Jet Propulsion Laboratory
California Institute of Technology

Wireless Applique for Integration and Test

Norman Lay

Communications Architectures and Research Section

Communications, Tracking and Radar Division

October 9, 2017

Overview

- The work described in this presentation is one of two activities at JPL that are focused on developing technologies for cable reduction in spacecraft operational and test environments
- This effort focuses on wireless replacement of data interconnects (the companion activity is pursuing power line communications)
- Identification and retirement of key risks in the adoption of these technologies is central to the development approach

Benefits and Need

General Benefits

- Cable mass savings
  - Decreased launch vehicle requirements
  - Allows for additional payloads
- Test and integration
  - Reduction/elimination of EGSE cable mass and routing complexities/limitations
  - Improvements in testing visibility for deeply integrated subsystems
- Spacecraft configurability
  - Reduced complexity in design, integration and test
  - Frees emplacement of instruments and subsystems from cable routing constraints
  - Provides flexibility for late additions/modifications to spacecraft designs
  - Enables dissimilar redundancy

Specific “real world” need examples

- Cable elimination to save on instrument mass
- Data cable replacement for bridging separating elements
- High rate data cable replacement to improve signal integrity
- Cable conductor count reduction across a mechanical joint

Objectives and Challenges

<u>Objective #1</u>: Retire key risks to use of secure wireless technologies in spacecraft design & test.

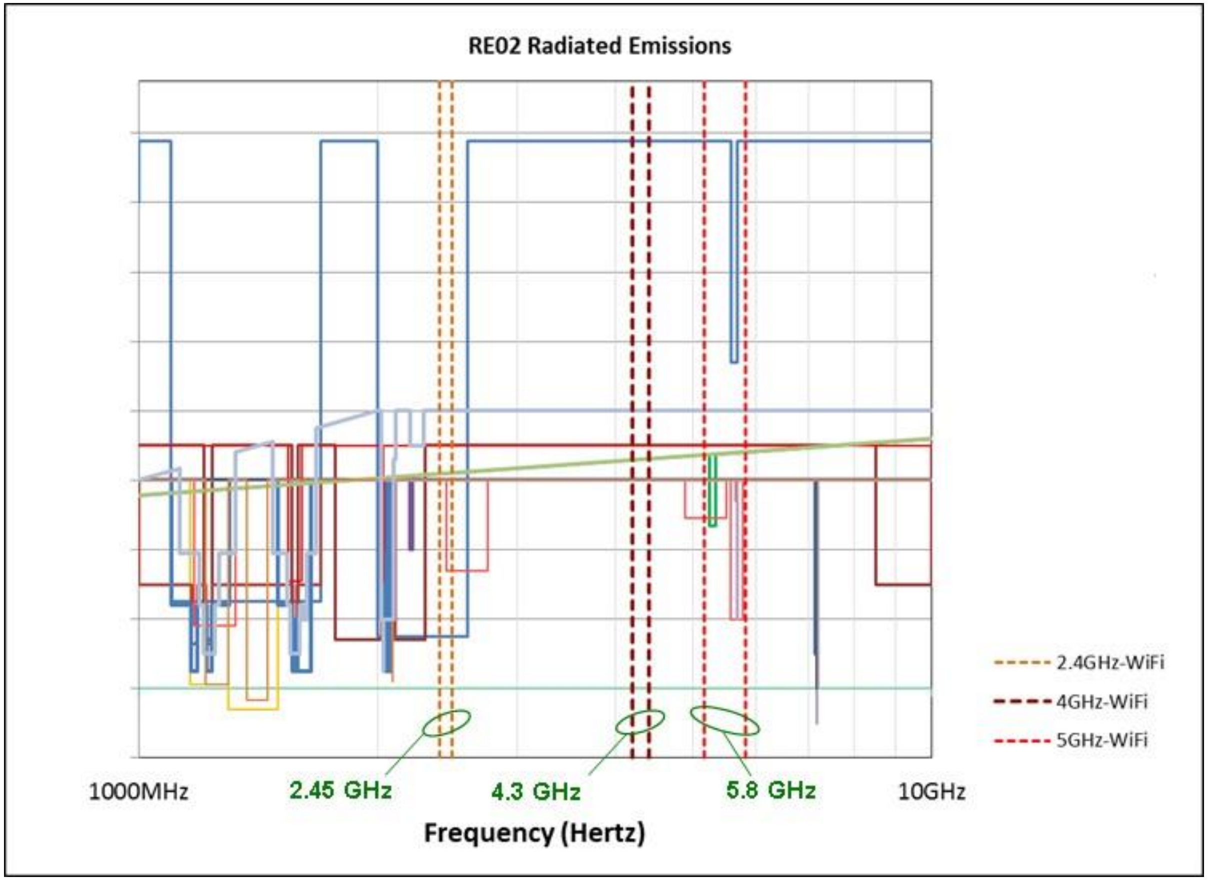
- Link Reliability:
  - Analytically model RF propagation in spacecraft test and operations environments.
  - Verify model through test.
- Network Scalability:
  - Analyze QoS (data throughput and latency) provided by available protocols.
  - Verify modeling analysis through test in networking testbed.
  - Challenge: Develop protocol customizations to guarantee high reliability and latency requirements.
- Electromagnetic Compatibility:
  - Survey existing spacecraft instruments, radios and other subsystems for susceptibility to interference.
  - Analyze and measure proposed wireless applique for compatibility and incorporate results into design approach.

