# Real-World Experience in Wireless Instrumentation and Control Systems

Presented by: Karl Kiefer
Invocon, Inc.
19221 IH 45 Conroe TX 77385
Phone: 281-292-9903
kiefer@invocon.com

CANEUS “Fly-by-Wireless” Workshop
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# Invocon, Inc.

- Founded in 1985
- Located in Conroe, Texas
- Veteran-owned Small Business
- Currently employs 45 Electrical Engineers, Technicians, Computer Science, and Administrative personnel.

*Invocon's core activities revolve around research and development of precision instrumentation and communication solutions for demanding applications in extreme environments.*

# Early concepts of wireless data acquisition

- 1968 Army unattended ground sensor program
  - Operational advantages
    - Quick installation
    - Accurate data
    - Real time data
    - Remote acquisition (no human assets at risk)
  - Tactical results
    - Identify targets
    - Track the targets
    - Initiate accurate fire on the targets
    - All without human assets at risk
  - Methodologies for success
    - Matching sensors to tactical situations
    - Diverse suite of sensor technologies
    - Diverse communications capabilities
    - Application to “high value” tasks
    - Command emphasis on imaginative applications
    - No standards to satisfy

# Prospects for a commercial wireless business

- Perceived advantages
  - More accurate data
  - More timely data
  - Quick installation/removal
  - Access to moving data sources
  - Battery operation
  - Smart relay networks
  - Remote acquisition

# Business Issues

- Early market was very small
- Cost of sales high
- No single application provided sufficient revenue/volume to boot-strap a company
- Successful applications seldom repeated
- Wireless “risk” difficult sell
- Data rate technology slow

# Business Plan

- Focus on high value applications
- Identify customers with repeat business potential
- Train a systems engineering staff to respond quickly and cost-effectively to diverse applications
- Identify applications which can only be serviced by wireless or SOA wired applications
- Introduce high speed robust radios to wireless data acquisition

# Wireless Advantage Summary

- No connectors
- No “hard” paths to route or secure
- Minimum cost retrofit
- Minimal documentation
- Trouble shooting reduced
- Reduced repair time
- Increased long term reliability
- Weight reduction

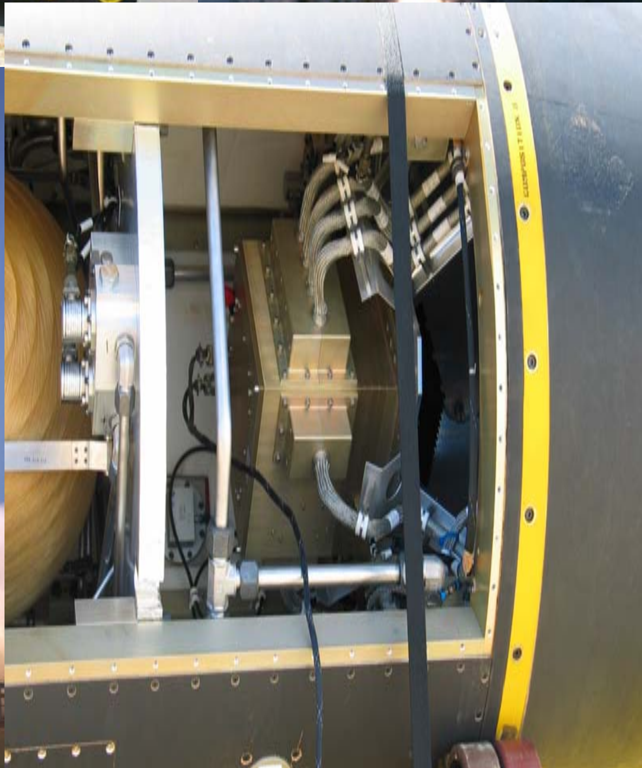
# Specific Design Advantage Examples

- Cessna 310R (General Aviation Aircraft)
  - Weight reduction - 90 lbs, range increase - 10%
- NASA APEX (High altitude research glider)
  - Weight reduction - 130 lbs., (total airframe weight - 750 lbs.)
- SH 60 - (Military helicopter)
  - Total wiring weight estimate (wire and connectors) - 627 lbs., (15% of wiring is power related)
  - Assuming only a 50% wire reduction - weight savings 267 lbs.
  - Performance delta - one more passenger or 35 gallons of fuel.

# Invocon, Inc. Capabilities

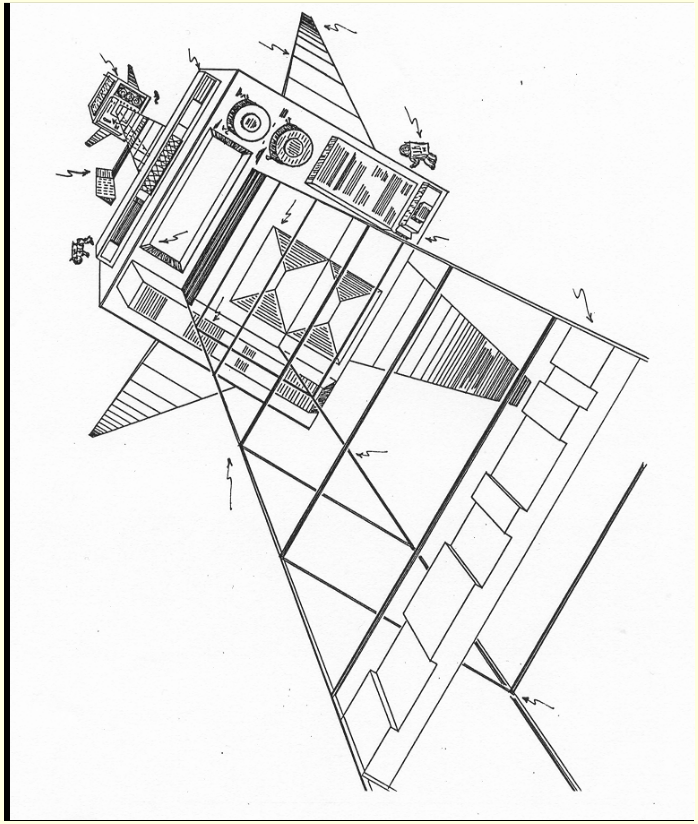
- Aircraft / Spacecraft Test and Evaluation
- Mechanical Condition-Based Maintenance
- Missile-Defense
- Civil Structural Monitoring

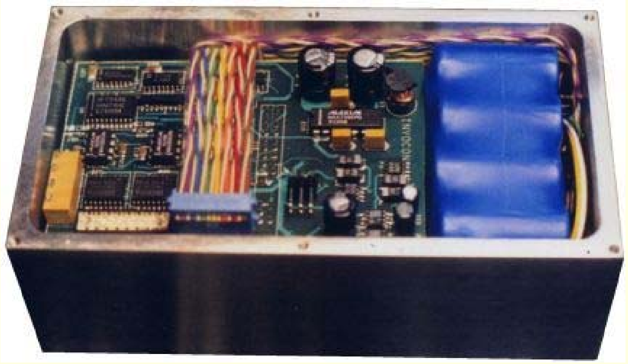
- Invocon Flight Systems:
  - Structural Analysis ISS
  - 20 Shuttle flights, including 12 unique systems
  - 4 systems aboard the International Space Station
  - 7 Flights – Lethality Assessment Navy/MDA Target Missiles



# Initial Work –
## Sensor Control and Acquisition Telecommunications (SCAT)

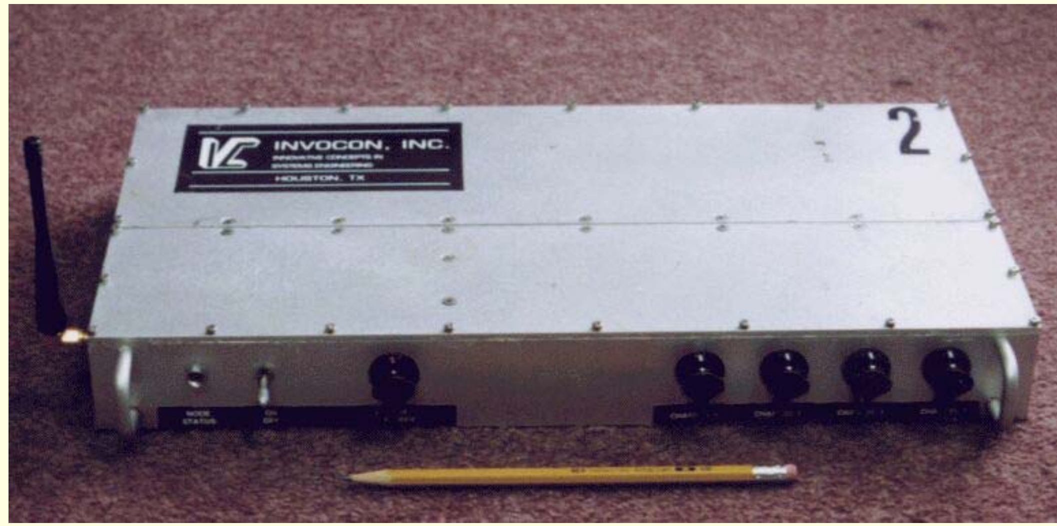
- 1995 Small Business Innovation Research Program for NASA JSC
  - Spread Spectrum technologies introduced to overcome multi-path environment
  - Low and high-rate data acquired in near real-time
  - Asynchronous relaying network implemented due to insufficient line-of-sight





# WIRELESS DATA ACQUISITION - FHWA STATE OF THE ART

## 1996




- WEIGHT - 16 LBS
- 16” x 8” x 2”
- SMART NETWORK TECHNOLOGY IN INFANCY
- SYNCHRONIZATION BETWEEN NODES ˜ 50 µs
- 4 CHANNELS / NODE
- MINIMAL PROCESSING CAPABILITY
- LIMITED USER INTERFACE
- 900 MHz DIRECT SEQUENCE SPREAD SPECTRUM @ 121 KBITS / SEC

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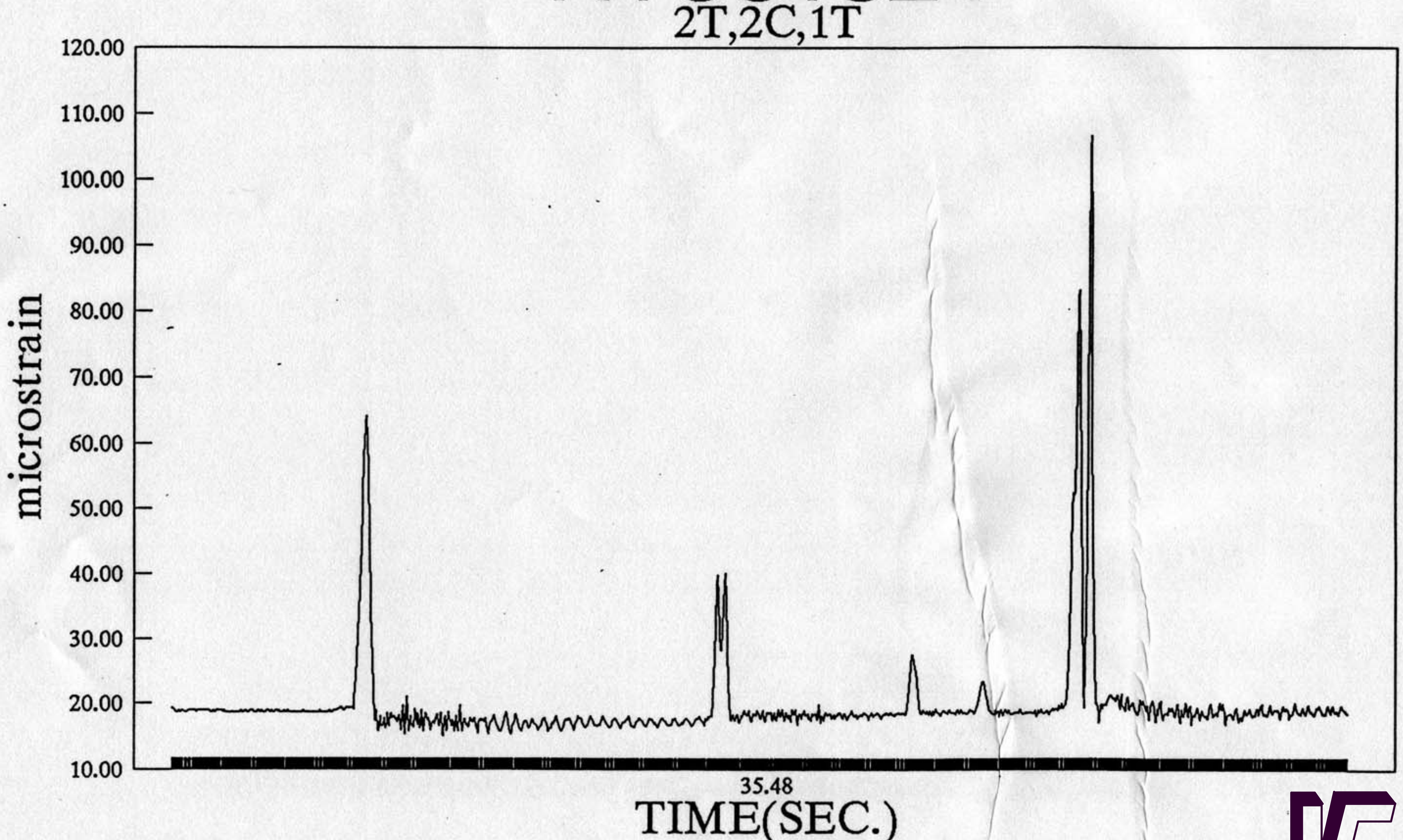
# N1C31324

