Microwave Interrogation of Woven Straps under Light Loading for Inflatable Applications

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TechConnect World

June 17-19, 2024, National Harbor, MD

Outline

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- Partnership Opportunities

Background

NASA's Inflatable Habitats go back to Von Braun's Space Station (1952).

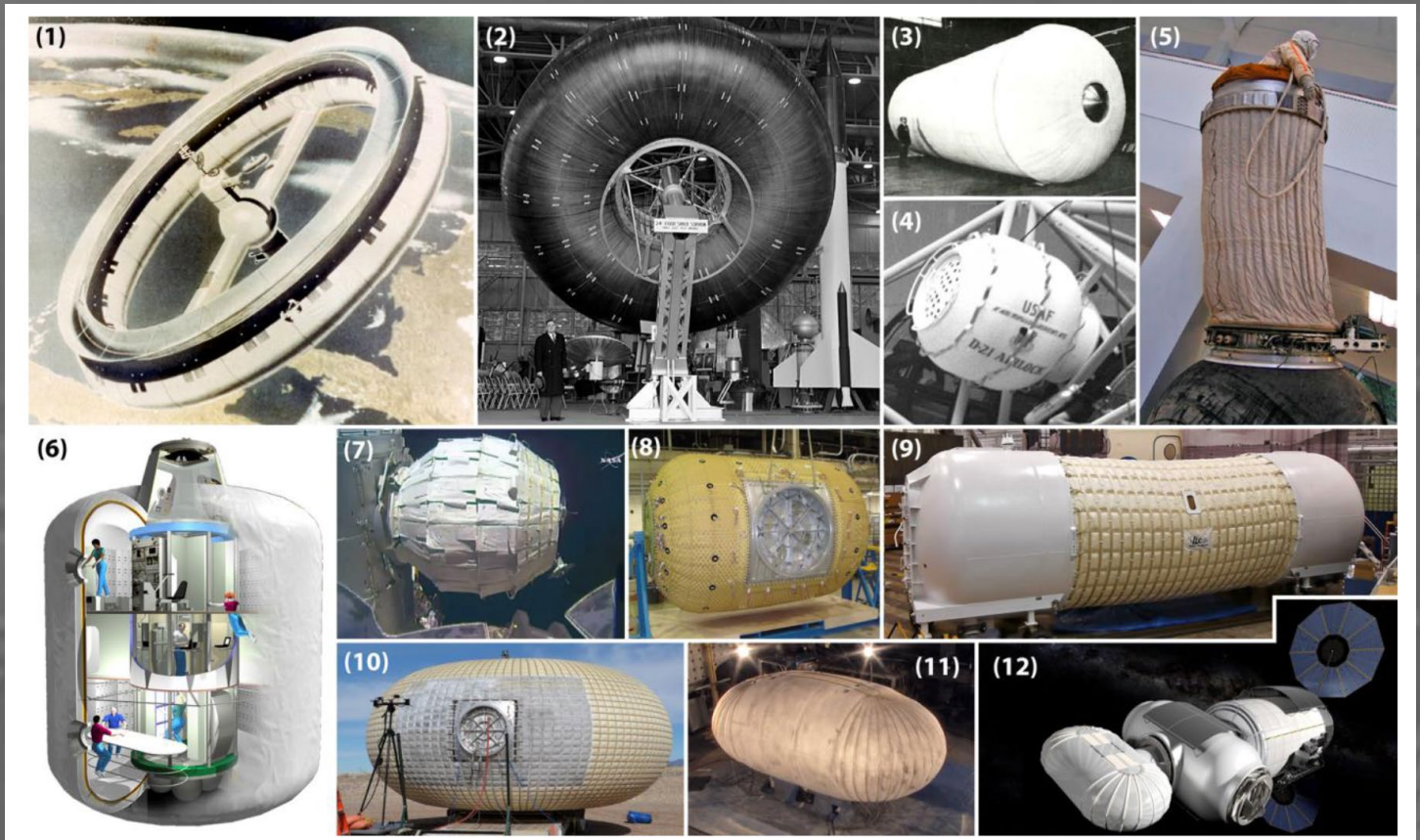
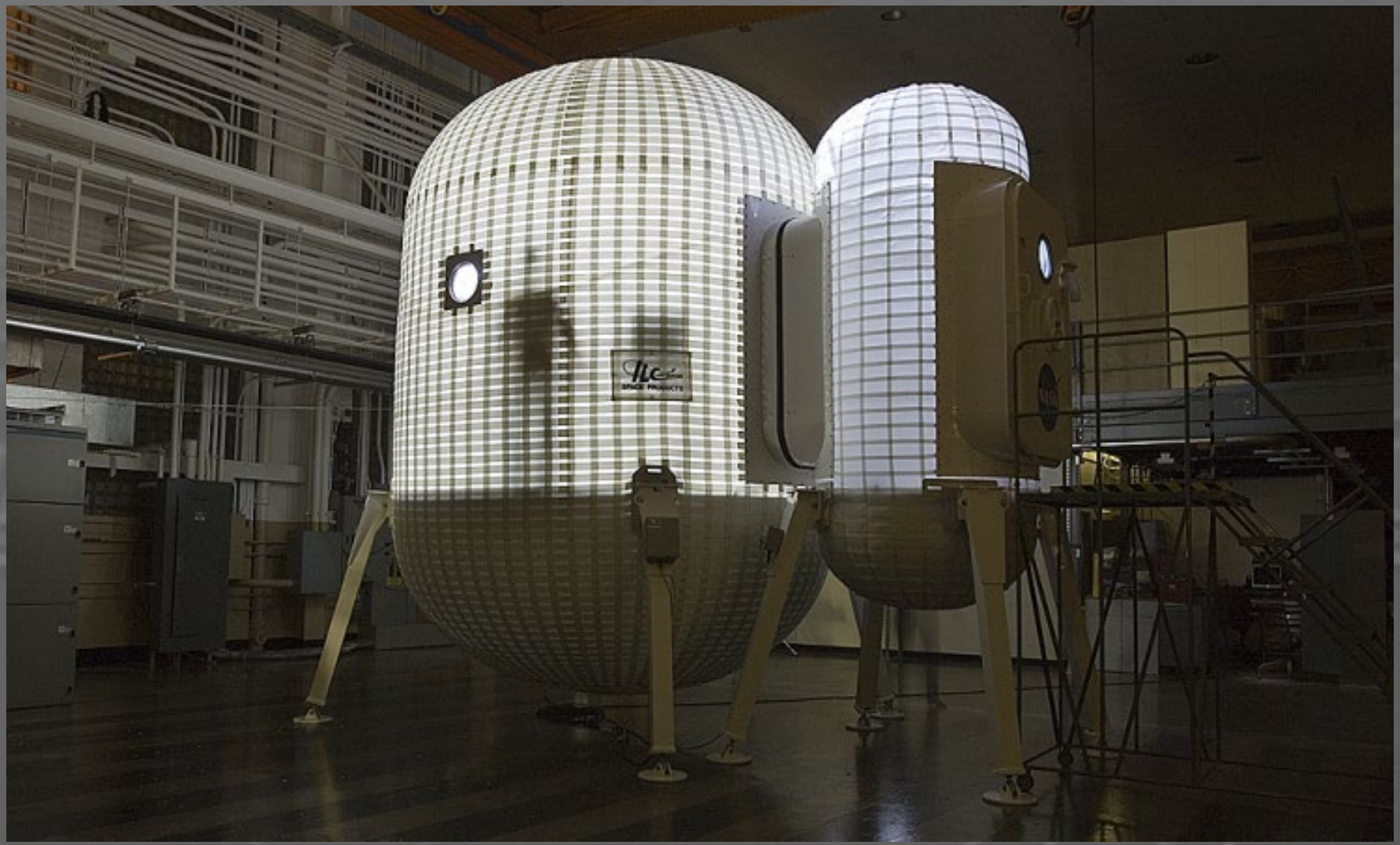