<u>Objective #2</u>: Develop and demonstrate wireless applique for GSE cable replacement in ATLO.

- Develop preliminary technical approach for GSE cable replacement
- Develop initial design & prototype of wireless applique device.
- Demonstrate final prototype of wireless applique for GSE cable replacement

EMC Survey: Radiated Emissions

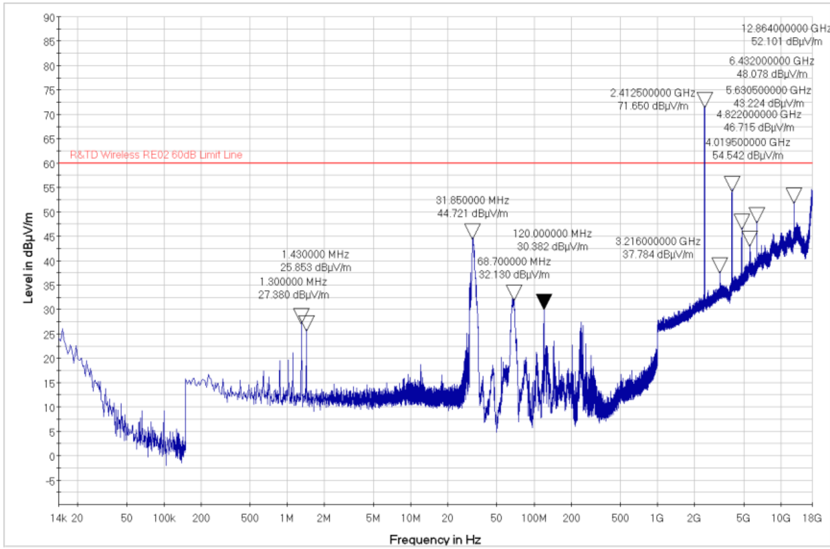
Radiated Emissions Limits for 15 Missions around 2.4, 4.3, and 5.8 GHz



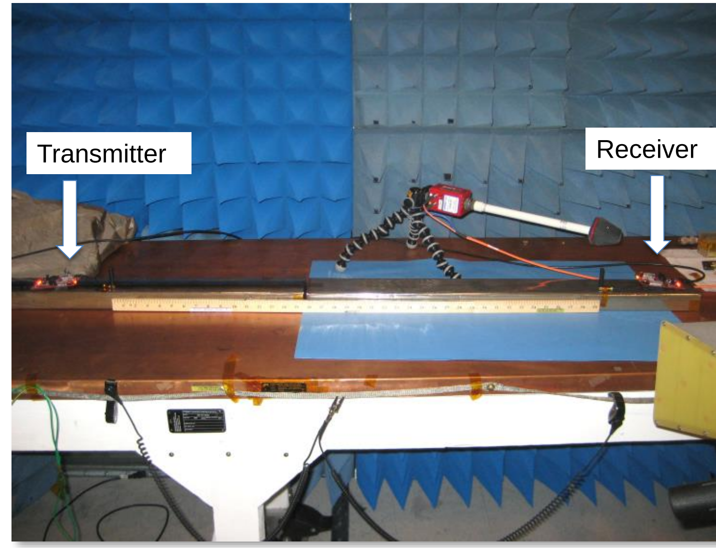
The pairs of vertical dashed lines indicate the boundaries of the 2.45, 4.3, and 5.8 GHz bands.

