Space Shuttle & Space Station Lessons Learned: Less Wires for Current & Future Spacecraft

December 11, 2018

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PWST Workshop S1-C4

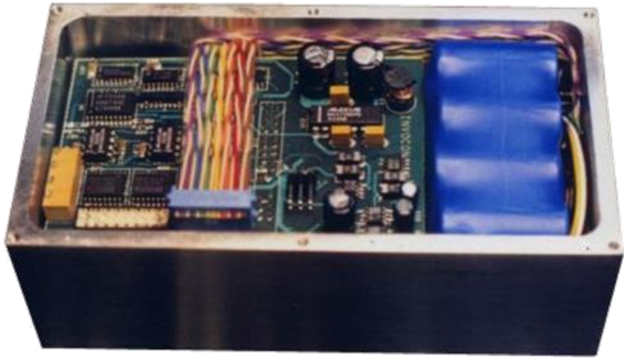
- What we did on Space Shuttle & ISS
- Lessons Learned from that
- Some Current and Future Spacecraft Needs

Wakeshield – 1995 – RCS Impingement Loads

STS-69 in September 1995 and STS-80 in November of 1996.

No Other Option

Wake Shield Data Acquisition System
Spread Spectrum Relay Network



For More:
See WiSEE Session 6 Presentation
Aaron Trott/ Invocon

Actual Space-flight Wireless Sensor Flight Applications:

Stand-alone data loggers – wireless to program and retrieve data

- **Shuttle Temperature**
  - Payload – Spacelab – time/cost to integrate into vehicle utilities
  - Middeck(interior) - Micro size – real-time transmitters - no other practical option
  - Wing(vacuum) – Micro-sized data loggers - no access to vehicle utilities
- **Shuttle Structural Loads/Dynamics** – only a few flights needed to characterize

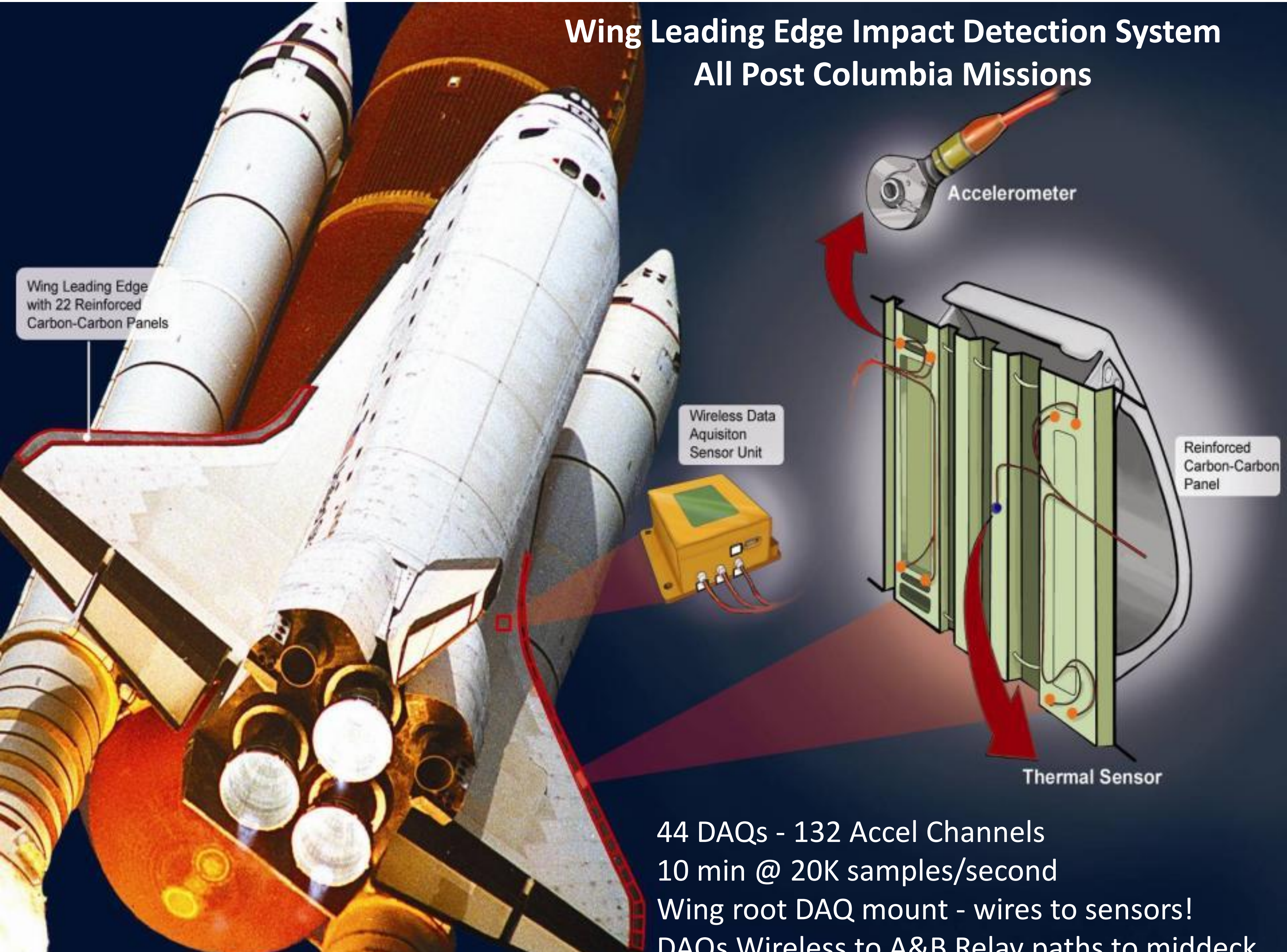
  Micro-sized Standalone data loggers – no other practical solution
  - Cargo Trunnions – Micro-size – time synch between units
  - SSME struts – LOX & LH2 environment – strain gauge wires a potential spark
  - SSME feedlines – LOX & LH2 + Cyro-cold mount for high-rate triax accelerometers
  - OMS Pods – Strain – difficult access

    \- Accelerometers – extremely short turnaround to flight(2 weeks)
- **Shuttle Remote Manipulator System(RMS – Canadian Space Agency) wit**h 50' boom

  – no utilities available
  - Strain(loads) at SRMS joints – data synch
  - Astronaut-induced loa(low freq) at Portable Foot Restraint
- **Shuttle Wing Leading Edge Ascent and MMOD Impact – Post Columbia missions**

  - Alternative Vehicle Mod much greater initial cost and schedule(Program impact)
  - High Data Rate Accelerometers and Temperatures; Ascent and On-Orbit modes
  - Scheduled, Triggered and Commanded Ops; Edge Computing of "answers"
  - Wireless Synch using Master – slave wireless pulses
  - Battery Changeout cost and schedule hit for repeat missions

Wing Leading Edge Impact Detection System
All Post Columbia Missions



44 DAQs - 132 Accel Channels
10 min @ 20K samples/second
Wing root DAQ mount - wires to sensors!
DAQs Wireless to A&B Relay paths to middeck

