A New Approach in Spacecraft Monitoring for Efficient Use of the Deep Space Network

M. K. Sue and T. Peng
Communications Systems and Research Section

E. J. Wyatt
Information and Computing Technologies Research Section

The Deep Space Network (DSN) is preparing to experiment with a new way of supporting highly autonomous missions. The spacecraft will use onboard intelligence to determine whether it is healthy and when ground contact is needed. It will transmit one of a very limited number of monitoring messages to the ground instead of 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 to once every several weeks. This approach will be demonstrated on the first New Millennium Deep Space One (DS1) mission through the Beacon Monitor Experiment; it is being considered for use on upcoming missions to Europa and Pluto and possibly other missions as well.

This article describes the experiment, end-to-end system design, operational scenarios, and cost benefits of implementation options using different signaling schemes and ground antennas.

I. 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," basically is an automated spacecraft-monitoring system. 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-indicating messages. Both DS1 and Pluto Express are planning to use four monitoring messages. The same will be assumed in this article. These messages will be monitored by a ground station and, based on the urgency of these messages, the DSN will schedule an antenna to receive telemetry.

Traditionally, deep-space missions schedule ground antennas to receive engineering telemetry several times per week. This new approach can reduce the monitoring time to a few minutes per day and engineering telemetry to once every several weeks, resulting in cost savings. Figure 1 shows the tracking time needed to downlink engineering data during cruise for existing and planned missions using the traditional health monitoring method.[1] Also shown is the time needed for Pluto Express, which plans to use the new monitoring approach. The reduction in 34-m antenna time translates directly into cost savings. The amount of savings depends on the hourly rate the project would have to pay for using the DSN antennas and associated equipment. Figure 2 shows the annual antenna cost as a function of antenna usage for a charge rate of $1200, $900, and $600 per hour.

II. System Overview

A conceptual design is shown in Fig. 3. The core elements include an onboard monitoring subsystem and a number of ground elements, which include an automated monitoring station and a multimission coordination computer (MMC). The monitoring system requires the support of project operations teams and the DSN network planning and preparation subsystem (NPP).

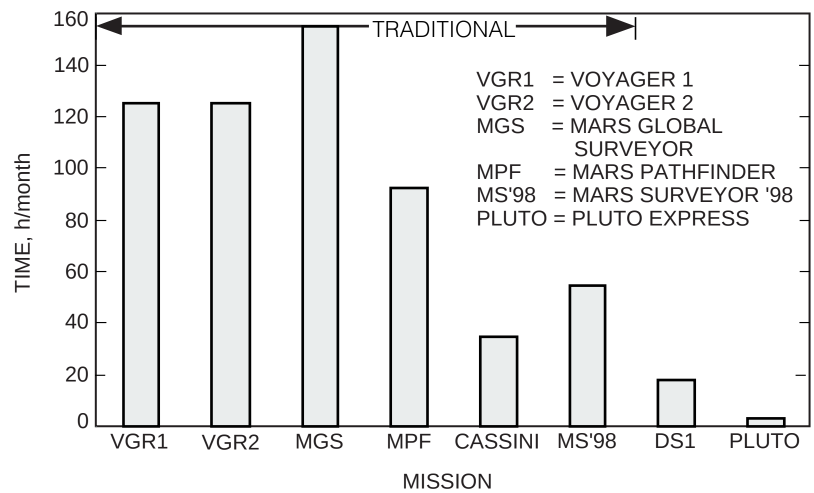

Fig. 1. The 34-m antenna time needed to downlink engineering data for deep-space missions in cruise. (Antenna usage for DS1 is based on an assumption of 1 track every 2 weeks.)

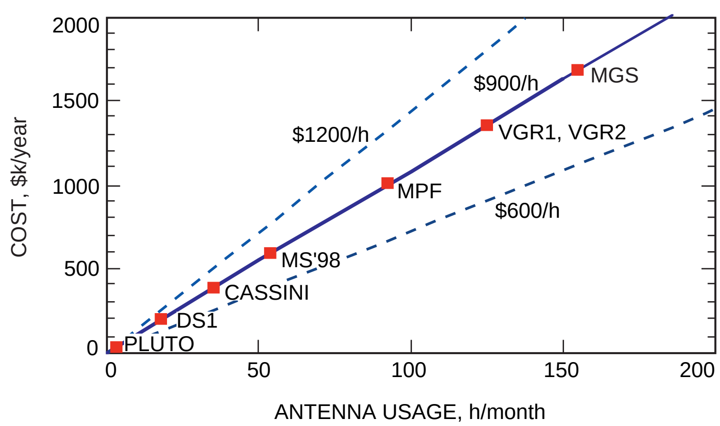

Fig. 2. The cost of 34-m antenna time for engineering data.

[1] *Near-Earth and Deep Space Mission Support Requirements*, DSN 870-14, Rev. AY (internal document), Jet Propulsion Laboratory, Pasadena, California, October 1996.

