Beacon Monitor Operations Experiment DS1 Technology Validation Report

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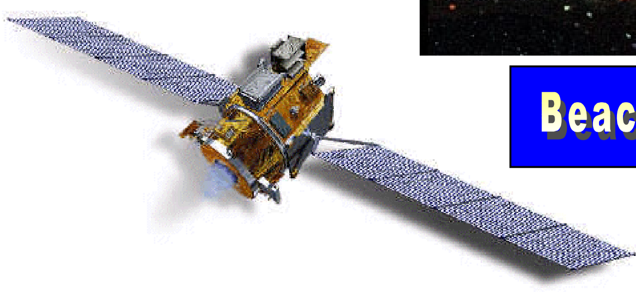
EXTENDED ABSTRACT

The Beacon Monitor Operations Experiment (BMOX) was one of twelve new technologies that were flight validated on NASA's Deep Space 1 Mission (DS1). The technology enables a spacecraft to routinely indicate the urgency of ground contact using a tone signal rather than telemetry while also summarizing onboard data to be transmitted whenever telemetry contact is required. This technology can be used to lower operational cost, decrease mission risk, and decrease loading on the over-constrained Deep Space Network antennas. The technology is baselined on upcoming NASA missions to Europa, Pluto, and the Sun. Successful flight validation has met a requirement to demonstrate the technology before routine use on the Europa mission.

The end-to-end, Beacon-tone signaling system was developed to provide a low-cost and low-bandwidth method for determining when ground intervention is required. With Beacon monitoring, the spacecraft sets the tone signal and it is transmitted either in a scheduled manner or continuously, depending on spacecraft operability constraints. The tone signal is detected on the ground with smaller aperture antennas than would be required for telemetry on a given mission. Tone detection times are short—on the order of 15 minutes or less for most mission designs. The flight validation experiment checked out the functionality of the tone-detection and message-delivery system, characterized operational performance, obtained parameter limits, and tested selection of tone states by flight software based on the spacecraft's assessment of its own health. The tone system was tested on the DS1 spacecraft in both the X-band and Ka-Band.

Engineering data-summarization flight software creates event-driven and periodic summaries of spacecraft activities since the last contact. Episodes are created by identifying the culprit and causally-related sensors around the time of important events. This data is gathered at a high sample-rate, assigned a priority, and stored for downlink at the next telemetry pass. The gaps are filled in by "snapshots" of all sensor channels at a much lower sample-rate. The software can use either traditional (static) alarm thresholds or adaptive alarm-limit functions that are determined by a statistical learning network. The adaptive alarm-limit technology, called the Envelope Learning and Monitoring using Error Relaxation (ELMER) is one of two artificial intelligence (AI) components in the current software design. The second AI-based method computes empirical transforms on individual data channels. These pseudo-sensors enhance the value of summaries and serve as an additional input in determining the adaptive limits. The software was originally developed to support Beacon monitor operations, an approach that enables the spacecraft to determine when ground contact is necessary. In this approach, summarization plays a key role in providing operators with the most important data because all of the stored data cannot be downlinked in a single telemetry pass. Efficient summaries also help facilitate quick troubleshooting and thus can reduce the risk of losing the mission. Summarization algorithms can also be applied to nonspace systems to decrease the time required to perform data analysis. The current version of the software runs on VxWorks and has been executed on the PowerPC and RAD6000 target processors.

The experiment also included operational testing of a ground system prototype, called BeaVis (Beacon Visualization), that was designed to facilitate quick interaction with BMOX data. The purpose of this system is to track Beacon-tone states throughout a mission and to display downlinked summary data. For Beacon missions, the user must be able to quickly maneuver through summary data to arrive at an assessment of overall system state and to diagnose any problems that occur. The software enables the user to scroll through a graphical depiction of telemetry downlinks throughout the life of the mission to select the desired data. Summary data is represented graphically with a hypertext style link to the strip charts of the sensor channels contained in each of the four types of summary data packets. A web version of the tool was also implemented.



Beacon Monitor Operations Experiment

What is It?

The Beacon monitor operations technology provides the spacecraft the functionality required to initiate telemetry tracking only when ground intervention is necessary.

Why Is It Exciting Technology?

- Mission operations cost is reduced substantially because there is less contact with the spacecraft
- Reduced loading on ground antennas enables more spacecraft to be operated with existing ground resources
- Beacon uses state-of-the-art techniques for summarizing onboard spacecraft performance data

How Does it Work?

- Instead of routinely sending spacecraft health data, the spacecraft evaluates its own state and transmits one of four Beacon tones that reveal how urgent it is to send high-rate health data
- When telemetry tracking is required, the spacecraft creates and transmits "intelligent" summaries of onboard conditions instead of sending bulk telemetry data to the ground

When Will it be Demonstrated?

- Flight demonstration occurred on the Deep Space 1 mission launched in October 1998
- The technology is being adopted by the DS1 Extended Mission to lower operations cost
- The technology has also been baselined for planned NASA missions to Europa, Pluto, and the Sun

Technology for Low Cost Operations

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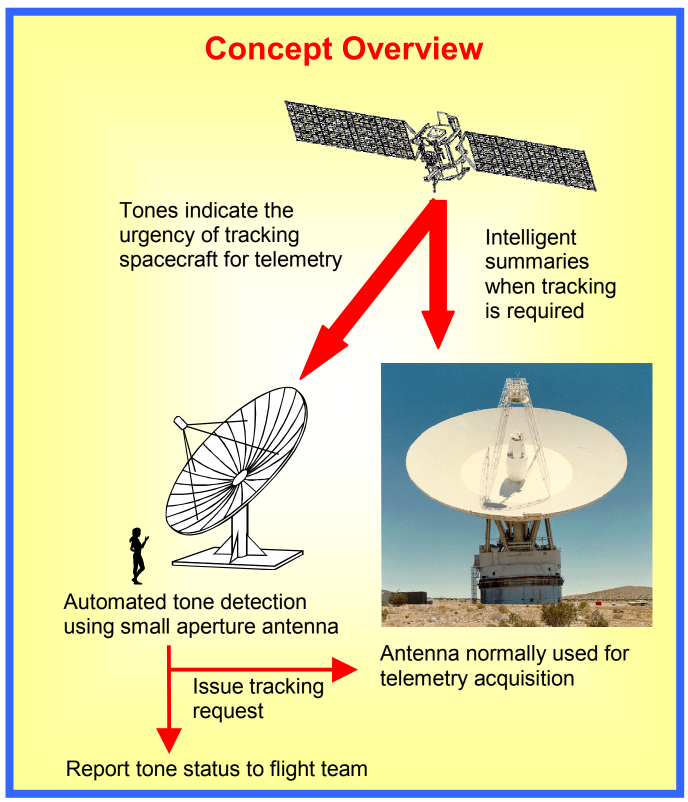

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1.0 INTRODUCTION

The budget environment that has evolved since the advent of NASA's Faster, Better, Cheaper initiative has caused mission-risk policies and mission designs to change in ways that have been conducive to the inception of new operations concepts and supporting technologies. Such was the case when the Beacon monitor concept was conceived to enable a mission to Pluto to be achieved within the budget constraints passed down from NASA. The technology was accepted into the New Millennium Program and baselined for flight validation on the DS1 mission. As the technology was being developed for DS1, the NASA community has expressed a growing interest and acceptance of adaptive operations and onboard autonomy.

In traditional mission operations, the spacecraft typically receives commands from the ground and, in turn, transmits telemetry in the form of science or engineering data. With Beacon monitoring, the spacecraft assumes responsibility for determining when telemetry will be sent and sends what amounts to a command to the ground to inform the flight operations team how urgent it is to track the spacecraft for telemetry. There are only four such commands. Thinking of Beacon operations in this way creates a paradigm shift over the way operations are traditionally approached. Also, it is very important to not think of the tone message as just a little bit of telemetry. If one does this, it is easy to make the argument that a little more telemetry is better. Our approach is one where telemetry is only transmitted when it is necessary for ground personnel to assist the spacecraft. If the spacecraft goes through long periods (a month or so) without requiring ground assistance. When telemetry tracking is necessary, the intelligent data summaries contain the most relevant information to provide full insights into spacecraft activities since the last contact. The key challenge has been to develop an architecture that enables the spacecraft to adaptively create summary information to make best use of the available bandwidth as the mission progresses such that all pertinent data is received in one four-to-eight-hour telemetry pass.

This work was funded from three NASA funding sources. The NASA Cross Enterprise Technology Development Program (CETDP) Thinking Systems Thrust Area funded flight software development. The Telecommunications and Mission Operations Directorate (TMOD) Mission Services Technology Program funded development of the tone detection algorithm and also funded development of flight software. Additionally, a small amount of funding from the New Millennium Program was supplied towards the end of the prime mission to help offset the additional costs imposed by DS1 schedule delays.

2.0 TECHNOLOGY DESCRIPTION

2.1 What It Is/What It Is Supposed To Do

Beacon Monitor Operations refers to a spacecraft-initiated operations concept and the supporting technology components. The supporting technology components are the tone subsystem and the onboard engineering data summarization subsystem, both of which were flight validated on DS1. The operational concept shown in Figure 1 depicts a typical end-use scenario where the spacecraft routinely sends one of four X-band tone messages that indicate how urgent it is to track for telemetry. This tone is received at a smaller aperture antenna than would be required for telemetry for that mission. If the tone indicated that telemetry tracking was required, a summary of the important telemetry data stored onboard since the last contact would be downlinked via a normal telemetry link.

