

# SansEC Sensing Technology - A New Tool for Designing Space Systems and Components

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<sup>1</sup>**Abstract**— This paper presents concepts for using the NASA developed SansEC sensing technology for reconfiguring/modifying many space subsystems to add to their original function the ability to be sensors/sensor arrays without the addition of the electrical circuitry typically used for sensors. Each sensor is a self-resonating planar pattern of electrically conductive material that is an open-circuit single component without electrical connections. The sensors are wirelessly powered using external oscillating magnetic fields and when electrically excited respond with their own magnetic fields whose frequency, amplitude and bandwidth can be correlated with the magnitude of multiple unrelated physical quantities. These sensors have been demonstrated for numerous measurements required for spacecraft and inflatable/expandable structures. SansEC sensors are damage resilient and simple to fabricate. Thin films of conductive material can be used to create sensor arrays that function as sensing skins. Each sensor on the skin can be tailored for a science or engineering measurement. Additionally, each sensor has an inherent damage detection capability. These sensing skins can be used to redesign inflatable habitat multi-layer insulation to provide additional functions of environmental measurement and micrometeorite/orbital debris damage detections. The sensing skins can be deposited on planetary exploratory vehicles to increase the number of measurements with negligible weight increase.

## INTRODUCTION

SansEC (*Sans Electrical Connections*) Sensing Technology was developed as a method to have a sensor circuit that does not have an “Achilles” point (a point on the circuit that if severed or damaged, results in the circuit becoming non-functional) [1-3]. The sensors are self-resonating patterns of electrically conductive material that do not use electrical connections. Each sensor is powered using time-varying magnetic fields and when electrically active, they respond with their own harmonic magnetic fields whose frequency, amplitude and/or bandwidth can be correlated to the magnitude of one or more physical quantities. The key advantage that SansEC offers space systems is that it is minimally intrusive, damage resilient and self-health

monitoring. The sensors are wirelessly powered and interrogated eliminating wiring harnesses. Connections are not needed to form the sensors allowing them to be applied as thin films of electrically conductive material to spacecraft non-conductive surfaces. The sensors can be applied with techniques like vapor deposition to minimize additional weight. Many systems can be redesigned to add sensing to their original function.

In this paper, two space systems will be used to provide examples of how SansEC sensing technology can be incorporated into spacecraft to design some of their common components to have additional sensing and vehicle health monitoring functions. The first example demonstrates how SansEC can be used to reduce the weight of inflatable/expandable structures like the NASA TransHab [4]; specifically, modifying the thermal protection layer to create a sensing skin that provides damage detection and environmental sensing while maintaining the original insulating function. The second is the Aerial Regional-scale Environmental Survey (ARES) of Mars plane concept. After ejection from a heat shield, the plane unfolds and glides to the surface collecting data [5]. An overview of SansEC sensing technology will also be presented. Examples of SansEC sensors will be presented along with empirical data. Development of sensing skins using SansEC arrays will also be described. Examples of how a single function component can be redesigned using SansEC technology to have two or more unrelated functions will also be presented and discussed.

## SANSEC SENSORS

The foundation of a SansEC sensor is exposing an open-circuit self-resonating pattern of electrically conductive material to external time-varying magnetic fields that induces an electromotive force in the pattern. When the pattern is electrically active, it responds with its own harmonic magnetic and electric fields. Changes to the fields due to deformation of the pattern; partial destruction of the pattern; dielectric material changing in the pattern’s electric field; magnetic permeable material changing in the pattern’s magnetic field; material conductivity changing in the fields; or, changes to the amount of either conductive, dielectric or magnetic permeable material that the pattern is

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exposed to result in changes to the patterns resonant frequency. These changes can be correlated to the magnitude of the physical quantity creating the change thus making a sensor. The amplitude of the responding pattern's field will change with the magnitude of the magnetic flux that the sensor is exposed to. Typically this occurs as the source of the time-varying external field moves relative to the pattern. The change in amplitude with relative position of the source with respect to the pattern can also be used to develop a sensor. A detailed discussion of the sensor is found in [3].

The significance of the method of designing, powering and interrogating an open-circuit device is that it consolidates the functions of many electrical components (collecting and storing energy, self-health monitoring, sensor, transmitting) into a single component. One fundamental difference between a typical closed-circuit device and the more recent open-circuit SansEC devices is the means of creating an electromotive force that in turn creates the current. Most closed circuit devices use an electrical potential difference such as a battery or an alternating current source. SansEC devices use an external time-varying magnetic field to induce an electromotive force via Faraday induction. Another difference is that, typically, closed-circuit devices are designed around lumped components while SansEC uses distributed capacitance and inductance. Use of an electric potential difference necessitates that the circuit must be electrically connected to the electric potential and its component must be connected directly or indirectly to the potential.