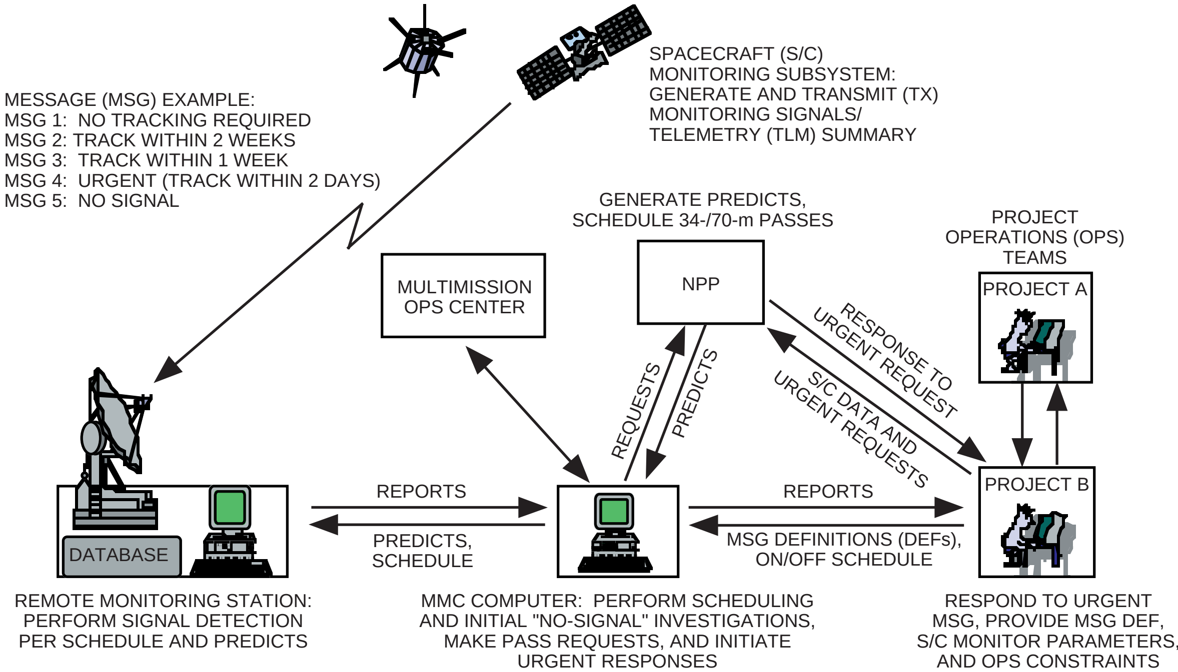

Fig. 3. Monitoring system conceptual design.

The onboard monitoring subsystem includes necessary flight software and part of the telecommunication subsystem. It is responsible for analyzing the spacecraft's engineering data to determine its health, reducing its health status to one of the four monitoring states (which are also known as beacon states or tone 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 be transmitted to the ground and analyzed to determine the condition of the spacecraft.

The monitoring station detects the monitoring signals using the schedule and predicts supplied by the MMC and sends the results to the MMC. The MMC is responsible for the operations of the system. It is there that 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 34-m or 70-m antenna and notifies the project when necessary; and it also initiates urgent responses when triggered by an urgent message. The NPP provides frequency and antenna-pointing predicts to the MMC, which then sends these predicts to the monitoring station. In addition, the NPP is responsible for scheduling 34-m or 70-m antenna passes in response to the MMC's requests, as triggered by the detected messages. During a spacecraft emergency, the NPP will work directly with the project operations teams, bypassing the MMC.

The project operations teams are responsible for defining the monitoring messages and the required responses, supplying necessary spacecraft data to the NPP/MMC for scheduling and predicts generation. They also are responsible for responding to urgent messages. Finally, the monitoring system is completed with the DSN 34-m or 70-m antennas, which track the spacecraft and send the data to the project operation teams in accordance with the NPP schedule.

III. System Operations

The monitoring system normally is used for spacecraft health monitoring. It also can be used to allow a spacecraft to make requests for 34-m or 70-m DSN antenna tracks. It is intended for use during cruise and low-activity mission phases. When intensive interaction is needed between the spacecraft and the ground, the monitoring mode can be terminated by a ground command or by an onboard computer. When a spacecraft emergency is detected by the onboard fault protection software, the spacecraft will revert to standard emergency mode operations and transmit low-rate telemetry to the ground.

When operating in the monitoring mode, each spacecraft normally will transmit its monitoring signal continuously and will at the same time maintain its ability to receive commands from the ground. 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 prearranged communication window can be established for monitoring purposes.

Each spacecraft will be monitored once per day, up to one-half hour per monitoring. The four urgency-based messages may have the following definitions:

(Message 1) Green: Spacecraft is nominal; no ground response needed.

(Message 2) Orange: Need a DSN pass within 2 weeks.

(Message 3) Yellow: Need a DSN pass within 1 week.

(Message 4) Red: Urgent; need a DSN antenna pass within 2 days.

The monitor state in general can be transitioned from a less urgent state directly to any one of the more urgent states. However, it will not be transitioned from a more urgent state to a less urgent one until the need for the more urgent state has been satisfied. To allow sufficient time for the ground station to detect the transmitted message, the monitor message will not be changed more often than once per hour. However, when a red state has been detected, the spacecraft will transmit the red message immediately.

When the spacecraft is healthy, it will transmit a green message either continuously or during a prearranged communication window. The monitoring station will detect the message once a day and send results to the MMC. If a green message is detected, the MMC simply will archive the result and forward it to the project operations team. This operation will be repeated daily until there is a change of the monitor state. 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 if there is no change in the monitoring state.

When the spacecraft needs a 34-m antenna pass, it will transmit a yellow, orange, or red message, depending on the urgency of the need. This message, after being detected by the ground monitoring station, will trigger an appropriate response from the various ground elements, as illustrated in the example in Appendix A.

By modifying some of the operational parameters, the system software can be reconfigured to meet individual project needs and to accommodate specific operational constraints. These parameters include message definitions, their required responses, message transition rules, lengths of the communication windows, frequency of monitoring, and performance requirements (e.g., probability of detection and false alarm rate, etc.). Many of these parameters are interrelated. Changing one parameter may affect another. For example, changing the message definition or the response time may impact the required frequency of monitoring and vice versa. Similarly, increasing the probability of detection may increase the required signal detection time. Care must be taken in selecting a set of workable parameters for the system to operate with. The operational concept described above is based on a set of parameters judged to be reasonable and realistic for both the spacecraft and the DSN.

IV. End-to-End System Design

The monitoring system is designed to support a large number of spacecraft. As previously stated, the major elements include an onboard monitoring subsystem, ground monitoring stations, the MMC, project operations teams, the NPP, and DSN antennas.

The onboard monitoring subsystem consists of part of the onboard telecommunication subsystem and specialized flight software. The telecommunication part of the subsystem is to generate and transmit monitoring signals representing the four monitoring messages. This function can be fulfilled readily by the onboard telecommunication subsystem using the Small Deep Space Transponder (SDST), currently being developed for deep-space missions. No modifications to the SDST are needed in order to support the monitoring function. The main function of the flight software is to analyze engineering data, determine the health status of the spacecraft, map the health states to one of the four monitor states (i.e., beacon states), and generate an engineering summary.

Various options are available for implementing the ground monitoring stations and the detector. The ground monitoring stations can be either new stations, each with a small antenna (8 m); the existing DSN 34-m antennas, each equipped with a signal detector; or a combination of both. Assuming everything else is equal, a 34-m antenna can support a much greater communication range at the expense of a higher operating cost. The signal detector can be a coherent binary phase-shift keying (BPSK) receiver traditionally used for deep-space communications or a noncoherent tone detector. The latter can achieve a lower detection threshold but requires initial capital investments. The trade-off between noncoherent tones and coherent BPSK is discussed in Section V.