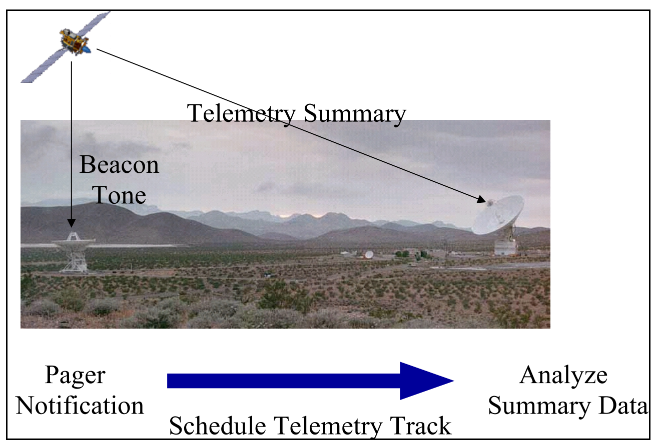


Figure 1. Operational Concept

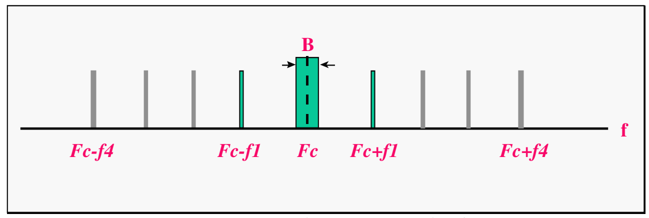
Advantages of using this technology fall into three categories: reducing mission cost, reducing Deep Space Network (DSN) loading, and reducing mission risk. Operations cost is reduced by reducing the frequency of contact and by reducing the total volume of downlinked data. Savings are realized through staffing reductions (because fewer people are required to analyze telemetry) and reductions in antenna usage. These reductions help the DSN contend with the oversubscription problem that exists today and that is poised to become worse in the future due to the large number of planned missions. Mission-risk reductions are another major advantage to this technology. At first glance, it may seem that Beacon operations is more risky than traditional operations. However, with today's faster-better-cheaper missions, scheduled telemetry tracking is being scaled-back due to cost constraints. With Beacon monitoring, the spacecraft can, at low cost, transmit assurances that the spacecraft is behaving as expected in between scheduled telemetry tracks. This reduces the chance of having a catastrophic, time-critical failure and, for ion-propulsion system, affords the additional advantage of verifying that thrusting is ON. If, for example, an ion mission lost thrusting immediately after a scheduled telemetry pass, a week or more may pass before ground personnel become aware of the problem. With Beacon, response time could be cut to just a few days (or less). Loss of thrusting for a week or more could cause the mission to not reach the target body.

2.2.1 Beacon Tone Monitoring System—As mentioned before, the tone system is used to routinely monitor the health of the mission. There are four tone signals; each signal uniquely represents one of the four urgency-based Beacon messages. The DS1 tone definitions are summarized in Table 1. These tones are generated as the spacecraft software reacts to real-time events.

Table 1. Tone Definitions

Tone	Definition
Nominal	Spacecraft is nominal. All functions are performing as expected. No need to downlink engineering telemetry.
Interesting	An interesting and non-urgent event has occurred on the spacecraft. Establish communication with the ground when convenient. Examples: device reset to clear error caused by Single Event Upset (SEU), other transient events.
Important	Communication with the ground needs to be achieved within a certain time or the spacecraft state could deteriorate and/or critical data could be lost. Examples: memory near full, non-critical hardware failure.
Urgent	Spacecraft emergency. A critical component of the spacecraft has failed. The spacecraft cannot autonomously recover and ground intervention is required immediately. Examples: PDU failure, SRU failure, IPS gimbal stuck.
No Tone	Beacon mode is not operating. Spacecraft telecom is not Earth-pointed or spacecraft anomaly prohibited tone from being sent.

It is important to communicate the urgency of ground response using a telecommunications method that has a low detection threshold and short detection times. Ease of detection translates to lower cost operations. The signal structure is shown in Figure 2. Each message is represented by a pair of tones centered about the carrier frequency. Tones are generated by phase-modulating the RF carrier by a square-wave subcarrier using a 90-degree modulation angle. The carrier frequency (Fc) is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. Four pairs of tones are needed to represent the four possible messages.



B=Frequency uncertainty Fc=Carrier frequency
fi=Subcarrier frequency for the i message

Figure 2. Tone-Signal Structure

2.1.2 Onboard Summarization System—If the Beacon tone indicates that tracking is required, the onboard summarization system provides concise summaries of all pertinent spacecraft data since the previous contact. This subsystem gathers high-level spacecraft information—such as the number of alarm crossings, spacecraft mode and state histories, and other pertinent statistics—since the last ground contact. It also gathers episode data for the culprit and causally related sensor channels whenever a sensor violates an alarm threshold and stores the data at a high sample rate. It collects snapshot telemetry at a much lower sample rate for all sensors and transform channels. Snapshot data serves only for rough correlation and to fill in the gaps between episodes. The last component of the downlinked summary—performance data—is similar to episode data but captures maneuvers or other events known in advance to be of interest to people on the ground. All of the summary algorithms are implemented in C for the VxWorks operating system.

The summary algorithms incorporate AI-based methods to enhance anomaly-detection and episode-identification capability. The Envelope Learning and Monitoring using Error Relaxation (ELMER) technology replaces traditional redlines with time-varying alarm thresholds to provide faster detection with fewer false alarms. The system uses a statistical network to learn these functions; training can be performed onboard or on the ground (ground-based for DS1). ELMER is particularly powerful because it requires very little domain knowledge and trains the statistical network with nominal sensor data. Another artificial intelligence (AI) method produces empirical transforms that have a heritage in previous AI research at JPL in selective monitoring. Once computed onboard, these act as virtual sensors. The current transforms for DS1 compute high, low, and average values, and first and second derivatives. Alarm limits can be placed on these transforms and also serve as an input to the ELMER adaptive-alarm limits. Additional transforms, if desired, can easily be defined and uplinked to the spacecraft as the mission progresses.

2.2 Key Technology Validation Objectives at Launch

The primary validation objective was to verify that the two subsystems (tone and summarization) were fully deployed and operating as expected. This was accomplished through a series of experiments to test the basic functionality of the deployed system. An additional validation objective was to evaluate the operational effectiveness of using the technology on future missions and on DS1 in the extended mission phase.

Validation objectives were captured in a signed Technology Validation Agreement between the BMOX Team and the DS1 project.

2.2.1 Objectives Prior to Experiment Turn-on—

1. Test summarization algorithms and ground visualization environment using representative spacecraft data (Topography Experiment (TOPEX/Poseidon)) prior to DS1 testbed data availability
2. Provide unit-test verification test runs in “Papabed” and Testbed environments for test of all BMOX flight software capability
3. Verify that the tone detector can automatically detect weak signals using schedule and predicts information

2.2.2 Expected In-flight Observables—

1. Tones detected at DSS 13 during experiment activities, conducted periodically throughout the prime mission
2. Tone message delivery to JPL
3. Engineering data summaries downlinked during scheduled DS1 project telemetry passes
4. Characterization of tone system behavior with mission distance
5. Demonstration of the ability to detect spacecraft anomalies, map to Beacon tones, and detect the tones on the ground in a timely manner
6. Produce summary data that provides value-added information if Beacon monitoring were to be used as the primary mode of operations
7. Characterization of DS1 staffing level for routine operations and a comparison of that staffing level to the expected level of support required in performing Beacon operations
8. Detailed analysis of antenna tracking time with and without Beacon operations
9. Assessment of the number of mission anomalies or events requiring ground intervention

Success Criteria (Quantifiable/Measurable Goals):

2.2.3 Prior to Experiment Turn-on—

1. Tones detectable at DSS 13 throughout the primary mission phase
2. Adaptive summaries of spacecraft health information that result in downlink bandwidth savings over traditional downlink approaches
3. Telecom system capable of generating X-band tones per Small Deep Space Transponder specifications

2.2.4 In-Flight—

1. Determination of the size of engineering data summaries required to adequately analyze spacecraft conditions when the tone indicates that ground intervention is required
2. Tone detection probability of 95% or greater
3. Onboard tone selection accuracy of 95% or better for urgent conditions
4. Message delivery latency less than 1 hour
5. Major (urgent) event capture in summary data 90% or better using traditional alarm limits, 70% or better using adaptive alarm limits (after initial checkout period)
6. Summary data sufficient for determining corrective actions at least 75% of the time
7. Ability to display summary data within 2 hours of downlink data available to DS1 project
8. Determine, through operational experiments, that Beacon operations will reduce routine operations cost on DS1 by at least 25%
9. Determine, through operational experiments, the exact level of expected savings in operations-staffing cost and antenna-tracking cost on future JPL missions.

2.3 Expected Performance Envelope

Table 2 illustrates the full set of validation objectives and the weighting of each in computing the percent validated at any point during the mission and includes brief descriptions of the experiments that were conducted and the associated success criteria.

Table 2. BMOX Validation Summary

Experiments	Goal	Success Criteria	Validation %	Antenna	When	How many tone passes	Pass Duration, hr
1. **Engineering Summary Data Generation & Visualization, and Tone Selection**			**50%**				
1.1 Data Generation and Visualization – Functional checkout	Demo end-to-end functionality of on-board data summarization system.	Summarization algorithms work as expected during DS1 mission operations.	**25%**	HGA	Starting late Feb., 99	(Regular DS1 Telem.)	Depends on bandwidth
1.2 Data Generation and Visualization – Detailed performance verification	Performed detailed analysis of all features of the software.	Summarization data successfully determines spacecraft anomalies with enough detail for spacecraft engineers to respond appropriately.	**15%**	HGA	Jul. – Dec., 99	(Regular DS1 Telem.)	Depends on bandwidth
1.3 Tone Selection	Demo FSW functionality to set and reset the tones and meaningful mapping from spacecraft health to urgency-based request.	Tones are set as a result of a spacecraft data out-of-limits condition. Parameter file can be easily updated and uploaded. Tones selector is reset.	**10%**	HGA or LGA	Apr. – Dec., 99	Some telemetry, some mid-week	1
1.4 Final analysis & report generation	Analyze and document results, lessons learned, and as-flown design in a final report.	The software system provides a viable means for conducting spacecraft-initiated operations on future space missions.	**Not included in validation**				
2.Tone Trans. & Detection			**40%**				
2.1 SDST functionality checkout	Verify that the SDST can correctly generate Beacon tones.	SDST generates and transmits the 4 Beacon tones, as instructed via uploaded commands.	**20%**	HGA	Jan., 99	1	2.5
2.2 Tone Calibration - X	Calibrate Beacon frequency & tone detector parameters, and verify predicts. Establish the lowest threshold and the longest integration time possible.	Successfully detect Beacon tones and obtain frequency uncertainty estimates.	**10%**	HGA or LGA	Feb. - Mar., 99	4	1
2.3 Tone Detection - LGA	Demonstrate weak-signal detection.	Detect signal with power level 5-10 dB Hz.	**5%**	LGA or HGA	Mar., 99	1	1
2.4 Tone Detection - Ka	Obtain Ka-band Beacon signal characteristics.	Successfully detect and record Ka-Beacon signal.	**5%**	HGA	Mar. – Apr., 99	1	1
2.5 Detailed analysis & report generation	Analyze and document tone-transmission and detection system results in a final report.	Beacon signaling system provides a viable means for conducting spacecraft-initiated operations on future space missions.	**Not included in validation**				
3.Multi-mission Ground Support			**10%**				
3.1 Functional demo of tone notification process	Demonstrate a low-cost and reliable process to detect and deliver Beacon messages in a realistic environment.	The tone detector detects and delivers Beacon messages within 1/2 hr after the Beacon tone pass.	**10%**		Feb. - Mar., 99	Use passes from 2.2 above	
3.2 DSN Track Automation	Demonstrate viable demand-based DSN antenna scheduling schemes and methods for automating the tone detection process.	Beacon- triggered DSN passes can be successfully scheduled using a real DSN station schedule.	Optional for extended mission				
4. Ops Concept Assessments			N/A				
4.1 Effectiveness Assessment	Produce a final report documenting results of cost benefit analysis.	Quantify future mission-tracking cost and personnel cost savings for Beacon operations.	Not included in validation				
4.2 Perform Beacon operations during DS1 prime mission operations	Evaluate effectiveness through Beacon ops for DS1 ops benefit.	Beacon ops is mature enough to support DS1 extended mission.	Optional post-validation activity				
4.3 Perform Beacon operations during DS1 extended mission	Provide updates to flight software and continue performance assessment.	Demonstrated ops-cost savings during DS1 extended mission.	Optional for extended mission				

2.4 Detailed Description

2.4.1 Tone Experiment Detailed Description—The tone monitoring technology consists of generation, transmission, and detection of the tone signals. The primary requirement was to transmit tones in X-band; however, Ka-band was tested to help pave the way for future missions that may use a Ka-band transponder. The experiments were also constructed so that detection of weak signals, such as from a mission to Pluto, could be validated. Finally, tone-message handling and reporting and overall low-cost operation of the tone system was assessed.

