ABSTRACT
Beacon monitoring is an automated satellite health monitoring architecture that combines telemetry analysis, periodic low data rate message broadcasts by a spacecraft, and automated ground reception and data handling in order to implement a cost-effective anomaly detection and notification capability for spacecraft missions. Over the past two decades, this architecture has been explored and prototyped for a range of spacecraft mission classes to include use on NASA deep space probes, military spacecraft, and small satellites. This previous work has also included formalization of performance assessment metrics to capture the cost and performance of the anomaly detection and notification tasks, thereby allowing a characterization of the suitability of beacon monitoring implementations for specific missions. In this paper, we describe a newly implemented beacon architecture that has been developed and commissioned for operation in support of several NASA and university-class small spacecraft. The architecture consists of a spacecraft with a beacon transmission system, a network of four automated receive-only communications stations installed across the United States, Internet-based ground segment communications allowing centralized processing and logging of all received beacon messages, and a notification service for alerting on-call operators to anomalous conditions. We also present initial operational results for this network as applied to the NASA GeneSat-1 spacecraft, which has been operated by Santa Clara University students since its launch in December 2006. Finally, we describe future adaptations that are planned for this system given its pending use in supporting two additional NASA spacecraft due to be launched later in 2010. To the authors’ knowledge, this is the first example of an operational satellite beacon-based health monitoring network.

INTRODUCTION
Anomalies are unexpected conditions that occur in a functional engineering system [1]. To maintain the functional capability of a system, anomalies must be rapidly detected, precisely diagnosed, and effectively resolved.

For space systems, managing anomalies can be particularly challenging given the system’s complexity, its remote location, and limits on availability, observability, and controllability. Nevertheless, high performance in the detection, diagnosis, and resolution of anomalies is necessary in order to maintain the operational status of systems, which can cost on the order of hundreds of millions of dollars.

Assessing the health, or lack thereof, of a space system has traditionally been done by human operators through the analysis of satellite telemetry broadcast to the ground. This approach can be very costly, however, given the required expertise of the operators, the need to have these operators available around the clock, and the cost of ground segment communication resources [2-4]. Ground automation is often introduced to address this cost challenge. This automation is typically in the form of software-based telemetry limit checking (TLC) which is used to alert, and in some cases to replace, operators. This software often takes the form of an “expert system,” which more precisely is generally a production rule system relying on an experiential knowledge base. Results have shown this approach to successfully address the personnel costs [5-6]; however, it does not eliminate communication expenses given the continuing need for standard telemetry services.

THE BEACON MONITORING CONCEPT
Beacon monitoring has been explored by several satellite operations organizations as a means of addressing communication costs relevant to detecting spacecraft anomalies. In the beacon monitoring concept, depicted in Figure 1, a low data rate satellite “beacon” communicates a small amount of satellite data to the ground. This data is automatically received and processed on the ground such that automated decisions regarding the presence of anomalies are made. If such anomalies are detected, a human operations crew is notified in order to take appropriate action.
The cost advantage for this architecture lies in the low data rate nature of the communications link. The low data rate dramatically improves the downlink’s signal to noise ratio to the point that much less capable (e.g., lower gain and sometimes omnidirectional) and therefore lower cost ground stations may be used; these stations are often simple enough that they may be reliably automated in a low-cost manner. For very simple spacecraft, such as some nanosatellites, a significant number of critical telemetry values sufficient for health analysis might be capable of being downloaded using this approach. On more complex spacecraft, the beacon monitoring concept often assumes the use of on-board telemetry analysis such that a compact health assessment message is produced and communicated through the beacon communications network.

**Prior Beacon Monitoring Systems**

Beacon monitoring has been explored and prototyped for a wide variety of spacecraft missions.

- The U.S. Department of Defense developed their beacon monitoring concept, called “Lifeline,” in the early 1990’s for spacecraft constellations such as the Global Positioning System and the Defense Satellite Communications System [8]. In this concept, a 3-bit health assessment was produced on-board spacecraft and combined with the spacecraft’s ID and position state vector. This message was periodically broadcast at a rate of 10-100 bits/sec, received by automated stations, and forwarded to a staffed central operations center. The concept was endorsed as being an enabling technology for low-cost operations; however, it was not adopted [9].