The MMC is simply a computer or a software package residing in an existing subsystem such as the NPP. The NPP and DSN 34-m or 70-m antennas are existing equipment.

A. Flight Software System Design

The amount by which beacon monitoring reduces mission operations cost depends largely on the level of autonomy achieved on board the spacecraft. Systems that can perform more robust recovery from anomaly conditions and provide flexible onboard data management enable innovative system designs for low-cost operations. In addition to onboard autonomy, there are two onboard technologies needed to enable the monitoring operation: onboard engineering data summarization and monitor message selection (which also is called beacon tone selection). The tone selection module is a software component that implements the functionality required to select tone states based on spacecraft health information.

The goal of onboard data summarization is to provide mission 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 is a technique for creating derived channels or "transforms" of engineering data channels. The current set of transforms includes computation of high, low, and average values as well as first and second derivatives 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.

Summaries consist of several types of downlink packets stored by the onboard telemetry management system. Episode packets contain high-resolution engineering data (and associated transforms) for culprit and causally related sensor channels during the time just before and just after an alarm threshold has been exceeded. Snapshot packets contain low-rate engineering data for a one time slice and accumulate continuously between track periods. Summary statistic packets contain top-level spacecraft mode/state information and data on the number of episodes. User summary packets are defined by the user a priori to capture important data around the time of preplanned events. It is expected that missions will fine tune or calibrate summary content in early mission checkout activities by adjusting prioritization of data stored for downlink.

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

B. Ground System Hardware

The ground monitoring station is a fully automated station; its operation is driven solely by schedule and predicts. A block diagram is presented in Fig. 4. The received signal first is downconverted, then sampled, digitized, and recorded. The digitized signal is processed by the signal detector. The detected signal is decoded by the message decoder, and the decoded message is then disseminated to the mission operations team and other users.

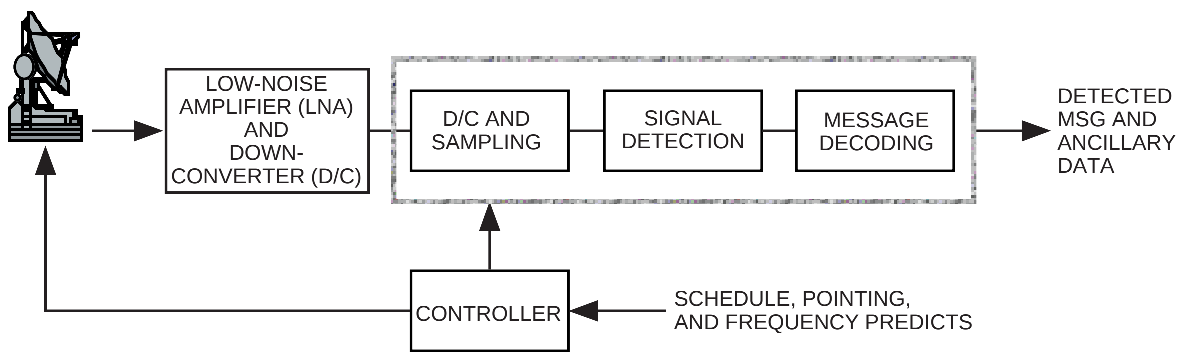

Fig. 4. Monitoring station block diagram.

C. Signaling and Detection Schemes

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 requirement. The goal is to reliably detect the monitoring messages with a 0 dB-Hz total-received signal-to-noise-spectral-density ratio, P_t/N_o, using a 1000-second observation time. These missions are assumed to carry a low-cost auxiliary oscillator as a frequency source instead of a more expensive ultra-stable oscillator. The downlink frequency derived from an auxiliary oscillator is not precisely known due to frequency drifts caused by onboard temperature variations, aging, and uncorrected residual Doppler frequency. In addition, the downlink frequency also exhibits short-term drift and phase noise. All of these affect the selection of signaling and detection schemes and complicate the design of the signal detector.

Figure 5 gives an example of the frequency drift and short-term random fluctuation of the RF signal derived from an auxiliary oscillator. The data were 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. Similar frequency drift and frequency jitters are expected for the SDST. Assuming that the onboard temperature can be maintained to within 2 deg C over a 24-hour period, the downlink frequency derived from an SDST type of oscillator is expected to have the following characteristics:

(1) Initial frequency uncertainty: 2 kHz

(2) Maximum drift rate: 0.05 Hz/s

Two signaling schemes that can be supported readily by the SDST can be applied to generate a signal set to represent the four monitor messages: traditional bit-based BPSK signals or tone-based signals. Coherent detection of BPSK signals and noncoherent detection of tones both have been considered for spacecraft-monitoring application. In the presence of unknown frequency and unknown phase, the noncoherent scheme offers a lower detection threshold for very low data-rate applications (e.g, to detect one of four possible messages with a 1000-second detection time). This is because the coherent scheme requires an accurate estimation of the unknown parameters (both frequency and phase). To obtain an accurate estimate, it would require an integration time equal to the signal detection time (1000 seconds) or, equivalently, it would require that the phase-locked loop bandwidth be narrowed to 0.001 Hz. This is not possible due to the frequency instability of the monitoring signal.

