Antennas for Space-Based Proximity Operations

11th Annual Military Antennas Event
September 2013

Patrick Fink
NASA Johnson Space Center

Outline

- Proximity Environment
- Autonomous Logistics Management and RFID
- RFID Sensors
- e-Textile Antennas
- High Performance CEM Tool

Proximity Environment

- Historically characterized by low data rate human-human communications: voice and telemetry
  - Particularly critical for External Vehicular Activity – EVA (spacewalks)
  - Antennas were robust, rigid, and highly reliable
- High data rate communications has become expected to support greater telemetry, and to a greater extent, video
  - Driving push for Multiple-Input/Multiple Output (MIMO) technology
  - Requires low mass, highly flexible antennas
- Largest increase in antenna demand: wireless sensing and automation, machine-to-machine communications
  - Particularly in logistics management: Autonomous Logistics Management
  - ISS environment: from 10's of antennas to 1000's of antennas in past 6 years

3

AUTONOMOUS LOGISTICS MANAGEMENT (ALM) AND RFID

The ISS is Huge

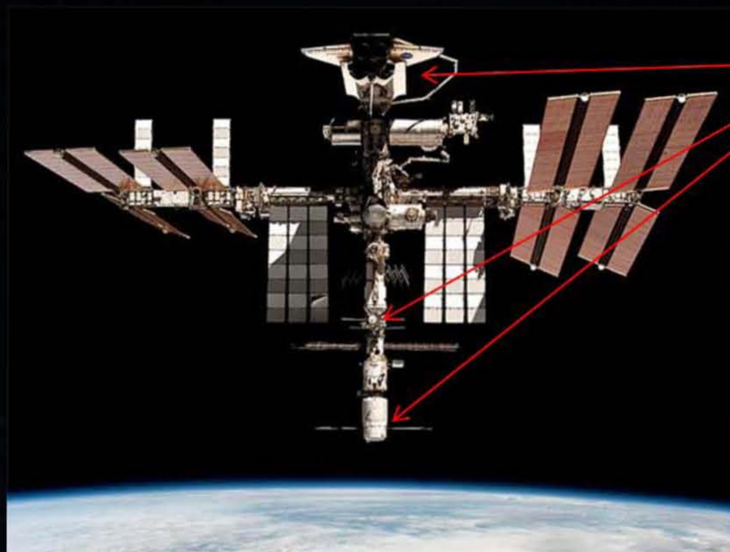


Photo credit: NASA

The ISS 400 km in space is resolvable to the human eye (seen here silhouetted against the sun (Photo credit: Thierry Legault)

- (Cargo ships the size of freight cars)
- 440,000 kg core station
  - 100m x70 m
  - 4-m diameter tubular living areas
- Six "permanent" crew
  - in 6-month overlapped shifts
- 6 partner agencies
- 30-year station life possible

Cargo Transfer Bags (CTBs)

Laboratory and Work Spaces Overlap

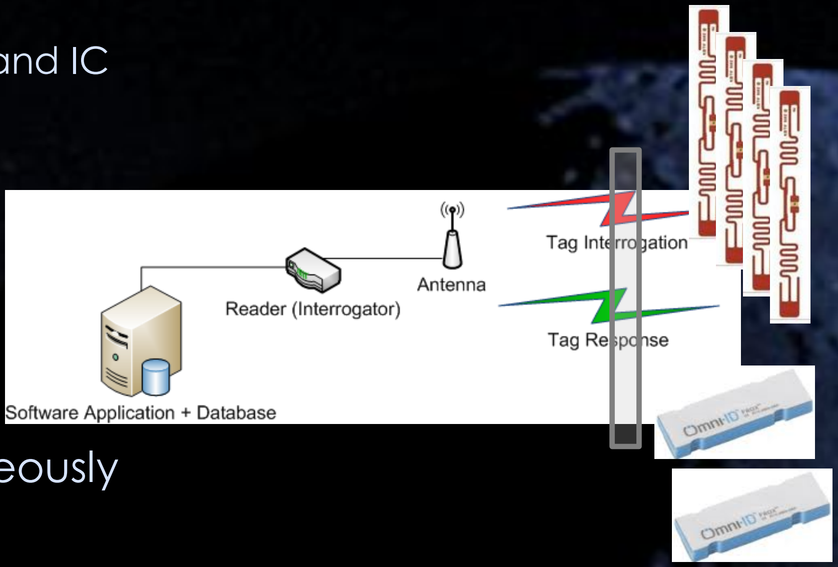
Space Logistics Management (LM) Experience and Prognosis

- Logistics Management on ISS has been a painful lesson
  - Inventory logging consistently requires large amount of crew time
  - Significant morale impacts to crew
- Beyond Low Earth Orbit: increased LM challenges compared to ISS
  - Limited or no resupply opportunities
  - Vehicles likely packed volumetrically denser with decreased visibility and item access
  - Fewer crew to manage and track inventory
  - Decreased crew time while on-target
  - ***Likely an increased requirement for logistics automation***

- Identified need to use ISS as a test bed for learning how to establish Autonomous Logistics Management for future human space-based operations

Key RFID Attributes that Benefit Automation

- Basic RFID system:
  - A Reader (interrogator) with antenna
  - A RF tag (transponder) containing an antenna and IC
- Line-of-sight is not a necessary requirement
  - Do not need to move cargo to read
- Can read many 100s of tags nearly simultaneously
- Reading accuracy is a function of
  - Tag size, battery powered tag or passively powered
  - Proximity to some types of metallic materials or fluids, quantity and spacing of tags
  - Both reader and tag antennas



9

RFID-Based Technologies Enable ALM

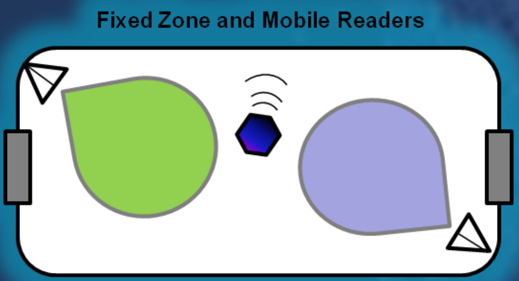
DENSE ZONE TECHNOLOGIES

- > 10 items in close proximity
- Storage areas capable of identification of densely packed items

- Examples:
  - CTB tracks items repacked on-orbit
  - Trash receptacle enables identification of consumed item