International Space Station Wireless

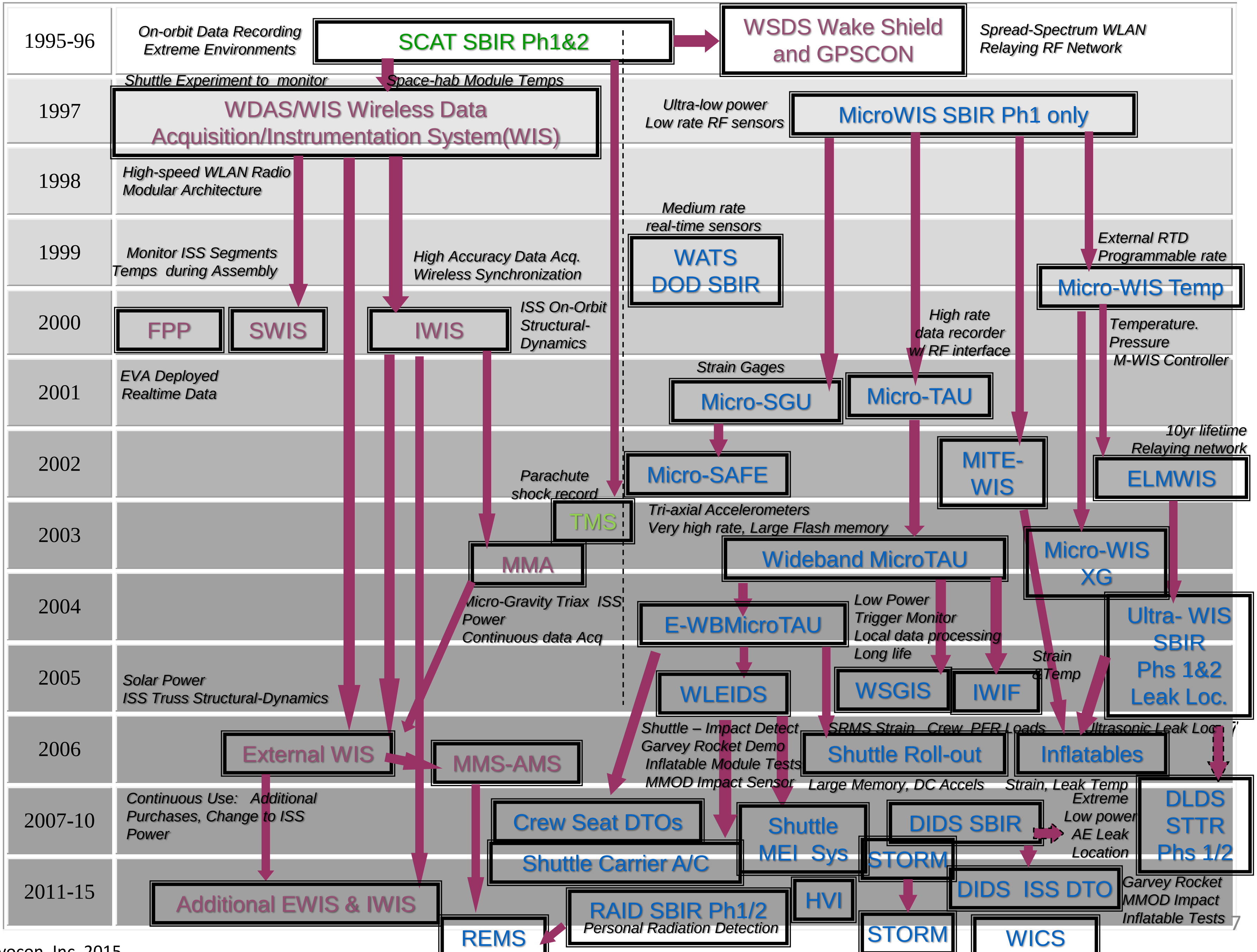
- **Wireless Data Acquisition System demo** – Spacelab STS-83(4/97), STS-94(7/97)
  - Proof of concept for SWIS Ops on Spacelab exterior with WDAS on Orbiter Sill to Middeck Antenna -> cost of wires!!
- **Shuttle-based Wireless Instrumentation System (SWIS)** - ISS Assembly of Z1 & P6
  - No other method available: ISS Truss segment avionics unpowered prior to ISS mate
  - 3 SWIS DAQs - 24 cables to RTDs – at $100K each!
- **Integrated ISS Structural Loads & Dynamics Model Validation**
  - **IWIS -** Re-locatable Interior low freq accelerometers (each mission changes ISS config)
  - **EWIS** - EVA deployable exterior low freq accels on truss segments without accels
- **ISS internal temperature monitors** – airlock temperatures for model validation
  - Micro-WIS - Invocon
- **ISS Ultrasonic Background Noise** – ultrasonic monitoring/location in module walls
  - Ultra-WIS – Eric Madaras/NASA Langley
- **ISS Bigelow Experiment Module** – deployment loads/dynamics and impact detection
  - Wells/NASA JSC: InSpace Inspection Workshop (ISIW2017) Presentation 6C-2
- **ISS External Wireless Network** –> External High Definition Camera
- **ISS REALM RFID-based Inventory System - > Gateway Readers -> Free-flyer (Astrobee)**
  - **Wagner/Fink – see Session 6 – Presentation C5**

Invocon Wireless Instrumentation Shuttle/ISS Flights

Flight	Launch	Invocon Systems	Sensor Type
STS-69	9/7/1995	WSDS	Pressure
STS-80	11/19/1996	GPSCON WSDS ADDS	GPS Pressure Acceleration
STS-83	5/4/1997	WDAS	Temperature
STS-94	7/1/1997	WDAS	Temperature
STS-96	5/27/1999	MicroWIS	Temperature
STS-101	3/19/2000	MicroWIS	Temperature
STS-106	9/8/2000	MicroWIS	Temperature
STS-92	10/11/2000	SWIS MicroWIS	Temperature Temperature
STS-97	11/30/2000	IWIS SWIS FPP MicroWIS	Accel/Strain Temperature Plasma Potential Temperature
STS-98	2/7/2001	IWIS	Accel/Strain
STS-100	4/19/2001	MicroWIS	Temperature
STS-104	7/12/2001	MicroWIS IWIS	Temp-Airlock Accel/Strain
STS-108 Note:	12/5/2001 SGU on all subs flts thru STS125	MicroTAU MicroWIS MicroSGU	Vibration Temperature Strain – Aft Comp
STS-109	3/1/2002	MicroSGU	Strain
STS-110	4/8/2002	MicroSGU	Strain
STS-111	6/5/2002	MicroTAU MicroSGU	Vibration Strain
STS-112	10/7/2002	MicroSGU	Strain
STS-113	11/23/2002	MicroSGU	Strain
STS-107	1/16/2003	MicroSGU	Strain
STS-114 – note: WLEIDS on all subs	7/26/2005	WLEIDS MicroTAU MicroSGU IWIS	Vibration Vibration Strain - OMS Accel/Strain
STS-121	7/4/2006	WLEIDS WSGIS IWIF	Accel Strain on SRMS Load/Accel
STS-115, 116, 117	9/6, 12/9/2006 6/8/2007	EWIS WLEIDS Shuttle Roll-Out	Micro-G Acce Accel
STS-118,120, 122, 123, 124, 126	8/8 & 10/23/07, 7/7, 3/11, 5/31, & 11/14/2008	WLEIDS MicroSGU	Accel Strain
STS-119, 125, 127, 128	3/15, 7/8, 5/11 & 9/11/2009	EWBMicroTAU Crew Seat DTO	Triax Accel
STS-128	3/11/2008	MMA	Micro-G on JEM
STS-129	11/27/2009	WLEIDS(MEI)	Accel - OMS
STS-130	2/8/2010	WLEIDS(MEI)	Accel&AE -OMS
STS-131, 132, 133, 134, 135	4/5,5/14/2010 2/25, 5/16, 7/8/2011	WLEIDS	Accel
ATV-2	2/16/2011	DIDS	AE Sensor

Note: Invocon systems have flown aboard other vehicles since 2011. Invocon is not always privy to the details of these flights. Additional systems are being prepared for flight.

Technology Development Tree (INVOCON, INC. Proprietary and Company Confidential)



Lessons Learned

- Add-on DAQs for spaceflight
- Motivation for less wires, connectors & penetrations
- "Fly-by-Wireless" approach/history

Space Shuttle Lessons Learned from Wireless Sensor Experiences

- **Need: Find a strong User Need that:**
  - **(1) can't be met with wired connectivity**
  - **(2) data is low criticality**
  - **(3) can operate fairly autonomously**
  - **(4) not needed for real-time operations**
- **DAQ: Minimize Vehicle integration & Operations Impact - biggest cost/schedule drivers.**
  - **(1) Minimize Vehicle Interfaces – drawings, data bus, synch, power and ground**
  - **(2) Go for Wireless DAQs that are Smart, Standalone, Small Size/Weight/Power**
  - **(3) Minimize data transmission needs – compute the answer near the sensor**
  - **(4) Better physical & functional access in future vehicle design**
  - **(5) Mature and grow the capability incrementally – SBIR/STTR phase 3+**
- **Sensor Cables: a BIG cost and schedule impact => Passive Wireless**
  - **Reduce the need for penetrations and connectors**
  - **Reduce the number of wireless DAQs – big affect applications and operations.**
  - **Eliminate wires between the DAQ and sensor (Passive Wireless Sensors)**
- **Safety & Communication Reliability concerns can be overcome with <u>Engineering</u>.**

What's the Problem?
"Wired" Connectivity

- WIRES
- CONNECTORS
- PENETRATIONS

WEIGHT
SIZE
DESIGN
INSTALLATION
MAINTENANCE

INTEGRATION
CAPABILITY
CAPACITY
RELIABILITY
FLEXIBILITY
MODULARITY

COST
SCHEDULE
PERFORMANCE
RISK

Sometimes the job just can't be done with wires!

