r '

A New Approach in Spacecraft Monitoring

Miles K. Sue, E. J. Wyatt, Robert Kahn, Victor Vilnrotter,
Gabor Lanyi, and Ted Peng

Jet Propulsion Laboratory
California Institute of Technology

A-E-96-1 7

Abstract

The NASA Deep Space Network (DSN) is preparing to experiment with a new way of supporting highly autonomous missions. The spacecraft will have on-board intelligence to determine whether it is healthy and when ground contact is needed. It will transmit one of 4 monitoring messages to the ground instead of normal full engineering telemetry of the spacecraft health. These messages will be monitored by a ground station. Based on the urgency of the message, the DSN will schedule an antenna to receive telemetry. Deep space missions traditionally schedule ground antennas to receive engineering telemetry up to several times per week. This new approach can reduce the monitoring time to a few minutes per day and engineering telemetry once every several weeks. This approach will be demonstrated on the first Ne w Millennium Deep Space One (DS1) mission through the Beacon Monitor Experiment (BMOX), and is being considered for use on upcoming missions to Europa and Pluto and possibly other missions.

This paper describes the end-to-end system design, operational scenarios, performance of the ground monitor, and the DS 1 experiment.

1.0 Introduction

The first New Millennium Deep Space One (DS1) mission and Pluto Express are planning to demonstrate and use "Beacon Mode" for missions operations. " Beacon Mode" or "Beacon Monitor" is basically an Automated Spacecraft Monitoring System (ASMS). The idea is to make use of the autonomy technology on-board a spacecraft to allow the spacecraft to do self-monitoring and send reports to the ground using a very limited number of urgency-based messages. These messages will be monitored by a ground station and based on the urgency of these messages, the Deep Space Network (DSN) will schedule an antenna to receive telemetry.

This monitoring concept requires a higher degree of on-board intelligence than before. It also requires an automatic ground monitoring system to detect and decode the 4 state messages. Both are under development and will be demonstrated with the DS1 mission. The DSN is developing an experimental monitoring system and an operational strategy to support the experiment.

2.o System Description

A conceptual design is shown in Figure 1. The core elements include a spacecraft monitoring subsystem and a number of ground components, which include a monitor station, and a Multi-mission Coordination Computer (MMC). The monitoring system requires the support of Project Operations Teams and the Network Planning and Preparation (NPP), which is a part of NASA's DSN. The monitoring system can be integrated as a pari of a future Multi-Mission Operation Center.

The spacecraft monitoring subsystem includes necessary flight software and part of the telecom subsystem. It is responsible for analyzing the spacecraft engineering data to determine its health, reducing its health status to one of the four monitoring states, mapping the monitoring state into an appropriate monitoring signal, and transmitting the monitoring signal to the ground, In addition, the spacecraft is responsible for generating an engineering summary that will summarize the conditions of the spacecraft.

The monitoring station is to detect the monitoring signals using the schedule and predicts supplied by MMC, and sends the results to MMC. The MMC is responsible for the operations of the system. It is where the detected messages are interpreted based on rules established by the project. It maintains a monitoring schedule for all spacecraft. It makes pass requests for a 34m/70m antenna and notifies the project, when needed. It also initiates urgent responses when triggered by an urgent message. The NPP provides frequency and antenna pointing predicts to MMC, which in turn sends these predicts to the monitor station. In addition, NPP is responsible for scheduling 34m/70m antenna passes in response to requests by MMC, which in turn are triggered by the detected messages. During a spacecraft emergency, NPP will work directly with the Project Operations Team, bypassing the MMC.

The Project Operations Teams are responsible for defining the monitoring messages and the required responses, supplying necessary spacecraft data to NPP/MMC for scheduling and predicts generation. They are also responsible for responding to urgent messages. Finally, the monitoring system is completed with DSN 34m/70m antennas, which track the spacecraft and send the data to the Project Operation Teams per NPP schedule.