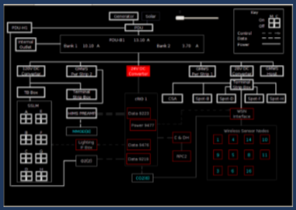
SPARSE ZONE TECHNOLOGIES

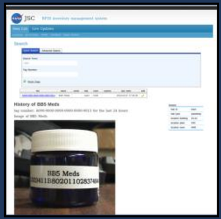
- All regions exclusive of dense zones
- Covers open regions (nodes & modules)
- Longer range identification
- Real-time location systems (RTLS)
- Possibly mobile search elements (e.g., robotic)



SMART / ENABLED APPLICATIONS

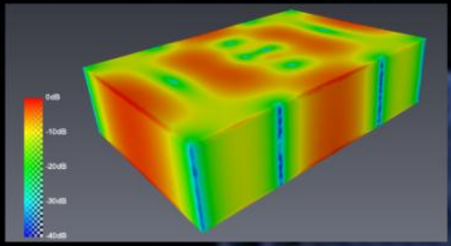
- Provides intelligent estimation of location
- Assisted operational planning and execution of procedures
- Augmented reality vehicle maintenance training
- Robotic automation applications



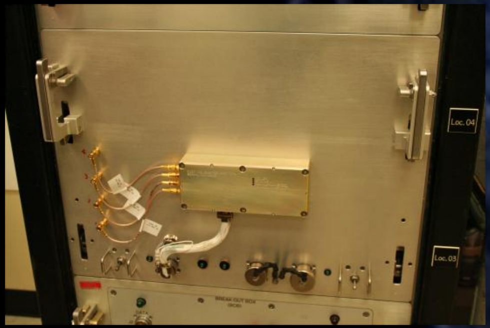


RFID DENSE ZONE ANTENNA CHALLENGES

- Provide highly accurate reads (>95%) of many (200-600) tags
- Requires RF-shielded enclosures and appropriate feeds:
  - enables RF penetration of dense tag populations
  - isolates extraneous reads of tags external to the enclosure
- 0-g mechanical dependencies include:
  - Self-sealing electromagnetic shielding
  - Actuated trigger mechanisms
  - Tag motion in 0-g
- 2013 launch of Human Research Facility RFID-Enabled 2-Drawer Pantry

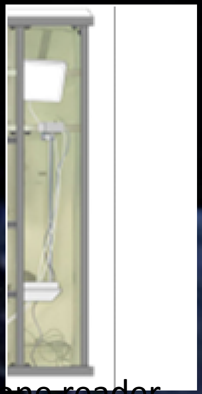


Simulated field distribution within RFID enclosure



11

RFID SPARSE ZONE ANTENNA CHALLENGES



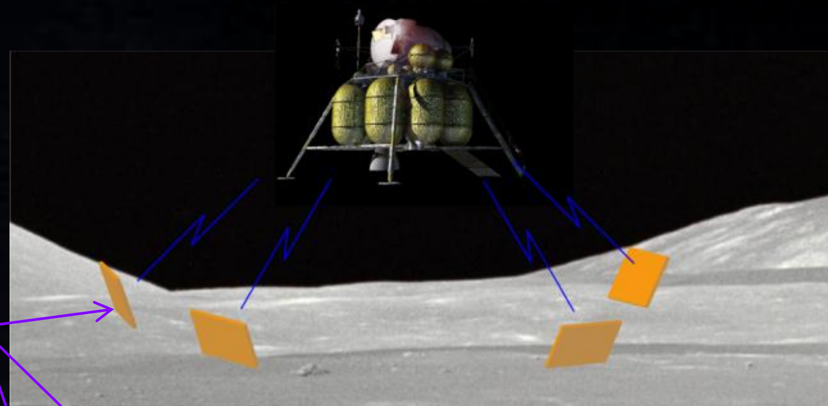
- Captures tags or collections of tags in more open environments
- Environment is characterized by strong scattering
- Typically unable to accurately read high densities of tags; e.g., 50 tagged items in Cargo Transfer Bag
  - Accuracy depends on density and material of tagged items
  - 80%-85% read accuracies of high density tags through hatch is typical

- Fixed Zone Reader
  - Narrow bandwidth utilized by UHF RFID protocol results in poor range resolution
  - Spatial resolution entails large reader antenna apertures or arrays
  - Small, "near-field" antennas that work in dense zones have very limited range
- Mobile Interrogator
  - Performs audit and search functions without crew
  - Potential for fine spatial resolution without large apertures
  - 0-g dependencies: extreme

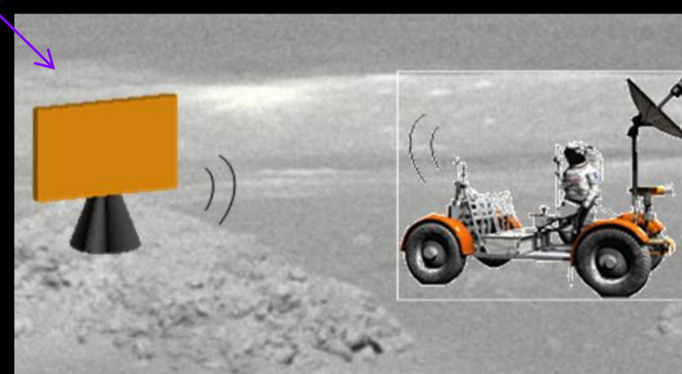
12

LONG RANGE PASSIVE RFID APPLICATIONS

RFID RETROREFLECTOR ANTENNA TECHNOLOGY



Landing Aid



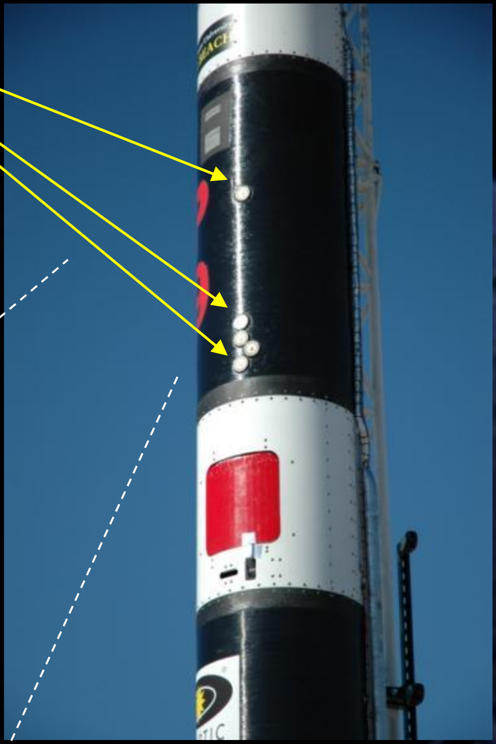
Passive RFID Sensors for Tank Fueling

Remote interrogation of passive RFID sensors permits fill level determination for experimental composite body fuel tank

