Cover Page

Research Title

In Orbit Structural Health Monitoring of Space Vehicles

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Project Summary

A significant step in addressing the safety of space vehicles is development and testing of the flight information recorder, or "black box". It is envisioned, that a structural health monitoring system (SHM) would be an integral part of the "black box" and would record information on structural integrity during all stages of spaceflight. In this project, the team proposes to investigate the effects of the space environment on piezoelectric sensors – active elements of SHM, to explore structural vibrations in microgravity and to demonstrate the feasibility of SHM during long term space missions. To achieve this goal, 1U and 3U payloads (depending on space available) are proposed that will fit into a Nanoracks system outside of the ISS. Mission duration is expected to be less than 1 year (1 year maximum) with minimum of crew time. The power requirement is estimated to approach a few watts. The data collected in the proposed experiment would also benefit the FAA Center for Commercial Space Transportation. The principal investigator is a mechanical engineering professor that has previously participated in a NASA EPSCoR project and launched several suborbital payloads through the NASA Flight Opportunity Program.

A. INTRINSIC MERIT OF MICROGRAVITY REQUIREMENT

The goal of this project is to investigate the effects of the space environment on piezoelectric sensors, to explore structural vibrations in microgravity, and to demonstrate the feasibility of structural health monitoring during long term space missions. To achieve this goal, 1U and 3U payloads (depending on space available) are proposed that will fit into a Nanoracks system outside of the ISS. Mission duration is expected to be less than 1 year (1 year maximum) with a minimum of crew time. The power requirement is estimated to approach a few watts.

A.1. EXISTING RESEARCH

In recent years, the space arena has witnessed a dramatic expansion in the number, nature and operators of space missions. An increasing reliance on global positioning systems, communication systems, situation awareness (both private and government sectors), and other space-based assets sets new challenges for space system development, pre-launch testing, deployment, maintenance, operational efficiency, and cost effectiveness. It is envisioned that technological advances in sensor technologies, intelligent structures, and data analytics could enable continuous structural health monitoring (SHM) of space vehicles aimed at improving the vehicle's safety and reducing its operational costs (Chona, 2005; Arritt, *et. al.*, 2008). Future space vehicles will incorporate SHM as an integral part of the "black box" that will collect, process and report information on structural integrity during all stages of spaceflight. The utility of the SHM of space vehicles spans from pre-flight diagnostics to in-orbit operation and to analysis of structural behavior (or disintegration) during spacecraft reentry. SHM information could also play a prominent role in space vehicle re-certification for the next flight. Figure 1 illustrates the details of the SHM modalities that may be accomplished at each stage of spaceflight.

Figure 1 Application of SHM to Reusable Launch Vehicle (RLV). SHM modalities at each stage of spaceflight.

Structural health monitoring (SHM) is a relatively mature technology targeting a broad spectrum of applications ranging from machinery monitoring to embedded diagnostics of aircraft (Boller *et. al.,* 2009).

In contrast to traditional nondestructive testing, distinct features of SHM include permanently-attached networked sensors, full system integration with structural elements, and automation of data collection, processing, and decision making. Every SHM system employs one or more damage-specific physical phenomena that enable damage detection, identification, and characterization. The signal change associated with material, structural or system damage is translated through elements of the SHM system and eventually leads to a diagnostic decision.

Typically, a physical phenomenon associated with damage may be explored using a variety of sensors. For example, changes in structural stiffness due to fatigue cracks may be diagnosed with a strain gage, accelerometer, or fiber-optic sensor. In addition, the same sensor system, with some changes in measurement hardware and data processing routine, may facilitate utilization of different damage detection methodologies. For instance, piezoelectric active sensors, which will be explored in this proposal, can be used in the transient wave propagation mode and in continuous wave (CW) impedance measurements. Such a broad spectrum of design options opens practically infinite opportunities for system tailoring to specific damage conditions and operational requirements.

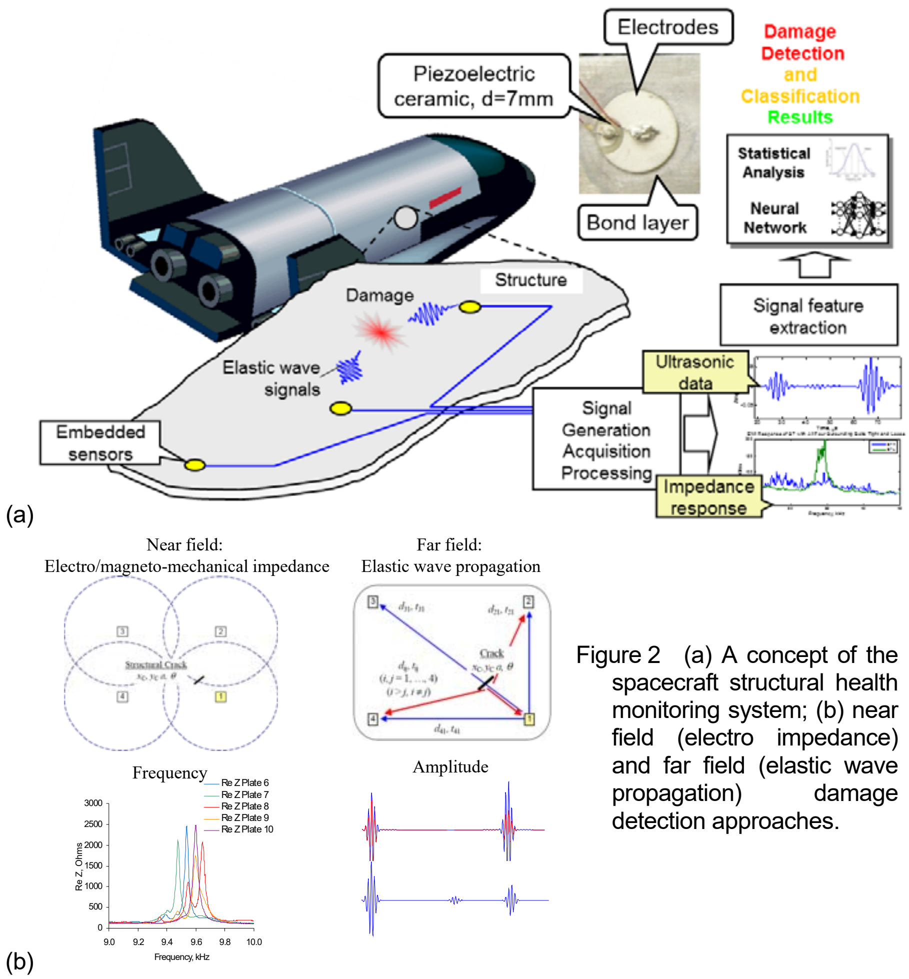


Figure 2 (a) A concept of the spacecraft structural health monitoring system; (b) near field (electro impedance) and far field (elastic wave propagation) damage detection approaches.