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# RCSS Plume Impact Force Recorder

- Wake Shield plume measurement experiment
- Quick reaction design and flight of pressure impact measurement
- Minimum impact to Wake Shield Facility Spacecraft
- Two months elapsed time from contract to dellivery

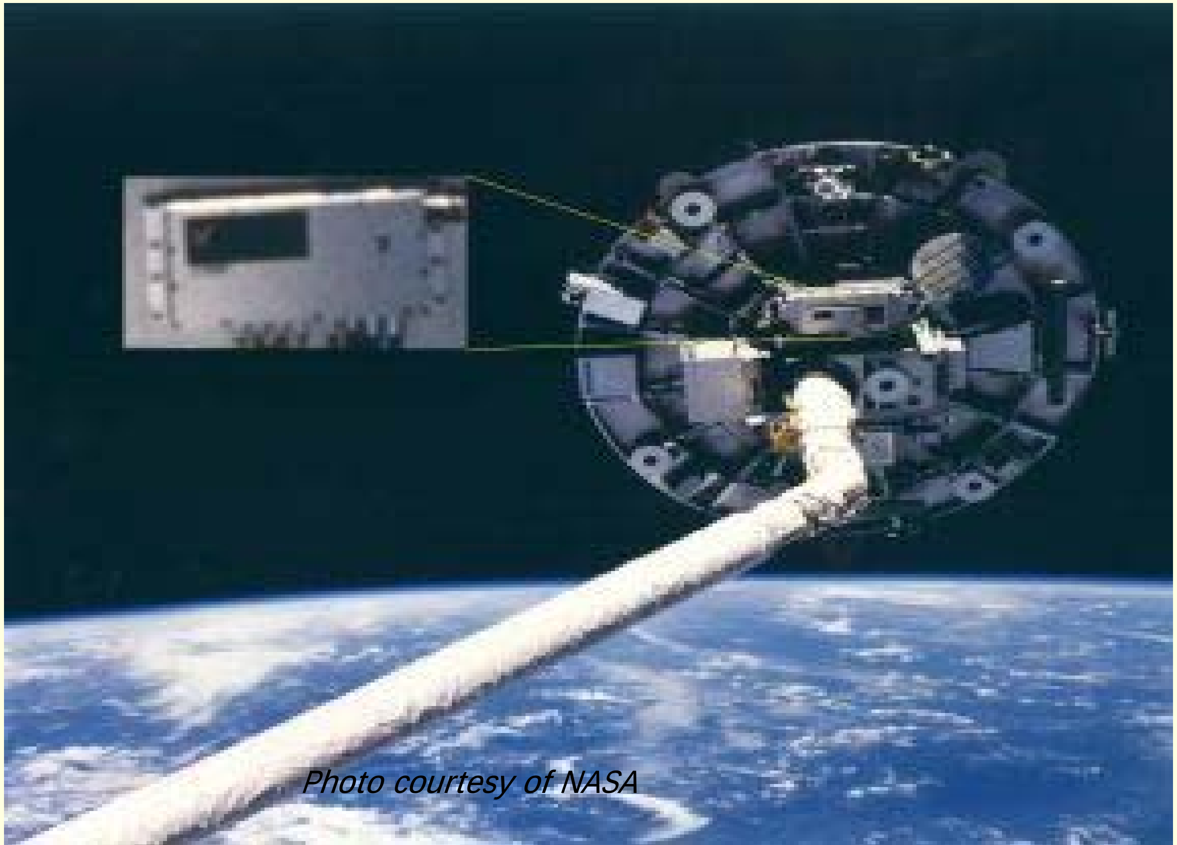
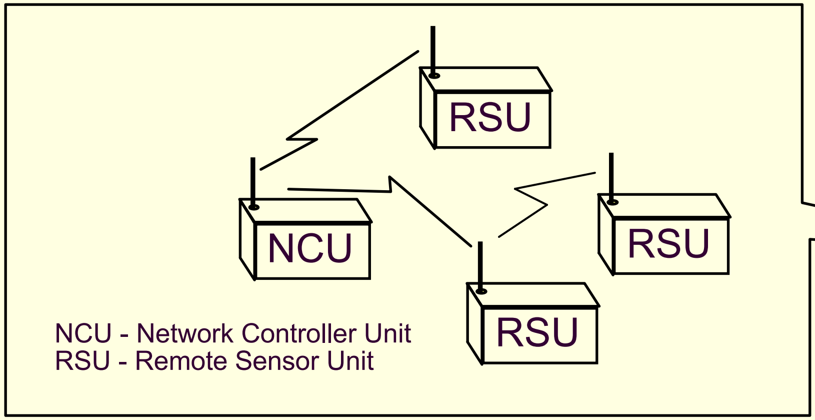
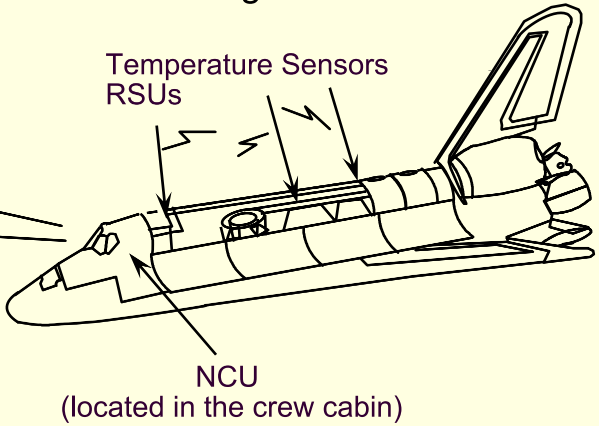


*Photo courtesy of NASA*

# Wireless Data Acquisition System - DTO

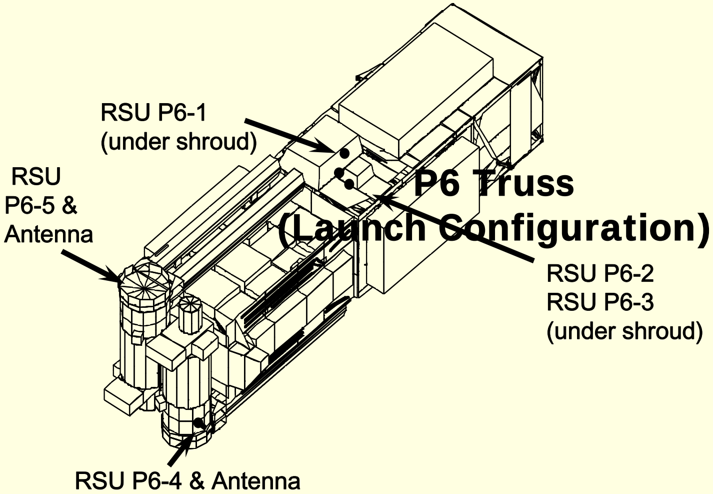

- 3 Remote Sensor Units (RSUs) each with 8 RTD channels and 1 Network Control Unit (NCU)
- Dynamically reconfigurable network
- STS-83 (4/97) and STS-94 (7/97)
- RSUs located on longeron rails in Payload Bay.  NCU in crew compartment.
- 100mW DSSS Proxim WLAN module at 115kbps
- RF testing showed good reception throughout flight deck and mid-deck
- Relays occasionally required with NCU in mid-deck
- Line of Sight NOT REQUIRED



# Shuttle Wireless Instrumentation System

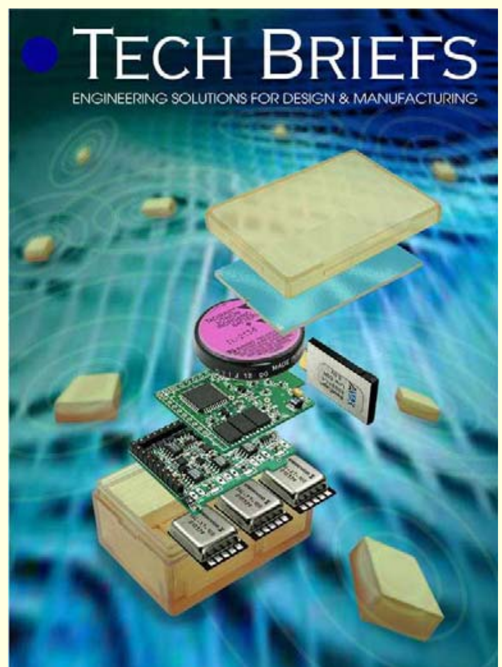
- Launch to Activation thermal monitoring of ISS modules – ISS flights 3A (Z1) & 4A (P6)
- 200mW 2Mbit/sec 900MHz WLAN module
- Excellent coverage throughout module extraction and installation on ISS despite no LOS – relays seldom occurred

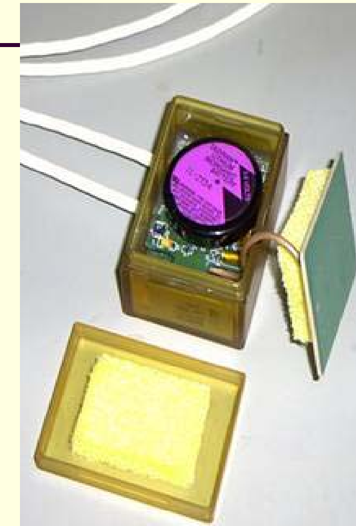




# Micro-Strain Gauge Unit (MicroSGU) and Micro-Triaxial Accelerometer Unit (MicroTAU)

- Radio Characteristics
  - ¼mW 916MHz low-power narrowband transceiver module
  - Omni-directional Patch Antenna
- Data Acquisition
  - Multiple channel
  - 1Mbyte data memory
  - Fully self-contained
  - RF configuration, synchronization, and downloading
- Synchronization via RF
  - Master – Multiple Slave configuration
- Triggers
  - Real-time clock
  - Primary data channel
  - Auxiliary trigger sensor (e.g. pressure)
  - Multiple event capability



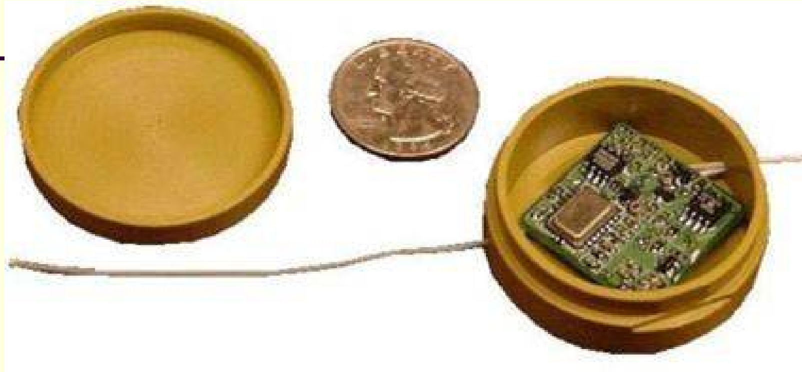



*Micro-Strain Gauge Unit*
*7 Shuttle missions on SSME Struts since 12/01*

*Micro-Triaxial Accelerometer Unit*
*installed on MPLM – 2 Shuttle Missions since 12/01*

# MicroWIS Temperature Transmitters

- Newly designed MicroWIS XG
  - Reduced size
  - Water resistant
- The first MicroWIS flight system
  - Low-power narrowband radio module
  - External RTD and internal temp channels
  - Asynchronous data transmission with random back off retransmissions
  - 20 year life with C-cell battery
- Multiple flights, including Joint Airlock on ISS flight 7A
  - Decision to use came L-2 months
  - Good RF coverage in Payload Bay, partial blockage due to Orbiter Docking System (ODS)
  - TDMA network (>60 units at 1 sample per second)



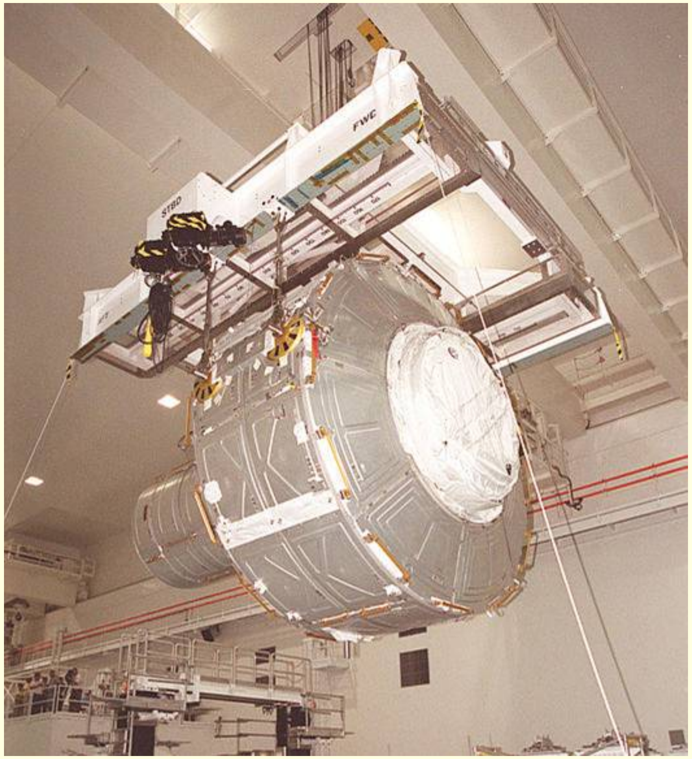
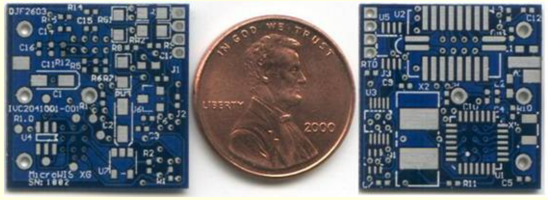
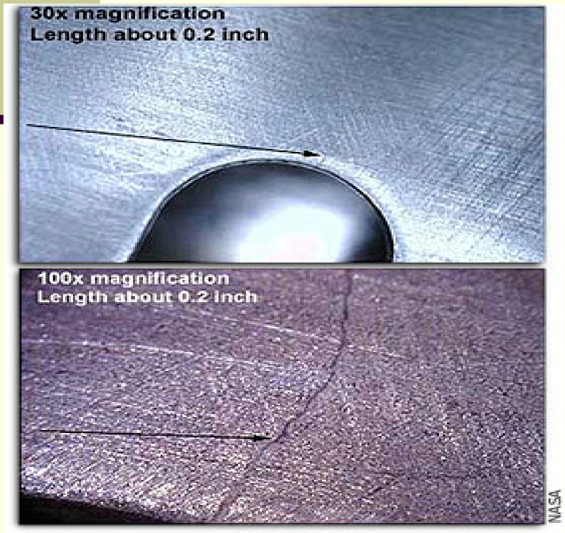