1. Mission Cost/Performance
   - Increasing each year
   - Increasing with missions beyond LEO
2. TRL6 Maturity by PDR…eliminates some add-ons
3. Contractors LOVE Change Traffic
   - Not incentivized to accommodate change
   - All past programs exhibit this problem

1. Motivation: Cost and Schedule of Wired Infrastructure

- **Expenses for Cabled Connectivity** beginning in Preliminary Design Phase and continuing for the entire system life cycle.
- **Reducing the quantity and complexity** of the physical interconnects has a payback in many areas.
  1. **Failures of wires, connectors** and the safety and hazard provisions in avionics and vehicle design to control or mitigate the potential failures.
  2. **Direct Costs**: Measurement justification, design and implementation, structural provisions, inspection, test, retest after avionics r&r, logistics, vendor availability, etc.
  3. **Cost of Data not obtained:** Performance, analyses, safety, operations restrictions, environments and model validations, system modifications and upgrades, troubleshooting, end of life certification and extension.
  4. **Cost of Vehicle Resources:** needed to accommodate the connectivity or lack of measurements that come in the form of weight, volume, power, etc.
  5. **Reliability Design Limitations**: avionics boxes must build in high reliability to "make up for" low reliability cables, connectors, and sensors. Every sensor can talk to every data acquisition box, and every data acquisition box can talk to every relay box -backup flight control is easier.

1. Motivation: The Cost of Wired Infrastructure (continued)

6. **Physical Restrictions:** Cabled connectivity doesn't work for monitoring: structural barriers limit physical access and vehicle resources, the assembly of un-powered vehicle pieces (like the ISS), during deployments (like a solar arrays, cargo and payloads, or inflatable habitat), crew members, robotic operations, proximity monitoring at launch, landing or mission ops.
7. **Performance**: Weight is not just the weight of the cables, it is insulation, bundles, brackets, connectors, bulkheads, cable trays, structural attachment and reinforcement, and of course the resulting impact on payloads/operations. Upgrading various systems is more difficult with cabled systems. Adding sensors adds observability to the system controls such as an autopilot.
8. **Flexibility of Design:** Cabling connectivity has little design flexibility, you either run a cable or you don't get the connection. Robustness of wireless interconnects can match the need for functionality and level of criticality or hazard control appropriate for each application, including the provisions in structural design and use of materials.
9. **Cost of Change**: This cost grows enormously for as each flight grows closer, as the infrastructure grows more entrenched, as more flights are "lined-up" the cost of delays due to trouble-shooting and re-wiring cabling issues is huge.

2. Motivation: Cost of Change for Instrumentation

The earlier conventional instrumentation is fixed, the greater the cost of change.

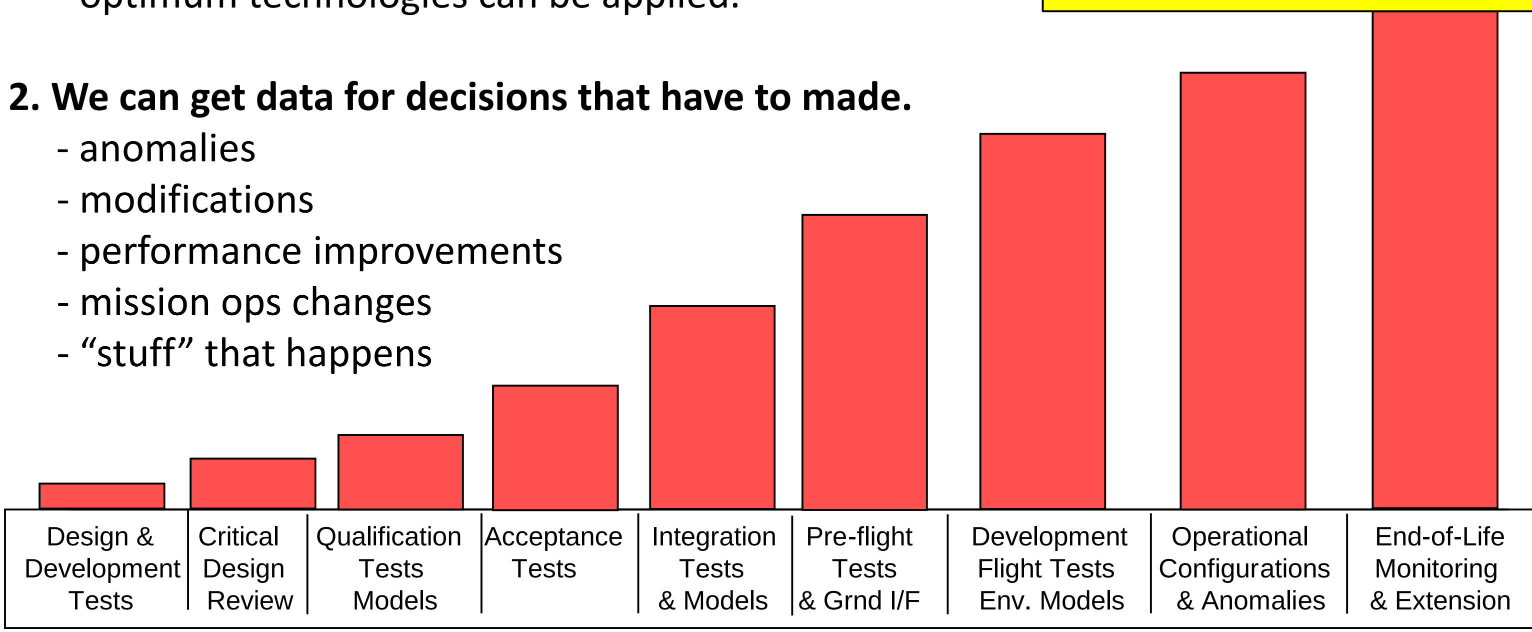
- Different phases uncover and/or need to uncover new data and needs for change.
- Avionics and parts today go obsolete quickly - limited supportability, means big sustaining costs.
- The greater number of integration and resources that are involved, the greater the cost of change.
- Without developed/test systems and environments, many costly decisions result.

We need to design in modularity and accessibility so that:

1. We can put off some decisions until:
- sufficient design, tests/analysis can be made.
- optimum technologies can be applied.

2. We can get data for decisions that have to made.
- anomalies
- modifications
- performance improvements
- mission ops changes
- "stuff" that happens

The more complete the vehicle the greater cost of change to the program and the facility used



3. Motivation: Reliability

Vehicle Reliability Analyses must include: the End to End system, including man-in-the-loop operations, and the ability to do effective troubleshooting, corrective action and recurrence control.

With Wireless Interconnects, the overall Vehicle Reliability is Increased:

Through Redundancy: All controllers, sensors, actuators, data storage and processing devices can be linked with greater redundancy. A completely separate failure path provides greater safety and reliability against common mode failures.

Through Structural and System Simplicity: Greatly reduced cables/connectors that get broken in maintenance, must be trouble-shot electronics problems, sources of noisy data and require structural penetrations and supports.

Through Less Hardware: Fewer Cables/Connectors to keep up with

Through Modular Standalone Robust Wireless Measurement Systems: These can be better focused on the system needs and replaced/upgraded/reconfigured easily to newer and better technologies. Smart wireless DAQs reduce total data needed to be transferred.

Through Vehicle Life-Cycle Efficiency: Critical and non-critical sensors can be temporarily installed for all kinds of reasons during the entire life cycle.

Through the Optimum Use of Vehicle and Human Resources: Wireless can enable distributed and more flexible instrumentation installations, which reduces demands on system experts to be involved with hardware and software integration planning and issues.

Wireless and Less Wire Options need to be added to System Engineering, Integration and Test

“Fly-by-Wireless” Vision:

To Minimize Cables and Connectors and Increase Functionality across the aerospace industry by providing reliable, lower cost, modular, and higher performance alternatives to wired data connectivity to benefit the entire vehicle/program life-cycle.

