements through software for specific applications..

A number of checks and safeguards exist within ESA space projects to guard against errors in interpretation of requirements through system testing by independent Assembly Integration and Verification (AIV) engineers and Reviews. AIV starts with the system requirements and produce a Verification Programme Plan in which it is set out how each of the requirements will be verified, by testing at system level, subsystem level or by analysis. Because on Huygens there was no requirement on Doppler shift specified at subcarrier or data stream level AIV did not identify any test requirement. A test was carried out at subsystem level and repeated at the Probe level with the carrier and sideband frequencies offset by a constant value to simulate Doppler. This test incorrectly represented the real frequency offsets on the side carriers induced by Doppler where the offset frequency is proportional to the actual frequency of sideband.

In reviews of the NASA Mars programmes a strong recommendation has been made to carry out end-to-end testing on the system as a final check. On Huygens, the problem would have been to simulate the Doppler shift on all frequencies required breaking the data-handling interfaces with the transmitter and connecting in test equipment. The Probe Relay Test team has since shown that this is possible, but without prior knowledge of the potential problem it is likely that such a test technique at a late stage in the programme would not have been accepted because of the need to verify the reconnections for flight.

The problem on Huygens has shown the value of an end to end test simulating the various mission conditions as close as possible during ground testing. With proper planning, techniques can be devised to verify reconnections with a test made on an earlier model of spacecraft if the test method is considered risky.

JPL, ESA, Aerospatiale and Alenia contributed to the Integrated Data Link Report, which sets out all of the r.f link parameters, with no overall authority responsible for checking, although ESA provided the editor. For example a polarization error was found during the integrated Cassini-Huygens test in the US.

The shortcoming with respect to Doppler did not surface during any of the ESA, NASA or independent reviews performed during the project life cycle. On Huygens the normal cycle of project reviews was followed and included NASA/JPL as well as ESA personnel on the review teams. In addition, two independent reviews were carried out in which the reviewers had face-to-face interviews with engineers across the project. The review process on Huygens was better than normal for ESA projects, but still the effect of Doppler shift on the subcarrier and bit data rate was missed. However, not all of the design information on the receiver was made available to NASA/JPL reviewers before the CDR. ESA and Alenia had an agreement that this design information could be viewed at Alenia's premises, but as NASA/JPL had no opportunity to review the restricted documents at Alenia, they could only submit Review Item Discrepancy (RIDS) reports on the documentation sent to them.

4 CONCLUSIONS AND RECOMMENDATIONS

After extensive investigation and interviews with the key players from the Huygens ESA and Industry teams, the Board concluded that the root cause of the communications anomaly was an error of omission throughout the project that was not detected until three years after launch. There are four years before the Huygens Probe is released from Cassini for its mission to the surface to Titan and in the intervening time there are recovery options that can be developed to overcome the problem. In any complex space mission problems can occur and it is not the occurrence of a problem but the recovery from it that is a measure of an organisation.

If the following steps had been fully implemented on the project the cause of the anomaly could have been avoided:

1. Project requirements, defined on the basis of the mission definition, should have been traced by means of the Verification Programme Plan.

2. An end-to-end test should have been performed on the complete system as a final test.

3. Flexibility should have been built in to allow changes to be made by ground commanding.

4. All issues relating to proprietary data should have been resolved at the time of signature of the contract.

Assessment of the cause of this specific problem and of the means for avoiding similar occurrences in the future cannot be decoupled from a critical assessment of the current ESA Review Process, which should be addressed as a matter of urgency.

The Board made the following recommendations to ensure that similar problems do not occur on future projects:

1. Adequate design margins and operational flexibility should become mandatory requirements for long-duration missions. The Hubble Space Telescope and the Soho spacecraft are examples of where problems occurring in orbit were resolved and operations continued by transmitting corrective software patches to the spacecraft. Patches to the Huygens avionics software (SASW) would have been a rather easy solution, but unfortunately the current design does not include such a capability.