- Completed survey & transcription to spreadsheet of RE02 requirements for 28 missions
- In-band overlap identified for the following applications:
  - 4.3 GHz landing radar (InSight only)
  - 5.8 GHz launch vehicle beacon/TT&C (various)
  - 2.4 GHz imaging radar (M3)
- Additional comparative analysis revealed available spectrum for wireless usage within the overlapping bands for all surveyed missions except InSight
- Transmit power and receiver sensitivity specifications for wireless components were utilized to produce candidate EMC requirements

EMC Testing: Summary



Wireless Module Radiated Emissions Testing: out-of-band emissions with multi-mission RE02 limits



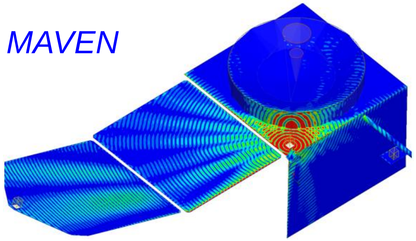
Wireless Module Test Configuration, Radiated Susceptibility: no observed degradation (36 Mbps)

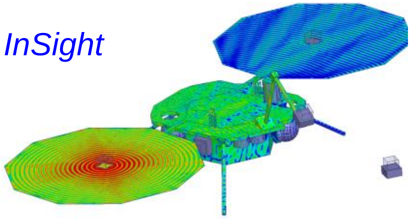
- Performed out-of-band, radiated emissions measurements and compare against RE02 requirements (“Smart Cabling: Wireless Applique Wi-Fi Unit EMC Radiated Emissions RE02 Test Report”, JPL IOM 5137-16-093, 19 September 2016)
- Evaluated wireless component damage threshold via analysis and testing based on RS03 limits (“Wireless Applique Conducted Susceptibility CS04 Test Report”, JPL IOM 5137-16-089, 20 September 2016)
- Evaluate wireless component communications performance via analysis and testing based on RS03 levels, S-Band focus (“Wireless Applique Wi-Fi Tx-Rx Radiated Susceptibility RS03 Test Report”, JPL IOM 5137-16-088, 20 September 2016)

Propagation Modeling: Overview

- **Objective:** Analytically model RF propagation in spacecraft test and operations environments
  - Assess impact of spacecraft structure on antenna patterns
  - Assess frequency response and loss characteristics between multiple accommodated antennas in line-of-sight (LOS) and non-line-of-sight (NLOS) configurations
  - Assess sensitivity to antenna placement
  - Validate Friis transmission calculations for the various case studies
- **Modeling approach:**
  - Modeling whole or large fractions of spacecraft using finite element and hybrid integral equation full wave solvers
  - Investigate propagation results using shooting-bouncing-ray modeling methods
  - Using simplified representative antenna elements (patch, dipole)
  - Using frequency bands commensurate with commercial ISM wireless parts / operation
- **Case Studies:**
  - InSight (Mars lander)
  - MAVEN (Mars orbiter)
  - Mars 2020 (Mars lander)
    - Descent stage
    - Rover

