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Solving Cassini's Data Glitch Problem during Coherency Mode Transition for Titan Radar Observations

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We describe the problem of regular small telemetry losses incurred during coherency mode transitions in Cassini's telecommunication. The project did not originally plan any corrective steps for avoiding these data losses, because of 1) the disparity between the small durations of the transitions (1-2 min) and large playback capability losses (15 min) needed for bracketing the transition time spans and 2) the unpredictable content of data downlinking during the transitions. However, as the intense science data return from the tour began, it became apparent that the impact of these small losses can sometimes be significant. We provide two examples of the impact on Radar-dedicated Titan flybys. In general, the impacts are larger for high-rate data and for data acquired during a targeted flyby of Titan and other icy satellites. Although the content of data during a transition for *every* downlink pass is unpredictable, we are certain that some important data will be lost on downlink passes dedicated to transmit the flyby data and it does not matter what part of the data will be hit by the transitions. We collected more than 200 days of data from Cassini tour operations between June 2004 and February 2005 to analyze the distributions of the start time and duration of the transitions. We found that the occurrence of a transition can be predicted within a 5-min window, with 95 percent confidence. Given that, it is possible to eliminate the data losses by pausing playback at the beginning of a transition for 5 minutes and resuming playback after transition completion. We briefly describe three operational fixes as to how to implement the playback pause, with the pros and cons for each method. Finally, we report the results of the method chosen by the project and implemented on the spacecraft for several Titan and icy satellites flybys between September and October, 2005.

I. Introduction

THE Cassini spacecraft began a four-year, 74-orbit tour in May 2004. It is the most ambitious interplanetary mission in history.[1] After more than a year of tour, with a dozen science instruments investigating the Saturn system close-up and mapping Saturn's huge electromagnetic field, Cassini has returned over 840 gigabits of

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telemetry data, resulting in a string of remarkable discoveries[2] including the most recent discovery of potential liquid water on Enceladus.[3]

Despite its tremendous success, Cassini's data playback regularly suffers small telemetry losses during coherency mode transitions (*i.e.*, one-way to two-way transitions) due to the spacecraft switching oscillators in order to provide navigation coherent Doppler data. The problem is well understood, and occurs during every downlink that provides two-way coherent link. The project policy is that, with the exception of critical science and engineering data, any data loss due to a coherency mode transition will not be recovered and the command sequence is allowed to proceed as if the data were returned. For critical science and engineering data, duplicate copies of the data are stored on two Solid State Recorders (SSRs) and would not be overwritten until authorized by ground commanding. The do-nothing policy for non-critical science and engineering data was mainly cost-driven and put in place to keep the Cassini project within budget.

Theoretically, the spacecraft could be programmed to detect a coherency mode transition (a radio frequency shift) and pause the playback during the transition. However, Cassini's flight software does not currently include this capability. It would require several months of development to make such a change in flight software. It is possible that the hardware of radio frequency subsystem may need to be modified as well. This was viewed as too costly for the small telemetry data losses.

Various operational fixes were proposed to mitigate the problem. None of them, however, appeared a worthwhile effort initially for various reasons. First, telemetry losses are small in terms of data volume and duration, on the order of 10-20 Mbits and 1-2 min, respectively. For a comparison, Cassini's daily data return is about 4 Gbits during a 9-hr downlink period. Second, the exact time when the coherency mode transition occurs could not be predicted very well, due to uncertainties in the actual uplink time at Deep Space Network (DSN) and fluctuations in the amount of time needed to lock onto the two-way signal. It was estimated that a minimum of 15 minutes was required in order to adequately bracket the coherency mode transition. It was considered a costly trade to lose 15 minutes of playback capability for saving a minute or two of data. Third, the content of the data lost during the transitions cannot be predicted accurately because of uncertainties in data compression (which also makes it impossible to plan and choose the order of data playback to avoid downlinking something important at the time of coherency mode transition). It was difficult to argue to save small data losses when the nature or the criticality of data is unknown.

However, as the massive amount of data for tour poured in, it became apparent that the impacts of these regular small telemetry losses were sometimes quite significant. During the first and second Radar-dedicated Titan flybys, some of the most valuable closest-approach data, including Synthetic Aperture Radar (SAR) imaging and altimetry data, were lost. From the experience we have learned that for high-rate data acquired during a targeted flyby of Titan or other icy satellites, a gap even as small as 1-2 minutes can be significant in terms of surface coverage on a planetary body. Since every bits of encounter data are unique (in particular, considering that the geometry of each flyby is unique and the observations conducted early in the tour cannot be repeated later in the tour), there is no doubt that scientifically valuable data will be lost due to the transition and it does not matter where the transition will hit the data. It became clear that something needed to be done to reduce the data loss.