There are four tone signals. Each tone uniquely represents one of the four urgency-based Beacon messages. For a description of the tone meanings, refer to Table 1.

BMOX was designed so that the urgent Beacon tones are sent when the spacecraft fault protection puts the spacecraft in standby mode. This condition occurs when the fault protection encounters a fault that it cannot correct. Standby mode halts the current command sequence, including IPS thrusting. The software to control this condition was onboard the spacecraft but never enabled.

During the DS1 tone experiment, the Beacon tone was sent at prescheduled times for about 30 minutes. The Beacon tone was not operated continuously because DS1 requires as much power as possible for IPS thrusting and the tone transmission reduces the power available for thrusting.

The tone is sent using the DS1 Small Deep Space Transponder (SDST). The signal structure is shown in Figure 2. A pair of tones centered about the carrier represents each message. These tones are generated by phase-modulating the RF carrier by a square-wave subcarrier using a 90-degree modulation angle. The frequency carrier (Fc) is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. For the DS1 experiment, the four-subcarrier frequencies (f_1, f_2, f_3, and f_4) are 20, 25, 30, and 35 kHz, respectively. Different frequency allocations can be assigned to different missions. The monitoring system is designed to achieve a low-detection threshold. The goal is to reliably detect the monitoring messages with 0 dB-Hz total-received-signal-to-noise-spectral-density ratio (Pt/No) using 1000 seconds observation time.

The Beacon message is first received and decoded by the Goldstone site and subsequently transmitted to a signal detector at JPL. Next, the Beacon message is forwarded to DS1 Mission Operations and other end users, including the Demand Access Scheduler, using e-mail or pagers.

The signal detector contains four tone detectors, one for each message. To ensure proper signal detection, the bandwidth of each tone detector must be sufficiently large to accommodate the frequency uncertainty and frequency drift of the downlink frequency: i.e., the Beacon tones for a given message will not drift outside of the passband of the detector for that message. The FFT (Fast Fourier Transform) is employed to compute the energy of all spectral pairs having spacing corresponding to the four Beacon signals. Because of oscillator instability, Fourier transforms cannot be produced over long time intervals. The total observation time is divided into short intervals. FFTs are first performed over these short intervals and then incoherently combined after the frequency drift has been removed. The maximum of the outputs of the four tone detectors is then selected and compared against a pre-determined threshold to determine which message has been received. A block diagram for the signal detector and the message decoder is shown in Figure 3.

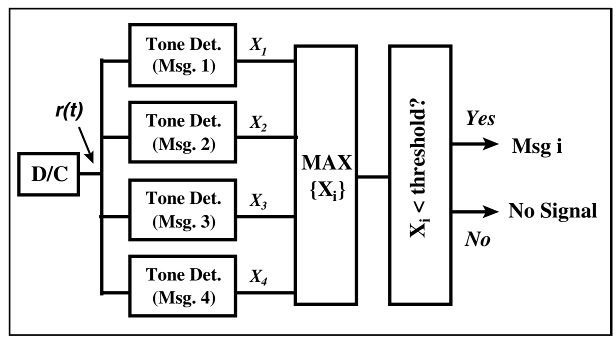


Figure 3. Monitoring Signal Detector and Message Decoder

2.4.1.1 Tone Transmission and Detection Experiment—The four Beacon messages are represented by four pairs of tones; these tones will be generated by modulating the downlink carrier with an appropriate subcarrier using a 90-degree modulation angle. The four subcarriers selected to represent the four Beacon messages are:

Beacon Message	Subcarrier Frequency, KHz
NORMAL	20
INTERESTING	25
IMPORTANT	30
URGENT	35

The DS1 spacecraft is equipped with two transmitters: X-band and Ka-band. When Beacon tones are being transmitted via one of the two links, no telemetry can be sent over the same link. However, DS1 can transmit Beacon signals using one link (e.g., X-band) and simultaneously downlink telemetry using the other link (e.g., Ka-band).

The first tone pass was used to verify the functionality of the Small Deep Space Transponder (SDST). Four commands were sent directly to the SDST software manager, each representing a different tone. The Beacon flight software was not used during this test. The tones were detected on the ground beginning in January, 1999.

The next part of the experiment used four Beacon passes to calibrate the signal and compare against prediction. A set of Beacon tone states was loaded into the command sequence on the spacecraft. Beacon tones were then generated onboard, transmitted to the ground, and detected by DSS 13 at Goldstone. The detector and tone frequencies were calibrated, predicts were verified, and detector parameters were determined. In the first three tests, the Beacon tone states were pre-selected, but unknown to the tone detection personnel. In the last test, a tone was generated by the onboard Beacon flight software. These tone passes occurred between February and April, 1999. This set of four tone passes was the minimum required to calibrate the detection system and validate its performance.

All Beacon passes require dedicated use of either the LGA or HGA during a Goldstone pass. Telemetry and Beacon signals cannot be transmitted simultaneously over the same communication link (of the same frequency, X- or Ka-band); therefore, Beacon passes were scheduled to accommodate the DSN telemetry passes. In addition to the above calibration-tone experiments, two additional experiments were scheduled to test the performance of the Beacon-tone detector using the Ka-band frequency and using the X-band frequency in a weak-signal regime. The Ka-band experiment was identical to the X-band experiment except for the frequency. The purpose of the weak-signal X-band experiment was to determine the threshold at which the signal can no longer be detected. These two experiments were scheduled to occur during March–April, 1999.

2.4.1.2 Multi-mission Ground Support Experiment—The objective of the Multi-mission Ground Support Experiment was to demonstrate a low-cost, reliable process to deliver Beacon messages to the flight project within a reasonable amount of time. For the DS1 Beacon experiment, this time was defined to be less than 30 minutes. The Beacon tone passes from the tone transmission experiments were used in this experiment. During these passes, Beacon messages were generated, transmitted, and subsequently detected by the ground station (DSS 13). The detected messages were delivered to the BMOX team at JPL via e-mail or pager. Post-Beacon pass telemetry was used to verify the correct transmission times.

2.4.2 Data Summarization Detailed Description—If the Beacon tone indicates that tracking is required, the onboard summarization system provides concise summaries of all pertinent spacecraft data since the previous contact. The summarization system performs three functions: data collection and processing, mission activity determination, and episode identification. The data collection sub-routine receives data from the engineering telemetry system via a function call and applies summary techniques to this data, producing summary measures for downlink to the ground. The mission activity sub-routine determines the overall spacecraft mode of operation. This determination is used to choose the appropriate data and limits monitored by the episode sub-routine. The mission activity is intended to be exclusive. When a new mission activity starts, the previous mission activity is assumed to have ended. The episode sub-routine combines summary and engineering data received internally from the data-collection sub-routine with the mission activity received from the activity sub-routine and compares the data with mission-activity-specific alarm limits. It is necessary to use the mission activities to determine which data to use for episode identification and to identify the limits of these data. If the limit is exceeded, the sub-routine spawns a new episode and collects past relevant data from the data collection sub-routine. The past data collected will be one-minute summaries that go back in time as far as the user has defined. (Therefore, a five-minute episode would contain summaries starting five minutes before the episode to five minutes after the episode.) At the end of the episode, the sub-routine outputs data to the telemetry subsystem for downlink.

Three different types of summarized data are produced onboard: overall performance summary, user-defined performance summary, and anomaly summary. Six different telemetry packets have been defined to contain this information (see Table 3. Taken as a whole, the telemetry packets produce summary downlinks that are used to enable fast determination of spacecraft state by ground personnel. The summary data is prioritized in the downlink so that the most important data is sent first (Figure 4). The first telemetry sent is a summary of events since the previous downlink. Next, the episodic data, the nominal data, and, finally, the user performance are sent.

The performance summaries are generated at regular intervals and stored in memory until the next telemetry-round contact. They are computed by applying standard functions, such as minimum, maximum, mean, first derivative, and second derivative, to the data. User-defined summary data can provide detailed information on a particular subsystem and are created at the user's discretion. Anomaly summary data (episodes) are created when the raw and summarized data violate high or low limits. These limits are determined by the subsystem specialist and stored in a table onboard the spacecraft. The limit tables are based on the current mission activity.

The software also has the capability to use AI-based envelope functions instead of traditional alarm limits. This system, called Envelope Learning and Monitoring using Error Relaxation (ELMER), provides a new form of event detection will be evaluated in addition to using the project-specified traditional alarm limits. Envelope functions are essentially adaptive alarm limits learned by training a statistical network with nominal engineering data (see Figure 5). The network can be onboard or on the ground. For DS1, envelope functions are trained on the ground and then uploaded to the spacecraft. DS1 spacecraft fault protection will only be based on project-specified static-alarm limits; however, the summary data can be generated based on the adaptive limits.