A concept of the SHM system of the spacecraft is depicted in Figure 2a. Small piezoelectric sensors may be attached or embedded into the spacecraft structure to enable passive and active detection of structural damage. Examples of passive assessment include monitoring of the acoustic emission activity, strain measurements, and impact detection. Information from such an assessment is typically very limited and does not offer sufficient details to estimate damage severity and criticality. For this reason, in addition to passive monitoring, an active approach can be used to provide such details. Figure 2 illustrates that embedded structural sensors transmit and receive elastic waves that are recoded and analyzed by a processing unit. Frequency domain data (Figure 2b) enables electro impedance assessment while time domain data furnish ultrasonically-derived characteristics and location of damage. Features sensitive to damage are derived from impedance and ultrasonic signatures and then are classified into three (healthy, moderate, unhealthy) states using statistical analysis or neural networks. This diagnostic decision is stored (displaced if necessary) onboard and may be also downlinked to designated spacecraft control and monitoring station.

Two of the early reports on the development of SHM systems for spacecraft include the work of Bauman *et al.* (1997) and Ellerbrock (1997), who reported details of the design, implementation, and operation of the structural health monitoring system for the NASA/McDonnell Douglas Delta DC-XA re-usable rocket. The key element of the system, a multi-channel Bragg-grating fiber-optic sensor module, was utilized to monitor strains exerted on the liquid hydrogen fuel tank. Data from fiber-optic and other sensors were integrated into a comprehensive SHM suite, which was flight tested in 1996. A series of research papers on application of fiber-optic sensing to SHM of space structures were published by Japanese researchers led by Takeda. Kabashima *et al*. (2001) described the development of fiber Bragg grating (FBG) SHM for satellite systems. The concept of the FBG-based satellite SHM system was discussed, which encompassed potential material condition assessment during manufacturing, establishing requirements for conventional sensors (e.g. accelerometers, thermocouples, etc.) during satellite environmental tests and on-orbit detection of impact and thermal damage. A further extension of this work, with FBG components in particular, was presented by Mizutani *et al.* (2006). The paper discussed design and development of an on-board strain measurement FBG system for ISAS/JAXA reusable rockets and presented results of the real-time strain monitoring during tests. The system demonstrated the capability of measuring strain during rocket operation and correlation of the FBG sensor strain data with strain-gage and internal pressure measurements. The experience of the European Space Agency (ESA) in application of fiber-optic sensing in space structures was discussed by Mckenzie and Karafolas (2005). Several applications of FBG sensors for spaceship monitoring were presented, including an adaptive leg of a telescope structure, a smart flywheel support, elements of propulsion system inter-tank composite structure, and a thermal protection system.

Structural health monitoring systems based on embeddable piezoelectric active sensors are widely used for assessment of aeronautical, civil, and naval structures (Boller *et al.,* 2009). Although a considerable number of papers suggest the potential of such systems for health management of spacecraft, limited studies are available on piezoelectric sensing systems geared specifically towards space applications. A review of SHM for future space vehicles by Mancini *et al*. (2006) focused on the description of available technologies and their perspectives in the context of their integration into a vehicle's design process. Our literature survey indicates that the practical use of piezoelectric SHM systems for space structures was considered primarily for monitoring the condition of the propulsion system (Qing *et al.*, 2006), monitoring the condition of the thermal protection system (TPS) (Yang and Chang, 2006; Yu, 2007) and assessing the integrity of bolted and adhesive structural joints (Clayton *et al*., 2008; Doyle *et al.*, 2011; Zagrai *et al.,* 2010).

Although there has been a significant volume of theoretical, computational, and laboratory work on the application of SHM to space systems and structures, there have been very few cases of validation of SHM concepts in the space environment. We are only aware of the Aerospace Corporation efforts in developing a REBR - a prototype of the "black box" for space vehicles (Ailor *et al.,* 2007). Although REBR could record some flight and re-entry data, it did not include SHM although integration of SHM was envisioned (Ailor *et al.,* 2011). Other practical testing of SHM in the space environment include efforts by our research group during two suborbital flights (Zagrai, 2011; Reiser *et al*., 2012; Zagrai *et al*., 2014) and one high altitude balloon flight (Zagrai *et al*., 2013). Discussion of these efforts is presented in the next section of the proposal. The suborbital flights have demonstrated the possibility and utility of SHM during all stages of the space mission. However, in the suborbital flight, exposure of SHM active sensors and electronics to the space environment is limited to a few minutes and doesn't fully represent exposure and associated effects during long-term missions. For integration of SHM into future space vehicles, the long-term effects of the space environment on active elements, electronics modules, and SHM modalities must be studied. ISS provides a nearly ideal setting for experiments studying the long term effects of the space environment on all elements of an SHM system. Data collected during ISS experiments will guide critical differentiation between material/structural/system changes associated with the space environment (i.e. healthy state) and diagnostic changes linked to damage in a space vehicle. In addition, the aforementioned experiments will allow researchers to better understand fundamentals of elastic wave propagation in spacecraft structural elements and vibrations of structures in space.

A.2. CONNECTION BETWEEN NASA'S EPSCOR AND THE PROPOSED ISS EXPERIMENT

The development of the topic described in this proposal started under an early NASA EPSCoR grant in 2008. The team further tested an electro-mechanical impedance SHM during one of its first commercial suborbital spaceflights and participated in an additional suborbital flight and a high altitude balloon flight sponsored by the NASA Flight Opportunity Program (FOP).

A.2.1. PRIOR NASA EPSCOR AWARD

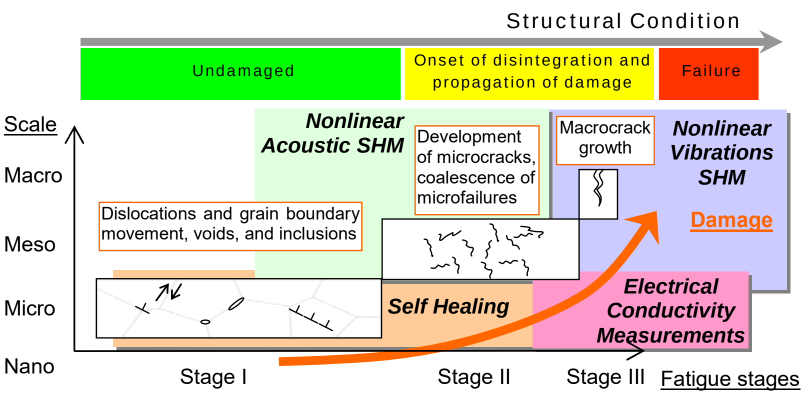


Figure 3 Damage accumulation in a structural system and the SHM methodologies associated with particular damage scales.