- The Jet Propulsion Laboratory has explored and prototyped beacon systems for deep space probes during their cruise phase, which may last on the order of years. Their objective has been to use a beacon system in order to reduce standard health contacts by an order of magnitude to a level of one every few weeks. Their early concept was to use a two-bit health assessment broadcast over 1000’s of seconds given the very long communication distances involved [10]. Large parabolic antennae on the order of 8- or 34-meters in diameter would be required, but this was still a dramatic change to the standard use of the Deep Space Network’s 70-meter antennae. A prototype demonstration of this technology was conducted for a period of one month during 1999 on the Deep Space 1 mission [11].

- In the small satellite community, the Sapphire microsatellite [12] was used in the late 1990’s to verify low-cost beacon monitoring technology and to validate its use through comparative evaluation with standard anomaly management techniques. Sapphire used an on-board production rule system [13], periodically-broadcast amateur radio packets, and a custom-built low-cost receive station [14] to implement a demonstration system. While the system was successfully evaluated in ground test, it was never put into routine operational use once Sapphire was launched.

For the work presented in this paper, the satellite in question, GeneSat-1, is so simple that a significant fraction of its critical telemetry is broadcast through the beacon. Filtering of this data is performed on the ground to detect on-board anomalies. Furthermore, the scope of anomaly detection is not just the spacecraft, but also the receive stations, the central workstation, and the human operators; simple anomalies in any of portions of the system are detected and communicated appropriately. In addition, to the knowledge of the operators, this system is the first beacon monitoring system put into standard operation for a space mission.

**The Pros and Cons of Beacon Monitoring Systems**

Beacon monitoring is typically offered as an option in order to address cost issues related to nominal health monitoring operations. Prior work in this area, however, has identified a set of competitive metrics that quantify performance and allow the net value of the use of such a system to be assessed [7].

- **Cost of Notification**: From a cost perspective, cost reductions in real-time contact operations must be balanced with investment in and operation of the beacon monitoring network.

- **Timeliness of Notification**: From a time perspective, the driving issue is the update rate of health assessments; it is often the case that many more health updates/day can be achieved with a modest beacon network.
Quality of Notification: For beacon monitoring systems, quality is driven primarily by the scope and fidelity of the automated reasoning system used to detect anomalies. It may be the case that confidence in such reasoning techniques is such that the quality of automated analysis is considered to be lower than that of a human operator. In such cases, beacon-based health monitoring can be used to extend times between human-based contacts until such time that a human-based contact is required to maintain an appropriate level of confidence. In [7], an analysis is provided to indicate how contact requirements can be modified in order to ensure a required level of confidence in a satellite’s health assessment.

IMPLEMENTATION

The SCU beacon health monitoring network is a geographically distributed network of four automated receive-only communications stations installed across the United States. Each station consists of an omnidirectional antenna, a pre-amplifier, a transceiver, a terminal node controller (TNC), and an Internet connected computer. Data received at each station is forwarded to a data handling system, which also performs orbit prediction, data logging, anomaly detection, and systematic state updates for mission operators. The system block diagram, shown in Figure 2, outlines the connectivity of components, the data path along with the control paths necessary for providing system automation, and the distribution of data handling resources. In conjunction with the GeneSat-1 satellite, a triple CubeSat developed at the NASA Ames Research Center, the distributed beacon health monitoring system has been validated and experimentation with anomaly detection has been conducted.

GeneSat-1 Background

GeneSat-1 served to further understanding of the viability of long-duration human space travel. The E. coli growth experiment was successfully conducted in December of 2006. GeneSat-1, in its end-of-life phase, still serves as a critical component in the current beacon health monitoring network.

Patch and whip antennae are used for S-Band and UHF communications, respectively. The S-Band link is used for commanding and downloading archived data, while the UHF link is used only for transmitting beacon data. GeneSat-1 uses permanent magnets for coarse attitude control. The orbit is roughly circular with an altitude of 300 km and an inclination of 40°.

Beacon packets, consisting of 64 bytes of data

![Figure 2: Receive-only station and full beacon monitoring network diagrams.](image)
represented in hexadecimal, are broadcast using the AX.25 packet protocol and contain key pieces of real-time telemetry and state data. An example of the raw packet data is as follows:

GeneSat1.org17F10F4B0011003E03350026006B009EB3 3A126236F812064002

Included in the packet is telemetry data such as payload temperature, bus time, and solar panel currents, which provide a means to conduct research in anomaly management.

