

# **Flight Software Implementation of the Beacon Monitor Experiment On the NASA New Millennium Deep Space 1 (DS-1) Mission**

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## **ABSTRACT**

A new technology that can lower the cost of mission operations on future spacecraft will be tested on the NASA New Millennium Deep Space 1 (DS-1) Mission. This technology, the Beacon Monitor Experiment (BMOX), can be used to reduce the Deep Space Network (DSN) tracking time and its associated costs on future missions. With BMOX, overall spacecraft health is translated into one of four states. Each of these states is represented by a tone, indicating how urgent it is to track the spacecraft for telemetry. These tones will provide assurances to the ground team that the spacecraft is functioning as expected. For Beacon monitor operations to be viable, it is necessary to provide ground operators with concise summaries of on-board events since the last contact. Without these summaries, ground personnel would have to analyze several days of recorded engineering data to understand the events leading to the anomaly. The BMOX data summarization includes a summary of spacecraft anomalies, which are triggered by minimum and maximum limits. These limits and their related data are either pre-defined in a table or defined using envelope functions for more precise selection of the anomaly data. This paper describes the implementation approach of the Beacon monitor experiment on the DS-1 spacecraft, both with and without the Remote Agent autonomous software. The discussion includes an overall description of the Beacon monitor concept, the trade-offs with adapting that concept as a technology experiment, the current state of the resulting implementation on DS-1, and a description of the validation objectives for the experiment.

## **INTRODUCTION**

### **Beacon Technology**

The end of the Cold War and the increasing U.S. budget deficit has put pressure on NASA to accomplish more with less money. In the past five years, NASA has been moving towards faster, better, and cheaper missions. Dan Goldin, the NASA administrator, has asked NASA employees for new mission operation concepts and new ways of doing business. The Beacon Monitor Experiment (BMOX) is a new technology that can reduce the mission operations cost for deep space missions.

BMOX is a technology experiment involving a spacecraft, a mission-specific ground system, and a set of Earth-based ground stations. In past deep space missions, routine spacecraft health data was relayed to Earth daily via the DSN. Frequent contacts with a spacecraft are costly because they require human interaction and tie up valuable DSN resources that then cannot be used by other missions. On the other hand, it is important for ground personnel to get spacecraft information frequently so they can react appropriately. Unfortunately, the DSN personnel are predicting they will not be able to support all currently planned missions with their existing resources. BMOX addresses this problem by changing the way the DSN and mission operations systems operate and interact.

Using the BMOX technology concept, routine spacecraft health data is evaluated on-board the spacecraft. This evaluation results in a simple spacecraft state indication, either Nominal, Interesting, Important, or Urgent, which can be sent to Earth daily. Each state is represented by a tone, indicating the level of urgency for contacting the spacecraft for a full health status report. Relatively small (4-12m) aperture ground stations can receive the state tones because of their low bandwidth.

Using BMOX tone monitoring instead of traditional routine ground contacts means detailed spacecraft performance history is unavailable to ground personnel. BMOX includes a data summarization component providing this past data in a concise format. Three different types of summarized data are used: overall performance summary, user-defined performance summary, and anomaly summary. The performance summaries are generated at regular intervals and stored in memory until the next telemetry ground contact. They are computed by applying standard functions, such as minimum, maximum, mean, first derivative, and second derivative, to the data. The summarized data are chosen so the spacecraft state can quickly be determined. User-defined summary data are used for obtaining detailed insight into a particular subsystem and are output at the user's discretion. Anomaly summary data are created when the raw and summarized data violate pre-defined high and low limits. These limits are determined by the subsystem specialist and stored in a table on-board the spacecraft. The limit tables are based on the current mission activity. Envelope functions are also used to define the limits based on spacecraft performance. BMOX uses the tone generation capability in conjunction with data summarization to fulfill the following five objectives:

- Reduce the frequency of telemetry ground contacts for routine status checks
- Reduce the amount of down-linked engineering data during each ground contact
- Reduce routine ground processing, monitoring, and analysis of telemetry data
- Schedule DSN antennas based on demand rather than pre-negotiated agreements
- Simplify operations procedures and provide quicker response to anomalies

## **DS-1 Implementation**

Deep Space 1 is the first in a series of advanced technology validation missions defined and implemented as an integrated program for NASA by the Jet Propulsion Laboratory. The main objective of the DS-1 mission is to space-validate a suite of advanced technologies that hold promise for future space science missions with low life-cycle mission cost. The mission profile for DS-1 includes flybys of a near-Earth asteroid, comet, and Mars.