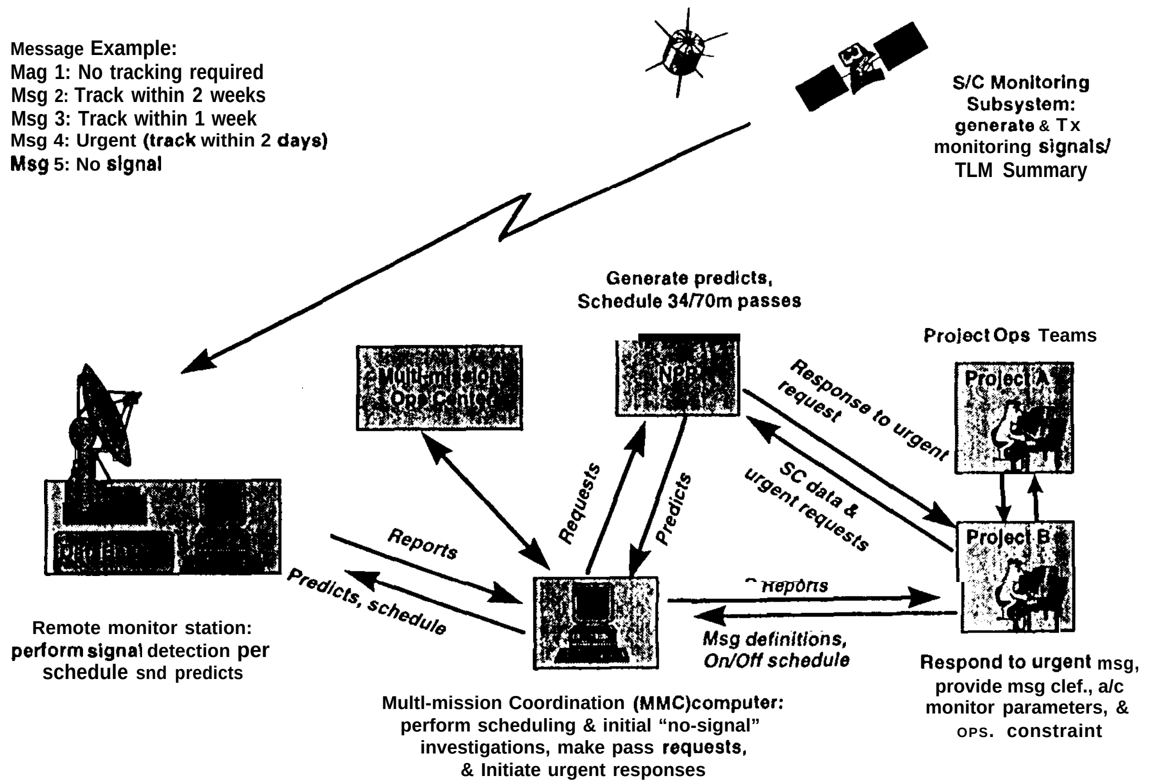


Figure 1. Monitoring System Conceptual Design

3.0 System Operations

The monitoring system as conceived can be used as a spacecraft health monitoring system as well as a system that will allow a spacecraft to make requests for 34m/70m DSN antenna tracks. It is intended for use during cruise and low activity mission phases. Once in operation, the monitoring mode can be terminated by a ground command, by on-board computer, or due to a spacecraft emergency. When a spacecraft emergency has been detected by on-board fault protection software, the spacecraft will automatically revert to standard emergency mode operations and transmit low rate telemetry to the ground.

When operating in the monitoring mode, each spacecraft will, when possible, transmit its monitoring signal continuously and at the same time maintain its ability to receive command from the ground. The ground station will monitor the spacecraft when it is most convenient. However, there may be spacecraft constraints (such as the need to conserve power) that do not allow the spacecraft to transmit the monitoring signal continuously. In this case, a pre-agreed communication window can be established for both monitoring and uplink command purposes. Each spacecraft will be monitored at most once per day, with an average of up to 1/2 hr. per monitor. The four urgency-based messages could have the following definitions:

GREEN:	I'm OK, no ground response needed.
RED:	I need help. Need a DSN (34m) pass within 2 days.
YELLOW:	Need a DSN pass within one week.
ORANGE:	Need a DSN pass within two weeks.

Each spacecraft will continuously broadcast one of the 4 messages, subject to mission-specific operational constraints. In order to allow sufficient time for the ground station to detect the transmitted message, spacecraft will not change messages more often than once per hour. However, when a RED state or a spacecraft emergency has been detected, the spacecraft will transmit the RED message or go into emergency mode immediately. The system can be customized to meet individual project needs and to accommodate specific operational constraints, including message definitions and their required response, length of communication windows, and performance requirements (e.g., probability of detection and false alarm rate, etc.).

