An C‹erview of th. Beacon Mo. tor Operatic. s Technolog.

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ABSTRACT

This paper summarizes the end-to-end design of a technology for low cost mission operations. Cost savings is achieved by reducing the total volume of downlinked engineering telemetry try decreasing the frequency of telemetry acquisition and the volume of data received per pass. Antenna resources are conserved and the antenna scheduling process can be more esaily automated. The technology is being developed for upcoming deep space missions, including initial flight validation on the Deep Space One mission to be launched in July of 1998. This paper provides an overview of the beacon monitor operations approach and describes the design of key flight and ground components of the technology.

1. INTRODUCTION

The beacon monitor operations technology was conceived in response to a need to lower the cost of mission operations for NASA's planned mission to Pluto. Since the spacecraft was to be highly 'autonomous', it seemed logical to leverage enhanced onboard capability to allow the spacecraft to determine when telemetry downlink should occur. Reducing the frequency and volume of downlinked engineering data would enable mission operations to be carried out with less staff and would reduce the loading on an already highly constrained Deep Space Network (DSN). [1] [2]

From an operations perspective, it is not viable to elmi nate telemetry tracking altogether. A much more appeal ing approach is to have the spacecraft cent inuousl y transmit one of four tones that indicate how urgent it is to track the spacecraft for telemetry. Since no telemetry is modulated with these tones, the detection scheme is simple and the ground station can be operated at very low cost, Tones provide the necessary assurances that the mission is proceeding as planned while conditions are nominal. When an anomaly occurs the tone system facilitates quick intervention.

In order to create a complete solution, certain ground and flight components must be present in the end-to-end design. One technology component is a capability for generating summaries of engineering data onboard the spacecraft. These summaries are needed to qu ickl y provide operators with data associated with important spacecraft events when telemetry downlink is necessary. Another technology component for NASA mission. is a new approach to scheduling DSN antennas bawd on events rather than pre-negotiated agreements.

The beacon monitor technology has been manifested for flight validation on the Deep Space One mission as the Beacon Monitor Operations Experiment (BMOX). This activity is currently the focal point in developing the technology. Funding for development of key aspects of the end-to-end design has come through alignment of several technology development efforts within the JPL community. All of the BMOX component technologies and the operational concept will be validated during 1X3-1 operations. Validation objectives fall into the following categories: (1) Onboard engineering summary data generation, and visualization, (2) Tone selection, transmission, and detection, (3) Multi-mission ground support, and (4) Operations concept demonstration and assessment. A detailed set of experiments has been defined. As the mission progresses, BMOX component technologies and the operations concept will be gradually validated and will be made available for use in baseline DS 1 operations. The goal is to provide some ~alrre.added to mission operations during the prime mission and a capability for full-up beacon operations in extended mission.

2. OI'ILRATIONS

Beacon monitor operations is most suited to mission cruise phase or other low-activity periods. A mission would likely transition gradually to beacon operations once routine operations are underway. The four tone system does not represent spacecraft state, but rather the spacecraft's assessment of how urgent it is to track the spacecraft for telemetry. For this reason, the basic four tone system described in Table 1 can support any type of deep space mission.

Tone	Definition
Nominal	Spacecraft is nominal, all functions are performing as expected. No need to down link engineering telemetry.
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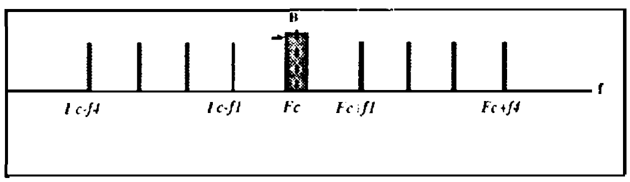
Table 1 Beacon Tone Definitions

Although the flight project determines how frequently to poll the beacon tone, a rate of once per day is generally considered optimal. When the tone idicates that tracking is required, an antenna is scheduled to retreive the summary. The duration of this track is short if the summary is small. If the summary indicates that further action is required, another track is scheduled to uplink commands, or retreive more data. The summarization technology scales with downlink rate, allowing much larger telemetry summaries in the early phases of the mission. As operators become more comfortable using the summaries, frequency of nominal tracking and summary size can be scaled-back for additional cost savings.

3. FLIGHT SYSTEM HARDWARE

The responsibility of flight hardware is to generate arid transmit beacon signals representing the four beacon states. In theory, this function can be supported with a very simple transmit subsystem that has a modulator, an exciter, an amplifier, and an antenna, The telecom subsystem for space mission in general is more complicated. The complexity varies from one mission to another and is affected by the coverage requirements, the number of frequency bands, and the redundancy requirements. For the DS 1 mission, the telecom subsystem includes a Small Deep Space Transponder (SDST), a 12.5 W X-band solid state power amplifiers (SSPA), a 2.5 W Ka-band SSPA, two X-band low-gain antennas (LGA), and one dual-frequency X- and Ka-band high-gain antenna (HGA). The gain of the HGA is -25 dBic gain at X-band and 27 dBic at Ka-band. The gain of the LGA is -9 dBic. The SDST is a highly integrated package that includes a telemetry modulator, exciter, and command detector. The DS 1 telecom subsystem will be used to generate and transmit beacon signals for the experiment, without modifications.

The four beacon messages are each represented by a pair of tones, centered around the carrier. These tones are generated by phased-modulating the RF carrier by a squarewave subcarrier using 90 degrees modulation angle. The carrier wi i i 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 wiii be ignored; oniy the tones at the fondamental frequency will be used to represent the transmitted message. Ignoring the higher harmonics results in a slight loss of signal strength, In return, it makes the detector more robust in the sense that reliable signal detection can be achieved without knowing the exact dowriiink carrier frequency. The SDST has the capability to generate a wide range of subcarrier frequency to represent the four beacon messages. However, the downlink frequency uncertainty and detector complexity together constrain the selection of the subcarrier frequencies. Tbc frequency uncertainty is caused by a combination of on-board temperature variations and uncorrected residual Doppler frequency. For the Beacon Monitor Experiment, the four subcarrier frequencies are 20, 25, 30, and 35 kHz. The signal structure is shown in Figure 1.



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

Figure 1 Signal **Structure**

4. FLIGHT SYSTEM SOFTWARE

The amount by which beacon monitoring reduces operations cost depends largely on the level of autonomy achieved onboard the spacecraft. Systems that can perform more robust recovery from anomaly conditions and provide flexible onboard data management can achieve the most benefit from beacon operations. Flight software for beacon monitor operations leverages the trend towards spacecraft autonomy and "fills in the gaps" by providing additional flight system functionality.

The two prin , flight software in vations whose development has been largely driven by the beacon monitor technology are onboard engineering data summarization and beacon tone selection. The tone selection module is a software component that implements the functionality required to select tone states breed on spacecraft health information. The summarization module is a comprehensive architecture for creating summaries of engineering data between telemetry downlink periods.

4.1 Tone Selection

The tone selector module maps fault protection messages to beacon tone states. This module outputs the tone state as a tele . try packet and a mes ge to the Small Deep Space Transponder to actually set the tone. The output of the module can be turned OFF, ON or RESET by issuing a ground command. Tone state always transitions to a higher level of urgency until reset by a ground command. The tone selection module for 1> S- 1 consists of 1583 source lines in C and uses 31039 bytes of memory when compiled for a Power PC series processor. The processing load is all in response to external messages which come at undetermi ned intervals (probably less than 1 per second). The processing time for one messsage is negligible (on the order of 1-2 msec).

4.2 Onboard Engineering Data Summarization

I'light software for summarization integrates several techniques into onc cohesive architecture for providing operators with information required to analyze spacecraft engineering data. The method for creating the summary data is highly even-driven and uses the data prioritization capabilities built into the telemetry management software. It has been a design goal to integrate the most advanced techniques possible into the architecture. Transforms and adaptive alarm thresholds are key components of an architecture for providing operators with top-level summary statistics, important episode data (higtl-resolution culprit and causally related data), low-resolution "snapshot" telemetry, and user-defined data

Transforms

Each sensor will use a selected subset of the five transforms included in the summarization software package. Those transforms are: minimum value, maximum value, mean value, first derivative, and second derivative. To compute the transforms, the raw data from each sensor is stored in a lag vector of a predetermined length, and the value of the transform is computed across the vector. It should be noted that the first and second derivative transforms are not true derivative functions. The first derivative transform simply computes the rate of change between the first an st points in the v or. Similarly the second derivative transform calculates the rate of change between the difference of the first two values in the vector and the difference of the last two values in the vector. Computing the transforms requires more computational cycles then straight limit comparison; however, the time required to perform the mathematical operations is inconsequential.

