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Abstract

The Cassini/Huygens Project is a joint undertaking between NASA, the European Space Agency, and the Italian Space Agency to conduct an in-depth exploration of the Saturnian system. The spacecraft consists of an orbiter vehicle and an atmospheric probe which has completed its mission in the atmosphere and on the surface of Titan, the largest moon of Saturn. The spacecraft was launched on October 15, 1997, has completed its nearly seven years of interplanetary flight, and by the time of the 56th IAC, it will have completed 17 of its planned 75 orbits during its four-year prime orbital mission. This paper gives an overview of the mission, and describes in detail the accomplishments and events over the past year, including the spectacularly successful descent of the European Space Agency's Huygens probe to the surface of Titan. Initial scientific results from both the Huygens mission as well as from the first one-and-a-quarter years of orbiting Saturn are summarized. The plans for the remainder of the orbiter's tour of the Saturn system and the many flybys of Titan and the smaller icy satellites are described.

Introduction

The past year has been a highly productive one for the Cassini/Huygens Project. The high point has to be the remarkably successful Huygens probe mission to Titan, beginning with the trajectory targeting in mid-December, the probe release from the Cassini orbiter on December 25 (GMT), the deflection of the orbiter's trajectory on December 28 to achieve the necessary geometry for the data relay, and culminating in atmospheric entry, descent, and contact with Titan's surface on January 14, and subsequent return of the data to Earth. Other less momentous but nevertheless significant events include seven close targeted flybys of Titan in addition to the flyby in support of Huygens entry and relay, three flybys of Enceladus, including one at 175 km above the surface, one close pass by Hyperion, and twenty additional somewhat more distant satellite flybys but still at ranges less than 100,000 km. In addition to the satellites, a large volume of data has been acquired on Saturn itself, its atmosphere, its rings, and its surrounding magnetosphere. Overall spacecraft performance continues to be excellent. The use of consumables (propellant, actuations of devices, etc) is progressing exactly on the planned schedule, power output is right on predict, and all engineering subsystems still have full redundancy, except for a lien on the redundancy of the reaction wheel system. All twelve orbiter science instruments are functioning well, albeit with relatively minor liens on a few. Two are having actuator problems, but normally functioning detectors, one is sorting out a software problem, one is working out some noise problems due to interference, and the Ka-band translator on the Radio Science Subsystem has failed, but the overall rate of science data collection and return has been only minimally impacted by these problems.

All of the satellite encounters in the tour so far have occurred within the past year because, even though Saturn orbit insertion (SOI) is now over 15 months ago (July 1, 2004), the initial orbit period following SOI was 120 days, with the first close Titan encounter coming near the end of that orbit on October 26, 2004. Figure 1 shows the path followed by Cassini over the past year with each of the close encounters indicated.

Satellite Encounters

The encounters the Cassini spacecraft has had with Saturnian satellites over the past year are shown in table 1. Eleven of the 13 were targeted encounters, meaning that the spacecraft was navigated to a specific set of encounter conditions. Non-targeted encounters are those for which the trajectory is not specifically controlled to a given flyby point, but rather those encounter conditions resulting from achieving the targeted encounters are accepted. Relatively close non-targeted encounters

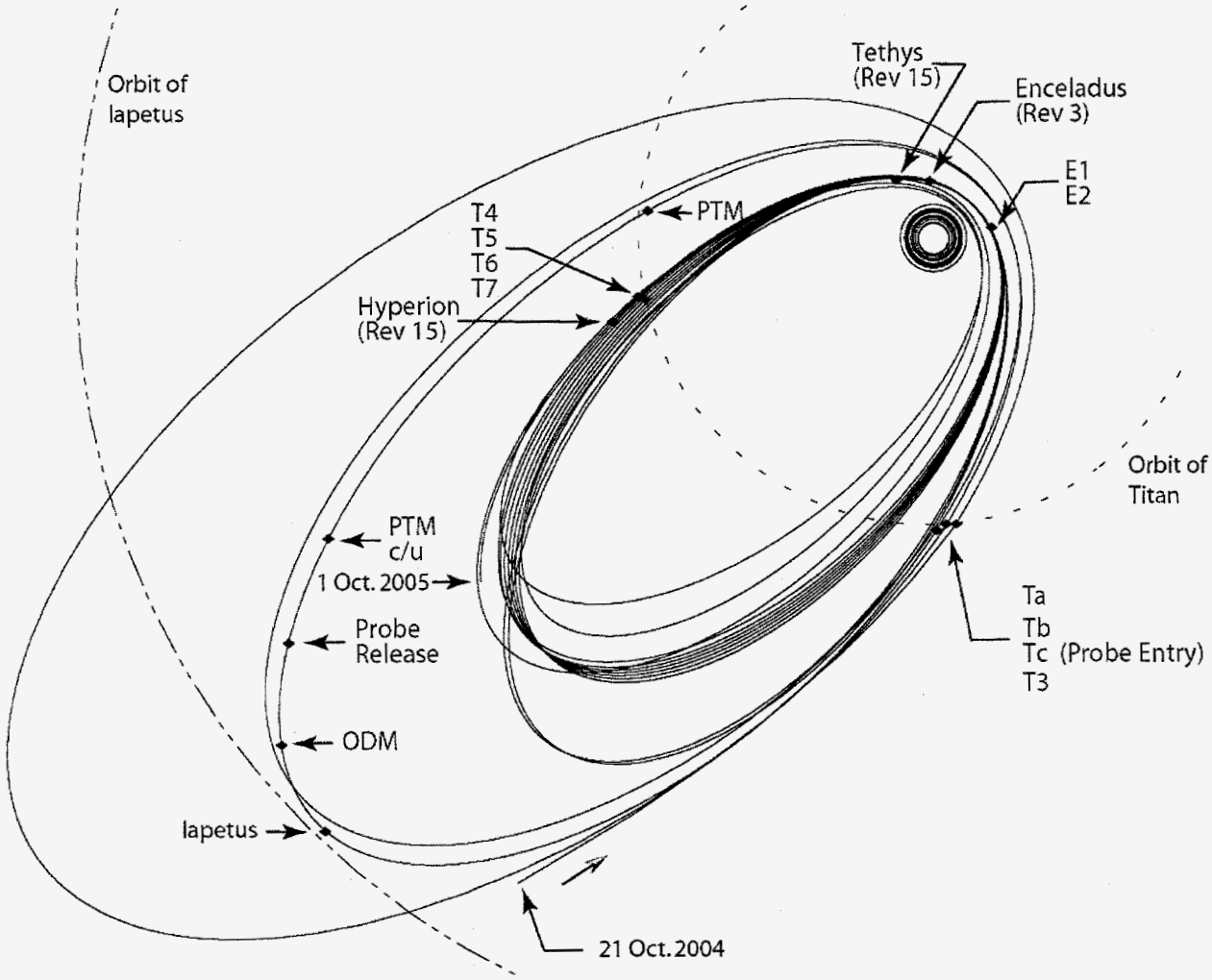

Figure 1 Cassini's Path Over the Past Year

usually occur within a day or two of a targeted encounter, and thus can not be targeted because there is neither time nor control capability to achieve two fixed targets over such a short trajectory arc in such a short time interval, but they still present significant science data collection opportunities. Of course there exists a point of closest approach for each satellite on each pass of the spacecraft through the system, but these often range up to one million km or more away and may not represent effective observation opportunities. The hiatus in satellite encounters from mid-April to mid-July was due to a deliberately designed feature of the tour where six occultations of Earth by Saturn and its rings were performed. The Radio Science Team used these events to observe the effect on the radio signal from Cassini to Earth during these events to obtain information about the rings and atmosphere, and it was these observations that were most in jeopardy if the orbiter trajectory had been modified to accommodate a one-orbit slip in the time of the Huygens mission. The high altitude targeted flyby on Jan 14 was the flyby that supported the Huygens probe data relay.

The Iapetus Complication

One of the consequences of the mission modifications made to accommodate the Huygens receiver anomaly was the appearance of a non-targeted but relatively close 57000 km flyby of the satellite Iapetus seven days after the release of the probe from the orbiter. This was generally considered to be a very favorable outcome because, for a spacecraft with scientific instrumentation as sensitive as Cassini's, considerable science can be accomplished at such relatively small distances. However, it turned out to cause some complications as well. One of the first tasks the Cassini navigation team needed to accomplish, starting even prior to reaching Saturn, was the development of very accurate ephemeredes for the satellites of Saturn,

Table 1

Satellite	Flyby date	Flyby altitude, km	Inbound/ outbound
Titan	Oct 26, 2004	1174	in
Titan	Dec 13, 2004	1192	in
Titan	Jan 14, 2005	60003	in
Titan	Feb 15, 2005	1579	in
Enceladus*	Feb 17, 2005	1264	out
Enceladus	Mar 9, 2005	501	in
Titan	Mar 31, 2005	2404	out
Titan	Apr 16, 2005	1026	out
Enceladus	July 14, 2005	172	in
Titan	Aug 22, 2005	3669	out
Titan	Sept 7, 2005	1075	out
Tethys*	Sep 24, 2005	1500	out
Hyperion	Sep 26, 2005	514	out
Dione	Oct 11, 2005	500	in

* Non-targeted encounter

including values for their masses. The primary method for accomplishing this was optical navigation, using images of the satellites taken against known star backgrounds from which very accurate estimates of their positions could be made. Initially the mass of Iapetus was considered to be fairly well known based on data available from Voyager observations some 20 years earlier as well as ground based observations, but as the Cassini solutions for the satellite ephemeredes began coming in, the estimates of the mass of Iapetus showed a significantly greater scatter than the *a priori* statistics would support. This led to the realization that if the Project was not successful in obtaining a sufficiently accurate estimate of Iapetus's mass prior to the final targeting of the probe to Titan,

then errors in the mass estimate would lead to unmodeled perturbations in the probe's flight path large enough to jeopardize meeting the delivery accuracy requirement of ± 3 deg, 99%, in the probe entry flight path angle. The formal plan

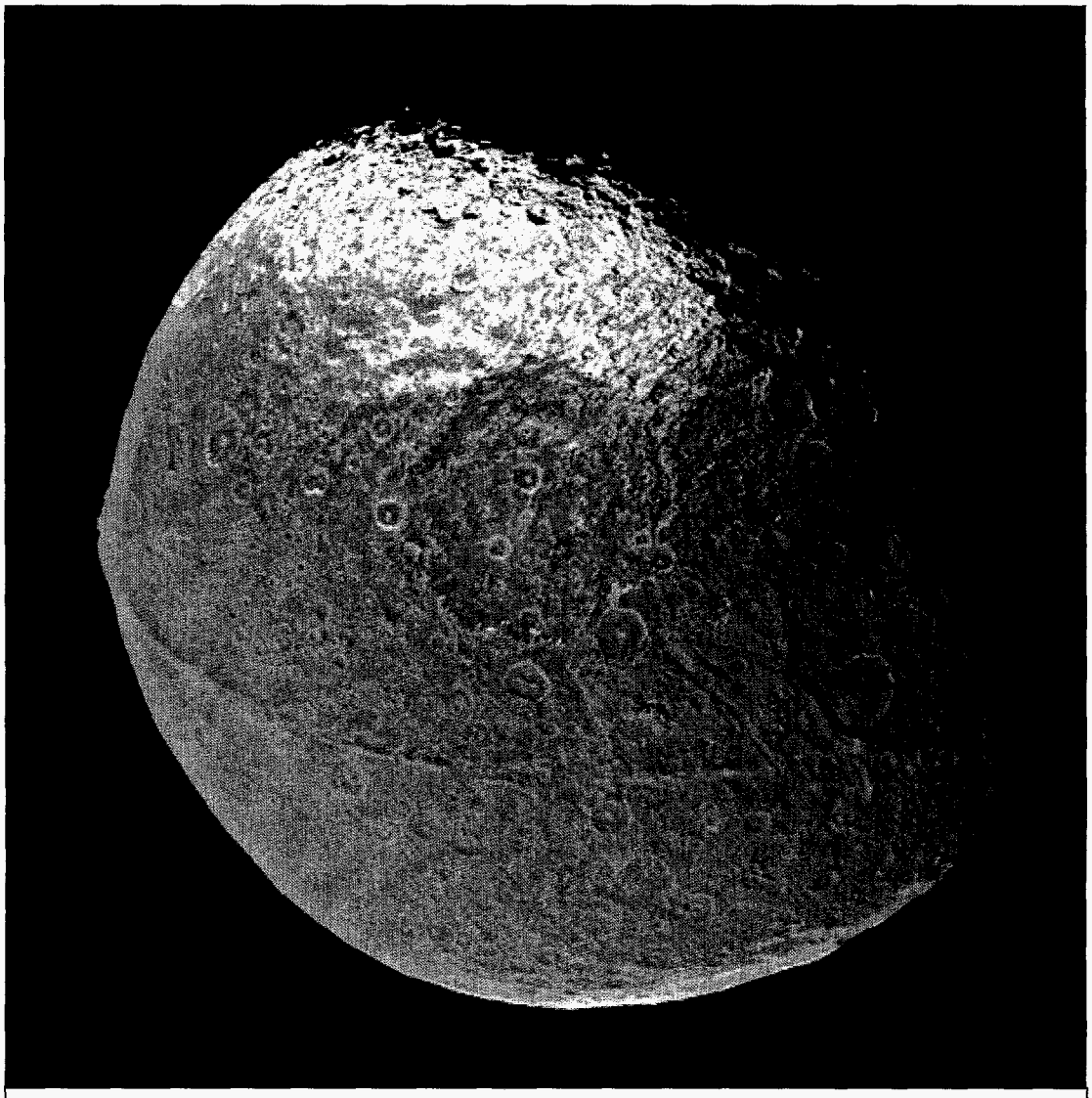

Figure 2 Iapetus

the Project was following to solve for the satellite ephemeredes showed that the necessary accuracy in Iapetus's mass would be achieved in time, but concerns remained that if this failed to materialize for whatever reason, then the Huygens mission, which was dependent on being within the specified entry angle corridor, would be in jeopardy. Three different options were considered. One was to delay the probe targeting and release until after the Iapetus flyby. By continuing to track the still combined orbiter and probe through the flyby, the mass uncertainty would no longer be a factor. Two major detractors to this approach were a very substantial increase in propellant required to deflect the orbiter's path after release away from Titan and onto the needed flyby path for the

Huygens data relay, and a significant reduction in the time available between probe separation and probe entry to be able to respond to any anomalies that might occur with the orbiter operations in that time period. A second option considered was to delay the probe targeting and release for one full orbit, when Iapetus was nowhere close. This solved the entry angle control problem quite easily, but had major implications for the orbiter mission. The nominal mission with the December 25 release date connected to the planned tour trajectory for the orbiter immediately after the Titan flyby where the probe mission was to be performed, but delaying the probe mission by one (or more) rev(s) meant that the planned orbiter mission trajectory couldn't be achieved for several more revs, which would have had a major impact on already planned science sequences as well as on some very carefully designed occultations of Earth by Saturn and the rings. The third option was to maintain the nominal timeline but to increase the distance of the Iapetus flyby by enough to reduce the sensitivity to mass variations to the point that they no longer impacted the entry flight path angle control. One drawback of this approach was that the trajectory changes required to accomplish this, in addition to requiring the use of additional propellant, also unraveled a considerable amount of sequence design work that had been completed, especially for the Titan encounter on December 13, and rather late in the process to recover and salvage a successful scientific encounter. An additional impact was the loss of an Earth occultation by Titan that occurred at the February 15 Titan encounter that was unique and considered very valuable by the Radio Science Team. The final decision was made to go with the third option and modify the trajectory to raise the Iapetus altitude to 117,000 km. The corresponding primary changes were to lower the December 13 flyby altitude targets from 2336 km to 1200 km, and to raise the February 15 flyby altitude targets from 950 km to 1579 km. The necessary modifications were made to both the December Titan and the Iapetus observation sequences, and both flybys were highly successful. The probe entry angle achieved was – 64.7 $\pm$ 0.3 deg, well within the required range. Figure 2 shows one of the images acquired of Iapetus during this flyby. Even with the increased altitude, this was the closest Cassini will come to this body until an approximately 1300 km targeted flyby in September 2007. The details are quite remarkable, especially the so-called "belly-band", a 20 km high ridge following the equator for as much of it as can be seen. The source of this feature is currently unknown, although it is the subject of considerable analysis.

Tracking Huygens from Earth

An ambitious plan to receive and record the signal from the Huygens probe directly on Earth during its descent through Titan's atmosphere was developed by two different groups with somewhat differing objectives. Two factors combined to make the concept even feasible – one being that the probe mission took place near opposition where the Earth to Titan range was near its minimum, and the other was that the angle between the Huygens antenna boresight and the direction to Earth was only about 30 deg, further enhancing the received signal strength. Still, with 12 watts of transmitted power from the

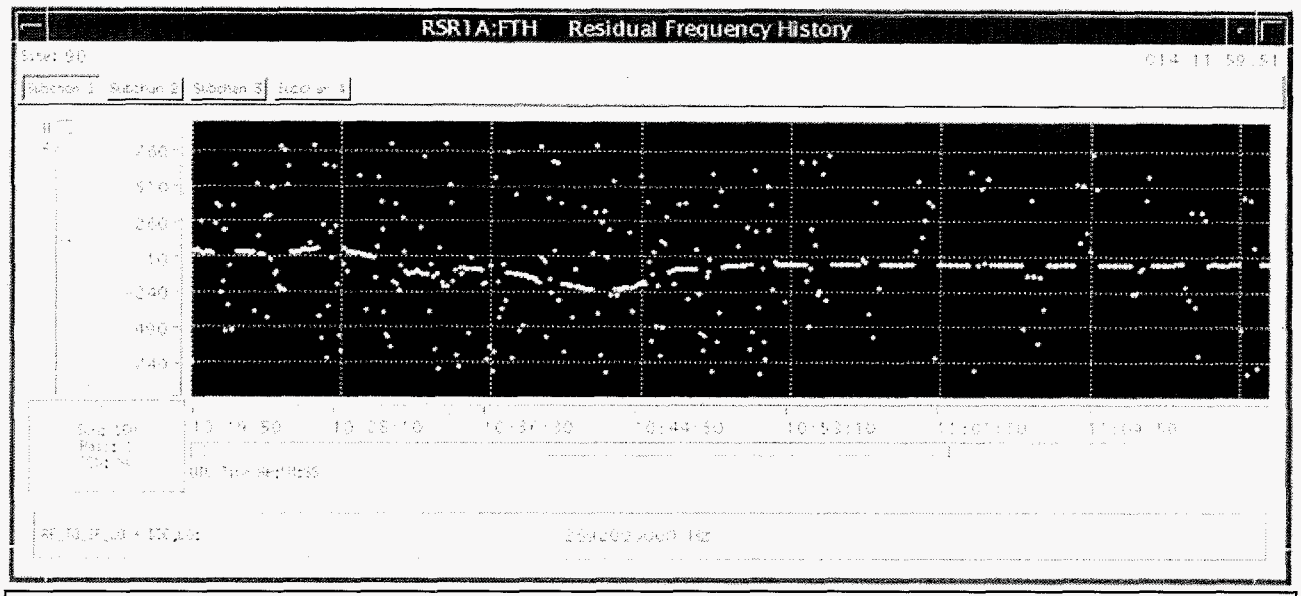

Figure 3

Huygens antenna and a range of nearly 9 AU, the concept was an ambitious one. One of the two groups was a team of radio scientists at JPL whose objective was to measure the winds in Titan's atmosphere by observing the Doppler shift in the Huygens signal during descent. This investigation was intended to enhance a similar experiment planned with the signal between the probe and the orbiter by giving a wind measurement along a line-of-sight in a different direction. The second group was a European based organization known as JIVE, Joint Institute for VLBI in Europe, whose primary interest was to determine the position of the probe during its descent as accurately as possible. This was to be done using a technique known as very long baseline interferometry where the Earth-based tracking antenna is slewed to alternately track first the spacecraft and then a known, near-by quasar on a time scale of every couple of minutes or so to "phase up" the array of antennas to allow detection of the weak probe signal as well as to position the probe accurately in the celestial coordinate system. The Doppler team would have preferred that the antennas were continuously pointed at the probe, but they agreed that their JIVE colleagues should nod the antennas since the scientific results of the Doppler experiment would not be weakened significantly.

The overall activity turned out to be outstandingly successful, even more so than originally anticipated for reasons mentioned later. Two large radio telescopes were used, the Robert C. Bird Green Bank Telescope in West Virginia, and the Parkes telescope in Parkes, Australia, both of which were able to receive the Huygens carrier signal and confirm it in real-time. Four other smaller radio telescopes also recorded the Doppler data, but their data could only be used to support after-the-fact detailed processing of the data. Figure 3 shows the data from the Green Bank telescope as displayed in real-time during the Huygens descent. Shown are the

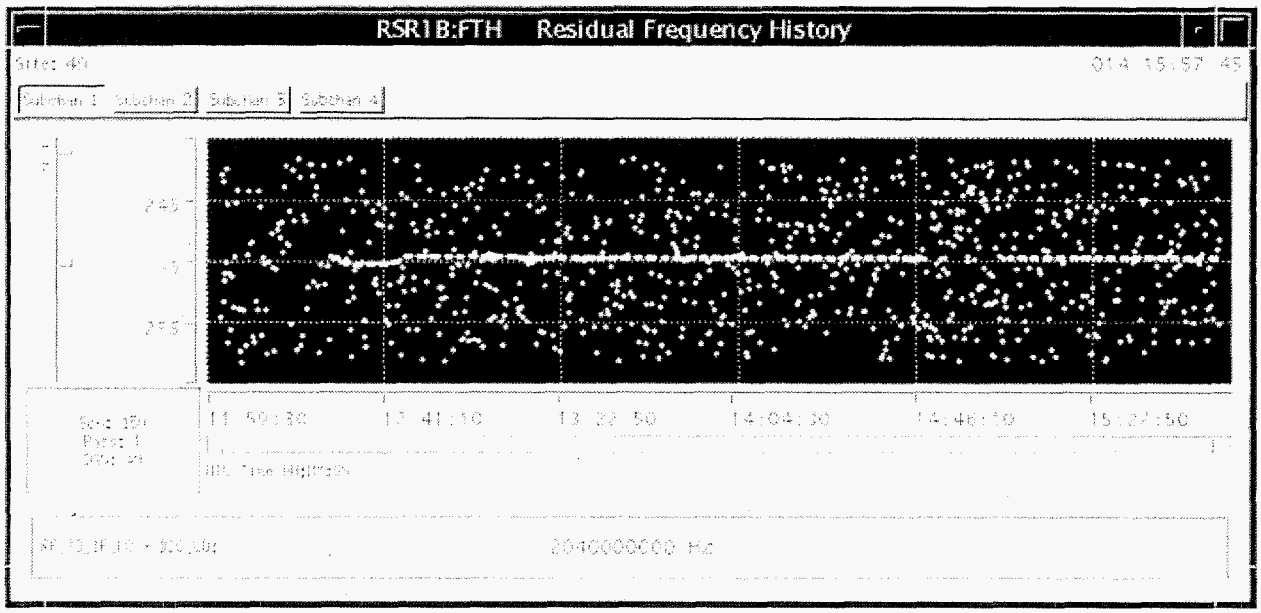

Figure 4

observed residual frequencies relative to a nominal, predicted wind model versus Earth received time in GMT. The line segments correspond to when the station was tracking Huygens, and the gaps with noise points spread vertically across the plot are times when the antenna was off-pointed to the quasar. The initial descent, for about the first half-hour, is seen to be rather rough, at least relative to the model, but after that it matched the winds model quite well. The full scale in time covers the time from initial signal acquisition to loss of signal at Green Bank. Figure 4 shows the signal as displayed in real-time from Parkes, and covers the time from loss of signal at Green Bank to loss of signal at Parkes. The lack of signal for about the first half-hour is due to the fact that there was a gap in tracking between when Titan set at Green Bank and then rose to an adequate elevation to enable tracking at Parkes. The frequency residuals are seen to exhibit some variation for about the first 15 minutes of tracking, and then at about 12:45 become flat for the remainder of the pass. This effect is due to the probe landing on the surface, after which there is obviously no effect due to winds. The gap seen at around 14:48 is where a 20 minute calibration activity on the quasar had been scheduled. Originally there was no expectation that the probe would continue to transmit for this long, or for that matter even survive the impact with the surface at all, hence there was little concern about not continuing the Huygens tracking in this period. In fact, the probe continued transmitting to the end of the Parkes pass, some three hours after landing, and then for some unknown time beyond this. No plans had been made for tracking beyond the Parkes pass because there was no expectation that the batteries in the probe would last for so long.

The thing that made the Doppler data turn out to be so valuable was that, due to an error in configuring the Huygens receiver carried on the Cassini orbiter, none of the

data that was required to support the orbiter to probe Doppler wind experiment was received, but with the Earth-based data, most of the objectives of the experiment will be able to be met anyway.

Delivering Huygens to Titan

The original plan for delivering Huygens to Titan called for the probe to be released from the orbiter in October of '04 (I need to check this.) from a 150 day orbit and to enter Titan three weeks later with the orbiter performing its data relay function from an overhead pass with a closest approach to Titan at 1200 km. When the mission was redesigned in 2001 to accommodate a receiver anomaly to instead put Cassini on a relay flyby at 60000 km closest approach, a different plan was required. Since all of the original close Titan flybys had to be maintained to preserve the tour, it was necessary to add an additional rev on which to place the 60000 km relay flyby, since it had essentially no gravitational effects on the trajectory. The final design was to reduce the initial orbit period to 120 days and insert the additional orbit as the third orbit on which the probe release, entry, and relay was performed. Figure 5 shows a plot of the three orbits going from Saturn orbit insertion on July 1, 2004, to probe entry on January 14, 2005, including the locations of the two Titan flybys and the rather distant Iapetus encounter that occurred prior to the Huygens entry. The first navigation action specifically designed to support the probe mission was the probe targeting maneuver (PTM) that was performed on December 17 with a delta-V of 11.9 m/sec. This maneuver placed the combined orbiter-probe craft on an impacting trajectory with Titan, targeted to exactly the planned entry conditions, but anticipating the velocity effects of the probe release from the orbiter eight days later. A PTM cleanup maneuver of 18 mm/sec (0.06 km/hr) was performed on December 23 as a final vernier correction to meet the probe entry flight path angle requirement. Probe separation occurred on December 25 (Christmas Eve at JPL local time), the attitude of which was used to control the probe entry angle-of-attack. The orbiter deflection maneuver (ODM), which changed the path of the orbiter from one that would enter Titan's atmosphere to one that would overfly Titan at 60000 km with just the right Huygens relative timing to perform the data relay, was performed on December 28 with a delta-V of 23.8 m/sec. The 117,000 km flyby of Iapetus by the probe that had caused concern previously occurred three days later, followed by an ODM vernier cleanup on the orbiter on January 3. The probe was on its own during all of the time from separation to entry with no guidance and no communications from the orbiter. On January 14, both vehicles performed their functions flawlessly, leading to an outstandingly successful mission to the atmosphere and surface of Titan.

Effects of Titan's Atmosphere on the Tour

The planned tour for the Cassini mission has 45 targeted encounters with Titan, of which 23 had closest approach altitudes of 950 km. This was a lower limit constraint imposed on the tour design process based on models of Titan's atmosphere and the desire to avoid atmosphere induced torques on the spacecraft that could cause loss of attitude control capability and cause the spacecraft to enter safing. The spacecraft would not be at risk in such an event, but, since execution of safing halts the executing background sequence, all planned Titan science data acquisition for that encounter from the point of safing onward would be lost, and the scheduled post-encounter orbital trim maneuver would be at some level of risk, depending on the time needed for safing recovery. On the other side, science desires to obtain the maximum possible data resolution meant wanting to target the encounter trajectories as close as possible. The altitude of 950 km was determined as the minimum altitude achievable with a reasonable likelihood of being flyable. However, it was recognized that there was some prospect that it would be necessary to raise this to higher values if the actual atmosphere turned out to be different than modeled, as well as the possibility of pressures from the scientific community to go even lower if the actual atmosphere would permit it. Either of these possibilities was undesirable from the Project's point of view because each would require a substantial amount of work to redesign the tour trajectory as well as the science observation sequences that had already

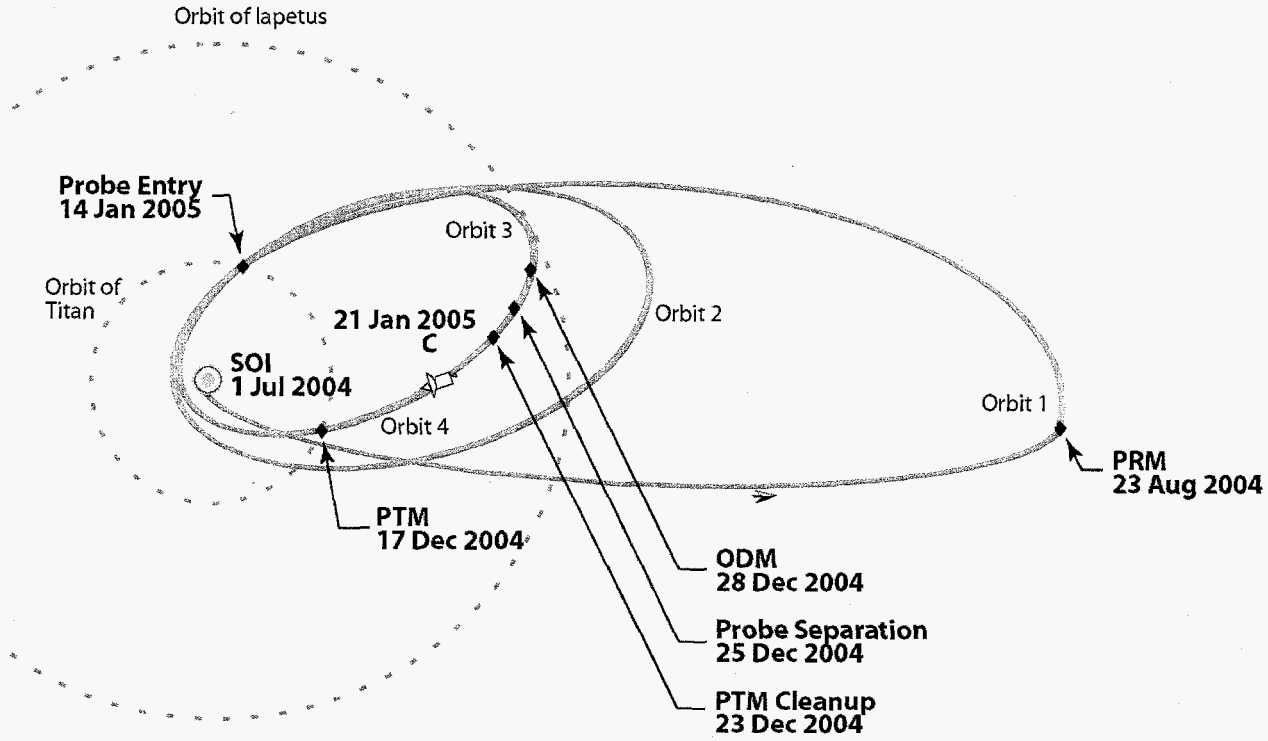

Figure 5

been developed, and the high likelihood that such changes either way would lead to increased propellant to navigate the tour.

The science observation sequence for the first close Titan flyby on October 26 was specifically designed to provide *in situ* atmospheric observations by the Ion and Neutral Mass Spectrometer (INMS) instrument to support a determination of whether the 950 km altitude originally planned for the February 15 encounter was prudent or not. However, the urgency in processing this data to support a decision to fly at 950 km was considerably alleviated by the response to the Iapetus issue and the resulting increase in altitude of the fourth Titan flyby on February 15 from 950 km to 1579 km, independent of the atmosphere question. This delayed the first potential 950 km flyby to April 16, a considerably more relaxed schedule for making the minimum altitude decision and implementing any corresponding required trajectory and sequence changes.

The October 26 and December 13 Titan flybys as well as the Huygens Probe data all indicated a greater atmospheric density at the higher altitudes than the models had predicted. This finding was not a large deviation from the predicted values, but was large enough to convince the Project that lowering the minimum altitude from 1175 km (on Oct. 26) to 950 km with no intermediate validation passes represented an unacceptable risk. This position was further confirmed by the fact that the duty cycle observed on the reaction control thrusters of the attitude control system in the vicinity of the closest approaches was also consistent with the more dense than predicted atmosphere. Accordingly, the decision was made to raise both the April 15 and September 7 Titan altitudes to 1025 km. The new reference trajectory was developed, the sequence changes were made, and the Project was ready to proceed. However, with the results of the April 15 flyby in hand, and with further work done on the overall problem, a new concern arose for the September flyby. The April flyby showed a lower density than had been expected based on earlier measurements and led to the realization that the atmospheric density at the higher altitudes was variable. Whether this variation is a time-varying phenomenon, or is a function of the geometry of the pass through the atmosphere, or both, is still an open question. The closest approach point for the September pass occurred at about 65 deg South latitude, the first close flyby with periapsis below Titan's equator so far. It also happens that it is now summer in Titan's southern hemisphere. These considerations led to a very plausible argument that Cassini may experience the largest atmospheric density seen yet on this pass. Additional analysis on the part of the spacecraft team motivated by the fact that atmospheric density has become a greater issue than anticipated has led to the conclusion that the attitude of the spacecraft near closest approach is an even bigger factor than originally thought. The spacecraft attitude is determined by the science sequence being executed, and hence is not easily modified to accommodate other considerations without a substantial impact to the science data. The attitude for the September pass turned out to be about twice as sensitive to atmospheric effects as was the April pass. Another factor in coming to a minimum altitude decision

was the fact that the semi-major axis of the navigation trajectory control ellipse at this encounter was nearly aligned with the direction to Titan, making the actual flyby altitude highly sensitive to navigation performance, so in early July, the decision was made to increase the September pass altitude to 1075 km. This encounter was performed on September 7 with excellent navigation performance and no adverse atmospheric effects.

Fortunately, there are no more 950 km altitude Titan passes planned until July 22, 2006, when the next of the remaining 21 such close passes is scheduled. In the meantime, the Project is analyzing all the atmospheric data available, is evaluating the spacecraft attitude profile for each of these encounters, and will make a final decision for the remaining altitudes in December of this year. A final ameliorating factor is a planned helium pressurant recharge of the hydrazine tank that supplies the reaction control thrusters prior to the July '06 flyby. This increase in the hydrazine supply pressure increases the thrust level of the attitude control thrusters which gives greater control authority. This action could not have been taken prior to the two recent flybys because insufficient hydrazine had been consumed to keep the thruster inlet valve pressures below an upper limit constraint.

Next Year – A Preview

The coming year has thirteen close targeted encounters – twelve with Titan and one with Rhea – as well as several more distant nontargeted encounters, the actual number depending on where one draws the distance cutoff. There are no major events such as the Huygens mission or the orbit insertion burn, but the Titan encounters are mostly different with different science objectives and different instruments designated prime for observation opportunities, and each encounter requires the operations team to be ready to perform three orbit correction maneuvers, so it will be an intense and exciting year. The orbital inclination with respect to Saturn's equator is near zero now, and remains there until the summer of '06, when it begins to be increased up to around 60 deg in preparation for what is referred to as the 180 transfer, actually a central angle of 3x180 deg, where the spacecraft is carried from an ascending Titan encounter direct to a descending encounter as a technique to achieve orbital geometries not otherwise available. The two Titan encounters that implement the 180 transfer occur in January and February of '07, but the initial inclination increase required to accomplish this begins within the next year.

During the period of near-zero inclination, the apoapsis direction is rotated into the magnetotail (anti-sun) direction to enable observations deep in the magnetotail region. During the time of increasing inclination, as the orbiter's path moves up and out of the plane of the rings, excellent opportunities for ring observations become available. Titan observations continue throughout the year, with the earlier, higher altitude, passes mostly focusing on optical remote sensing, while the later potentially as low as 950 km passes will provide several opportunities for RADAR mapping of the surface.

Conclusion

The past year has been a highly successful one for the Cassini/Huygens mission. Both the orbiter and the probe

have performed flawlessly, the probe completing its mission, and the orbiter now over one-fourth of the way to completion of its four year prime mission tour. The science results have been spectacular, with surprises, answers, and many new questions coming regularly. The process for designing science observations and then implementing the sequences that will accomplish them with twelve different instruments and investigation teams has always been a challenge for the Cassini Team, but the process is working very well and all sequences to this point in the mission have been delivered and executed completely and on schedule. The team is looking forward to three more years of exciting exploration at Saturn.

The work described in this paper represents the work of the entire Cassini team, including the current flight team at JPL, a large group of scientists from across the United States and Europe, as well as the engineers and supporting staff who designed, built, and launched this marvelous spacecraft.

The preparation of this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with the National Aeronautics and Space Administration.

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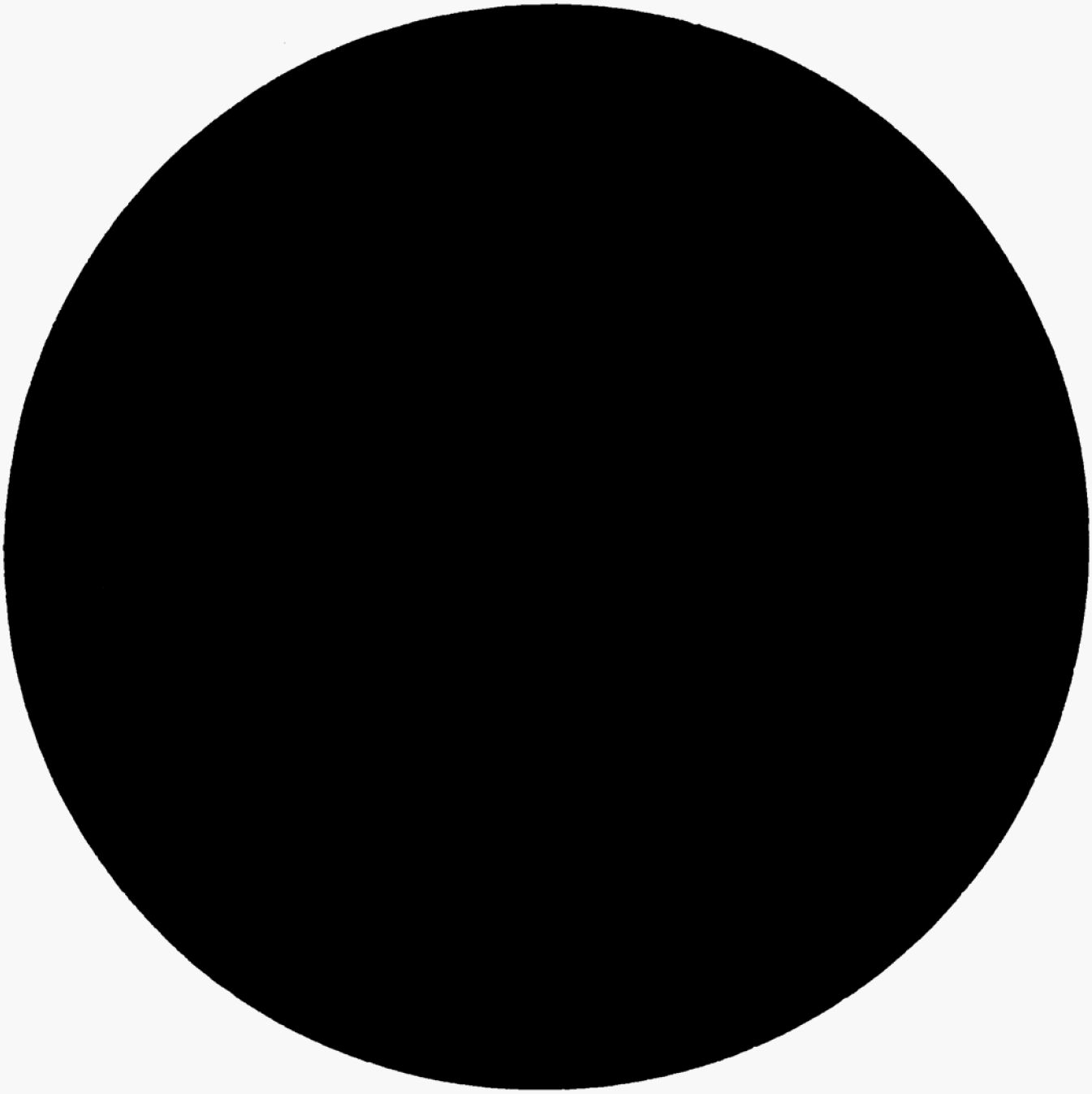
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