An example of a pattern that is capable of having distributed electric and magnetic fields is a planar spiral pattern or a 3-D helical pattern. Shown in Fig. 1(a) is a 10 cm x 10 cm spiral pattern of copper with a trace width of 2 mm and 0.13 mm between neighboring traces. It has a resonant frequency of 17.1 MHz. Sensor geometry is not limited to spirals or the dimensions presented above. The range of sensor sizes tested to date range from 1.5 cm x 1.5 cm to 61.0 cm x 45.7 cm. The sensor is electrically excited using the interrogation method discussed in [6, 7]. Other methods for interrogating resonant sensors are impedance techniques [8-10]. In Fig. 1(b) are an edge view illustration of the sensor and the responding magnetic and electric fields. The fields extend beyond the surface of the sensor. Measurements are related to changes in the sensor's response frequency such as dielectric or permeability changes to material in the sensor's electric field and magnetic field, respectively. Deformation and damage to the sensor also changes the frequency. Measurement responsive material does not need to be in physical contact with the SansEC circuit as shown in the Fig. 1(b). The measurement sensitive material may also be on one side of a protective barrier while the SansEC circuit and

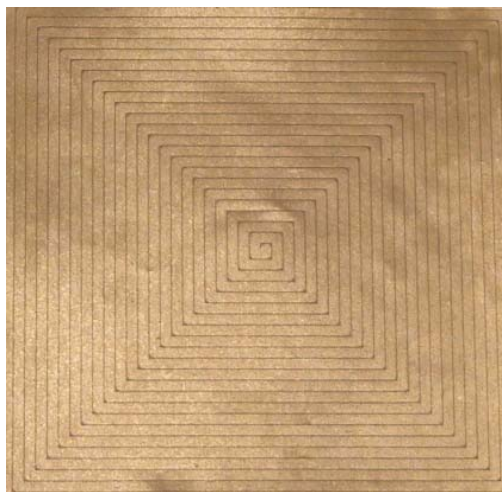
interrogation system remain on the other side of the barrier. Measurements such as displacement and rotation can be related to the sensor's response amplitude. The sensor's resistance is dependent upon temperature and results in the sensor's response bandwidth increasing with temperature.

The interrogation method used in [6, 7] transmits a harmonic that induces an electromotive force in the sensor. A time history of the sensor magnetic field response during the interrogation process is shown in Fig. 1(c). The sensor responds with its own damped harmonic field. After a predetermined number of harmonics, the transmission is stopped. The system is then switched to a receiving mode and the sensor response decays. A peak detector rectifies the responding amplitude and the rectified amplitude is placed in memory. The transmit-pause-receive process is repeated for a predetermined series of increasing harmonics. The current rectified amplitude is compared to the previous amplitude to identify the inflection of the amplitude that occurs when the sensor has been interrogated at the first harmonic greater than the resonant frequency of the sensor. The harmonic nearest the resonant frequency (i.e., the harmonic creating the amplitude inflection) is correlated to the measured physical parameter.

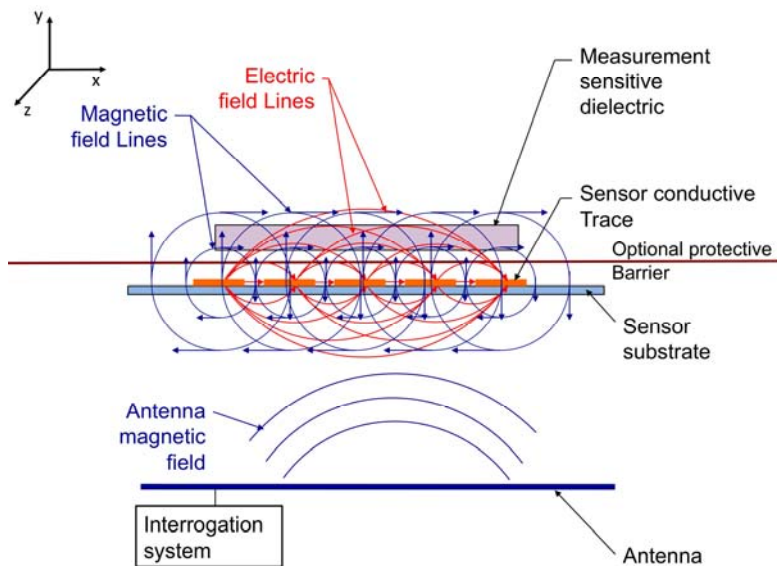
Examples of sensor measurements resulting from the sensor design of Fig. 1(b) are shown in Figs. 2 and 3. Results of placing a variety of temperature sensitive dielectric material; piezoceramics TRS-100C, TRS 200HD, TRS 300HD<sup>2</sup> and glass; in the sensor electric field are shown in Fig 2. A detailed discussion of the testing is found in [11]. Other examples of measurement sensitive material placed in the electric fields are chemical sensors in [12, 13]. Chemical sensitive material is placed in the sensor's fields that react specifically with another chemical or has a specific absorption to another chemical [12, 13]. When the material is exposed to an analyte of interest, the material dielectric or conductivity will change resulting in a response frequency change. Results of using the sensor for fluid-level measurement are shown in Fig 3 [3, 14]. The sensor was placed external to a glass container while it was filled with water. Response measurements were taken in intervals of 0.5 cm. In the tests of Fig. 2 and in [12, 13], material remains stationary with respect to the sensor but its dielectric or conductivity changes. In Fig. 3, the dielectric remains constant but the sensors field exposure to the water increases as the container is filled. SansEC sensors can be powered and interrogated if damaged. The sensor in Fig. 3(a) was punctured with a 0.53 cm hole. The fluid level measurements were then repeated and are shown also in Fig. 3(b).