DS-1 uses Solar Electric Propulsion (SEP) to drive the spacecraft to its three targets. SEP has a very low thrust level so it must be run almost continuously throughout the mission. In fact, with the exception of the telemetry contacts which off-point the spacecraft from a thrusting attitude, SEP must run for 50 of the first 52 weeks. This SEP continuous "on" requirement increases the importance of BMOX. If there is a problem that shuts down the SEP, it could be up to one week before the ground is contacted via the regularly scheduled telemetry telecommunication pass. This problem would have been handled by the on-board autonomous software Remote Agent (RA), which would have detected the problem, re-configured the spacecraft to solve the problem, and re-planned the mission using the new configuration. In March 1997, RA was taken out of the baseline mission plan and replaced with a more traditional mission operations system. This new operations system relies on the

ground to build the command sequences and send them to the spacecraft during the weekly telemetry contact. The new system stops the on-board command sequence whenever a major problem is encountered. The SEP system is shut down as well. With BMOX enabled, the SEP shutdown could be detected in less than a day. Without BMOX, the ground personnel must wait until the next scheduled telemetry contact to get a spacecraft status report.

Summarization is also important to a mission with weekly ground contacts. Many events can occur between ground contacts. The spacecraft has the capability to store telemetry during this time but if there is a problem, it could take days to sort through the data to find the cause. Summarization capability can help by giving ground personnel a concise history of spacecraft anomalies since the previous contact.

## **FLIGHT SOFTWARE OVERVIEW**

The Beacon Monitor Software (BMS) is part of the DS-1 flight software (FSW). We have implemented BMS as a VxWorks task to be run on the DS-1 flight processor. BMS receives inputs from the ground and from other FSW modules via the DS-1 Inter-Process Communication (IPC) services, and produces output via the same medium. Every internal table is implemented using a generic architecture that can be applied to future missions. BMS can be turned off, on, and reset with an IPC message. Normally, this message would be sent via a command from the ground or the on-board command sequence.

## **TONE SELECTION SOFTWARE**

A design philosophy of the DS-1 project is to separate BMOX from the other flight software as much as possible. This philosophy evolved because Beacon is an experiment that should not interfere with other spacecraft subsystems. Although this philosophy has posed some significant design challenges, it makes the software easier to test and easily adaptable to future spacecraft. The design challenges have primarily involved the interface between Beacon and the fault protection software. When the RA software was included in the design, a task called Mode Identification and Recovery (MIR) handled the fault protection duties. MIR would use information provided by the Smart Executive and monitors to determine the spacecraft state. MIR would pass the spacecraft state to the Beacon software, which in turn would map that state to a Beacon tone. After the RA was removed from the baseline plan, the fault protection design has been based on the Mars Pathfinder Spacecraft fault protection. We are currently designing the interface between the Beacon software and the new fault protection. We will describe our thoughts on the design later in this section.

The Beacon tone can be one of four different states: Nominal, Interesting, Important, and Urgent. Each state represents the urgency of communicating with the spacecraft for a status check. A fifth state in which no tone is received when one is expected is also possible. The tones are defined in Table 1. While the Beacon tone is enabled, the telecommunications system will continuously transmit a representation of the Beacon tone by modifying the sub-carrier frequency of the transponder. For a detailed description of the telecommunications system related to BMOX, see reference [1]. BMOX software will not allow the Beacon tone to be changed to a less urgent state unless a reset command is sent from the ground. This prevents the ground from missing a higher urgency tone should a lower urgency tone follow.

The current design of the Beacon software uses two methods to set the Beacon tone. Interesting and Important messages are generated when the episode identifier (EI) module of the Beacon software starts an episode. The EI module is described in detail later.

