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Title: *The Potential for Health Monitoring in Expandable Space Modules: the Bigelow Expandable Activity Module on the ISS* for Proceedings of the **11th International Workshop on Structural Health Monitoring 2017**

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(FIRST PAGE OF ARTICLE)

ABSTRACT

Expandable modules for use in space and on the Moon or Mars offer a great opportunity for volume and mass savings in future space exploration missions. This type of module can be compressed into a relatively small shape on the ground, allowing them to fit into space vehicles with a smaller cargo/fairing size than a traditional solid, metallic structure based module would allow. In April 2016, the Bigelow Expandable Activity Module (BEAM) was berthed to the International Space Station (ISS). BEAM is the first human-rated expandable habitat/module to be deployed and crewed in space. BEAM is a NASA managed ISS payload project in partnership with Bigelow Aerospace. BEAM is intended to stay attached to ISS for an operational period of 2 years to help advance the technology readiness for future expandable modules. BEAM has been instrumented with a suite of space flight certified sensors systems which will help characterize the module's performance for thermal, radiation shielding and impact monitoring against potential Micro Meteoroid/Orbital Debris (MM/OD) providing fundamental information on the BEAM environment for potential health monitoring requirements and capabilities. This paper will provide an overview of how the sensors/instrumentation systems were developed, tested, installed and an overview of the current sensor system operations. It will also discuss how the MM/OD impact detection system referred to as the Distributed Impact Detection System (DIDS) data is being processed and reviewed on the ground by the principle investigators.

INTRODUCTION

From the beginning of NASA, there has been interest in maturing expandable/inflatable technologies that offer strategic advantages over traditional rigid material habitat designs. Notable projects ranged from Echo 1 in 1962 [1] up to the Transhab in 2000 [2,3] and Bigelow Aerospace's unmanned modules Genesis

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I and Genesis II launched in 2006 and 2007, respectively [4,5]. The advantages of these types of structures include: a) small launch volume to habitable expanded volume ratio, b) low launch mass, and c) opportunity for lower launch cost. In addition, habitable structures must provide environmental protection for humans once the habitat has been deployed, providing shielding against MM/OD impacts, ionizing radiation and provide thermal isolation.

The Bigelow Expandable Activity Module (BEAM) is an International Space Station (ISS) Payload project which is a collaboration between the National Aeronautics and Space Administration (NASA) and Bigelow Aerospace [6-8]. The BEAM project is important because it represents the first time an inflatable habitable module will become a part of a crewed system. As a part of this collaboration, NASA instrumented the BEAM module with various sensor systems to characterize the module's performance in a low earth orbit environment while berthed to the ISS Node 3 Aft port over a 2-year operational period. During the majority of the operational period, the BEAM will remain with its hatch closed, with scheduled ISS crew ingresses for periodic sensor removal and replacement, microbial air and surface sample collections, and planned sensor tests.

SPACE FLIGHT CERTIFIED SENSORS SYSTEMS

BEAM Sensor/Instrumentation Operations and Installation Overview

The BEAM structural health monitoring instrumentation systems are comprised of the following wireless instrumentation systems that were developed specifically for spaceflight applications: 1. Deployment Dynamic Sensor (DDS); 2. Distributed Impact Detection System (DIDS); and 3. Wireless Temperature Sensor (WTS).

The DDS system was used for characterizing the acceleration environment of the BEAM Aft Bulkhead during the inflation deployment of the module while attached to ISS Node 3 Aft. The DDS hardware was the only ground installed system inside of the module. Other systems (WTS and DIDS) were installed by the ISS Increment #48 commander, Jeff Williams, after the module had been inflated and the inside was accessible to the crew for ingress. The other systems had to be installed by a crew member once in the inflated configuration. This avoided the risk of damaging the inside air barrier surface layer of the module while expanding from a compressed volume state to the fully inflated module state. To help ease the level of difficulty for the on-orbit sensor/instrumentation installation, the hardware had been pre-configured into kits and the internal BEAM air barrier had been pre-marked on the ground to identify where each of the sensors needed to be installed. Refer to Figure 1 for an example of the BEAM sensor air barrier marking. The installation was designed to be straight forward so that the crew member could take a kit bag and install all of the components easily onto the interior BEAM walls using loop & hook Velcro fastener, Polyimide (Kapton) & double-sided 3M 966 transfer tapes.