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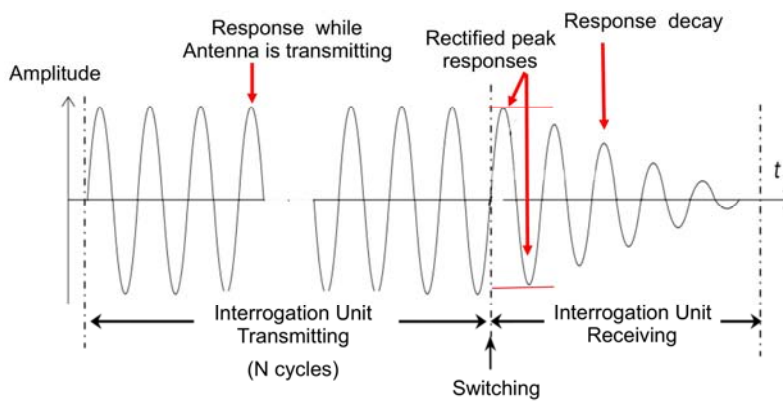
<sup>2</sup> Trade names of TRS Technology, Inc. for DOD Type I, Type II, and Type III compositions, respectively.



(a) SansEC open-circuit sensor.

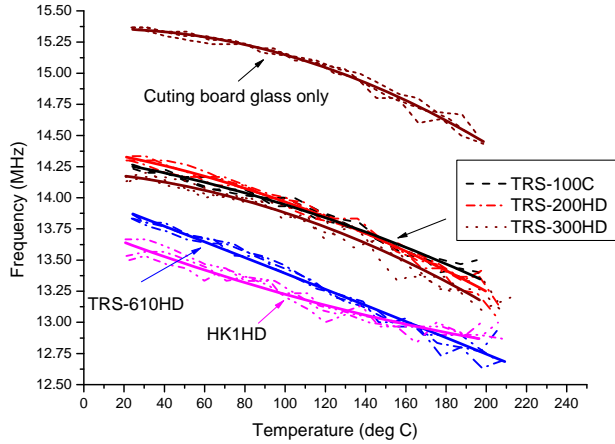


(b) Edge view of SansEC open-circuit sensor (spiral pattern) during interrogation

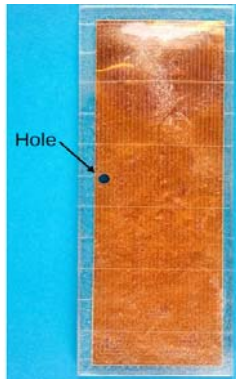


(c) Time history of sensor magnetic field response while interrogation antenna is transmitting and after antenna is switched to receiving mode

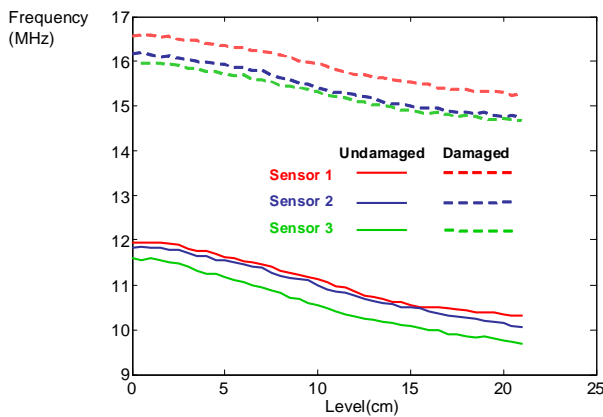
**Figure 1 - SansEC sensor, schematic of sensor interrogation, and time history of sensor response.**



**Figure 2 - Experimental results of SansEC sensor with glass and piezoceramics as temperature sensitive dielectric material.**



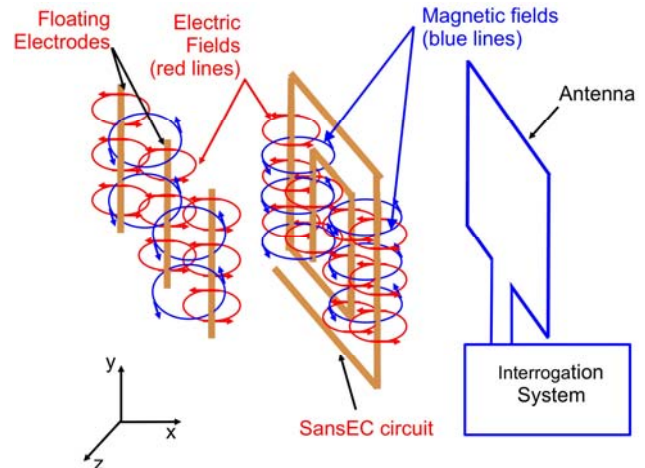
(a) Damaged sensor encased in urethane.



(b) Response frequency variation with fluid-level measurements of undamaged and damaged sensors.

**Figure 3 - SansEC sensor punctured with 0.53 cm hole and its response to fluid-level before and after being punctured. The sensor was placed external to a glass container to measure the water inside.**