Using the transforms to determine when an episode should begin provides more flexibility than simply testing the raw data against red-line limits. If an episode were to begin whenever a sensor value moved above/below a certain value, then red-line limit sensing would be sufficient. This functionality, which is adequate for many sensors, is still provided when we use the ansforms. By using the maximum and minimum value transforms, we can duplicate the red-line limit sensing. If the maximu m/minimu m value goes above/below the set boundary, then an episode is started. However, using the transforms also provides this functionality while better handling some cases, where the traditional method would either fail or signal false alarms.

In traditional limit sensing, there is no concept of memory or time in examining values, i.e. an episode cannot be triggered if a value stays above/below a certain level for a certain amount of time. However, this type of behavior can be captured with the mean value transform. A value falling below a limit for too long will reduce the mean, causing an episode to begin. With traditional methods, an episode would occur anytime the value dropped below the threshold, possibly leading to many false alarms.

During nominal spacecraft operation, some sensors may change value in a cyclical manner. Traditional limit sensing would be able to detect when the sensor went above or below its expected values, but would fail to detect the anomalous situation where the value did not change. To handle this case, we could use the first and second derivative transforms. For a constant value, both first and second derivative functions would be zero, signaling that an episode should be triggered. The first derivative would show that the value wasn't changing, but if the size of the lag vector equaled the period of the cyclical sensor, the first deri vative would be zero. The second derivative transform would show that the first derivative was also unchanging, verifying that the sensor value was remaining constant.

Adaptive Alarm Thresholds [3]

The current state-of-the-art in anomaly detection is to use limit-sensing, in which the current sensor value is compared against predetermined high and low 'kx-tines". Such red-lines are typically constants across many or all mission modes and it is difficult to determine tight limits which will work well throughout the mission. Thus, to and frequent false alarms, the red-line are made imprecise, leading to missed alarms and missed opportunities for early anomaly detection.

An alternative to red-line limits is envelope functions learned from historical and/or simulated data. In our approach, limits become dynamically changing values instead of static constants. These limits are functional values based upon the values of related sensors and other factors, such as the current operational mode of the spacecraft. Although learning precise envelopes can take longer than determining red-lines, initial loose envelopes can be learned quickly. With further training, the bounds can be incrementally tightened, while still retaining a low false alarm rate. Since the learned envelopes are tighter than red lines, they have a much lower missed alarm rate. Novel training methods are being employed to avoid bounds which cause alarms in nominal training data Therefore, these envelopes are loose enough to avoid false alarms, provided the training and validation data are representative.

In order to learn the envelopes, the ELMER (Envelope Learning and Monitoring via Error Relaxation) algorithm will be used. For training purposes, ELMER can be run on the ground using historical spacecraft data, examining both anomaly and nominal data sets in order to determine accurate bounds. For certain phases of the DS- 1 beacon monitor experiment, the ground trainer will produce limit functions for uplink as shown in Figure 2.

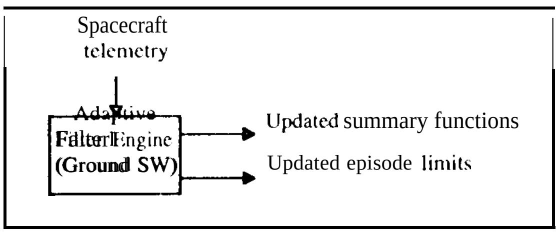


Figure 2 Ground Trainer Software

Flight Software Architecture

The summarizer consists of 3 subroutines: data collection and processing, episode, and mission activity. The data collection and processing module receives data from various domain units via C function calls and applies summary techniques to these data, producing summary measures for downlink to the ground. The Sampler/Summarizer/Episode identifier module is awakened once per processing interval (1 sec. for DS-1), at which time it reads the current value of all the spacecraft data items available, computes derived data such as running minimum, mean and trends, checks the raw and derived data against upper and lower limits, starts and ends "episodes" describing out-of-limits conditions, and produces historical and episodic telemetry. It also responds to spacecraft state messages to determine the current spacecraft activity, which determines which set of bounding limits to use. The architecture diagram shown in Figure 3 shows the interfaces between the subroutines and the major constituents of the summaries.

Data collection is performed by providing a central memory array accessible to all flight software. The various flight software modules update the memory array once per second or whenever the data changes, whichever is less often. The update is done by direct write, thus the time for a single update is just a few microseconds. The actual details of the memory write are hidden from the flight software developer by providing an enumerated list of data id's and a macro. The developer merely invokes the macro giving the id and the new value.

The episode subroutine looks for anomalies within the data and summarizes all data relevant to the anomaly. The episode subroutine receives summary and engineering data internally from the summarizer/sampler module and compares the data with alarm limits. If the limit is exceeded, the subroutine spawns a new episode and collects past relevant data from summarizer/sampler. The past data collected will be 1 minute summaries that go back episode length minutes from start of episode. (So a five minute episode would contain summaries starting 5 minutes before the episode to 5 minutes after the episode.) At the end of the episode, the subroutine outputs episode name (out of limit data ID), high limit, low limit, relevant data, start and end times (relevant data is a vector of the 1 minute summaries.)

The mission acti vity subroutine determines the overall spacecraft mode of operation. This determination is used to choose the appropriate data and li mits for a particular episode in the episode subroutine. For example, solar electric propulsion (SEP) sensor values may be important while using SEP, but if the satellite is in RCS control mode then SEP sensor values could be ignored. In addition, the ACS rate limits might be different during cruise than during a maneuver. As this example points Out, it is necessary to use the mission activities to determine which data to use for episode identification. The mission activity is intended to be exclusive. When a new mission mode start message is received, the previous mission mode is assumed to have ended.

The sampler module and its related data gather ing module currently consist of 3038 lines of source code and 222,677 bytes of memory on the Power PC series processors. Activity determination is a rare event and processing time is negligible. The once-per-wakeup processing time for DS-1 averages out to 30ms.

5. TONE DETECTION SYSTEM

The ground monitor station is a fully automatic station and 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 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 4.

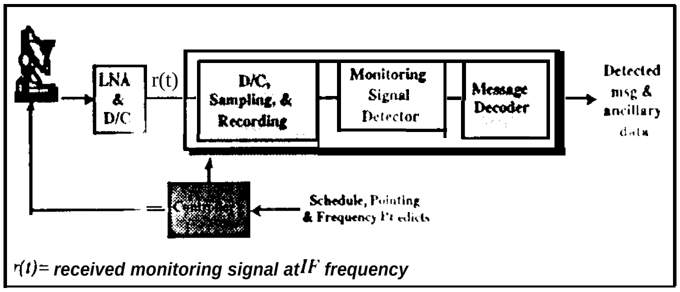


Figure 4 Monitor Station Block Diagram

The signal detector contains four tone detectors, one for each message. 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 frequency, i.e., the beacon tones for a given message will not drift outside of the passband of the detector for that message. Fast Fourier Transform (FFT) 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 performed over long time intervals. The total observation time is divided into short intervals. FFTs are first performed over these short intervals and then incoherent y 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 5.

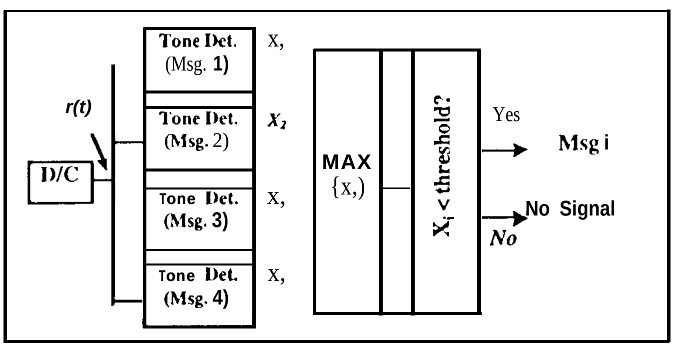


Figure 5 **Monitoring** signal detector and message decoder

6. TONE HANDLING & REPORTING

The beacon signal detection and message delivery system for the DS- 1 experiment is shown in Figure 6. DSS-26 (a 34m DSN antenna) will double as a monitoring station as well as a demand access station. The beacon message is first received and decoded by the remote monitoring station 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 DS 1 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 tone indicates that telemetry tracking is required, the Demand Access Scheduler will schedule a downlink track for the demand station to receive telemetry from the spacecraft. The Scheduler will notify the BMOX team of the schedule. BMOX will in turn notify the Mission Operations team and obtain its approval to carry out the downlink track triggered by the beacon message. Onc 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 34m antenna station to initiate the downlink pass. The downlink telemetry will be received by the demand access station, forward to the Mission Operations and the BMOX teams, and analyzed.