Deployment Dynamic Sensor (DDS)

The Deployment Dynamic Sensor system consists of a set of three small, low-power, battery-operated accelerometer data acquisition (DAQ) units, piezoelectric charge

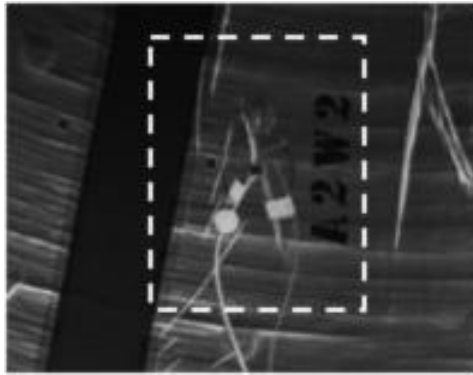


Figure 1: Example of BEAM sensor marking with an accelerometer and RTD installed.

output accelerometers, a RF transceiver, and associated flight software. The DDS, which is mounted to internal BEAM Aft bulkhead structure (see Figure 2) prior to launch, was commanded/pre-set to collect tri-axial acceleration data during the module inflation period. Data is stored in local memory until BEAM is safely inflated and crew is ready to ingress. The data is then transferred to the Station Support Computer (SSC) utilizing a USB cable plugged into the port of the DDS and downlinked to the ground for review. On May 26th, the three DDS units were programmed by ground controllers to start data acquisition mode at a scheduled time on May 27th to capture the BEAM deployment event. The module was expanded on May 28 over the course of seven hours, ment event. On May 28th, the BEAM deployment was with air being injected 25 times for a total of 2 minutes 27 seconds. [6]. Each of the DDS units recorded ~10 hours at a 1KHz sample rate of accelerometer data for each of its channels to non-volatile memory. The DDS data was downloaded/downlinked once the crew had ingressed on June 7th, 2016. Refer to Figure 2 for DDS location on the BEAM internal aft bulkhead surface.

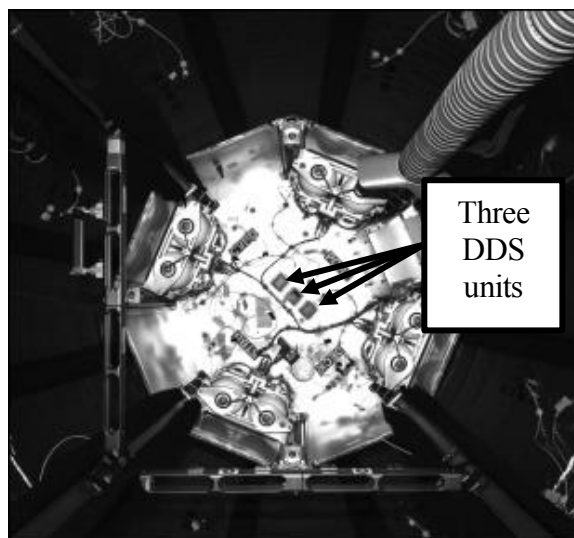


Figure 2. Three DDS systems installed on BEAM Aft bulkhead

Distributed Impact Detection System (DIDS)

The Distributed Impact Detection System (DIDS) consists of a set of small, low-power, battery-operated accelerometer data acquisition units, accelerometers, a wireless transceiver and associated flight software. Refer to Figure 3 for a photo of the DIDS Kit contents. On June 7th and 8th, a total of four DIDS DAQ units were installed internal to the BEAM; one of the four units was installed on the aft BEAM bulkhead, and the other three were installed on the inner shell soft goods of the BEAM (see Figure 4). The DIDS units were adhered to the surfaces using Velcro dots. The piezoelectric accelerometers associated with the DIDS unit on the aft bulkhead were installed on the bulkhead prelaunch, secured by a bolt attachment. The piezoelectric accelerometers associated with the DIDS units on the inner shell soft goods were mounted using double-sided 3M 966 transfer tape to pre-marked circle locations inside of BEAM (see Fig. 1). These locations were pre-coordinated on the ground and based on the highest Micro Meteoroid/ Orbital Debris (MM/OD) predicted impact risk locations.