<b>TONE</b>	<b>DEFINITION</b>	<b>EXAMPLES</b>
<b>Nominal</b>	Spacecraft is nominal; all functions are performing as expected. No need to downlink engineering telemetry.	<ul style="list-style-type: none"> <li>• Spacecraft operating normally</li> </ul>
<b>Interesting</b>	An interesting and non-urgent event has occurred on the spacecraft. Establish communication with the ground when convenient to obtain data relating to the event.	<ul style="list-style-type: none"> <li>• Device reset to clear error caused by Single Event Upset</li> <li>• Other transient events that do not repeat</li> </ul>
<b>Important</b>	The spacecraft needs servicing. Communication with the ground must be achieved within a certain time or the spacecraft state could deteriorate and/or critical data could be lost.	<ul style="list-style-type: none"> <li>• Solid state memory near full</li> <li>• Non-critical hardware failure</li> </ul>
<b>Urgent</b>	Spacecraft emergency. A critical component of the spacecraft has failed. The spacecraft cannot autonomously recover and ground intervention is required immediately.	<ul style="list-style-type: none"> <li>• Spacecraft bus failure</li> <li>• Power Distribution Unit failure</li> <li>• Star Tracker failure</li> <li>• Ion Propulsion System gimbal stuck</li> </ul>
<b>- No Tone -</b>	No Beacon Tone was received by the ground station at the scheduled time.	<ul style="list-style-type: none"> <li>• Beacon software is not operating</li> <li>• Anomaly prohibited tone from being sent</li> <li>• Spacecraft destroyed by meteor</li> <li>• Ground system problem</li> </ul>

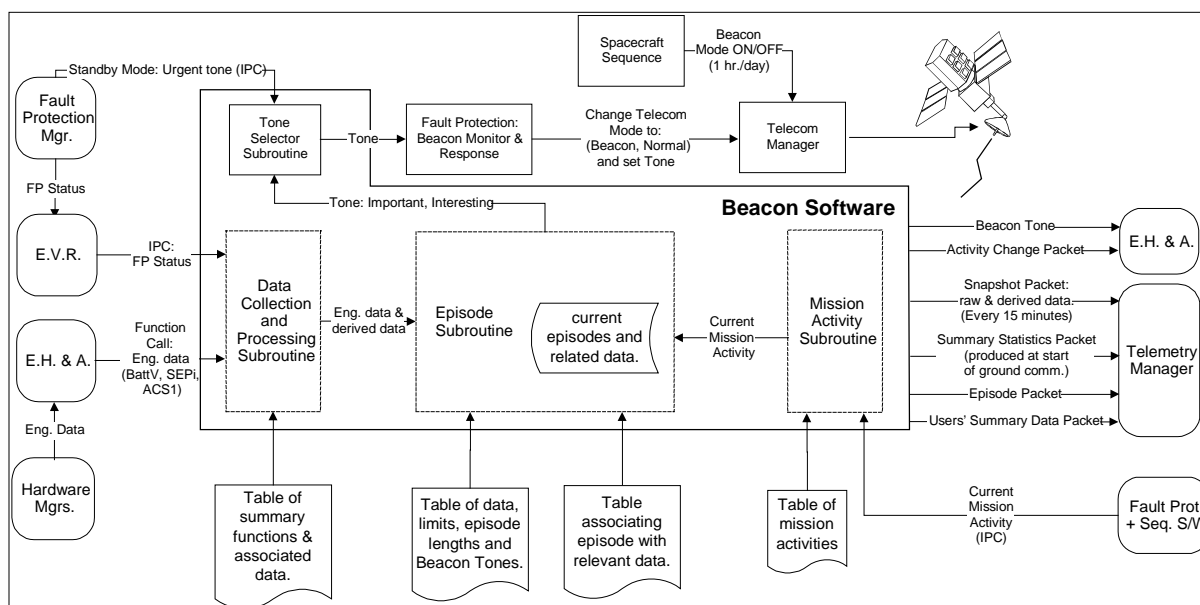
**Table 1 Beacon Tone Definitions**

Urgent Beacon tones are set by the spacecraft fault protection when standby mode is entered. This condition occurs when the fault protection encounters a fault that it cannot correct. Standby mode halts the current command sequence, including SEP thrusting. The operational margin for SEP thrusting at launch based on current mass and power estimates is two weeks (plus eight hours per week since launched.) This margin represents the duration for which SEP could be off and still allow the spacecraft to reach both the asteroid and the comet. During the second half of the primary mission, DS-1 only communicates with the ground once per week. A single standby mode could conceivably last several days. The project engineers are concerned that one or two standby modes could use up all the SEP operational margin. They have asked the BMOX team to investigate using the Beacon tones to notify the ground in case of standby mode.