7. SUMMARY DATA VISUALIZATION

Moving to a paradigm where downlink is infrequent requires new approaches for data handling and visualization on the ground. The onboard summarization architecture provides data at variable resolution based on total available downlink bandwidth and the number of significant episodes since the last downlink. The operator will need to quickly locate the high resolution episode data and would likely use the low resolution (snapshot) data for gaining overall system context. It is also possible to automate the ground system to automatically present the user with data associated with the episodes that have been identified in the summaries. Emphasis is currently being placed on visual ization to support pre-flight development testing. Launch-ready ground system displays will be designed and constructed over the next few months.

8. ANTENNA SCHEDULING [4]

Current missions using the Deep Space Network, negotiate tracking schedules well in advance of the launch date. While this approach is adequate for missions that have pre-defined tracking requirements, it does not mesh with demand access paradigm of the beacon monitor approach. Since beacon monitoring requires that the spacecraft initiate tracking, antenna schedules must be formed adaptively. For this reason, automated approaches for enabling low-cost, adaptive tracking of DSN antennas are part of the end-to-end solution. The DSN Advanced Technology Program is supporting beacon monitor operations development by providing a dedicated antenna that can be used for tone detection, telemetry acquisition and command uplink. This segregation of pre-scheduled missions from beacon monitor missions avoids conflicts in scheduling paradigms while at the same time evolving a long-term capability within the DSN to support beacon monitor operations.

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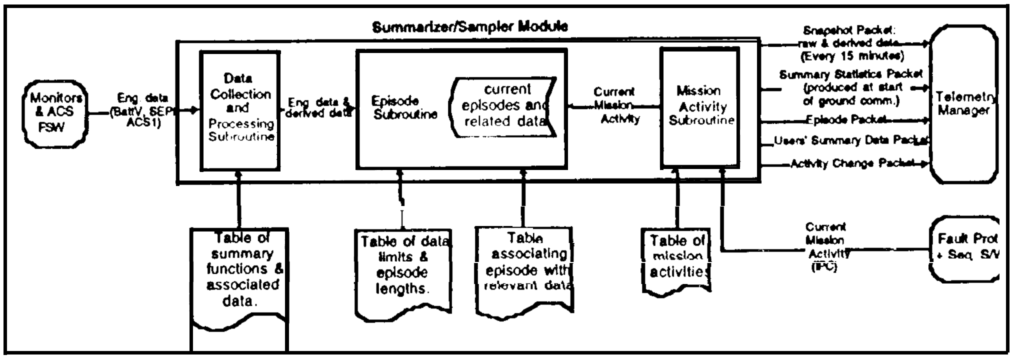

Figure 3 Onboard Engineering Data Summarization Flight Software Architecture

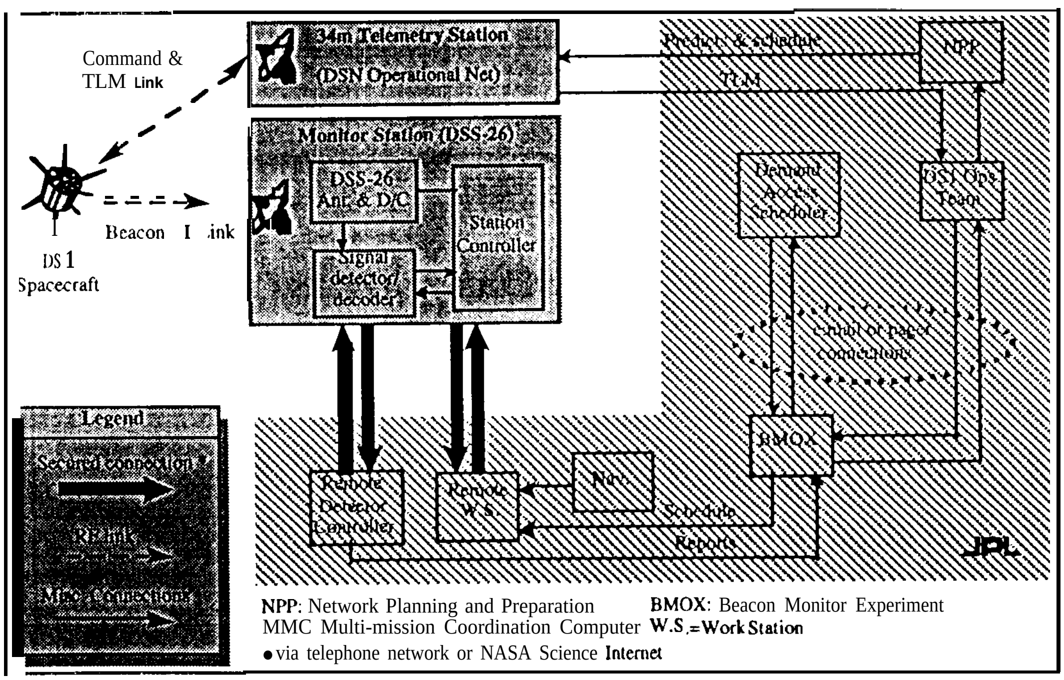

Figure 5 Signal detection and message delivery system

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ABSTRACT

The beacon monitor operations technology is aimed decreasing the total volume of downlinked engineering telemetry by reducing the frequency of downlink and the volume of data received per pass. Cost savings is achieved by reducing the amount of routine telemetry processing and analysis performed by ground staff. Antenna resources are also conserved so more missions can be supported with existing ground stations, At the heart of the concept is a process for allowing the spacecraft to transmit a tone indicating the urgency of ground intervention. Technologies for onboard engineering data summarization and automated ground antenna scheduling are part of the system design. This paper provides an overview of technology by describing the key flight and ground components. The technology is mission enabling for planned missions to Pluto and Europa and flight validation will occur on the New Millennium Program Deep Space One (DS-1) mission to be launched in July of 1998.

1. INTRODUCTION

The beacon monitor operations technology was conceived in response to a need to lower the cost of mission operations for NASA's planned mission to Pluto. Since the spacecraft was to be highly 'autonomous', it seemed logical to leverage enhanced onboard capability to allow the spacecraft to determine when telemetry downlink should occur. Reducing the frequency and volume of downlinked engineering data would enable mission operations to be carried out with less staff and would reduce the loading on an already highly constrained Deep Space Network (DSN). [1] [2]

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In order to engineer a complete solution, certain ground and flight components should be present in the end-to-end design. One technology component is a capability for generating summaries of engineering data onboard the spacecraft. These summaries are needed to quickly provide operators with data associated with important spacecraft events when telemetry downlink is necessary. Another necessary technology component for NASA deep space missions is a capability for scheduling DSN antennas based on events rather than through pre-negotiated agreements.

The beacon monitor technology has been manifested for flight validation on the DS-1 mission as the Beacon Monitor Operations Experiment (BMOX). This activity is currently the focal point in developing the technology. Funding has come through alignment of several technology development efforts within the JPL community. All of the BMOX components and the operational concept will be validated during DS-1 operations. Validation objectives fall into the following categories: (1) onboard engineering summary data generation, and visualization, (2) tone selection, transmission, and detection, (3) multi-mission ground support, and (4) operations concept demonstration and assessment. A detailed set of experiments has been defined. As the mission progresses, BMOX component technologies and the operations concept will be gradually validated and will be made available for use in baseline DS-1 operations. The goal is to provide some vahre-added to mission operations during the prime mission and a capability for full-up beacon operations in extended mission.

2. OPERATIONS CONCEPT

Beacon monitor operations occurs when the **spacecraft is allowed to transmit tones instead of telemetry.** The four tone system does not represent spacecraft state, but rather the spacecraft's assessment of how urgent it is to track for telemetry. For this reason, the basic four tone system described in Table 1 can support most any type of deep space mission

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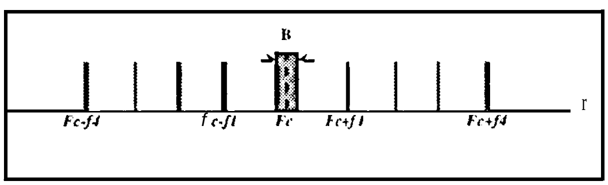
3. FLIGHT SYSTEM HARDWARE

The responsibility of flight hardware is to generate and transmit beacon signals representing the four beacon states. In theory, this function can be supported with a very simple transmit subsystem that has a modulator, an exciter, an amplifier, and an antenna. The telecommunications subsystem for space missions in general is more complicated. The complexity varies from one mission to another and is affected by the coverage requirements, the number of frequency bands, and the redundancy requirements. For the DS-1 mission, the telecom subsystem includes a Small Deep Space Transponder (SDST), a 12.5 W X-band solid state power amplifiers (SSPA), a 2.5 W Ka-band SSPA, two X-band low-gain antennas (LGA), and one dual-frequency X- and Ka-band high-gain antenna (HGA). The gain of the HGA is -25 dBic gain at X-band and 27 dBic at Ka-band. The gain of the LGA is -9 dBic. The SDST is a highly integrated package that includes a telemetry modulator, exciter, and command detector. The DS-1 telecommunications subsystem will be used to generate and transmit beacon signals for the experiment, without modifications.