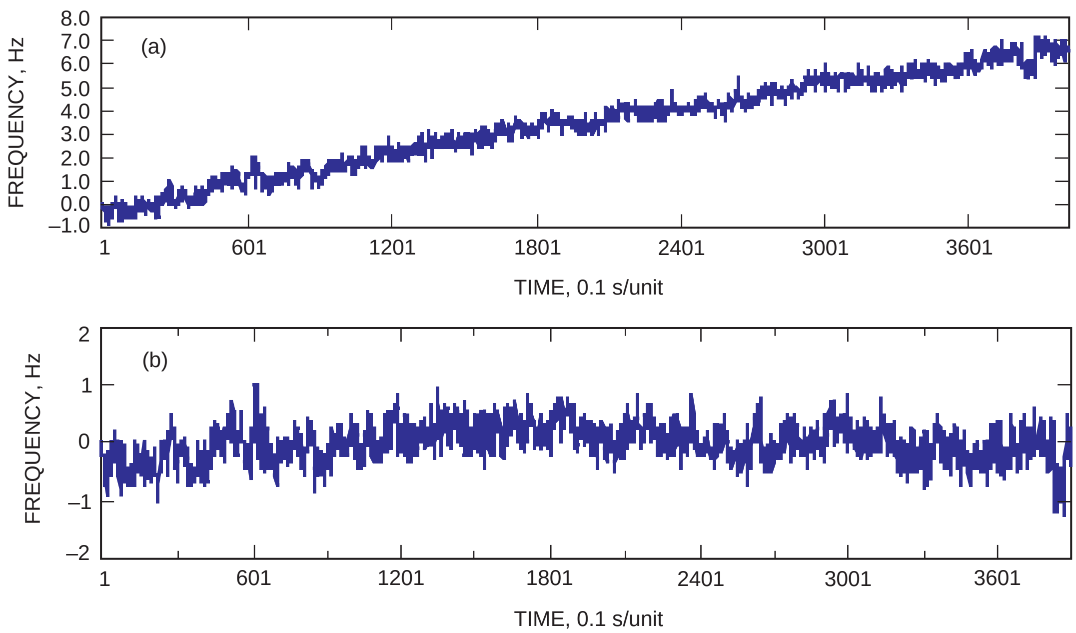

Fig. 5. Galileo auxiliary oscillator frequency versus time as measured in the TDL on March 1, 1996 (400.1–800.1 s): (a) with the mean removed and (b) with the linear drift removed.

A tone-based signal structure is shown in Fig. 6. Each message is represented by a pair of tones centered about the carrier. These tones are generated by phase modulating the RF carrier by a square-wave subcarrier using a 90-degree modulation angle. The carrier, f_c, is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. The higher harmonics are ignored; only the tones at the fundamental frequency are used to represent the transmitted message. Four pairs of tones are needed, one for each of the four possible messages. While the SDST can generate a wide range of subcarrier frequency, instability of the downlink signal and detector complexity together constrain the selection of subcarrier frequency. 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 sets of frequencies can be used for different missions.

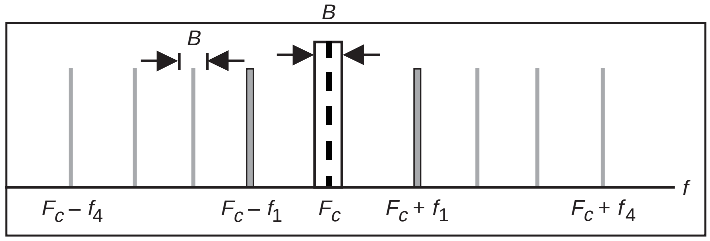

Fig. 6. Signal structure, where *B* is the frequency uncertainty (2 kHz), F_c is the carrier frequency, and F_i is the *i*th subcarrier frequency, *i* = 1, 2, 3, and 4.

D. Noncoherent-Detection Receiver Structures

Two noncoherent signal detectors have been studied. In both cases, a frequency drift model was applied to “dedrift” the signal, and an energy measurement derived from an incoherent sum of power spectra was compared with a threshold. A functional block diagram for the signal detector and the message decoder is shown in Fig. 7. The detector structures are described briefly below. A detailed discussion can be found in [1,2] and a related discussion in [3].

The signal detector for the first method contains four subcarrier detectors (which are also called tone detectors), one for each message or channel. Each subcarrier detector is designed to compute the power spectrum of a pair of baseband channels containing the upper and lower first harmonics of that subcarrier. To evaluate the power spectra, the fast Fourier transform (FFT) algorithm is employed for computational efficiency. The FFT (coherent) integration time is limited because of oscillator instability; if the integration time exceeds the limit, the received signal may move across multiple Fourier frequencies, resulting in a significant reduction of the signal-to-noise ratio. Experimental and theoretical analyses indicated a proper Fourier integration time of approximately 1 second for signals derived from an onboard auxiliary oscillator. Thus, assuming a 1000-second observation interval, 1000 1-second FFTs are performed on successive segments of data, giving 1000 power spectra.

The power spectra obtained from the 1000 FFTs then are summed to form combined spectra. Because of the frequency drift, the spectra must be aligned (dedrifted) properly during the summation. This is accomplished by using a simple frequency-drift model (either a linear, a piece-wise linear, or a quadratic model) with a range of drift rates constrained by a priori knowledge of the maximum possible frequency

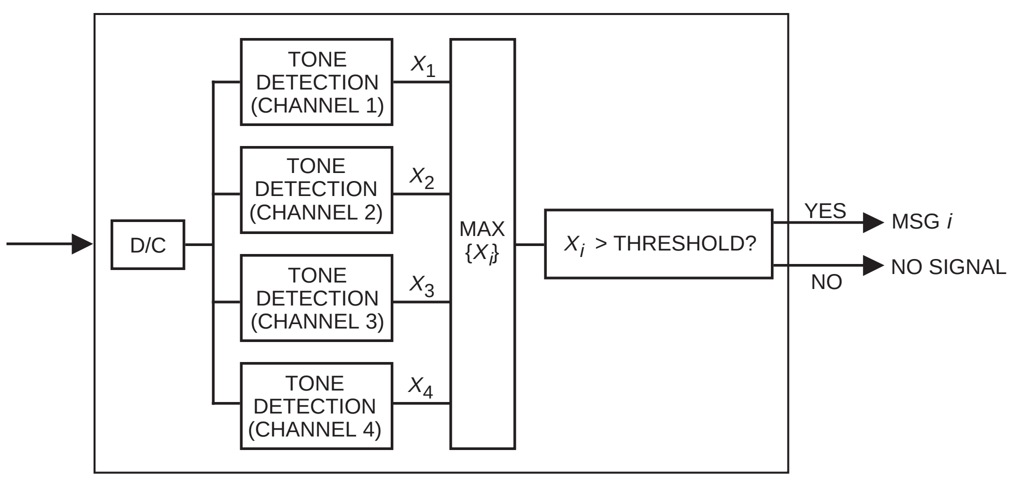

Fig. 7. Monitoring signal detector and message decoder.

drift. Simulations and experiments with the Galileo auxiliary oscillator data indicate that the detection loss, including the dedrifting loss, is approximately 1 dB for a 50-second incoherent average of 1-second FFTs. The loss for a 1000-second average is estimated to be less than 2 dB.