When the spacecraft is healthy, it transmits a GREEN message either continuously or during a pre-arranged communication window. The monitor station monitors the spacecraft once a day and sends results to MMC. If the GREEN message is successfully and correctly detected, MMC simply archives the result and forwards it to the Project Operations Team. This operation will be repeated daily until there is a change of the monitor state (or the detected message). The system as currently conceived does not require an uplink acknowledgment. As such, the spacecraft will not know if its message has been received correctly by the ground. The spacecraft will transmit the same message day after day, until there is a change in the monitoring state or the monitoring state has been reset by an uplink command.

When the spacecraft needs a 34m antenna pass, it transmits a YELLOW, ORANGE, or RED message, depending on the urgency of the need. This message, after being detected by the ground monitor station, will trigger an appropriate response from the various ground elements as described in Appendix A.

4.0 Overview of the End-to-end System Design

The monitoring system is designed to support a large number of spacecraft. The major elements as previously stated include the spacecraft monitoring subsystem, monitor stations, MMC, Project Operations Teams, NPP, and DSN 34m/70m antennas.

The spacecraft monitoring subsystem is based on the Small Deep Space Transponder (SDST), currently being jointly developed by the Telecommunications and Mission Operations Directorate (TMOD) and flight projects. No modifications to the SDST are needed in order to support the monitoring function.

The monitor stations can be new stations each with a small antenna (8m), or the existing DSN 34m antennas each equipped with a signal detector, or a combination of large and small antennas. The signal detector can be a coherent BPSK receiver traditionally used for deep-space communications, or a non-coherent tone detector. The system discussed in the rest of this section assumes non-coherent detection of tones as a signaling and detection scheme. The tradeoff between this method and coherent BPSK is discussed later.

The MMC is simply a computer that can be implemented as part of DSN's NPP, as part of a future Multi-Mission Operations Center, or as a separate entity. The NPP and DSN 34m/70m antenna are existing equipment.

4.1 Flight Software System Design

The on-board beacon subsystem consists of both software and hardware. The main function of the software is to analyze engineering data, determine the health status of the spacecraft, and map the health states to one of the four monitor states. In addition, the software generates engineering summary for later transmission to the ground, Some of these functions requires dedicated software, and others can be fulfilled by the spacecraft autonomy software or by the normal fault protection flight software.

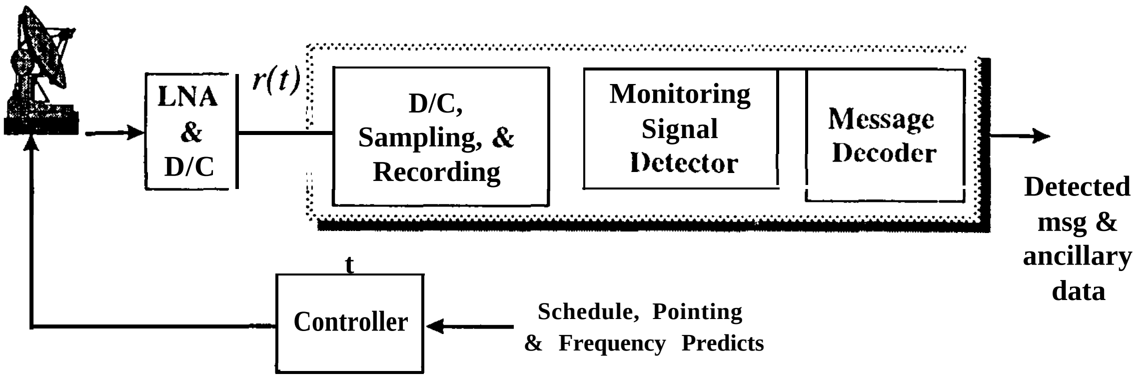
The goal of onboard data summarization is to provide operators with concise summaries of spacecraft health at times when tracking is required. Engineering data channels are adaptively prioritized and stored between track periods. When a downlink pass is initiated, data transfer to the ground proceeds in priority order. The design is easily scaleable to accommodate changes in downlink bandwidth throughout the mission timeline.