II. Origin of Data Glitches due to Coherency Mode Transition

In the same way an FM radio receiver tunes in a broadcast station and locks onto the signal, a DSN receiver locks onto a downlink from a spacecraft. Likewise, a spacecraft's receiver locks onto an uplink from a DSN station. The communication mode for only receiving a downlink from a spacecraft is called "one-way." The communication is "two-way" when a DSN station is receiving a downlink from the spacecraft, and at the same time sending an uplink to the spacecraft. "Three-way" is when a downlink is being received on one station and a different station is providing two-way (Fig. 1).

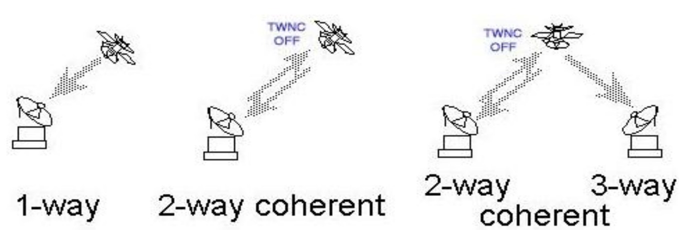

Figure 1. Illustration of DSN telecommunication modes.[4]

Two-way coherent is different than the aforementioned simple two-way. Two-way coherent can be described like this. For tracking and navigation, an extremely stable downlink frequency is required so that Doppler shifts on the order of fractions of a Hertz can be detected out of many GHz and over periods of many hours. Spacecraft transmitters are subject to wide temperature changes, which cause their output frequency to drift. The solution is to have the spacecraft generate a downlink that is coherent to the uplink it receives whose frequency, generated by the massive, sensitive equipment at the DSN stations, is extremely stable. The stability of uplink frequency can be equivalent to the gain or loss of 1 second in 30 million years. Once the spacecraft receives the stable uplink frequency, it multiplies that frequency by a predetermined constant (to avoid interference with the uplink) to generate its downlink frequency. For example, Cassini's X-band transponder uses the constant 1.1748999.[4] This way, the downlink enjoys all the extraordinarily high stability in frequency from the uplink. It can thus be used for precisely tracking and navigating the spacecraft.

Consider a DSN station in lock with a spacecraft's one-way downlink. Now that station sends an uplink. When the spacecraft locks onto the uplink, it abandons the onboard frequency reference that it was using to create its one-way downlink frequency. Now it uses the uplink to generate a new downlink frequency. That new downlink frequency will be a lot more stable, but it will most likely be a slightly different frequency than the one generated on its own. When the new coherent downlink reaches the DSN station, the station's receiver drops lock, changes to the new frequency, and locks onto it.

The DSN station knows the time a coherent downlink will arrive (which is a round-trip light time after the transmitter sends an uplink), and will waste no time looking for the new frequency. However, when the DSN receiver goes out of lock, the telemetry system also loses lock and the data transmitted during this time are lost. It is common to experience a minute or two with no telemetry data while the lockup proceeds. It should be pointed out that coherency mode transition losses are expected; they are not a DSN performance problem.

Lastly, most interplanetary spacecraft may also invoke a mode that does not use the uplink frequency as a reference for generating downlink, even if an uplink is present. When this happens, the spacecraft uses its onboard oscillator for generating its downlink frequency. This mode is known as Two-Way Non-Coherent (TWNC). Typically, the default state of TWNC is off (Fig. 1), so the telecommunication enjoys the advantages of a coherent link.

III. Examples of Data Glitches from Titan Radar Observations

During the first two Radar-dedicated Titan flybys in October 2004 (known as Ta – Titan encounter on Cassini's Saturn orbit number "a") and February 2005 (known as T3 – Titan encounter on Cassini's Saturn orbit number "3"), the data gap while the station was locking onto the two-way coherent frequency caused a loss of some of the most valuable data, as displayed in Figures 2 and 3. In Ta, about 100 seconds, 8.2 Mbits altimetry data were lost, which