**Receive-Only Station**

Functional requirements of the beacon health monitoring system outline receive capabilities from the distributed stations as sufficient. Thus, the station design goals focused on automation and minimization of maintenance due to limited capacity to physically access station equipment.

**Omnidirectional Antenna.** An omnidirectional antenna was chosen as an alternative to an antenna rotor and pointing system. Although the omnidirectional antenna resulted in a significant performance loss as compared to a directional high gain antenna, this trade-off has proven to be acceptable given the intended system function; the existence of data, even at relatively low frequency, is sufficient to support anomaly detection. The omnidirectional antenna, shown in Figure 3, provides significant reductions in both fixed station and maintenance costs by eliminating the need for a rotor and associated maintenance costs and time.

**Station Automation.** Applications with minimal system computation requirements enable the use of a low-cost netbook to provide a fully functional receive-only station.

Ham Radio Deluxe (HRD), freely available for HAM radio amateurs, provides computer control for commonly used transceivers. HRD is used to automate the Doppler shift compensation needed to receive beacon packets. In addition, HRD provides automatic updating of the most current two-line element (TLE) sets.

The terminal node controller (TNC), which is responsible for data handling prescribed by the AX.25 packet protocol, is connected to the station computer that, in turn, forwards raw beacon information within the beacon monitoring network. The software associated with the data communication and forwarding process also provides the means by which to configure TNC settings as necessary.

Handling of data communication is accomplished through the use of the Creare DataTurbine Ring Buffered Network Bus software server. The DataTurbine, which has also been employed for the implementation of the RSL satellite operations software suite, serves as the medium through which data is transmitted to the central data handling software suite. Along with the functional responsibilities of HRD, Figure 4 shows the flow of data within the software services.

![Figure 3: Omnidirectional antenna setup, showing the pre-amplifier and mechanical stand.](image)

![Figure 4: Functional diagram of the services on the receive-only station computer which provide automated beacon receive tasks.](image)
**Geographically Distributed Network**

There are currently four automated receive-only communications stations installed across the United States. These stations are located at Santa Clara University in California (SCU), St. Louis University in Missouri (STL), Pennsylvania (PA), and University of Hawaii at Manoa in Hawaii (HI). Table 1 presents the deployment date and latitude of each facility.

Table 1: Deployment Date, Latitude, and Packet Summary of Each Receive-Only Station

<table>
<thead>
<tr>
<th>Facility Name</th>
<th>Deployment Date</th>
<th>Latitude</th>
<th>Total Packets</th>
<th>Packets Per Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCU</td>
<td>2010-01-14</td>
<td>37.35 N</td>
<td>733</td>
<td>35</td>
</tr>
<tr>
<td>PA</td>
<td>2010-01-14</td>
<td>40.16 N</td>
<td>121</td>
<td>6</td>
</tr>
<tr>
<td>STL</td>
<td>2010-02-27</td>
<td>38.64 N</td>
<td>256</td>
<td>19</td>
</tr>
<tr>
<td>HI</td>
<td>2010-05-07</td>
<td>21.30 N</td>
<td>48</td>
<td>16</td>
</tr>
</tbody>
</table>

The loss in performance resulting from the use of an omnidirectional antenna is supplemented by including multiple receive-only stations as part of the beacon monitoring system. The geographic distribution, as shown in Figure 5, provides increased coverage and an improved ability to track the real-time state of the spacecraft while collecting data over all four stations. For a single satellite pass, the current configuration of stations is capable of providing a three-fold increase in consecutive line-of-sight time, e.g., 9 minutes for one station vs. 27 minutes from AOS at HI to LOS at PA.

As part of the performance characterization of the beacon monitoring network, Satellite Tool Kit (STK) has been used to log the relative azimuth and elevation of each packet received by a given station. Figure 6 shows the distribution of beacon packets received by the four stations, along with the total number of packets received by each station.

Figure 6: GeneSat-1 azimuth and elevation of beacon packets received by the receive-only stations.

Figure 5: Beacon Health Monitoring Network consists of four geographically distributed receive-only communications stations.
It is worth pointing out that a given station’s latitude constrains the range of azimuth and elevation from which packets can be received. Further, GeneSat-1 characterization data up to this point has revealed that the current receive-only station design performs best when the satellite is above an elevation of 40° relative to a given station.

**Central Data Handling Software Suite**

The central data handling suite, supported by the geographically distributed, automated receive-only stations, represents the core functionality of the beacon health monitoring network. The suite utilizes MATLAB, STK, and MySQL database to provide automated anomaly detection and operator notification functions. Although an instance of the software suite is currently running at SCU, the Internet-based architecture of the monitoring network allows the data handling suite to operate at any location.