A significant element of data summarization from a research perspective is a technique for creating derived channels or "transforms" of engineering data channels. The current set of transforms includes computation of high, low, average as well as first and second derivative of selected channels. Another important element of onboard summarization involves replacing static alarm thresholds with adaptive alarm thresholds that are learned. Approximation functions create "behavior envelopes" that can be tighter than the traditional approach to anomaly detection. These function approximations are learned through training on nominal sensor data. In the Beacon Monitor Experiment (BMOX) on DS1, both approaches to episode identification will be demonstrated and comparisons will be drawn between them.

Monitor states (or monitor messages) are determined by on-board software based on fault protection health status messages. Each message is then relayed to the onboard executive (sequencing engine) via an interprocess communication system. The executive then commands the telecom subsystem to transmit an appropriate monitoring signal representing that monitor message.

4.2 Ground System Hardware

The ground monitor station is a fully automated station; its operation is driven solely by schedule and predicts. The received signal is first down-converted to IF, sampled, digitized, and recorded. The digitized signal is processed by the monitoring signal detector, which performs a non-coherent detection using Fast Fourier Transform (FFT). The detected signal is then decoded by the Message Decoder, and the decoded message is then disseminated to the mission operations team and other users. A block diagram of the ground monitoring station is shown in Figure 2.



*r(t)= received monitoring signal at **IF** frequency*

Figure 2. Monitor Station Block Diagram

4.3 Downlink Signal Characteristics

The monitoring system is designed to support future small, low-cost missions. It is highly desirable for the monitoring system to achieve a low detection threshold so that it can support distant spacecraft, or relax the spacecraft antenna pointing requirements. The goal is to reliably detect the monitoring messages with O dB-Hz total received signal-to-noise spectral density ratio (Pt/No) using 1000s observation time. These missions are assumed to carry a low-cost auxiliary oscillator as a frequency source, instead of a more expensive, ovenized, ultra-stable frequency oscillator (USO). The downlink frequency derived from an auxiliary oscillator is not precisely known due to frequency drift caused by on-borad temperature variations, aging and uncorrected Doppler frequency. In addition, the downlink frequency also exhibits short-term drift and phase noise. The frequency drift and phase noise affect the selection of signaling and detection schemes and complicate the design of the signal detector that must reliably detect the monitoring message with minimum signal level.

Figure 3 gives an example of the frequency drift and short-term random fluctuation of the downlink signal derived from an auxiliary oscillator on-board the spacecraft. The data was obtained from the Telecommunication Development Laboratory (TDL) using the Galileo (GLL) spare transponder. As indicated, the downlink signal exhibits both frequency drift and random fluctuation. The maximum observed drift rate is 0.05 Hz/s. The auxiliary oscillator for the SDST has similar phase noise specifications as the GLL's and similar frequency drift and frequency jitters are expected for the SDST.