Table 3. Summarization Telemetry Packets

Telemetry Name	Description	Output Frequency
Activity	Current value of mission activity	Output on change
Data Sample	Records a snapshot of every raw and summarized data channel	Regular interval: i.e., 15 min.
Episode Summary	Records general data about an out-of-limits data condition called an "episode"	One per episode
Episode Channel	Records specific data about a single data channel's behavior during an episode	One or more per episode
Tone Change	Current state of the Beacon tone	Output on tone change
Channel Summary	Summary data about a single data channel's behavior since the last downlink	One for each channel out of limits
User Summary	A user-specified packet containing raw and/or summarized data	Duration user-specified

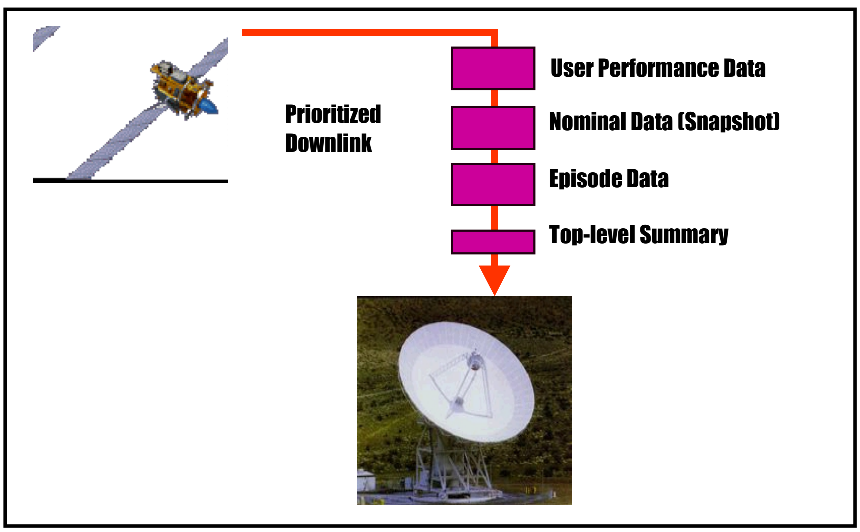


Figure 4. Prioritized Summary Data Description

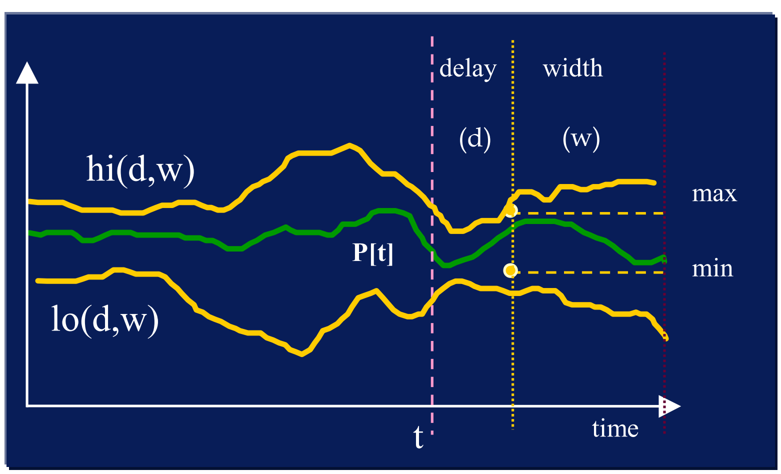


Figure 5. ELMER Adaptive Alarm Limits

The sampler module and its related data-gathering module currently consist of 3038 lines of source code and 222 KB of memory on the Power PC series processors. Activity determination is a rare event and processing time is negligible. The once-per-wake-up processing time for DS1 averages 30 ms.

2.5 Technology Interdependencies

DS1 BMOX was designed to have minimal impact on the operation of the baseline DS1 mission. There are, however, some important interdependencies to note for future missions that may be interested in deploying the technology. These are summarized as follows:

- The transponder should be capable of transmitting beacon tone signals. The Small Deep Space Transponder (SDST) has this capability, as does the Space Transponding Modem (STM).
- The algorithms used for anomaly detection within the Summarization System should be the same as those used for fault detection within the fault-protection subsystem. Otherwise, summary data may not capture the relevant data.
- Bandwidth-constrained missions will likely have more of a use for tone monitoring.
- Operationally-constrained spacecraft designs make unattended operations difficult, adding cost and decreasing the utility of Beacon operations.

2.6 Test Program

2.6.1 Ground Test—A number of system-level tests/demonstrations were conducted throughout the development process to validate the design concept and hardware/software interfaces. These tests/demonstrations were also conducted to satisfy project-related requirements.

2.6.1.1 SDST/Tone Detector Compatibility Tests—The first major test was to validate the compatibility between the tone detector and the SDST. Beacon signals were generated by the SDST (engineering model) in the radio laboratory in Building 161. The signals were transmitted to a test facility in Woodbury, where the signals were down-converted to 300 MHz IF and recorded by the Full Spectrum Recorder (FSR). The recorded signals were processed by the tone-detection algorithm installed in the FSR.

An example of the detection results is shown in Figure 6 and Figure 7 using 20 KHz as a signal frequency. Figure 6 gives the Fourier spectrum of a 1-sec snapshot of the monitoring signal before being processed by the detector: i.e., the spectra of the input signals to the four tone detectors. Figure 7 gives the Fourier spectra of the outputs of the four tone detectors after aligning, summing and averaging over 10 FFTs, each of 1-sec duration. The horizontal line is the detection threshold corresponding to a given false-alarm probability. As shown in the figure, the aligning and summing process significantly reduces the noise fluctuation and enhances signal detection.

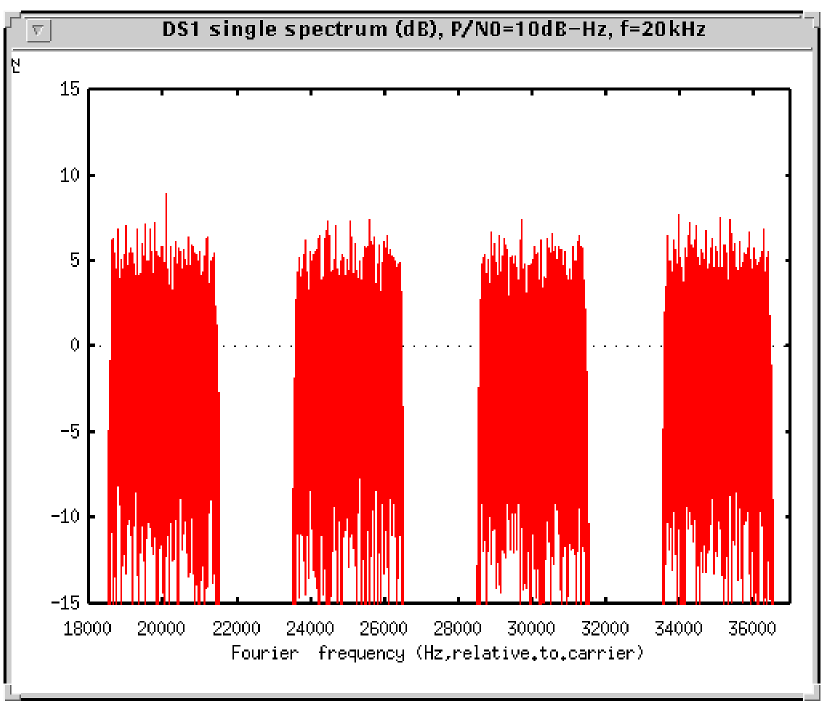


Figure 6. 1-sec Fourier Spectra of the Input Signals to the Four-Tone Detectors

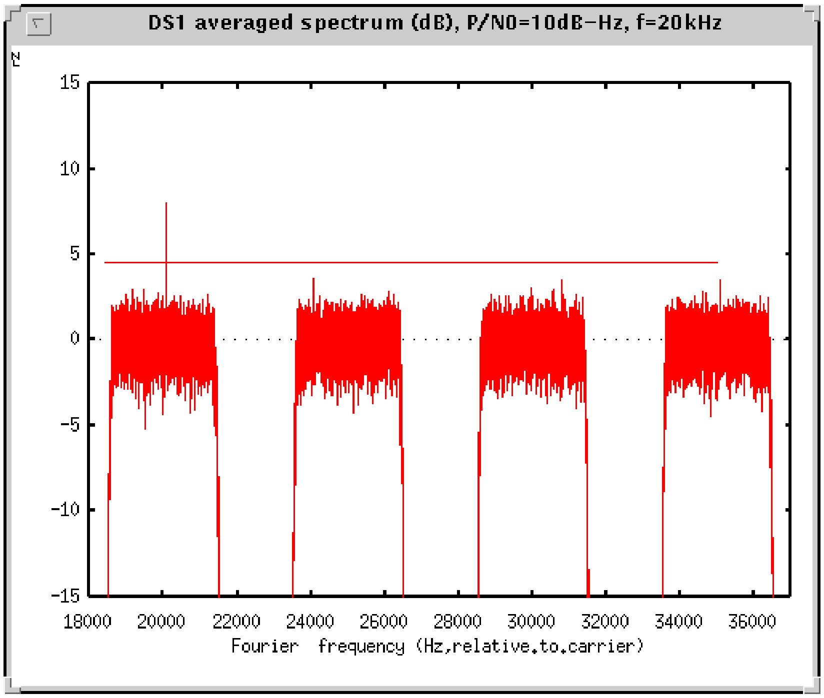


Figure 7. Fourier Spectra of the Output of the Tone-Detectors after Aligning and Summing (and averaging) 10 FFTs of 1-sec Each

The recorded data was subsequently and successfully used in a concept demo, which is one of the requirements imposed on technologies by DS1. During the conceptual demo, segments of the previously recorded SDST Beacon signal data were selected for the tone detector to perform real-time detection. The detector, located in Building 111, was remotely operated from the SMOCC room in Building 301, where the concept demo was given. Detection results were sent to the SMOCC room via a network connection and displayed on a projection screen in real-time. Segments of the recorded data were selected for the demo and the tone detector successfully detected the signals and displayed the detection results.

A second compatibility test was performed with the flight transponder, during which the spacecraft was in the thermal vacuum chamber and the tone detector was transported to the Telecom Development Laboratory (TDL). The SDST was commanded to send Beacon tones one at a time to the TDL using a fiber-optic link. The signal was demodulated and down-converted to IF at the TDL. The received signal was displayed on a spectrum analyzer. The observed spectra confirmed that the SDST had correctly generated and transmitted all monitoring signals as commanded. In addition, the received monitoring signals were fed to the tone detector, where they were digitized, recorded, and subsequently detected. These tests revealed that there are no interface or compatibility issues between the SDST and the tone detector and ensured that they would work smoothly as a tone system.