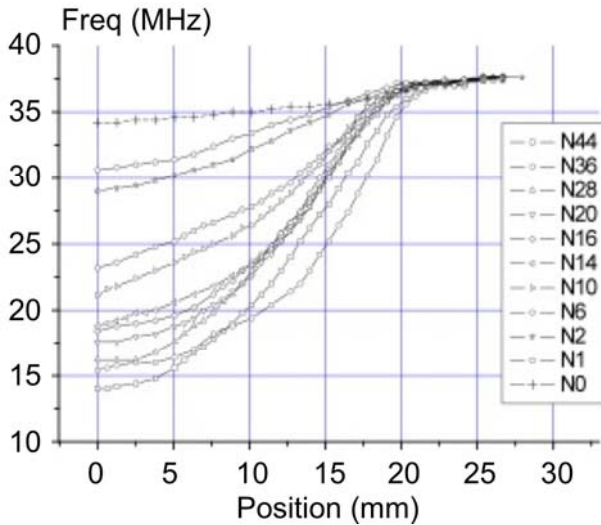
Conductive material placed in proximity to the sensor can also be used for a variety of measurements. If the material has a low length to width aspect ratio, the material will attenuate the magnetic and electric fields produced by the sensor. The attenuation increases monotonically with the material conductivity, the proximity of the material to the sensor and the amount of material that overlaps the sensor. As the material gets closer, or the area of the material overlapping the sensor increases, the response frequency increases and the response amplitude decreases until it is no longer discernible. If a narrow conductive strip is placed in proximity to a responding SansEC sensor, the response frequency decreases and the amplitude increases; indicative of more energy being stored in the system. The strip is not electrically connected to the sensor and is referred to as a “floating electrode.” Fig. 4 illustrates the SansEC sensor response to the antenna excitation and the magnetic and electric field response of a set of narrow conductive strips resulting from the electromotive force induced from the sensor response.



**Figure 4 - Schematic of “floating electrodes” in proximity to SansEC circuit.**

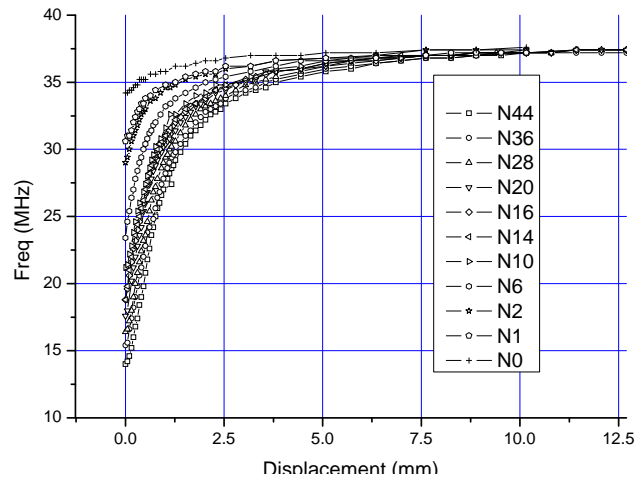
Figs. 5 and 6 are the response frequency variation with respect to the relative displacement of the sensor and strips in the parallel (y) and normal (x) directions, respectively. In each figure, results are shown for using a different number of strips. The initial position for the displacement measurements, when the strips are moved parallel to the SansEC sensor, is the center of the circuit. Measurements were taken in 1 millimeter increments using a different number of strips, N. The variation is monotonic but not linear for the entire measurement range. In the 7 – 17 mm range for  $N \geq 14$ , the sensitivity is approximately 1.5 MHz/mm. The interrogation system of [6, 7] typically uses a frequency resolution of 25 KHz resulting in a displacement resolution of 0.017 mm. During testing, the resolution between frequency increments was 5.0 kHz. The interrogation resolution is programmable and interrogation resolution can be programmed to be 5 kHz, resulting in a

displacement resolution of 0.00320 mm. A SansEC displacement sensor can be configured to be a strain sensor by constraining the outboard ends of the strips and sensor to be fixed while the inboard ends are allowed to move relative to each other.

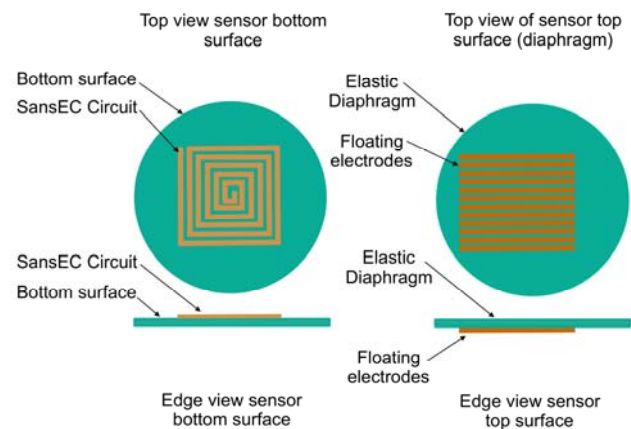


**Figure 5 - Sensor response to floating electrode parallel displacement along y direction relative to stationary SansEC circuit. Each curve is for a different number, N, of floating electrodes.**

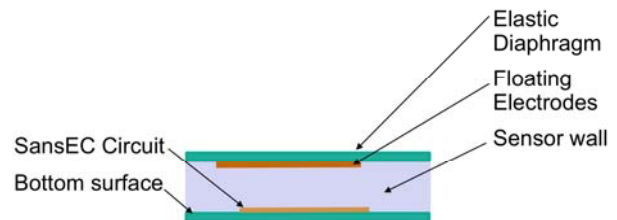
Fig. 6 shows results of out-of-plane displacement of the conductive strips relative to the SansEC sensor. Sensor response frequency also varies monotonically with out-of-plane position with sensitivity increasing with decreasing displacement. The most sensitive range is for displacement less than 1 mm. For sensors having more than 10 strips, the sensitivity is 15 MHz/mm resulting in a displacement resolution of 320 nm and 0.0017 mm when 5 kHz and 25 kHz interrogation resolutions are used, respectively. This sensor can be configured into a pressure sensor by using the embodiment illustrated in Figs. 7 and 8. The SansEC sensor is placed on a rigid substrate and the narrow conductive strips are placed on a flexible membrane. Having the membrane affixed to the top surface of a rigid wall while the substrate is affixed to the bottom surface of the wall forms a sealed container. A partial vacuum,  $p_r$ , is placed in the closed system. The measurement reference configuration is when the ambient pressure,  $p_a$ , is equal to the vacuum pressure,  $p_r$ , Fig. 9(a). Under this condition, the measured response frequency,  $\omega_s$ , is equal to the reference frequency  $\omega_0 = \omega_0(p_r)$ . When ambient pressure is greater than the pressure inside the sensor, the membrane having the narrow strips moves closer to the SansEC circuit resulting in the response frequency decreasing, Fig. 9(b). If the ambient pressure is less than the ambient pressure, the response frequency increases, Fig. 9(c).