Photos of spacecraft in ATLO

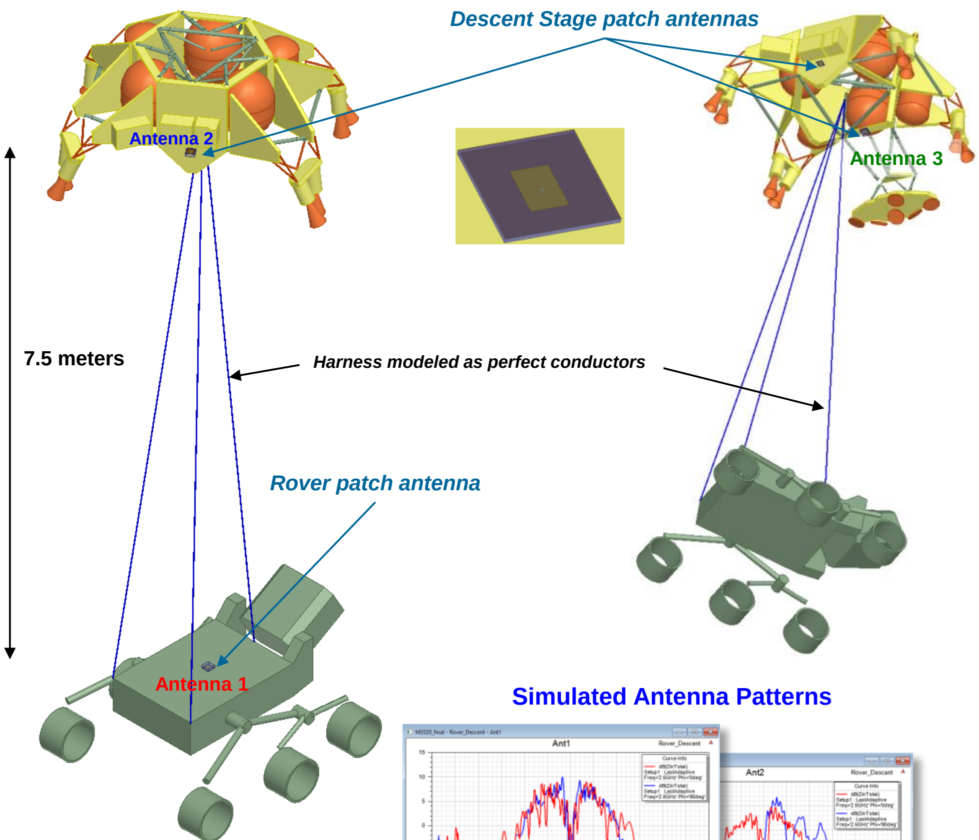




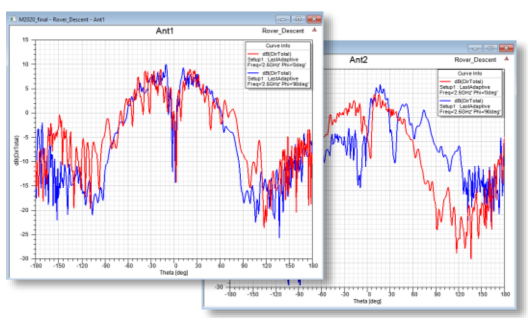
De-featured HFSS models showing surface currents

M2020 Skycrane-to-Rover EM Modeling

Electromagnetic Modeling System Configuration

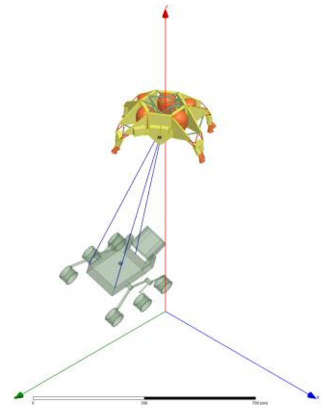


Simulated Antenna Patterns



DS-Rover Graphic

Pendulum Analysis

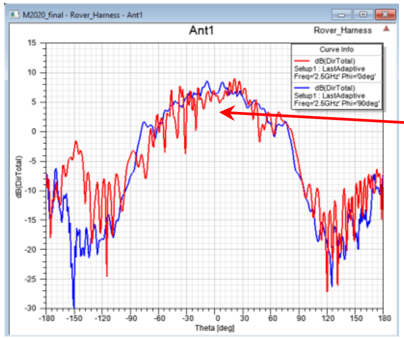


- Completed EM modeling of Mars 2020 Descent Stage-to-Rover wireless link
- All parts shown are modeled as perfect conductors – some smaller parts removed to simplify modeling
- DS has two nadir-pointed antennas
- System is modeled in free-space (assumes altitude is sufficient to ignore ground reflections)
- All antenna modeled as linearly polarized patch elements

M2020 Detailed Modeling Examples

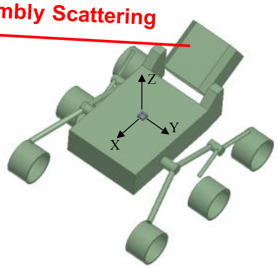
Rover Pattern Notch Analysis

Rover + harness (no descent stage)



De-featured Rover Model
(wireless link is in the +z direction)

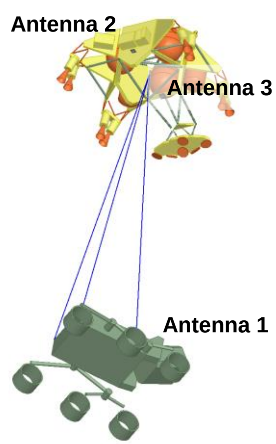
RTG Assembly Scattering

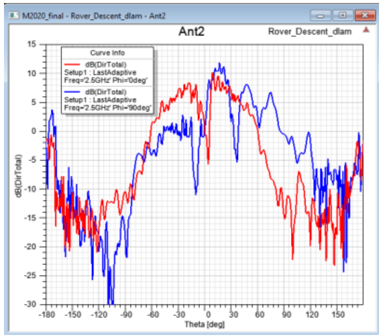


- Standalone rover has a pattern more closely resembling a patch antenna element
- Main lobe null is due to Descent Stage and Rover combination