2.6.1.2 Tone Detection System Test—In addition to being able to detect very weak signals, it is envisioned that an operational tone system would be capable of schedule-driven, predicts-driven, fully-automated tone detection and message delivery. This would lower the operations cost, which is critical if this technology were to be employed as an operational capability. The original DS1 experiment plan was to leverage on the DST technology to demonstrate in-flight such a capability. A series of system tests was designed and conducted in the TDL to demonstrate (1) predicts generation capability, (2) DST/Tone detector interface and file transfer, and (3) automated detection using frequency predicts. Frequency predicts were generated by the DST controller using a SPK file obtained from the DS1 Project database. The predict file along with a trigger file were then sent to the tone detector and were subsequently used to detect the TDL-simulated Beacon signals. Two automated Beacon detection demonstrations were conducted by using simulated spacecraft tones at TDL. DS-T-generated frequency predicts and a trigger file were used to initiate the detection of a scheduled pass. The detector detected Beacon signals at the 7 dB-Hz power signal-to-noise level using 10-s integration time with a probability of false detection of 0.01. BMOX team members, Section 331 engineers, and DS1 management attended this demo. It fulfilled the pre-launch readiness requirement. This test also paved the way for a subsequent in-flight demo.

2.6.2 Flight Test—The test program consisted of executing the experiments described in Section 2.3. Testing began in

January, 1999 and continued through the end of the prime mission in September, 1999. Table 4 depicts the flight-validation schedule.

3.0 TECHNOLOGY VALIDATION SUMMARY

The technology was declared fully validated in July, 1999, after both the summarization and tone systems were fully deployed and tested as described in Section 2. The overall system performed as expected and was considered a success.

3.1 Tone Experiment Results

A series of experiments were run to test the end-to-end tone delivery system. These experiments were designed to incrementally test additional capability for the Beacon-tone system. Prior to launch, the ability of the SDST to generate Beacon tones was tested by the telecom engineers. A similar test was performed on the spacecraft several times after launch. This test was called “X-tone” because it tested the capability to send the Beacon tones using X-band transmission. The X-tone test, expanded to use a series of tones to test the ground detection system, was repeated several times throughout March and April, 1999. The dates of these and other tests are listed in Table 5.

The ability of the software to select tones and transmit them in DS1 telemetry was tested on February 26, 1999. This test, called b-tone, consisted of ground commands that set the Beacon tone during a downlink pass. The tone was verified in regular DS1 telemetry but was not transmitted to the tone detector. Each tone was verified during the b-tone test. In addition, the tone-reset command was tested.

The next test to run onboard DS1 was the b-transmit test. This test involved setting the Beacon tone using information from the software on board, then transmitting the tone using the SDST. The tone was received at the DSS 13 antenna and forwarded to the tone detector at JPL. No advance knowledge of the commanded tone was given to the ground detection engineer. After the tone was detected, it was delivered to other members of the Beacon team in an e-mail message. The b-transmit test was run three times in April, 1999.

The last tone test to be run was the Ka-tone test. This test was identical to the X-tone test except that it used the Ka-band transmitter to send the Beacon tone. This test was run in April, 1999.

3.2 Data Summarization Results

The data summarization was first turned on February 19, 1999. The Beacon team determined the limits applied to the engineering data for testing the summarization capability. The limits were set just outside of the minimum and maximum value seen for the data since launch. Shortly after the first turn-on, several of the data channels went into episode (out-of-limits) condition. Upon further inspection, it was determined that many limits were based on engineering units (EU), but much of the data was being stored using data numbers (DN) in EH&A. The data summarization was turned off after several hours, and the initialization file (also called sampler init file, or SIF) was updated with DN-based limits.

On March 8, 1999, the data summarization was turned back for several hours. A few channels went into alarm; however, the number was reduced from the previous test. Inspection of the data revealed negative values for some eight-bit sensors. This was impossible because all eight-bit sensors should range from 0 to 255. After careful debugging in the DS1 test bed, an error was found in the DS1 flight software. It was discovered that when data are passed from the originator to EH&A, EH&A converts the data to its own internal double-precision format as though it were 8 bits and signed. This results in the values from 0 to 127 being

Table 4. BMOX Validation Schedule and Matrix

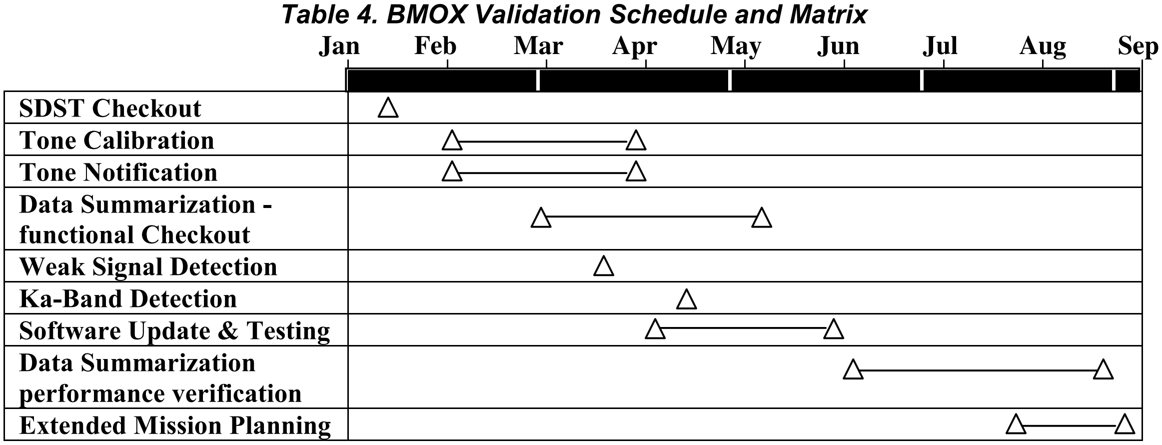


Table 5. List of Tone Experiments

Date	Experiment Type	Results
Jan 6	X-tone, 20, 30, 25, & 35 kHz	Tones found in this order after accounting for 20-second offset in spacecraft internal time. Detection time = 5 min. Frequency offset (FRO) = -4.25kHz, (high gain antenna)
Feb 4	X-tone, 35 & 20 kHz	Noisy and stable sub-carriers used with low modulation indexes from low gain antenna. All successfully detected. FRO = -1.98kHz
Feb 26	B-tone & X-tone	Software tone test. All four tones were commanded and transmitted through regular telemetry.
Mar 3	X-tone, 35 & 20 kHz	Antenna computers down and wind speeds halted antenna several times and early, but several detections were successful at very low levels. FRO=1.25 kHz: 20.0001 kHz, DN=3, Pd/N0=8.8, 10 sec, 35.0013 kHz, DN=2, Pd/N0=4.2, 15 sec.
Mar 18	X-tone, 30, 20, 25, & 35 kHz	X-tone successful. After 4.4 kHz carrier offset was found and applied. Spacecraft time found to be 10 seconds later than predicted. IPS was on.
Mar 24	X-tone	X-tone semi-successful. X-tones found but wrong frequencies because carrier predicts were off by 4.5 kHz and not entered in FSR.
Apr 7	X-tone, 20, 25, 30, & 30 kHz	X-tone successful. Station needs 45 minutes pre-cal vs. 30. FRO=5.0 kHz.
Apr 13	B-transmit & X-tone, 20, 25, 30, & 35 kHz	B-transmit successful, 25 kHz tone, needed visibility of carrier before carrier suppression to get correct FRO of 5.5 kHz. X-tone was also successful.
Apr 19	Ka-tone	The FSR at DSS 13 tracked the Ka carrier but the Ka-tone sequence did not get transmitted to the S/C as the auto-nav processing took longer than expected. FRO=0.0 (3-Way).
Apr 20	B-transmit	B-transmit successful, detection code found 25 kHz tone, needed visibility of carrier to find correct FRO of 6.0 kHz.
Apr 26	Ka-tone, 20, 25, 30, & 35kHz	Ka-tone was successful for the sequence that was activated. Detection of 20 kHz tone at DN=1 was 4.5 Pd/N0 for 15 sec. FRO=9.9 kHz (wrong up-link freq. in predicts).
Apr 27	B-transmit	Detection code found 25 kHz tone, FRO of 6.9 kHz was used to center the signal.

represented correctly, and the values from 128 to 255 being represented as -128 to -1, respectively. EH&A apparently does not have a data-type code for unsigned 8-bit integers. The effect of this problem was that limits were harder (and sometimes impossible) to specify. With a new set of rules, it was possible to create a SIF that would work around this problem for some of the data. If both high and low limits were 128 or greater, they had to be converted by subtracting 256. However, if the low limit was 127 or less and the high limit is 128 or greater, the limits won't work. Sensor values with both limits less than 127 could remain unchanged. With these rules, another SIF was created and uploaded to DS1. Data summarization was restarted on March 22, 1999. Everything appeared to operate correctly in data summarization. A few data channels went into episode condition. It was determined that temperature sensors were drifting colder due to DS1 moving away from the sun. The limits were updated and a new SIF was uplinked.

Data summarization ran smoothly on and off during the month of April and May, with minor modifications to the SIF due to noisy channels. During this period, a new version of the Beacon FSW was developed and tested. This version included a work-around for the limitation of EH&A data described above. In addition, the following new features were added:

- The criteria for determining mission activity was parameterized in the SIF
- Episodes will now end if a new SIF is loaded
- Additional protection for divide-by-zero conditions
- SIFs can now be loaded from EEPROM or RAM
- User-data packets can now have start and stop times associated with them

The new version was started up on June 15, 1999. A new SIF was included with limits determined by the DS1 spacecraft engineers. Since that time, data summarization has needed a few updates due to false alarms. There are several reasons for these false alarms. The Beacon FSW is able to sample the data once per second. This is a much higher rate than the data sent to the ground for analysis. Because of the higher rate, the FSW is able to see events that are normally missed on the ground. These events have been confirmed by correlating with fault-protection monitors that capture maximum excursions on the same sensors.

Another reason for false alarms has been activities such as optical navigation (OPNAVs) that move power and thermal sensors outside their normal ranges. The subsystem engineers respond, "Yes, these events take the sensors outside their normal ranges, and yes, this is expected behavior." So where does the Beacon team set the limits? Since the Beacon data summarization is context sensitive, a new "mission activity" for OPNAVs could be created with its own set of limits. An OPNAV activity consists of several spacecraft turns, with picture taking occurring at each target. This is similar to a maneuver. With this in mind, the mission-activity determination criteria for maneuvers has been changed to include optical-navigation activities. This will also make the maneuver activity determination more robust. Prior to this change, switching to maneuver activity when DS1 was actually firing thrusters was only used to change the velocity. Maneuvers involve turning to a thrusting attitude and turning back after the thrusting. Now, the maneuver activity includes these turns and their respective settling times as well. This makes sense because it is during this entire period that power and thermal sensors may deviate from their nominal cruise values. This change was uplinked in early September, 1999. The current list of engineering data being monitored is listed in Appendix A. A summary of this list is contained in Table 6.