Structural health monitoring (SHM) was the subject of a previous NASA EPSCoR award (NNX07AT64A). The title of the project was "Structural Health Monitoring and Self-Healing of Aerospace Structures". A number of SHM methodologies were considered in this project and relationship between them is presented in Figure 3.

The elements of self-healing in metallic structures were also considered and successfully implemented in the project. The prior EPSCoR project was aimed at "development of SHM technologies combined with self-repairing materials concepts would contribute to economic and social benefits by enabling condition-based maintenance of aged and new aerospace structures and by prevention of catastrophic failures and loss of human lives. The project also benefited the State-funded aerospace engineering (undergraduate and graduate) programs in New Mexico." In essence, the project started "an interdisciplinary program which brought together expertise in micromechanics, vibrations and non-linear dynamics, materials science, and sensors array technology and controls to solve problems of great importance to NASA." This proposer's contribution to that project included development of nonlinear acoustic SHM methodology and advancing an electro-mechanical impedance method into a nonlinear regime. The application of the SHM concept to space systems was also considered.

A.2.2. PRIOR SUBORBITAL FLIGHTS

A concept for the use of SHM for space vehicles was further developed and tested in two suborbital spaceflights and one long-duration high altitude balloon flight. The first active piezoelectric SHM experiment in space was flown on the SL5 suborbital flight on the SpaceLoft rocket (Zagrai, 2011). During this flight, electro-mechanical impedance of structural elements was measured using a portable impedance measurement board developed by Los Alamos National Laboratory. The experiments focused on the use of electro-mechanical impedance methods

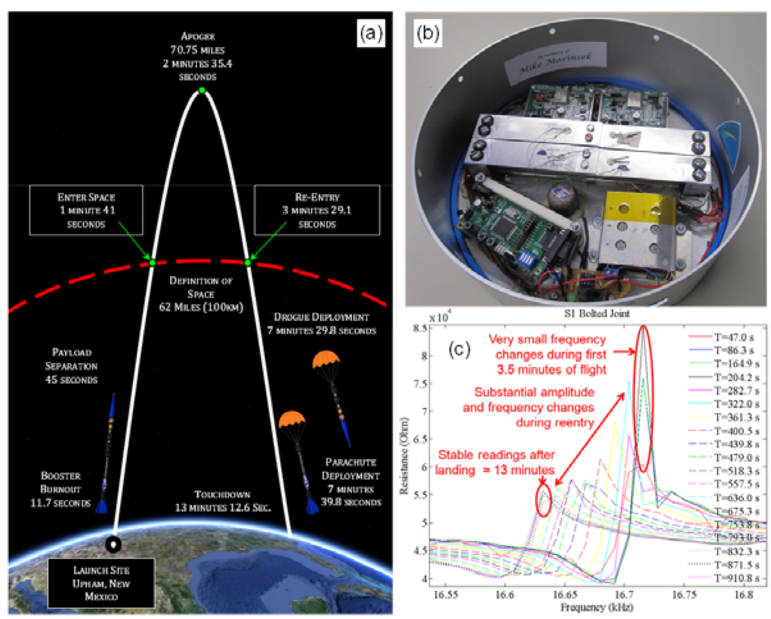


Figure 4 New Mexico Tech SL5 mission: (a) payload trajectory, (b) payload, (c) collected electromechanical impedance data.

as a promising SHM methodology for space systems. As seen in Figure 4, the electro-mechanical impedance signatures recorded during the suborbital flight showed little changes at the initial stages of the trajectory and substantial changes during payload re-entry. The results suggest that the piezoelectric-based SHM system is useful not only during pre-launch qualification but also during spacecraft operation, reentry, and landing (for reusable spacecraft).

Our research team conducted two additional flights with improved SHM systems: a high altitude balloon flight on January 20, 2011 (Zagrai *et al.*, 2012 and http://www.nasa.gov/topics/technology/features/nsc_balloon.html) and a SL8 sub-orbital flight on November 12, 2013 (Zagrai *et al.*, 2014). Results from these flights are available in associated publications and NASA reports.

Six SHM experiments were flown on a high-altitude balloon and on a SL8 suborbital flight. These experiments included (1) electro-mechanical impedance diagnostics of sensors and structures during flight, (2) a wave propagation experiment for measuring structural sound speeds in near-space conditions, (3) the collection of acoustic emission data, (4) the diagnosis of bolted joints, and (5) wireless sensing of strain and temperature at considerable distances. Schematics of these experiments on a payload and an actual payload photo are presented in Figure 5.

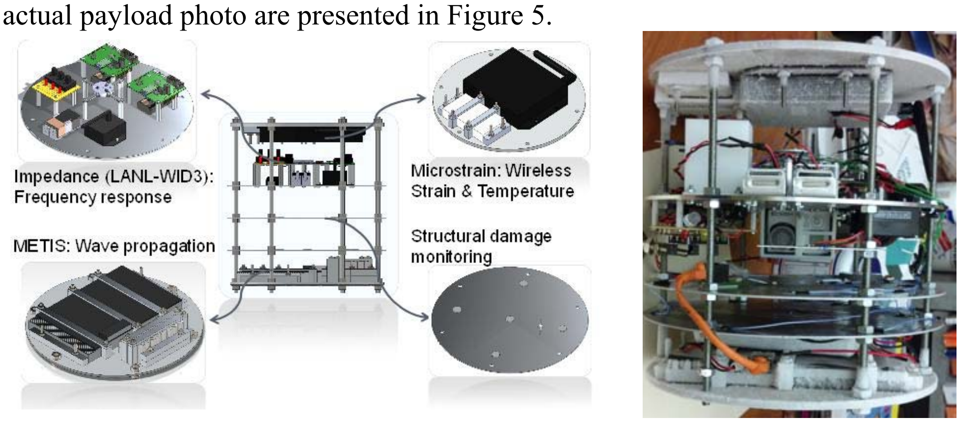


Figure 5 Schematics of payload experiments and a photograph of New Mexico Tech's SL8 payload (during environmental testing) flown on sub-orbital flight November 12, 2013.

Results from these flights demonstrated the potential of embedded ultrasonic SHM in stratospheric and space environments. For example, data in Figure 6 indicate that temperature can affect phase changes in acoustic waves, and that there is a direct correlation between acoustic wave phase shift and node temperature. These results suggest that a permanent structural change can occur, even after one suborbital flight. Such changes have implications for rocket reusability and the interpretation of science experiments. Our research team has also demonstrated monitoring of bolted joints and crack detection during both high-altitude balloon flights and sub-orbital flights.