Focus Areas:

1. **System engineering & integration methods to reduce cables & connectors.**
2. **Vehicle provisions for modularity and accessibility.**
3. **A “tool box” of alternatives to wired connectivity.**

Active Wireless
Passive Wireless
Other Technologies

What it is NOT:

- **A vehicle with no wires.**
- **Wireless-only for all control systems.**

“Fly-by-Wireless” Focus Areas

(1) <u>System engineering and integration to reduce cables and connectors</u>,
- **<u>Capture the true program effects</u>** for cabling from launch & manned vehicles.
- **<u>Requirements</u>** that enable and integrate alternatives to wires.
- **<u>Metrics</u>** that best monitor progress or lack of progress toward goals.(# cables, length, # of connectors/pins, # of penetrations, overall weight/connectivity, total data moved/lb).
- **<u>Design Approach</u>** that doesn’t assume a wires-only approach, but optimizes all practical options, providing for the inevitable growth in alternatives to wired connectivity.

(2) <u>Provisions for modularity and accessibility in the vehicle architecture</u>.
- **<u>Vehicle Zone Accessibility</u> –** Considers standalone sensors along with system assembly, inspections, failure modes/trouble-shooting, system/environment monitoring, remove & repair.
- **<u>Vehicle Zone Modularity</u> –** Vehicle wired buses provide power, two-way data/commanding, grounding and time in a plug-and-play fashion. Wireless networks are standardized by function and are also plug-and-play.
- **<u>Centralized & De-centralized approaches</u>** are available for measurement & control.
- **<u>Entire life-cycle</u>** considered in addition to schedule, performance, weight & volume.

(3) <u>Develop Alternatives to wired connectivity</u> for the system designers and operators.
- Plug-n-Play Smart wireless devises
- Wireless no-power sensors/sensor-tags
- Standalone wireless smart data acquisition
- Standardized I/Fs, networks & operability
- Wireless controls – back-up or low criticality
- Robust high speed wireless avionics comm.
- Inductive coupling w/rechargeable batteries
- Data on power lines, light, structure, liquids
- No connectors for bulkheads, avionics power
- Robust software programmable radios
- Light wt coatings, shielding, connectors
- RFID for ID, position, data, & sensing.
- Various Passive Wireless Sensing Options
- Other power & comm scavenging schemes

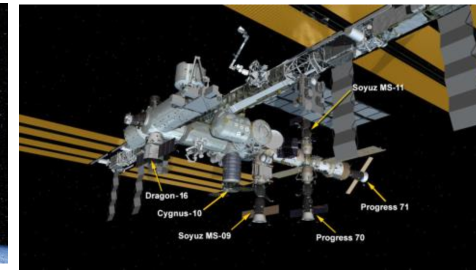
“Fly-by-Wireless” Progress

NASA/JSC “Fly-by-Wireless” Workshop	Oct 1999
USAF Reserve Report to AFRL	Nov 1999
DFRC Wireless F-18 flight control demo - Report	Dec 1999
ATWG “Wireless Aerospace Vehicle Roadmap” & ONR Wireless Mtg	Feb 2000
NASA Space Launch Initiative Meeting	Aug 2001
World Space Congress, Houston	Mar 2002
International Telemetry Conference	Apr 2004
VHMS TIM at NASA LaRC	May 2004
CANEUS 2004	Oct 2004
Inflatable Habitat Wireless Hybrid Architecture & Technologies Project:	Sep 2006
CANEUS 2006 “Lessons Learned Micro-Wireless Instrumentation”	Sep 2006
CANEUS/NASA “Fly-by-Wireless” Workshop- investigate common interests	Mar 2007
NASA/AIAA Wireless and RFID Symposium for Spacecraft, Houston	May 2007
AVSI/other intl. companies organize/address the spectrum issue at WRC07	Nov 2007
Antarctic Wireless Inflatable Habitat, AFRL-Garvey Space Launch Wireless	Jul 2008
NASA RFIs for Low Mass Modular Instr	May/Nov 2008
Gulfstream demonstrates “Fly-by-Wireless” Flight Control	Sep 2008
AFRL announces “Wireless Spacecraft” with Northrup-Grumman	Mar 2009
CCSDS Wireless Working Group – NASA & International Space Partners	Apr 2009
JANNAF Wireless Sensor Workshop	Apr 2009
Wireless SAW Symposium – Vienna, Austria	Nov 2010
JANNAF Wireless Sensor Workshop	Dec 2010
ISA-NASA-BP Passive Wireless Sensor Technology Workshop	Jul 2011
International Workshop on Structural Health Monitoring - #8	Sep 2011
JANNAF Wireless Sensor Workshop	Apr 2012
ISA-NASA Passive Wireless Sensor Technology Workshop	Jun 2012
Wireless SAW Symposium – SAWHOT – Villach, Austria	Sep 2012
ISA-NASA Passive Wireless Sensor Technology Workshop	May 2013
IEEE – Wireless for Space and Extreme Environments	Nov 2013
Wireless SAW-Symposium – Villach, Austria	Oct 2014
DOE/Future Instrumentation – NASA Passive Wireless Sensor Workshop	May 2015
World Radio Conf. approves AVSI proposal for WAIC Spectrum 4.2-4.4 GHz	Nov 2015
IEEE-NASA WiSEE Conf & Passive Wireless Sensor Workshop	Dec 2015
WiSEE2016 and Passive Wireless Sensor Workshop; also SAW-Symposium	Oct 2016
WiSEE2017 and Passive Wireless Sensor Workshop(Montreal)	Oct 2017
WiSEE2018 and Passive Wireless Sensor Workshop(Huntsville)	Dec 2018
WiSEE2019 and Passive Wireless Sensor Workshop(Ottawa)	Oct 2019

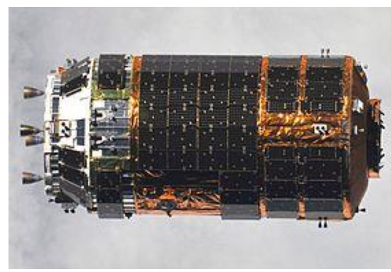
A Sampling of Spacecraft Needs

Spacecraft Fight the Cost to Orbit each Mission

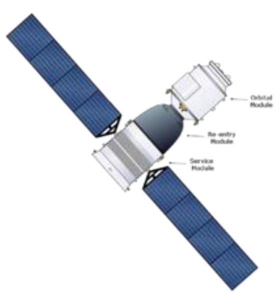
Shuttle 1981-2011 -> Soyuz -> + Dragon V2 SpaceX + CST-100 Boeing => International Space Station

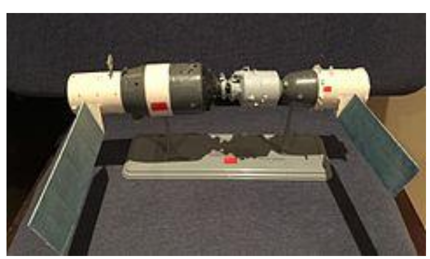


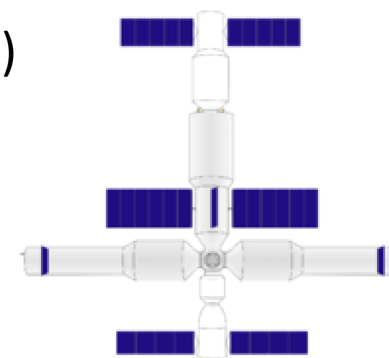
Supply: Cygnus (Orbital) + HTV (JAXA) + ATV (ESA)



Shenzhou 5-11 (1999-2016) -> Tiangong 2 (2016) => Tianzhou (2017) => Tiangong (2020?)