Figure 1. Inflatable Structures: (1) Von Braun's Space Station, (2~4) Goodyear Aerospace's toroidal space station, 'Moby Dick' habitat module, and D021 airlock, (5) Volga airlock, (6) TransHab, (7) BEAM, (8) JSC module with integrated hatch, (9~10) ILC/NASA expandable and toroidal habitats, (11) NASA's MASH inflatable airlock, (12) NextSTEP-2 cis-lunar habitat and airlock concept.

Valle, Gerard D., Doug Litteken, and Thomas C. Jones. "Review of habitable softgoods inflatable design, analysis, testing, and potential space applications." In *AIAA Scitech 2019 Forum*, p. 1018. 2019.

Motivation

New inflatable structures will require new sensing methods to monitor the load bearing restraint layer.



Inflatable Lunar Habitat model at NASA Langley Research Center.

NASA's NextSTEP* A: Habitation Systems program

- NASA's NextSTEP* A: Habitation Systems program is developing light weight inflatable structures.
- This initial work supports an ongoing project to integrate sensors for real-time nondestructive evaluation (NDE) of woven restraint straps within inflatable structures.
- This effort addresses two areas in NASA's 2020 Technology Taxonomy roadmap,
  - TX12.2.1 Lightweight Concepts
  - TX08.3.5 Electromagnetic Wave-Based Sensors
- To support the NextSTEP project we are investigating the change of relative permittivity of the strap as the loading is changed .

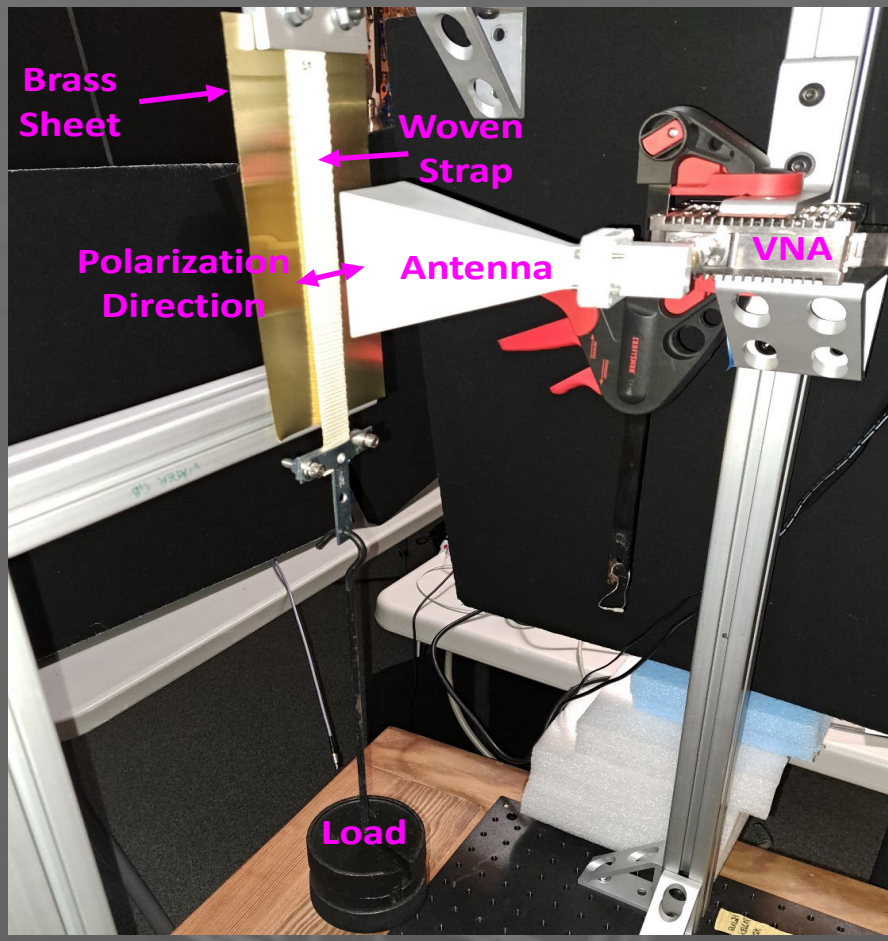
Woven Restraint Layer Straps

- Four Straps were tested
- Kevlar 6k lbs and 12k lbs
- Vectran 6k lbs and 12k lbs
- 6K straps are 25.4mm wide, 250mm long, and are 1.6mm thick
- 12K straps are 25.4mm wide, 250mm long, and are 3.175mm thick