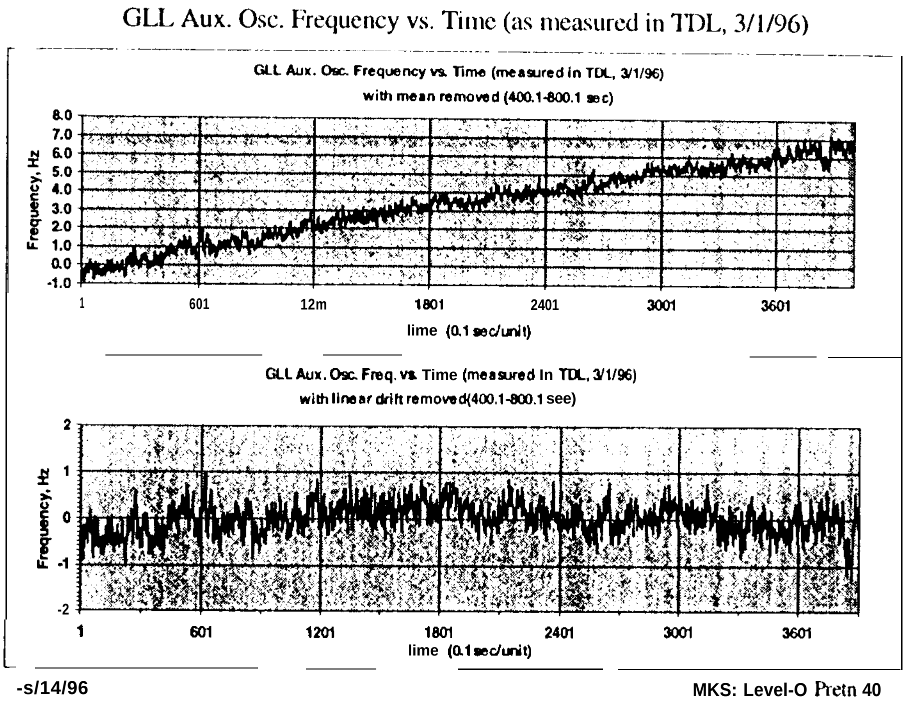


Figure 3. Galileo Auxiliary Oscillator Frequency vs. Time (as measured in TDL, 3/1/96)

4.4 Tone-based Signal Structure

The signal structure is shown in Figure 4. Each message is represented by a pair of tones centered about the carrier. These tones are generated by phased-modulating the RF carrier by a squarewave subcarrier using 90 degrees modulation angle. The carrier will be completely suppressed. The resulting downlink spectrum will consist of tones at odd multiples of the subcarrier frequency above and below the carrier. The higher harmonics will be ignored; only the tones at the fundamental frequency will be used to represent the transmitted message. Four pairs of tones will be needed to represent the four possible messages. While the SDST can generate a wide range of subcarrier frequency, the downlink signal stability and detector complexity together constrain the selection of subcarrier frequencies. For the DS1 experiment, the four subcarrier frequencies are 20, 25, 30, and 35 kHz.

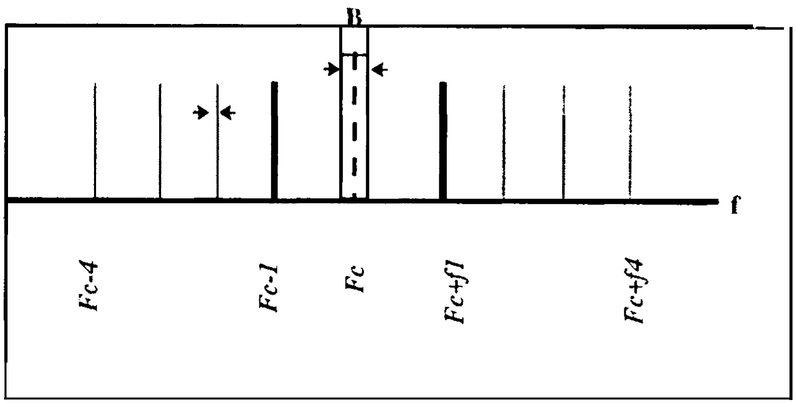


Figure 4. Signal Structure
B is the frequency uncertainty (2 kHz),
Fc is the carrier frequency, and
Fi is the subcarrier frequency for the i^{th} message.

4.5 Non-coherent Detection Receiver Structures

Two types of non-coherent detection receiver structures have been studied. One can be called "FFT with Incoherent Averaging and post-FFT De-drifting" while the other is called "Subband Squaring Receiver with Drift Matching".

The baseline signal detector contains four tone detectors, one for each message or channel. The tone detector is designed to compute the energy of all spectral pairs of a given spacing. To insure proper signal detection, the bandwidth of each tone detector must be sufficiently large to accommodate the frequency uncertainty and frequency drift of the downlink signal, i.e., the tones for **a given message will not drift outside the passband of the detector for that message. Fast** Fourier Transform (FFT) is employed for implementation efficiency, Because of the instability of the downlink frequency, Fourier transforms cannot be performed over long time intervals. The total observation time (e.g.,1 000s) is divided into a number of small intervals, say 1 s each. FFTs of 1-second duration will be performed on the incoming signal. For each FFT, the outputs of like-bins are incoherently combined to form a combined spectra. The like-bins for a give channel (or message) are a pair of bins having a frequency separation equal to the spacing of the pair of tones representing that message. In the absence of frequency drift, the combined spectra for different time intervals are incoherently added to give a set of outputs from which the maximum will be selected and compared against a pre-determined threshold to determine which message has been sent. The threshold is chosen to meet the false alarm probability requirement, which can vary from one mission to another.