*Photo courtesy of NASA*



# Wideband MicroTAU


- High-cycle fatigue suspected cause of cracks in Shuttle Main Engine (SSME) flow-liners
- System will monitor vibration environment during entire launch sequence
- Designed, manufactured, qualified for flight, and installed in 4 months
- System Enhancements
  - 20K samples/second
  - 128Mbyte Flash memory
  - External cryogenic piezoelectric accelerometers
  - USB interface for faster downloads post-mission





*Photos courtesy of NASA*

# Micro-gravity Systems

- # IWIS / EWIS

  ## Internal / External Wireless Instrumentation System

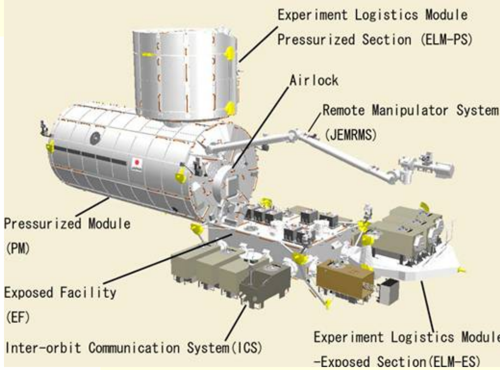
  For Space Station Structural Impulse Response Analysis

  Launched on ISS assembly flight 4A

- # MMA

  ## Micro-gravity Measurement Apparatus

  For "Kibo" Japanese Experiment Module Pressurized Module Micro-gravity Monitoring

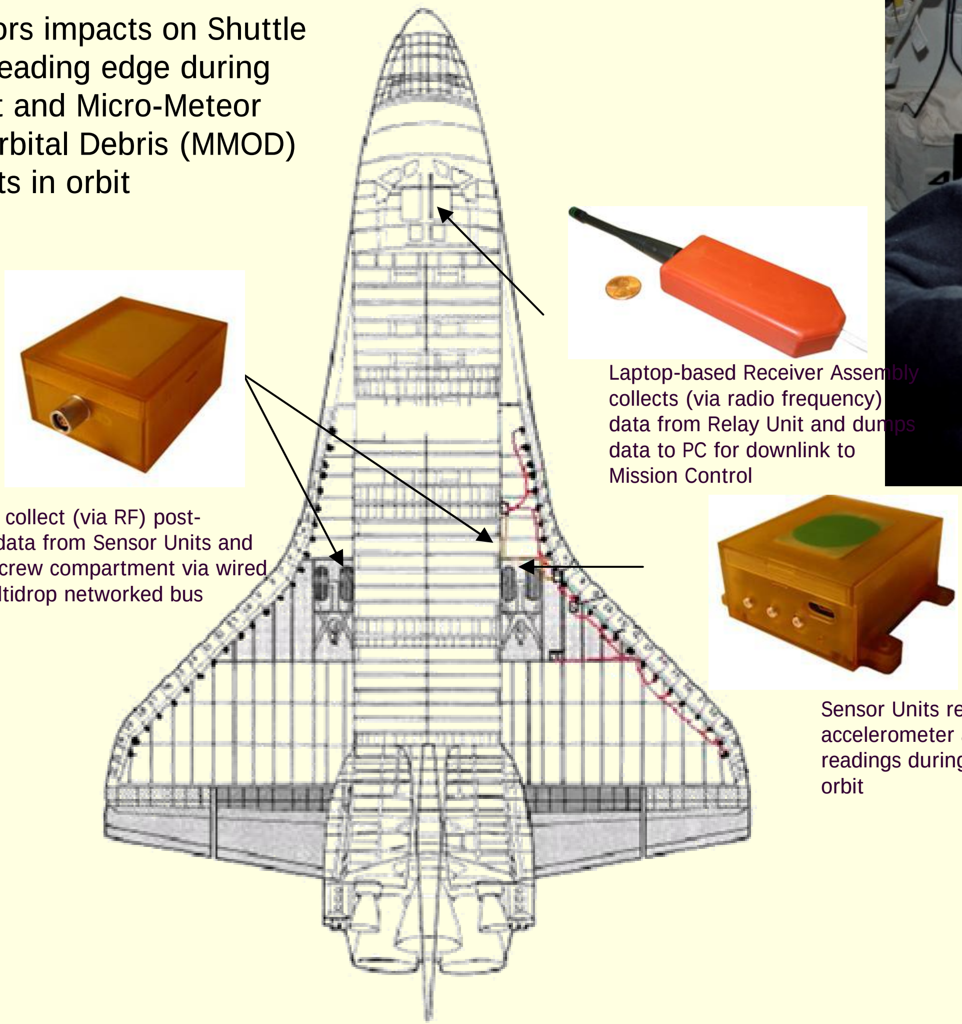



*Courtesy of NASDA*

- *Micro-g resolution (18bits)*
- *900MHz DSSS WLAN Module*

# Wing Leading Edge Impact Detection System

Monitors impacts on Shuttle wing leading edge during ascent and Micro-Meteor and Orbital Debris (MMOD) impacts in orbit

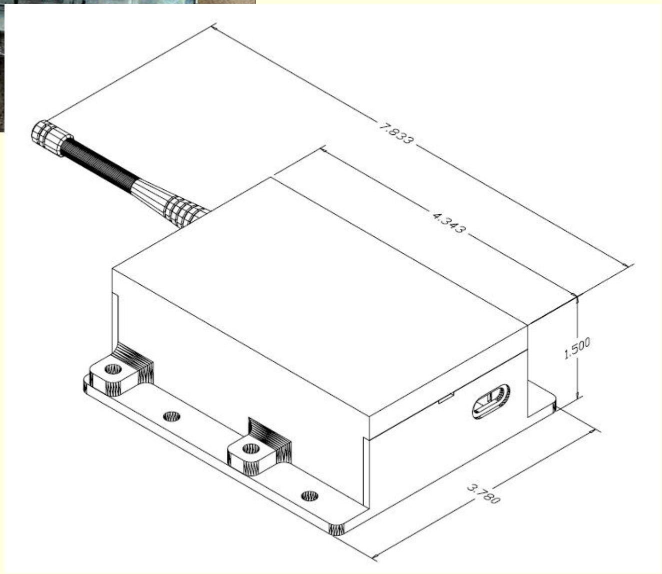


Relay Units collect (via RF) post-processed data from Sensor Units and transfer to crew compartment via wired RS-485 multidrop networked bus

Laptop-based Receiver Assembly collects (via radio frequency) data from Relay Unit and dumps data to PC for downlink to Mission Control

Sensor Units record and post-process accelerometer and temperature readings during ascent and while on-orbit

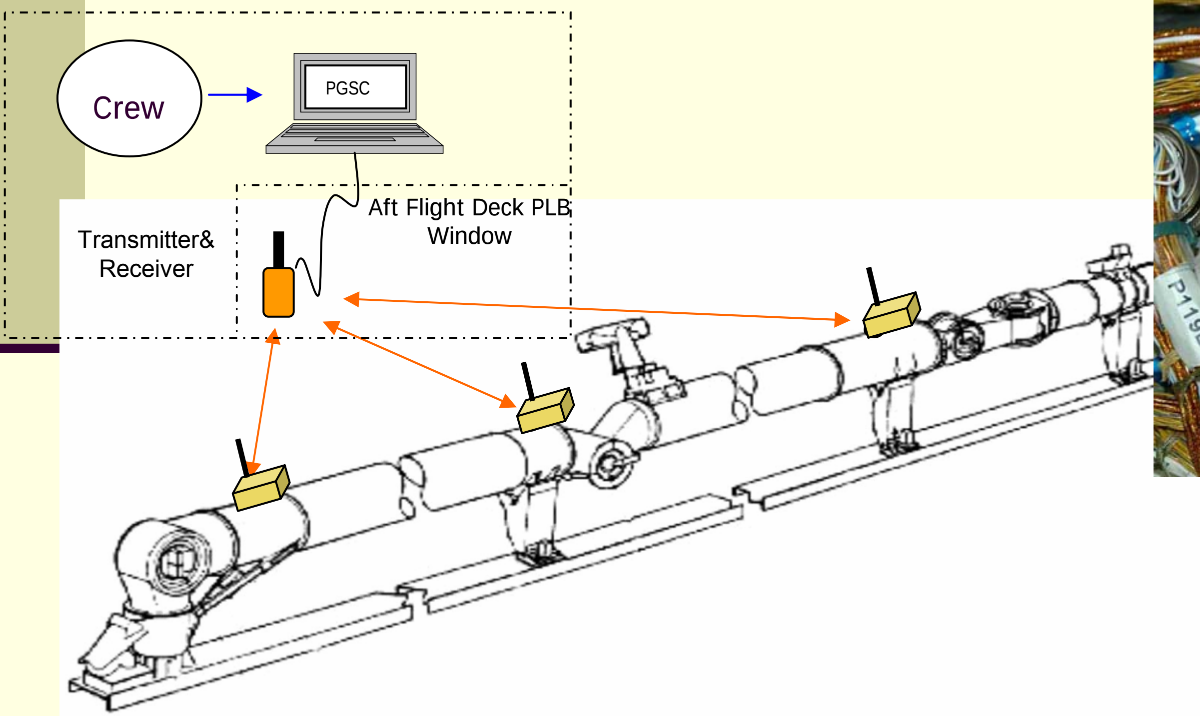
# Shuttle Rollout System

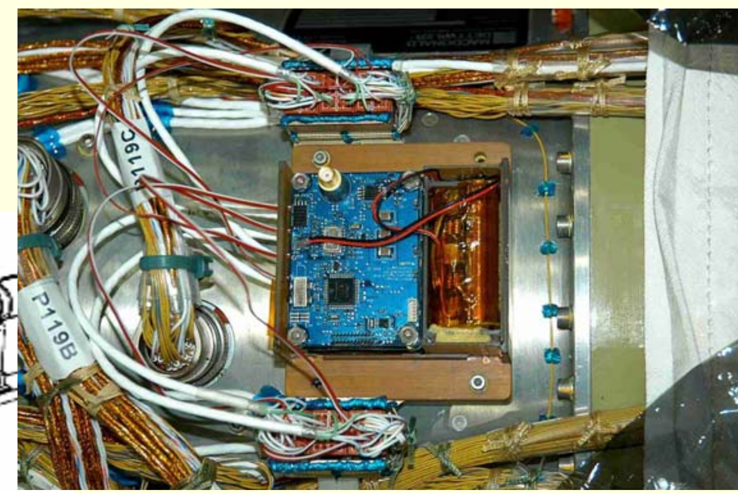



- Enhanced Wideband MicroTAU based
- Internal Triaxial Accelerometer
  - No external wires
- Up to 10 hrs of recording time at 512 samples per second.
- Colibrys MS8000 series DC MEMS Accelerometers
  - High accuracy
  - 100Hz bandwidth
- Synchronized between multiple wireless sensors to within ±4μs.
- Flexible base station design with relaying synchronization and IRIG timing

# Wireless Strain Gauge Instrumentation System

- A Wireless Strain Gauge Instrumentation System (WSGIS) is installed for STS-121 to monitor the structural loads within the mechanical arm portion of the Shuttle Remote Manipulator System (SRMS) during flight operations.
- The instrumentation system will monitor RMS structural loads through the measurement of RMS material strain at three locations (cross sections): the Shoulder, Elbow and Wrist Pitch/Yaw/Roll Electronic housings as shown below.