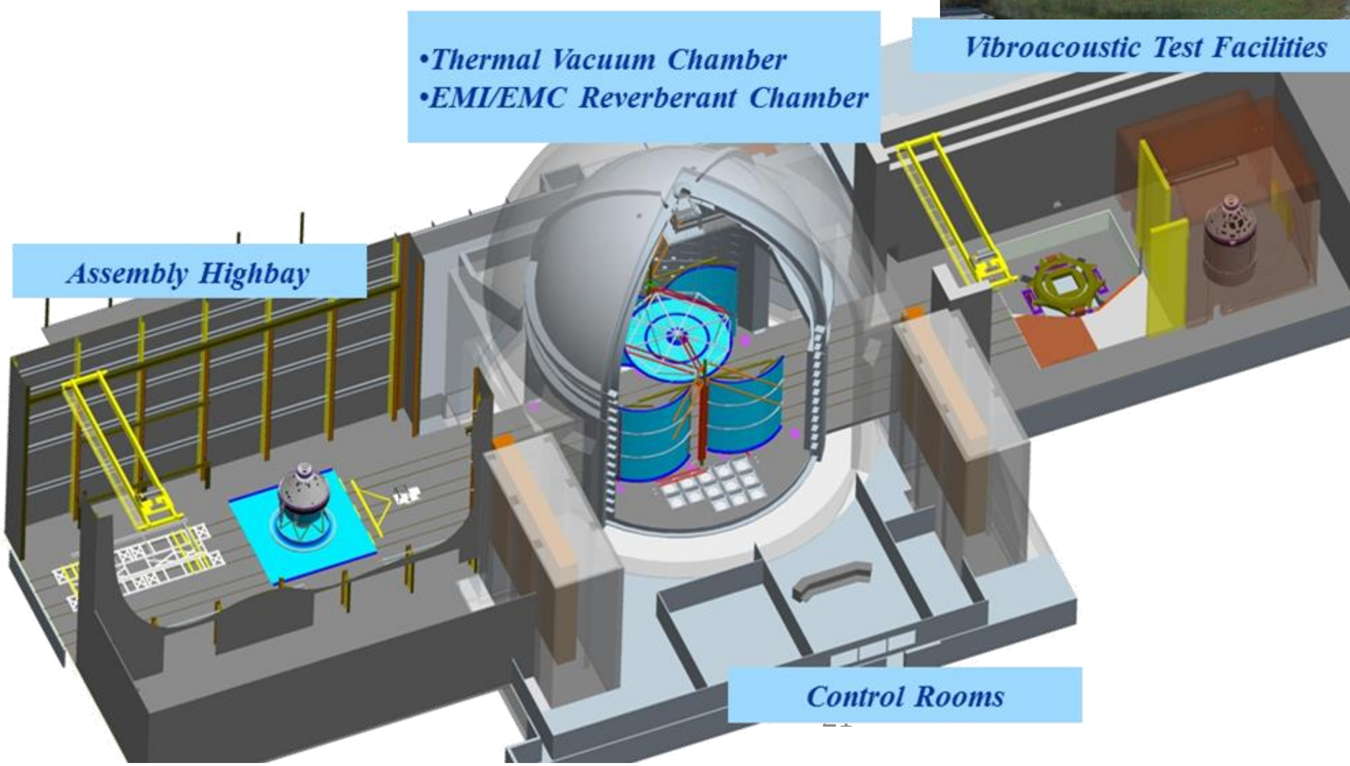
Orion Instrumentation – REALM opportunity

NASA/JSC Ray Wagner-ISIW 2017 -> Learn more at PWS Workshop S6-C5

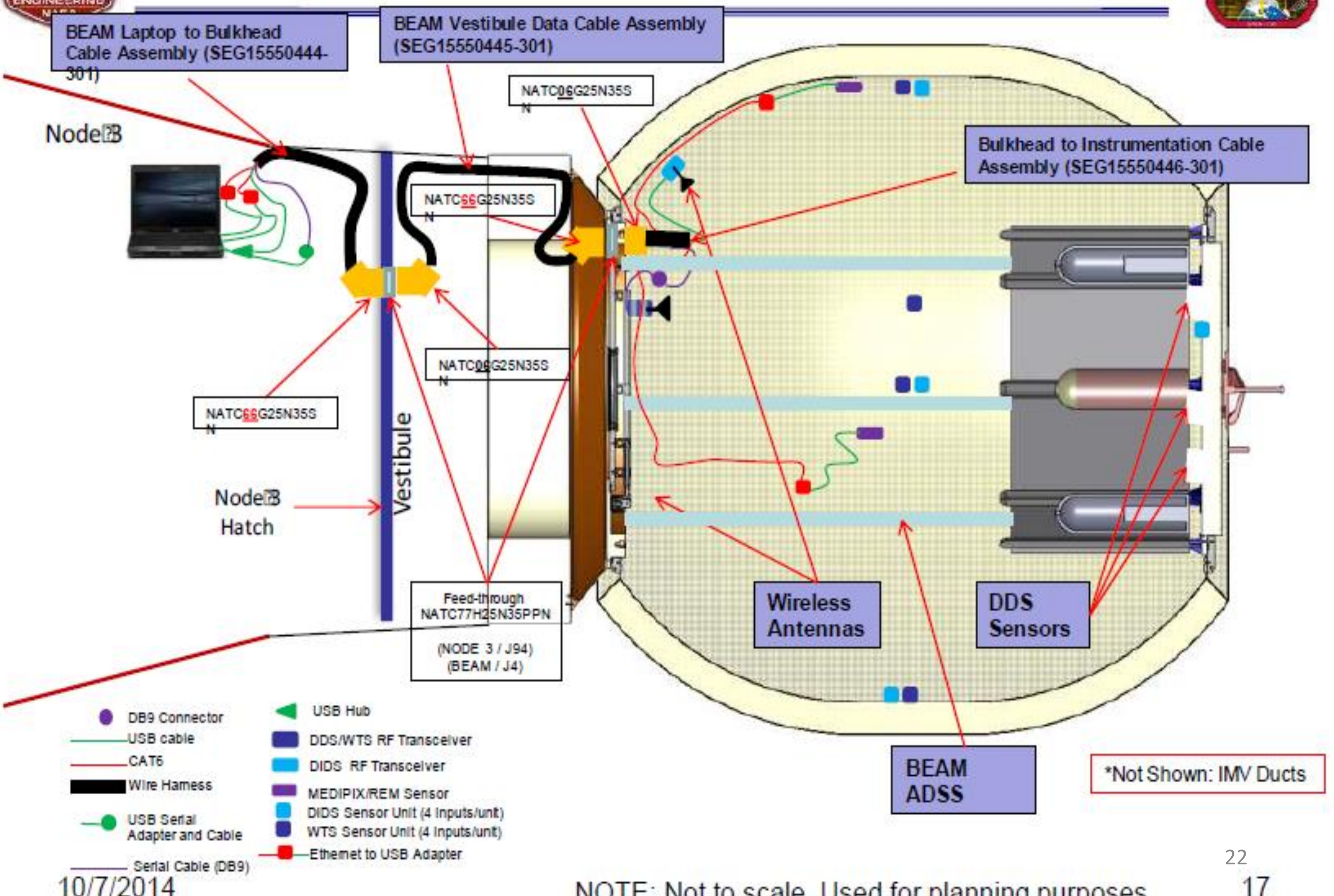
Space Power Facility (SPF)

Space Environment Testing under "one roof"