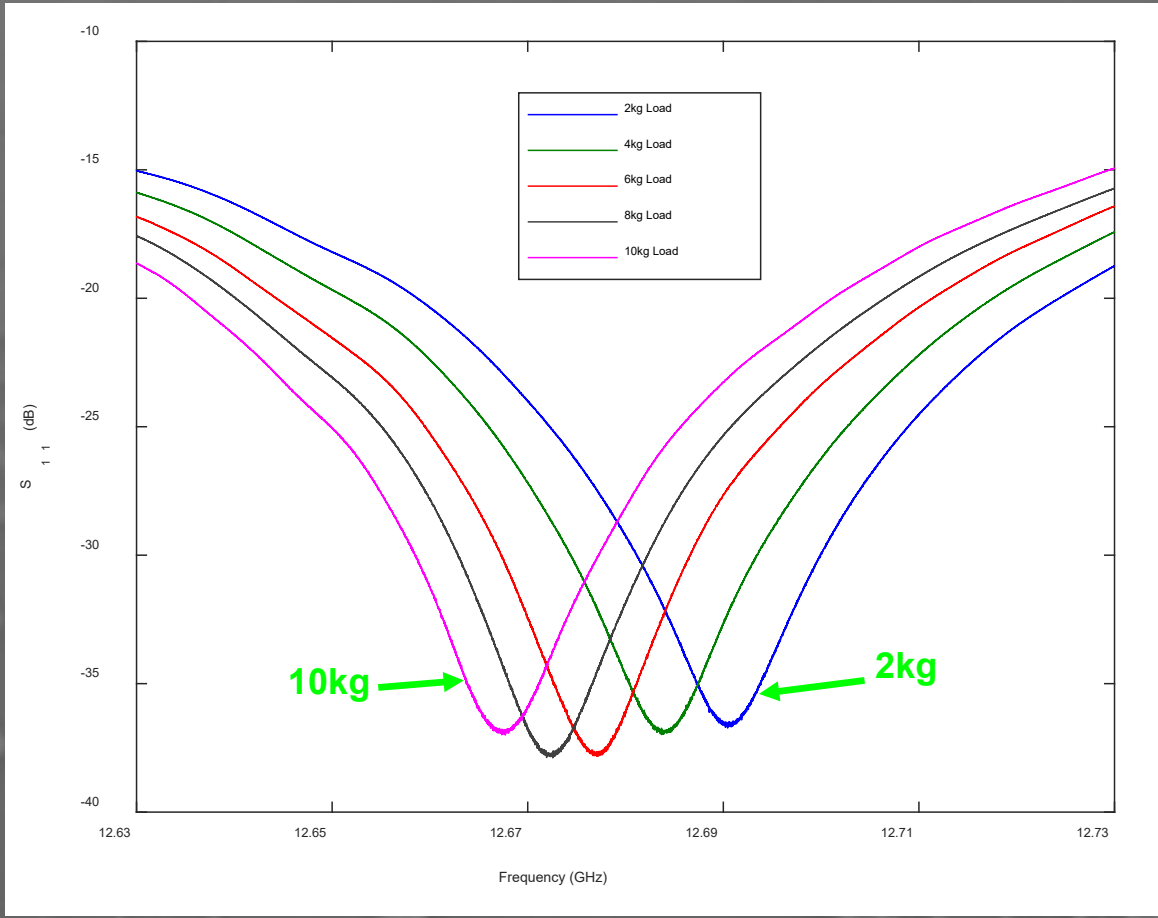
Test Setup

- Linearly polarized, horn antenna positioned 67 mm from the strap, which is connected to a Planar R180 Vector Network Analyzer (VNA) that measures the S_{11} response.
- The frequency sweep was 12.63 to 12.73 GHz. A metal plate is located behind the strap (in contact) to simulate a conducting layer that is in the inflatable layup.
- The antenna is horizontally polarized with respect to the strap, the EM field oscillations are aligned across the width of the strap.



Experimental setup: polarized horn antenna, and network analyzer, woven strap, and metal plate.

Raw S_{11} Response



The EM response (log magnitude S_{11} response) of the woven strap (Vectran 6K) from 12.63 GHz to 12.73 GHz as a function of frequency for loads from 2kg to 10kg in 2kg increments. S_{11} is the reflection S-parameter.

Some amplitude changes but a large spectral shift.