In the presence of frequency drift, the signal may have drifted from one FFT bin to another between successive FFTs. Alignment or de-drifting before combining is therefore needed. This can be accomplished by using a drift model (such as linear, quadratic, or piece-wise linear) with a range of drift rates to "de-drift" the FFT outputs of different time intervals. The FFT outputs are combined after de-drifting. Based on simulation and experiments with actual spacecraft data, the loss due to de-drifting is estimated to be about 1dB for de-drifting over 100 FFTs of 1-see each (i.e., total observation time of 100 see).

A block diagram for the signal detector and the message decoder is shown in Figure 5. A detailed description of this detection scheme is given in [1].

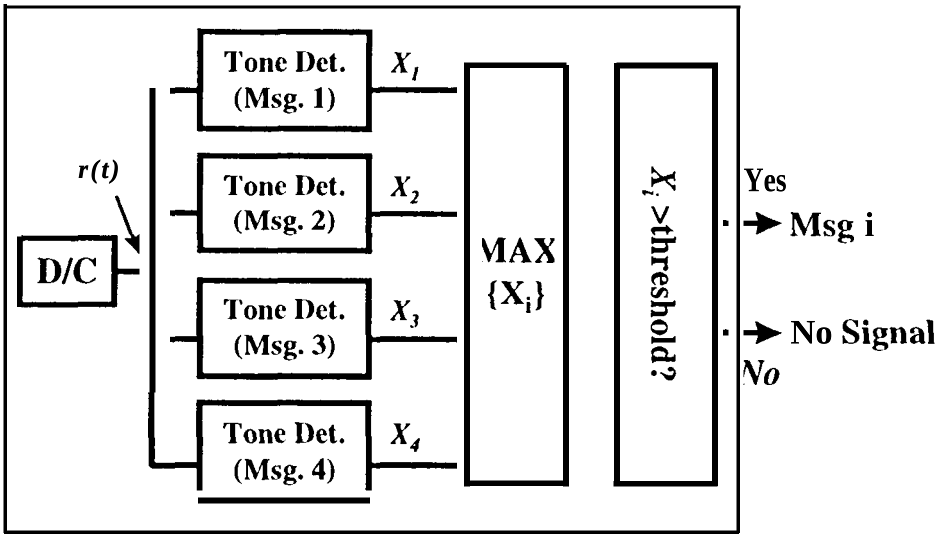


Figure 5. **Monitoring Signal** Detector and Message Decoder
r(t)= the received monitoring signal
D/C=down-converter

The subband squaring receiver is similar to the “FFT with Incoherent Averaging and Post-FFT De-Drifting” detector. The main difference is that the subband squaring receiver attempts to remove the frequency drift first before signal integration. The operation of this receiver can be summarized as follows: The received signal is channelized into 4 channels, one for each message. A detector will be assigned to each of these channels. Each channel is divided into k subbands. Each subband will be processed by a bank of “Subband Processors”. Each Subband Processor is drift-matched to a given drift rate. If there are j drift rates and k subbands, then jxk subband processors will be needed for each channel. The basic function of a Subband Processor is to compute the total energy of signal and noise components contained in that subband, after de-drifted with a given rate. Similar to the other detection algorithm, the maximum output will be selected and compared against a pre-determined threshold to determine which message has been sent. A detailed description of this detection scheme is given in [2].

5.0 Coherent vs. Non-coherent Detection Schemes (Coherent BPSK vs. Tones)

Coherent and non-coherent detection schemes have been studied for ASMS applications. In the presence of unknown frequency and unknown phase and for very low data rate application (e.g, to detect one of 4 possible messages with up to 1000s of detection time), non-coherent detection is better in terms of detection threshold. This is because that coherent detection requires estimation of the unknown parameters (frequency an phase). To obtain an accurate estimate, it would require an integration time equal to the signal detection time (1000 s), or equivalently it would require the phase-locked loop bandwidth be narrowed to 0.001 Hz. This is not possible due to the instability of the monitoring signal that is corrupted by frequency drift and phase noise of the on-board auxiliary oscillator from which the downlink signal frequency is derived.