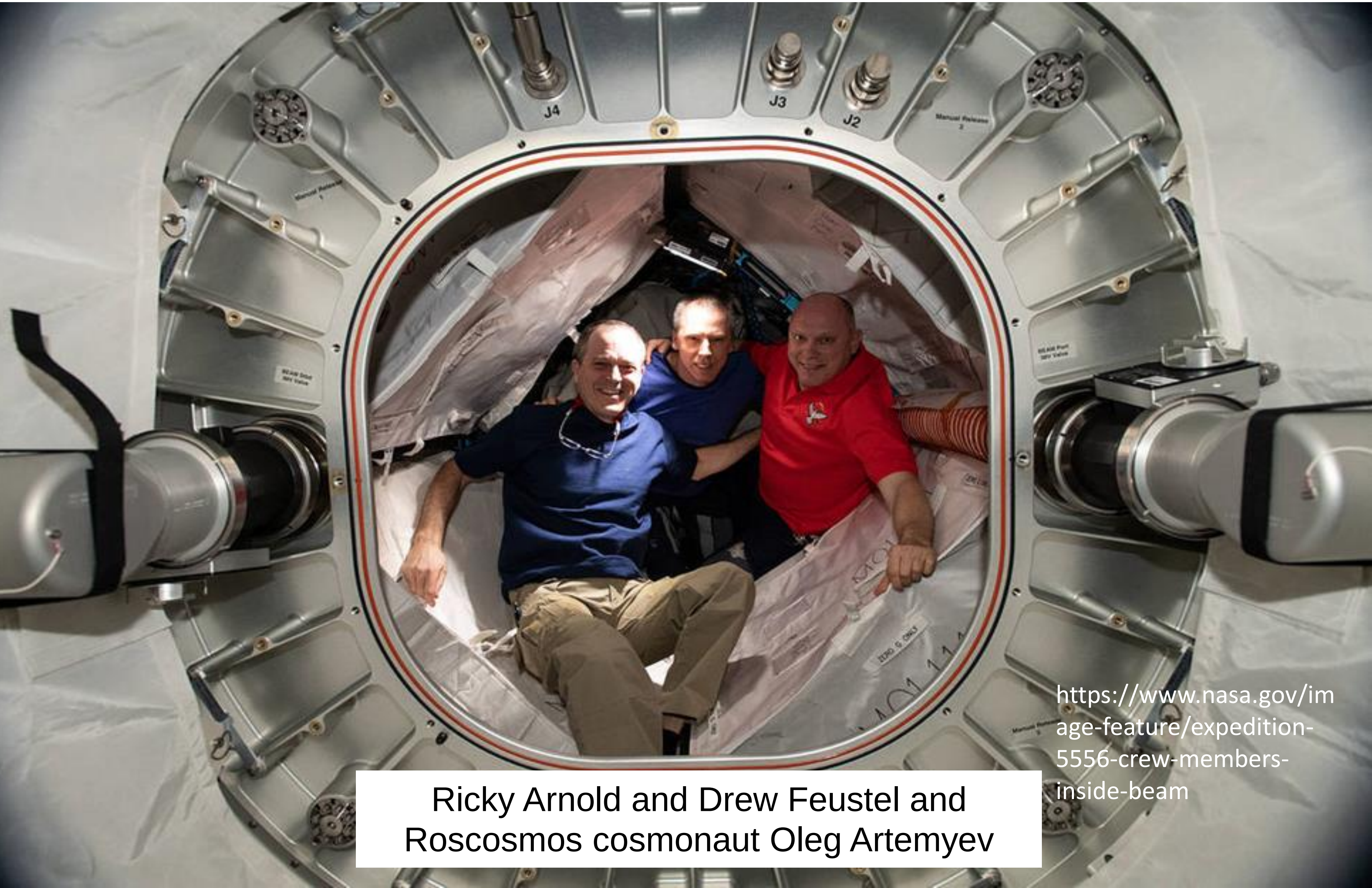
- Upper Stage (Payload) fairing separation Testing
- Thermal-Vacuum (Thermal Balancing) Testing
- EMI/EMC (Electromagnetic Effects) Testing
- Reverberant Acoustic Testing
- 3-axis Base Sine Vibration Testing
- Modal Testing
- Pyroshock (Separation Event) Testing
- Structural Static Loads Testing



Wireless & Passive Wireless on BEAM
NASA/JSC/Nathan Wells ISIW 2017



Bigelow Expandable Activity Module
April 2016 -> ?



Ricky Arnold and Drew Feustel and Roscosmos cosmonaut Oleg Artemyev

https://www.nasa.gov/image-feature/expedition-5556-crew-members-inside-beam

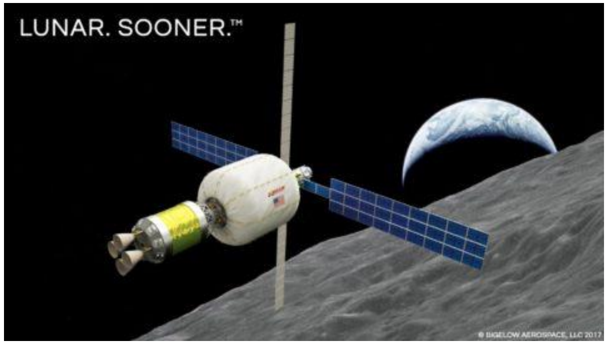
Inflatable Habitats

Bigelow BEAM on ISS
Video:
https://www.youtube.com/watch?v=Kle19Ca-P3A

Bigelow B330 on ISS and Beyond LEO:

http://bigelowaerospace.com/pages/b330/

Aerospace/Bigelow/ULA "Lunar Sooner" (2:31)
https://www.youtube.com/watch?v=jx6zWsmpXz0
https://www.youtube.com/watch?v=a62_n1zo4I0



Bigelow Aerospace illustration of lunar depot concept. Image credit: Tweet from @BigelowSpace Oct, 17, 2017.

?

Habitats beyond LEO: Some CHANGES for Human Spaceflight:

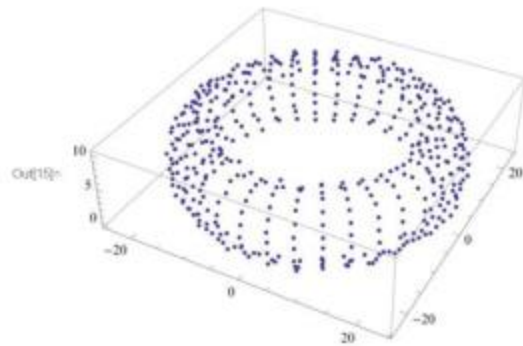
- **Long, 30year Life – got to be more modular than ISS**
- **Exposed to Radiation – Background and Bursts**
- **Expensive Trips – crew won’t get there very often**
- **Optionally manned – has to run itself “automagically”**
- **Robotic and Autonomous Inspection & Maintenance**

Plug ‘n’ Play for a Deep Space Habitat
JPL/Kim Simpson – WiSEE 2015

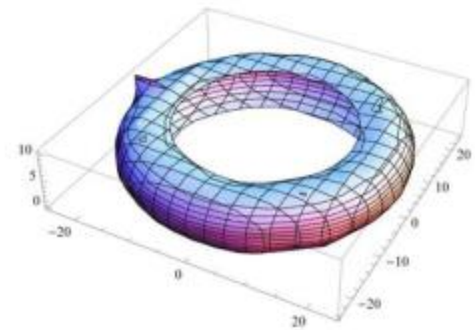
eXploration Systems and Habitation (X-Hab) 2019
Academic Innovation Challenge

Location and Temperature Passive Wireless Sensor-Tags

Univ of Maine/Ali Abedi http:\\wisenet.eece.maine.edu - ali.abedi@maine.edu



2D Shape Reconstruction

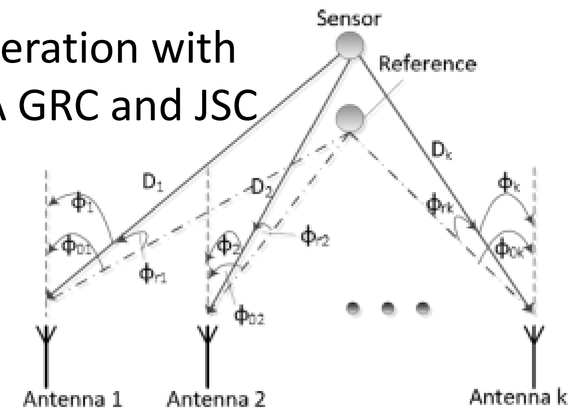


3D Shape Reconstruction

Passive SAW Tag for Location/Shape

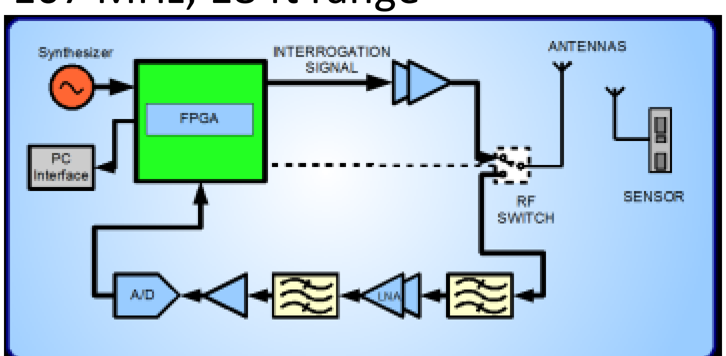
- 860-960 MHz -10 ft read range
- Passive – no battery
- EPC Global Gen 2 / ISO 18000-6C Standard
- Motorola Reader with 70 degree field of view