Post Processing Methods

Spectral Centroid

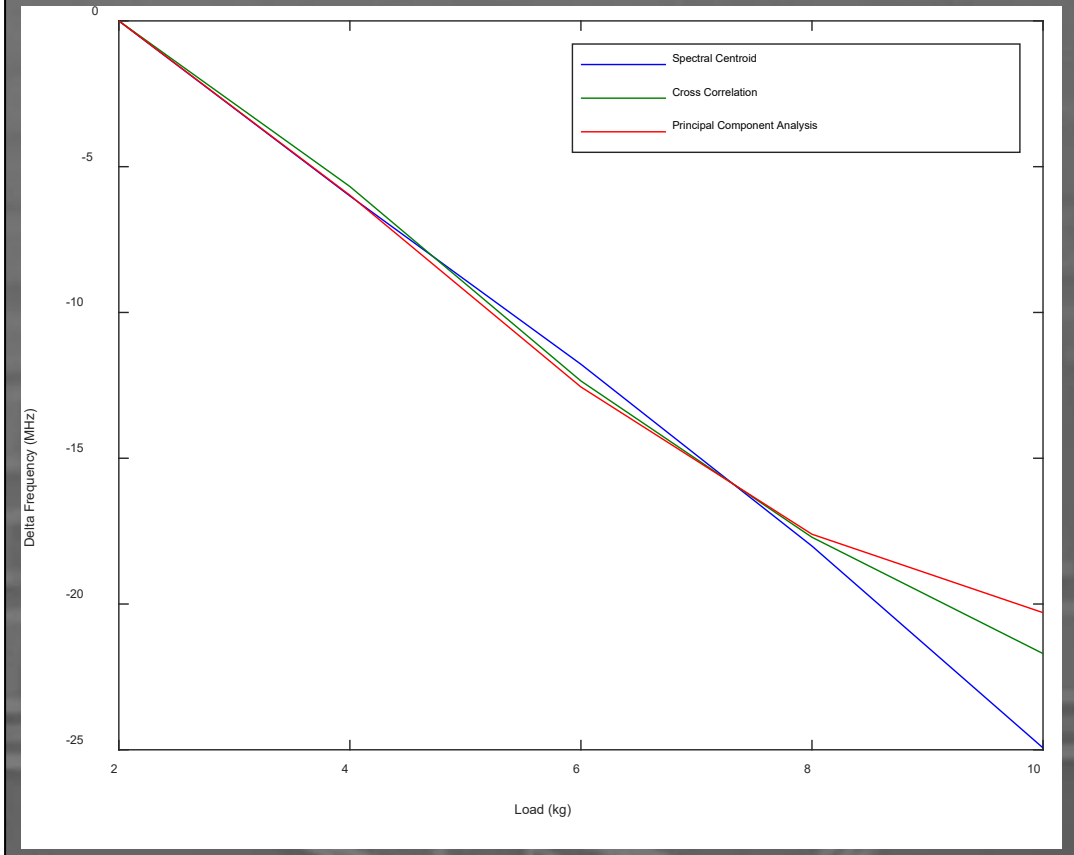
$$SC = \frac{\sum_{n=1}^{N} f_n m_n}{\sum_{n=1}^{N} f_n}$$

Cross Correlation

$$(f * g) = \sum_{m=1}^{N} \overline{f[(m-n)_{mod\ N}]} g[m]$$

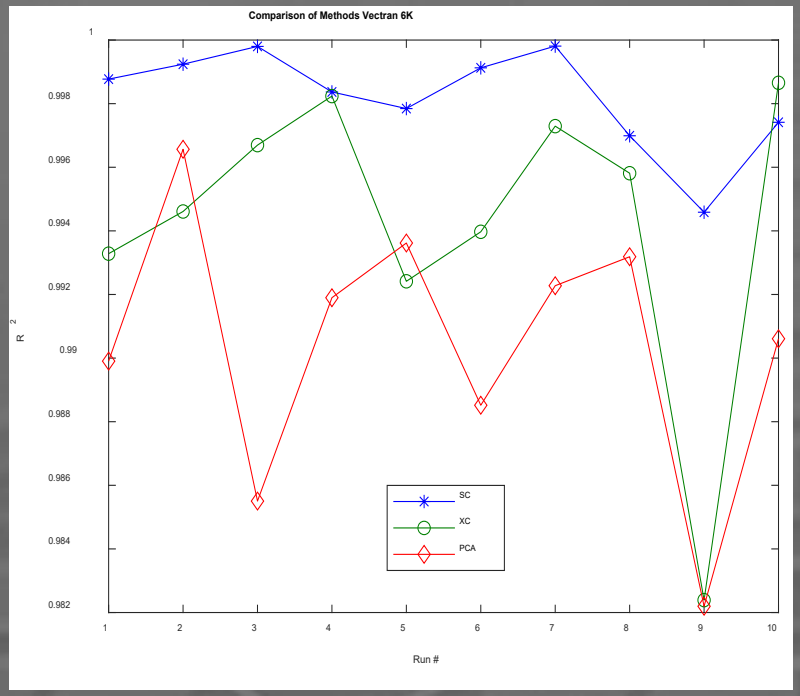
Principal Component Analysis (using SVD)