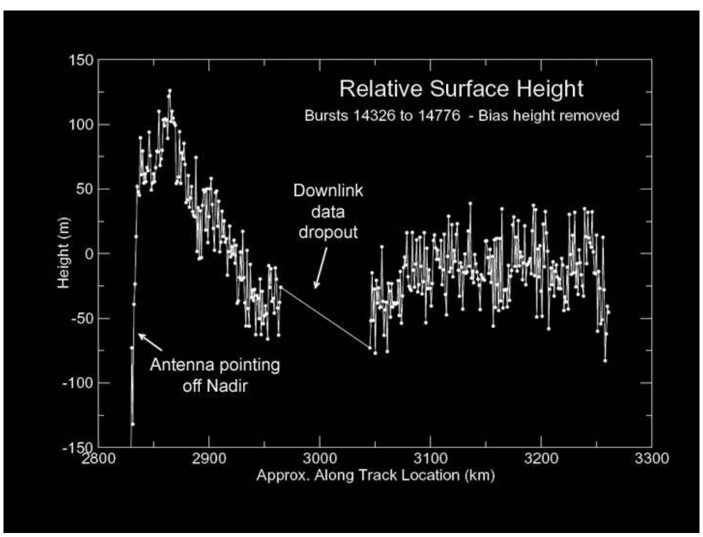

Figure 2. Gap in radar altimetry data during Ta flyby (October 2004) due to a coherency mode transition.[5]

caused an approximately 100 km altimetry data gap along the track. In T3, about 46 seconds, 13.7 Mbits SAR imaging data were lost, resulting in “gores” in the image equivalent to an area of 80 km × 400 km.

Fortunately, we did recover the lost altimetry data in Ta through a contingency plan. It was fortunate that a number of circumstances happened to line up correctly so that uplink commands to recover the lost piece of data could be sent in time before the data were overwritten by the new data that had been planned to be stored there. But this case is exceptional; it is not a common practice to recover such lost data.

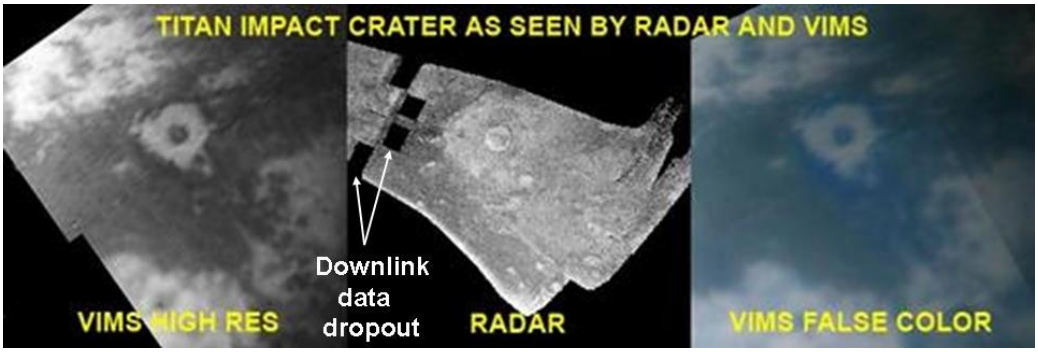

Figure 3. Gap in Synthetic Aperture Radar image data during T3 flyby (February 2005) due to a coherency mode transition.[6]

From Figure 3 we can see that small losses in SAR data produced unrecoverable gores in the image. SAR provides the highest spatial resolution image on the surface of Titan (with a best resolution of 300-500 meters[7]), and the surface covered during each Titan flyby is unique and cannot be duplicated later in the tour. In this sense, every bit of SAR data is valuable and any data glitch is a loss to science communities.

IV. Analysis of Data Glitches for the Tour Operation

As discussed earlier, there two reasons that the original decision to ignore the data loss was based on: 1) the disparity between small durations of the actual data gap (1-2 min) and large playback capability losses (15 min) for effectively bracketing the coherency transition time spans, and 2) the unknown content of the data downlinking during the transitions. We have seen from the above Radar examples that the second argument is not always true: when a downlink pass is dedicated to transmit the data acquired during a Titan or any other icy satellite flyby, it is certain that some scientifically valuable data will be lost due to the coherency mode transition, regardless when the transition occurs and that we are not able to predict the importance of the data for *every* downlink passes. As for the first argument, it is essential to see whether 15 min is *really* necessary to cover the transition time spans. For that purpose, we collected a data set from actual tour operations from June 2004 to February 2005 (approximately 200 days).

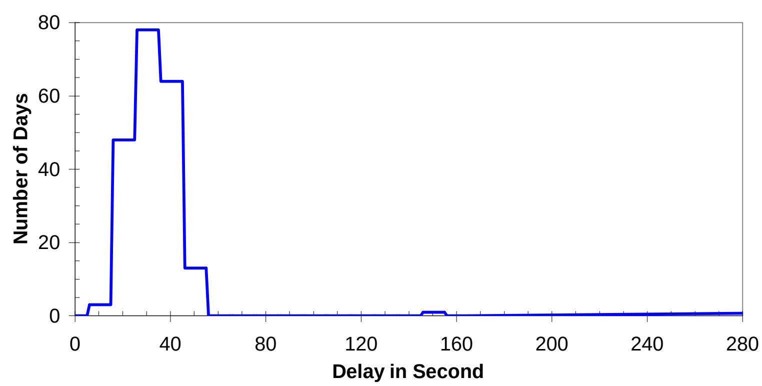

Figure 4. Distribution of the delay of the start time of the data gaps for the operation period of June 2004 – February 2005.