For the second method, the detector applies the frequency drift model first, before signal integration. The operation of this detector can be summarized as follows: Like the first detector, the received signal is channelized into four frequency channels, one for each message. A tone detector is assigned to each of these channels. Each frequency channel is divided into k subbands. Each subband is processed by a bank of "subband processors." Each subband processor is drift matched to a given drift rate. The dedrifted signal is filtered, squared, and integrated to obtain the decision statistics. If there are j drift rates and k subbands, then $j \times k$ subband processors are needed for each channel. The maximum output of the subband processors is selected and compared against a predetermined threshold to determine which message has been sent.

E. Performance Comparison: Coherent BPSK Versus Noncoherent Tones

Figure 8 shows the performance of coherent detection of BPSK signals and noncoherent detection of orthogonal tone pairs as a function of integration time (signal detection time), under the condition that the frequency drift is roughly linear or quadratic and the initial frequency uncertainty is within 2 KHz. Under this condition, noncoherent detection of orthogonal tone pairs would require about 0 dB-Hz of P_t/N_o. However, coherent detection of BPSK signals would require 15 dB-Hz of P_t/N_o with a carrier-tracking loop bandwidth set at a practical limit of 2 Hz.

For a given spacecraft effective isotropic radiated power (EIRP), the 15-dB threshold advantage of the tone-based scheme allows the monitor system to support a greater communications range or to use a smaller antenna. The required spacecraft EIRP as a function of the monitoring station's antenna gain-to-system noise temperature ratio, G/T, is given in Figs. 9 and 10 for detection times of 100 and 1000 seconds, respectively. While the tone-based scheme has a performance advantage over the coherent BPSK scheme, other factors may affect the choice of a signaling and detection scheme, as discussed in the following section.

V. Monitoring Station Implementation Approaches

The performance advantage of the tone-based scheme coupled with the low operating cost of small stations appears to favor the use of a small antenna and the tone-based scheme. These advantages, however, are counter balanced by the initial capital investments required to implement the new system.

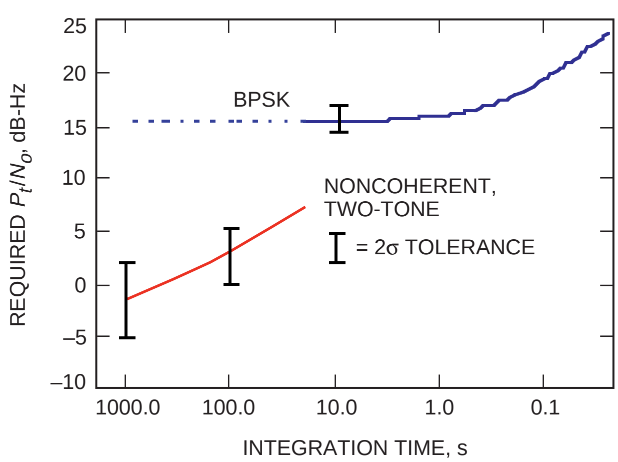

Fig. 8. Required P_t/N_o versus integration time.

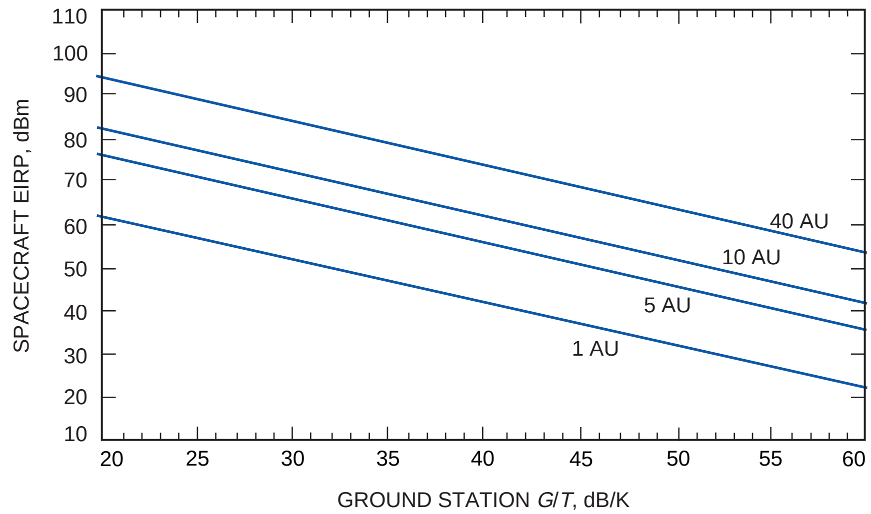

Fig. 9. Required spacecraft EIRP versus ground station *G/T* for a 100-s signal detection time.

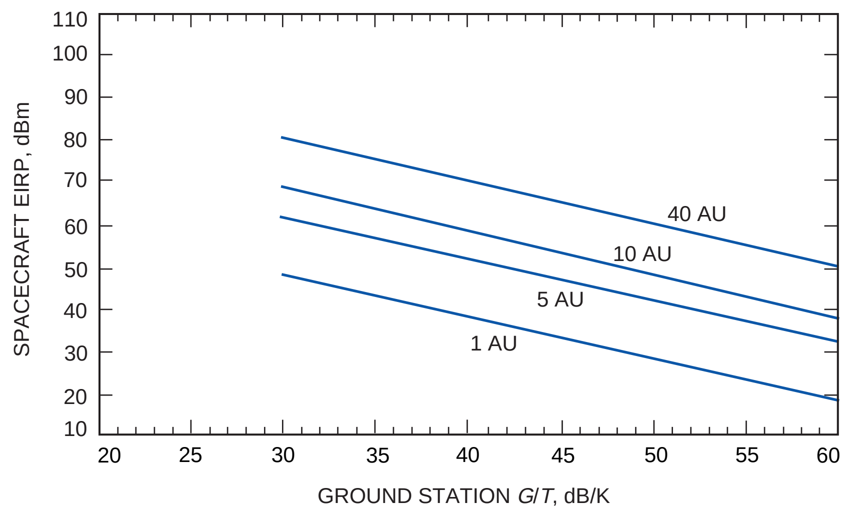

Fig. 10. Required spacecraft EIRP versus ground station *G/T* for a 1000-s signal detection time.