$$X = U\Sigma W^T$$



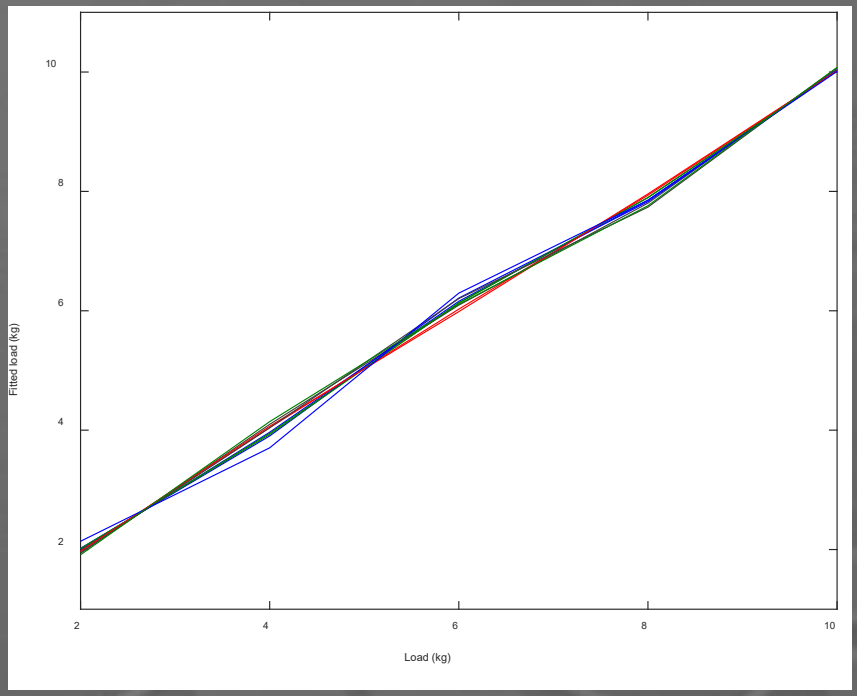
The spectral shift of the response, as determined by the three post-processing methods vs. Load from 2kg to 10kg in 2kg increments

Fitting



The goodness of fit R^2, for the three post-processing methods, for ten runs. The fit equation:

$$Le=\alpha X^2+\beta X+\gamma$$



The fitted spectral centroid of the Vectran 6K strap response, vs. Load from 2kg to 10kg in 2kg increments for all 10 runs.

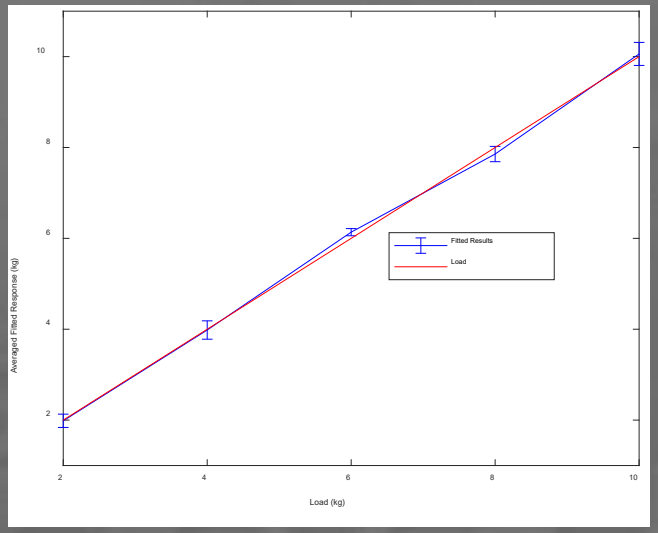
Where *Le* is the estimation for the load, and *α, β*, and γ, are the quadratic fit coefficients, and *x* is the antenna response data.