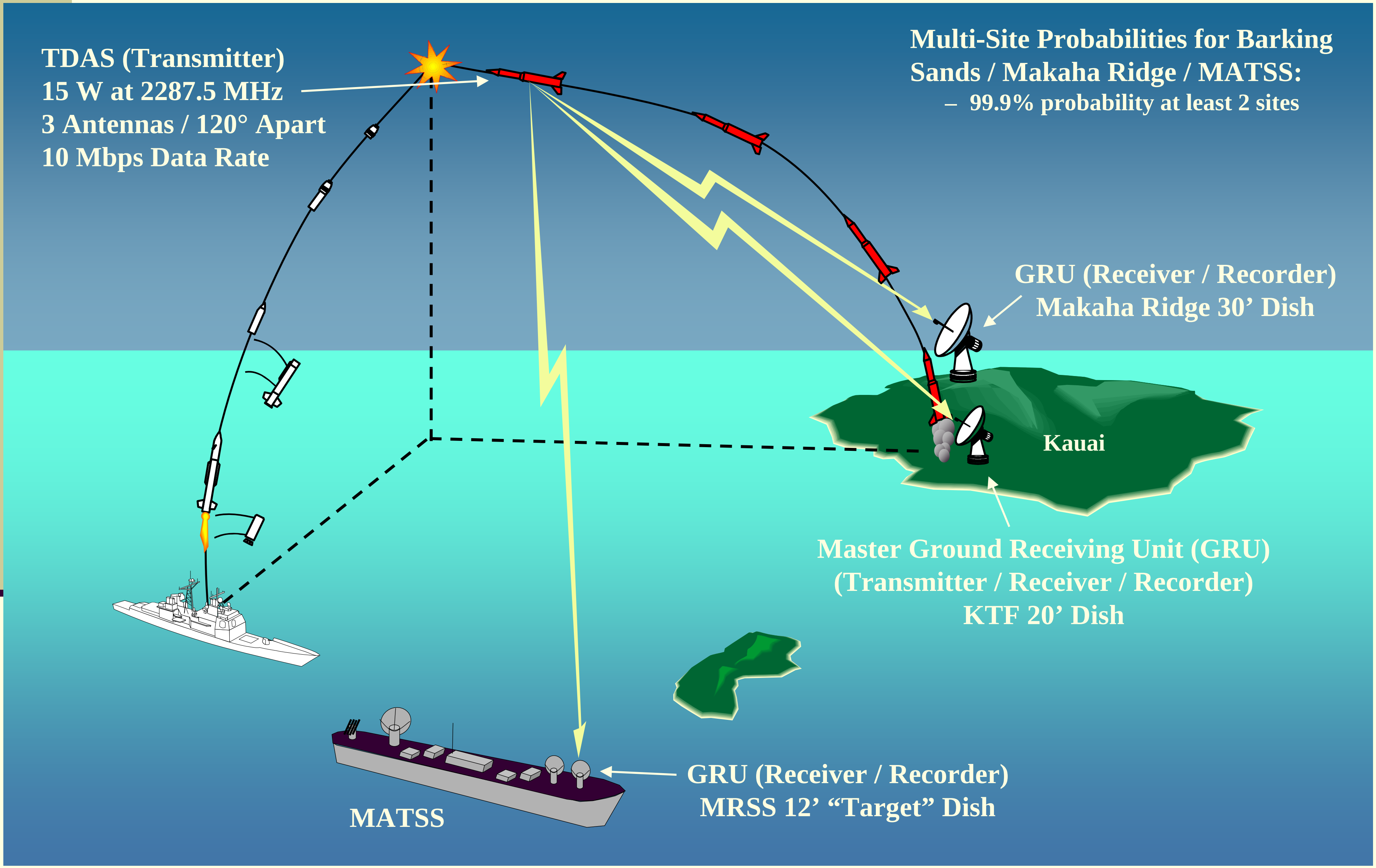


# High Speed/Low Latency Air to Ground Link

- Under a U.S. Navy-sponsored project, Invocon has developed the Target Data Acquisition System (TDAS) for high-speed penetration and lethality measurements on missile intercept programs.
  - Measures the response of a grid of up to 256 coaxial wires that are excited with a digital pulse every 160 nanoseconds.
  - Determines the wire numbers of all wires broken during each 160ns period.
  - Condenses and encodes 6.4 billion bits per second, and telemeters this data to land or sea-based Ground Receiving Units (GRUs) is at a rate of 10Mbps using DQPSK modulation techniques.

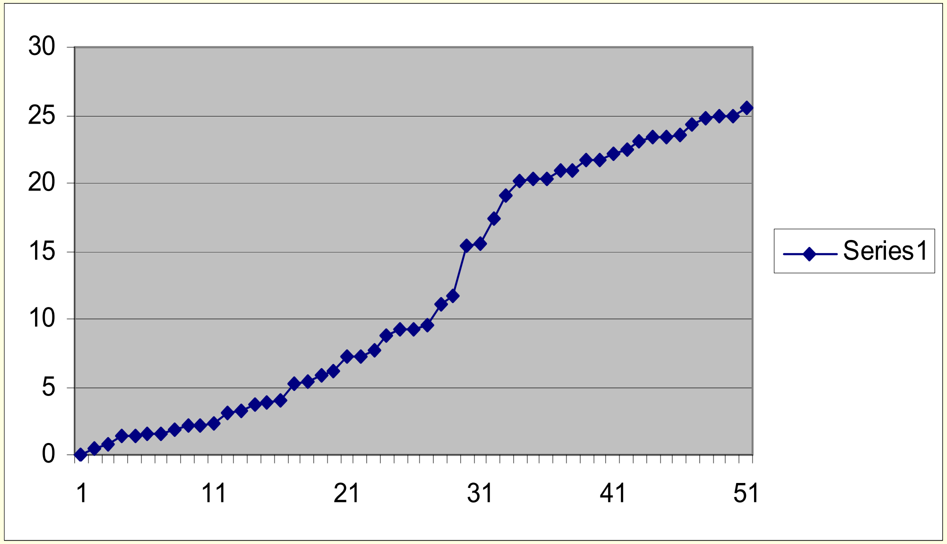
# CONCEPT OF OPERATIONS:  PMRF



# INITIAL PENETRATION RATE ANALYSIS (relative)

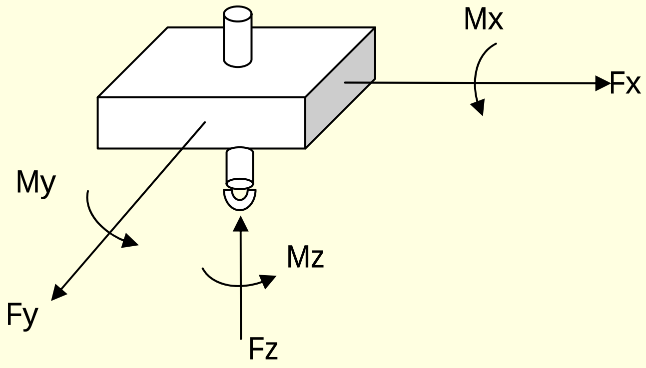
- X axis = wire breaks
- Y axis = time in usec

- 27 wire breaks in 10 usec
- 6 wire breaks in 10 usec
- 18 wire breaks in 6 usec
- Initial estimate – target detonation started at 33 usec after first wire break

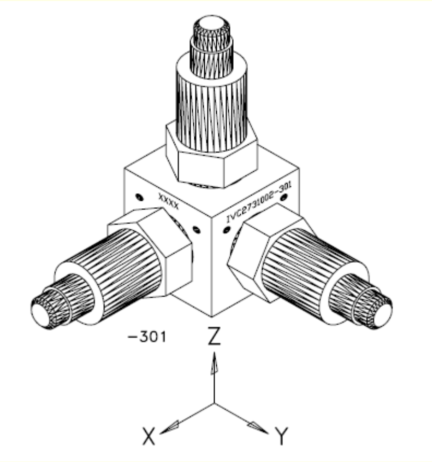


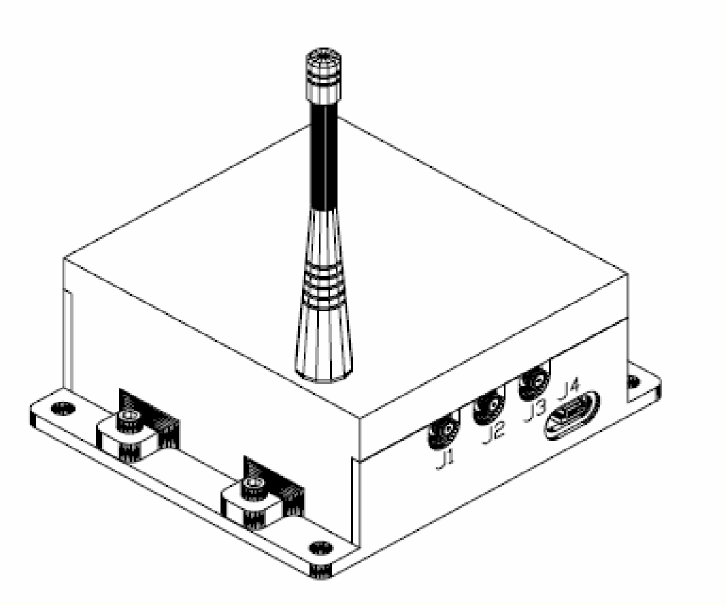
# Instrumented Worksite Interface Fixture (IWIF)

- 4 Enhanced Wideband-based units used for acquiring data from 12 degree of freedom load cell for EVA loads analysis for Shuttle Arm
  - External Colibrys MEMS accelerometers
  - External Strain Gauges
  - Commanded  from Shuttle flight deck
  - Data stored for post-flight retrieval
  - Manifest on STS-121



# Accelerometer Data Acquisition Unit (ADAU)



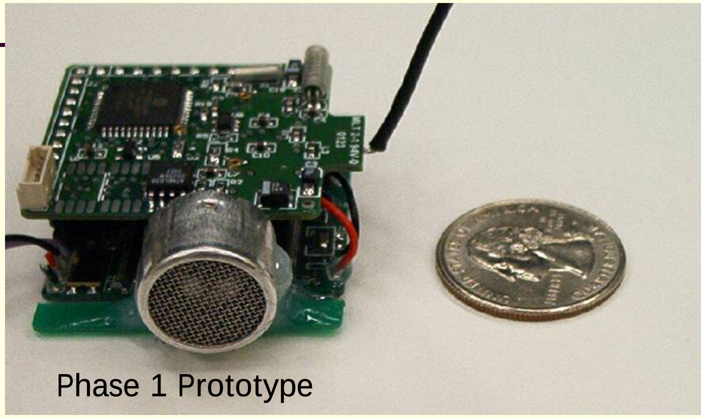



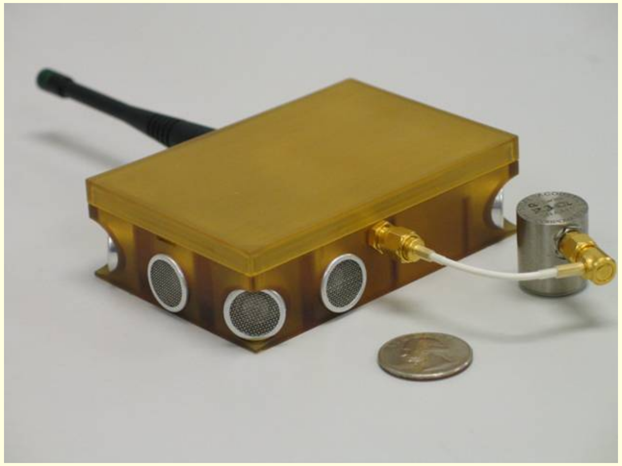

- Major airframe customer
- Extremely low power trigger mode
  - Input from piezoelectric accelerometer above a programmable threshold wakes the unit.
  - Data acquisition can begin within 2 seconds.
  - Trigger mode battery life > 3 years on D-cell battery
- Data processing on-board verifies trigger based and determines end of event based on RMS threshold calculation of acquired data.

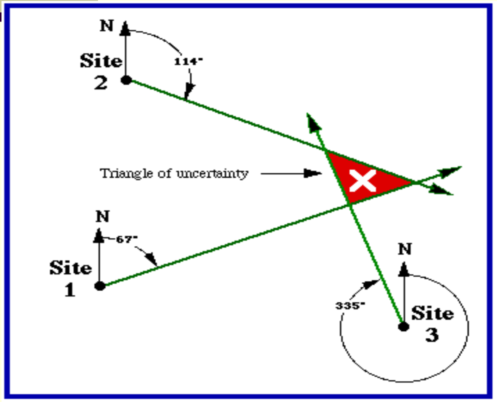
2002 Phase 2 SBIR - NASA JSC

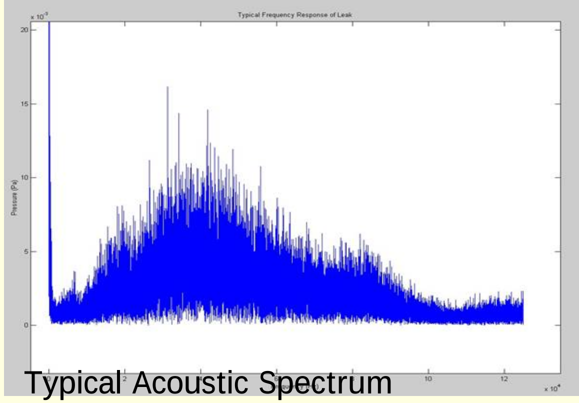
# UltraWIS

- Automated monitoring of pressurized vehicles for leaks to space is needed.
  - Reduce risk to crew and vehicle
  - Minimize loss of vehicle expendables due to holes or cracks
  - Automate leak location process to reduce crew time requirements
- Airborne and surface-borne ultrasonic transducers
  - Spark/Corona detection
  - Rotating machinery health monitoring
  - MMOD Impact Detection