A cost analysis has been performed for three implementation approaches with different combinations of antennas and signal detectors, as follows:

(Option A) Existing 34-m antennas using existing coherent BPSK receivers: The four monitoring messages are represented by binary bits, which modulate the downlink carrier using BPSK. The monitoring signal is received by a 34-m antenna and coherently detected by an existing receiver.

(Option B) Existing 34-m antennas with noncoherent tone detectors: The four messages are represented by four pairs of tones. The monitoring signal is received by an existing 34-m antenna and noncoherently detected by a tone detector.

(Option C) New stations with small (8-m) antennas and noncoherent tone detectors: This is similar to option B, with a new monitoring station replacing the 34-m antenna. This option requires a large capital investment.

One way to evaluate the merits of the various implementation approaches is to compare their life-cycle costs (LCC). The LCC as a function of the number of users has been estimated for the three options and is shown in Fig. 11. As indicated by the figure, the trade-off is affected by the number of users. For a large number of users, option C would have the lowest life-cycle cost. A number of assumptions were made in calculating the LCC. One is the 34-m antenna charge rate, which was assumed to be $900/h. Additional assumptions are detailed in Appendix B.

Another way to evaluate the implementation approaches is to compare their cumulative costs, which are shown in Figs. 12 through 14 with the number of user spacecraft as a parameter. Again, the 34-m antenna charge rate is assumed to be $900/h. These figures show that option A has the lowest cumulative cost if the number of users is small. If the number of users is large, option C would have the lowest cost. Assuming 36 user spacecraft, the figure shows that it will take about 4 years to recover the capital investments needed to implement option C. It will take longer if the number of users is smaller.

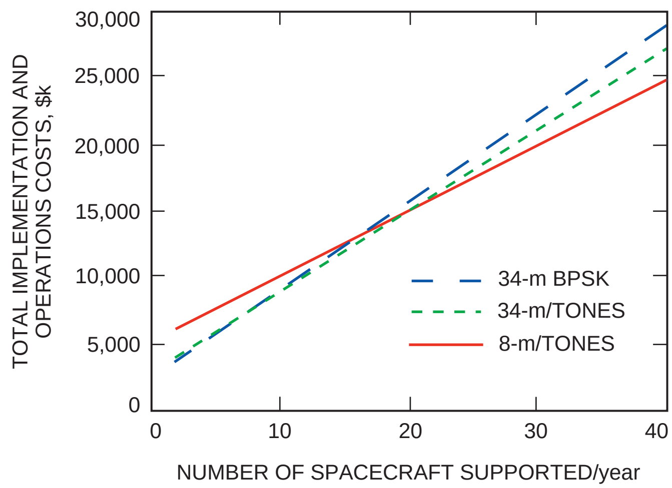

Fig. 11. Life-cycle costs versus number of user spacecraft.

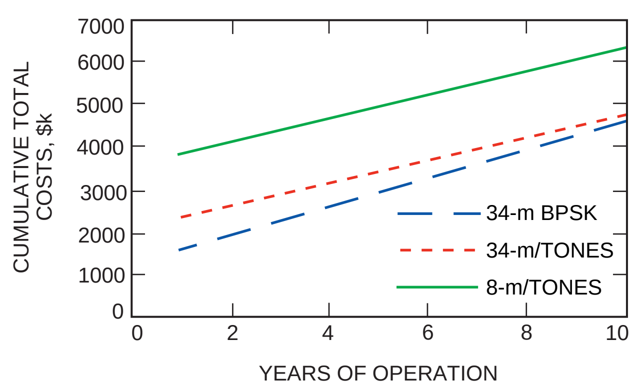

Fig. 12. Cumulative cost versus time for five spacecraft users.

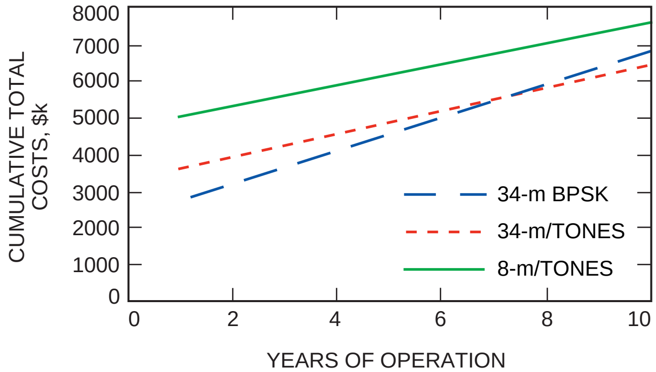

Fig. 13. Cumulative cost versus time for ten spacecraft users.

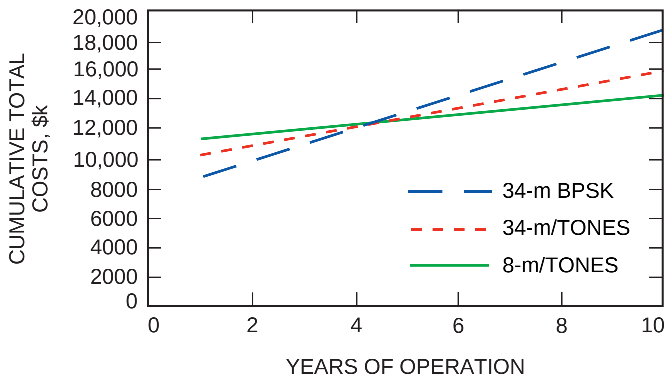

Fig. 14. Cumulative cost versus time for 36 spacecraft users.

VI. Conclusion

A conceptual system design and an operational strategy have been established for the new spacecraft monitoring concept, along with candidate signaling and detection schemes and alternative ground implementation approaches. The operational strategy and the signaling and detection scheme have provided a basis for implementing the flight experiment to be conducted on DS1 (Appendix C).

While the tone-based signaling and detection scheme will be demonstrated by the DS1 experiment using a 34-m antenna, the decision on the implementation approach for an operational system will be affected by many factors, such as the availability of a 34-m antenna, spacecraft EIRP, and the number of user spacecraft. Based on results of the cost analysis, the following conclusions can be drawn:

(1) If the existing 34-m antennas are available for monitoring, it is more cost effective to use the 34-m antennas and employ either coherent BPSK or noncoherent tones. The tone-based scheme is needed if user spacecraft do not have sufficient EIRP; otherwise the traditional BPSK scheme is adequate.