Antenna Location Sensitivity Analysis

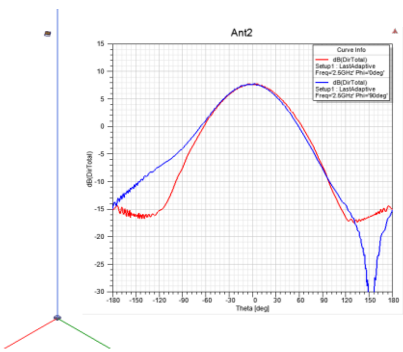
Rover moved $\lambda/4$ towards Skycrane



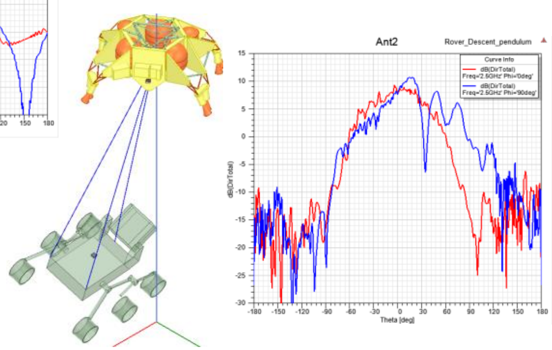


- Null in DS antenna pattern remains in place after rover repositioning, suggesting that the cause is not simple specular reflection

Pendulum Analysis

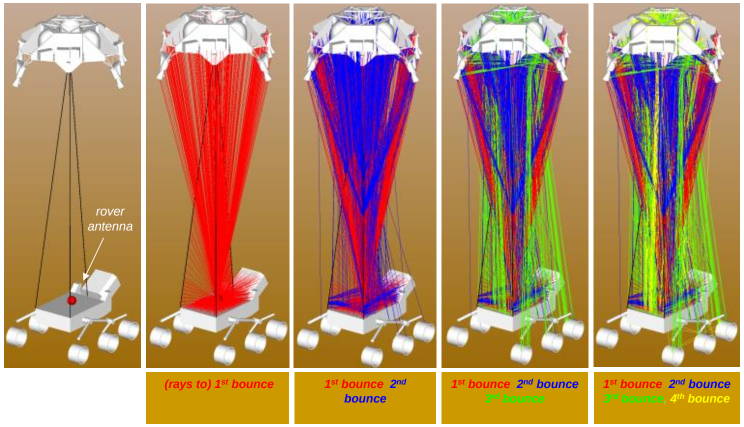


- Rover-harness assy. rotated 14° around x-axis and 14° around y-axis at origin of harness, while descent stage remains nadir pointed
- Antenna null behavior reduced



- Smooth antenna pattern modeling without either Descent Stage or Rover

Scattering Analysis Using Ray Tracing Tools

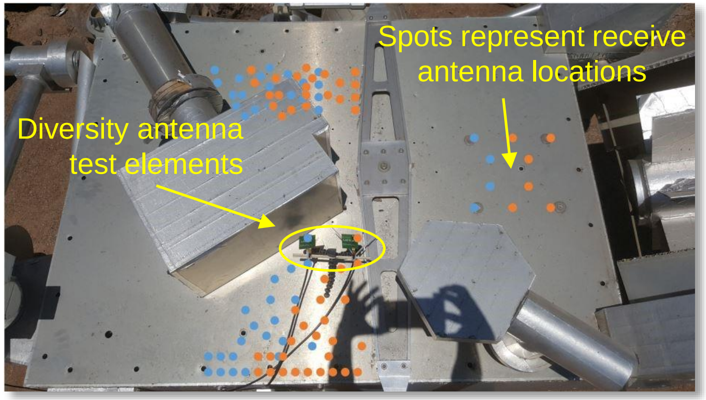


- Ray tracing analysis in Savant suggests a complex scattering interaction between Rover and Descent Stage, and scattering within the structure of each respective spacecraft (exit rays not shown for clarity)