Phase 1 Prototype



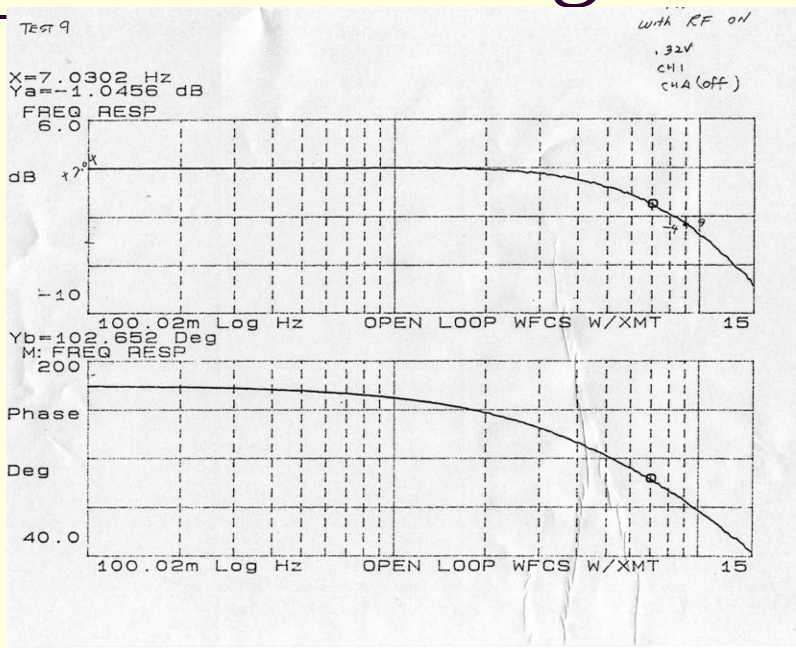


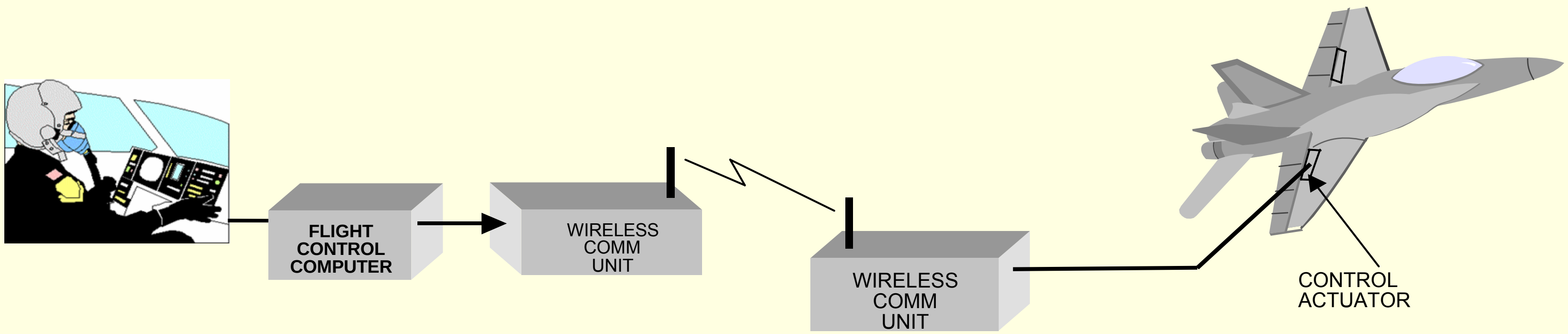
Typical Acoustic Spectrum

NASA Dryden

# Wireless Flight Control System

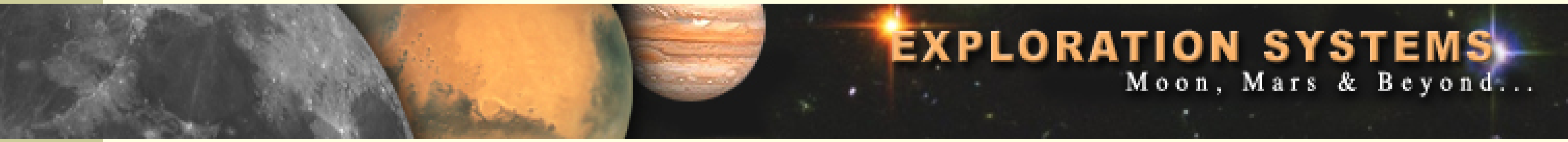



- **PURPOSE:** Define and demonstrate a prototype wireless control system that can be tested and flown on the F-18 NASA test aircraft.
  - Demonstrate feasibility as a possible backup control system for military and commercial aircraft.
  - Demonstrate potential for primary control system using spread spectrum communications links not subject to signal jamming.
  - Demonstrate potential size, weight, and power reductions of controls applicable to future deep space missions.

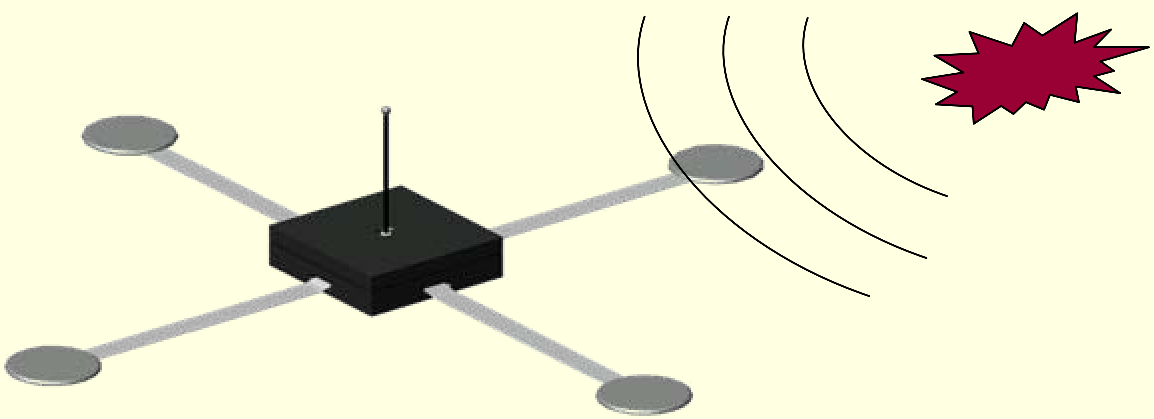


2005 Phase II SBIR – NASA Langley

# Distributed Impact Detection System



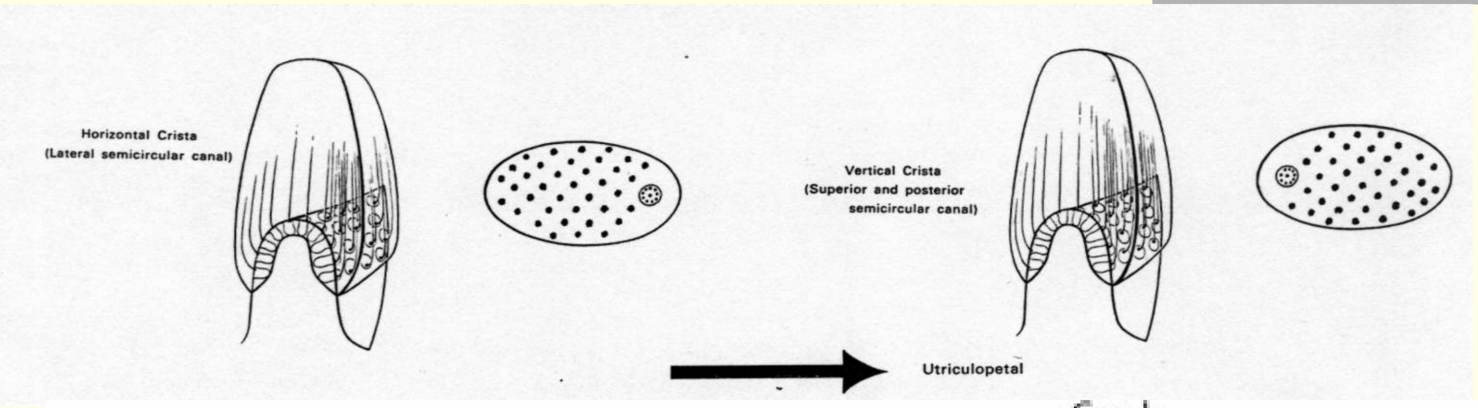

- To provide ultra low-power impact detection circuitry designs for continuous monitoring of spacecraft structure for accelerations or high rate strains caused by impacts throughout all mission stages
  - Sample rates up to 500KHz
  - 4 channels / device
  - Low-power trigger modes

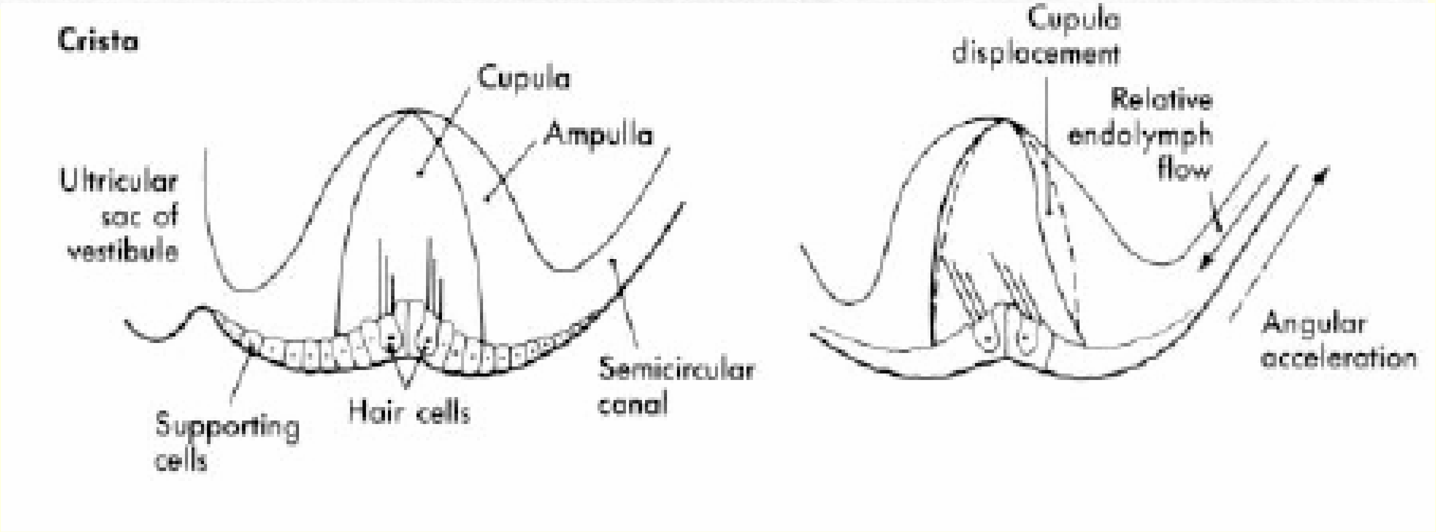


# Electromagnetic Personnel Interdiction Control (EPIC)

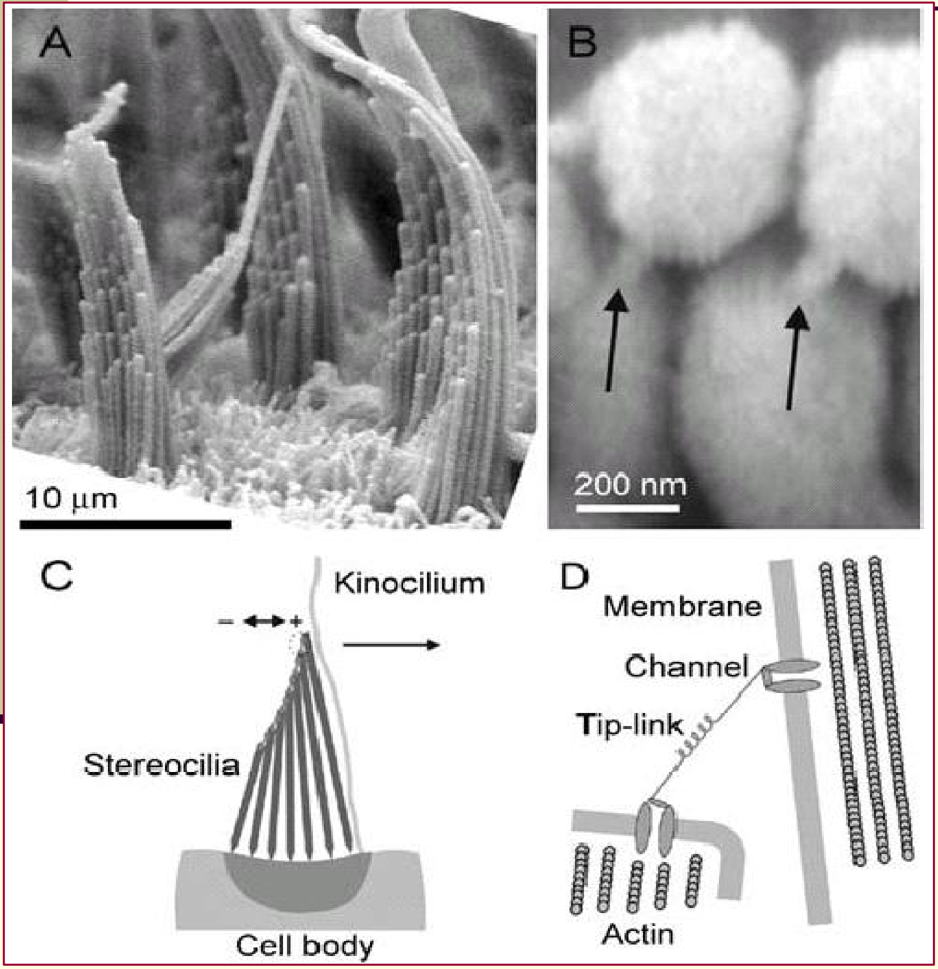
- Sponsor:  SBIR, Marines Non-lethal Weapons.
- Purpose:  Use directed energy to temporarily incapacitate an enemy by interfering with his or her sense of balance.
- Phase II SBIR underway