The four beacon messages are each represented by a pair of tones, centered around the. carrier. These tones are generated by phase-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. Ignoring the higher harmonics results in a slight loss of signal strength. In return, it makes the detector more robust in the sense that reliable signal detection can be achieved without knowing the exact downlink carrier frequency. The SDST has the capability to generate a wide range of subcarrier frequency to represent the four beacon messages. However, the downlink frequency uncertainty and detector complexity together constrain the selection of the subcarrier frequencies. The frequency uncertainty is caused by a combination of on-board temperature variations and uncorrected residual Doppler frequency. For the Beacon Monitor Experiment, the four subcarrier frequencies are 20, 25, 30, and 35 kHz. The signal structure is shown in Figure 1.



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

Figure 1 Signal Structure

4. FLIGHT SYSTEM SOFTWARE

The amount by which beacon monitoring reduces operations cost depends largely on the level of autonomy achieved onboard the spacecraft. Systems that can perform more robust recovery from anomaly conditions and provide flexible onboard data management can achieve the most benefit from beacon operations. The two primary flight software innovations impelmented through the beacon monitor development effort are onboard engineering data summarization and 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 summarization module is a comprehensive architecture for creating summaries of engineering data between telemetry downlink periods.

4.1 Tone Selection

The tone selector module maps fault protection messages to beacon tone states. This module outputs the tone state as a telemetry packet and a message to the Small Deep Space Transponder to actually set the tone. The output of the module can be turned OFF, ON or RESET by issuing a ground command. Tone state always transitions to a higher level of urgency until reset by a ground command. The tone selection module for DS-1 currently consists of 1583 source lines in C and uses 31 Kbytes of memory when compiled for a Power PC series processor. The processing load is all in response to external messages which come at undetermined intervals (less than l/see). The processing time for one message is negligible.

4.2 Data Summarization

Flight software for summarization integrates several techniques into one cohesive architecture for providing operators with information required to analyze spacecraft engineering data. The method for creating the summary data is highly event-driven and uses the data prioritization capabilities built into the telemetry management software. It has been a design goal to integrate the most advanced techniques possible into the architecture. Transforms and adaptive alarm thresholds are key components of an architecture creating top-level summary statistics, episode data (high-resolution culprit and causally related data), low-resolution "snapshot" telemetry, and user-defined data .

Transforms

Each sensor will use a selected subset of the five transforms included in the summarization software package. Those transforms are: minimum value, maximum value, mean value, first derivative, and second derivative. To compute the transforms, the raw data from each sensor is stored in a lag vector of a predetermined length, and the value of the transform is computed across the vector. It should be noted that the first and second derivative transforms are not true derivative functions. The first derivative transform simply computes the rate of change between the first and last points in the vector. Similarly the second derivative transform calculates the rate of change between the difference of the first two values in the vector and the difference of the last two values in the vector. Minimum, maximum, and mean values are also calculated for the first and second derivative transforms. Transforms require more computational cycles than straight limit comparison; however, the time required to perform the mathematical operations is inconsequential.

Using the transforms to determine when an episode should begin provides more flexibility than simply testing the raw data against red-line limits. If an episode were to begin whenever a sensor value moved above/below a certain value, then red-line limit sensing would be sufficient. This functionality, which is adequate for many sensors, is still provided when we use the transforms. By using the maximum and minimum value transforms, we can duplicate the red-line limit sensing. If the maximum/minimum value goes above/below the set boundary, then an episode is started. However, using the transforms also provides this functionality while better handling some cases, where the traditional method would either fail or signal false alarms.

In traditional limit sensing, there is no concept of memory or time in examining values, i.e. an episode cannot be triggered if a value stays above/below a certain level for a certain amount of time. However, this type of behavior can be captured with the mean value transform. A value falling below a limit for too long will reduce the mean, causing an episode to begin. With traditional methods, an episode would occur anytime the value dropped below the threshold, possibly leading to many false alarms.

During nominal spacecraft operation, some sensors may change value in a cyclical manner. Traditional limit sensing would be able to detect when the sensor went above or below its expected values, but would fail to detect the anomalous situation where the value did not change. To handle this case, we could use the first and second derivative transforms, For a constant value, both first and second derivative functions would be zero, signaling that an episode should be triggered.

Adaptive Alarm Thresholds [3]

The current state-of-the-art in anomaly detection is to use limit-sensing, in which the current sensor value is compared against predetermined high and low "red-lines". Such red-lines are typically constants across many or all mission modes and it is difficult to determine tight limits which will work well throughout the mission. Thus, to avoid frequent false alarms, the red-lines are made imprecise, leading to missed alarms and missed opportunities for early anomaly detection.

An alternative to red-line limits is envelope functions learned from historical and/or simulated data. Limits become dynamically changing values instead of static constants. These limits are functional values based upon the values of related sensors and other factors, such as the current operational mode of the spacecraft. Although learning precise envelopes can take longer than determining red-lines, initial loose envelopes can be learned quickly. With further training, the bounds can be incrementally tightened, while still retaining a low false alarm rate. Since the learned envelopes are tighter than red-lines, they have a much lower missed alarm rate. Novel training methods are being employed to avoid bounds which cause alarms in nominal training data, Therefore, these envelopes are loose enough to avoid false alarms, provided the training and validation data are representative.

In order to learn the envelopes, the ELMER (Envelope Learning and Monitoring via Error Relaxation) algorithm will be used. For training purposes, ELMER can be run on the ground using historical spacecraft data, examining both anomaly and nominal data sets in order to determine accurate bounds. For certain phases of the DS- 1 beacon monitor experiment, the ground trainer will produce l imit functions for uplink as shown in Figure 2.

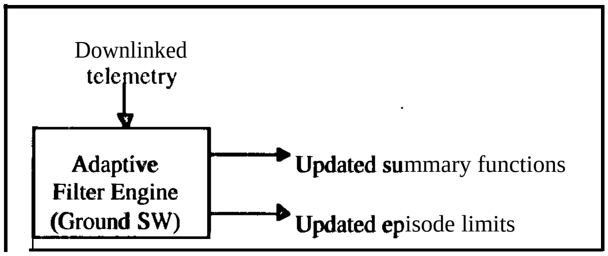


Figure 2 Ground Trainer Software

Flight Software Architecture

The summarizer consists of 3 subroutines: data collection and processing, episode, and mission activity. The data collection and processing module receives data from various domain units via C function calls and applies summary techniques to these data, producing summary measures for downlink to the ground. The Sampler/Summarizer/Episode Identifier module is awakened once per processing interval (1 sec. for DS- 1), at which time it reads the current value of all the spacecraft data items available, computes derived data such as running minimum, mean and trends, checks the raw and derived data against upper and lower limits, starts and ends "episodes" describing out-of-limits conditions, and produces historical and episodic telemetry. It also responds to spacecraft state messages to determine the current spacecraft activity, which determines which set of bounding limits to use. The architecture diagram shown in Figure 3 shows the interlaces between the subroutines and the major constituents of the summaries.

Data collection is performed by providing a central memory array accessible to all flight software. The various flight software modules update the memory array once per second or whenever the data changes, whichever is less often. The update is done by direct write, thus the time for a single update is just a few microseconds.

The episode subroutine looks for anomalies within the data and summarizes all data relevant to the anomaly. The episode subroutine receives summary and engineering data internally from the summarizer/sampler module and compares the data with alarm limits. If the limit is exceeded, the subroutine spawns a new episode and collects relevant data from the summarizer/sampler. This data is in the form of one minute summaries that start five minutes before the episode and end five minutes after the end of the episode. At the end of the episode, the subroutine outputs episode name (out of limit data ID), high limit, low limit, relevant data, start and end times.

The mission activity subroutine determines the overall spacecraft mode of operation. This determination is used to select data and limits for a particular episode in the episode subroutine. For example, solar electric propulsion (SEP) sensor values may be important while using SEP, but if the satellite is in RCS control mode then SEP sensor values could be ignored. In addition, the ACS rate limits might be different during cruise than during a maneuver. As this example points out, it is necessary to use the mission activities to determine which data to use for episode identification. The mission activity is intended to be exclusive. When a new mission mode start message is received, the previous mission mode is assumed to have ended.