2. Independent external reviews by an experienced review team should be encouraged during the development phase, in addition to the normal project reviews. Unbiased opinions on the validity of the system design can benefit the project.
   The “RID” system used on the Huygens project for the nominal project reviews might be too rigid and formal. Other review procedures, similar to those of the JPL reviews involve formal presentations of requirements along with design and operational features. Experienced reviewers are able to identify potential faults and deficiencies, which are corrected by subsequent work.
   The major benefit of these reviews is in the preparation work by the project, which allows many open design items to be solved in a timely manner.
   The “RID” system can identify requirements issues early in the project life cycle, while the more open review style helps in resolving technical issues during the design phases. Consequently, such open reviews could be more advantageous, less time-consuming, and more suitable for future scientific projects.

3. Promote dialogue between system, subsystem and critical equipment designers, with direct dialogue between the reviewers and the design engineers, to better understand and appreciate the necessary feedback from operational requirements into the design of the system and its equipment.

Establishing a “questioning attitude” on both sides of the procurer/supplier interface can greatly improve understanding of the known requirements, as well as the identification of any that are lacking.
Had anyone on the receiver design team at Alenia or Alcatel Cannes, ESA or JPL asked about the effect of Doppler on the data stream, the current problem would probably have been discovered in time to effect corrections.
A “questioning attitude” may very well encounter cultural impediments and occasional economic ones, but the benefits are clear.

4. Critical subsystems or equipment should not be changed late, during or at the end of Phase-B, from one contractor to another. It could prove more beneficial to the project to select such procurements during the system-level competition.

5. Establish clear responsibility for integrated hardware/software design.
   For future projects, it is suggested that responsibility for the system software architecture and design be assigned to the system designer, and that for the embedded equipment software to the equipment designer.
   It must also be ensured that all embedded software tools and codes are provided to the system responsible.

6. Resolve proprietary issues at the beginning of a project; arrange and conclude, in the future, adequate non-disclosure agreements on proprietary technologies and data at the beginning of the project between all parties involved, to ensure unrestricted access and evaluation of such features, and thereby assure verification of full compatibility with the performance requirements established for the system.

A key recommendation by the Board is that on future projects, particularly those with long missions, any new hardware should have sufficient flexibility designed into it to be able to make changes by ground command. On Huygens, if either the Probe clocks had commandable frequency offsets or if the inbuilt software in the receiver were accessible by ground command, then the problem could easily be corrected.

The Board went onto consider ways of overcoming or mitigating the problem of potential loss of data errors caused by increased bit errors. It is strongly believed that changes can be made to the telemetry transmission properties, which alone could achieve a higher probability of receiving a major part of the data. Other changes to the mission, such as late release of the Probe with active AGC tracking by the Cassini Antenna may achieve complete reception of the telemetry data.

5 RECOVERY OPTIONS

The Board also addressed the issue of potential recovery options.
Those listed here are intended to solve the Huygens Probe Doppler data link problem whilst minimising the impact on the Cassini Orbiter in terms of any tour redesign. A decision on any such redesign must be between March and May 2001. The Huygens

Probe's part of the mission needs to be completed close to its originally planned time to minimise risk to the Probe itself. Tests and analyses need to be performed to verify the gains that will be achieved. The options listed here, in order of priority, provide confidence that most of the presently planned Probe and Orbiter science can be preserved. Items 5.1, 5.2, 5.3, 5.4 and 5.5 together will probably solve the problem. Work should, however, continue on evaluating the other options, with the expectation that adding option 6 will not only help to solve the problem, but also provide an additional safety margin. The decision on its implementation should only be made once the detailed impacts of each option have been properly identified. The Board strongly feels that the design for the Probe's early entry into Titan's atmosphere should not be modified. In addition, a risk analysis should be made of the final plan to verify that risks are at an acceptable level.