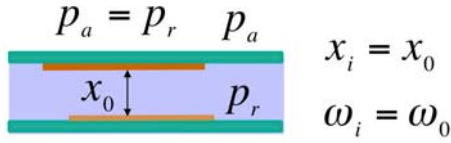
**Figure 6 - Sensor response to floating electrode out-of-plane displacement along x direction relative to stationary SansEC circuit. Each curve is for a different number, N, of floating electrodes.**



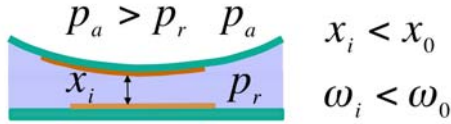
**Figure 7 - Top and bottom surfaces of SansEC-FE pressure sensor.**



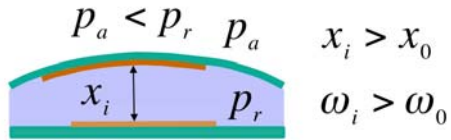
**Figure 8 - SansEC Floating Electrode pressure sensor.**



(a) Reference pressure,  $p_r$ , equals ambient pressure,  $p_a$ .



(b) Reference pressure,  $p_r$ , is less than ambient pressure,  $p_a$ .



(c) Reference pressure,  $p_r$ , is greater than ambient pressure,  $p_a$ .

**Figure 9 - Pressure sensor deformation under different ambient pressure conditions.**

The sensors can be arranged in an array that has 9 sensors in a 3 x 3 array, as shown in Fig. 10 (a). Numerous examples of SansEC sensors have been presented in this section. Each sensor in Fig. 10 (a) can be tailored to be one of the sensors discussed in this section as shown in Fig. 10(b). Collectively, the sensor array functions as a spectroscopy system. The suite of sensors in Fig. 10(b) can be included in a larger array as shown in Fig. 10(c).

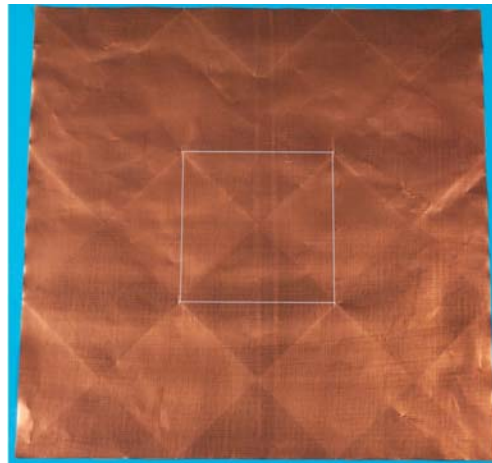
## APPLICATIONS FOR INFLATABLE HABITATS

Many spacecraft systems require thermal protection. TransHab, Fig. 11, is a hybrid structure with a hard, rigid core and an inflatable outer shell. The outer shell layers are, from left to right: multi-layer thermal insulation (MLI), micrometeorite/orbital debris (MOD) shielding, a Kevlar® (para-aramid synthetic fiber and trademark of Dupont) restraint layer, a redundant bladder, and an interior “wall” or scuff barrier [5]. The debris shielding uses layers of Nextel™ (ceramic woven fiber and trademark of 3M Company) woven ceramic fiber with open cell foam between the layers. Multi-layer insulation is comprised of multiple layers (sometimes as many as 15) of very thin (< 0.0025 mm) low emittance films such as Mylar® (polyester