(2) If the existing 34-m antennas are not available, a new station may be necessary. This station would have a small antenna and a tone detector. An antenna as small as 8 m would be sufficient. (The existing DSN 11-m antennas also could be used, if available.)

Acknowledgments

The authors would like to acknowledge the technical contribution or programmatic support made by Chien Chen, Nasser Golshan, Robert Kahn, Peter Kinman, Neal Kuo, Gabor Lanyi, Alex Mileant, Mazen Shihabi, Marvin Simon, Victor Vilnrotter, and Wallace Tai.

References

[1] M. K. Simon, V. Vilnrotter, A. Mileant, and S. Hinedi, "Optimum Strategies for Monitoring the Operational Status of a Spacecraft," *The Telecommunications and Data Acquisition Progress Report 42-127, July–September 1996*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–51, November 15, 1996. http://tda.jpl.nasa.gov/tda/progress_report/42-127/127C.pdf

[2] G. Lanyi and R. Kahn, "Tone Detection Via Incoherent Averaging of Fourier Transforms to Support the Automated Spacecraft-Monitoring Concept," *The Telecommunications and Data Acquisition Progress Report 42-129, January–March 1997*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–22, May 15, 1997. http://tda.jpl.nasa.gov/tda/progress_report/42-129/129E.pdf

[3] V. Vilnrotter, S. Hinedi, and R. Kumar, "Frequency Estimation Techniques for High-Dynamic Trajectories," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 25, no. 4, July 1989.

Appendix A

A Sample Operation Scenario

Figure A-1 gives an example of an operation scenario. When the spacecraft (S/C) needs a ground track, it transmits, for example, a yellow message. After detecting the yellow message, the MMC responds 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) The MMC sends a request to the DSN NPP/scheduler for an 8-hour pass with a 34-m antenna in 1 week.

(2) The DSN scheduler schedules a pass to take place, say, 5 days later over DSS 15 (assuming availability) and informs the MMC and the project of the schedule.

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

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

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

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

(7) After receiving the uplink (U/L) command, the spacecraft stops other ongoing activities, if necessary, and starts to downlink as instructed.

(8) The DSN (DSS 15) receives and delivers the telemetry data to the project.

(9) The project analyzes the data and sends a command, via a 34-m 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 "no signal," a spacecraft anomaly investigation will be conducted. The project operations team will be in charge of such an investigation after being notified by the MMC.

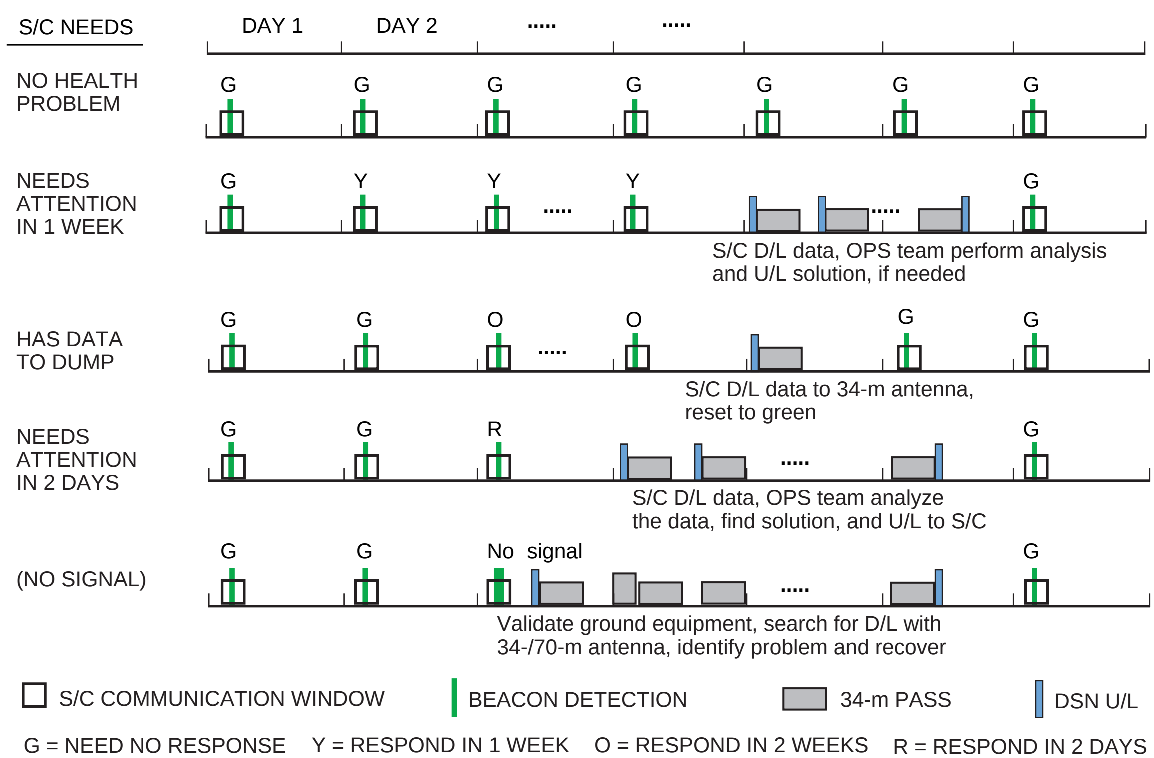

Fig. A-1. An operation scenario.

Appendix B
Assumptions for Life-Cycle Costs Computation

The life-cycle costs include the following cost elements:

(1) Monitoring station implementation costs.

(2) Cost of the 34-m antenna time to detect the monitoring signals (for options A and B only).

(3) Monitoring station operation cost (option C only).

(4) MMC operation cost.

The following cost elements, which are common to all implementation approaches, are not included in the life-cycle costs:

(1) The cost to develop the spacecraft autonomy technology.

(2) The cost for receiving engineering summary data.

(3) Mission operations costs associated with the analysis, processing, and archiving of engineering data.

Additional assumptions used in calculating the life-cycle costs are as follows:

(1) The life cycle is 10 years for ground equipment and 5 years for the spacecraft.

(2) The spacecraft will be operating in the self-monitoring mode 70 percent of the time, during which time it will be monitored once per day, except for days it is downlinking telemetry to a 34-m antenna.