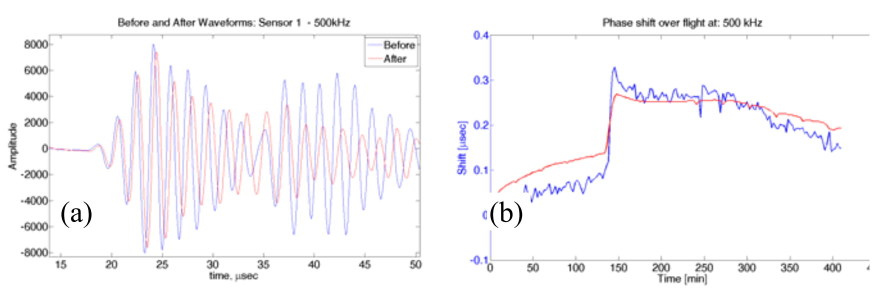


Figure 6 Ultrasonic signals collected during SL8 mission: (a) waveforms acquired before and after the flight, (b) phase shift of the initial pulse vs. time during SL8 mission. Red curve is temperature reading.

Suborbital flights have demonstrated that spacecraft structure changes under flight conditions. These changes are most pronounced during reentry, but the influence of the space environment is also possible. Unfortunately, due to the short duration (2-3 minutes in space) of these flights, it is difficult to infer the influence of the space environment on SHM sensors, hardware and modalities during suborbital flight. A long-term exposure test is needed and proposed in this proposal.

A.3. BENEFIT OF A MICROGRAVITY ENVIRONMENT TO THE RESEARCH

A series of experiments is planned that will uncover the influence of the space environment on piezoelectric material as an element of SHM sensors, the dynamics of structures in space, and the associated SHM methodologies and performance of SHM hardware

A.3.1. PROJECT DESCRIPTION

A.3.1.1. Electro-Mechanical Impedance Structural Health Monitoring

The electro-mechanical impedance is a structural diagnostic method that utilizes thin piezoelectric wafer active sensors to measure structural dynamic characteristics at high (kHz) frequencies (Park, *et al*. 2003). Essentially, mechanical coupling between piezoelectric sensors and a host structure and the electro-mechanical transformation inside the sensor allow for manifestation of a structural dynamic signature in the cumulative electro-mechanical impedance measured at the sensor terminals. A pioneering work on this method was conducted by Liang and colleagues (1993). Foundation and applications of electro-mechanical impedance were afterward expanded by many other researchers including, but not limited to, Chaudhry *et al*. (1995), Giurgiutiu and Rogers, (1997), Park, *et al*. (1999), Zagrai and Giurgiutiu, (2001), Tseng and Naidu, (2002), and Bhalla and Soh, (2004).

It has been shown by Giurgiutiu and Rogers (1997) that the total impedance measured by the sensor, $Z(\omega)$, contains both structural, $Z_{str}(\omega)$, and sensor, $Z_{PZT}(\omega)$, contributions.

$$Z(\omega) = \left[i\omega C \left(1 - \kappa_{31}^2 \frac{Z_{str}(\omega)}{Z_{str}(\omega) + Z_{PZT}(\omega)} \right) \right]^{-1}, \tag{1}$$

where C denotes the zero-load capacitance and κ_{31} represents the coupling coefficient of a piezoelectric active sensor for in-plane vibration. Appearance of structural response $Z_{str}(\omega)$ in Eq. (1) suggests opportunities for damage diagnosis as structural impedance may be affected by incipient damage or changes in stress conditions. This feature of Eq. (1) is exploited for detection of damage (delamination, cracks, an inadequate bolted joints) in space structures.

(a) (b) (c)

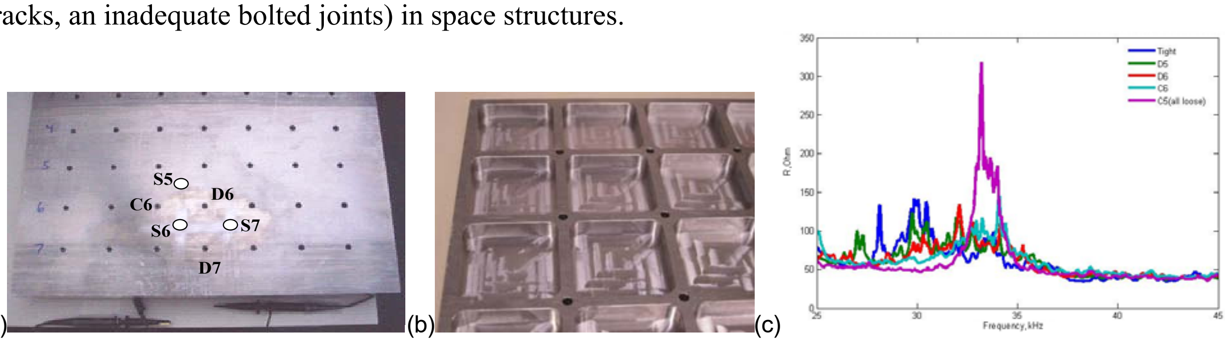
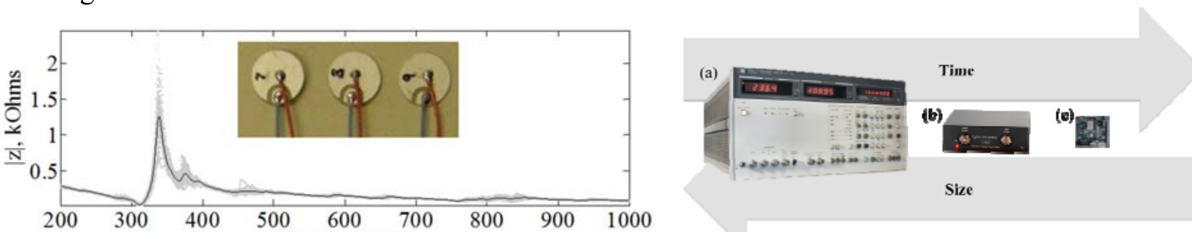


Figure 7 A realistic satellite panel consisting of two aluminum plates with iso-grid frames on the back side: (a) the sensor layout and position of bolts, (b) details of the iso-grid structure, (c) Impedance (real part) changes of sensor S5 as surrounding bolts are loosened incrementally.