The timing of a coherency mode transition can be described by two parameters: when the transition starts and how long it lasts. For the start time, we know it will be at Round-Trip-Light-Time (RTLT) after the transmitter is turned on (sending an uplink). But in reality, there is always a delay in the *actual* transmitter-on time from the *planned* transmitter-on time: $t_{start} = t_\tau + t_{RTLT} + t_{delay}$, where t_τ is the planned transmitter-on time. In other words, the receiver does not lose "lock" at exactly the same second as planned. The transition ends when the receiver successfully locks onto the new coherent frequency. Typically, there is a minute or so with no telemetry data while the lockup proceeds: $t_{duration} = t_{end} – t_{start}$.

We calculated these two parameters for the data set collected. Figure 4 shows the distribution of t_{delay} in the data set, indicating a mean of 33 sec and a standard deviation of 12 sec. The majority of the delay falls from 15 sec to 55 sec. There are 7 occasions where the delay is larger than 55 sec, which were due to unforeseeable software or hardware problems or due to a bad weather at the DSN station. These are outliers of the statistical distribution. When an anomaly like this occurs, the worry for the small telemetry data losses subsides because a much larger chuck of data will most likely be lost. An important finding of the analysis is that, by introducing the delay parameter, it is possible to know ahead of time when a uplink will most likely occur, from which we can plan ahead of time and command the spacecraft to pause SSR playback during the coherency mode transition.

The distribution of $t_{duration}$ from the same data set is shown in Figure 5. It has an average of 105 sec and a standard deviation of 24 sec. Note that 95 percent of the duration falls between 75 sec and 135 sec and 99.5 percent of the duration is less than 4 min. There are only two instances where the duration is more than 4 min. The importance of finding the relatively short durations, compared to the original 15 min, is that it makes the cost to save the 1-2 min data losses more reasonable.

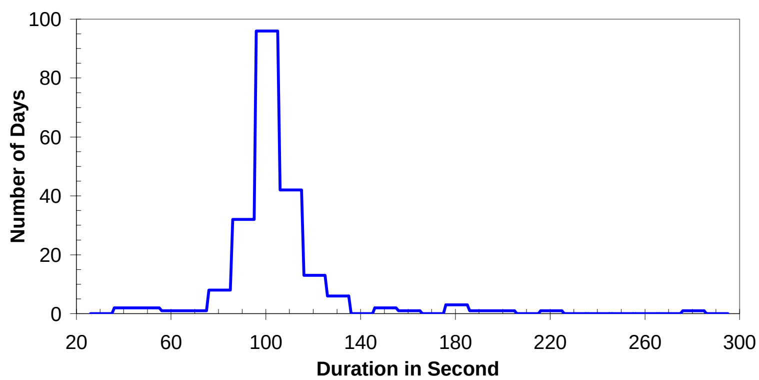

Figure 5. Distribution of the duration of the data gaps for the operation period of June 2004 – February 2005.

As a first order approximation, we estimated that $t_{delay} \approx 1$ min and $t_{duration} \approx 4$ min. With that, we can predict with at least 95 percent confidence that a data gap would occur within a 5-minute window starting from (t_τ+t_{RTLT}). Obviously, losing 5 min playback capability is a much more appealing trade-off than the previously estimated 15 min for eliminating these small data glitches. If we can command the spacecraft to pause playback for 5 minutes at the beginning of the DSN station's acquisition of two-way coherent communication and resume it after acquisition completion, then no data should be lost, except for the relatively rare anomalies at DSN stations.

V. Operational Fixes

How to command the spacecraft to pause SSR playback? Three operational fixes will be discussed here: 1) a SSR playback delay patch method, 2) snap and restore pointer method, and 3) a telemetry mode change method.

The SSR playback delay patch method would use a Command and Data Subsystem (CDS) flight software memory patch to change the CDS playback countdown delay parameter to a desired value, for example, 5 minutes. SSR playback is automatically delayed until the value counts down to zero. Once the value reaches zero, SSR playback resumes. Since this method involves patching a CDS flight software parameter, there are certain risks, which need to be mitigated by testing before implementation.