Several scenarios have been investigated for operating the Beacon tone during the primary mission. All scenarios involve transmitting the Beacon tone at a prescheduled time regularly, i.e., 30 to 60 minutes per day. The Beacon tone is not operated continuously because DS-1 requires as much power as possible for SEP thrusting. One possible scenario is to transmit the urgent tone for the first 24 hours of standby mode and then switch to low rate

telemetry. This would ensure the Beacon tone was retrieved during the scheduled daily Beacon track. One problem with this scenario occurs if the 24 hours of Beacon tone broadcast coincides with the regular 8-hour weekly telemetry pass. In this situation, the ground would be expecting telemetry but would receive the Beacon tone.

Another possible scenario for detecting standby mode involves alternating the Beacon tone and telemetry during standby mode. The time each would be on would depend upon the time needed to acquire telemetry at the ground station. The most likely option serving the needs of the DS-1 project uses the Interesting and Important tones during the regularly scheduled Beacon contacts. The urgent tone would be replaced by standard spacecraft telemetry. In this case, the Beacon team would not detect a tone and eventually look for standard telemetry. This design gradually phases in BMOX while providing assurances to the project that telemetry can be received in an emergency. We plan to use this mode of operation after the asteroid encounter. The cruise to the comet encounter will be used to verify the operation of BMOX.



**Figure 1 Beacon Software Inputs and Outputs**

### Tone Selector Internal Operation

At start-up, and each time the tone selector software (Tonesel) transitions from the OFF state to the ON state, it publishes a current tone message and a telemetry packet reporting the current setting of the Beacon tone. The fault protection to Beacon interface receives this message and commands the telecommunications system to transmit the Beacon tone if tone generation is enabled. A flow diagram showing these interfaces is contained in Figure 1. When Tonesel is started for the first time or reset, a nominal tone message will be generated. When Tonesel receives an off message, it stops mapping faults to Beacon tones, but retains the current setting of the Beacon tone.

### Current Status

Tonesel was functionally complete for the original DS-1 flight software configuration. We will be modifying Tonesel to conform to the new fault protection software, the new inter-process communication services, the new timing services, and the new telemetry services.

## DATA SUMMARIZATION

The data summarization part of BMOX is vital to the Beacon operations concept. Without it, if an Urgent tone is received and the ground has not communicated with the spacecraft for several weeks, ground personnel would need to analyze vast quantities of past recorded data. This scenario assumes that the spacecraft has the capacity to store the data. Summarization gives the ground personnel a quick look at spacecraft activity since the previous ground contact. With summarized data, ground personnel will be able to identify the causes for the Beacon tone and take corrective action to avoid further problems.

### Summarization Internal Operation

The Summarization/Sampler Module (Sampler) begins in the OFF state, with all summarization values zeroed out. First, Sampler reads an initialization file containing definitions of each raw data item to be received, every summarization formulae to be applied, all data limits to be checked, and every user summary packet to be produced.

Telemetry Name	Description	Output Frequency
Activity	Documents the changes in mission activity as detected by Sampler.	One packet is produced each time the activity changes
Data Sample	Records a snapshot of every raw and summarized data channel collected by Sampler.	Regular interval, e.g., 15 minutes
Episode Summary	Records general data about an out-of-limits data condition, known as 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
Value Summary	Records summary data about a single data channel's behavior since the last downlink.	One for each channel out of limits since the last downlink
User Summary	A user-specified packet containing raw and/or summarized data previously specified by the user.	Duration specified by the user

**Table 2 Summarization Telemetry Packets**

Once the initialization file is read, Sampler waits for message input via function calls from the engineering telemetry module (EHA). Sampler also receives mission activity updates via an IPC message that it uses to determine which summary calculations and data limits to apply. All of the Sampler interfaces can be seen in Figure 1. The different telemetry packets published by Sampler are in Table 2.