An example of monitoring a realistic satellite panel is given in Figure 7. Three sensors S5, S6 and S7 placed in the neighboring iso-grid quadrants were selected for impedance testing of the satellite panel. The position of these sensors on the panel is illustrated in Figure 7a. A standard instrument, HP 4192A Impedance Phase Gain Analyzer, was utilized to collect sensor impedance signatures in the 25-45 kHz frequency range. This frequency range was selected due to the high density of impedance peaks. To develop an understanding of electro-mechanical impedance sensitivity to the torque change and the detection range, the first set of tests considered “tight” and “loose” states of the four bolts surrounding each sensor. Figure 7c presents the real part of sensor impedances for this experiment. According to the figure, the “loose” condition of four bolts in the quadrant produces an assembly of high amplitude impedance peaks clustered around 34-35 kHz. The “tight” condition results in substantially decreased impedance peak amplitudes accompanied by broadening and lowering the frequency band. It is suggested that this effect may be attributed to local changes in the boundary conditions of an iso-grid quadrant. Additional experimental trials showed that the electro-mechanical impedance measurements of bolts outside the area of the iso-grid quadrant had a minimal effect on recorded peaks. This example demonstrates utility of the impedance method in monitoring complex structures such as satellite panels with iso-grid structures.



(i) (ii)

Figure 8 (i) Piezoelectric active SHM sensors (in free condition) and associated impedance spectrum. (ii) Impedance analyzers: (a) HP 4192A, (b) Cypher Instruments C-60, (c) LANL WID3.

If a piezoelectric sensor is detached from a structure, its response follows that behavior of a free sensor. Understanding the response of a free sensor is important to determine the influence of environmental effects on piezoelectric materials and smart structure response, in general. Piezoelectric sensors exhibit resonance behavior determined by material composition, boundary conditions and sensor dimensions. An example of the impedance of a free sensor with soldered electrodes is presented in Figure 8i. To this date, our research team has explored the influence of vacuum, temperature and radiation on piezoelectric sensors in a laboratory environment. In particular, Figure 9 shows the equipment and the results of a radiation experiment suggesting little effect on aluminum structure and noticeable effect of gamma radiation on piezoelectric sensors. Standard impedance measurement instruments (Figure 8ii) were utilized for laboratory tests and a LANL WID3 with maximum band of 100 kHz was employed in the space environment. Due to the limitation of the measurement hardware, we were not able to conduct real-time impedance tests on free sensors in space during the suborbital flights. Understanding the effects of the space environment on piezoelectric sensors and smart structures with piezoelectrics, in general, is extremely important to (a) infer capability of piezoelectric sensors for space weather monitoring, (b) estimate life expectancy of smart structures in space, (c) separate effects linked to structural and material damage from effects associated with the space environment. The new hardware planned for the proposed ISS experiment will give our team the capability to measure the response of free sensors at resonances (300 kHz) and address important issues such as discussed above.

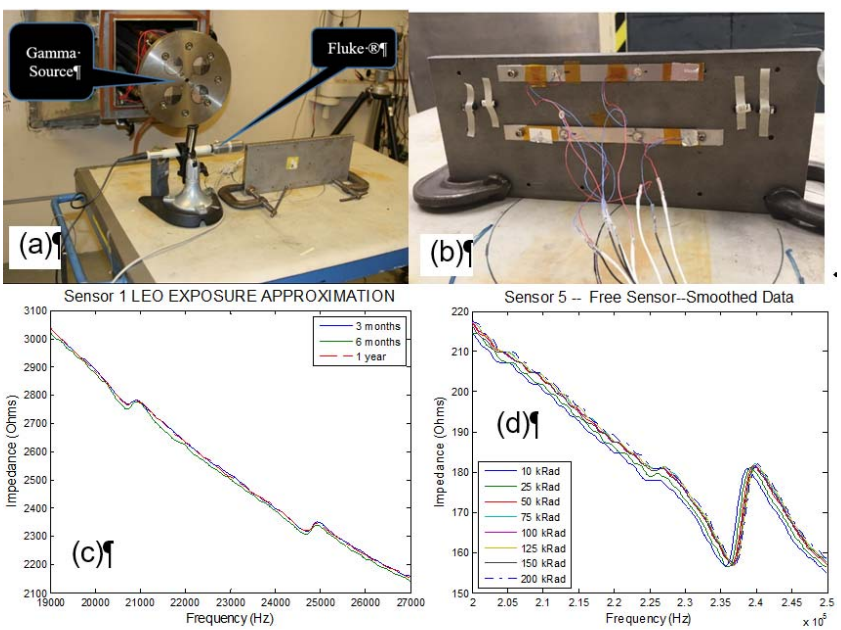


Figure 9 (a) White Sands Co-60 radiation equipment (b) Gamma radiation test setup with free piezoelectric sensors and smart beam structures, (c) structural impedance response at various time equitant to LEO radiation exposure, (d) piezoelectric sensor impedance (in free condition) at various radiation exposures.

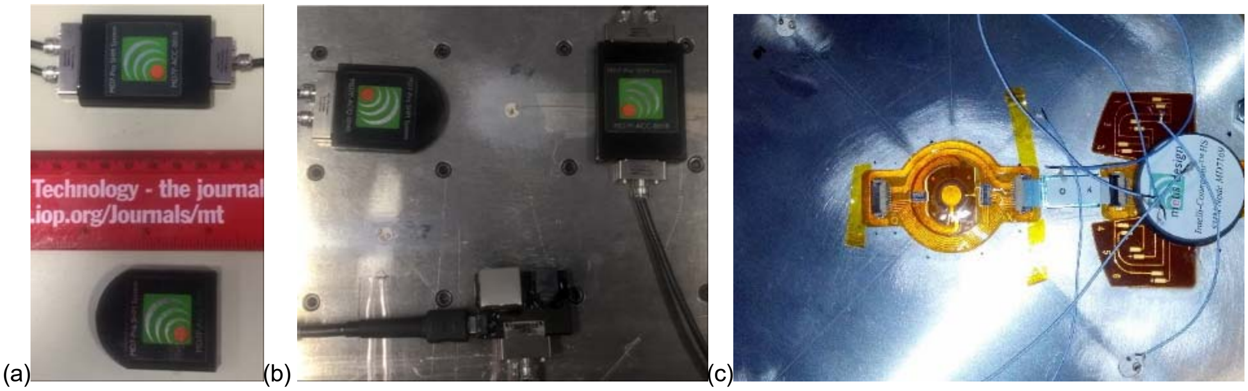


Figure 10 Metis Design hardware for elastic wave propagation and impedance tests: (a) top – Accumulation node and bottom with semicircular cap - signal generation/acquisition node, (b) both nodes are shown along with communication adapter on a realistic satellite panel, (c) older version of hardware flown on an SL8 sub-orbital mission (metisdesign.com).

A.3.1.2. SHM Hardware.