No-Battery RFID tags provide:

- Unique ID
- Temperature
- Range
- Direction-of-arrival possible

Adaptive Digital Beamforming Array Interrogator



Experimental Rocket Test

E-TEXTILE ANTENNAS

E-Textile Materials

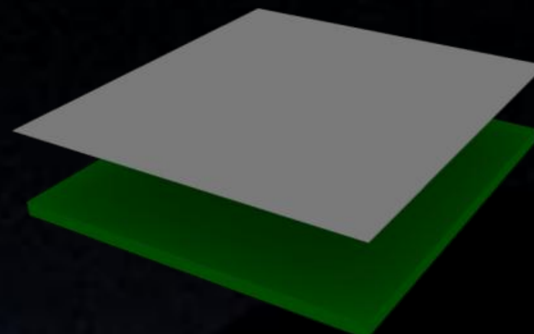
- Conductive materials
  - Increasing variety of conductive fabrics available
    - Existing materials for EMC/EMI applications
    - Novel fabrics being developed for e-textile applications
  - Woven conductive fabrics can have similar surface resistance to copper at microwave frequencies!
- Fabric-based dielectrics typically low ε_r and Low-mass
  - Excellent for making lightweight and efficient antennas

Material	Rs (Ω/□ at 3GHz)
Nora (Shieldex)	$\leq$ 0.03
Copper	0.019

7 fold decrease in mass

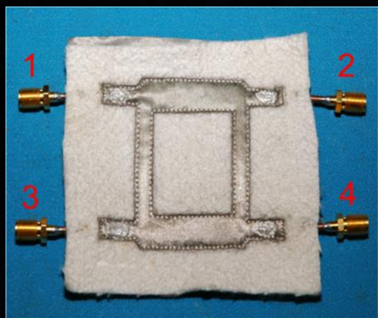
Patented Laser-based Processing of E-Textile Circuits

Conductive fabric is attached to non-conductive fabric and artwork is laid out via embroidery machine

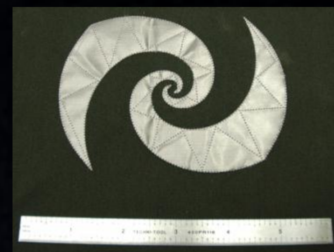


Removal of unnecessary conductive material via laser-based processing (0.8 mil resolution)

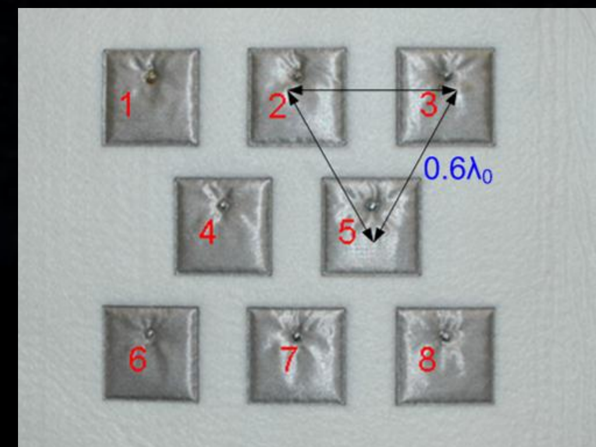
E-Textile Antenna and RF Circuit Examples



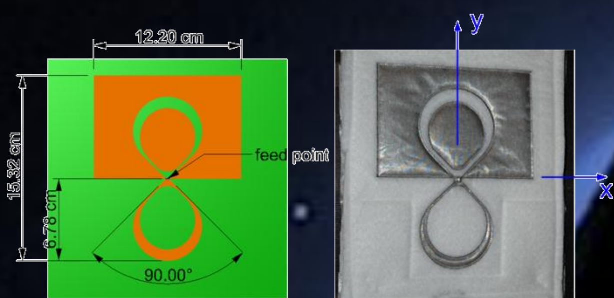
Fabric hybrid coupler (2.4 GHz)

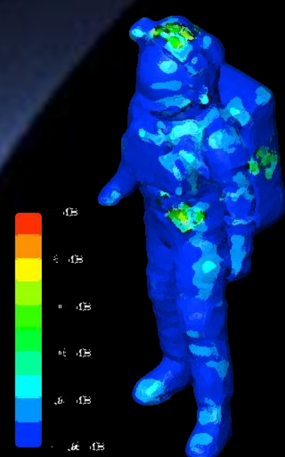


Fabric equiangular spiral antenna



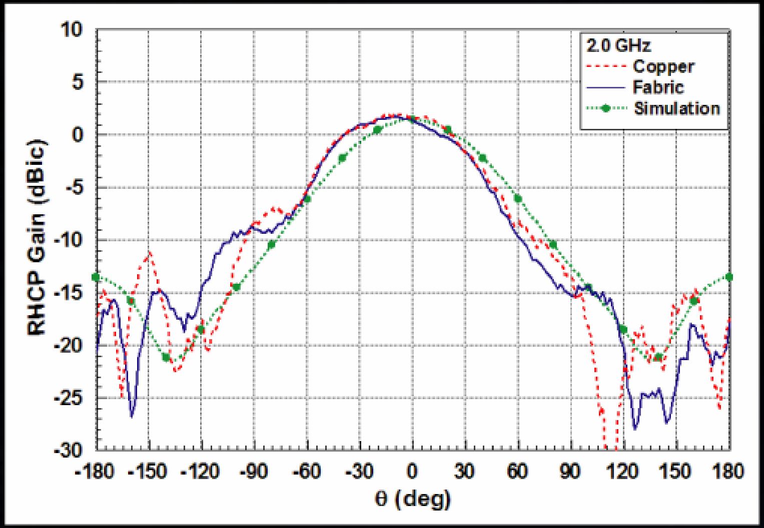
8-element fabric array antenna (2.4 GHz)