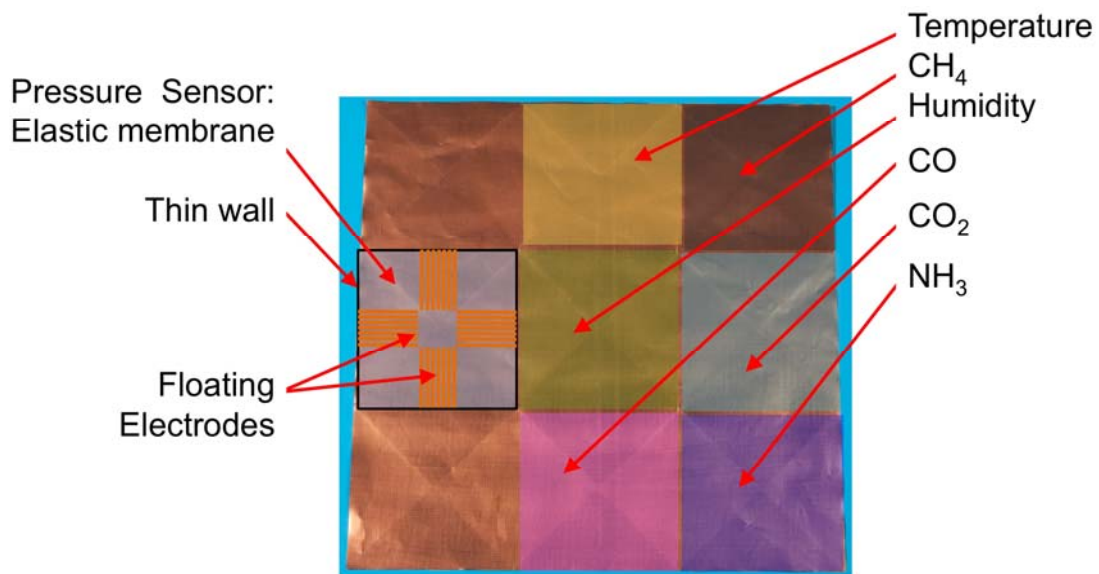
film and trademark of Dupont) or Kapton® (polyimide film and trademark of Dupont). The films are typically completely metalized on one or both sides and separated with a spacer material, such as sheets of polyethylene terephthalate (PET) fibers to prevent contact of the adjacent metalized layer [2]. All the shell layers are electrically nonconductive except for those used in the multi-layer insulation. The metalized films act as a Faraday shield that does not allow magnetic fields to permeate them. To reduce the amount of attenuation, Ref [2] designed two types of metalized insulation layers. One layer was a SansEC array with the sensors separated by 0.13 mm resulting in an effective area of reflective material to be 94% of the original. The remaining MLI layers were designed as staggered patterns of small copper traces to reduce the magnetic coupling between the sensor response and the MLI metalized film. The modified MLI layers resulted in the sensors’ magnetic field response amplitudes being more than sufficient for interrogation. The thermal protection/MOD damage detection system was successfully tested as a MOD damage detection system in 2006 [2].

Results of using the redesigned multi-layer thermal insulation are shown in Fig. 12. Undamaged, the lowest response resonant was 3.5 MHz. A 2.9 cm by 2.6 cm hole was then placed in the MLI center sensor. When any sensor in the array was damaged, there was an abrupt change in frequency. The lowest measured response frequency of approximately 7.7 MHz was measured after the sensor was damaged. If any sensor of the multi-layer insulation system is modified to have an additional sensor capability; like pressure or chemical sensing (i.e., creating a sensing skin similar to Fig. 10(c)); damage can be distinguished from these measurements because the other parameters being measured are quasistatic which results in continuous changes to the sensor response. Damage instantly changes the sensor’s electric and magnetic field distributions resulting in an abrupt change to the sensor response. Because the sensor of the array responded after being damaged, it could be used to detect additional damage events to the sensor.

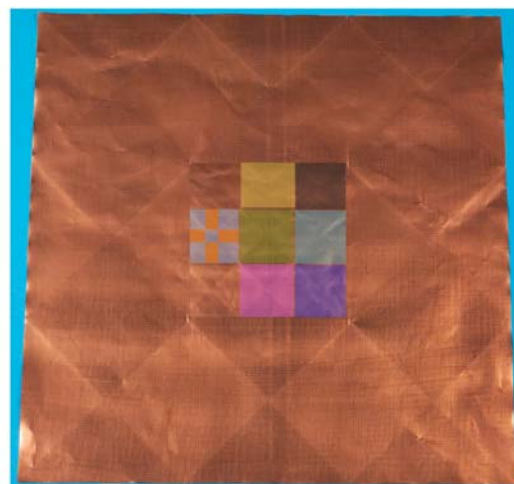
Inflatable structures are also being considered as lunar habitats. Environmental instrumentation includes temperature, CO<sub>2</sub> and pressure monitoring. The redesign of a multi-layer insulation system to add a damage detection system also resulted in the inflatable habitat being magnetically transparent. The system can be further modified to include the additional measurements that are shown in the sensing skin of Fig. 10(c). Furthermore, other SansEC sensors could be placed external to the habitat shell and interrogated from inside the shell.



(a) SansEC sensor array with center sensor highlighted.

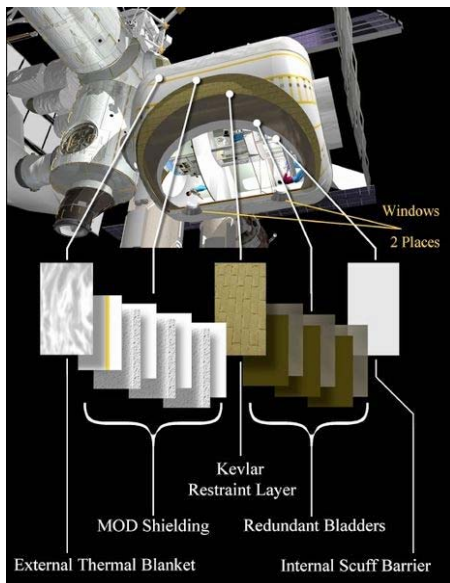


(b) SansEC array with overlay of 6 sensors on measurement sensitive material and one pressure sensor.