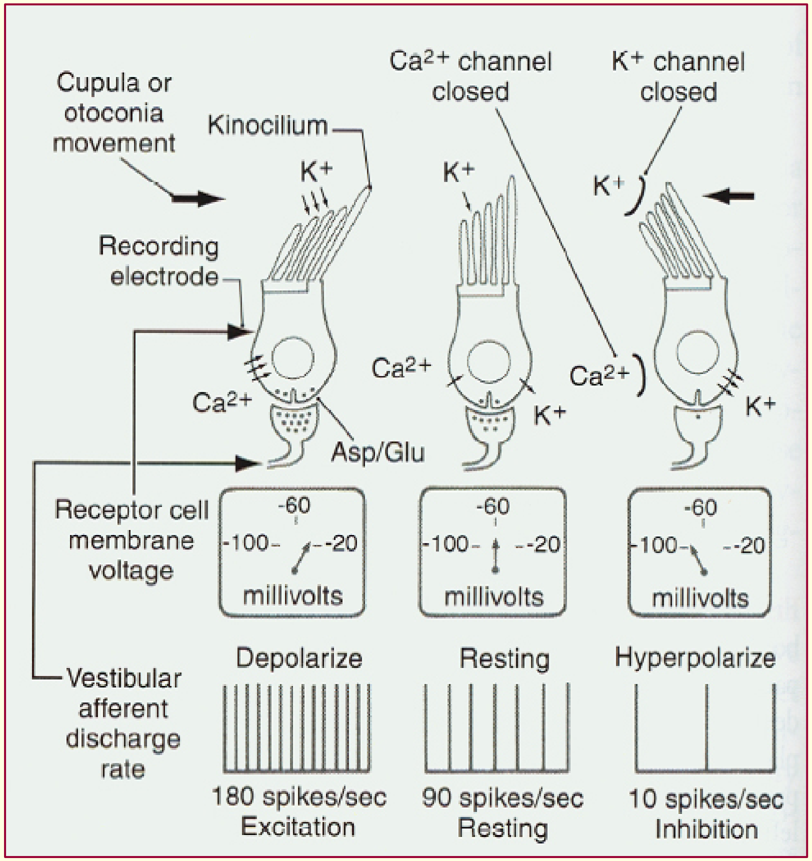
# Hair Sensory Cells in the Inner Ear (Cupulae)



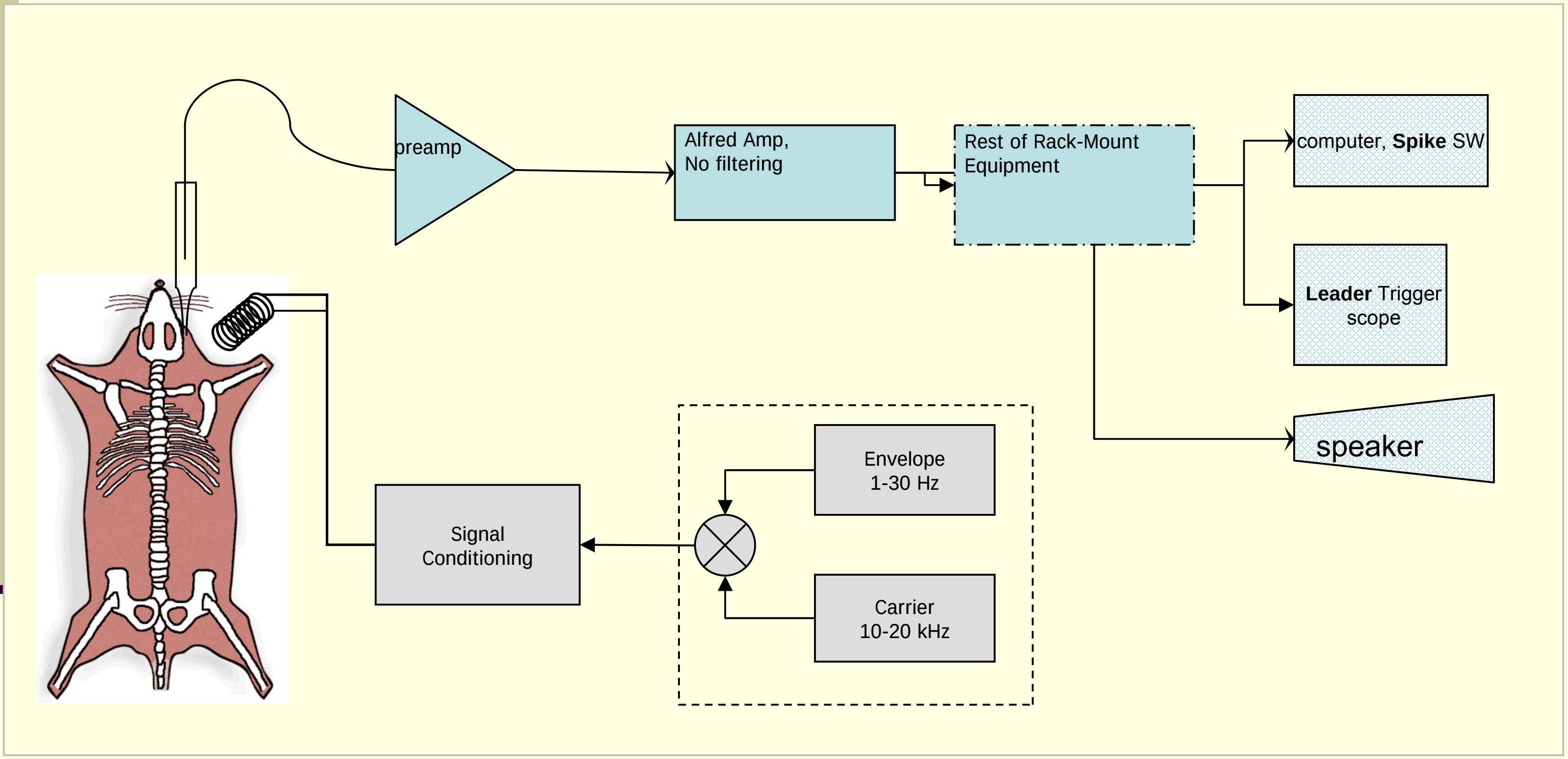



# Sensory Bundles and Tip Links



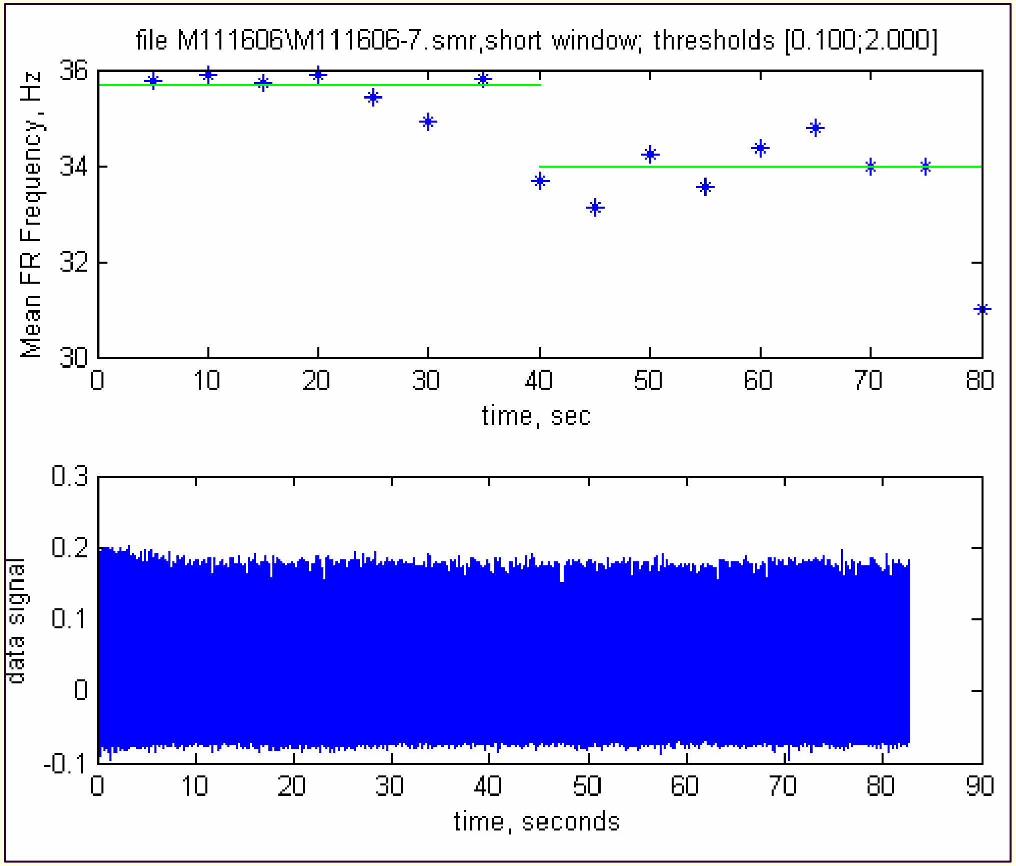



# Technical Achievement – Animal Test Setup Diagram



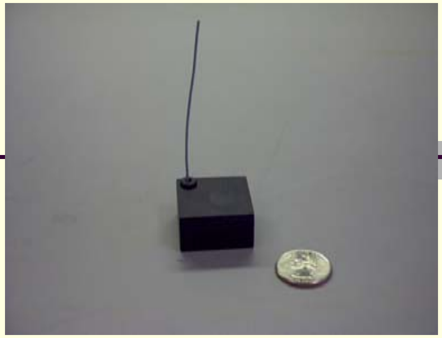
# Animal Test Results

- Demonstrated change in cell firing rate!
- Example:

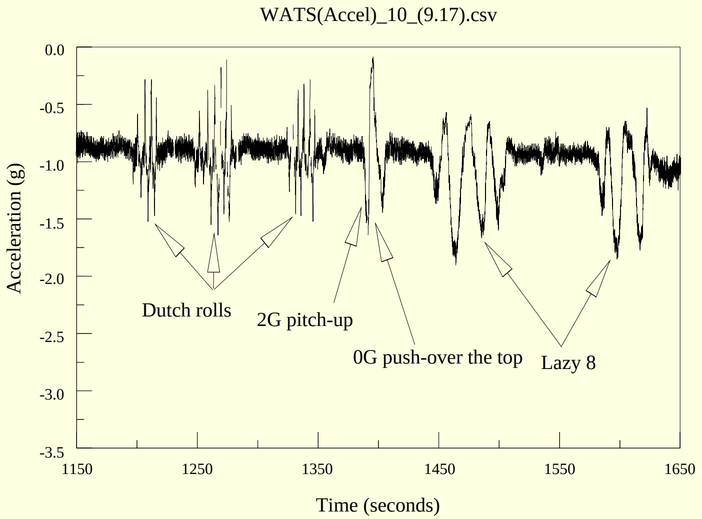


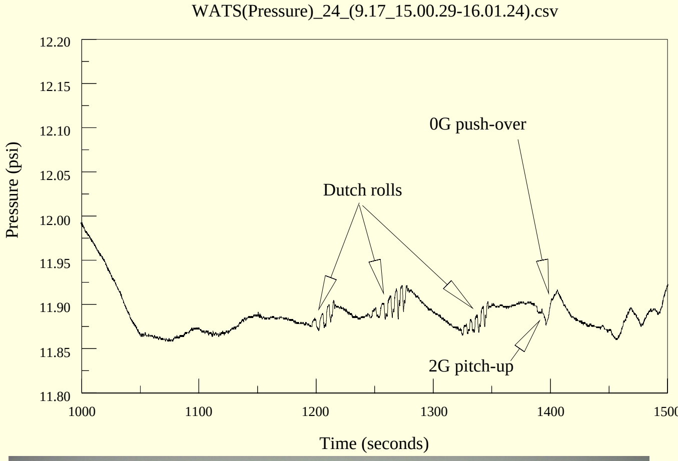

- **Data file M111606-7**
- **EPIC Stimulus on from 0 to 40 seconds**
- **Stimulus off 45-85 seconds**

# WATS - Wireless Airborne Telemetry System



- Quickly installed “stick on” sensors
- Simultaneous data from 4 sensors
- Data synchronized to within 20 uSec
- Aerodynamic shape for flight surface measurements
- Setup and operation via laptop GUI or equivalent computer

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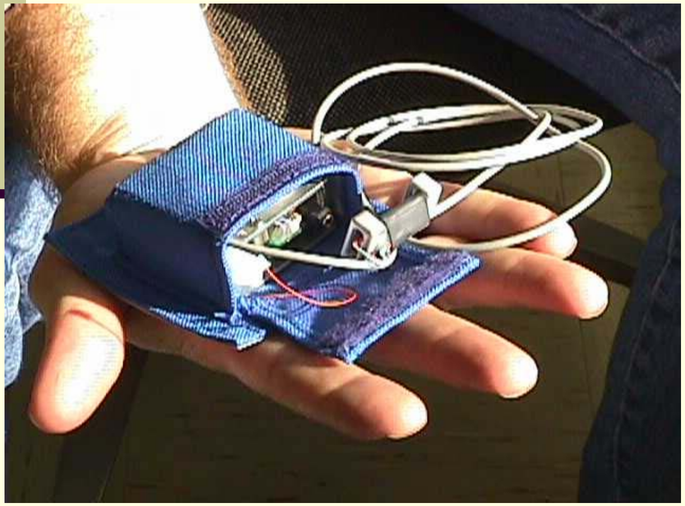
# X-38 PARAFOIL PROGRAM
# (TENSION MEASUREMENT SYSTEM)

Initial Prototype Unit flown



Modified flight unit

**SPONSOR**: NASA Johnson Space Center

**INNOVATION**:

- Measure bridge dispersion loads of X-38 parafoil to gain an understanding of the flight dynamics of the parafoil and verify the various staging processes.
- Small, light-weight, modular, remote data acquisition units easily installed, programmed and operated.
- Communicates to PC using small, battery-operated adapter box.