### Episode Identification

An essential element of summarization processing is the "episode." An episode, for BMOX purposes, is a ten-minute period that begins five minutes before any monitored data channel goes out of limits. When an episode starts, the Interesting or Important tone message associated with the out of limits channel is sent to the tone selector module. Only one

episode can be in progress at a time; all data channels that go out of limits during that time are recorded as part of the episode. An episode is always ten minutes long, even if all channels return to within limits before the end of the episode, with one exception: If the mission activity changes during an episode, the episode is ended immediately. If any channel is still out of limits when the episode ends, another episode is begun. Termination of an episode produces an episode summary packet and episode channel packet(s). The summarization process is run once per second.

### **ELMER Limit Checking**

In an episode, the method of anomaly detection is limit checking, in which the current sensor value is compared against predetermined high and low "red-lines." Determining tight limits, which will be valid throughout an entire mission, is a difficult task. Thus, to avoid frequent false alarms, the red-lines are made imprecise, which could lead to missed alarms and missed opportunities for early anomaly detection.[2] Several alternatives to basic limit checking have been examined for addition to the DS-1 Summarization software.

One alternative to limit checking is discrepancy checking, which examines the difference between the actual sensor value and a predicted value determined through simulation. Because the simulation uses knowledge of the current spacecraft state in the prediction, the bounds will be much tighter than the red-lines, leading to significantly fewer missed alarms. However, due to inherent imprecisions in the simulation model, discrepancy checking would be overly precise, producing an unacceptable number of false alarms. [3]

This historical knowledge of the spacecraft can also be used to generate high and low envelopes of valid sensor values. The use of high and low bounds is similar to the red-lines used in limit checking, but instead of static constants, these generated envelopes are dynamic functional limits based on the current sensor and other factors, such as the values of other sensors and the spacecraft's operational mode. This is the approach that the ELMER (Envelope Learning and Monitoring via Error Regression) algorithm takes. [2]

Running ELMER with a single sensor as input will produce high and low red-lines which reflect the expected maximum and minimum values of the sensor. Further iterations of the algorithm, adding sensor dependencies and lag vectors, will incrementally tighten the envelopes. As a rule, ELMER rejects any bound causing alarms in nominal training data, therefore avoiding the problem of increased false alarms that occurs with tighter red-lines. Provided the historical data is representative of the sensor's nominal values, the envelopes will be loose enough to avoid false alarms (as red-lines are), but tight enough, due to the training, that fewer alarms will be missed and anomalies will be detected sooner (as in discrepancy checking). [2, 3]

For BMOX, ELMER will be used to generate the high and low envelopes that will be used to test whether an anomaly has occurred and the Beacon tone should change. ELMER is being tested on the ground with historical data from NASA's TOPEX mission.

### **Current Status**

With the exception of the adaptive calculation of data limits, Sampler was functionally complete for the original DS-1 flight software configuration. Adaptive limits will be added before final delivery of the software. In addition, under the original

configuration tone commanding was only done by Tonesel in response to health state messages received from the Remote Agent. Under the new configuration, Sampler is responsible for sending SET\_TONE commands to Tonesel. Sampler will be modified to do so, and also to conform to the new interprocess communication services, the new timing services, and the new telemetry services.

## **VALIDATION OBJECTIVES**

A series of experiments for BMOX are used to validate the Beacon technology. The five validation objectives for BMOX are:

- Engineering summary data generation and visualization
- Tone (state) selection
- Tone generation, transmission and detection
- Ground support including message handling and reporting, and DSN track scheduling
- Operations effectiveness assessments

The majority of these objectives can be achieved within the first three months of the mission. The overall goal is to demonstrate the end-to-end system of tone selection, detection, and scheduling the DSN for a demand access telemetry pass.

## **CONCLUSIONS**

The BMOX concept is a major paradigm shift from the standard mode of spacecraft operations. The Deep Space Network does not have the resources to support the numerous smaller missions planned for the years ahead. BMOX is an enabling technology for these better, faster, and cheaper deep space missions. Although the DS-1 mission has changed from an autonomous spacecraft to a more traditional system, the Beacon software has evolved to meet the needs of DS-1 and future missions.

## **ACKNOWLEDGMENTS**

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