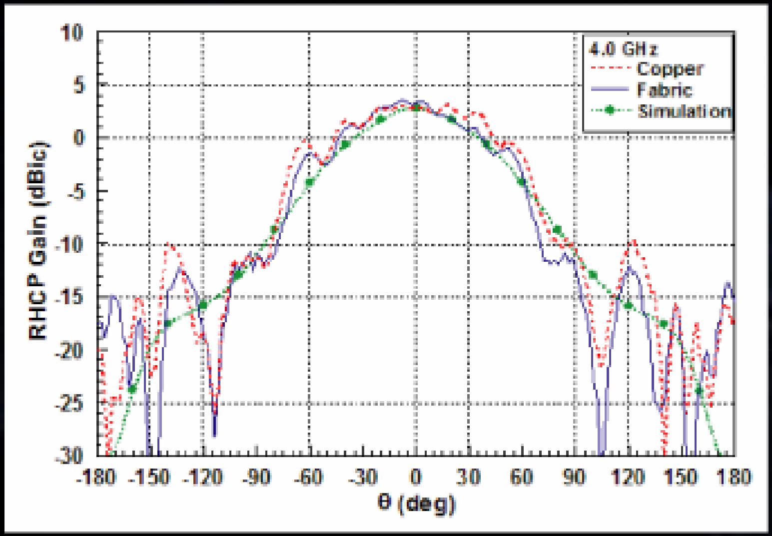




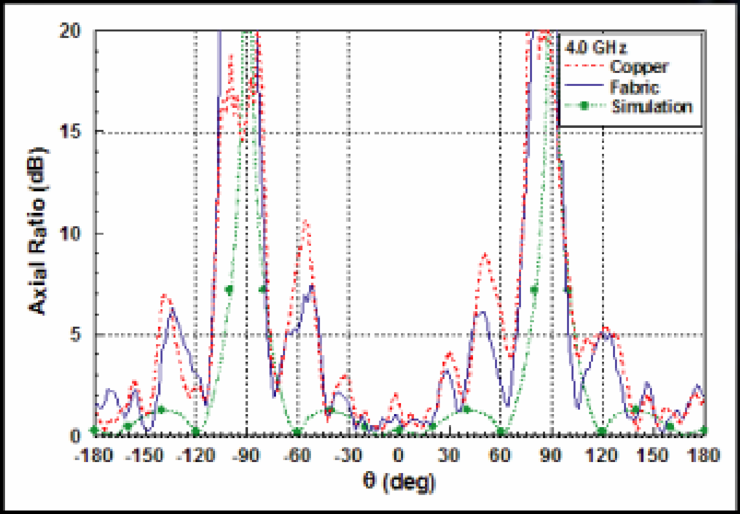
Self-complementary wideband antenna element for EVA or body-worn applications

E-Textile-Based Equiangular Spiral Antenna

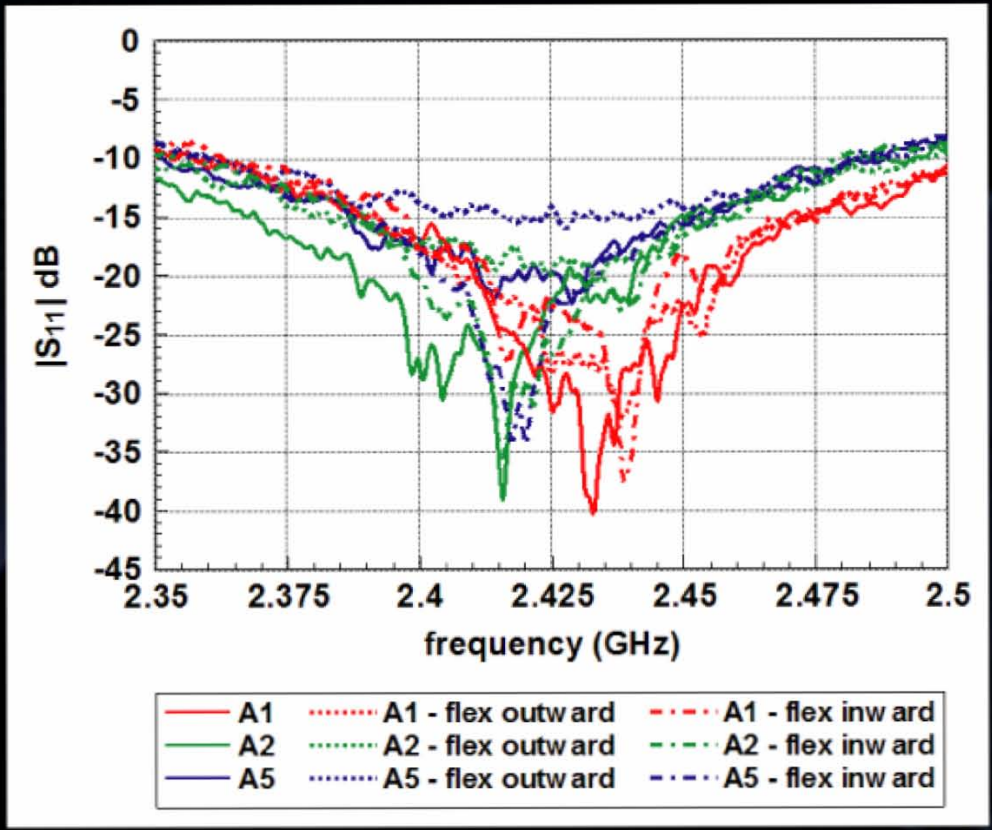




Similar radiation pattern and axial ratio performance between conventional and fabric spiral antennas at 2 GHz and 4 GHz.