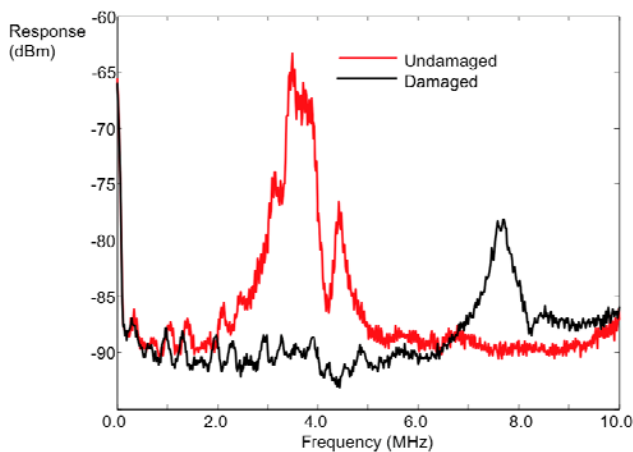


(c) SansEC sensor array embedded inside SansEC sensor array.

**Figure 10 - SansEC sensing skin.**



**Figure 11 - TransHab habitat shell.**

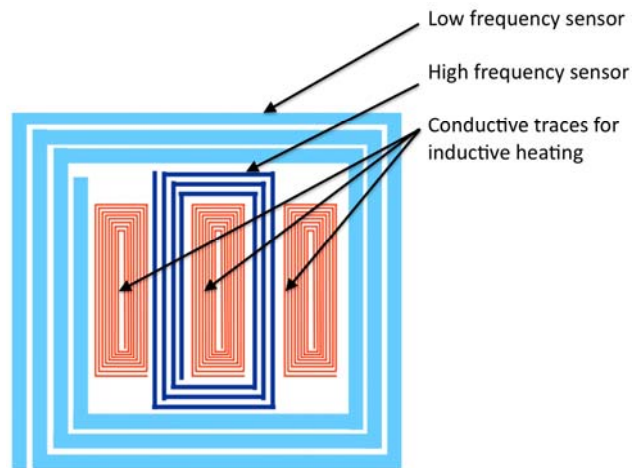


**Figure 12 - Sensor response measured at center of array before array was damaged and after center sensor was damaged with a 2.9 cm by 2.6 cm hole.**

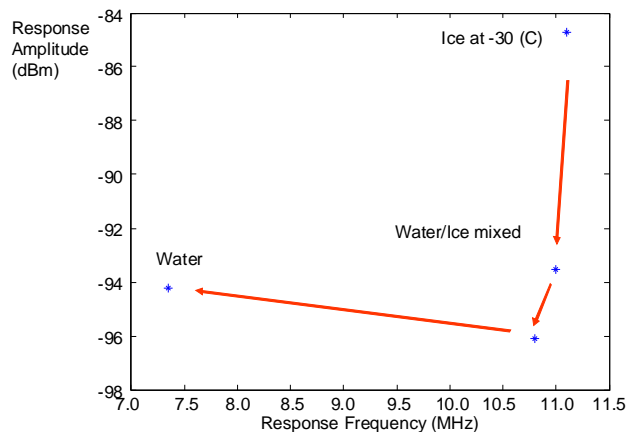
### PLANETARY EXPLORATORY VEHICLES WITH DAMAGE RESILIENT SENSING SKIN

In this section, concepts for using SansEC sensing skins for planetary exploratory vehicles are presented. Two types of vehicles will be considered: the Mars ARES plane and a ground-roving vehicle. The goal for using SansEC on the Mars ARES plane is to facilitate measurements after its flight is completed. The goal of using SansEC sensing skins on roving planetary vehicles is provide a means to significantly increase the number of sensors used for science measurements without the additional weight that is associated with sensors and their interrogation systems. The sensing skin will be similar to that presented earlier for the inflatable habitats with measurements tailored to the

planet being explored. An additional skin of electrically insulating material can cover all of the sensor circuits to prevent external electrical shorts. For a Venus probe, the sensing skin could be behind a barrier of thermally and chemically resilient material. To facilitate measurements after landing, an innocuous sensing skin could be developed that will be immediately applicable to detecting water on Mars. A portion of the skin will have an array of the patterns shown in Fig. 13(a).



**(a) Open-circuit electrically conductive geometric patterns for inductive heating and dielectric-conductive spectroscopy.**



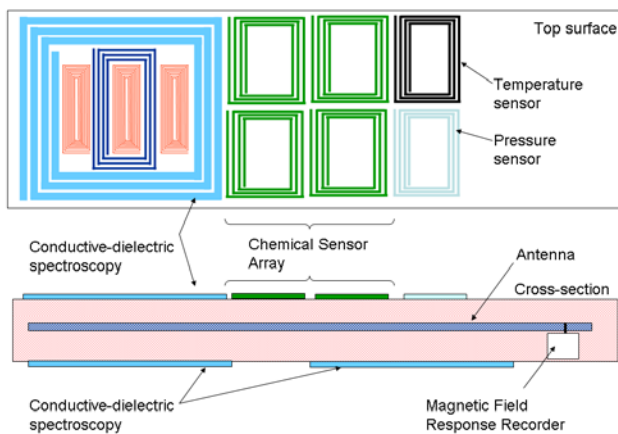
**(b) Measurement of ice to water phase transformation using SansEC sensor.**

**Figure 13 - Electrically conductive geometric patterns for inductive heating and conductive-dielectric spectroscopy.**

The SansEC circuits shown in red have high resistance, low resonant frequency, and should be made from a high relative magnetic permeable material such as nickel ( $\mu_r \approx 100$ ). These circuits will be used to melt ice using inductive heating. The interrogation system can also supply