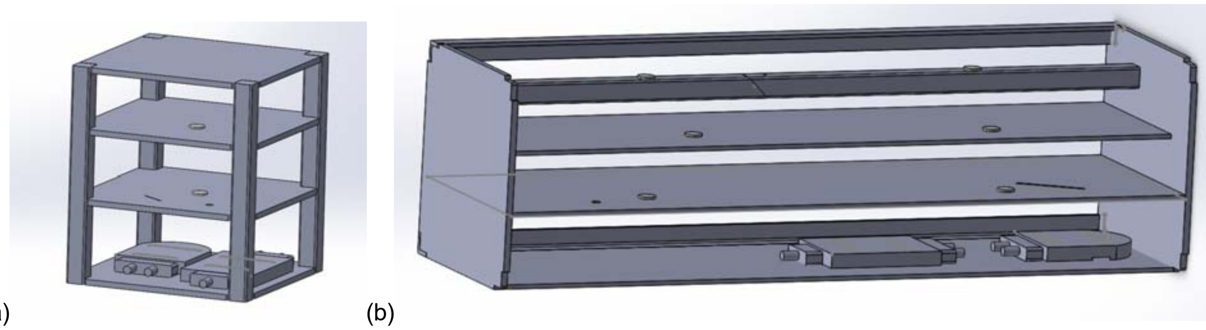
Elastic wave propagation and electro-mechanical impedance measurements are popular SHM methodologies requiring pulse (for elastic waves) and continuous wave (CW – for impedance) generation, reception and analysis. In recent years, technological advances allowed for miniaturization of hardware for elastic wave SHM, which now features a signal generator/amplifier unit and FPGA on the same breadboard measuring 50 x 40 x 5 mm and weighting 15 grams. Visible in Figure 10a is an MD7-Pro system featuring a signal generation/acquisition node that will be connected to piezoelectric sensors using a special adaptor (not shown). According to Metis Design (http://www.metisdesign.com/structural-health-monitoring-company), manufacturer of this equipment, 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. A triaxial accelerometer and temperature sensor are also integrated into each device. 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 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 protocols. In addition, the Accumulation Node offers 16 digital inputs and boasts 64-GB of static memory. A powerful FPGA with an ARM core processor can be programmed to execute embedded diagnostic algorithms or prognostic and health management (PHM) logic. The overall power requirement for a wave propagation test is 28VDC×28/108 mA min/max, which results in a few watts.

In its present form, the MD7-Pro allows for elastic wave propagation studies and acoustic emission monitoring. We have been in contact with the company to configure units for electro-mechanical impedance SHM. Efforts are currently underway to demonstrate electro-mechanical impedance SHM with MD7-Pro. We are exploring long pulse generation mode to obtain frequency response at high frequencies and anticipate completion of this task during first year of the project.

A.3.1.3. Payload

The aim of the payload is to investigate effects of space environment on piezoelectric active sensors, to explore structural vibrations in microgravity and to demonstrate the feasibility of SHM a during long term space mission. To achieve this goal, it is proposed that the payload is located outside the space station on one of the racks accepting 1U or 3U payload configurations. Orientation of the payload with respect to Earth or Sun position is not critical; although, a location allowing for minimization of thermal effects is desirable.

Miniaturization of the test hardware and the availability of electric power from the ISS led to consideration of the payload in 1U and 3U geometrical configurations. The 1U design includes studies of the electro-mechanical impedance of the SHM and the effect of the space environment on piezoelectric active sensors. If expansion to 3U design is allowed, an additional elastic wave propagation experiment could be included.



(a) (b)

Figure 11 (a) 1U configuration of a payload, (b) 3U configuration of a payload.

A.3.1.3.1. 1U payload

The 1U payload configuration is considered first. In this geometrical configuration payload electronics and experimental hardware are packaged into the 10×10×11.35 cm volume. A sketch of a payload is shown in Figure 11a. The lower plate features MD7-Pro electronics and will also include the necessary power and data connections (not shown on the sketch). The second plate houses the SHM experiment in which several piezoelectric sensors are used to monitor the condition of a structural element with an artificial crack or an isolated (not structurally significant) loose joint at the boundary. During the time on orbit, the vibration signature of the "damaged" plate will be compared with the signature of the "pristine" or "undamaged" third plate (from bottom) and conclusions will be drawn on the potential of SHM in space and the influence of the space environment on the SHM process. The third plate will additionally serve in the experiment to study structural vibration in microgravity. The objective of this experiment is to improve the understanding of structural vibrations, especially vibrations of small structural elements, in space, which could advance structural design and control of future spacecraft. It is anticipated that different structural damping values will be seen in space in comparison with the ground experiment and that structural constraints may also behave differently. The last experiment will be housed on the top plate. It will be located on the underneath side of the top plate and is not shown on the sketch. In this experiment, the electro-mechanical response of the free piezoelectric sensor will be studied under the influence of the space environment. Sensors and the acquired response will be similar to that pictured in Figure 8i; but, will reflect the contribution of the space environment to sensor dynamics. From these responses (on the ground and in space), the fundamental parameters of a piezoelectric ceramic can be extracted and, for the first time, the variation of the parameters due to the space environment may be reported. This study is essential to differentiate the influence of the space environment on sensors from the influence of structural damage occurring in structures operating in space

A.3.1.3.2. 3U payload

The 3U payload is 3 times longer than the 1U payload. The reason for consideration of the 3U payload is to include an additional ultrasonic wave propagation experiment that physically needs longer structural elements to propagate elastic wave. A sketch of the 3U payload is presented in Figure 11b. Similar to the 1U configuration, the bottom plate of the 3U design will feature an MD7-Pro test system and other electronic components of the experiment in the payload. The second and the third plates will support experiments with "damaged" (second) and "undamaged" (third) scenarios explored by both the electro-mechanical impedance method and the ultrasonic elastic wave propagation method. In the latter case, a short pulse is transmitted from piezoelectric actuator, propagates across plate structures and is collected by other piezoelectric sensors distributed on the plates. This additional experiment will allow for a fundamental study of elastic wave propagation in structures in a space environment. It is anticipated that it will result in uncovering dependencies governing elastic wave propagation in structures operating in space. Such a study is important for possible application of ultrasonic testing in space. A fourth segment of the payload includes an experiment studying the influence of the space environment on piezoelectric sensors. The electro-mechanical response of free piezoelectric sensors in space environments will be periodically measured in a way similar to that described in the previous section.

A.3.1.4. Mission Details

The maximum duration of a mission in orbit is 1 year. However, considerable volume of data and associated dependencies may be inferred over a period of several months. Electromechanical impedance measurements will be conducted automatically (without astronauts involvement) every six minutes to capture environmental changes occurring over one orbit. We will correlate these changes with data from other instruments available on the ISS (e.g., radiation measurement, temperature measurements, etc.). Data will not be collected every day; but, at certain times specified by software. The duration of a mission will allow for collecting large amounts of data necessary to study effect of the space environment on piezoelectric sensors and the SHM process. Data will be temporarily stored on a hard drive in the MD7-Pro system; but, an opportunity to downlink the data would be extremely beneficial for verification of system performance and uncovering early analysis data trends. Initial data will come in the form of an electronic file resulting in the graph depicted in Figure 8i. Further data reduction is possible, but not advisable as space environment will likely alter not only natural frequencies, but also a shape of the impedance curve. The suggested position of a payload is outside of the ISS in one of the racks supporting 1U or 3U configurations. Orientation of the payload with respect to Earth or Sun position is not critical although a location allowing for minimization of thermal effects is desirable. In the case of a 3U configuration being allowed, the MD7-Pro hardware will be configured to alternate electro-mechanical and elastic wave experiments.