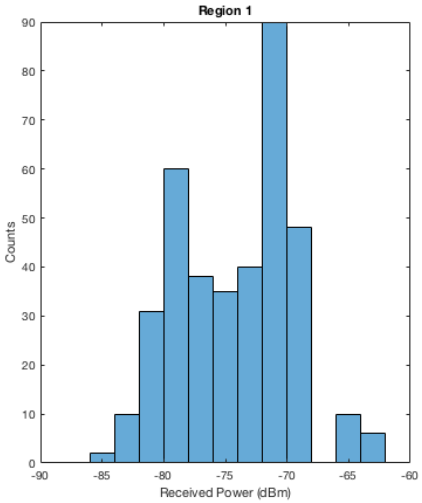
Propagation Measurements: Mars Yard

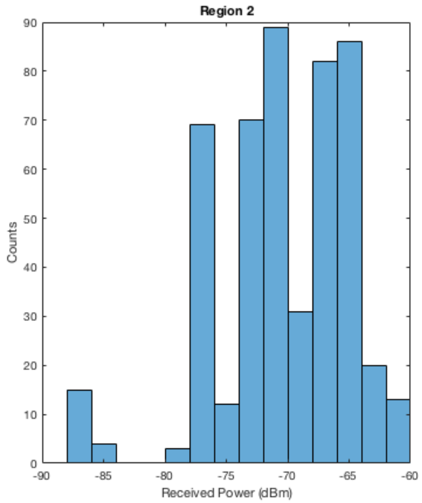
Field test configuration

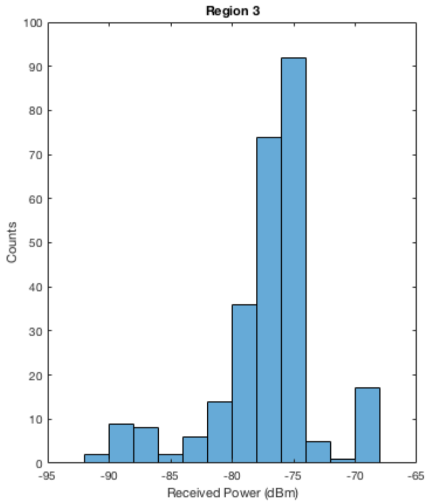
Rover top deck receiver locations



Signal level distributions for three measurement regions





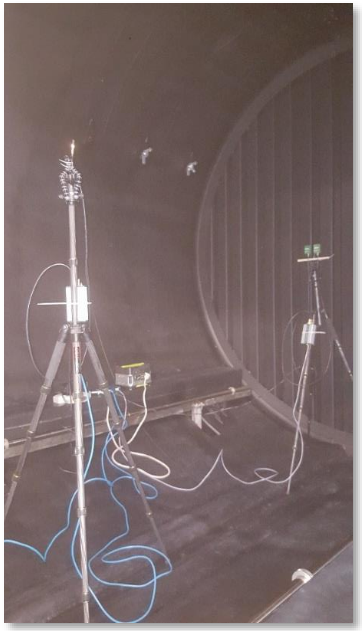


- Single transmit antenna, dual receive antennas
- Transmitter and receiver locations spread across the rover body (e.g. wheel to deck, arm to deck, etc.)
- 20 MHz BPSK signal used as the channel sounding waveform
- Correlation analysis used to estimate received signal strengths
- TX/RX frequencies: 2.5 GHz, 5.8 GHz
- Software defined radios used to transmit and capture waveforms

Propagation Measurements: Environmental Test Lab

Ten foot environmental chamber

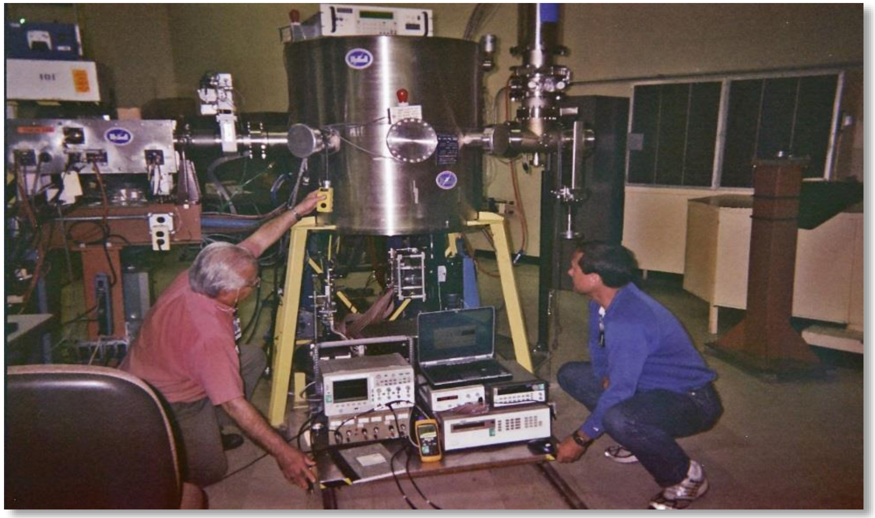
Transmit/Receive antennas located within test chamber