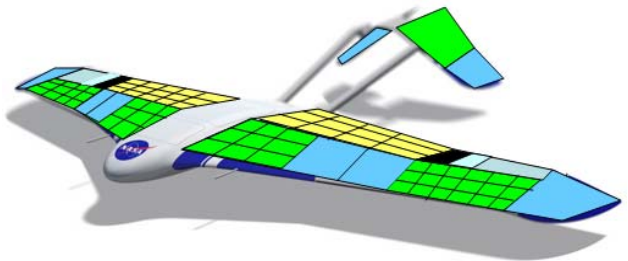
the harmonic field for the inductive heating. The sensors shown as light blue patterns will be used to examine a low frequency response of the phase transformation of the ice as it melts and possibly the water-to-vapor phase transformation. Similarly, the sensors shown as dark blue patterns will be used for high frequency examination of the material. Frozen water is relatively non-conductive, compared with liquid water. Results of measuring a SansEC sensor's frequency and amplitude response when the sensor was placed in proximity to melting ice are shown in Fig. 13(b). The change of conductivity has a pronounced effect of the response, Fig. 13(b). The ice-to-water transformation increases the amount of electrically conductive material within the sensor's magnetic field. In performing the measurements of Fig. 13(b), neither the water nor the ice were in physical contact with the sensor used to measure the phase transformation. Thus far, the patterns have only been used for sensing but if they can be used for inductive heating, it should facilitate a means to detect water on other planetary surfaces using a sensing skin with an inductive heating capability. Should any of the surface patterns be damaged or broken, they are still functional but with a different response frequency range. The change in response baseline indicates damage giving the patterns a health monitoring function. A cross-section of the sensing skin is shown in Fig. 14. The interrogation system is embedded within the skin and is protected from atmosphere, dust and soil exposure. Fig. 15 shows the Mars ARES plane before and after redesign. With the redesign, surface areas on the plane that previously provided only an aerodynamic function, now serve also as sensor arrays. Fig. 15 (b) shows the array exposed but the blue and white painted design in Fig. 15(a) could be painted over the sensor array. This method of examining ice provides an alternative and potentially simpler system to the Phoenix Mars Lander's Thermal and Evolved-Gas Analyzer (TEGA).



**Figure 14 - Cross-section of planetary probe showing interrogation system (magnetic field response recorder and antenna).**



(a) Initial design of Mars ARES flyer with sensing skin.

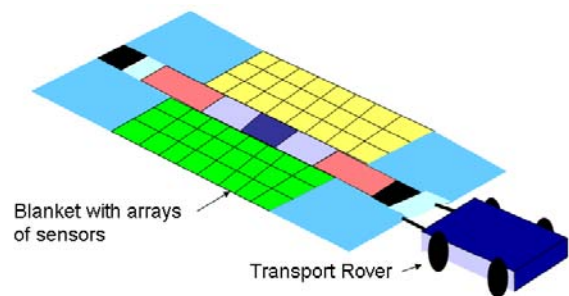


(b) Mars ARES flyer with sensing skin. Bottom surface of wing and fuselage would have inductive heating circuits.

**Figure 15 - NASA Mars ARES flyer redesigned with sensing skin.**

Other sensors for science measurements of atmospheric pressure, chemical sensing and ambient temperature have been presented earlier. All the sensors and inductive heating pattern can be part of the sensing skin. Note that using SansEC as a basis for developing the sensing skin facilitates measurements without any electrical component of the system in physical contact with the measured parameter. An electrically insulative layer can also be placed on the sensing skin with the measurement sensitive material placed on top of the insulative layer.

Another method of using the using sensing skins is to perform planetary measurements by dragging a blanket having these SansEC sensors along a planetary surface, Fig. 16, or the planetary rover could be a simple shell with the sensing skins with a means of mobility. This method allows surfaces that are typically unused for measurement to be used for sensing.



**Figure 16 - Transport rover with sensing blanket.**

## CONCLUSIONS

Methods of using SansEC sensing technology for inflatable habitats and planetary exploratory vehicles have been presented. SansEC sensors use self-resonating patterns of electrically conductive material. Magnetic fields are used to power and interrogate the sensors. Arrays of the SansEC sensors can be made from thin conductive films placed on non-conductive surfaces and can be used as sensing skins. Each sensor can be tailored for a specific measurement. The sensing skins can be incorporated into space system innocuously. Existing systems can be redesigned to be a sensing skin while maintaining their original functions. Sensing skins developed from arrays of SansEC sensors can incorporate science and engineering measurements. The sensing skin is a relatively simple method of increasing the number of sensors used.

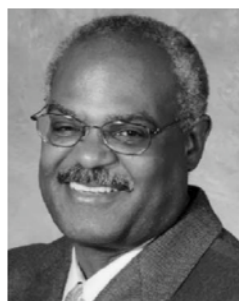
An example of redesigning multi-layer insulation showed that the insulation could serve as a sensing skin. Sensor response measurements before and after a damage event showed that the sensing skin/insulation system could be interrogated and could detect damage that was indicated by an abrupt change in frequency. The skins sensors could also be used for environmental measurements.

The sensing skin concept was then also applied to two planetary exploratory vehicles. The first was the NASA Mars ARES plane. A sensing skin similar to that used with the inflatable habitat was applied to the outer surface of the plane. An inductive heating pattern was included to facilitate detecting water by warming the ground and identifying any response change that would be indicative of ice melting. The sensing skin could be placed on the outer surface of a planetary rover or made into a blanket that could be dragged along the surface by a moving vehicle on the planet.

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