Table 6. Summary of Engineering Data Monitored

Subsystem	Number of Channels
Attitude Control	8
Fault Protection	1
Navigation	1
Other	2
Power	22
Propulsion	1
Telecommunications	6
Temperature (all subsystems)	35

Beacon data summarization has been an evolving process requiring several limit refinements from the spacecraft team. This should be expected in the development of any data summarization system. This process is very similar when any new mission launches. For the first several months, ground alarms are updated as the flight team learns about how the spacecraft really operates. The ground-testing activities give a good first cut at setting alarm levels; however, the spacecraft never operates exactly as it did in test. Implementing context-sensitive limits is a similar process. Engineering data limits are no longer set based on the worst case. Now the worst case can be viewed based on the spacecraft activities. This should ensure more accurate discovery of anomalies.

One activity that produced important results involves analyzing summary-system performance on DS1 anomalies to date. Although capabilities were limited due to onboard memory restrictions, preliminary results when running ELMER on historical data are showing that adaptive alarm thresholds can track gradual trending of sensor data much tighter than the current DS1 static alarm limits. This is seen in monitoring the gradual drift in eight solar-array-temperature sensors, one of which is shown in Figure 8. Comparing traditional limits with ELMER limits during the 81 days of operations, ELMER limits track actual spacecraft performance much more precisely than static limits, which would be off the scale of this chart.

Another validation exercise has confirmed that summarization can capture subtle, yet important spacecraft episodes. In ground tests, ELMER detected an unexpected heater turn-on that occurred when the solar panels went off-axis during a spacecraft maneuver. Since ELMER trains across multiple parameters using nominal data, the summarization system detected this event without explicit a priori knowledge of the scenario. This data is shown in Figure 9.

ELMER has been running onboard with only 10 sensors, all temperature. This limitation is primarily due to limited onboard memory. There have only been three ELMER limit violations (episodes) during the primary mission. Two have occurred during OPNAV events and can be explained by the temperature excursions associated with spacecraft turns. These are basically "false alarms." The third episode has not yet been explained. The ELMER limit functions were developed after training on data from the first four months of the mission. It is hoped that additional training on spacecraft data since February will correct these false alarms in an extended mission. There will be additional ELMER limit functions added in an extended mission as well.

3.3 Operational Effectiveness Assessment

The experiment afforded insights into the operational cost savings that a future mission might realize. Computing cost savings for DS1, however, was not possible in the prime mission because Beacon technology was not used operationally by the mission. Although not specified in any plans, the best measure of the effectiveness of the technology turned out to be the interest expressed by the DS1 team in using it for the extended mission phase. In August, 1999, work began with the DS1 team to help infuse the technology into the planned two-year extended mission to two additional target bodies. The technology was seen as a way to contend with the severe cost constraints that extended missions face. Luckily, one of the BMOX design objectives was to deploy the technology experiment in a manner that would allow the mission to use it once validated.

There were many important results on how to design, implement, and operate Beacon-monitor operations systems on future missions. The entire end-to-end experience of working with a flight project team to field this experiment resulted in uncovering important design considerations and lessons learned that will be useful to future missions that plan to use the technology. These are described in the remainder of this section.

3.3.1 Data Processing Issues—Beacon summary data was delivered to the Beacon team through an automated batch script that queried the data each night. The data was placed in a public directory and then processed by the Beacon team the next morning. The processing was a simple task, but was not automated because data summarization was frequently turned off for days to weeks at a time. During DS1's extended mission, data summarization should be on continuously and, therefore, the data processing should be automated.

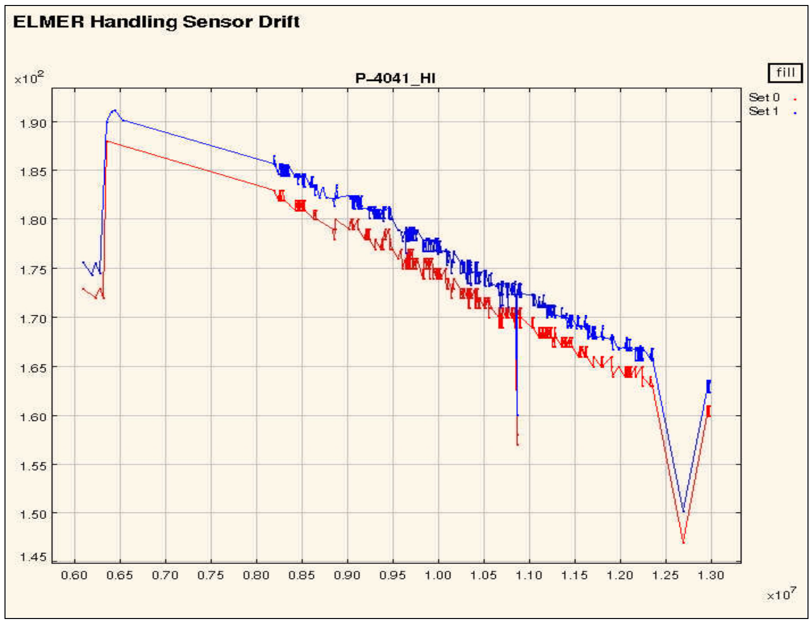


Figure 8. Tracking of Adaptive Alarm Limit to DS1 Solar Array Temperature

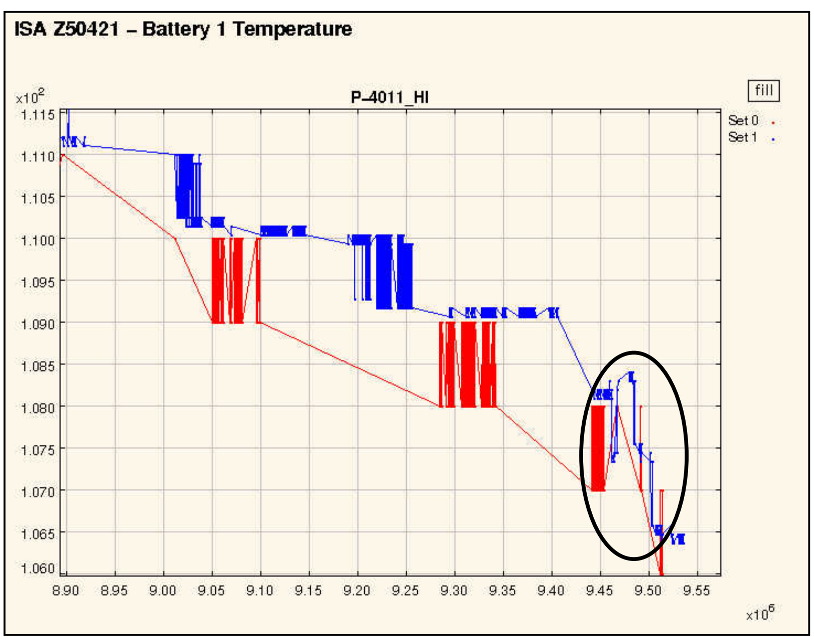


Figure 9. Battery Temperature Episode Detection

The database used to store Beacon summary data was created specifically for the Beacon task. Because summary data is not easily formatted for commercial databases, it was decided to develop a DS1 database. In hindsight, this was the wrong decision. It has been very difficult to maintain a custom database. The users do not have good visibility into the database if the tools are not working correctly. Changes to the database take a programmer to change the code instead of running a tool that would be provided with a commercial database. In addition, commercial databases have built-in query features that are easy to set-up and use. There were instances in which data was requested, but it could not be provided in a timely fashion. Also, custom requests such as one for all episodes involving a specific channel could not be provided. The limitations of using a custom database hindered the operational effectiveness of Beacon.

3.3.2 Data Summarization Software Enhancements—The data summarization software was not relied upon for determining spacecraft state. Although the algorithms and returned summary data seemed adequate, there were several suggestions made by the Beacon personnel and flight team for further enhancements. Some of these suggestions will be incorporated into the M7 version of the flight software to be uploaded during DS1 extended mission operations.

The episode data was lacking depth because it only provided ten samples, each separated by two minutes. The long time between samples was set to ensure that Beacon summary data would not overflow the telemetry buffer in the event of repeated episodes on a single channel. For the M7 version of the software, the number of samples is being changed to 20 and the user will be allowed to set the number of times a channel can go into episode before it stops producing episode packets. With these changes, the sample interval can be set much shorter. In fact, a six-second-sample interval will be used. This will give the episodes more visibility while not overloading the telemetry buffer with false alarms. Making a change and adding all data on change-to episodes was considered; however, the DS1 project only wanted very minor software changes in M7.

During the course of operations, the initialization file with the episode limits was changed and uplinked many times. Many times the changes only involved one or two limits in the file. Because the file is on the order of 15 kilobytes, there were periods of low communications bandwidth when it would take several minutes to uplink the file using the low-gain antenna. Operationally, it is much easier to have a capability to update limits without sending out the entire initialization file.

The flight team made a few suggestions for improving the usefulness of the summary data. The derivative summary functions, but one of the subsystems suggested that integrals be added to the summary functions. Several other flight-team members suggested adding different persistence for each episode limit check. Currently, there is a global persistence parameter that applies to all episodes. This change will be implemented in our M7 software release. Another suggestion was to add a sample rate to user-performance packets.

Two capabilities that fault-protection monitors have that should be present in Beacon are conditional monitors and maximum excursion tracking. Conditional monitors enable the user to check multiple sensors based on the values of the sensors. The DS1 fault protection software also has the capability to track and save the minimum and maximum values for sensors. The summarization software will only track these values if the sensor goes into an episode condition. This may be important data for future missions relying on summary data even though the sensors are not outside their limits. As mentioned in the Lessons-Learned section, there should be tighter integration between the Beacon software and the fault-protection software.

3.3.3 Reporting Results to the Flight Team—A set of tools for examining the summary data was developed. These tools were only located on the Beacon team workstation. Since launch, some web-based tools were developed to access the summary data. These tools have made it easier to report the results to the flight team, but are very limited in their capabilities. These tools will be improved during extended mission. The goal is to make the data easily accessible to the flight-team users. Easy access to the Beacon data is very important for making the technology operationally effective; unfortunately, access was not available during the DS1 primary mission.