**ACCOMPLISHMENTS**:

- Unit consists of 32 Kbytes of non-volatile memory (EEPROM). Samples one channel at programmable data rates for 5-27 minutes. Download to PC for data retrieval.
- System Dimensions: 2.75 in. x 2.25 in. x 1.5 in.
- Programmable gain and sample rate
- Active duty cycle of 12 mA. 400 $\mu$A while in sleep mode
- Able to withstand 4 ton packing loads

**COMMERCIALIZATION**:

- Applications in both military and general parachute.
- Lower cost dispersion line tension measurement..
- Precision data acquisition of dispersion line and canopy tension distribution profiles.

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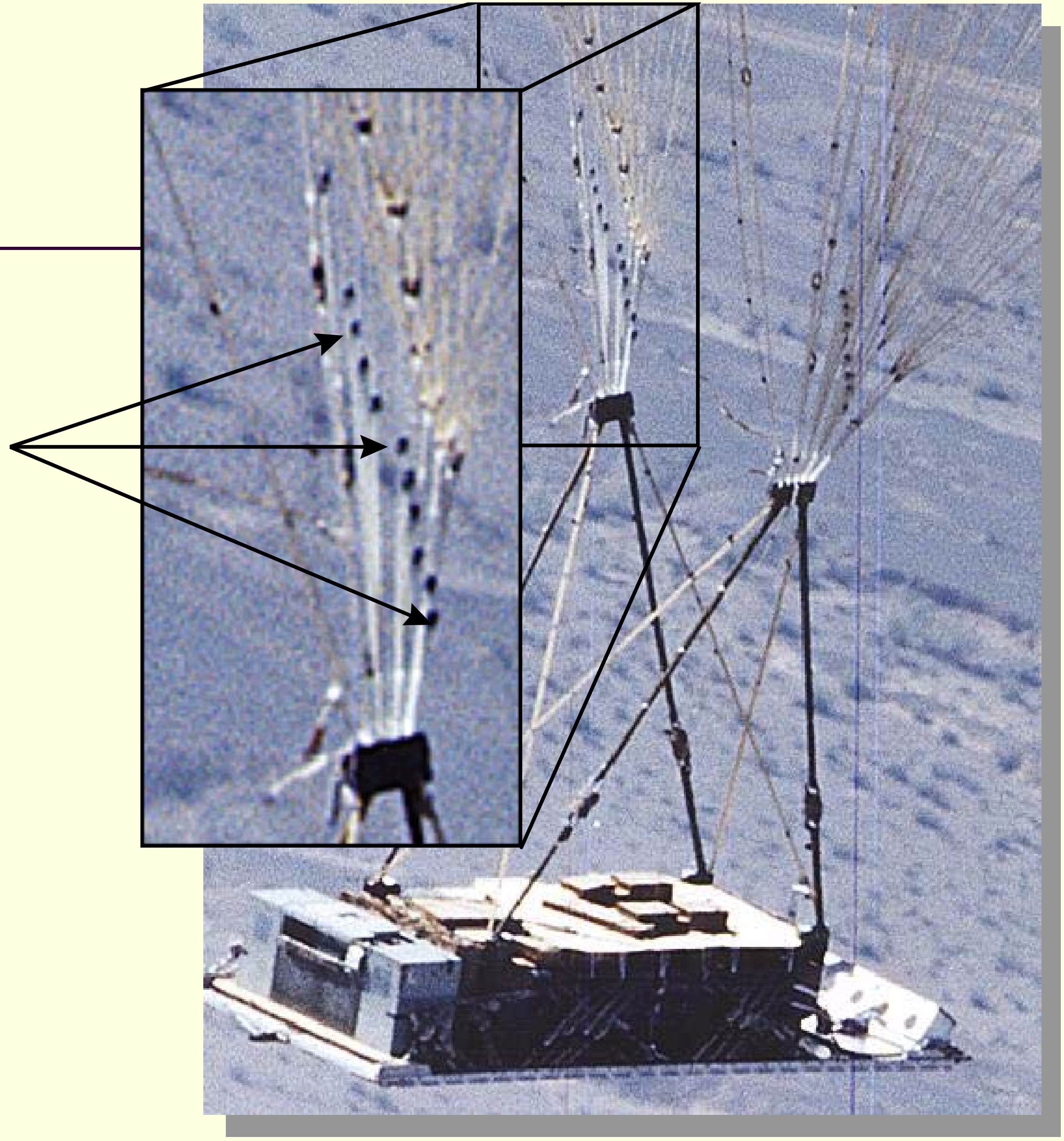


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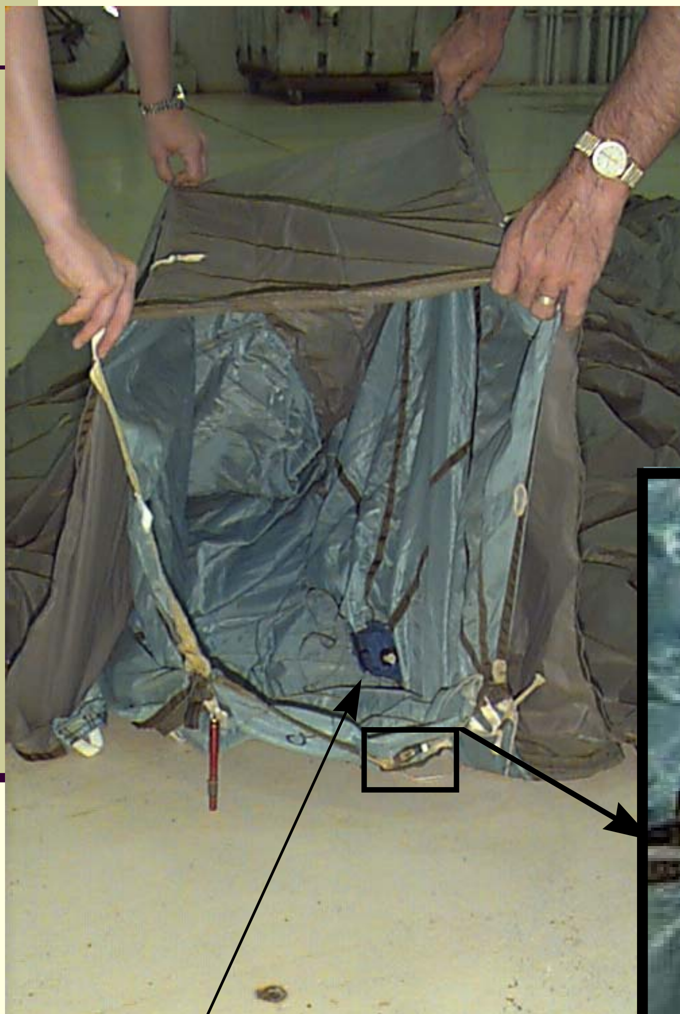
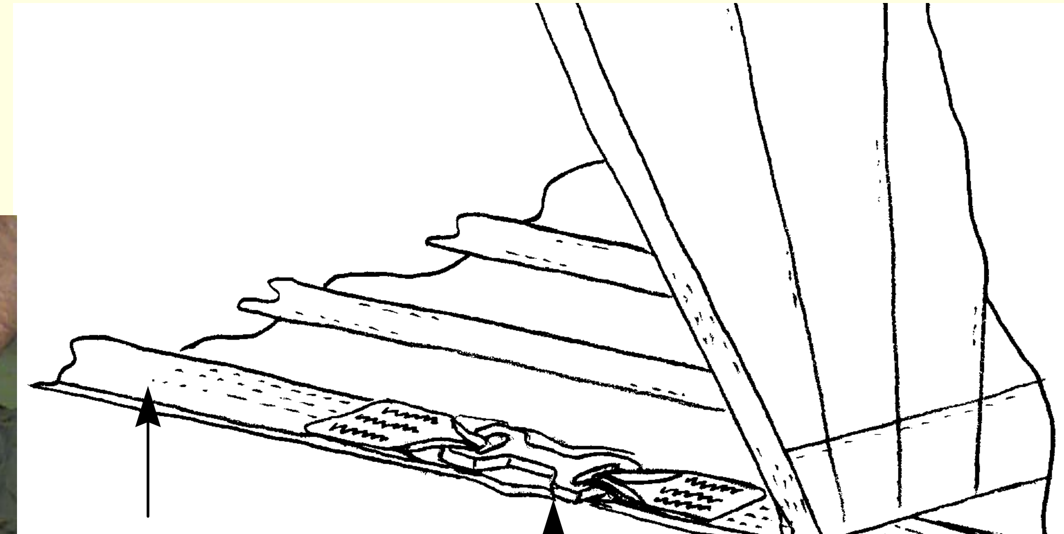
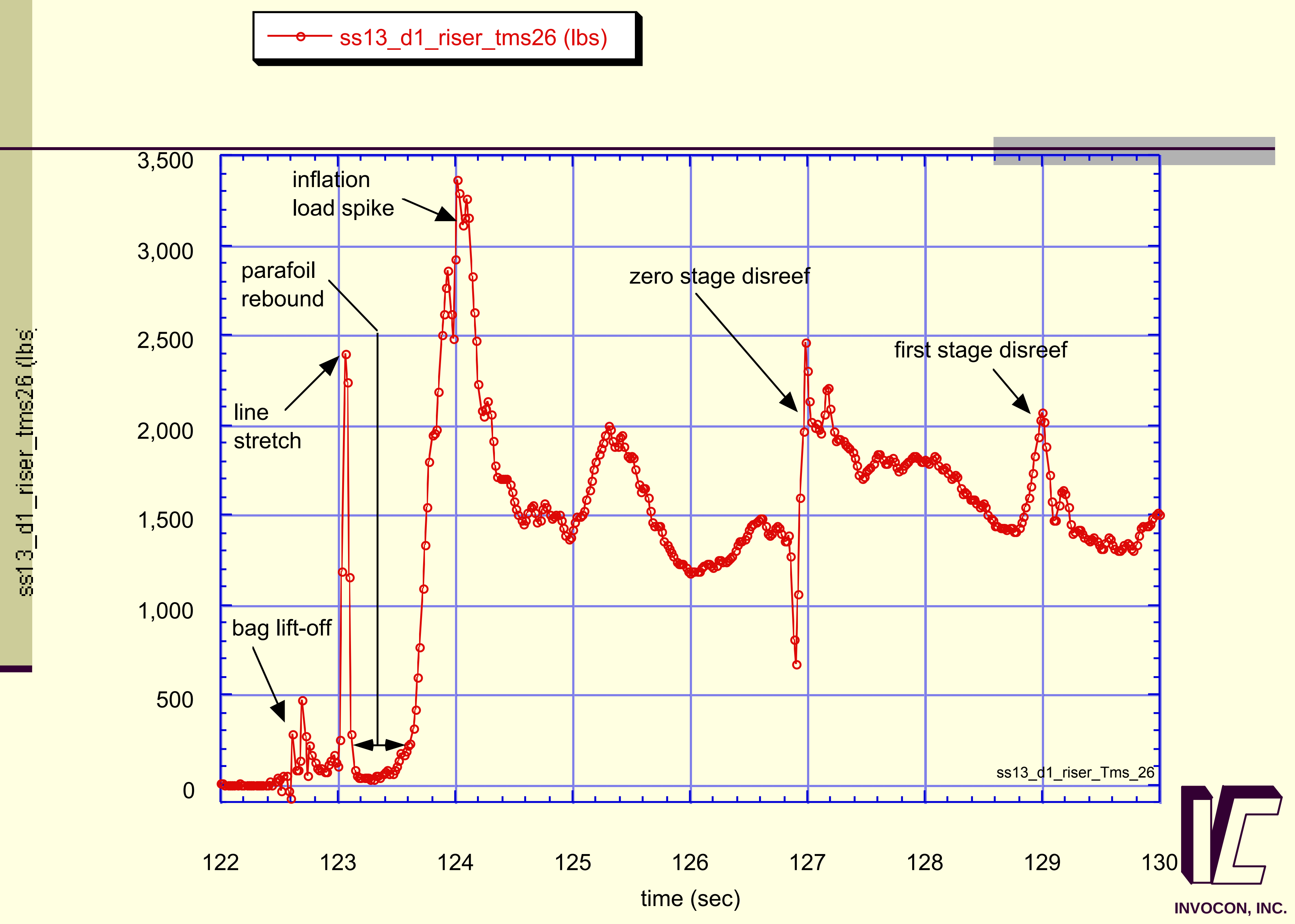





TMS Recording Unit



ss13_d1_riser_tms26 (lbs)
inflation load spike
parafoil rebound
line stretch
bag lift-off
zero stage disreef
first stage disreef
ss13_d1_riser_Tms_26
3,500
3,000
2,500
2,000
1,500
1,000
500
0
ss13_d1_riser_tms26 (lbs)
122
123
124
125
126
127
128
129
130
time (sec)
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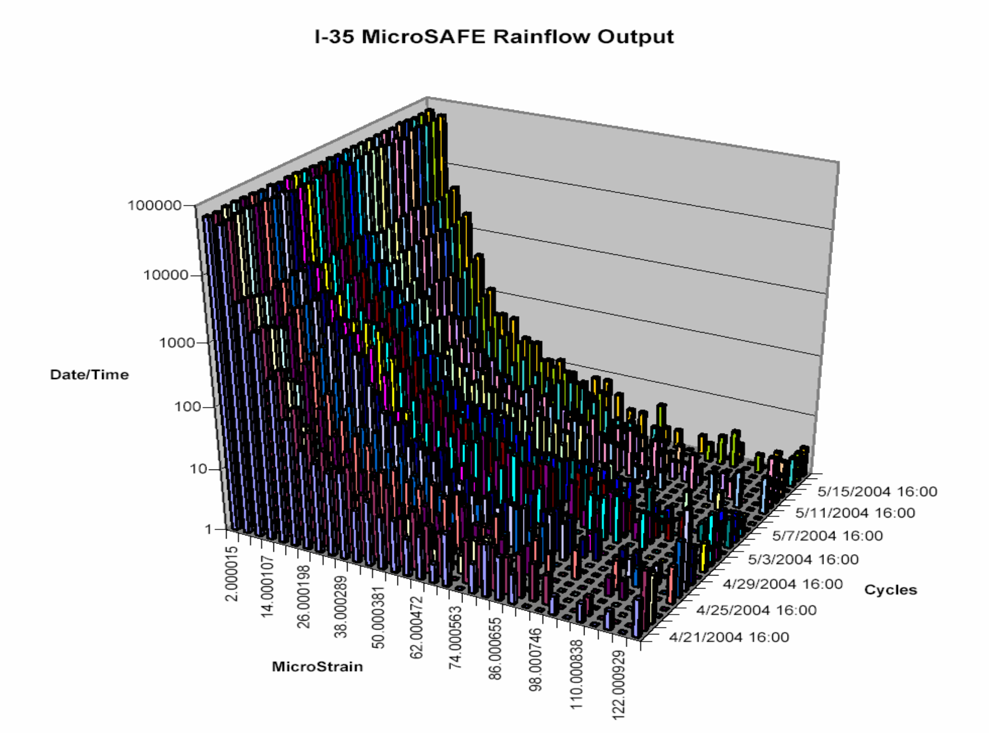
# MicroSAFE