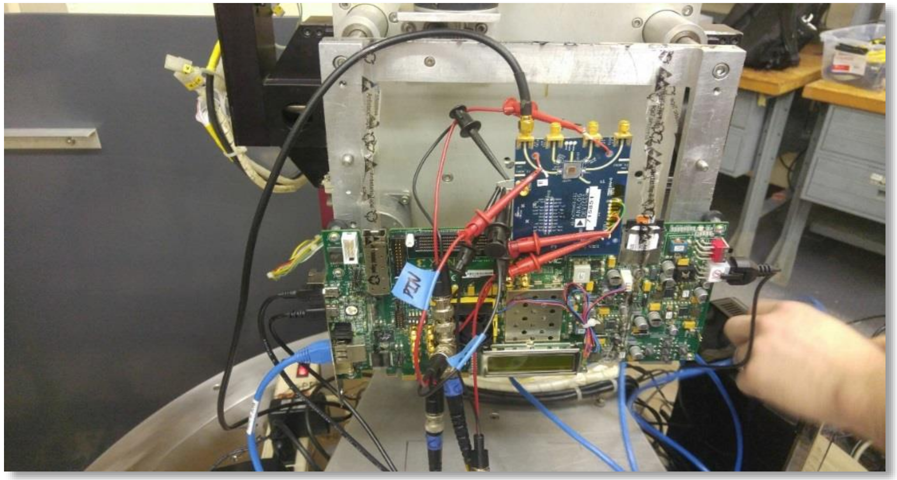
- Performed preliminary collection and analysis of propagation measurement data to assess signal variability and multipath environment
- Test waveform employed 20 MHz BPSK reference sequence at 2.5 and 5.8 GHz
- Receiving system tested with antenna diversity and spatially sampled local region
- Test configurations included receive antennas inside and outside of test chamber

Wireless Device Radiation Testing

BNL Vacuum Chamber and Test Set Up

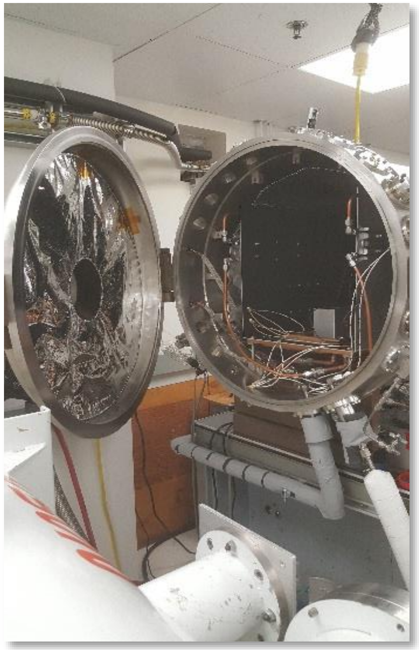


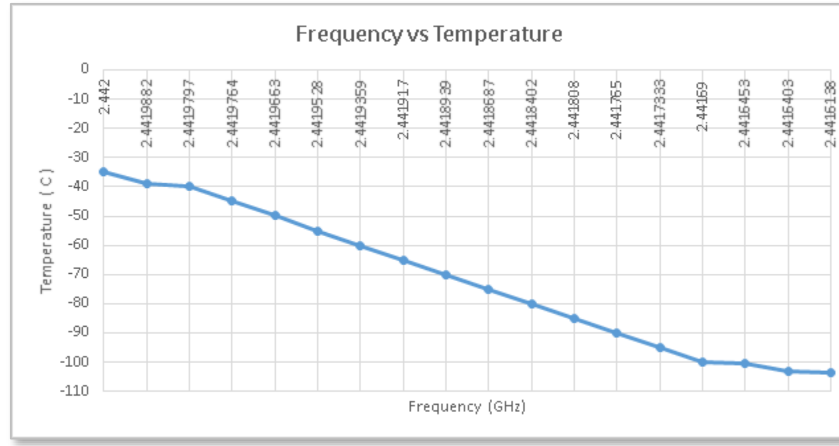
Test Configuration for RF Front-end Chip