Under a typical condition where the spacecraft phase stability is of the auxiliary oscillator grade, the frequency drift is roughly linear or quadratic, and the initial frequency uncertainty is within 2 KHz, non-coherent detection of orthogonal tone pairs would require about O dB-Hz of total received signal power to noise spectral density ratio (Pt/No). However, coherent detection of BPSK signal in the presence of similar auxiliary oscillator frequency instability would require a

carrier tracking loop bandwidth of about 2 Hz, and about 15 dB-Hz of Pt/No, which is 15 dB higher than non-coherent detection of tones.

Figure 6 shows the performance of coherent detection of BPSK signals and non-coherent detection of orthogonal tone pairs as a function of integration time (observation time), assuming auxiliary oscillator type of frequency stability. As indicated by the chart, coherent BPSK requires a higher Pt/No than the non-coherent scheme, by more than 10 dB for 100s or more integration time.

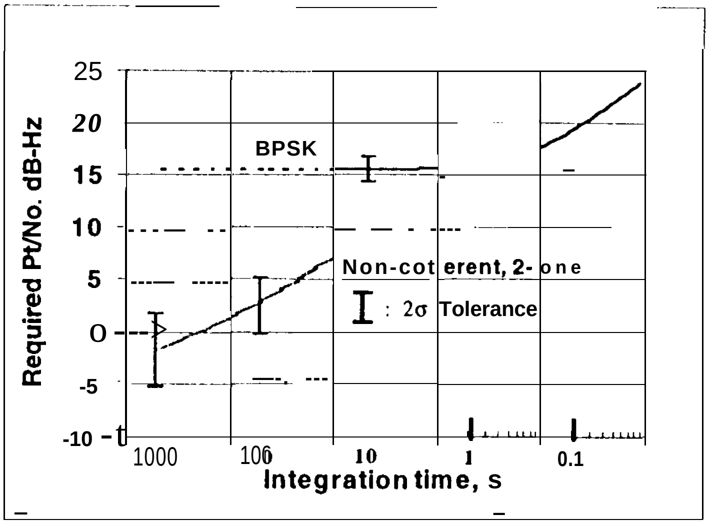


Figure 6. Required Pt/No vs. Integration Time

5.1 Monitor Station Implementation Approaches

While non-coherent detection of tones has performance advantage over the traditional coherent BPSK scheme, and stations with smaller antennas are less costly to operate than the 34m antennas, these advantages are counter balanced by the required initial capital investments. A cost analysis has been performed for three implementation approaches with different combinations of antennas and signal detectors as follows:

(A) Existing 34m antennas with existing coherent BPSK receivers.
(B) Existing 34m antennas with non-coherent tone detectors.
(C) New stations with small antennas (8m) and non-coherent tone detectors.

The detailed analysis is beyond the scope of this paper; but the study indicates that the selection of an implementation approach largely depends on, among other factors, the number of user spacecraft, number of years of operations, and the operating cost of the antennas.

6.0 Conclusion

A conceptual system design and operational strategy have been established for the new spacecraft monitoring concept. A non-coherent signaling and detection scheme capable of achieving very low detection threshold has been identified. The system design and operational strategy have provided a basis for the design of the DS1 BMOX experiment, which will begin shortly after launch of DS1 in July of 1998. Operational performance will be observed and evaluated for 9 months during the mission. Cost benefits will be assessed at the end of the experiment.

References:

(1) G. Lanyi and R. Kahn , “Tone Detection via Incoherent Averaging of Fourier Transforms to Support the Automated Spacecraft Monitoring Concept”, TDA Progress Report 42-129, January-March 1997, Jet Propulsion Laboratory, Pasadena, California, May 15, 1997

(2) M. Simon, V. Vilnrotter, A. Mileant and S. Hinedi, “Optimum Strategies for Monitoring the Operational Status of a Spacecraft,” TDA Progress Report 42-127.

Acknowledgment

The authors would like to acknowledge the technical contribution or programmatic support made by John Carraway, Chien Chen, Bruce Crow, Semi Hinedi, Peter Kinman, Neal Kuo, Richard Mathison, Mazen Shihabi, Marvin Simon, and Wallace Tai.

Appendix A. Sample Operation Scenarios

This appendix gives an example of the operation scenario, which is depicted in Figure A-1.