Once mounted to internal BEAM structure, the DIDS units will detect and record structural impacts from both MMOD and internal vehicle activity events. Each DAQ unit (1.71" X 1.72" X 0.82"; 34 g) has 4 input channels for piezoelectric accelerometers, a local processor and memory, and an RF transmitter. The DIDS units were built to record 270 ms of data at a 30 KHz rate simultaneously on all four channels once triggered. Each unit is triggered independently of the other units. The interest in sampling at this high rate was based on ground hypervelocity testing results, which showed that higher frequencies were created by significant damage levels on the restraint layer. Thus, detection of these higher frequencies could be necessary for purposes of predicting the scale of hidden damage on the restraint layer. Each unit is powered by the Extended Life Battery Assembly (ELBA). DIDS units remain in a low-power "sleep" mode until a trigger event wakes them, at which point they transmit event data via RF (915 MHz) to a wireless transceiver installed post inflation in the BEAM. Data is then passed to the ISS laptop through bulkhead connectors from the BEAM module to the SSC USB port residing in Node 3.

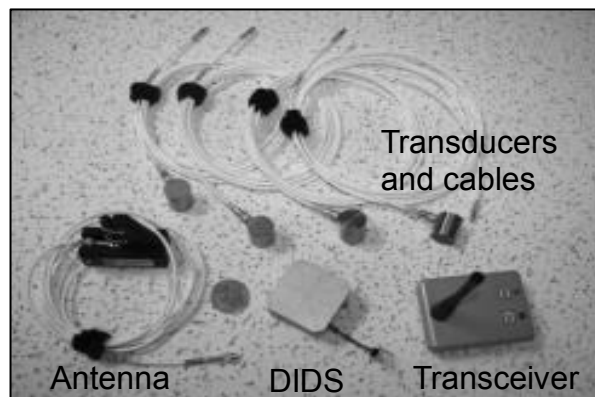


Figure 3: DIDS Kit contents (DIDS sensor unit, Antenna, Transceiver, Transducers and Cables).

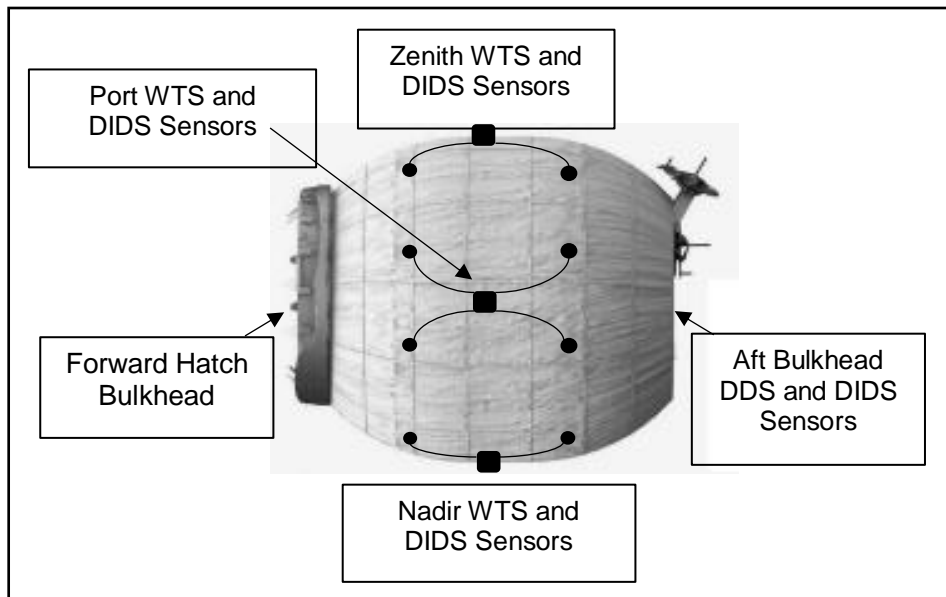


Figure 4. Graphic showing an exterior view of the BEAM mockup module overlaid with the relative locations of WTS, DIDS and DDS sensor units (which reside on the BEAM interior). The square symbols represent the DIDS and WTS sensor units' locations while the solid dots represent the related accelerometers and the RTD transducer locations on the interior wall. There is a set of WTS sensors on the Starboard side which mirror the Port side sensors, but are not seen in this figure.

Hypervelocity impact testing of a mock up section of the BEAM's wall was performed at NASA's White Sand Test Facility. Wave speeds in the BEAM mockup section were also measured during those tests. The restraint layer wave speeds were also derived from the Modal test on orbit and helped to confirm the ground based testing results. The anisotropic velocity behavior indicated a biaxial directional dependence of sound in the restraint layer. This general behavior was expected based on the construction of the restraint layer.

On Feb. 28, 2017, there was an event that triggered all three of the DIDS units that were on the BEAM's soft goods. Most of the accelerometer channels recorded signals in the range of 1 to 3 g's of acceleration. Figure 5) shows the early time and frequency response result of the acceleration signals on the channel 2 transducer of the Zenith DIDS sensor set. This accelerometer data received in the BEAM, can be more challenging for processing as the BEAM is not a simple shell structure, but is a more complicated multi-layered structure. If the MM/OD material does not impact the restraint layer directly, then the sound must travel a complicated path to that restraint layer and that requires several assumptions for location of the impact event. If it is assumed that there is a unique epicenter for the event with respect to restraint layer, one can set up a set of time-of-flight based equations that can be used to estimate a location and then use a search algorithm to find the best solution to that set of equations. One extra piece of information from this particular event is that the frequency content for this event showed more high frequencies on the Zenith region (See circled area in Figure 5b). Our ground testing has confirmed for us that higher

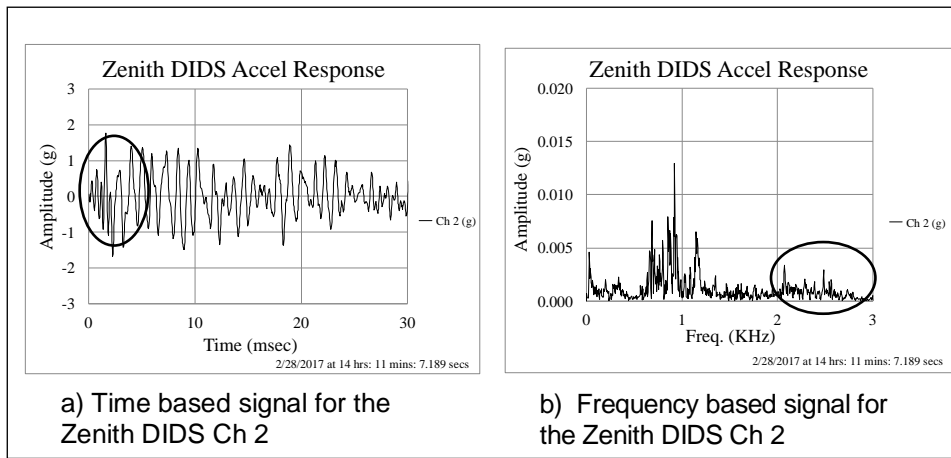


Figure 5. (a) The initial time response on the zenith DIDS unit, channels 2. (b) The corresponding frequency behavior for the Zenith DIDS unit, channel 2.

frequencies tend to be attenuated more strongly with distance travelled than lower frequencies. A review of the Port sensor channels showed that they had lower levels of higher frequency amplitudes than the Zenith sensors. Similarly, the Nadir sensor channels had lower high frequency content than the Port channels. This suggests that the epicenter of this event was in the Zenith region and that the sound wave's high frequency energy was attenuated more and more as it moved through the Port region and then into the Nadir region.

In the time domain, none of the channels provided an obvious unique phase point for reference for source triangulation. As a way to handle this data, a correlation of the data with a short time narrowband signal was used to produce a signal where a phase referenced point could be better tracked. Inspection of the frequency content of all the channels on the three triggered sensor units indicated that a major frequency component for this event occurred at 0.9KHz (See figure 5a), which provided a good the reference signal to process at. For additional simplicity, we chose to approximate BEAM's shape as a cylinder rather than the prolate spheroidal shape that it looks like. This made the time of flight equations easier to set up. The search algorithm indicated the best solution was an event on the Zenith region a little bit toward the Zenith, channel 2 transducer.