(3) Spacecraft that are simultaneously visible to a monitoring station are bundled together so that they can be monitored successively over one monitoring pass. The prepass setup time for the 34-m station at the beginning of a monitoring pass is 5 minutes, which is needed to reconfigure the station, perform a safety check, etc. Additional time (3–5 minutes per spacecraft) will be needed to load predict files to the tone detector, initialize the tone detector, and slew the antenna. Based on 10 user spacecraft, the total preparation time is 6 minutes per spacecraft.

(4) For the 8-m antenna, the annual operation cost is $90k.

(5) The spacecraft EIRP is such that it can support 10 bps with a 34-m DSN antenna, corresponding approximately to an 18 dB-Hz received P_t/N_o. The received P_t/N_o is 0.5 dB-Hz for an 8-m antenna, due to a lower G/T.

(6) The false alarm rate is 0.001, and the probability of detection is 0.98.

(7) The signal detection time for option A includes the lock-up time (200 s) for the receiving system.

Appendix C

Message Handling and Reporting for the DS1 Beacon Monitor Experiment

A beacon signal detection and message delivery system for the Beacon Monitor Experiment (BMOX) is shown in Fig. C-1. The current plan is to use DSS 26 as a monitoring station as well as a demand access station. The beacon message first is received and decoded by the monitoring station in Goldstone and subsequently transmitted to the BMOX team at JPL via a secured link, such as the NASA Science Internet. BMOX in turn forwards the beacon message to DS1 mission operations and other end users, including the demand access scheduler, using e-mail or pagers. Depending on what message has been received, different activities will be carried out by the BMOX team, the demand access scheduler, the mission operations team, and the DSN station. If the received message is a green message, no action will take place. If a red message has been received, the demand access scheduler will schedule a downlink track for the demand-access station to receive telemetry from the spacecraft. The scheduler will notify the BMOX team of the schedule.

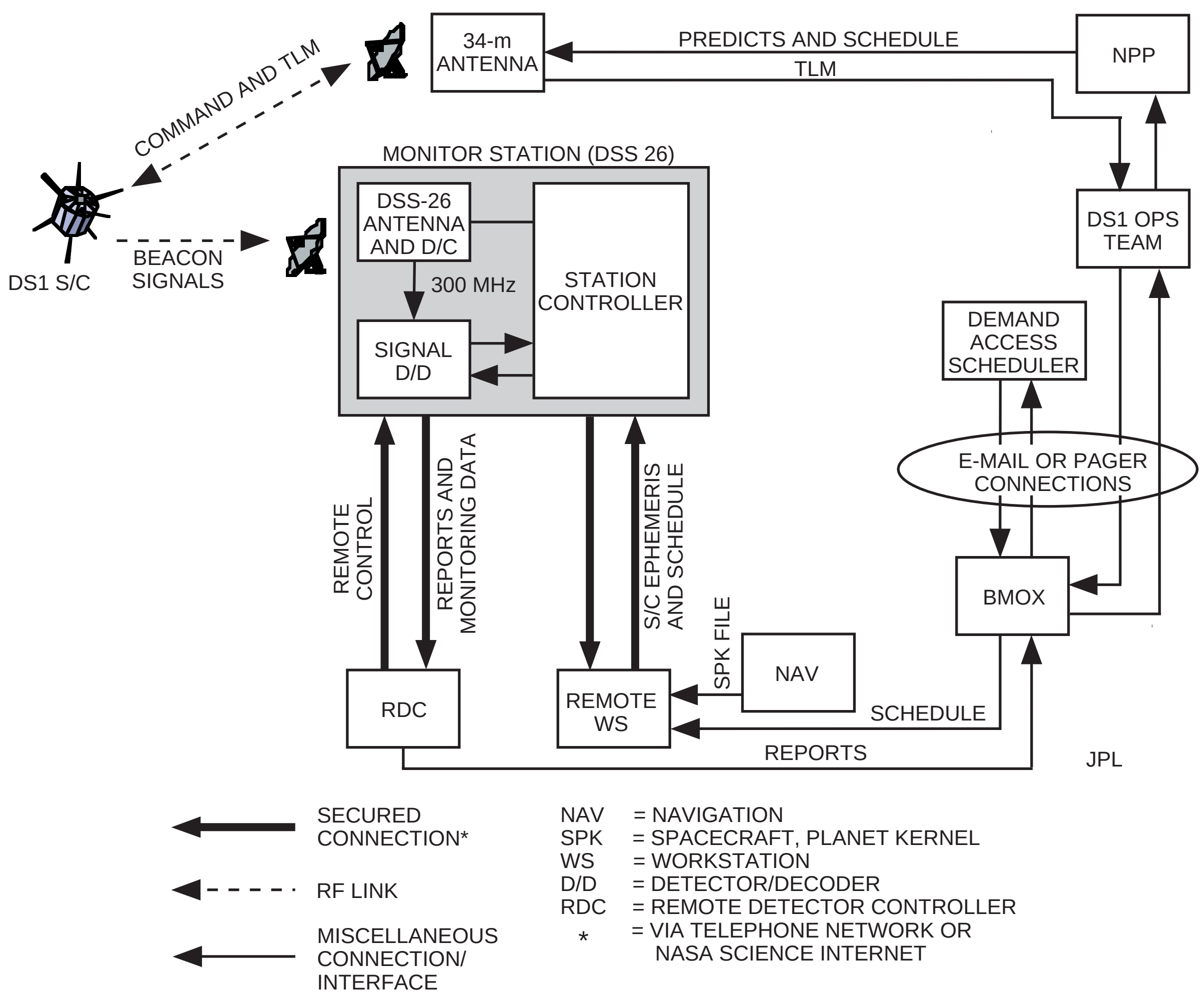

Fig. C-1. BMOX signal detection and message delivery system.

BMOX in turn will notify the mission operations team and obtain its approval to carry out the downlink track triggered by the beacon message. One round-trip light-time prior to the downlink track, a canned command will be transmitted to the spacecraft by the demand-access station or by another 34-m antenna station to initiate the downlink pass. The downlink telemetry will be received by the demand access station, forwarded to the mission operations and BMOX teams, and analyzed. It should be noted that the DS1 operations team can choose to ignore the beacon messages during the experiment and to not carry out the beacon-requested passes. It should also be noted that the support provided by DSS 26 is experimental in nature and any telemetry received is on a best-effort basis.