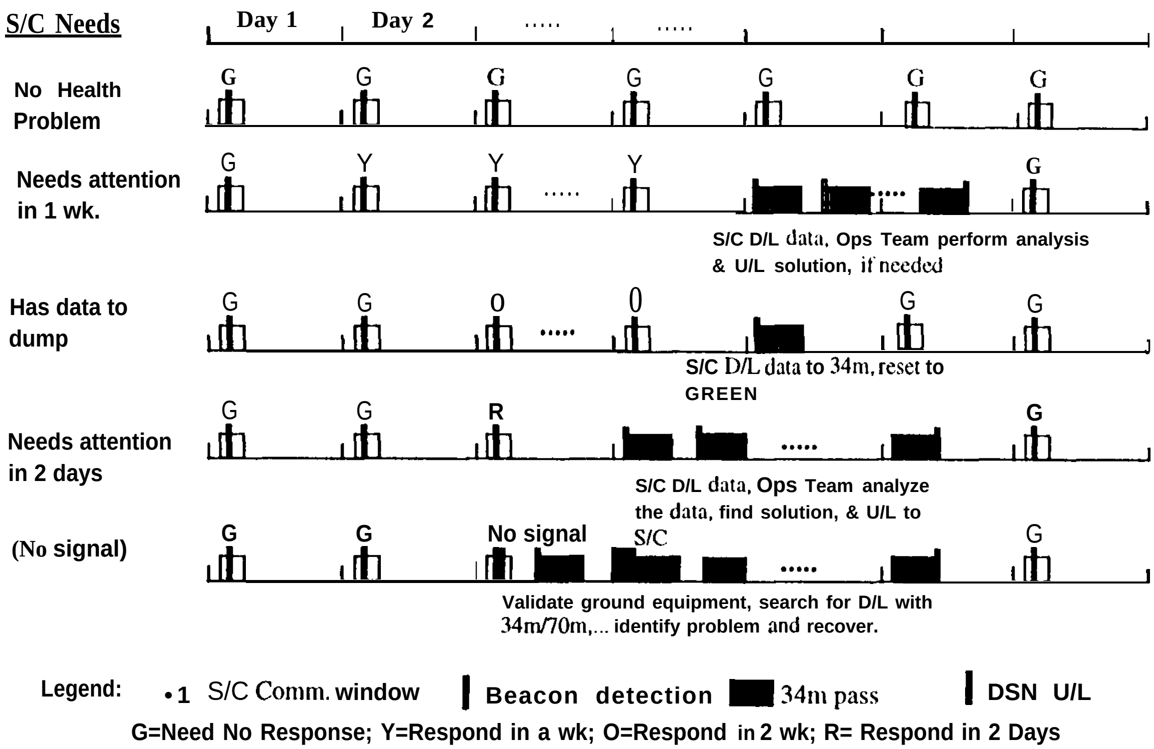


Figure A-1 Operation Scenarios

When the spacecraft needs a ground track, it transmits, say, a YELLOW message. After detecting the YELLOW message, the MMC will respond to this message according to the rules established by the project. The following is an example of possible actions after detecting a YELLOW message :

(1) MMC sends a request to DSN NPP/Scheduler for an 8-hour pass with a 34m antenna in 1 week.

(2) DSN Scheduler schedules a pass to be taken place, say, 5 days later overDSS-15 (assuming availability) and informs MMC and the project of the schedule.

(3) Spacecraft continues to transmit the same message (assuming no change of states during this period).

(4) Monitor station continues daily monitoring and reports results to MMC.

(5) MMC takes no further action except archiving the message and forwarding it to the project,

(6) On the 5th day,DSS-15 or another 34m station sends an command to the spacecraft one round-trip-light-time (RTLT) before the start of the scheduled downlink pass (or during a pre-determined communication window) to initiate the downlink pass.

(7) After receiving the uplink command, the spacecraft stops other on-going activities, if necessary, and starts to downlink as instructed.

(8) DSN receives and delivers the telemetry data to the project.

(9) The project analyzes the data and sends a command, via a 34m station, to the spacecraft to reset its state to GREEN.

This completes the space-ground exchange for a YELLOW message.

In the case of a RED message or “No Signal”, a spacecraft anomaly investigation will be conducted. The Project Operations Team will be in charge of such investigation after being notified by MMC.