FIT AVERAGED QUADRATIC PARAMETERS

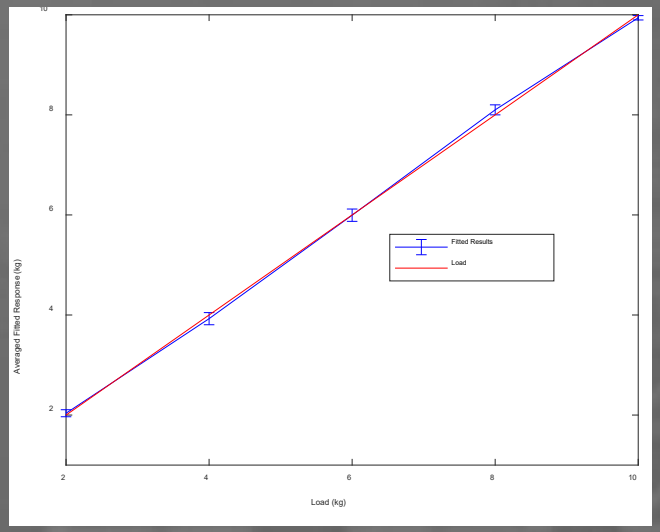
$$Le=\alpha X^2+\beta X+\gamma$$

	α_a	β_a	γ_a
Vectran 6K	-2.5428e-15	-0.001643	0.99947
Vectran 12K	-4.4314e-16	1.1567e-05	-7.5465e+04
Kevlar 6K	4.7100e-14	-0.0012	7.7743e+06
Kevlar 12K	2.4145e-14	-6.1732e-04	3.9459e+06

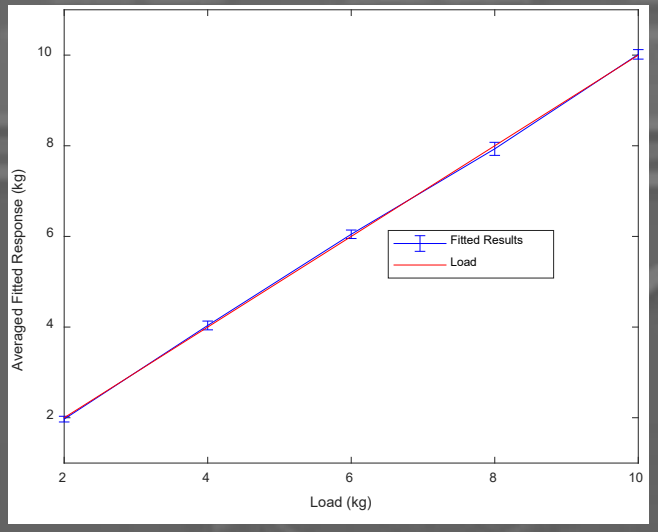
Results Average Fitted Spectral Centroid



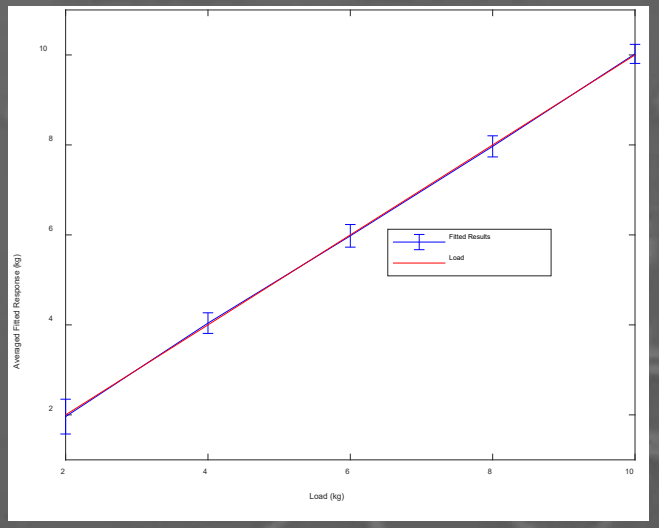
Vectran 6K strap response.



Kevlar 6K strap response.



Vectran 12K strap response.