The sampler module and its related data gathering module currently consist of 3038 lines of source code and 222 Kbytes 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 DS - l averages out to 30ms.

5. TONE DETECTION SYSTEM

The ground monitor station is fully automated and 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 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 deeded message is then disseminated to the mission operations team and other users. A block diagram of the station is shown in Figure 4.

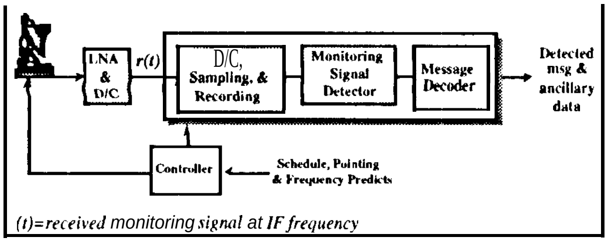


Figure 4 Monitor Station Block Diagram

The signal detector contains four tone detectors, one for each message. 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 frequency, i.e., the beacon tones for a given message will not drift outside of the passband of the detector for that message. Fast Fourier Transform (FFT) 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 5.

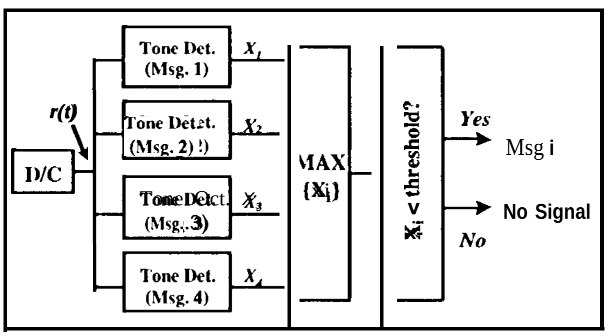


Figure 5 Monitoring signal detector and message decoder

6. TONE HANDLING & REPORTING

The beacon signal detection and message delivery system for the DS-1 experiment is shown in Figure 6. DSS-26 (a 34m DSN antenna) will double as a monitoring station as well as a demand access station. The beacon message is first received and decoded by the remote monitoring station 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 DS-1 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 tone indicates that telemetry tracking is required, the Demand Access Scheduler will schedule a downlink track for the demand station to receive telemetry from the spacecraft. The Scheduler will notify the BMOX team of the schedule. BMOX will in turn 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 command will be transmitted to the spacecraft by the demand access station or by another 34m antenna station to initiate the downlink pass. The downlink telemetry will be received by the demand access station, forwarded to the Mission Operations and the BMOX teams, and analyzed.

7. SUMMARY DATA VISUALIZATION

Moving to a paradigm where downlink is infrequent requires new approaches for data visualization on the ground. The onboard summarization architecture provides data at variable resolution based on total available bandwidth and the number of significant episodes since the last downlink. The operator will need to quickly locate the high resolution episode data and would likely use the low resolution (snapshot) data for gaining overall system context. An incremental development process is being used with an end vision to develop automated software that searches the data for important information identified in the downlink and guides the operator through analysis of that data.

8. ANTENNA SCHEDULING [4]

Current missions using the DSN negotiate tracking schedules well in advance of the launch date. While this approach is adequate for missions that have pre-define tracking requirements, it does not mesh with demand-access paradigm of the beacon monitor approach. Since beacon monitoring requires that the spacecraft initiate tracking, antenna schedules must be formed adaptively. For this reason, automated approaches for enabling low-cost, adaptive tracking of DSN antennas are part of the end-to-end solution. The DSN advanced technology program is supporting beacon monitor operations development by developing methods for automated scheduling and providing dedicated antenna resources that can be used for tone detection, telemetry acquisition and command uplink. Segregating pre-scheduled missions from beacon monitor missions avoids conflicts in scheduling paradigms while at the same time evolving a long-term capability within the DSN to support beacon monitor operations.

CONCLUSION

Concentrating on reducing the downlink offers extremely high payoff for deep space missions. The technology an important. yet practical step in creating advanced mission system designs for low cost operations. As an added benefit, this approach is highly compatible with ongoing work in other areas of spacecraft autonomy and the benefits from using beacon monitor operations are enhanced as space systems become more robust.

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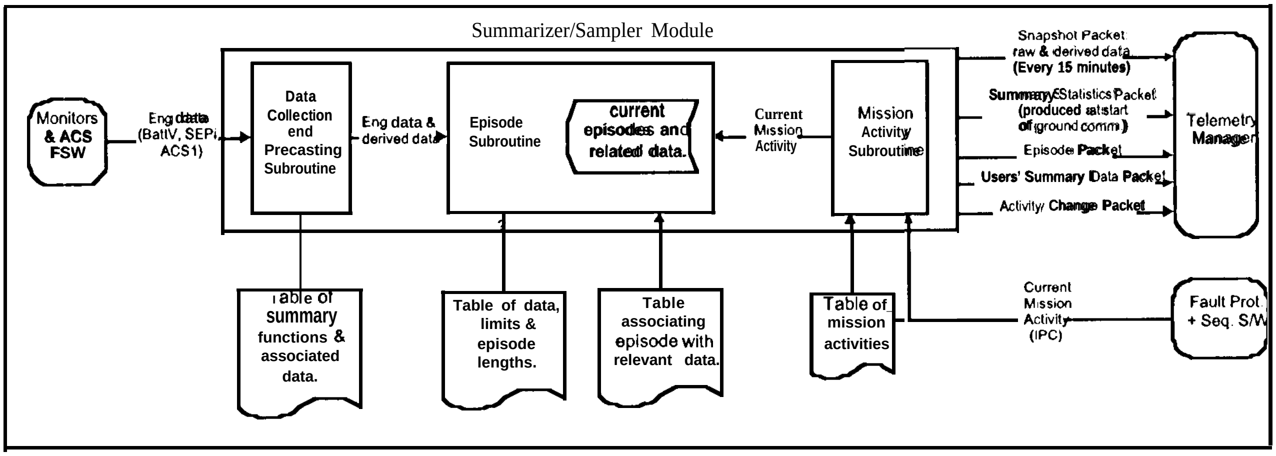

Figure 3 **Onboard Engineering Data Summarization Architecture**

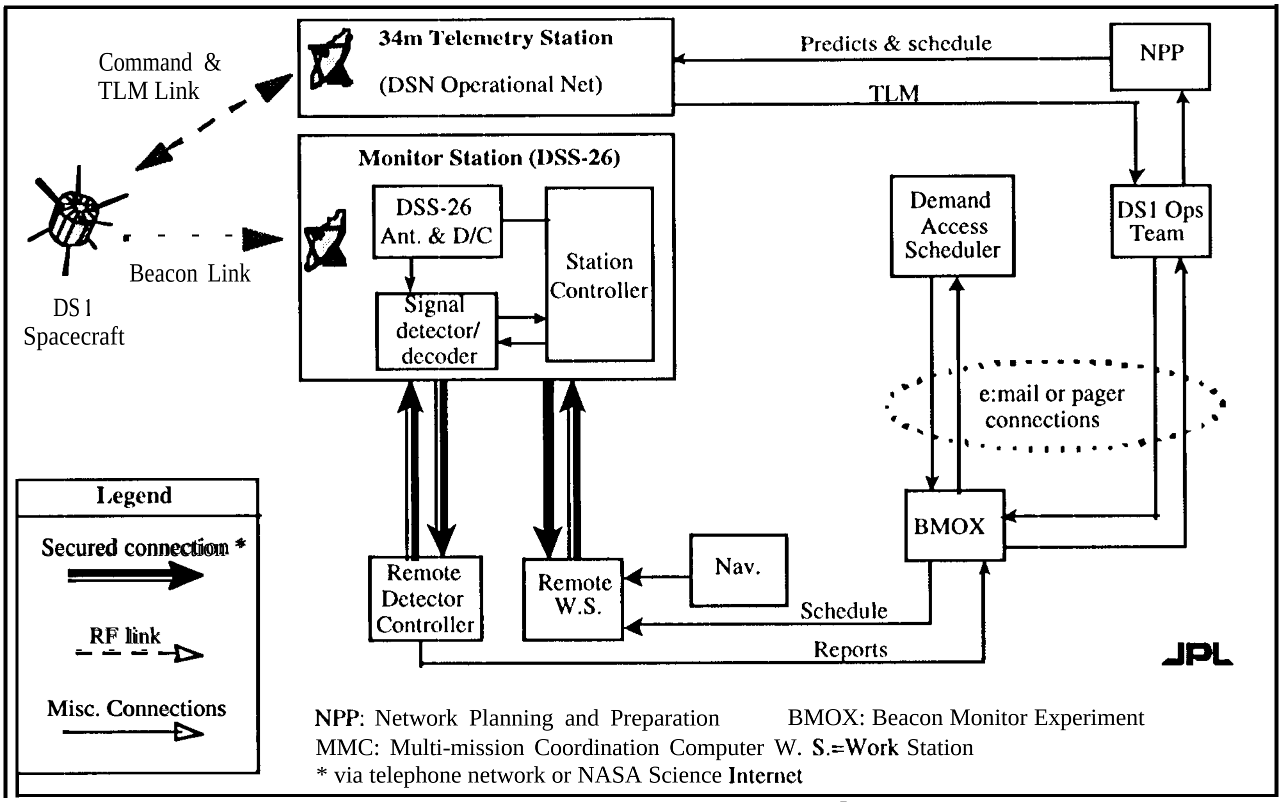

Figure 6 **Signal detection and message delivery system**

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INSTRUMENT DESIGN FOR SUB-PPB OXYGENATED CONTAMINANTS DETECTION IN SEMICONDUCTOR PROCESSING