- Selected a representative set of COTS wireless components (WiFi, Zigbee, Bluetooth, general purpose RF) for radiation latch-up testing
- Tests performed at the Single Event Upset Test Facility (SEUTF) located at Brookhaven National Laboratory (BNL)
- Power supply control software used to provide automatic latch-up detection, counting and device protection
- Identified parts that successfully passed latch up testing – additional measurement campaigns planned in FY18

Wireless Device Thermal Testing



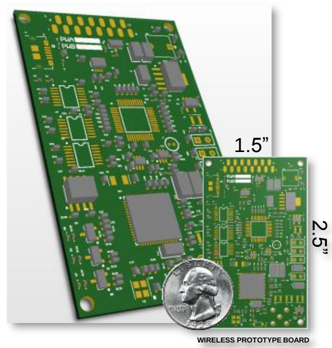


Example frequency offset performance vs. temperature

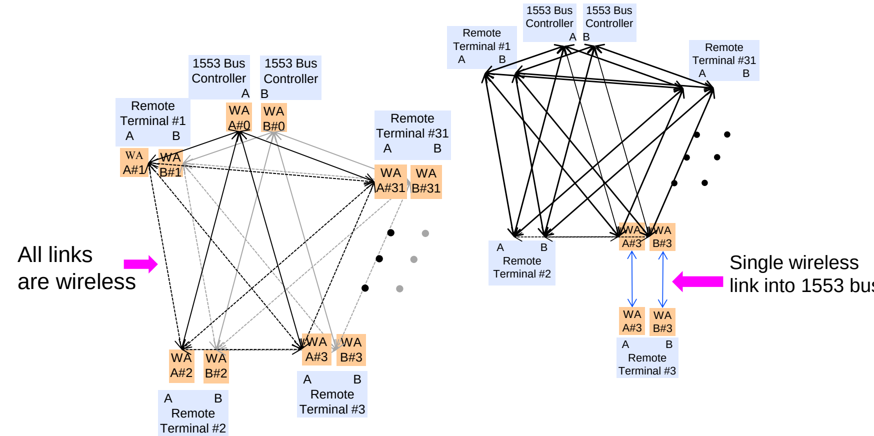
- Performed communications performance testing for a commercial wireless chip over temperatures within and beyond device specification range
- Device impairment observed near the vicinity of -100^{o} C
- Transmitted waveform also recorded for quality assessment to determine if the source of the impairment is strictly related to carrier frequency offset
- Anticipate the ability to correct for frequency errors for I&T applications

Additional Activities

Signal attenuation measurement through multi-layer insulation

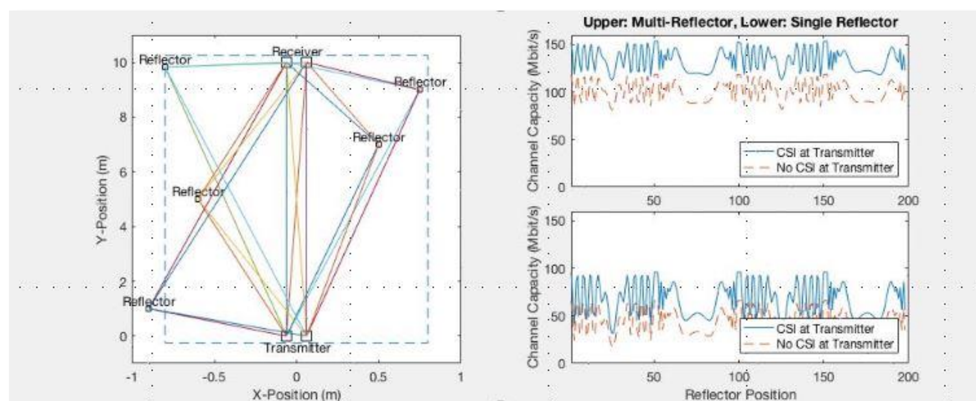


Wireless prototype development



Wireless network overlay architectures of 1553 bus and preliminary fault behavior analysis

Frequency agile OFDM test capability – enables wireless link testing in non-standard bands (e.g. 4.3 GHz)



MIMO channel capacity analysis

Summary

- Studies, measurements and analyses show the viability of wireless interconnections for a variety of use cases
- Prototype development is currently underway with several standardized interfaces identified as candidates for wireless testing
- Functional and performance testing planned using internal testbeds
- Continuing to seek additional demonstration and infusion opportunities

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov