The Spacecraft SHM Experiment, Part 1: Development for Space Flight

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Structural Health Monitoring (SHM) technologies have been under development for decades as an enabler of condition based maintenance (CBM), with the goal of providing damage detection capabilities to facilitate remaining useful life estimates. The spacecraft industry has applied these tools to some manned systems as a way to detect potential risk factors early-on and alert personnel to repair. Satellites however, are not designed to consider maintenance, thus the motivation for SHM technologies on unmanned spacecraft are considerably different. Here, the focus is on providing greater insight into the state of the structure as it is built and flown to quickly diagnose any anomalies. This paper discusses an experiment being developed at the Air Force Research Laboratories utilizing commercially available SHM hardware. Technical challenges will be discussed along with details into the planned experimental campaign.

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I. Introduction

Structural Health Monitoring (SHM) is a form of Non-Destructive Evaluation (NDE) that utilizes permanently integrated sensors to feed an onboard data acquisition unit. SHM system can incorporate embedded algorithms for assessing and characterizing damage states, and is meant to limit the need for highly trained experts performing manual data collection and interpretation. The business case for terrestrial applications SHM is driven by Condition Based Maintenance (CBM). This approach would allow systems or structures to transition away from scheduled based maintenance, where service is done based on a risk derived timeline to ensure critical components are serviced or repaired before their design life reached maturity. Such an approach results in very expensive Operation and Maintenance (O&M) budgets, especially for US DoD systems. Air and ground vehicles for the US military are exposed to harsh environments and conditions and, as a result, are required to be serviced regularly. For example, the UH-60A Black Hawk has three levels of maintenance: unit, intermediate, and depot. While the first two are done at the base site, the third requires special facilities. Basic preventative services take 15 to 20 man-hours and is required every 40 hours of flight [1]. Additionally there are interval schedules for various subsystems done every week, month, and quarter. With these types of schedules, the benefits of CBM are clear, allowing for service only when it is actually needed. However, for space assets the traditional maintenance payoff decreases. Spacecraft are usually designed to survive an extreme launch environment only once. This lasts up to 45 minutes for GEO payloads and less for lower orbits. Once in space, structural loads are typically only of concern to deployed hinges or components vulnerable to thermal expansion effects. Space assets are therefore over-designed to ensure that required stiffness and boundary conditions will be maintained. A comprehensive reference of where spacecraft where not properly designed and the resulting mission impact is available in literature [2]. When damage does occur to a system, the costs of repair are astronomical. The Hubble Space Telescope servicing mission is a great example, in that the costs to repair the faulty system was over $500 million. This figure doesn't include the cost of transportation, operation, and analysis [3]. So if maintenance during service life is impractical for permanently placed space assets the question becomes focused on the utility of SHM to spacecraft. Authors have already focused on this topic in previous literature [4,5] which can be effectively summarized in the lower figure.

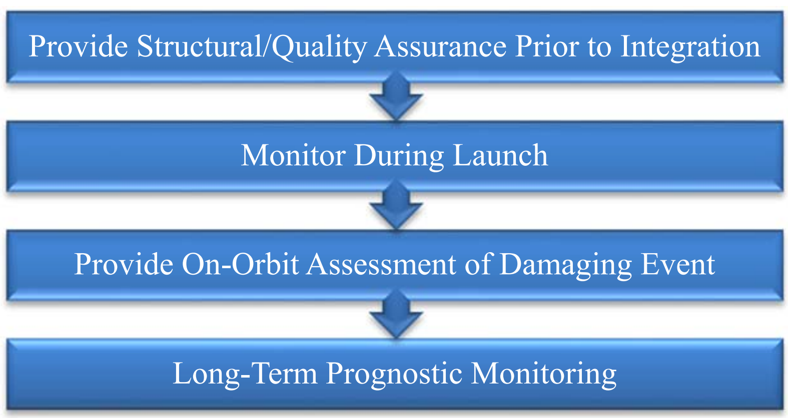

Figure 1 Staggered SHM benefit to space assets

The greatest benefit of SHM is achieved during the Assembly, Integration and Test (AI&T) phase where the system can be monitored in real-time or on-demand as it assembled, stored, transported to various sites, and tested for qualification prior to being integrated with a launch vehicle. Capturing problems before launch can all be repaired. Although repairs may require disassembly and therefore result in schedule slip and possibly additional testing, it is likely cheaper than the cost impact of a failed mission. Additionally, much of the testing done during AI&T is a global test, where pinpointing causes to poor test results require reverse engineering to estimate sources or even disassembling until the root is identified. SHM can be applied to critical areas of interest to provide localized hot spot monitoring over the entire structure. While the first response from the traditional space community would be focused on Size Weight and Power (SWaP), it should be noted that many payloads utilize parasitic ballast weight to shift the center of gravity, and current SHM hardware has been developed that weighs less than a 1 kg and can be integrated in the small spaces usually wasted on spacecraft to provide access and routing. Once the system is integrated, removal becomes impractical since many components would not be accessible without disassembly. By integrating the data Acquisition (DAQ) hardware onto the satellite, it can then be utilized after AI&T.

The next payoff therefore comes from the launch phase. This is a challenging technical issue as most spacecraft are launched unpowered to prevent potential electrical errors that may jeopardize the launch. However, by monitoring loads during launch two things may be achieved. The first is a validation of modeling done prior to launch assessing the accuracy of Coupled Loads Analysis (CLA). Given the safety margin that is applied for space assets, it is expected that we would find significant mass saving opportunities by designing to the actual environment rather than the bloated required values. Additionally it may alleviate concerns with new standard components. The second benefit would be capturing damaging events as they occur so that design changes can be considered for future systems or so operations teams can properly mitigate risk with certain operations once on orbit. This could be the case for deployable secondary appendages where deployment may be delayed to allow all other missions to be accomplished before risking impact from faulty hardware, as was seen for example on the MARSIS satellite [2].

Once a system is operational, there is not much that can be done about any detected damage. However, when anomalies occur, satellites are typically placed into a safe mode and a team of scientist and engineers are required to evaluate and correct the issue. GOES 13 experienced an attitude disturbance in May 2013, which resulted in over 3 weeks of safe-mode operations while a team diagnosed the problem. The final theory is that the system was hit by debris on its solar panel. NOAA 17 went through a similar event in 2005, and while it was also attributed to debris, later repeats confirmed it was a fuel leak [6]. The utility of SHM in this scenario would have been either the recording of the impact event utilizing acoustic emission through the structure, or in a post event scan of the system using guided waves after the anomaly. Both methods could have been performed and analyzed minutes after the anomaly and, if it was an impact event, GOES could have been returned to an operational state that day, instead of swapped out with a backup GOES system and commissioning of a standing army of forensics personnel.

The final payoff then becomes prognostic monitoring of the system during its mission life. In the event of an impact, MLI may be destroyed, deployed appendages may be damaged or communication system apertures compromised. SHM can be used to assess the extent of damage and evaluate the Remaining Useful Life (RUL) of the system as it operates at continued non-optimal states. This would then give mission planners time to change future operation configurations or plan replacement/supporting systems. However, to get the space industry to implement a non-traditional system is no trivial task, especially if that system has no primary mission function and is only supporting. This was the motivation behind the present Spacecraft SHM experiment.

SHM can be performed with a variety of sensing technologies including: traditional structural characterization sensors (strain, temperature, pressure, and acceleration), Piezoelectric Wafer Active Sensors (PWAS), fiber optic sensors, and electrical property (conductance, resistance, dielectric, etc.) sensors. There are also several companies that provide commercial systems that can be used for SHM. Acellent Technologies Incorporated patented the Smart Layer approach that is able to provide users with a complex thin layer patch with embedded sensors and wiring network to trace back to a centralized DAQ system with embedded SHM software.. Mistras Group Inc. developed a completely wireless battery powered SHM system for civil applications using ultrasonic transducers. Many other companies can be found participating at the biannual International Workshop for SHM at Stanford or the European Workshop for SHM during the “SHM in Action” demonstration exhibit. The most recent lists of participants are generally available online [7]. The particular technology that was identified as a viable commercial product demonstrator for SHM on spacecraft was the MD7-Pro Digital SHM System developed by the Metis Design Corporation under USAF funding[8]. The selection of this particular hardware should not be considered an endorsement from the USAF, and readers are encouraged to check with recent developments from numerous hardware providers. For the interest of this mission, the MD7-Pro system met most of the principal investigators needs with the least amount of additional work. Details of the experiment are provided in the following sections.

The SHM experiment will fly on two different systems. The first will be as part of the DoD Space Test Program’s STP-H5 payload. STP-H5 is attached to an ExPA (Express Pallet) and will attach to the International Space Station’s ELC-1 (Express Logistics Carrier). There will be 8 nodes on this structure supporting 56 PZT elements, 12 accelerometers and 30 temperature sensors attached to the common structure of STP-H5. STP-H5 is currently slated to launch as part of the SpaceX 10 Mission in 2016. The second space flight platform that SHM is involved with is the Evolved Expendable Launch Vehicle (EELV) Secondary Adapter (ESPA) Augmented Geostationary Laboratory Experiment (EAGLE) space flight program. SHM will likely be flying onboard the ESPA-based spacecraft bus (EAGLE Platform) which is scheduled for a period of at least one year in geosynchronous orbit. The EAGLE Platform utilizes a six-port standard ESPA ring as part of its structure, thereby improving launch access to geosynchronous orbit, as well as providing a cost-effective modular platform that could be used for Geostationary Transfer Orbit (GTO) or enabling payload hosting for low-orbit operations [9]. The current plan is to integrate 24 nodes onto EAGLE supporting 168 PZT elements, 72 temperature sensors, several single axis and tri-axis accelerometers, and microphones. The rest of the present paper will focus on the development of the experiment and the testing done to date required to ruggedize commercial hardware for space use.

II. Experiment CONOPS and Challenges

Each mission will have both unique Concepts for Operations (CONOPS) based on the operational environment and program setup and others that overlap. The purpose of these functions is to provide analysis on the utility of SHM to different space systems and identify technical issues that need to be addressed for future systems. The mission operations for both systems are generalized as follows:

System setup and optimization (Both): Every SHM sensor setup has some optimal settings that best function for the structure it is mounted to due to the unique resonances and feature inherent in every system. For both of these experiments, SHM is a hosted payload and not part of the spacecraft design process. Therefore traditional modeling approaches used to define optimal sensor placement can't be easily utilized. Each system is packed with hardware and cable routing which often changes during the design process and hinders sensor placement. Therefore each experiment focused on sensor distribution that provided the most coverage within the allowed SWaP envelope. Once nodes are placed the first step is to execute a chirp scan of each node to identify strong and weak frequencies for future focused scans to operate at. Measurement windows will also be sized based on the sensing range of interest and used to reduce data file sizes.

Monitor assembly of the bus in real-time (STP-H5): The STP program is unique in that it focuses heavily on achieving as much science and integrating as many components as possible. Since it is mounted to the ISS, it is a less complex structure than free-flying spacecraft that require more systems (propulsion, attitude control, power, etc.). This gave the present authors the choice of being the first hardware mounted to the pallet. Once attached we will coordinate a constant measurement cycle to run during assembly of the bus with other payloads. A dedicated Graphical User Interface (GUI) is under development to manage the data as it comes in and analyze changes as bolts are tightened. The present authors have shown the ability of SHM to track bolt load very precisely in the past on similarly complex structures [10] and this will allow us to see how accurately we can track the build process and keep up with the assembly.

AI&T tracking (Both): This testing will be done to scan both systems at various intervals in the labs with no change present to identify the repeatability of the SHM hardware and also prior/after any configuration changes including mounting and tests. Since spacecraft are almost entirely bolted together, it is not uncommon for stress relaxation and joint slips to occur during vibration testing. Acoustic emissions will also be tracked during vibe and thermal tests. The challenge with this test will be operating through the extreme environments. Dynamic testing is usually done with the hardware unpowered. It is possible during this tests for contacts to disconnect or short out and damage electronics. During thermal testing, electronics may overheat and protocols should be in the firmware of the SHM system to preserve the electronics before overheating occurs.

Launch environment monitoring (EAGLE): The current expectation is to be able to power the SHM experiment during the EAGLE launch to monitor random vibration, shock, and pressure across the EAGLE spacecraft and compare measured loads with traditionally modeled results. Future systems may have better chances of doing this if they harvested the necessary power from the dynamic environment rather than from the vehicles batteries. This experiment is still in question. One of the current concerns is the amount of data possible from the ~45 minute direct accent to GEO. With the current sensors considered, the hardware can generate up to 7 Gigabytes of data. Space downlink speeds for secondary payloads are quite slow at times, and if this data where to be transmitted at 1Mbit/s that would take 15.5 hours. This, in addition to the fact that the full bandwidth is typically not available, becomes critical to consider compression techniques or on-board data processing. Additionally more effort will be required to align measurements with launch phases to minimize the magnitude of irrelevant data.

ISS environmental monitoring: NASA had similar interest for acceleration data at the location of the STP-H5 pallet. These regions are typically utilized for experiments and questions have arisen about the low-g dynamic environment which is needed for sensitive optics experiments. This CONOP will witness data from three MEMS tri-axial accelerometers and sensor temperature during various phases of ISS operations (thermal extremes, docking procedure, space walks, etc.). The three accelerometers must be positioned to be aligned in the same orientation and orthogonal to each other with the greatest spacing possible. This may require longer cable lengths to reach the measurement electronics. With sensitive analog measurements it is important to reduce cable lengths and digitize the data as soon as possible to prevent excessive noise generation.

Environmental sensitivity effects (Both): SHM sensors are sensitive to the environment they operate in. Temperature is the most common sensitivity to address for sensors as the temperature effects the material properties of both the monitored structure and the sensor itself. This operation will require scans at similar thermal conditions and EM conditions (for example, the ISS goes through the South Atlantic Anomaly) where the space radiation environment is consistent. Additional measurements will be made at off nominal settings to observe the effect of environmental boundary condition changes.

Acoustic emissions (Both): On-orbit several events occur that can cause acoustic emissions to be generated in a structure. Rapid thermal changes can take a structure from 200ºC sun facing exposure to a -200ºC deep space exposure. When this happens, any disparate materials with different Coefficients of Thermal Expansion (CTE) may experience interface slips releasing a mechanical wave into the structure. Micro-Meteoroid and Orbital Debris (MMOD) can also release shockwaves in spacecraft as they impact the system. Separations and deployments can release noise as springs and hinges unload. Sometimes these deployments can hit the spacecraft as well (ex. MARSIS boom deployment). Sensor nodes will be placed into a listening mode during periods of expected events to listen for any noise. PZT elements can be conditioned to amplify or attenuate signals and threshold defined based on strength and duration of events. While MMOD is not expected, it is possible and will require special ground testing to calibrate sensors and correlate impact events with potential projectiles. This can be a very expensive test phase require hypervelocity shots at a firing range. Authors have developed a supplementary test setup that can be used to simulate impact energies but not impulses in a lab environment. If on orbit measurements prove to experience MMOD events on the scale of less than 1mm often, then testing at White Sands Test Facility will be commissioned to study impact events.

Hardware degradation (Both): Regular system scans will be performed to track measurement consistency and quality over 1 year. Space radiation and temperature extremes can damage electronics and as of now there are no specialized radiation hardened parts being considered. Aluminum shielding is being applied to reduce ionizing dosages but it is expected that the hardware will experience upsets and diminished performance of either the electronics or PWAS. Piezoelectrics can become depolarized when exposed to extreme temperatures and radiation [11]. While it is vital for primary systems to survive the entire lifetime of the satellite, SHM may have to balance cost savings of having SHM with cost increases incurred ruggedizing a supporting system to survive for 20 years.

III. Hardware Development

A. COTS Metis Hardware

Off-the-shelf in-service monitoring techniques utilize a dense web of analog sensors connected by individual wires routed to centralized data acquisition and processing units. This traditional approach carries a significant weight penalty, can be complex to instrument and is susceptible to EMI. To address these issues, a fully digital SHM solution has been developed. The MD7-Pro system is composed of 3 core elements: an Accumulation Node for remote data concentration and diagnostic processing, an Acquisition Node for distributed signal digitization, and analog sensor bases that mate with both types of nodes. Each element of the MD7-Pro system is networked on an 8-wire serial bus that carries command, data download, node synchronization and power. Benefits of this distributed infrastructure approach include higher fidelity data through digitizing sensor signals at the point of measurement, reduced computational burden through local signal processing and feature reduction, and overall minimal mass through the consolidation of cables and elimination of bulky off-the-shelf hardware.

The Accumulation Node is the first element placed at the front of any MD7-Pro bus. Measuring 60 x 40 x 5 mm with a mass of 20 g, the fundamental role of the Accumulation Node is to serve as an interface between the SHM network and the platform being monitored. It accepts 28VDC to distribute power for up to 100 daisy-chained nodes in a MD7-Pro network, along with relaying commands, facilitating synchronization, and storage of the resulting data. It can be programmed to run autonomously, communicate over Ethernet, or accommodate flexible provisions for other wired and wireless protocol. In addition, the Accumulation Node offers 8 analog and 8 digital acquisition channels (up to 16-bit 1MHz) and boasts 64-GB of static memory. A powerful FPGA with an ARM core processor can be programmed to execute embedded diagnostic algorithms.

The MD7-Pro system can be efficiently expanded by daisy-chaining Acquisition Nodes. Measuring 50 x 40 x 5 mm with a mass of 15 g, the Acquisition Node is a direct replacement for traditional instrumentation such as rack-mounted oscilloscopes and function generators, enabling distributed data acquisition and signal processing. Each Acquisition Node provides a 20 Vpp 20 MSample/sec arbitrary function generator, 6 independent 12-bit channels of up to 50 MSamples/sec with programmable gain up to 500 or attenuation down to 1/500 in addition to 8 multiplexed 16-bit channels that share up to 1 MSamples/sec and 2 Gbit of DDR3 memory. The nodes are potted in urethane to provide resistance to moisture, chemicals, flame and shock loading, and have been designed to pass aerospace EMI standards. The Acquisition Nodes are capable of synchronously facilitating high sampling rate damage detection methods (guided wave, acoustic emission, and frequency response) while collecting multiple pre-conditioned differential voltage sensor signals (strain, temperature, acceleration, etc).

Both MD7-Pro nodes can accept a large range of appropriately configured sensor bases, which not only provide a mounting interface to the structure, but provide a physical connection to the external analog and/or digital sensors being monitored. Traditional SHM methods require dense sensor meshes to precisely resolve the position of damage, however this drives up system weight and complexity. Thus, in addition to customer specified custom configurations, MDC has patented a standard PZT beam forming array package that mates with the MD7-Pro Acquisition Node to facilitate both active and passive structural sonar scans. The Structural Sonar Array can indicate damage event coordinates using a novel sensor design along with an innovative algorithm with minimal information about the material or structure. From a single node position, a probability of damage map can be generated in response stiffness changes detected by an active guided wave scan, or due to the passively captured acoustic response from an impact event. Results from multiple nodes can be combined synchronously and/or asynchronously to enhance sensitivity and resolution.

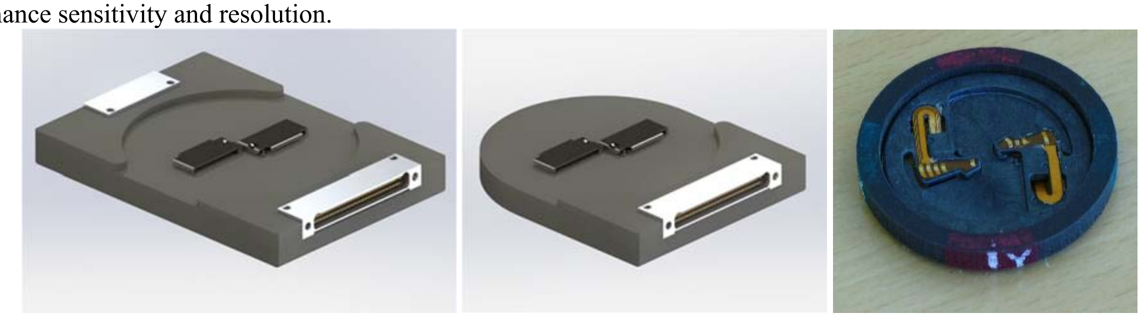

Figure 2 Basic Components of MD7-Pro SHM hardware showing (left to right) accumulation node, acquisition node and structural sonar array

B. Adapting for Space

1. Materials

When preparing to fly hardware that was developed for terrestrial applications, special attention must be paid to the materials being considered. Optimally it is best to avoid materials that are prone to shatter during failure as extreme launch shock loads or handling errors may then create hazardous debris. Depending on when the debris is released it could just add to the current space debris problem. The materials selected must also be chosen such that vacuum stability, exposure to atomic oxygen and other chemicals, and corrosion resistance are not a cause of breakdown. Outgassing of vapors can condense onto sensitive optics and electronics and ruin scientific measurements. Detailed consideration must be given to all parts with regard to their function and lifetime as well. Off-the-shelf connectors are one area of concern because of the prevalence of tin (which splinters in the space environment) and could then contaminate or short pins. Coatings, tapes, and sealants can eliminate problems with many components exposed to vacuum or reactive atomic oxygen, but not all, and they too must be verified for compatibility with the space environment. Additionally, potentially problematic vapors from materials can be conditioned with a bake out process that exposes the material to a space vacuum under high temperatures to extract the unwanted chemicals. Which are then usually replaced with atmospheric water after the test is over. The current hardware comes with potting already applied to meet standards required for terrestrial applications. The particular material has no official outgassing specifications which would ideally be less than 1% total mass loss (TML) and 0.1% collected volatile condensable material (CVCM).

While most of the materials on the hardware were able to utilize space appropriate options, the potting material needed to be tested. The Materials Engineering Branch, at NASA Goddard, performs this testing for its public outgassing database, but researchers wanted to attempt a secondary approach on-site at Kirtland Air Force Research Laboratories (AFRL). While TML and the subsequent water vapor retention (WVR) are trivial to obtain with a vacuum chamber and heat plate, the CVCM requires specialized chamber geometries and collection plate setup to properly trap and assess extracted chemicals. The first step is to heat and pressurize the chamber to space levels to draw out any chamber contaminants not removed during cleaning. Even water absorbs into the chamber. Background measurements are taken with a Residual Gas Analyzer (RGA) and two Quartz Crystal Microbalances (QCMs) to quantify the composition of the gases in the chamber and the deposition rate of said gases. The chamber is held in high vacuum and the temperature allowed to approach ambient. Once the chamber background is measured and it has been brought down to a safe temperature a bake-out of the potting is performed. A sample of the cured potting material is weighed with a Mettler AE 163 laboratory balance to 4 decimal places in grams. The mass before testing is 15.1337 g. The sample is then placed in the vacuum chamber and taken to high vacuum (~10^-5 torr). The temperature is increased to the highest expected operational temperature (100^{O}C) and is held there until the chamber pressure can be brought down into the mid to high 10^-7 torr range which is a typical pressure of an empty chamber at elevated temperatures. The sample is held at an elevated temperature for upwards of 20 non-continuous hours or until the chamber appears to be clean and no obvious outgassing from the sample is evident. The RGA and two QCMs quantify differences between the empty chamber environment and that with the sample. Temperature is then dropped to ambient but held at a high vacuum. Once the temperature is low enough to be safe the chamber is backfilled with dry nitrogen gas. The sample is removed from the chamber, immediately weighed of the laboratory balance, and the TML% calculated. The sample then sits in a clean room for 72 hours (or until the weight gain rate has significantly diminished) and weighed periodically to determine the WVR properties of the material. While this will not yield an official CVCM% value, researchers hope that it will be comparable. At the time of this writing, NASA Goddard is performing the official test to use for comparison of approaches.

From the testing here it was found that no clear signs of outgassing occurred with the sample in the form of physical property changes or unacceptable vapors. The RGA ionized vapor particles and collected them on its spectrometer to measure molecular masses. Typical molecules (air components, water, alcohol) were identified as well as very small traces between 50-60 atomic mass units (amu) but these are typical of epoxy samples tested and are believed to be a remnant of the chemical disassociated from the potting hardener. The QCM measured a deposition rate of 5e-10 g/cm^{2}sec which seems higher than typically seen here but for a much larger temperature range than commonly tested making it an expected result. NASA test comparisons will allow researchers to adjust the view factors and gain constants applied in calculating the value. An empty chamber test was performed and found that 75% of the measured deposition rate likely came from the chamber walls and not the sample. The TML was measured as 0.9%. Almost all the mass returned within 2 weeks after testing further implying that the CVCM percentage should be trivial as the returned weight is atmospheric water from the micro-porosity of the material. The testing appears to indicate that the potting material is suitable for space.

2. *Electrical*

The electrical design of space electronics must be robust. It must handle power that has not been conditioned from the satellite. Grounding presents interesting challenges and must be handled carefully throughout the payload. Charges can build up on spacecraft as it goes through radiation belts or sun exposure resulting in standing surface charges that may result in dielectric breakdown and arcing. The MD7-Pro hardware already incorporates elaborate levels of electrical protection, and a daughter card is included to interface the accumulator nodes data and power to the space vehicles requirements. STP requires separate connections for data (D-sub 9 pin) and power (canonical 5 pin) to preserve signal clarity. To protect the measurement system from the electrical environment, the accumulation node is being house in an aluminum 6061 box with a 3/8" thick lid to minimize ionization damage and single event upsets (SEUs). The nodes are not receiving additional protection as they can be cycled off and tolerate corrupted measurements. Electronics have advanced significantly over the last few decades with many processes developed that make many component tolerant of the space environment in terms of damaging latch-ups. The majority of SEUs can be corrected by power cycling the hardware. Since the SHM experiment is not a primary function of the system, it can be made to tolerate more risk than items like a satellite flight board may accept. This allows COTS (cheaper and more capable) parts to be implemented in the design.

Shielding is required to protect for ionizing radiation, which comes in like a wave onto all electronics. To determine the dosages expected and shielding required researchers use measured and modeled dosing rates for electrons and protons from the AE/AP-7/8/9/etc ('E' and 'P' designate the particle and '7' is the model version which increases incrementally every few years as new data is recorded). At this time, AE9 and AP9 can be used for analysis. As hardware is delivered, authors will be able to test electronics for performance against simulated environmental conditions and performance metrics. Experimenters should use available models like AE9/AP9 along with software packages such as CRÈME-96 to get an understanding of what to expect for Total Ionizing Dosage (TID), heavy ions, trapped protons/electrons, and the likelihood of upset rates. Schedule delays of hardware prevent authors from presenting our results in this area at this time.

3. *Thermal*

Additional challenges when using off-the-shelf hardware are handling the thermal loads of the electronics. Many electronics that are designed for terrestrial use require creative solutions to move heat from the printed circuit boards to the rest of the payload or require special planning during on-orbit operations so that the unit does not overheat. This is especially true of PCBs that include heat fins because convection is not practical in the vacuum of space. Communication can be a challenge because in many cases a true end-to-end test is not available until the payload launches. This is the greatest concern for the current hardware. All nodes are highly insulated from the bus due to the kapton layered sensor patch. The connector back shell will be mated to the bus plate to move heat from the PCBs to the panel. If this tested configuration is not adequate for achieving required measurements, CONOPs changes will be required to compensate for the thermal management. Potting electronics is actually a useful tool for thermal management of electronics as it helps spread heat through conduction. The current configuration is shown below.

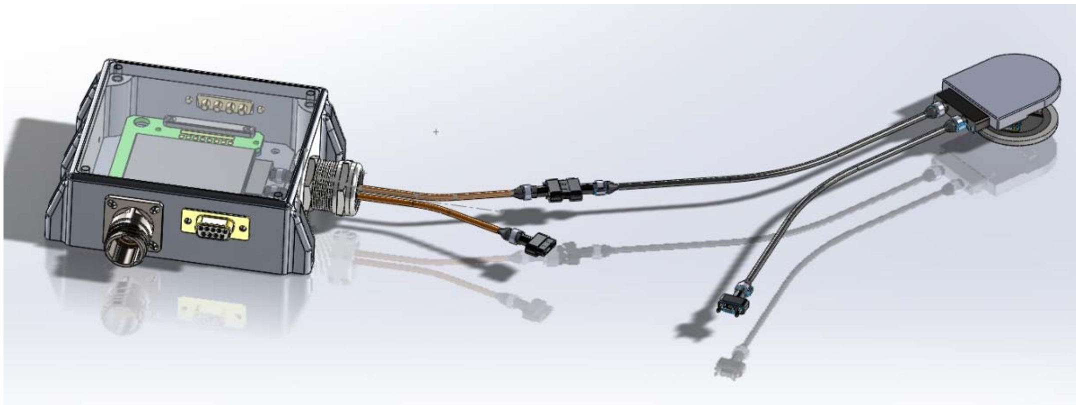

Figure 3 Space experiment configuration for SHM hardware showing just the accumulation node housed on the right and one acquisition node on the right.

Additionally, many off-the-shelf components include communication protocols that require large bandwidths. The challenge in modifying the component for space use is to determine the relevant parameters that must be passed to the ground and making the most efficient use of the available bandwidth and then testing the communications in as robust of a manner as possible.

C. Testing

Prior to the proposal of this flight experiment, the COTS hardware was tested for aerospace standards and low level space flight tests on the Up Aerospace SL-8 sounding rocket and a high altitude balloon experiment through NASA's Flight Opportunity Program (FOP) [12-19]. This flight experiment requires separate testing stages prior to integration acceptance and operational testing. One phase is an experiment validation phase in which the acoustic emission expected from MMOD needs to be characterized. This testing usually requires hypervelocity firing ranges which can exceed $6K per shot due to equipment utilized and maintenance of chambers. This seemed to be prohibitive due to low chances of MMOD impacts and the small percentage of overall science from that objective. Therefore, authors developed a compliment test that could be done in the lab using lower velocities but higher projectile mass to simulate dents, scratches, pitting, and punctures. The second series of testing required is required for all hosted experiments to verify that the experiment won't damage the spacecraft during launch and on orbit. The two principal component of this test are vibration testing and thermal-vacuum but others may also be required for other launch providers.

Acoustic Emission Testing:

In collaboration with AFRL, Space Vehicle Directorate, Space Component Technology Branch, Guidance Navigation and Control (AFRL/RVSV GNC) group, authors utilized an Attitude Control System Proving Ground (ACSPG) test bed for simulated MMOD testing. The ACSPG, shown in Figure 4, is the largest spherical air bearing platform currently known of in the world for satellite testing. The test bed simulates spacecraft control in a zero-g environment

Figure 4 The Attitude Control System Proving Ground (ACSPG) at Kirtland Air Force Base in AFRL/RVSV.

An inverted gravity impact hammer was built to enable testing of SHM hardware. The main objective behind the design was focused on the characterization of impact energies comparable to MMOD projectiles to determine the location on the impact, the force of the impact, the size of damage, and the trajectory of the impact to isolate debris orbit. In order to understand this phenomenon, we developed an impact machine with known force characteristics to impact a plate containing piezoelectric sensors that are bolted to the ACSPG. The design of the impact machine that was chosen for this application was based from the Charpy impact test, thus referred to as the Modified Charpy Impact Machine (MCIM).

The basic experimental concept of operations consists of the MCIM, the ACSPG, test fixture frame, and plate, shown in Figure 5.

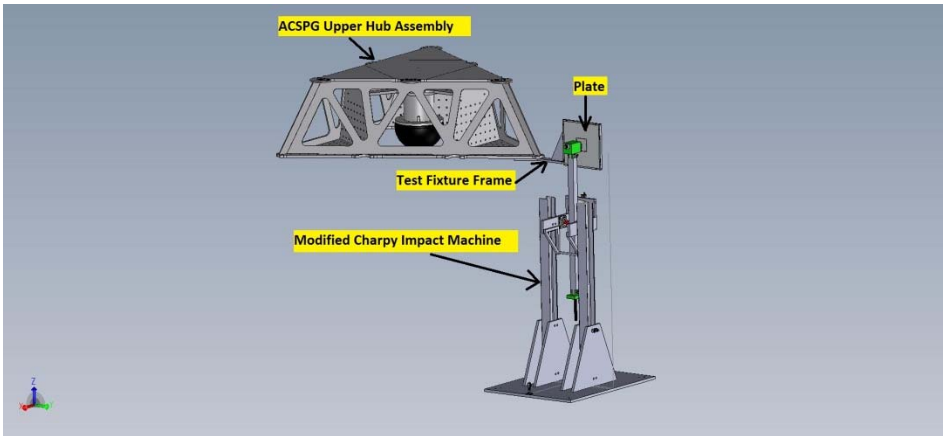

Figure 5 The ACSPG upper hub assembly with test fixture frame and plate attached and the Modified Charpy Impact Machine (at the moment of impact with the plate).

The mass of the MCIM and the machine itself is designed, engineered, constructed, and maintained such that the energy losses due to pendulum air drag (windage), forces and energy from the deformation of the plate, friction in the pendulum bearings, vibration, shock, and dissipated energy from the components of the machine are eliminated or minimized. Upon activation of the pendulum holding latch using the rope, the weight falls causing the hammer to strike the bolted plate on the ACSPG platform. The plate that is impacted by the hammer will host Piezoelectric sensors and utilize the onboard Inertial Measurement Unit (IMU) to capture information on the low frequency response of the resultant simulated debris impact, shown in Figure 6.

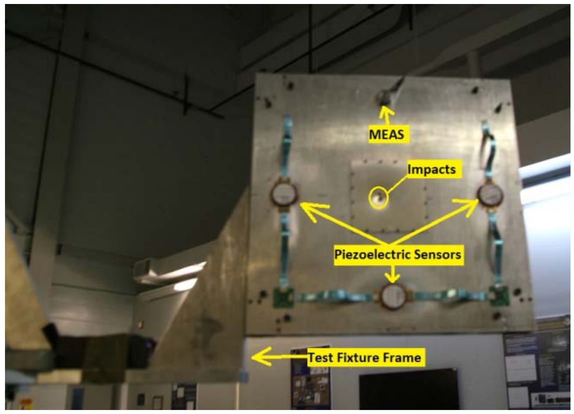

Figure 6 Plate with Piezoelectric Sensors and Magneto-Elastic Active Sensors (MEAS) mounted onto test fixture frame on ACSPG platform.

The known force and its direction from the impact hammer on the MCIM will be compared to the reconstructed results from the Piezoelectric sensors and IMUs, knowing the mass properties of the ACSPG platform. Combined with the high frequency information from the Magneto-Elastic Active Sensors (MEAS), the low frequency measurements should provide enough information to infer direction, and resultant force and moment on the spacecraft.

IV. Impact Test Results

While more work is needed to fuse heritage sensor data with SHM data, authors can provide insight into the challenges involved. Figure 6 shows a fairly complex plate with an impact location that must go through a bolted boundary. Additionally, impacts may result in acoustic emissions from other boundaries that are fixed and subject to interface slips. The piezoelectric sensors in Figure 6 are identified (left to right) as nodes 38, 33 and 32. The raw data from one impact and the filtered corrected data are shown below.

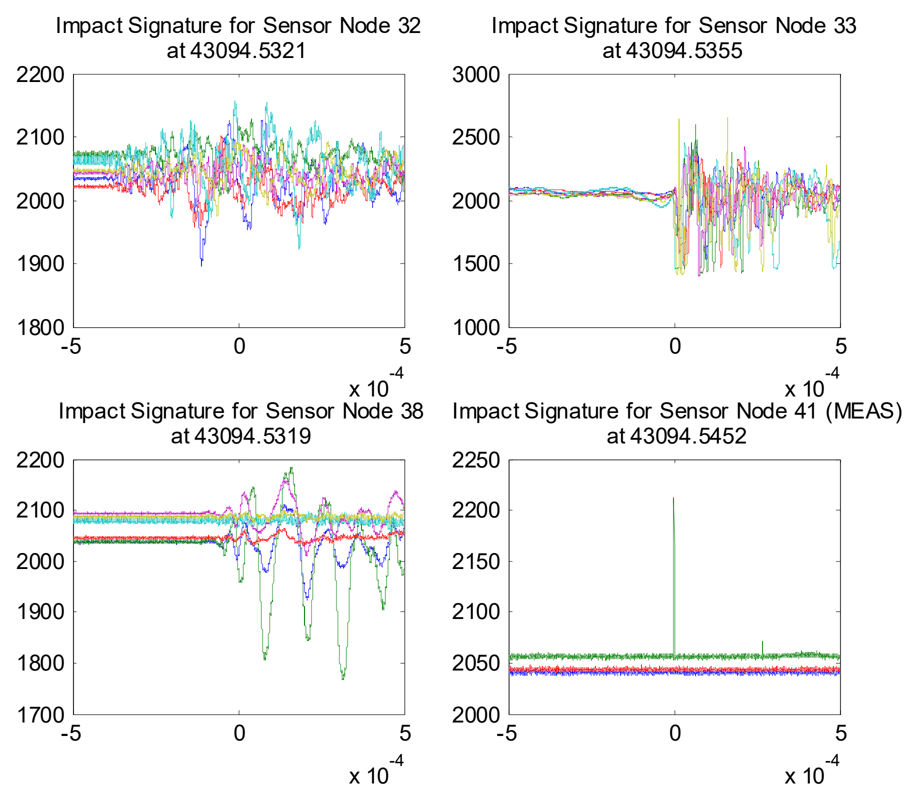

Figure 7 Raw impact signatures from plate hit by impact hammer

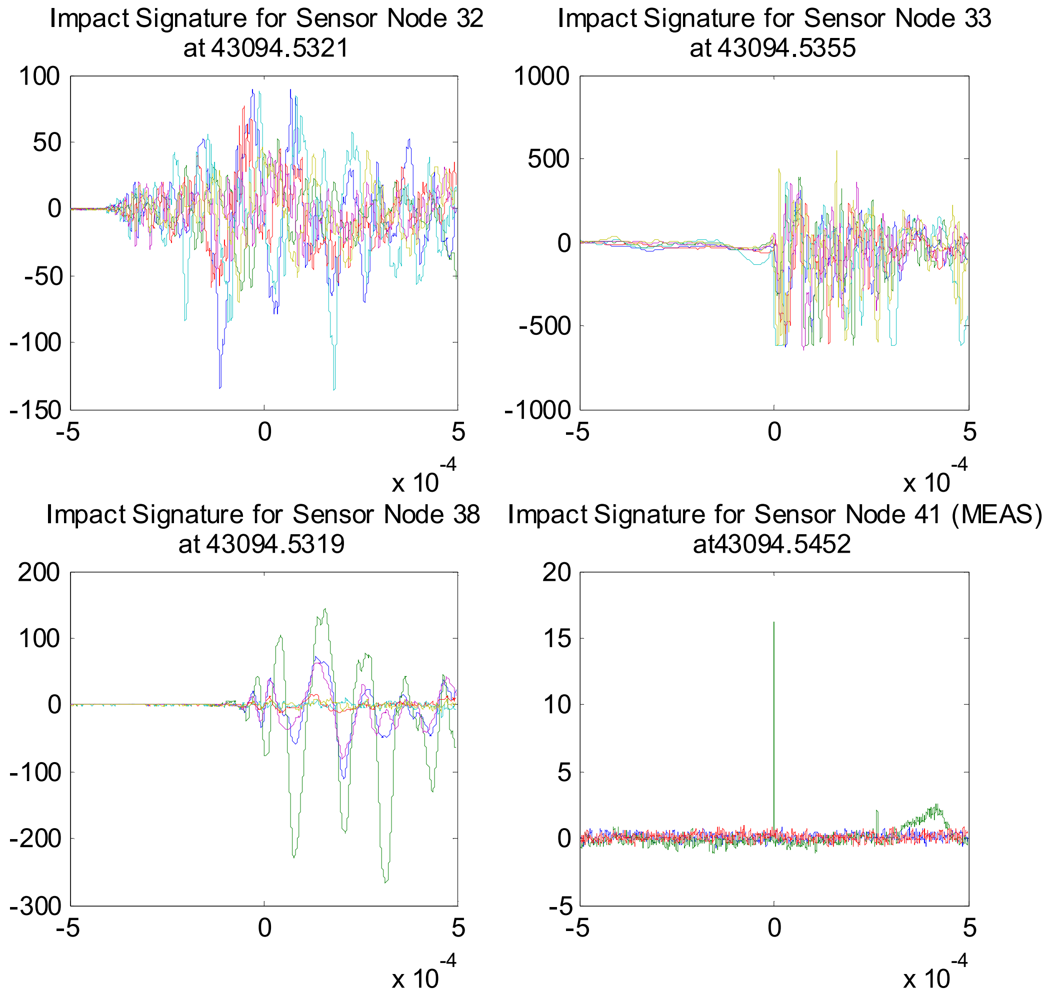

Figure 8 Filtered unbiased waveforms from impact test

Worth noting are the variety of frequencies captured from all sensors. Some sensors picked up high frequency lamb waves while others seemed dominated by the lower frequency structural modes. Sensor 38 which was furthest from a fixed boundary recorded the lowest frequency modes. The MEAS, however, are not mechanically coupled so they are far less sensitive to impact energies making them more likely to record signatures that would otherwise clip piezoelectric sensors. In this test, they did not capture a usable record of the impact event. With such a wide variety of recorded modes, it becomes difficult to define parameters for acoustic localization. In this paper, an interaural time difference approach is considered. Ideally, cross correlation would be used to identify the Time-Of-Arrival (TOA) between two sensors but since the boundary conditions of the highly nonlinear plate influences the generated waveforms significantly, a more basic approach of defining TOA by flagging acoustic signals once they passed the inherent noise floor. Between 3 nodes exist 18 receiving piezos and recorded waveforms. Two waveforms are considered at a time to compare delta TOA, Δt, the sensor spacing, x, and knowing the materials speed of sound for a given frequency, c, the vector angle, θ, can be estimated using the following

$$\boldsymbol{\theta} = \mathbf{asin}((\boldsymbol{c\Delta t})\,/\boldsymbol{x}) \qquad \text{Eq. 1}$$

When all possible pairs are grouped by similar frequency content and analyzed a collection of impact vectors can be identified, and is seen in the following figure.

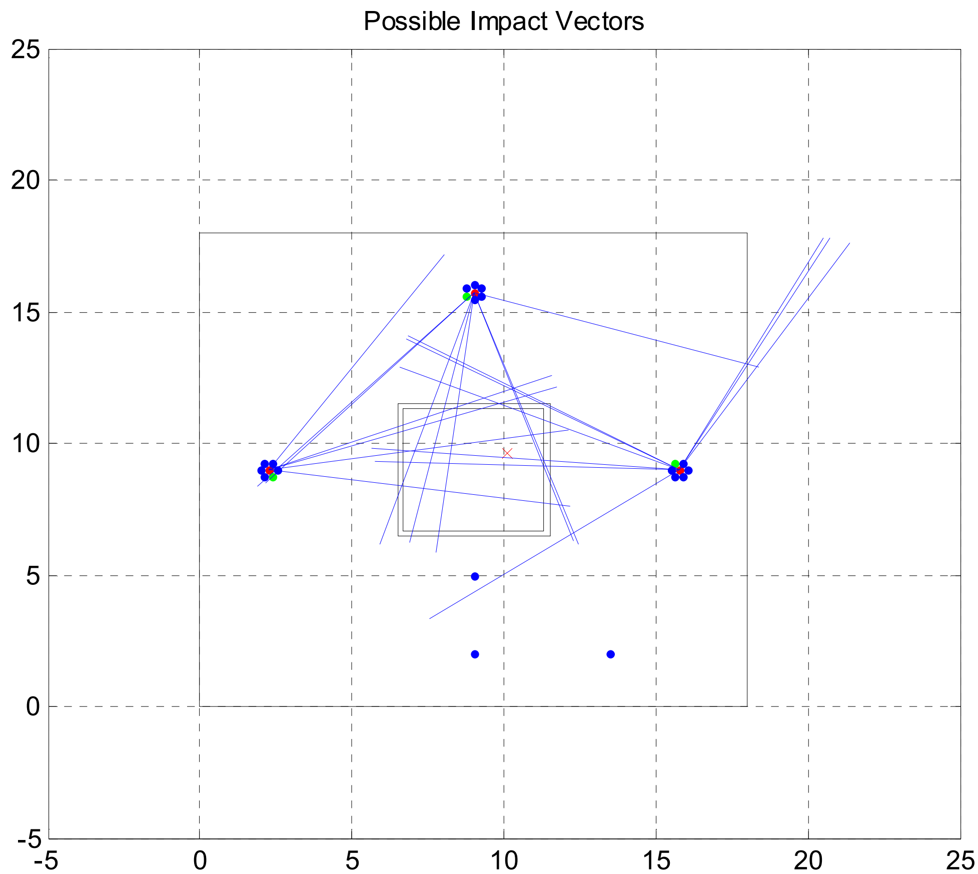

Figure 9 Possible impact vectors from recorded waveforms. Red 'X' shows actual impact location

A complex vector mapping is expected given the fact that the strike plate is bolted to the larger plate with a hole cutout at its center. This means, waves have to travel through the strike plate, through the bolted joint, and through the impact plate. Additionally, the energy in the impact may release acoustic emissions from the right side of the plate in Figure 9 as that is where the plate is bolted to the testbed, and from the bolts holding the striker plate on.

Once a structure is impacted, one may wish to do an active inspection to see if any permanent change is seen. The zero crossing method developed previously [10] is used to compare baseline data prior to impact with scans taken afterwards. Essentially, the method looks at both waveforms for when the phase of the waveforms deviate. The greater the deviation, the greater the damage is likely to be. The resulting damage paths of that approach are shown in the next figure.

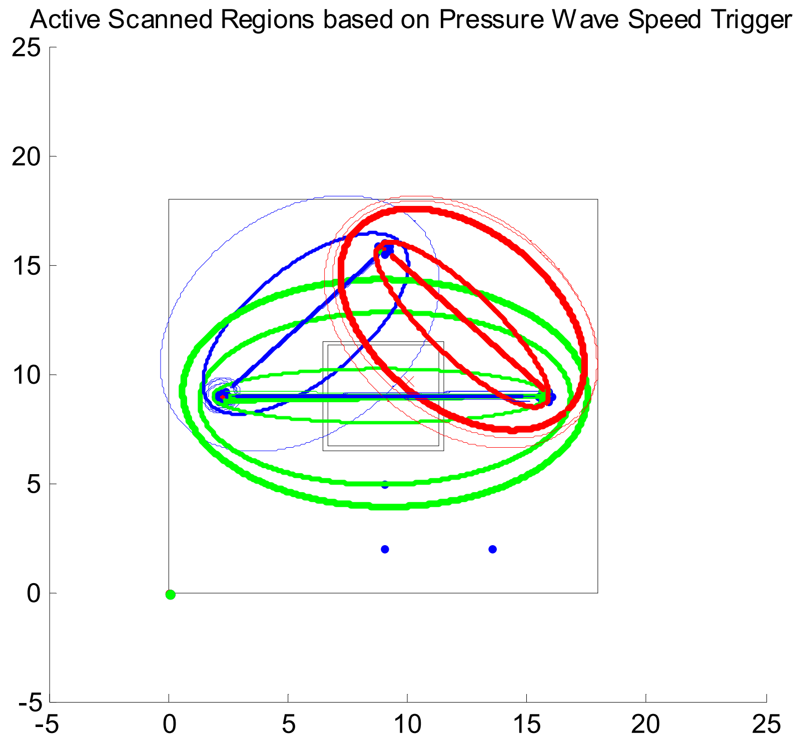

Figure 10 Damage regions based on zero-crossing method

While this approached worked within centimeters on a bolted satellite panel, the panel was still one continuous plate. With this structure, the cutout for the striker plate prevents direct path for wave propagation and the numerous bolts in the way diminish the accuracy but the overlapping region does show reasonable estimation of areas to look. It is furthermore likely that the bolted interfaces slipped when the striker plate was dented by the impact and as the first point of inspection would flag first.

V. Conclusion

New SHM hardware is being developed for multiple upcoming flight experiments. Such a capability allows technicians to track the structural state of the vehicle from initial build to operation in orbit. As anomalies arise, SHM may be able to isolate the approximate region to inspect or the severity of damage present. The hardware has to undergo several design considerations to be ready for flight in terms of material selection, electrical/thermal robustness, radiation tolerance, and algorithm development for assessing complex structures. Simulated impacts were performed on a floating testbed to initiate data fusion efforts with heritage space sensors relating the guidance, navigation and control to better analyze impact parameters. As of now, authors have identified significant challenges going forward in terms of precise localization on highly complex structures. With spacecraft, it is rare to find a nice open plate with few geometrical changes and bolted/bonded interfaces (omitting the back of a honeycomb solar array face sheet). Future algorithms need to be refined to better assess the statistical likelihood of identified vectors and inspection points as the source for primary damage.

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References

[1]Donner, R., “A Look at the UH-60A Black Hawk Helicopter,” *Aviation Pros* [online database], URL: http://www.aviationpros.com/article/10370631/a-look-at-the-uh-60a-black-hawk-helicopter [cited 15 May 2014].

[2]Harland, D., Lorenz, R., *Space Systems Failures: Disasters and Rescues of Satellites, Rockets and Space Probes*, Praxis, UK, 2006.

[3]Tatarewicz, J.N., "The Hubble Space Telescope Servicing Mission," *From Engineering Science to Big Science*, edited by P.E. Mack, The NASA History Series, NASA, Washington D.C., 1998, pp. 365-396.

[4]Arritt, B. J., Robertson, L. M., Henderson, B. K., Ouyang, L., Beard, S., Clayton, E. H., Todd, M. D., Doyle, D., Zagrai, A., Buckley, S. J., Ganley, J. M. and Welsh, J. S. "Structural Health Monitoring: An Enabler for Responsive Satellites", Proceedings of SPIE, Vol. 6935, pp. 6935.1-6933513.10, 2008.

[5]Doyle, D., Reynolds, W., Arritt, B., "Structural Health Monitoring as an Enabler for Responsive Satellites: an Update", *ASME 2010 SMASIS Conference*, Sept. 28 – Oct. 1, 2010, Philadelphia, PA, paper # SMASIS2010-3747, 2010.

[6]NASA Orbital Debris Program Office, "High-Speed Particle Impacts Suspected in Two Spacecraft Anomalies," Orbital Debris Quarterly News, Vol. 17, Is. 3, July 2013.

[7]Stanford University, "SHM in Action: How SHM Works in Practice," *9th International Workshop on Structural Health Monitoring,* URL: http://structure.stanford.edu/workshop/SHMinAction.html [cited 15 May 2014].

[8]Metis Design, "MD-7 Pro Digital SHM System," *Metis Design Corp. Media*, URL: http://www.metisdesign.com/structural-health-monitoring-company/md7-digital.html [Cited 15 May 2014].

[9]Beneski, B., "Orbital Awarded Contract by U.S. Air Force for EAGLE Spacecraft Platform," *Orbital News* Room [online Press Release], URL:http://www.orbital.com/NewsInfo/release.asp?prid=832 [cited 15 May 2014].

[10]Zagrai, A., Doyle, D., Gigineishvili, V., Brown, J., Gardenier, H., Arritt, B., "Piezoelectric Wafer Active Sensor Structural Health Monitoring of Space Structures," *Journal of Intelligent Materials Systems and Structures*, Vol. 21, pp. 921-940, 2010.

[11]Giurgiutiu, V.; Zagrai, A., "The Use of Smart Materials Technologies in Radiation Environment and Nuclear Industry", *SPIE 7th Annual International Symposium on Smart Structures and Materials*, 5-9 March 2000, Newport Beach, CA, 3985-103, 2000, pp. 855-865

[12]Kessler S.S., Spearing S.M. and C. Soutis. "Structural Health Monitoring in Composite Materials using Lamb Wave Methods." Smart Materials and Structures, v.11, April 2002, 269-278.

[13]Kessler S.S., Amaratunga K.S. and B.L. Wardle. "An Assessment of Durability Requirements for SHM Sensors." Proceedings of the 5th International Workshop on SHM, 12-14 September 2005, Stanford University.

[14]Chambers J.T., Wardle B.L. and S.S. Kessler. "Lessons Learned from a Broad Durability Study of an Aerospace SHM System." Proceedings of the 6th International Workshop on Structural Health Monitoring, 11-14 September 2007, Stanford University.

[15]Flynn E.B., Todd M.D., Dunn C.T., and S.S. Kessler "Identifying Scatter Targets in 2D Space using In Situ Phased-Arrays for Guided Wave Structural Health Monitoring." Proceedings of the 8th International Workshop on Structural Health Monitoring, 12-15 September 2011, Stanford University.

[16]Kessler S.S., Flynn E.B. and M.D. Todd. "Hybrid Coherent/Incoherent Beam Forming Diagnostic Approach to Naval Assets." Proceedings of the 8th International Workshop on Structural Health Monitoring, 12-15 September 2011, Stanford University.

[17]Cooper B., Zagrai A. and S.S. Kessler "Effects of Altitude on Active Structural Health Monitoring." Proceedings of the ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 16-18 September 2013, Snowbird, UT.

[18]Zagrai A., Cooper B., Schlavini J., White C. and S.S. Kessler "Structural Health Monitoring in Near-Space Environment, a High Altitude Balloon Test." Proceedings of the 9th International Workshop on Structural Health Monitoring, 10-12 September 2013, Stanford University.

[19]Kessler S.S. and E.B. Flynn. "Hybrid Passive/Active Impact Detection & Localization for Aerospace Structures." Proceedings of the 9th International Workshop on Structural Health Monitoring, 10-12 September 2013, Stanford University.