3.3.4 Automation of Tone Detection—Tone-detection automation is proceeding as an activity in support of DS1 Extended Mission and was not an objective of the as-launched system. Tone-detection automation was an objective prior to the TMOD redirection wherein BMOX antenna support was changed from DSS 26 (which supported automated demand-access antenna operations) to DSS 13. Full automation involves automatic-predicts generation, automatically running scripts to perform tone acquisition, detection, and automatic tone-message reporting. Tone-message reporting can, in fact, be quite elaborate, where the autonomous-reporting system expects confirmation from users that tones were received. If not, a fully automatic reporting system would have a roster of the team members and would keep contacting people until the tone message was acknowledged. The lessons learned from conducting tone-detection operations during the mission is that tone acquisition is highly amenable to automation and would substantially lower the cost of performing Beacon operations. Automatic-predicts generation would also serve other users of DSS 13 and would support broader DSS 13 automation objectives.

3.3.5 Cost Savings from Using Beacon—Part of future work in Beacon technology involves infusing the Beacon technology into DS1 mission operations as an end-to-end system. Technology infusion is not an easy task and traditionally has not been done well. DS1 will benefit from this work by reducing the amount of tracking time used.

In extended mission, DS1 will have two tracking passes per week, an 8-hour, high-gain pass on Mondays, and a 4-hour mid-week pass to check spacecraft status. Utilizing Beacon, the DS1 project will not have to use a 4-hour mid-week DSN pass to check spacecraft status. It can use a 30-minute (or less) Beacon pass that actually provides them with additional information over a carrier-only pass. In addition, the frequency of eight-hour telemetry passes can be reduced and 30-minute Beacon passes substituted. The number of 8-hour telemetry passes that can be eliminated has not been determined, but DS1 expects it could be as many as every other pass. In this case, there would only be two eight-hour telemetry passes each month and four 30-minute Beacon passes each month. The overall savings for this case are summarized in Table 7. This results in savings of 30 hours of DSN tracking time or $18,248 per four-week period. This does not include the substantial savings of mission-engineering-labor costs of performing routine telemetry analysis.

The benefits of infusing a regular Beacon operation technology on DS1 are apparent in the cost savings of reduced-DSN utilization. In addition, the four-hour mid-week passes are replaced with 30-minute Beacon passes that contain additional status information. Future missions will benefit from the experience of a flight mission using a regular Beacon tone for an extended period of time. This includes the experience of scheduling the DSN for Beacon operations as well as the success of the Beacon tone system in relaying the spacecraft status to the ground. New missions that could benefit from this technology include ST-4, Pluto Express, Europa Orbiter, and MDS. Each of these missions is planning on using either part or all of the Beacon operations technology. The continuation of work on the Beacon technology by revising the operations concept will add value to these mission customers. In addition, the operations procedures for using the Beacon technology can be fully developed.

Demand-access scheduling of DSN antennas is another important feature of an operational Beacon system. Scheduling antennas based on demand rather than a pre-negotiated agreement is important to the success of this technology within the DSN. During the DS1 extended mission, there is no funding to demonstrate automated scheduling of antenna resources. If a Beacon tone is received that requires contacting the DS1 spacecraft, it will be necessary to manually request a station pass. Until the DSN changes their scheduling paradigm, it will be difficult to implement demand-access scheduling.

3.4 Lessons Learned

3.4.1 Ion Propulsion Missions—The utilization of the ion propulsion system (IPS) (also called solar-electric propulsion) on DS1 offers an additional advantage in using Beacon monitoring. The IPS provides continuous thrust for much of the cruise phase. The operational margin for IPS thrusting represents the duration for which IPS could be off and still allow the spacecraft to reach the target asteroid. Due to the low thrust associated with IPS and because actual thrusting did not start until several weeks after launch, the operational margin is only a few weeks. Telemetry-downlink passes are becoming less frequent as the DS1 mission progresses. Eventually, there will only be one telemetry pass per week. If the spacecraft experiences a problem that requires the standby mode, the IPS engine will be shut down. It could be up to one week before the flight team has visibility to that standby mode. Using the Beacon-tone system during the periods between scheduled-telemetry downlinks can be a cost-effective way to decrease mission risk because it reduces the likelihood of losing thrusting time and not making the intended target. Other future IPS missions have taken note of this fact and requested Beacon-tone services to lower their mission risk.

3.4.2 Software Testing—It was decided to redesign the DS1 flight software about 18 months before launch. This decision greatly compacted an already full schedule to complete the software. As a result, the testing of all non-essential software functions was delayed until after launch. The Beacon experiment was considered a non-essential piece of software and, therefore, was only tested pre-launch

Table 7. Tracking Cost Per Month (34m BWG, 2 contacts per week)

	Monthly cost: DS1 Operations without Beacon	Monthly Cost: DS1 Operations with Beacon	Monthly Savings
8-hour telemetry passes	$19,465	$9,733	
4-hour carrier only passes	$9,733	not applicable	
Beacon tone passes	not applicable	$1,217	
Total	$29,198	$10,950	$18,248

* assuming reduction of two 8-hour telemetry passes per month

for non-interference with the other flight software. In post-launch testing, a few problems were discovered that prevented the Beacon software from starting until a new version could be uploaded. These problems related to differences between the flight-hardware based testbed and a simulated-hardware testbed. This is the age-old lesson learned by performing system testing on the software prior to use. But even beyond that, it is important to run tests on the actual hardware-based testbed. Unfortunately, the DS1 schedule would not allow this until post launch.

3.4.2 Fault Protection Integration—Before the software redesign, the Beacon software was tightly integrated with the DS1 fault-protection software. The decision was made after the redesign to de-couple the two pieces of software. Previously, the fault-protection monitors triggered the Beacon tones. After the redesign, the mapping of faults to tones was performed using two different methods. All spacecraft standby modes are now mapped to the urgent Beacon tone. The interesting and important Beacon tones are mapped using Beacon software-determined limits. De-coupling the fault protection software from the Beacon software gives this organization maximum flexibility to determine what sensors to monitor. Unfortunately, our algorithms for determining faults are not nearly as sophisticated as the fault-protection monitors. These monitors can look at many different values based on conditional logic before determining what fault has occurred. Future spacecraft designed to use Beacon operations should plan on completely integrating the Beacon tone software with the fault-protection software.

3.4.4 Beacon Signal Frequency Stability—The signals used for Beacon monitor are characterized by three things: (1) the signal strength can be extremely low, (2) the initial tone frequencies, which are derived from an onboard auxiliary oscillator, are not known exactly, and (3) the tone frequencies are constantly drifting. The tone detector is designed to detect these types of signals with a high level of confidence. The maximum-frequency uncertainty and the maximum-frequency drift rate for the tone detector were established using a Galileo spare transponder. An operational issue was encountered with the DS1 Beacon experiment: How and to what extent can the auxiliary oscillator's temperature be stabilized before the start of a Beacon pass? Stabilizing the temperature will reduce the frequency uncertainty and frequency drift, making it easier for the tone detector to detect the Beacon signal. Based on data provided by the DS1 telecom personnel, the auxiliary oscillator temperature can undergo a wide range of changes after an OPNAV maneuver. This results in a very large frequency uncertainty and a very high rate of change (>6 Hz/sec), both of which would exceed the limits of the tone detector (when the signal level is low).

One solution to the OPNAV-related problem is to wait for the transponder temperature to stabilize. Studies by the DS1 telecom personnel indicated that about four hours are needed for the transponder temperature to stabilize after running the OPNAV activity. This operational constraint would not have much impact on the spacecraft and is believed to be the simplest, lowest-cost solution to this problem. This procedure is recommended to improve weak-signal detection for DS1 and future missions using Beacon Monitor.

During the DS1 tone experiments, the initial frequency uncertainty was much larger than expected. A bias was manually introduced to keep the received signal in the recorded band. Without the bias, the frequency might be outside the recorded band. In an automated detection mode, it is necessary to record at least 3 times the current bandwidth, unless a better way to predict the frequency can be found. One possibility is to make use of the auxiliary-oscillator frequency vs. temperature-calibration table to improve frequency prediction.

3.4.5 Downlink Carrier Phase Noise—Post analyses of the received-signal frequency indicated that the phase noise of the downlink carrier was fairly significant. This would result in detection loss. Analyses should be performed to estimate the impact of this phase noise on detector performance and to factor this into future detection experiments.

3.4.6 Spacecraft Clock Accuracy—During one of the experiments, it was observed that the actual tone switching times did not seem to agree exactly with the predicted switching times. This led to the discovery by the DS1 team that there was an error of 18 to 19 seconds in the SCLK/SCET conversion.

3.4.7 DSN Equipment Issues—A couple of tone passes were not successful due to DSS 13 weather and equipment. In one experiment, the spacecraft started transmitting tones before it rose above the horizon of DSS 13. In another case, a scheduled pass was cancelled due to spacecraft activities. While the overall tone experiments have been very successful, future experiment plans should allow for this kind of contingency.

3.4.8 Beacon Operations Paradigm—The Beacon software makes determinations of spacecraft anomalies. The data summarization component of Beacon attempts to summarize related data from these anomalies. These determinations are based upon high and low limits on sensor data. It is important to involve the spacecraft subsystem engineers in the determination of which data to monitor and the setting of the limits on these data. They are the personnel most familiar with the operational characteristics of each subsystem and, therefore, should be determining interesting and fault conditions for their subsystem. Also, by involving them in the data summarization definition, they will become better acquainted with the Beacon software and will be more inclined to use it during crisis situations.

Ground-alarm limits on telemetry are generally set using the worse possible state of each data channel. This practice can hide problems with the spacecraft if the alarm limits are set at wide boundaries. Beacon data summarization offers context-sensitive limits. In the case of DS1, limits can be set for cruise, downlink, IPS thrusting, maneuver, and standby modes. Spacecraft operations personnel are not accustomed to working with summarized-engineering telemetry or context-sensitive limits. When data limits were requested, generally one set of limits was received with instructions to apply them to all mission activities. Setting limits like this does not utilize the capabilities of the Beacon data summarization. For future implementations of Beacon, it will be important to educate the flight team about Beacon's capabilities early in mission design. Beacon data summarization should also be used during spacecraft testing to familiarize operators with the technology. This will help ensure reliance on Beacon data during the mission.

3.4.9 Systems Engineering—As previously mentioned, there were problems with false-episode alarms due to mission activities such as Optical Navigations, camera calibrations, etc. It is important to carefully define each of the mission activities and how they are related to engineering data. In the DS1 case, the maneuver activity was defined to only occur when the thrusters were firing. Since maneuvers also involved turning the spacecraft, it was important to include all events that turned the spacecraft in our maneuver-mission-activity criteria. Once mission activities are carefully defined, then episode limits for those activities can be developed.