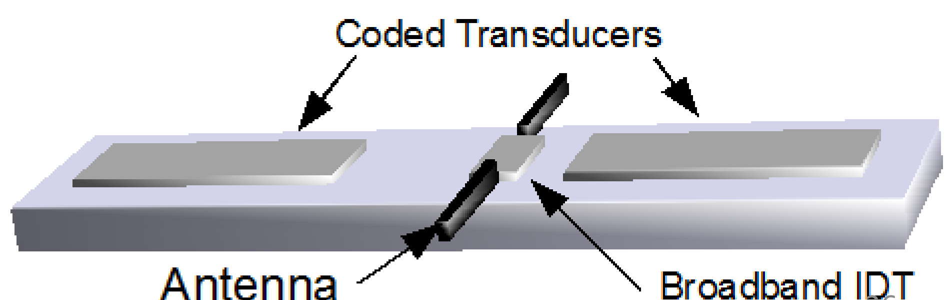
Cooperation with NASA GRC and JSC



Passive SAW Temperature Tag

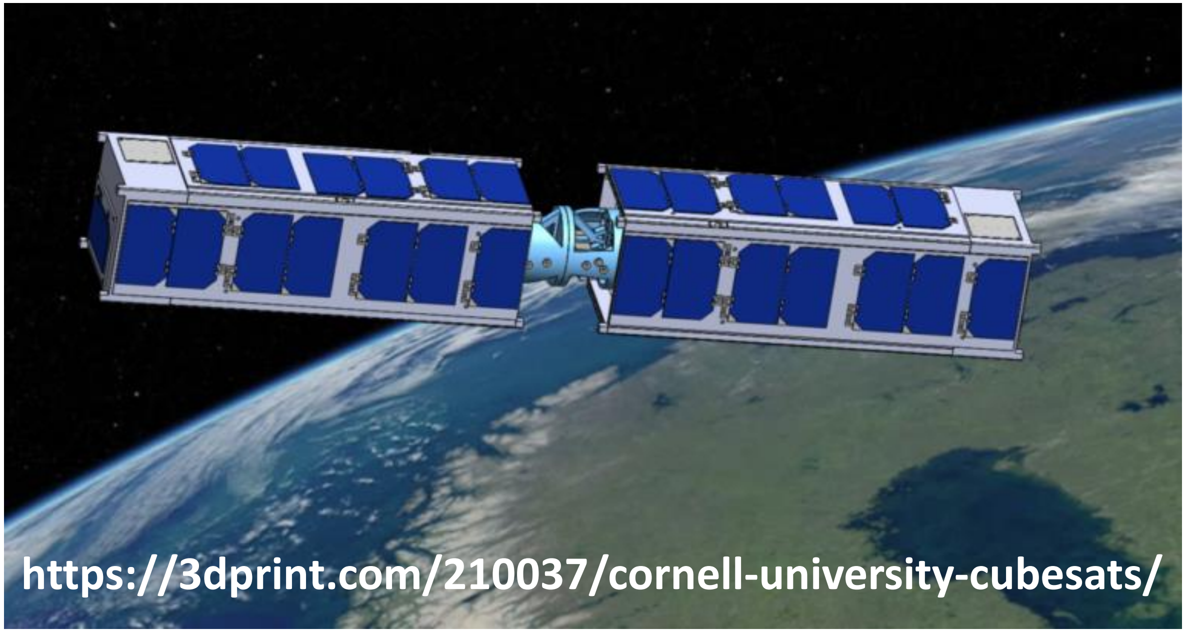
- Designed and built at Umaine/Prof Mauricio Pierra da Cunha
- 107 MHz, 18 ft range





CubeSats

- Cornell Cubesat



Why PWS?

- Internal reduction of wires/connectors – failure points
- Interrogation and check out of cubesat
  test, after integration, on launch vehicle
- Cubesat interrogation of deployer/environment
- 3D Print Cubesat

Chip-Sats:

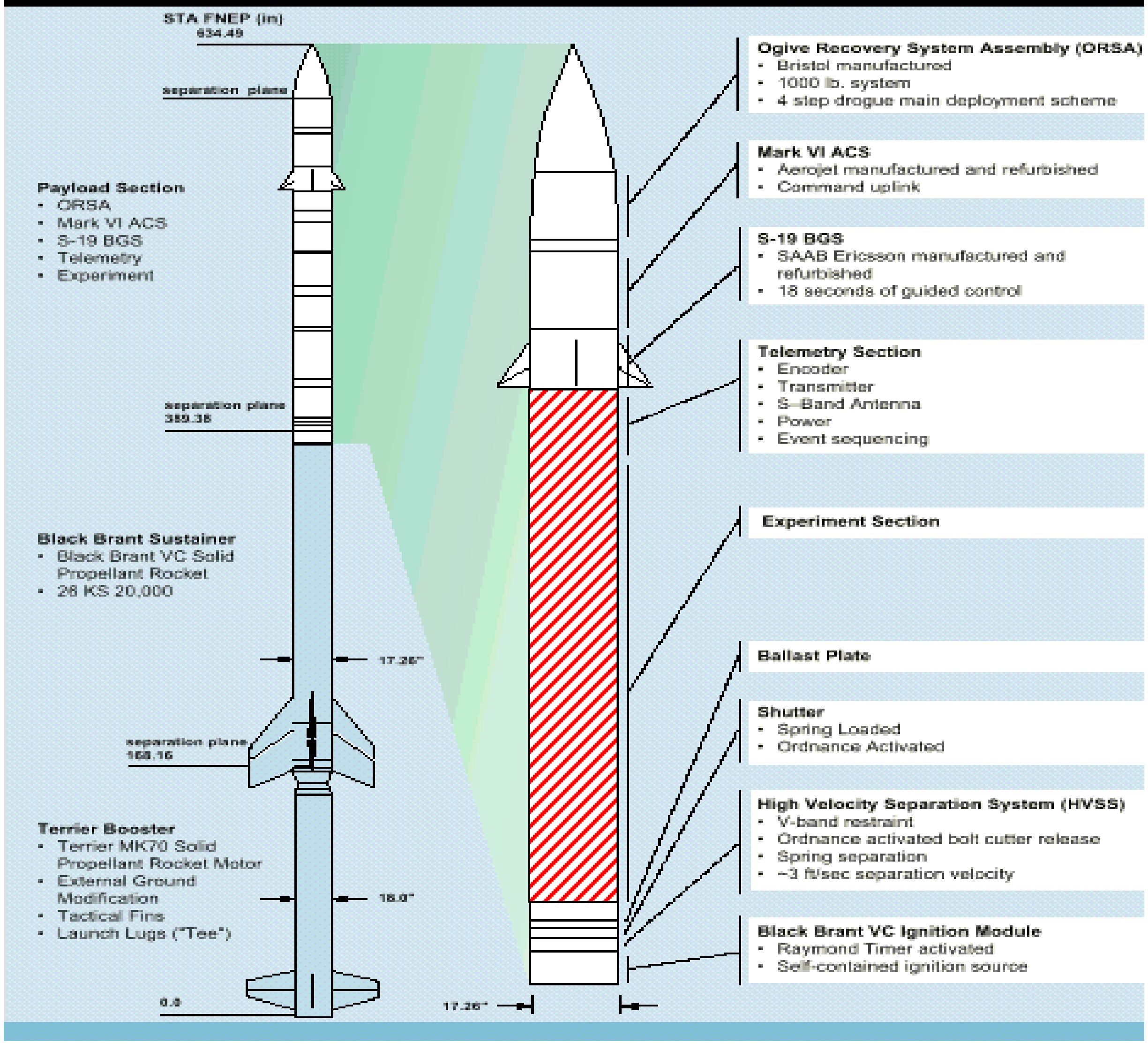
https://3dprint.com/210037/cornell-university-cubesats/

http://www.3ders.org/articles/20180410-nasa-to-launch-cornell-labs-2-3d-printed-cubesats-into-space-in-2019.html

The "Sounding Rocket"

Brian Hall Wallops
WiSEE 2015

Exhibit 1.A.0-1. Representative NSRP Sounding Rocket Vehicle



The Black Brant IX MOD I (Terrier MK70 – Black Brant VC) is the reference vehicle used for discussion purpose.