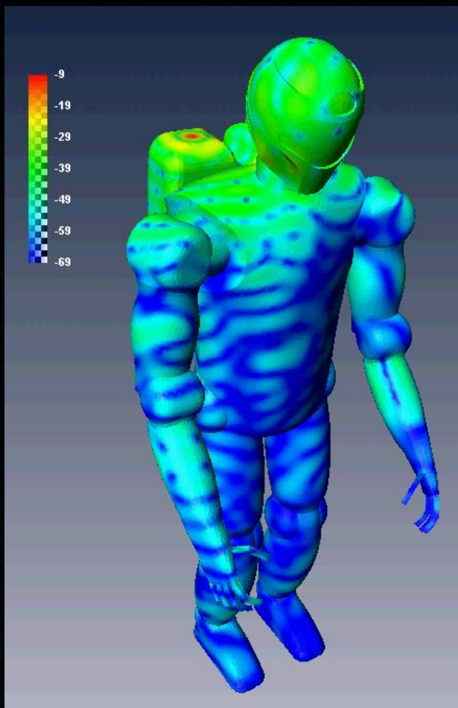


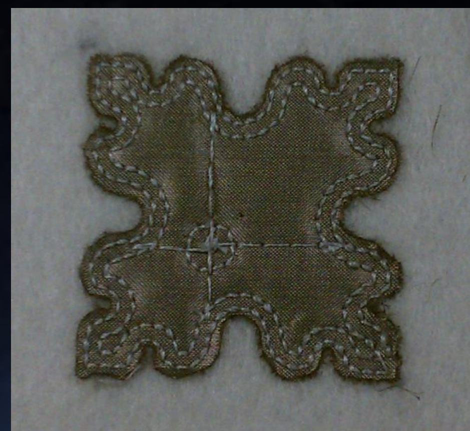
Array Impedance Match with Flexure

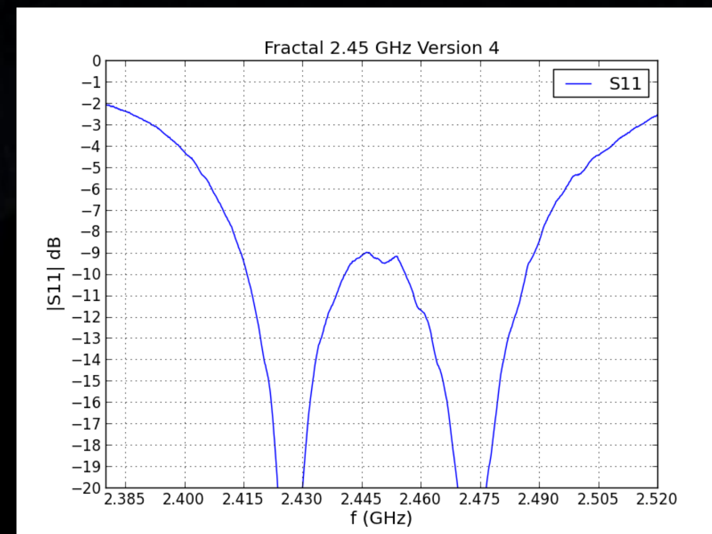


- Representative elements 1, 2, and 5 selected
- Similar performance among antennas (~6% BW)
- Moderate flexure and wrinkling detune the elements only slightly

E-Textile Wi-Fi Antenna for Robonaut (R2)



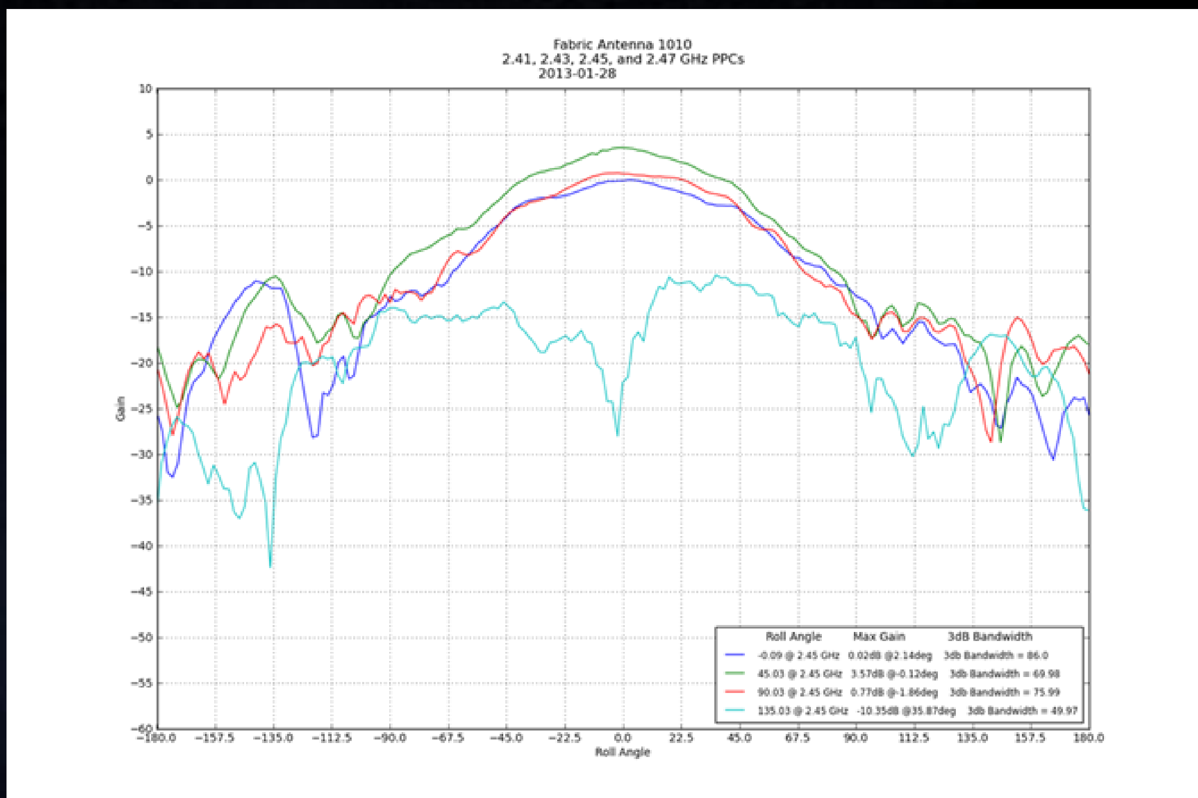




802.11 WLAN antenna being developed for R2
Integration with fabric-based R2 skin

Fabric Fractal Antenna Pattern – Flat Ground

- Single feed circularly polarized antennas tend to have narrow axial-ratio bandwidth
- Effects of flexure are more prevalent on narrow-band antennas



Reliable E-Textile Interfaces: Research Area

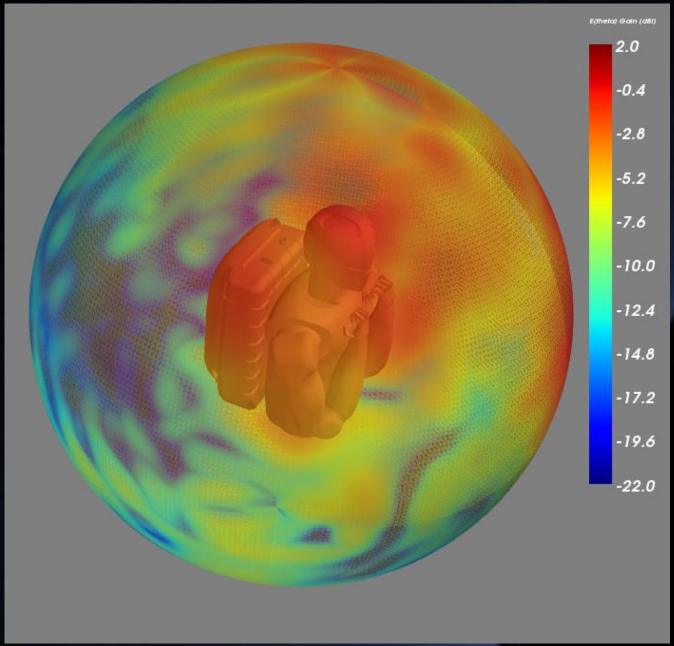
- Reliable interfaces to conventional technologies (e.g., coaxial cable) is still a research topic