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Dr. Kin F. Man received his B. SC. degree in physics and D. Phil. degree in atomic physics both in England. He has held research positions at the University of London and the United Kingdom Atomic Energy Authority's Culham Laboratory. In 1987, he was awarded an NRC-NASA Research Associateship to study, among others, electron-ion excitation, electron-atom, and electron-molecule collisions in the Earth and Space Sciences Division at the California Institute of Technology, Jet Propulsion Laboratory. He has subsequently served as the Task Manager for Environmental Control in Microgravity Containerless Material Processing, as part of the Microgravity Containerless Processing Facility Project for the Space Station. Dr. Man is currently in the Reliability Technology Group at the Jet Propulsion Laboratory where he is managing and conducting research and development in various efforts to improve the reliability of spacecraft and their subsystems and components.

Dr. Said Boumsellek received his PhD in physics from University of Paris, France, at the Laboratoire des Collisions Atomiques et Moleculaires. He was a post doctoral research scientist in the Earth and Space Sciences Division at the California Institute of Technology, Jet Propulsion Laboratory, where he was developing detectors with sub-ppb capabilities for trace species, such as explosives and narcotics. He also designed charge particle analyzers for the Discovery space program. Dr. Boumsellek is currently a senior scientist at Ferran Scientific Inc., where he is developing small-size, low-cost residual gas analyzers with large dynamic ranges (10 decades).

ABSTRACT

This paper describes a technique for measuring trace quantities of oxygen and moisture contaminants present in a semiconductor and/or containerless processing environment. Monatomic negative oxygen ions, 0-, formed by electron dissociative attachment through interaction with the molecular oxygen and water, are measured to infer the presence of the contaminants. This technique exploits the fact that the cross section for the reaction is greatly enhanced at the resonant energy. The device built to demonstrate this technique combines a small gridded electron ionizer with a conventional mass spectrometer. The concentrations of oxygen have been measured using the method of standard additions by diluting O_2 in N_2. The lowest detection limit obtained was 1.2 kHz (0- count rate) at a concentration of 10^{-10}, corresponding to 0.1 ppb. Sensitivity calculations for detecting moisture, and electron and ion trajectory modeling using the SIMION program are presented. The detection of trace quantities of water vapor was attempted. The difficulties with handling water in the experiments are also described.

KEYWORDS

Oxygen Detector, Moisture Detector, Contamination Control, Processing Environment, Sub-ppb Detection, Mass Spectrometry, Resonant Electron Attachment, Ray Tracing, Reversal Ionizer.

1. INTRODUCTION

Gaseous contaminants such as oxygen, water vapor, nitrogen and hydrocarbons are often present in semiconductor device fabrication [Ref. 1] and containerless materials processing [Ref. 2]. Oxygen and water vapor are some of the most reactive gases and they therefore have the most adverse effects on the operations. These contaminants arise as a result of outgassing from hot surfaces or they may be part of the impurities in the process gas (even in commercial ultra-high purity gases). Sources of moisture arc usually from chamber wall and silicon wafer resorption, or as reaction by-product. They can cause surface oxide formation, hence affecting the quality of semiconductor devices; or become unwanted nucleation sites in undercooling experiments.

The measurement and control of residual oxygen and moisture at the sub-ppb level in semiconductor processing is crucial to several production lines, such as the production of highly integrated chips (64-Mb and higher DRAMs, for example). The thin film properties can be irreversibly affected by localized defects caused in the presence of these contaminants. In the case of metal films, the presence of oxygen and/or moisture leads to the formation of an oxide layer, causing a decrease in electrical conductivity, a reduction in optical reflectivity, and corrosion of the metal. Real-time in-situ contaminant monitoring enables the deployment of statistical process control to minimize yield loss.

Most commercial instruments for trace oxygen measurement use an electrochemical cell as the sensor element. Solid electrolytic detectors have an oxygen detection limit of around 50 ppb and liquid electrolytic detectors generally have a lower limit. Although the Atmospheric Pressure Ionization Mass Spectrometer (APIMS) can potentially measure below one ppb level for many gas species, its complexity, cost, and size limit its utility. A number of vacuum instrumentation has been used for monitoring moisture. Ionization gauges and residual gas (or partial pressure) analyzers are most commonly used. The exposure of these instruments to moisture during operation can sometimes seriously affect their performance. Some sensors determine moisture concentration by measuring the electrical impedance using aluminum oxide. The sensitivities of these sensors are claimed to be in the low-ppb range. However, in *some* operations, even concentrations below ppb levels have a detrimental effect on the processing where continuous monitoring is necessary. More sensitive detectors are therefore highly desirable.

This paper describes a technique for measuring trace quantities of oxygen and water vapor at sub-ppb levels that utilizes the resonant electron attachment method. This method exploits the fact that the electron dissociative attachment cross section is largest at the target resonance energy, giving a much higher detection sensitivity and enabling lower concentrations to be measured. It also describes the experimental setup for demonstrating this method. The results for oxygen detection will be presented, along with electron and ion trajectory modeling for water molecules, and the difficulties with handling water vapor in the experiments.

2. SENSITIVITY CALCULATION FOR O^- DETECTION FROM O_2

When electrons of appropriate energies collide with molecular oxygen, negative oxygen ions, 0-, are formed. This dissociative electron attachment process can be expressed as:

$$e^- + O_2 \Rightarrow O + O^-$$

The detection of O^- is used as signature for the presence of the contaminant molecular oxygen. In order to evaluate the capability of this technique and to obtain an estimate of its detection limit, wc have performed a calculation based on realistic experimental parameters applicable to our experimental set-up. The detected O^- signal count rate, S (in Hz), from electron attachment to O_2 (in single collision conditions) at the resonance energy is given by:

$$S(Hz) = \kappa \cdot n_T \cdot V \cdot n_e \cdot v_e \cdot \sigma(E) \qquad \text{(Eqn. 1)}$$

where

E is the electron energy, at the resonant dissociative attachment energy, = **6.8 eV (Figure 1).**

$\sigma(E)$ **is the cross section** for O-production at the resonance energy =1.34x 10-*8 cm^2 [Ref. 3, 4].

v_e is the electron velocity at the resonance energy (6.8 eV) = 15.4×10^7 cm. s^{-1}.

n_e is the electron density, estimated to be $2.6 \times 10^8 \, cm^{-3}$ for a 50 mA beam.

V is **the size of the collision region, which is a spherical** volume, estimated to be - $2 \times 10^{-2} cm^3$.

n_T is the molecular oxygen density at room temperature, a quantity to be determined.

κ is the transmission coefficient corresponding to the quadruple mass efficiency and the loss of ions during **extraction, estimated to be -0.005.** This includes the 50% duty cycle.

Assuming a signal rate of 100 Hz is necessary for a reasonable signal-to-noise ratio one may calculate from equation 1 the corresponding value of n_T in the atmosphere to be detected:

$$n_T = 1.86 \times 10^7 \, cm^{-3}$$

This corresponds to a fractional concentration, C, in air of

$$C = 0.68 \times 10^{-12}$$

where

$C = n_I / n_A$

n_T is the molecular oxygen density given above

$n_A = N_A / V_m = 2.73 \times 10^{19} \, cm^{-3}$; where N_A is the Avogadro number (6×10^{23}) and V_m is the molar volume at standard temperature and pressure (22400 cm^3)

This calculation shows that this technique is capable, theoretically, of detecting oxygen concentrations in the sub-ppt level.