Atmospheric Explorers:

VEXAG – Venus Exploration Analysis Group

https://www.lpi.usra.edu/vexag/

Venus Aerial Platforms Study - 2017

"Altitude-controlled balloons represent a 'sweet spot'"

(for obtaining data of optimal data value)

- **Long Duration**
- **1 Atmosphere at ~ 30km – "reasonable" temps**

<u>AFIT Passive Vacuum Lighter than Air Vehicle</u>

- **Passive Wireless Sensors – lightest payload**
- **"Ping" from Space or Balloon**
- **Need Longer Range PWST**

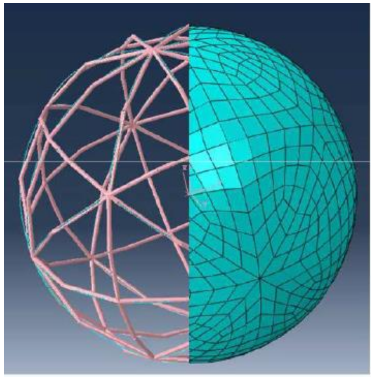
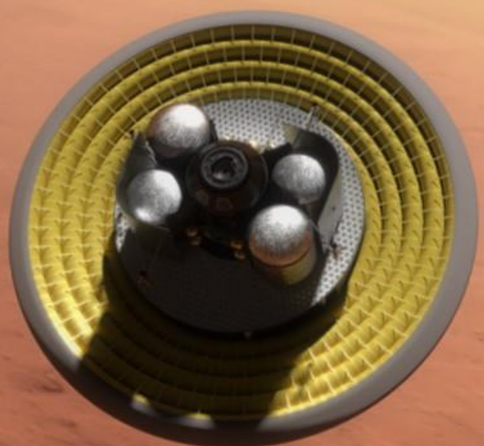
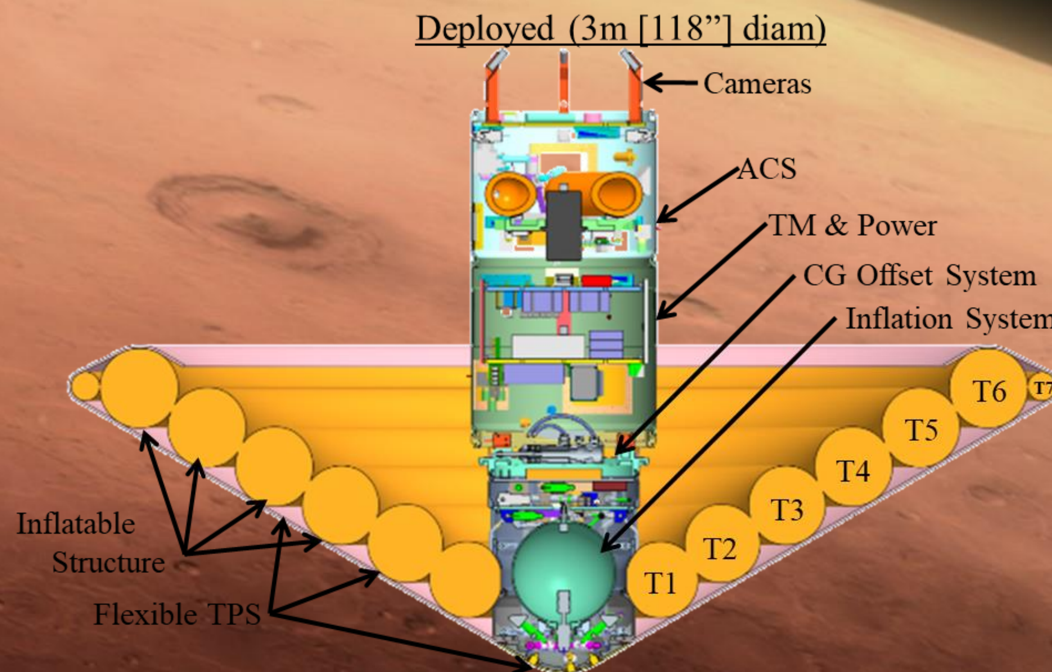


Figure 2.6. Cutaway of frame structure with attached skin

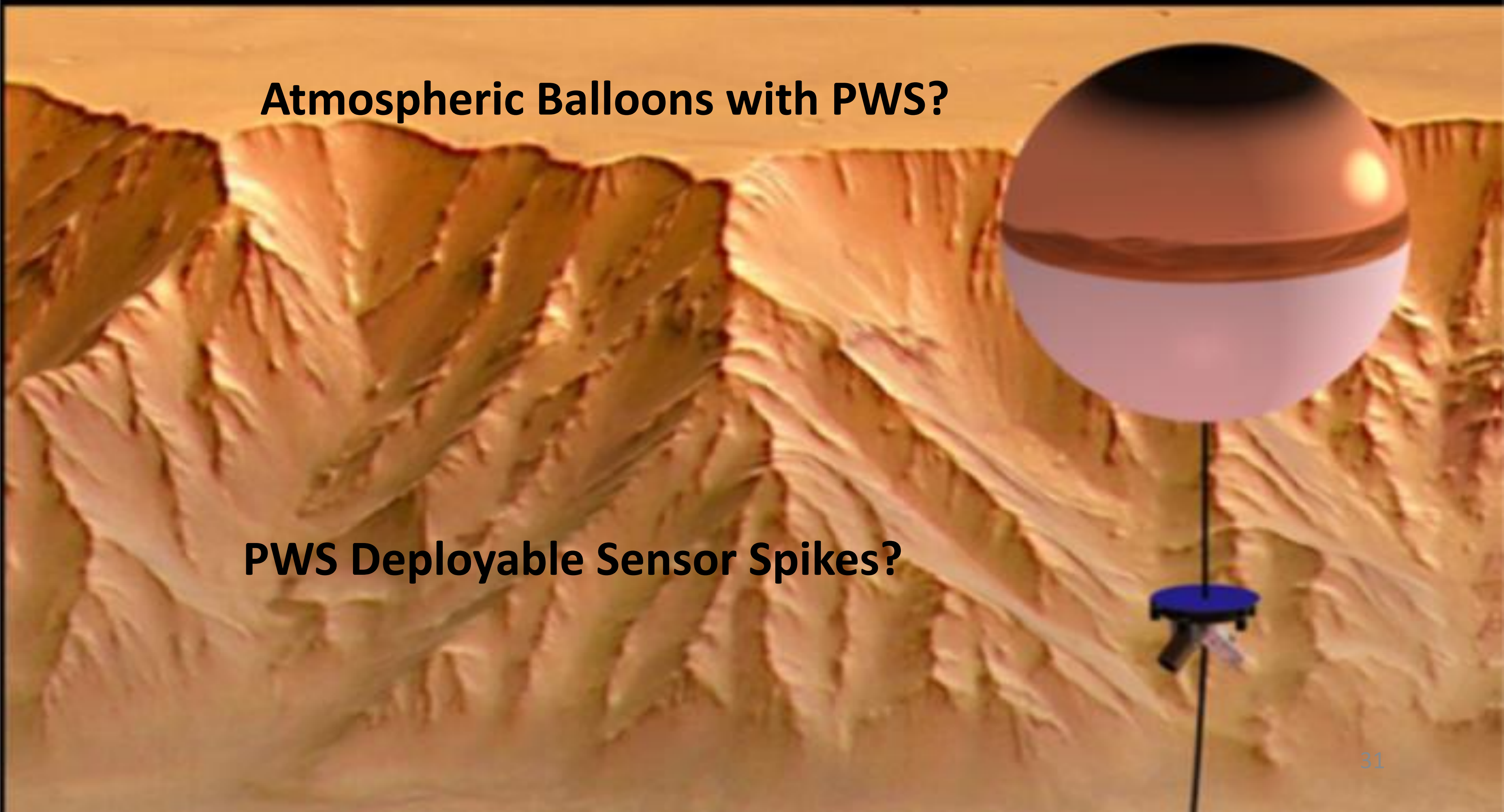
Robert Dillman, NASA Langley Research Center
December 15, 2015

Inflatable Reentry Vehicles and Instrumentation Needs





PWS for Mars Spacecraft?



One-on-One Table – Thursday 10:50am – Sign-up!!

Or Contact:

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