STK is used for calculating pass times for contact planning and pass statistics. TLE sets provided by Space Track (www.space-track.org) are automatically retrieved once a day and are used by STK to determine azimuth, elevation, range (AER) calculations for characterization of the beacon monitoring network. Figure 7 shows an example of this STK usage.

A MySQL database instance stores both fixed and dynamic information. Static information includes facility names and locations, satellite names and IDs, and the information of mission operators. Dynamic information includes pass times, raw beacon packet data, incoming and outgoing messages, and anomaly details. This set of information is maintained for the complete process of detecting anomalies and notifying mission operators of any information that provides insight to diagnosing and resolving any anomalies.

The MATLAB/Simulink platform is utilized for the computational tools that ultimately serve as the means by which to accomplish anomaly detection. The Simulink modeling environment will be leveraged for the further investigation of model-based reasoning for anomaly management. A software service, running within the MATLAB Java Virtual Machine (JVM), provides an application interface between the DataTurbine to MATLAB-based functions that provide all data handling functionality. Implemented functions are called when beacon data is published by any of the remote stations. The functions parse, calibrate, and archive data to the system database. Combined with the archiving of data, functions for validating nominal function of the spacecraft and ground station determine whether an anomaly exists and which operators are to be notified for further investigation of the anomaly.

**Implementation of Rules**

Anomaly detection is carried out by a set of predefined rules based on expert knowledge of the overall system. Spacecraft-specific anomalies are monitored by checking data which is available in the beacon packets. Anomaly checking for the ground segment is accomplished by making use of the stored data in the central database.

Packet rules consist of a logic statement constraining the range of a given sensor value. For example, the payload temperature control for GeneSat-1 is designed to maintain temperature at a desired set point to within +/− 1°C. This constraint is implemented by checking the following logic statement:

\[
\text{ExpTempM} > 15000 \ \&\& \ \text{ExpTempM} < 17000
\]

Note that \text{ExpTempM} represents the payload temperature, which is represented in milli-degrees C. Thus, for this case, the nominal operating temperature range is 15 to 17°C.

As another packet rule example, the on-board computer startup counter is included in the beacon packet. The known value is 1, which is constrained using the following statement:

\[
\text{StartupCounter} = 1
\]

If the startup counter value changes, e.g., to 2, indicating a bus reset, the cause of which is a potential
anomaly, further investigation is required and operators are notified appropriately.

Ground segment rules are implemented in a similar manner. Based on the orbit profile of GeneSat-1 and the expected performance of the receive-only network, it is expected that each station receive a beacon packet at least once every 24 hours. Thus, rules are implemented to check that the timestamp of the last packet for a given station is not greater than 24 hours. For example, the rule for the STL station which must hold true in order to ensure nominal operating conditions is as follows:

\[
\text{STLLastBeaconTime} < 24
\]

**Notification System**

The notification system is centered around two primary software functions implemented in MATLAB: an automated email handler which checks email and logs incoming messages with operator info, message content, and message time, and an anomaly checking handler which checks decoded beacon packets as well as various other checks implemented by operators. The interaction between MATLAB and MySQL and operators is shown in Figure 8.

![Figure 8: Interactions between MATLAB, MySQL, and operators showing operator notification and response.](image)

On-call operators are notified upon detection of a potential anomaly. Currently, the notification consists of an email message which includes the time of anomaly detection, the rule or constraint which was violated, the value or relevant parameter which triggered the detection of the anomaly, and a request for confirmation. An example message sent to an operator for the HI (Hawaii) station violating the 24-hour packet rule is as follows:

An anomaly (anomalyid94) was detected at 2010-05-30 20:54:47 (UTC) due to 
"'HI.LastBeaconTime = 30.5056'", which violates 
"'HI.LastBeaconTime < 24'" (ruleid9). Please confirm receipt of this notification message.

Operators confirm receipt of the notification message by replying to the email. Once an operator has replied, all on-call operators, including the operator who has replied, are sent a confirmation receipt, indicating that the operator confirmation was received successfully by the central data handling suite. Upon confirmation of the anomaly notification, it is left to the operations team to decide on what actions are to be taken.