5.1 Determine wind direction and velocity

According to this option, the Probe's mission would take place after the wind's direction and velocity have been determined, at end of the second orbit. It is presently unknown whether the wind direction is East or West; and a factor of two has been introduced for the uncertainty regarding its velocity.

The Probe could also be released during the third orbit, with the advantage that the Titan ephemeris can be significantly reduced by having two Titan flybys before the Probe's mission starts.

If the new back-up Probe release were to take place at a much later state, the present tour and plan remain unchanged. This would reduce these error sources by a factor of four. The Cassini High Gain Antenna pointing errors would be reduced, providing improved gain at the end of the descent perhaps by a factor of more than 5.

5.2 Take advantage of clock bias

The present mission has a planned 5.534 km/s Doppler shift. The CDMU clock is presently biased in a direction that helps offset the Doppler by 1.2 km/s. This clock bias is derived from the in-flight Probe tests. If the clock were to shift or drift in the same direction until the Probe's release in November 2004, it would further offset the Doppler. This drift might be enough to compensate for the existing problem. The Probe CDMU bias will have to be monitored at the planned March 2001 test and during all subsequent Probe tests. The difficulty here is the uncertainty about why this clock bias exists and whether it will continue to shift in the same direction, at the same rate. Information from Laben on each of the CDMU crystals indicates that the temperature effects are three times the size of aging effects. Thermal analysis is therefore needed to investigate the effect further.

5.3 Increase data transitions

Provide a number of zero data packets (or partial zero packets) in the data stream, which can provide up to 3dB improvement in performance. This will be particularly advantageous for the weak signals at the beginning of Huygens' entry phase. The EM testing, provided by ESOC, provides useful data on how many zero data packets would be required and the look-up table can be tailored to the descent times of choice.

5.4 Improved assumptions about Huygens probe antenna patterns

The Probe is rotating at 15 rpm at the beginning of communications and decreases to 1 rpm for the final decent phase. The antenna gain varies from 2 to 5.5 dBm for the expected communication angles to the Orbiter. In addition, the Probe will be in pendulum motion due to wind gusts with an expected swing of ∀3 degrees. The present plan uses ∀10 degrees and it might be worthwhile investigating the benefits if the expected ∀3 degrees were used. The Probe's antenna pattern has been measured to determine what signal strength can be depended on for each 10-15 degrees of motion as the probe rotates. The Probe's top equipment shelf carries the two antennas plus the parachute boxes. The antennas interfere with each other, at the communications angle to the Orbiter; a strategy might be devised to determine a better offset time between communications data channel A vs B if possible (presently 6 seconds). This could be of particular benefit when the Probe is rotating at the 1 rpm during the latter descent time.

5.5 Reduce the Probe Descent Time

The Probe descent time is planned to last 3h: 2¼h for the nominal descent to the Titan surface, a ¼h tolerance, plus 3 min of surface science, plus 27 more minutes of desired surface time. This 2 h 33 min mission can be optimised against the expected receiver Doppler data performance. A small additional time can be removed by shortening the time the large parachute is used. The present time on the large parachute is 15 minutes, which could be shortened to as little as 5 minutes by sacrificing some upper atmosphere data. The Probe would then descend to the surface more quickly. This shorter time can be analyzed to see if an additional 10-15 minutes might be gained. Again this could be a good trade-off to optimise the mission for the expected Doppler data capability. This shorter data time is also a good match with the additional capability achieved by using the clock bias.

5.6 Reduce the Orbiter Delay Time

The mission could be revised to change the Orbiter Delay Time (ODT) from the present 4 h to 3 h, which would reduce the Probe to Orbiter communication distance at the beginning from 77 000 km to approximately 57 000 km. This would provide an about 3dB stronger signal at the beginning of the descent. If this approach is used, active Orbiter pointing of the Probe (using AGC of the received signal) is required to capture the last part of the descent. A better understanding of the Probe antenna patterns (described in paragraph 5.4) will greatly help in understanding the expected AGC pattern. Also, the shorter descent time described in paragraph 5.5 could be used to further shorten the ODT to achieve an even larger gain at the beginning of the decent time.