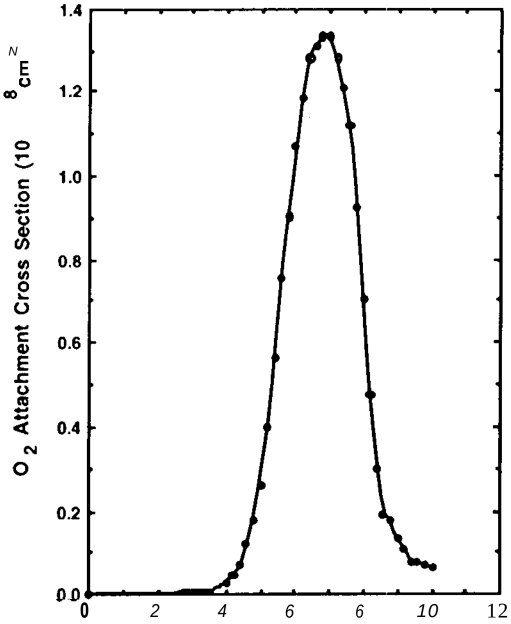

Fig. 1. Cross section for the formation of O^- from O_2 as a function of electron energy. The cross sections are taken from Ref. 4.

3. SENSITIVITY CALCULATION FOR O^- DETECTION FROM H_2O

The dissociative electron attachment process for water vapor can be expressed as:

$$e^- + H_2O \Rightarrow H_2 + O^-$$

A similar calculation of the sensitivity for producing O^- in resonant electron attachment with water molecules was also performed. The resonant attachment cross section is a curve with a peak centering around a resonant electron energy of 10.5 eV [Ref. 5]. The maximum cross section value at the peak is approximately 1.48x 10^{-*8} cm^2 [Ref. 5]. Assuming all the other parameters to be the same as oxygen above and again assuming a signal rate of 100 Hz is necessary for a sigmrl-to-noise ratio of 10 (for an accuracy of 93.390), onc may calculate, from Equation 1, the water density in the atmosphere to be detected:

$$n_T = 1.21 \times 10^7 \ cm^{-3}$$

This corresponds to a tractional concentration, C, in air of:

$$C = ().45X10^{-12}$$

This calculation shows that this technique is also capable, theoretically, of detecting water vapor concentrations in the sub-ppt level.

4. EXPERIMENTAL DESCRIPTION

An instrument was built to detect the monatomic negative oxygen ions, 0-, as signature for the presence of the contaminants. A schematic diagram of the device is shown in Figure 2. Electrons are produced at the filaments F, and arc accelerated through a cylindrical grid G. Within G is an electrically-isolated stainless steel tube T which is perforated by several rows of small holes to allow the oxygen molecules to effuse through.

Potentials on F, G and T arc arranged so that electrons from F are accelerated towards G, then decelerated and reflected near the surface the tube. Around this reversal region electrons have a range of energies from near-zero to several eV, depending on the local equipotential. Electron collisions with the oxygen or water vapor effusing through Tat the appropriate electron energy (6.8 eV for oxygen and 10.5 for moisture) lead to the process of dissociative electron attachment of the contaminant gas species. The resulting negative ions, 0-, are extracted along the length T by the extraction cone EC and lens L_1. Ions are focused with a three-clcmcnt lens system L_1, L_2, and L3 onto the entrance aperture A of a quadrupole mass analyzer (QMA). They arc dctcctcd with a channel multiplier (CM), amplified (AMP), and counted by a single-channel scaler with variable counting time.

The electron acceleration and ion extraction are operated in a pulsed mode with 5070 duty cycle at a repetition rate of 9 kHz. During the "electrons ON" cycle, typically 12 V potential is applied to G. Electrons from F are accelerated through G towards the grounded T and attach to oxygen or water molecules effusing through T. In this phase the voltages on elements EC and L_1 are held at ground so that penetrating fields from these elements do not interfere with fields in the collision region and hence do not distort the motion of the low energy electrons. During the "electrons OFF" and "ions ON" cycle the voltage at G is reduced to - 0.05 V and the voltages on EC and L_1 are both raised to approximately 50 V. L_2 and L_3 are set to approximately 170 V and 40 V respectively (not pulsed) to extract the O^- ions from the collision region.

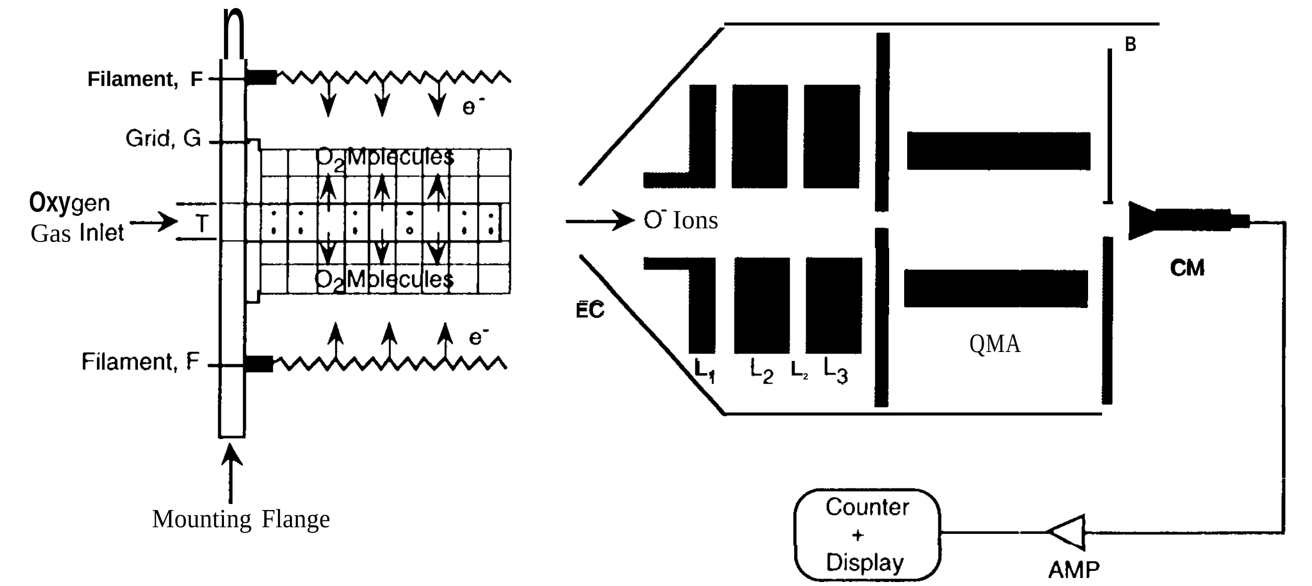

Fig. 2. A schematic diagram of the experimental setup to demonstrate the resonant attachment method

4.1. Computer Simulation For Water Vapor

Ray tracing simulations were performed using the SIMION program [Ref. 6], for the attachment of water molecules by electrons with energies around 10.5 eV. Figure 3 shows the combined trajectories of electrons and 0^- ions, even though the two processes occur at two different time intervals of the experimental procedure. This curve serves to illustrate the effect of the electric fields on the relative trajectories of the electron and ions during the attachment and ion extraction cycles.

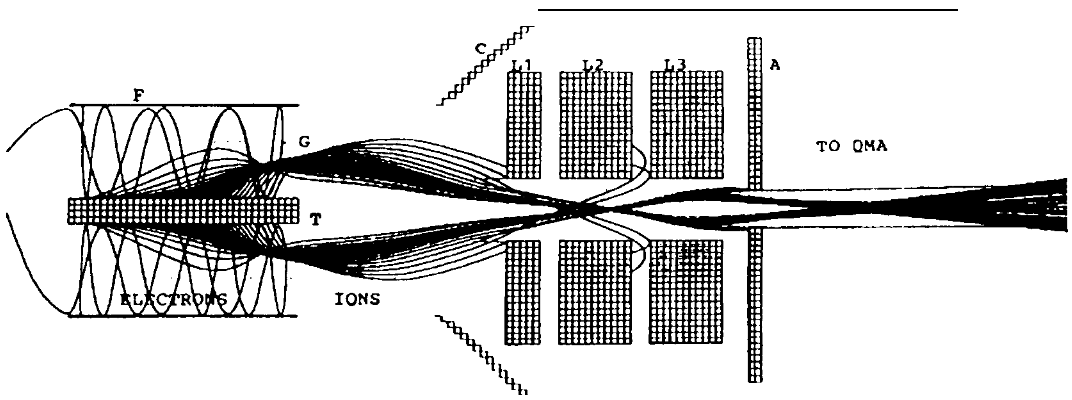

Fig. 3. Ray tracing simulations using the SIMION program for the attachment of water molecules by electrons with energies around 10.5 eV. It shows the combined trajectories of both electrons and 0^- ions.