A.3.2. MICROGRAVITY GOALS AND OBJECTIVES

The **Project Goal** is to demonstrate the feasibility of structural health monitoring during long-term space missions. This goal will be achieved by completing the following project objectives.

Project Objectives:

(i) Investigate the influence of the space environment on piezoelectric ceramic sensors and study the dynamic behavior of the piezoceramic sensors utilized in SHM. This objective will be achieved by periodically measuring the electro-mechanical impedance of a sensor within the resonance frequency band.

(ii) Explore structural vibrations in microgravity by measuring the dynamic response of a plate payload element. The response will be measured periodically under different space weather conditions to yield a dependence of structural parameters on space environmental factors.

(iii) Demonstrate the feasibility of detecting structural damage in the space environment using electro-mechanical impedance and/or elastic wave propagation SHM methodologies. This objective will be achieved by measuring and comparing responses of “damaged” and “intact” structural elements.

Expected Significance and Impact: Project realization will have long lasting significance to the space industry and, particularly the commercial space industry. It is expected that SHM system will provide real-time data on structural conditions at all stages of the spaceflight and will be used in re-certification for the next flight; or, as a part of a “black box” for event investigations. The specific benefits provided by the SHM at different stages of the spaceflight are indicated in Figure 1. As the space industry is moving towards smart structures with integrated sensors and actuators; understanding functionality, performance, and longevity of such structures in the space environment is of paramount importance.

A.3.3. ANTICIPATED RESULTS

The project will provide data, analysis, and guidelines for use of SHM in the space environment. The specific outcomes grouped by project objectives are listed below.

Project Outcomes include:

(a) Piezoelectric ceramic parameters extracted from electro-mechanical impedance signatures measured on the ground and in space. The variability of these parameter due to mission conditions (space weather, daily cycles, etc.) will be investigated. The study will result in first available reference on performance of piezoelectric ceramic sensors in space and the variability of piezoelectric ceramic parameters due to changes in the space environment.

(b) Structural dynamic signatures of plate payload elements. It is expected that the analysis of such signatures will improve the understanding of structural vibrations in space. The goal is to extract natural frequencies and damping values for a known payload element and track these values as the space environment changes. The availability of such data is important in the design of spacecraft components and in structural control.

(c) Structural dynamic signatures reflected in electro-mechanical impedance responses of the “damaged” structural element. These signatures will be analyzed for the influence of structural damage in the form of a crack or localized (without compromising payload integrity) loss of the torque on a bolted joint. The signatures from the “damaged” structure will be compared to the dynamic signatures of a “pristine structure” (previous outcome) and the difference will be investigated and tracked with respect to the influence of the space environment.

A.3.4. TIMELINE

The project duration is three years. The first year will be devoted to the development of the payload and associated experiments. The second year will focus on tuning the payload to meet NASA requirements for the ISS mission. The third year will include integration of the payload with the ISS mission. The table below presents tentative schedule of the project.

Table 1 Schedule of project activities.

Activity	Year 1	Year 2	Year 3
Impedance measurements with MD7-Pro			
Payload design and configuration			
On the ground baseline for payload experiments			
Payload adjustments to meet mission requirements			
Payload environmental and functionality tests at NASA			
Final payload configuration and pre-flight tests			
In-orbit data acquisition, analysis, payload recovery and results	reporting	**Beyond 3**	**years**

Reporting requirement is integrated in each project activity and reports will be provided with periodicity determined by NASA.

B. APPROACH TO FLIGHT AND GROUND SAFETY REVIEW PROCESS

B.1. PAYLOAD REQUIREMENTS

The payload is considered in 2 configurations: 1U and 3U systems. The availability of additional space for the 3U configuration will allow for an additional elastic wave propagation experiment. A detailed description of the payload is presented in the Payload sections of the project description. Additional requirements are presented below.

Time to flight: A 3-year plan is proposed for the payload development and for adjustments to facilitate adequate integration with the NASA ISS mission.

Crew time requirement: It is envisioned that the crew will spend several hours for payload deployment into one of the Nanoracks outside of the ISS and an additional hour verifying electrical and data connectivity of the payload.

Power requirements: Power requirement is estimated from overall power for the wave propagation test, which is 28VDC×28/108 mA min/max. These numbers result in a few watts. Even if longer elastic wave pulses are used, the power requirement will still be of the order of a few watts. Being extremely conservative, the maximum power requirement should not exceed 50 watts.

Physical space: The payload is designed to fit a 1U or a 3U configuration. The 1U means that the payload is enclosed into the 10×10×11.35 cm volume. The 3U configuration utilizes a 10×10×34 cm volume.

B.2. PRELIMINARY HAZARD ANALYSIS

In the development of the payload, relevant NASA Flight Opportunity Program (FOP) documentation was considered for the preliminary hazard analysis. It is understandable that safety requirements for the ISS payload will differ from requirement for the FOP. However, the FOP approach will be used in the initial stage of payload development and once a contact with a NASA ISS safety officer is established and interactions started, the safety process for the ISS payload will be implemented.

The approach to the flight and the ground safety review process will include review and compatibility assessment for the following:

1. Physical and mechanical characteristics of the payload, which include mass budget, physical dimensions, materials, structure and assembly, insulation, center of gravity location, dynamic characteristics of payload including natural frequencies, attachments to space vehicle/ISS module.
2. Electrical characteristics of the payload: power, life expectancy, and safety, electrical interfaces and connectors, electrical insulation and grounding, electrical switches, LEDs and indicators, electromagnetic interference (EMI), radiation shielding of electronics, RF frequencies transmitted by payload, communication and data storage.
3. Hazardous substances: ensure absence of radioactive sources, aggressive chemicals, laser sources, components under pressure, toxic materials, biological substances, corrosive elements, explosive materials, flammable materials, sources of gas and vapor release.
4. Operational environment: minimum and maximum temperatures of operation, ionizing radiation, vacuum, free oxygen, electrical charge, micro-meteorite impact.
5. Are there any in-flight or ground operations that present a risk to personnel, near-by equipment, or the environment?
6. Does the payload have any specific sensitivities to influences from the vehicle or other payloads such as EMI, off-gassing, vibration, pheromones, etc.?
7. In your estimation, will your payload have any potential influences on other payloads flown in the same cargo bay?