In addition to anomaly notification messages, an on-call operator check-in is implemented, which provides operators with the knowledge that the notification system is working, and it is a way for the automated notification system to know that on-call operators are, in fact, on call. This check-in is performed once a day. If there is no check-in from at least one on-call operator within 24 hours, the entire operations team is notified. On the contrary, if the on-call operators do not receive a check-in notice during a given 24-hour period, it is assumed that there is a potential anomaly with the central data handling suite and/or the associated equipment, and thus investigation into the potential anomaly is required.

**RESULTS**

The beacon health monitoring network has been operational since January 2010, with all four stations running and successfully forwarding beacon data as of May 2010. Part of the experiment has been assessing the acceptability of the data frequency which the current beacon monitoring network provides. Successful detection of various spacecraft and ground segment anomalies has shown that beacon packet frequency on the order of ten packets per week is acceptable. The following sections describe two instances of anomalies and the associated investigations and actions taken for each.

**STL Facility Outage**

A 24-hour timeout flag for the STL facility prompted investigation into the operational status of the station. The inability to log in to the remote workstation prompted correspondence with the STL facility point of contact. It was determined that the source of the anomaly was a lab reorganization, which left the workstation in an unintended, unpowered configuration. Once power was restored, the workstation was successfully checked out and nominal operation resumed.

**GeneSat-1 Temperature Sensor Anomaly**

A described earlier, a rule was implemented to check that the payload temperature was within an acceptable range, given a known set point temperature and a
temperature control tolerance of \(\pm 1^\circ C\). High frequency violation of this rule led to further investigation and it was determined that not only was the temperature sensor data being broadcast in the beacon packet corrupt, but examination of telemetry data downloaded through the S-Band communications link resulted in the realization that payload temperature control had been lost.

The sensor anomaly was determined to be acceptable given the post-experiment, non-critical mission phase. Temperature control was no longer needed and thus the rule/constraint for payload temperature was relaxed (no longer checked).

**FUTURE WORK**

A number of improvements and extensions are being planned for the beacon monitoring system given its pending operational use for a number of additional spacecraft, to include NASA’s O/OREOS and NanoSail-D, both scheduled to launch in September 2010.

First, the receive stations are being adapted to automatically support multiple spacecraft. This requires station radios to be tuned to the appropriate downlink frequencies as a function of the expected contact schedule. Second, a more refined operator notification system is being developed to accommodate varying degrees of alert levels. Third, software-defined radios will be explored as a low-cost alternative to providing easily tunable and consolidated signal processing services within the beacon stations.

Given Santa Clara’s expertise in advanced reasoning techniques for detecting, diagnosing and resolving anomalies, a significant upgrade of particular interest focuses on the reasoning techniques used to perform anomaly detection within the beacon network. In particular, model-based reasoning algorithms will be incorporated into the system in order to provide more precise and focused anomaly detection and to also support diagnostic and anomaly resolution activities within Santa Clara’s satellite operations environment. Furthermore, the incorporation of such advanced reasoning systems on-board the spacecraft is being explored for future missions [15].

Santa Clara will also continue its work in validating the performance of beacon monitoring technology. This will be done by collecting long term performance data and using conceptually formulated performance metrics to assess cost, timeliness and quality of anomaly detection and notification tasks in satellite operations environments.

Finally, beacon technology will be applied to non-spacecraft systems in order to reap its benefits in different domains. For example, the technology will soon be incorporated into the operation of an autonomous bathymetric mapping boat built at Santa Clara and being prepared for estuary and coastal water deployments on behalf of NOAA. The applicability of beacon technology to systems as diverse as spacecraft and boats demonstrates its general applicability in improving the manner in which anomalies are managed in complex engineering systems.

**CONCLUSION**

In this paper, we have presented the design of an operational beacon monitoring system currently in use for routine health operations for the NASA GeneSat-1 spacecraft. The system consists of four automated, receive-only communication stations located across the United States, Internet ground segment links to the Santa Clara University operations facility, a central workstation that archives messages and performs anomaly detection functions, and an on-call satellite operations team. To the knowledge of the authors, this is the first operational beacon monitoring network. In addition, it is unique in that the scope of its anomaly detection analysis consists not just of the spacecraft but also of the communication stations, the central server and the operations team. The system has successfully detected and notified operators of a number of operational anomalies. A number of extensions are planned for this system in order to improve its cost-effectiveness, and the system will be used for routine operations for two new NASA nanospacecraft due to be launched later in 2010.

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