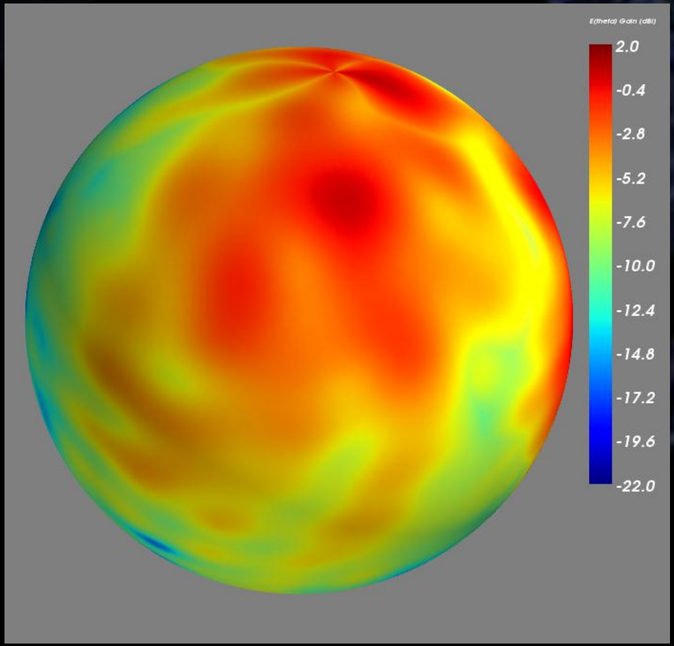
- Shown here – experiments with local stiffeners at interface point

Co-planar waveguide transition is sewn directly to e-textile ground plane

CEM Tool for Optimal Antenna Placement

- Computational Electromagnetics (CEM) tool used to locate e-textile antennas on robotic skin for optimal coverage





Patterns Assessed on Mockup of Robot

- Patterns were measured on the mockup and compared to simulation results

MILITARY ANTENNA CONFERENCE - BACKUP

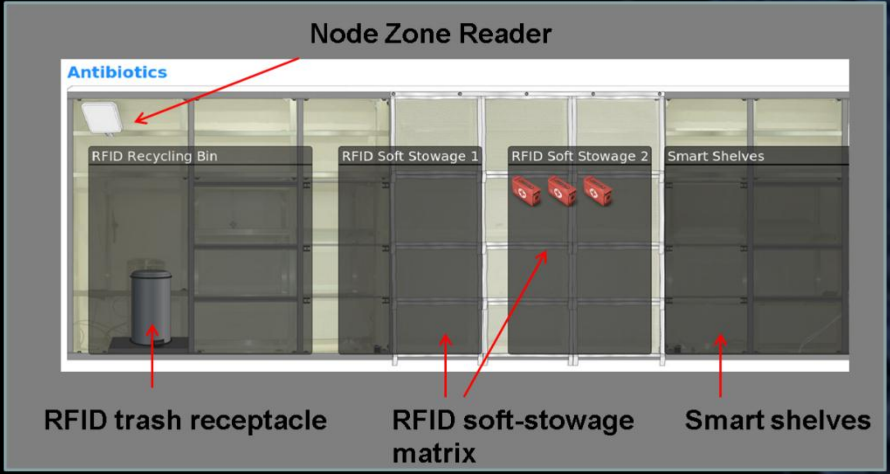
SPARSE ZONE TECHNOLOGIES – Technology Growth Required

- Combination of studies/simulations/analogs/ISS required to determine the best Sparse Zone interrogation approaches
  - e.g., fixed beam directive antennas, phased arrays, free-flyer
- Robotic elements have great potential as Sparse Zone readers as robotic technology matures
  - Mitigates power wiring constraints for readers
  - Allows close-range tag inspection and searches
  - Potential for fine resolution localization of assets
  - More adaptive than fixed antenna readers
- Understanding optimal solutions will require a combination of analog studies, simulations, and on-orbit testing in dynamic environment

27

Analogs: Wireless Habitat Test Bed (WHAT)

- Developed under Innovative Partnerships Program (IPP)
  - 3m diameter x 6m length horizontal cylindrical architecture
- Used to demo advanced RFID concepts
- Used by OC to test handheld RFID in audit and search modes
- Used to test Delay/Disruption Tolerant (DTN) database synchronization
  - e.g., in transferring RFID-tagged inventory from MMSEV (Multi-Mission Space Exploration Vehicle) to Habitat