4.0 TECHNOLOGY APPLICATION FOR FUTURE MISSIONS

There are essentially three paths to future work in this area. One is continuing to follow the technology-development roadmap for AI-based onboard-summarization methods. In the coming year, this involves also investigating the notion of summarizing spacecraft data in order to create a comprehensive onboard archive in addition to downlinking summary telemetry. Missions to Europa and Pluto only plan to downlink about 5% of the total volume of engineering data. The summarization algorithms developed for DS1 form a good foundation for investigating how to intelligently capture the most important data in order to maintain an adaptive long-duration onboard archive. This archive may serve as an input to other onboard-autonomy software or it may just be available for downlink if ground personnel require additional insights into past-spacecraft activity. In addition to pursuing this archiving concept, there are many, many new automated data-analysis methods to investigate for use in onboard summarization systems. This will also be researched in the coming year.

The second thrust has to do with future mission deployments. After the DS1 Extended Mission, the next mission customer is the Europa Mission. Europa is the first mission funded by the JPL Outer Planets/Solar Probe program and currently has a planned launch in 2003. New versions of flight software for summarization and tone selection will be developed in the coming year and will be compatible with the JPL Mission Data System architecture. This architecture is currently baselined for the Europa mission. MDS-compliant software prototypes that build on lessons learned from the DS1 experiment will be delivered to the Europa mission in November, 2000. More generally, the technology is useful to a broad range of deep-space missions. In this era of faster, better, cheaper, there are many advantages to using this type of operations approach instead of more traditional operations. Earth-orbiter missions have different requirements, but can benefit from having Beacon-based adaptive operations. The Beacon-monitor team has long standing ties to Stanford University, Santa Clara University, and the University of Colorado, all of which are developing Beacon-based operations concepts and systems for Earth-orbiting missions.

There is another proposed Beacon concept for an Earth-trailing spacecraft (SIRTF) that involves using one tone. SIRTF plans to track every 12 hours, but would like to have Beacon tracking every 2 hours. The idea is that the spacecraft would only send a Beacon tone if it had a problem. The possible Beacon detections are 1) help tone or 2) no detection. Normally, the spacecraft would be busy doing observations; however, if it had a problem it would turn to Earth point and start transmitting a carrier signal. This Beacon signal could shorten the anomaly response time from 12 hours to a maximum of 2 hours. This requires no modification to the already-designed spacecraft since there is no need to distinguish fine levels of urgency. SIRTF management considers this important because their design does not include a transponder that supports Beacon tones. There is one drawback with this operation. When the tone detector fails to detect a Beacon signal, one can not tell whether (1) the spacecraft is fine and no Beacon has been transmitted or (2) the spacecraft has an anomaly and fails to transmit.

The third thrust involves development of the ground-system infrastructure for conducting Beacon operations. The NASA Space Operations Management Office (SOMO) and the JPL Telecommunications and Mission Operations Directorate have high-level objectives to support Beacon monitoring on future missions. The exact scope and implementation of this multi-mission support has not yet been worked. In the meantime, tone detection for the DS1 Extended Mission is being supported through special arrangements with the experimental DSS 13 ground station. A more generic tone detection system needs to be implemented if the DSN antennas will support Beacon-monitor missions. In addition, the full benefit of adaptive operations requires demand-based scheduling of DSN antennas. This is also a high-level objective for the DSN.

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Appendix A. List of Telemetry Channels and Names

Channel #	Description	
A-0259	ACS_TELEM_ALLOCATED_ENTRY_59	x
A-0534	ACS_TELEM_ALLOCATED_ENTRY_363	x
A-0563	ACS_TELEM_ALLOCATED_ENTRY_117	x
A-0762	ACS_TELEM_ALLOCATED_ENTRY_149	x
A-1619	ACS_TELEM_ALLOCATED_ENTRY_182	x
A-1621	ACS_TELEM_ALLOCATED_ENTRY_184	x
A-1622	ACS_TELEM_ALLOCATED_ENTRY_188	x
B-2014	FSC_IPCU_VME_N15_SUP_VOLT_MEAS	x
B-2040	FSC_BTF_SOFTWARE_VERSION_MEAS	x
B-4001	FSC_RAD6000_TEMP_MEAS	x
B-4004	FSC_UDL_OSC_TEMP_MEAS	x
D-0900	DWN_PRYOR_STATE_0	
F-0692	FPR_SYMPTOM_SUMMARY1	
F-1098	MON_ACS_INFO_EHA_MDC_STATE	x
G-4001	FSC_PEPE_TEMP1_MEAS	x
G-4002	FSC_PEPE_TEMP2_MEAS	x
G-4003	FSC_PEPE_CALORIMETER_TEMP_MEAS	x
I-4002	FSC_MICAS_OPT_BENCH_NXNZ_TEMP_MEAS	x
I-4003	FSC_MICAS_OPT_BENCH_PYNZ_TEMP_MEAS	x
I-4004	FSC_MICAS_M1_MIRROR_TEMP_MEAS	x
I-4006	FSC_MICAS_OPT_BENCH_CUBE_TEMP_MEAS	x
I-4007	FSC_MICAS_IR_DET_TEMP_MEAS	x
I-4008	FSC_MICAS_UV_DET_TEMP_MEAS	x
I-4010	FSC_MICAS_COVER_MECH_TEMP1_MEAS	x
N-0141	NAV_EHA_WHICH_MACHINE_RUNNING	x
O-4001	FSC_UPPER_BUS_TEMP1_MEAS	x
O-4002	FSC_UPPER_BUS_TEMP2_MEAS	x
P-0020	FSC_BATTERY_1_SOC	x
P-0022	FSC_BATTERY_2_SOC	x
P-2002	FSC_BATTERY_VT_MODE_MEAS	x
P-2010	FSC_BATTERY_MID_VOLT_1_MEAS	x
P-2011	FSC_BATTERY1_CURRENT_MEAS	x
P-2020	FSC_BATTERY_MID_VOLT_2_MEAS	x
P-2021	FSC_BATTERY2_CURRENT_MEAS	x
P-2030	FSC_SCARLET_VOLT_MEAS	x
P-2031	FSC_SCARLET_VAL_MOD_CUR_1_MEAS	x
P-2032	FSC_SCARLET_VAL_MOD_VOLT_1_MEAS	x
P-2040	FSC_SCARLET_WING1_CUR_MEAS	x
P-2050	FSC_SCARLET_WING2_CUR_MEAS	x
P-2060	FSC_PDU_ESS_BUS_CUR_MEAS	x
P-2061	FSC_PDU_ESS_BUS_VOL_MEAS	x
P-2062	FSC_PDU_NEB1_CUR_MEAS	x
P-2063	FSC_PDU_NEB1S_CUR_MEAS	x
P-2064	FSC_PDU_NEB2_CUR_MEAS	x
P-2065	FSC_PDU_NEB3_CUR_MEAS	x
P-2070	FSC_PDU_RELAY_FET_STATUS_WORD0_MEAS	x
P-2071	FSC_PDU_RELAY_FET_STATUS_WORD1_MEAS	x
P-2072	FSC_PDU_RELAY_FET_STATUS_WORD2_MEAS	x
P-4011	FSC_BATTERY_TEMP1_MEAS	x
P-4021	FSC_BATTERY_TEMP2_MEAS	x

Channel #	Description	
P-4022	FSC_BATTERY_CHARGE_TEMP_MEAS	x
P-4041	FSC_SCARLET_WING1_VAL_TEMP1_MEAS	x
P-4042	FSC_SCARLET_WING1_VAL_TEMP2_MEAS	x
P-4043	FSC_SCARLET_WING1_VAL_TEMP3_MEAS	x
P-4044	FSC_SCARLET_WING1_VAL_TEMP4_MEAS	x
P-4045	FSC_SCARLET_WING1_VAL_TEMP5_MEAS	x
P-4046	FSC_SCARLET_WING1_VAL_TEMP6_MEAS	x
P-4047	FSC_SCARLET_WING1_VAL_TEMP7_MEAS	x
P-4048	FSC_SCARLET_WING1_VAL_TEMP8_MEAS	x
P-4051	FSC_SCARLET_WING2_VAL_TEMP1_MEAS	x
P-4052	FSC_SCARLET_WING2_VAL_TEMP5_MEAS	x
T-0001	FSC_SDST_XPDR_STATE_MEAS	x
T-0014	FSC_SDST_X_PWR_MEAS	x
T-0024	FSC_SDST_EXCITER_SPE_MEAS	x
T-2015	FSC_PDU_SDST_CUR_MEAS	x
T-2016	FSC_PDU_KASSPA_CUR_MEAS	x
T-2017	FSC_PDU_XSSPA_CUR_MEAS	x
T-4002	FSC_XSSPA_TEMP_MEAS	x
V-2005	ACS_N2H4_TANK_PRSS_MEAS	x
V-4001	FSC_PROP_MOD_TEMP1_MEAS	x
V-4002	FSC_PROP_MOD_TEMP2_MEAS	x
V-4003	ACS_N2H4_TANK_TEMP1_MEAS	x
V-4011	ACS_RCS_CLUSTER1_TEMP_MEAS	x
V-4012	ACS_RCS_CLUSTER1_CAT_TEMP_MEAS	x
V-4021	ACS_RCS_CLUSTER2_TEMP_MEAS	x
V-4022	ACS_RCS_CLUSTER2_CAT_TEMP_MEAS	x

Appendix B. DS1 Technology Validation Power On/Off Times

Date	Experiment Type
Jan. 6, 1999	X-tone, 20, 30, 25, & 35 kHz
Feb. 4, 1999	X-tone, 35 & 20 kHz
Feb. 19, 1999	Data Summarization turned on
Feb. 26, 1999	B-tone & X-tone
Mar. 3, 1999	X-tone, 35 & 20 kHz
Mar. 8, 1999	Data Summarization turned on
Mar. 18, 1999	X-tone, 30, 20, 25, & 35 kHz
Mar. 22, 1999	Data Summarization turned on
Mar. 24, 1999	X-tone
Apr. 7, 1999	X-tone, 20, 25, 30, & 30 kHz
Apr. 13, 1999	B-transmit & X-tone, 20, 25, 30, & 35 kHz
Apr. 19, 1999	Ka-tone
Apr. 20, 1999	B-transmit
Apr. 26, 1999	Ka-tone, 20, 25, 30, & 35kHz
Apr. 27, 1999	B-transmit
June 1999 - May 2000	During this period, beacon tone passes were done just about every week and data summarization was left on continuously.