The snap and restore pointer method would take a snapshot of the playback pointer location at the beginning of the coherency mode transition and restore the pointer to the "snapped" location at the end of the transition. This method commands a second playback of the data that is normally lost during the coherency mode transition. The drawback of the method is that it can cause complications for SSR operations. It is possible that between the snap and restore times, CDS could automatically swap the pointer from one SSR to the other when the end of a partition is reached, invalidating the snapped value of the location.

The telemetry mode change method would take advantage of an automatic SSR playback delay after every telemetry mode change. The length of the delay is set by command. The problem for this method is that because the telemetry modes in nominal operations have already been optimized to the communication arrangement, any change in telemetry modes from the nominal operation would force the playback to go to a lower downlink rate. Playback would have to stay at that lower rate for at least 15 minutes to meet the minimum time requirement between any two telemetry mode commands on the spacecraft. This would result in an additional playback capability loss.

Table 1 lists the pros and cons of each method. In the end the project chose to use the playback delay patch method. It is a good decision for the obvious reasons: the method is straightforward, there is no significant additional playback capability loss, thus maximizing the science return, and risks can be mitigated by testing. This method will place an additional workload upon the CDS operations team, but at a level that can be managed within the scope of the current budget and schedule. The beneficiaries are the twelve science teams of Cassini and science communities at large.

Table 1. Comparison of various operational fixes.

	Pros	*Cons*
Playback delay patch method	• No additional playback capability loss • No SSR complications	• Risks associated with patching a flight software parameter • Need for extensive ground testing • Workload for developing a new ground software tool
Snap and restore pointer method	• No additional playback capability loss	• Potential complications for SSR operations • Need for closely monitoring the configuration of SSRs
Telemetry mode change method	• Compatible with existing ground software tools • No SSR complications	• Additional playback capability loss

VI. Results of Implementing the Playback Delay Patch Method on the Spacecraft

Between September and October, 2005, we had opportunities to manually implement the playback delay patch method on the spacecraft for several Titan and icy satellite encounters. Table 2 summarizes the targeted flybys on which the playback pause was implemented and their results. A 5-minute playback pause period was commanded in these operations.

Note that the data for the Titan flyby on Sept. 7, 2005 was played back over two different downlink passes at two different stations. Unfortunately, in both passes, the uplink was not able to be transmitted on time. These were statistical outliers mentioned earlier. For the remaining flybys, the commanded playback pause period successfully bracketed the station's coherency transition period and the data gaps were completely eliminated. It should be pointed out that we were still able to observe the data gaps in real time channels, but the gaps in the science data packets via SSR playback are no longer present.

We can see that a disadvantage of this method is that it cannot react to any anomaly in real-time. Since the playback pause commands are sequenced ahead of time, it is impossible to change them in real-time, especially given the fact that it takes more than one hour for a command sent from a DSN station to reach Cassini's receiver. One way to overcome this is to re-program the flight software so that it can detect the coherent frequency change and issue the playback pause command automatically. But this, as we have known, is not feasible at present.

Table 2. Summary of the results of the playback delay patch method implemented on the spacecraft.

Flyby Date	*Target*	*DSN Station on Duty*	*Effective Playback Pause Period*‡	*Actual Coherency Mode Transition Period at DSN*
Sept. 7, 2005	Titan (T7)	Madrid*	7:03:51 – 7:08:42	8:09:22 – 8:11:20
		Goldstone†	15:23:33 – 15:28:31	17:44:09 – 17:45:52
Sept. 24, 2005	Tethys	Goldstone	14:30:31 – 14:35:30	14:31:13 – 14:32:58
Sept. 26, 2005	Hyperion	Goldstone	14:50:05 – 14:55:36	14:50:46 – 14:52:36
Oct. 11, 2005	Dione	Goldstone	14:01:12 – 14:06:09	14:01:53 – 14:03:42
Oct. 28, 2005	Titan (T8)	Madrid	4:46:39 – 4:51:42	4:47:22 – 4:48:59

* The transmitter uplink time was 1 hr 5 min later than planned due to a glitch in ground software.
† The transmitter uplink time was 2 hr 25 min later than planned due to an antenna pointing problem.
‡ Note that the effective playback pause periods slightly differed from exact 5 minutes, since they were inferred from the time of the last and first real time packets received before and after the pause and varied a little depending on where the command hit in the packet cycle.

VII. Conclusion

We have shown that we can eliminate the data gaps incurred during a coherency mode transition by applying the playback pause patch method. The method is straightforward and maximizes science return. It will not work every time, but it works when the uplink of a DSN station is on schedule. The statistical distribution of past DSN passes during the Cassini's tour operation indicated that at least 95 percent of the data glitches can be eliminated by this method with a 5 minute pause of SSR playback.

Acknowledgments

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