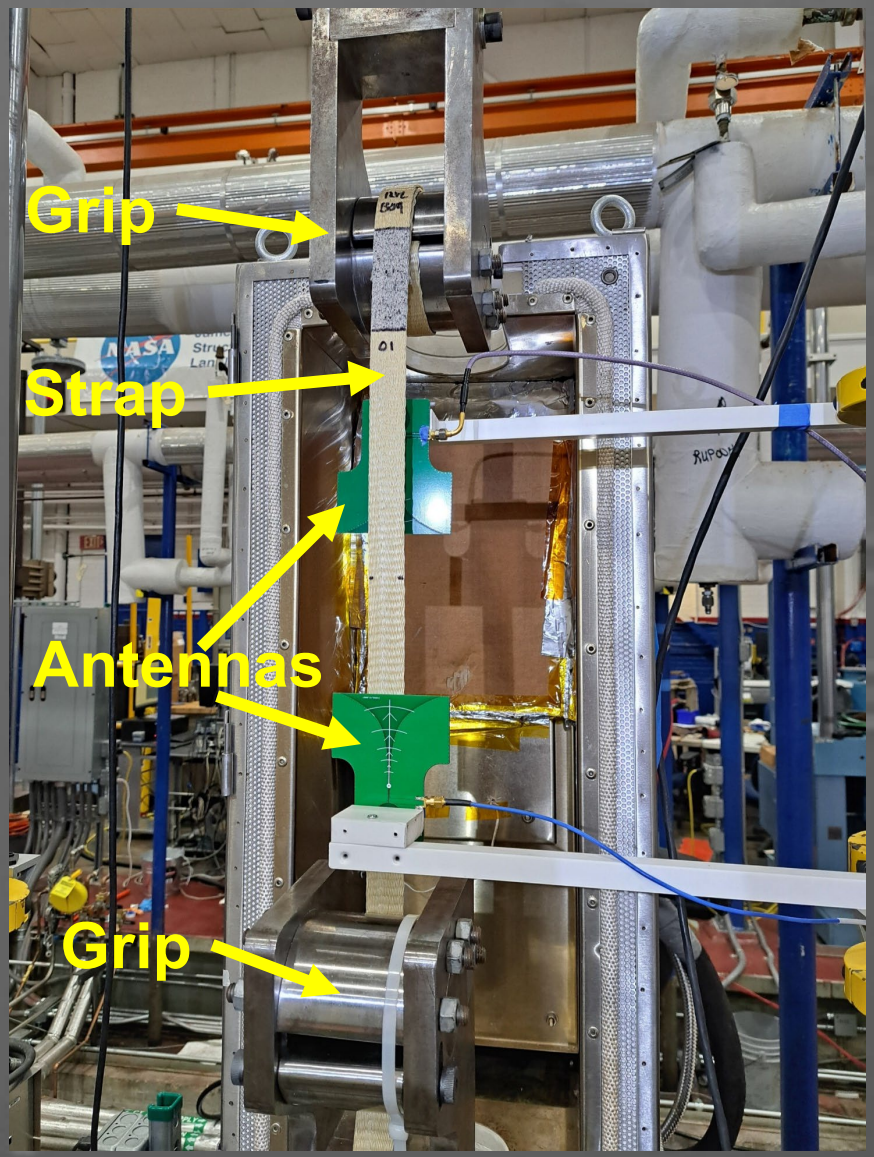
Kevlar 12K strap response.

Project Goals

- One of the main goals of this work was to develop the initial parameters for use on later testing:
  - **Interrogation frequency ~12GHz**
  - **The bandwidth ~100MHz**
  - **Polarization direction, across strap 25.4mm width (horizontal when strap is hanging)**
  - **Post processing method Spectral Centroid**
  - **Fitting Parameters**

Future Work

- Future work
  - **Load Frame Testing of Straps**
  - **Vivaldi Antennas**
  - **Microwave interrogation of the straps longitudinally.**
  - **Initial testing shows a potential for strain measurement.**
  - **Further testing will investigate the maximum distance of interrogation.**



Conclusions

- A microwave system has been demonstrated to sense loading in woven restraint straps for inflatable structures under light loads from weights of 2kg to 10kg.
- This initial work supports an ongoing project to integrate sensors for real-time NDE of woven restraint straps within inflatable structures.
- While this effort demonstrates the feasibility of making load measurements using microwaves at light loads, future work will investigate the measurement of the restraint material layups subjected to realistic loads in a load frame.

Funding/Partnership Opportunities

- NASA Research Opportunities (NRAs)
  Grants & Contracts
  - http://nspires.nasaprs.com/

- Small Business Innovation Research (SBIR)
  - http://sbir.gsfc.nasa.gov/
  - Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis
  - H5.05 Inflatable Softgoods for Next Generation Habitation Systems

- Space Act Agreements (SAA)
  - Partnerships with and without exchange of funds