During the attachment period, electrons arc accelerated by the cylindrical grid (G biased at 50 V) and then decelerated and reversed at the surface of the tube (T biased slightly negative). Electrons with the resonant energy arc available near the surface of the tube. While the electrons arc attaching to the water molecules, the extraction cone (C) and the first lens L_1 are grounded in order not to disturb the electrons trajectories. The simulations show that with the present voltage configuration, the electrons are oscillating between the filaments and the tube. This "trapping" effect allows **the electrons more than** one opportunity to get attached to a water molecule effusing from the tube, thus enhancing its sensitivity.

During the ion extraction period, the grid and the tube arc grounded to prevent interference of the ion extraction cycle by the electrons. The extraction cone as well as the first electrode of the Einzel lens system arc biased positively (100 V). The O^- ions arc launched at different positions along the length of the tube with a thermal energy of O. 14 eV at zero angle. This figure also shows O^- ions being extracted as they are formed along the length of the tube and then focused with the Einzel lens system into the entrance aperture of the mass spectrometer. The potentials on the Einzel lenses are L_1=100, L_2=400, and L_3 =60 V. Calculation of the equipotentials between the filaments and the tube shows that the equipotential with 10 V is parallel and is at 1.5 mm from the surface of the tube.

5. RESULTS

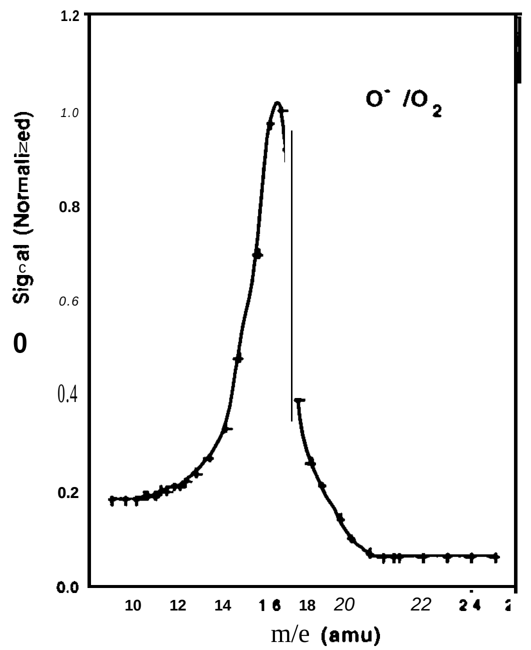

Fig. 4. A mass spectrum of dissociative electron attachment of O_2, showing a peak at m/e= 16 corresponding to O-.

A mass spectrum corresponding to the negative *ions* formed in dissociative electron attachment of O_2 is shown in Figure 4. The peak clearly visible at m/e= 16 corresponds to O-. To determine the analytical capability of this technique, a sensitivity curve was *obtained* using *the* method of standard additions [Ret, 7]. Mixtures 0102 in N_2 (99.99% purity) were prepared at various fractional concentrations C (by particle density) from 1.0 (pure O_2) to Ix1 O-'"‚in a stainless steel vacuum system. All lines were thoroughly outgassed to prevent contamination of the mixtures during preparation. The O_2-N_2 mixture was transferred to the target region which was kept at 2x 10^{-7} torr pressure.

The O^- signal was measured as a function of C and the sensitivity obtained from the slope of the standard-additions plot. These results are shown in Figure 5. Errors in the data represent the quadrature sum of the statistical counting error, and the error in reading the pressure gauges used to make up each fraction. They arc given at the 1.7 CT (90%) confidence level. The O^- signal S(Hz) has a maximum value S=21 kHz in the pure oxygen case (C=1) then decreases uniformly to a value of S=1.2 kHz at C = 1x1 O-10 (O. 1ppb). Below the 10^{-10} concentration, the signal began to fluctuate and a stable reading with the same 90% confidence level was not obtained. Improvements to the stability of the signals in order to increase the measured sensitivity at low concentrations are being pursued. Possible solutions include increasing the electron current (with addition of more filaments) and designing more efficient ion extraction optics.

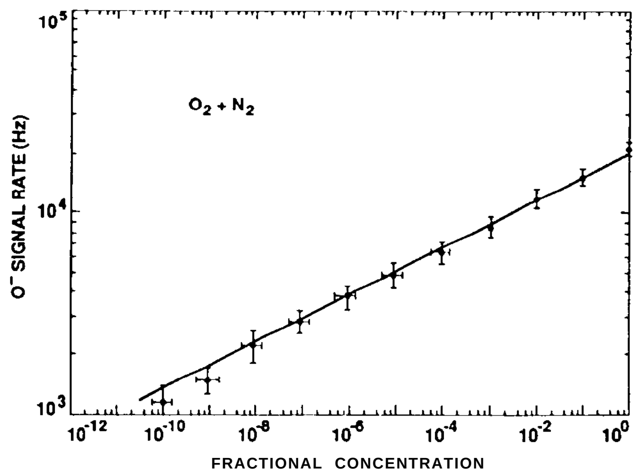

Fig. 5. A sensitivity curve for detecting O^- in various concentrations of O_2 in N_2. The solid line represents a Icast-squares tit to the data.

5.1. Water Vapor Measurements And Experimental Difficulties

Figure 6 shows a mass spectrum obtained by introducing moisture in the attachment region. The spectrum corresponds to the negative ions formed in dissociative electron attachment of water molecules and the peak at m/c= 16 corresponds to 0^- ions. However, sensitivity measurements with water vapor were extremely difficult. The method of standard additions described above for oxygen measurements requires stable mixtures over a long period of time. It was not possible to achieve this with the present set-up duc to condensations of the water along the transfer lines. This led to large instabilities of the output signal, rendering the data unreliable. Consequently, no sensitivity curve was obtained with water vapor despite intense efforts to maintain a heated line to transfer tbc water vapor into the vacuum chamber. Alternative methods arc currently being explored.

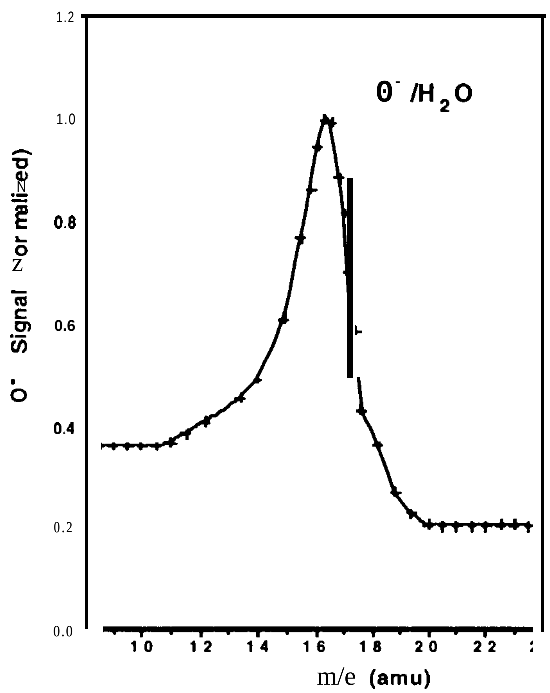

Fig. 6. A mass spectrum of dissociative electron attachment of H_2O, showing a peak at m/e= 16 corresponding to O-.

6. CONCLUSIONS AND DISCUSSION

A technique for measuring trace quantities of oxygen and moisture contaminants present in a semiconductor and containerless processing environment has been developed. Calculation shows that this technique is Capable, theoretically, of detecting oxygen and water vapor concentrations in the sub-ppt level. The device, built to demonstrate this technique, measured a sub-ppb sensitivity level for oxygen, This instrument combines a small gridded electron ionizer with a compact mass spectrometer. The ionizer part itself is no larger [ban a traditional Bayart-Alpert ion gauge. The ion extraction optics and the mass spectrometer (QMA) represent the bulk of the mass. The maximum operating pressure (10^{-5} torr) is primarily determined by the operation of the QMA. In order for this oxygen/moisture detector to be widely applicable to different industries, such as in semiconductor manufacturing, higher operating pressures (in the millitorr range) need to be achieved. A miniature assembly of several quadrupoles, capable of operating up to 10 mtorr [Ref. 8], may be a possible solution. This quadrupole array, mounted on a mini-Conflate flange, makes it ideal to interface to the ionizer. Furthermore, scaling down the dimensions of the ionizer would decrease the path length of the electrons and ions, thus allowing an increase in the operational ambient pressure.

7. ACKNOWLEDGMENTS

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