5.7 Reduce the Probe Release Time

The present plan has the Probe released 22 days before Cassini reaches Titan. It might be an advantage to reduce that time, which would allow a shorter orbit to be used for the Probe release if needed. The disadvantages are that it takes more propellant to move the Orbiter at this later time and the dispersion ellipse will be larger. However, the active AGC pointing would compensate for the larger dispersion ellipse.

5.8 Do the Probe Mission at a Later Time (orbit)

There is a possibility of releasing the Huygens Probe during a later orbit. This preserves the early trajectory tour, in which the entire Cassini Huygens Team has made a very significant design investment. Near the middle of and at the end of the 4-year tour phase, there are orbits where the high altitude flyby could be accommodated with a much smaller impact on the tour work that has already been accomplished. The Huygens Probe team is investigating the impacts of waiting until later orbits. Clearly the Probe will be going through the Saturnian’s ring plane many times, but it should easily be able to survive that environment, as the Orbiter also must. The radiation environment at Saturn is not very strong, but later times means greater exposure. These later times are within the pre-launch secondary launch opportunity flight times. Therefore, the ageing concern was part of the Probe original design. The Orbiter would be impacted slightly if the Probe is kept on board for longer. The Probe mass has to be moved along with the Orbiter mass, this increases propellant use by a maximum of 15% for the whole tour phase. This can be accommodated within the existing reserve. Also the Probe slightly obscures the field of view of a couple of the Orbiter instruments, which although undesirable could be accommodated. This approach does, of course, provide the Huygens science data later than the existing plan.

5.9 Redesign the First Two Orbits

Another (see 5.10 below) possibility, which involves raising the Orbiter flyby altitude and minimizing the impact on the tour, is presently being investigated by the Cassini Team. This involves modifying the present first two orbits, to shorten the first orbit from 157 days and the second orbit from 48 days to smaller orbits so that a 32-day orbit could be inserted for the Probe release before returning to the existing tour. This approach takes advantage of the existing propellant reserve. The 157-day orbit was originally selected to minimize the propellant requirements to start the Probe mission and Orbiter tour.

5.10 Raise the Orbiter Flyby Altitude

The possibility of raising the orbit flyby altitude to 50 000 km, 75 000 km or 100 000 km instead of the present 1200 km would reduce the Doppler from 5.5 km/s to an acceptable value. This acceptable value appears to be between 2.4 km/set and 3.4 km/s from the ESOC EM tests. Further EM tests and the spacecraft flight tests will determine the Doppler value that can be accommodated for the 4 h ODT. The advantage of this approach is that it appears to solve the entire Probe receiver Doppler problem; the disadvantage is that the Orbiter tour has to be modified to allow this very high altitude flyby. This requires insertion of an additional orbit in the tour, because the next orbit has to be at the correct flyby altitude and velocity to continue on the presently planned tour. The work that has been accomplished on the existing tour is so extensive that it may not be possible to design a new tour and recover by the Saturn Orbit Insertion (SOI) time. A decision in the March to May 2001 time frame is therefore mandatory if a new tour is required.

6 CONCLUDING REMARKS

The Board has succeeded in characterising the current anomaly, isolating the causes and offering possible solutions. Due to the complex project structure and the time that has passed between the spacecraft development phase and now, it has not been possible to clearly assign responsibility for this anomaly and the Board has come to the conclusion that it really lies with the entire project structure.

The accurate characterisation of in-flight properties and the refined analysis of all tolerances with flight hardware still available on the ground are key activities for a final selection of the safe recovery measures, and for deciding the best possible mission planning.

A dedicated ESA/NASA Recovery Task Force is expected to be put in place to analyse the possible recovery scenarios and follow their implementation.