In the initial stage of payload development, the team will coordinate our safety review process with NASA representative in bi-weekly meetings. As payload will be close to completion, frequency of meeting will vary depending on particular needs. At the end of the first year of the project, a complete payload development review will be organized, which will include assessment of payload safety.

Table 2 Criticality analysis of individual risks

		Consequence Index ⟶		
Probability index ⟶		1	2	3
	3	R3	R8	R7, R5
	2		R4, R6	R9
	1		R2	R1

B.3. PRELIMINARY RISK ANALYSIS

In the preliminary risk analysis, we consider several possible scenarios organized in accordance with probability of occurrence and associated consequences (NASA/SP-2011-3422). The following risks were identified during preliminary analysis.

R1 – Payload mechanical failure during deployment. Mitigation: Ensure proper mechanical fit to deployment mechanism. NASA test.

R2 – Initial electrical and data connectivity of the

payload to ISS. Mitigation: NASA ground connectivity test
R3 – Radiation damage of payload electronic hardware. Mitigation: extra aluminum thickness to protect a box with electronics
R4 – Thermal damage to payload hardware. Mitigation: payload location and thermal shielding.
R5 – Measurement program execution during long-term experiments. Mitigation: program execution test during diagnostic tests at NASA. Ability to reboot and communicate with the system on orbit.
R6 – Data storage and downlinking. Mitigation: Data storage (lab) and connectivity (NASA) tests.
R7 – Damage to payload during transportation and launch. Proper packaging, handling and integrity verification during all pre-launch stages
R8 – Material changes in space environment (adhesive, etc.) Mitigation: proper shielding and use of space-qualified materials.
R9 – Influence of considerable temperature swing (day and night). Mitigation: proper thermal shielding.

C. BUDGET

C.1. GENERAL INFORMATION

The project will be administered by New Mexico Space Grant Consortium (NMSGC), Director Dr. Patricia Hynes (575-646-6414, pahynes@ad.nmsu.edu). Proposed research efforts will be carried out at New Mexico Institute of Mining and Technology (NMT) and will be managed in accordance with existing NMT policies and procedures available at http://infohost.nmt.edu/~red/policies.html. The budget will be administered by NMSGC and NMT Restricted Funds Department will track monthly expenditures of the NMT contribution. The NMT Contract Administrator for this project is Ms. Gayle Bailey (575-835-5915, gayle.bailey@nmt.edu . Project investigator, Dr. Andrei Zagrai (575-835-5636, andrei.zagrai@nmt.edu) will be responsible for overseeing technical and NMT budget matters of the project.
3 Year budget for the project is presented below.

NMSGC				
Pat Hynes	Year 1	Year 2	Year 3	Total for 3 Years
Salary 1%	$1,447.67	$1,447.67	$1,447.67	$4,343.01
Fringe 36.5%	$528.40	$528.40	$528.40	$1,585.20
Total Salary and Fringe	$1,976.07	$1,976.07	$1,976.07	$5,928.21
F&A 48%	$948.51	$948.51	$948.51	$2,845.54
Total NMSGC	$2,924.58	$2,924.58	$2,924.58	$8,773.75
NMT				
Faculty Salary 4.4%	$0.00	$4,812.40	$4,812.40	$9,624.80
Students	$10,500.00	$10,750.00	$10,750.00	$32,000.00
Fringe 35% and 2%	$210.00	$1,899.34	$1,899.34	$4,008.68
Travel	$3,000.00	$0.00	$0.00	$3,000.00
Supplies and Materials	$2,398.21	$9.21	$6.97	$2,414.39
Total Indirect Cost	$16,108.21	$17,470.95	$17,468.71	$51,047.87
F&A 55.2%	$8,891.73	$9,643.96	$9,642.73	$28,178.42
Total NMT	$24,999.94	$27,114.91	$27,111.44	$79,226.29
F&A on NMT Sub	$11,999.97			
Project Total	$39,924.50	$30,039.50	$30,036.02	$100,000.02

C.2. EXPENDITURES

Administrative cost of this project includes 1% monthly salary of Dr. Patricia Hynes, director of New Mexico Space Grant Consortium (NMSGC), which results in $1,447.67 annual expenditure.
The **Senior Personnel** of this subcontract includes Dr. Andrei Zagrai, a faculty member of NMT. The faculty rates are based on a combination of an academic year and a summer term. Dr. Zagrai's 2017 monthly rate is $9,080. Faculty contribution is estimated as 0.53 month (5.88%) annually for two years of the project, i.e. $4,812.40 per year with $9,624.80 total.
Other personnel include one **graduate student**. Projected 2017 rate for a NMT graduate student is $10,500 for 9 months, including tuition and university fees. The budget indicates 9 months per year of graduate student support totaling $32,000.
Fringe benefits for NMT faculty and students are applicable to direct salaries and wages and are treated as direct costs. Actual fringe benefits vary with salary level and elected employee benefit options. For faculty participating in the project, fringe benefit rate was estimated as 35%. Student employee fringe benefit rate is 2%. NMSGC fringe benefit is 36.5%.
Supplies/materials budget of $2,414.38 will include items such as sensors, batteries, cameras, materials, cables, connectors, adhesives, power supplies, wires, soldering accessories, assorted electronic components (resistors, capacitors, breadboards etc.) to build and operate experimental setups. Supplies/materials also may include computing products permitted by the project, software, electronic devices, information dissemination, communication/phone (cell and landline)/data/internet fees to support the project. Supplies/materials imply any item that is not equipment by New Mexico Tech property office definition. Significant expenditures in this segments are expected in the first year of the project.
The budget includes **travel** in the amount of $3,000. Federal per diem and mileage rates will be applied for associated travel cost. Travel to NASA facilities is anticipated as well as dissemination of project progress at conferences and symposia.
The **Indirect Cost** Rate is the mechanism used to allocate a portion of NMT infrastructure to research funding agencies. The current NMT Fixed Overhead Rate is 55.2% of MTDC for organized research on campus. NMSGC F&A is 46%. Because NMSGC will provide a subaward to NMT, the first $25,000 of the subaward will be subjected to 48% of F&A and will results in additional first year expenditures of $11,999.97.
Total funds requested from NASA EPSCoR program is $100,000.

D. ISS PROGRAM VETTING OF SELECTED PROPOSALS

The table below summarizes payload characteristics with respect to ISS program requirements.

Criterion	Strong (10 points)	Average (5 points)	Weak (0 points)
Feasibility	Some elements of the SHM have already been tested in suborbital flights		
Time to flight		Less than 2 years	
Crew requirements	Installation and connection only		
Power requirements		Few watts	
Physical space	Fits in 3U		
Funding feasibility	Funding is low, but will	be leveraged with other existing projects	

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