28

Analogs: RFID in Deep Space Habitat

Original MOWS

MOWS RFID-Enabled Drawers

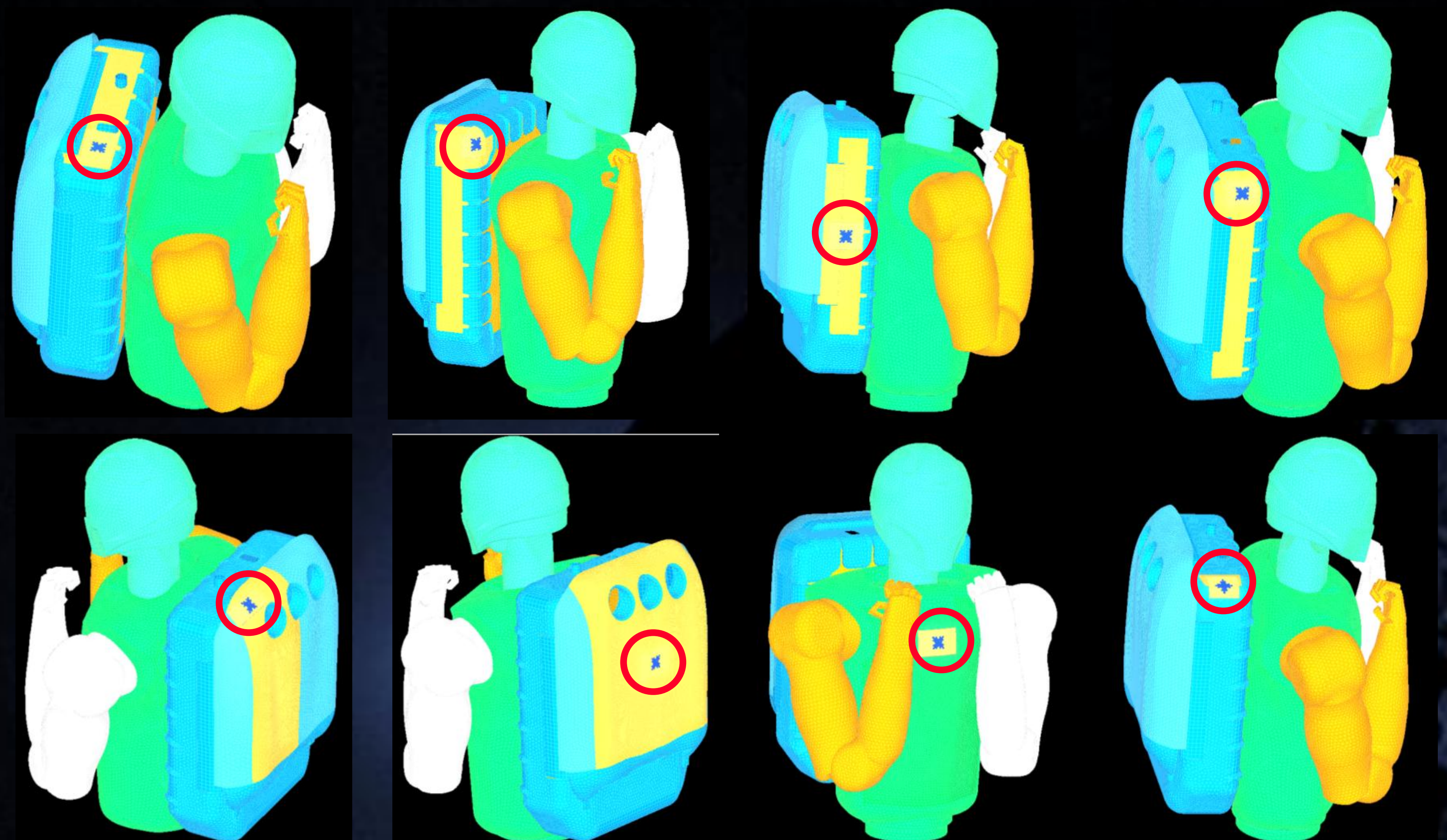
RFID Hygiene Module Installation

RFID GeoLab

29

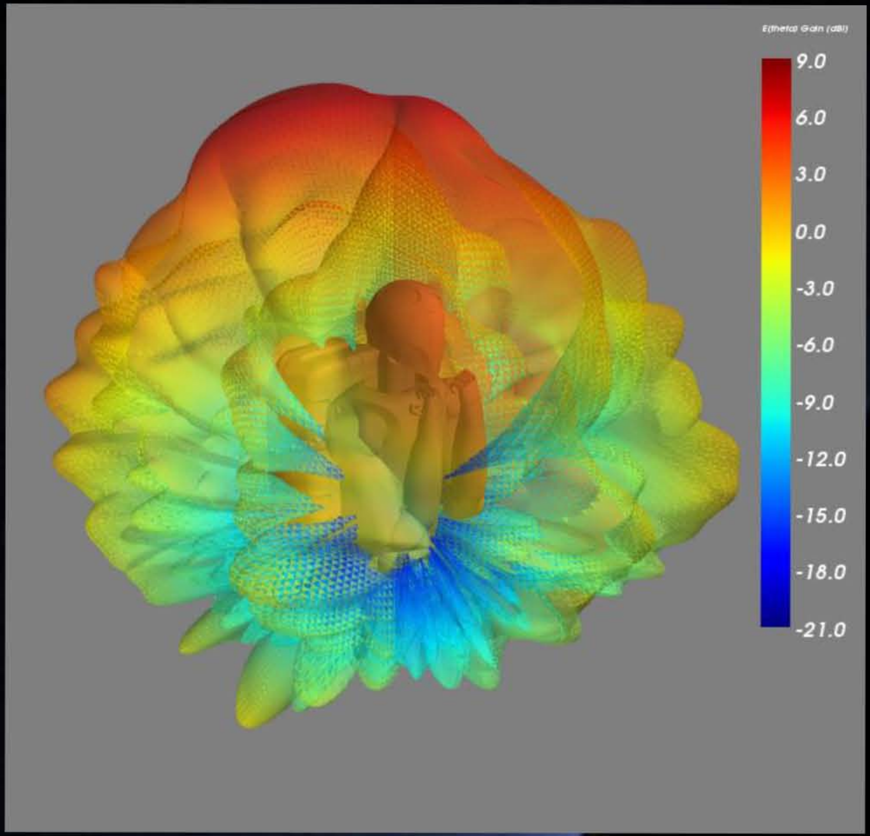
Sample of Antenna Locations Analyzed

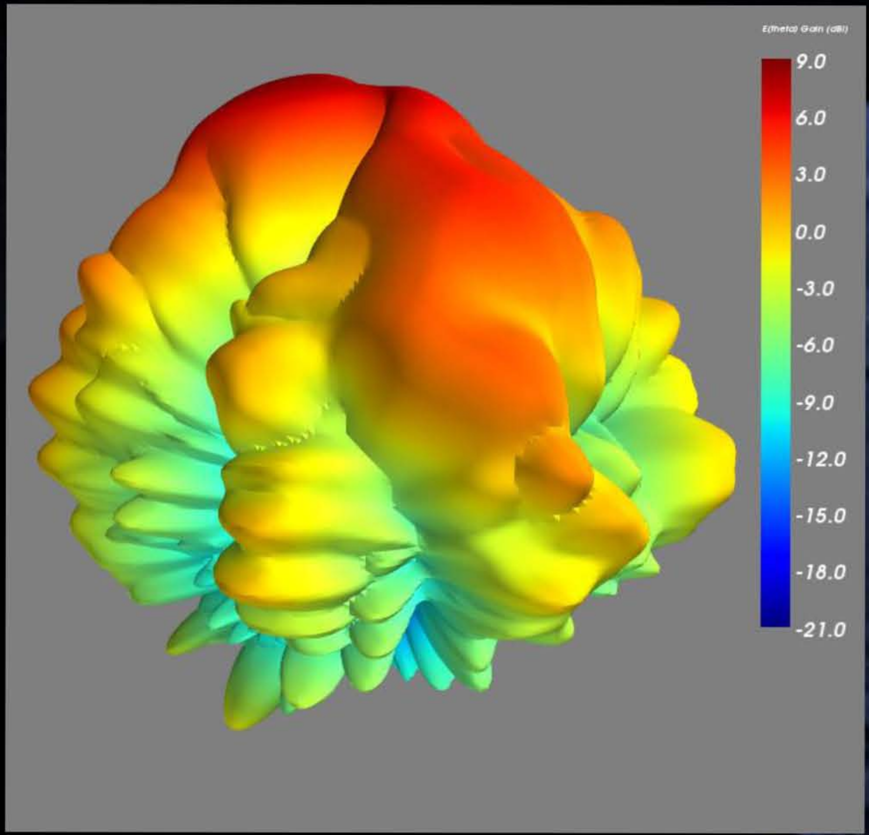
- Multiple antenna locations were analyzed for this study. A sample of the positions is given in the figures below. The antenna is circled in red.



Optimized Location Without Normalization

- G_{θ} - 3D Visualization

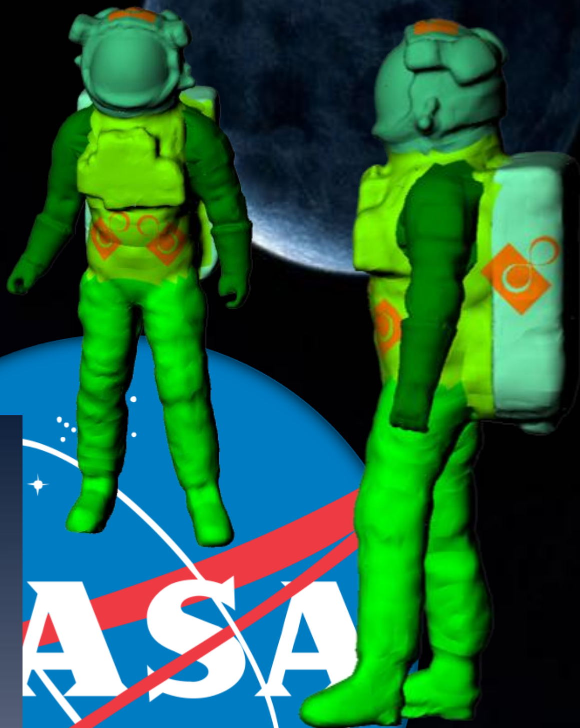




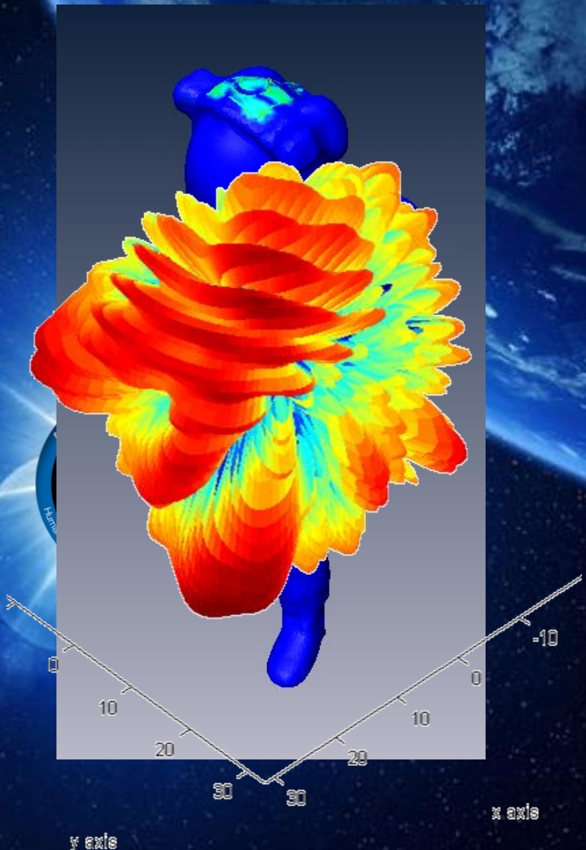
E-Textile Antenna Mounted on the Astronaut Suit

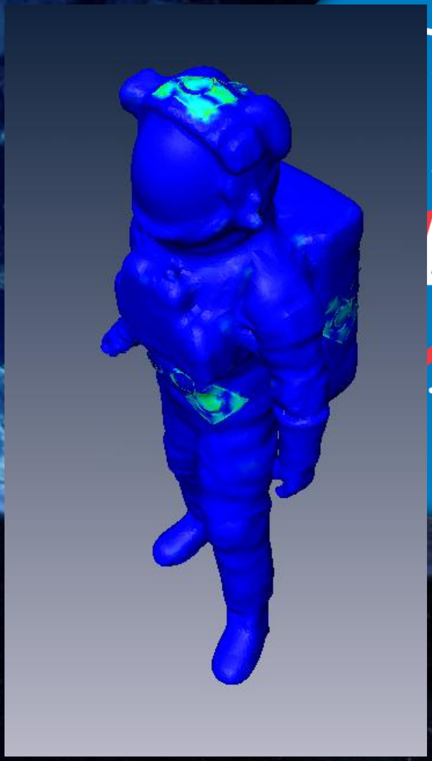
Antenna

CAD Models



Simulation





The CEM Software

- Parallelized, frequency domain, US government-use code.

NASA

University of Houston

University of Washington

University of Kentucky

Lawrence Livermore Natl. Lab

Sandia Natl. Labs

SSC – San Diego

- Publications and Conference Proceedings

1. *"Integrating the Gradient of a Thin Wire Kernel,"* 2008, Antennas and Propagation Society International Symposium.
2. *"An Improved Transformation and Optimized Sampling Scheme for the Numerical Evalation of Singular and Near-Singular Integrals,"* 2008, IEEE Transactions on Antennas and Propagation.
3. *"Simple and Efficient Numerical Evaluation of Near-Hypersingular Integrals,"* 2008, Antennas and Wireless Propagation Letters.
4. *"Body-Worn E-Textile Antennas: The Good, the Low-Mass, and the Conformal,"* 2009, IEEE Transactions on Antennas and Propagation.