To try to corroborate this answer, External High Definition Camera (EDHC) views of the exterior of the BEAM were sought for review for any visible damage to the outer layers of the BEAM. Only the Port side of the BEAM has such a camera view (see Figure 6). From that view-point, we were able to detect a potential MM/OD strike indication on the lower Port surface of the BEAM, but it was not a new event. Evidence of that MM/OD strike was first seen back on 09/21/16. Unfortunately, the EDHC system gave very little viewing area of the Zenith region, which did not enable us to detect the suspected surface area predicted for the DIDS trigger, but it did confirm that this new event was not on the Port side.

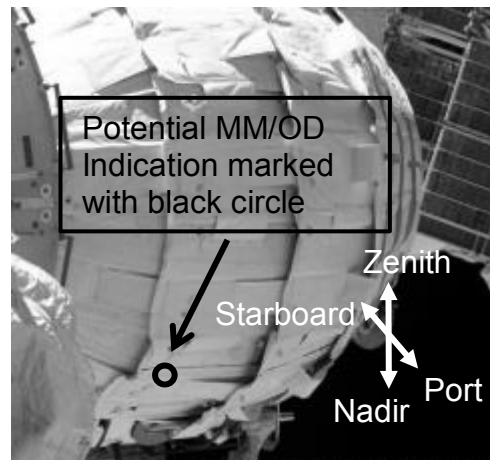


Figure 6. Potential MM/OD strike location marked with the double circle taken with External High Definition Camera EHDC P1LOOB; photo taken on 09/21/16

Wireless Thermal System (WTS)

To help characterize the BEAM internal thermal environment during the 2-year operational life, a battery powered, thermal data acquisition system called the Wireless Temperature Sensor (WTS) (refer to Figure 7) will be used to take 16 independent Resistive Temperature Device (RTD) temperature readings at a sample rate of once every minute per channel. The WTS system hardware was installed inside of BEAM on June 7th and 8th by the ISS crew and has been collecting internal BEAM temperature data since installation. The WTS record the temperature data to local non-volatile memory and the engineers with Limited Ground Users access download and downlink their data on a monthly basis to ground for the thermal analysts to review. Wall temperature is important since if cold spots should form on the BEAM wall, then moisture can condense on the wall and that would be a possible site for unwanted microbial growth.

The WTS units were mounted using Velcro dots to the internal BEAM surfaces, and the RTDs were attached using Kapton tape to pre-marked locations. Each RTD was taped inside of the pre-marked circles. Each DAQ has 4 RTD channels and is powered by the Extended Life Battery Assembly (ELBA) via external connection.

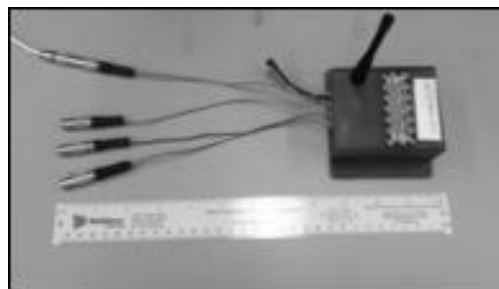


Figure 7. WTS sensor unit

Data will be stored in local memory until wirelessly commanded to transfer the data to the Station laptop. Note that the WTS shares a RF transceiver inside the BEAM with the DDS, however, the DDS and WTS will not be using the same transceiver concurrently.

CONCLUSION

The ISS-BEAM collaboration has historical importance as the first demonstration of a crewed inflatable habitat module in space. This demonstration will help open the doors to the use of inflatables in many future applications such as deep space human exploration (e.g. en route to Mars or asteroid) and for planetary habitats (such as Moon or Mars). Since June 2016, NASA has been monitoring the “vital signs” of the BEAM module on orbit, both to verify performance characteristic of the BEAM as well as obtain experience with hardware systems that could be valuable for monitoring future inflatable habitat structures. In addition, this work will help ensure flight safety by giving NASA experience in addressing issues that inflatables will face. Success in this environment offers significant potential for enabling mankind’s expansion of space exploration.

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