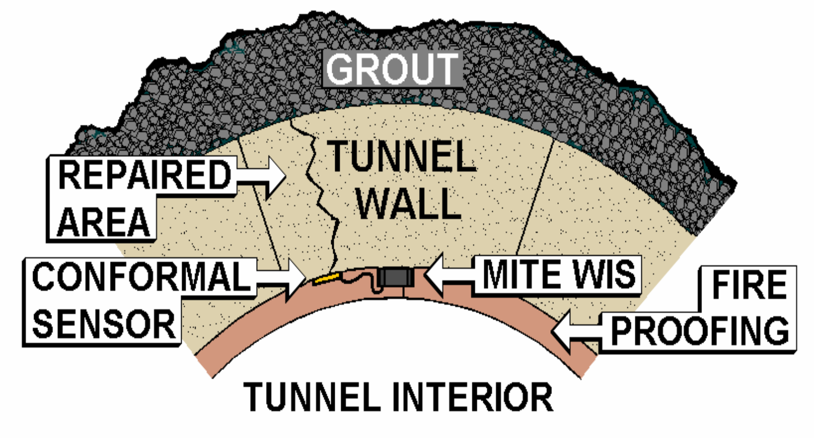
## Structural Analysis and Forecasted Endurance

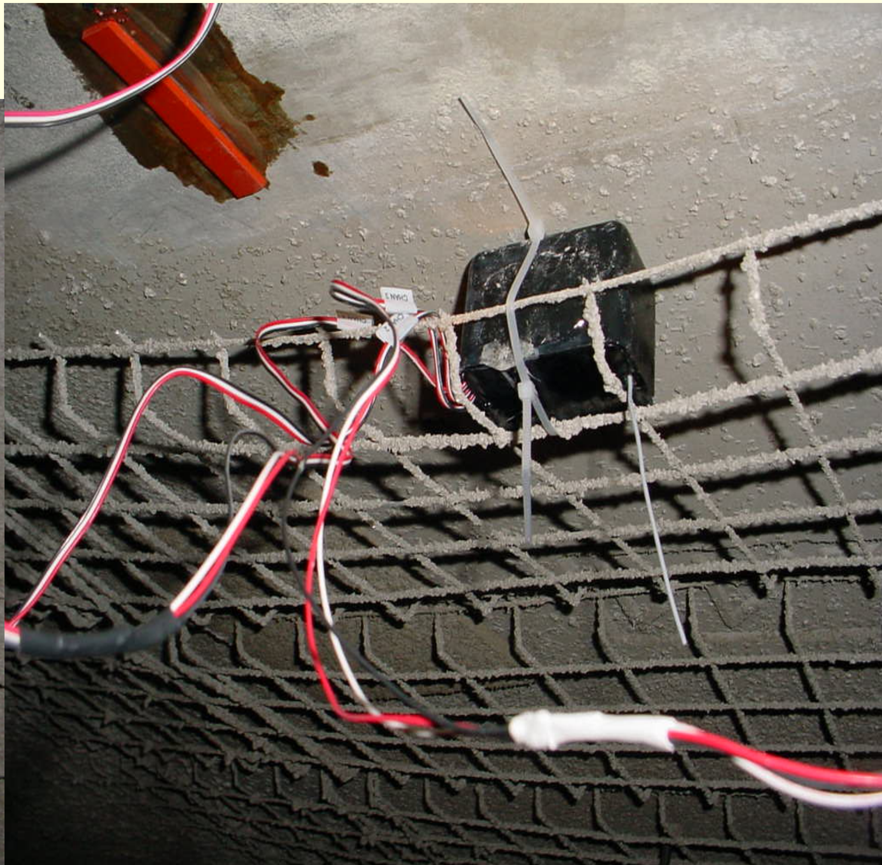
- A "Smart" Sensor
- Structural Monitoring Applications
- Performs the ASME Rainflow Cycle Counting Algorithm in Real-Time
- Provides an answer—not just raw

# Tunnel Construction Repair Monitoring

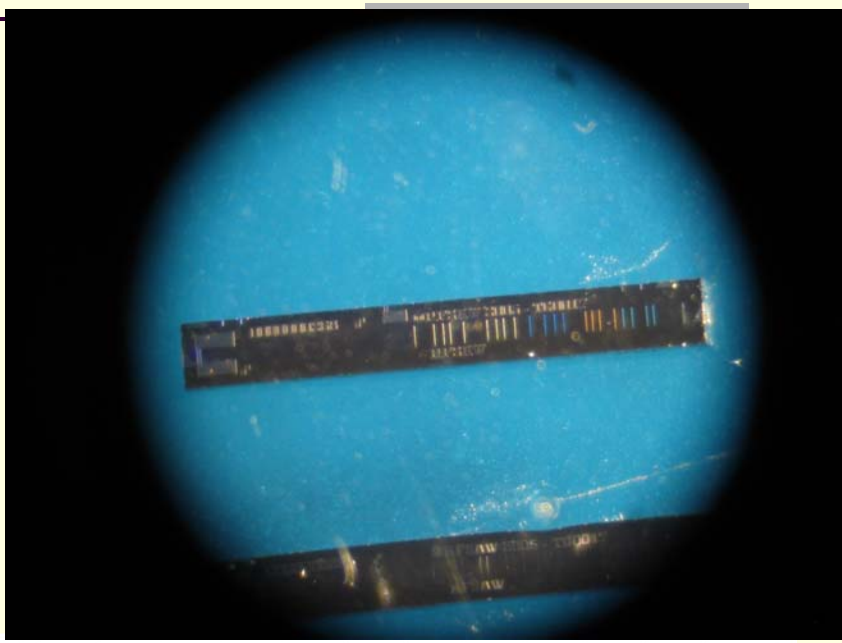
- Tunnel section damage during assembly
- Repairs must be monitored for integrity
- Tunnel interior covered in fire-proofing
- Wireless provides access to data
- No removal of fire proof required

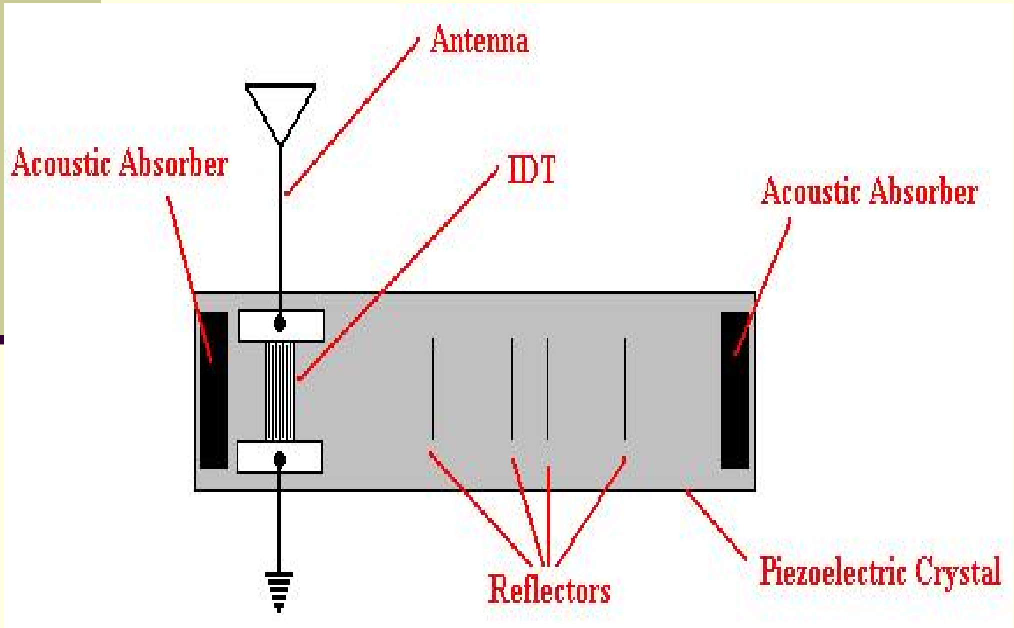


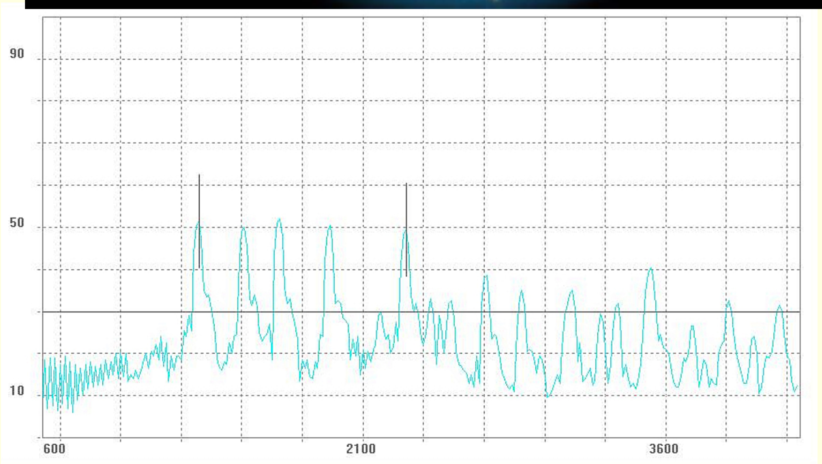



# RFID Application to Transducers

Air Force sponsored work on high temperature transduction devices with wireless capability



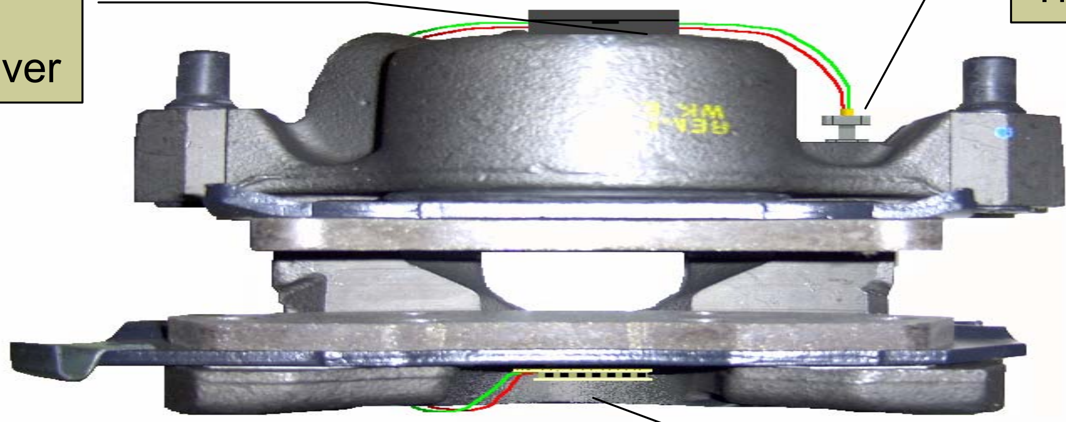


# Orbiter Boom Sensor System (OBSS) Load Cell

- Monitor Crew Member loads on Shuttle Arm during EVA
- 12 DOF Load Cell including strain and Colibrys Accelerometer
- Real time and recorded data
- Remotely operated from crew compartment

# Wireless in Vehicle Health Monitoring




## BRAKE PAD CONDITION MONITOR

* No Batteries required for operation
* No vehicle power interconnect
* Measurement of brake pad thickness
* Measurements made every time brakes are applied
* Easily integrated into existing caliper designs
* Maintenance free for the life of the caliper/vehicle
* Wireless transmission of brake condition to VHM system
* Integrated system can withstand the “under vehicle” road environment
* Antenna integrated into final design - no invasive protrusions to caliper

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# Turbine Engine Gear Case Sensors

## Problem

* Gear case planetary wear
* Requires tear-down to verify
* 70% tear-downs not faulty
* Planet gear bearing sounds difficult to isolate due to other gear noise
* "Good" gear reassembled with faults due to error
* No current method of non-invasive fault detection
* Estimated annual cost of unnecessary tear-downs - $80M

## Potential Solution

* Locate sensor inside of the planet gear bearing within the gear case
* Motion of the planetary assembly powers the wireless sensor
* High frequency miniaturized accelerometer monitors bearing sounds
* DSP computer performs time to frequency domain transformations
* RISC computer executes analysis of frequency data
* Wireless transceiver in the planet gear sends data to aircraft VHM
* Antenna for external VHM device through a modified case bolt

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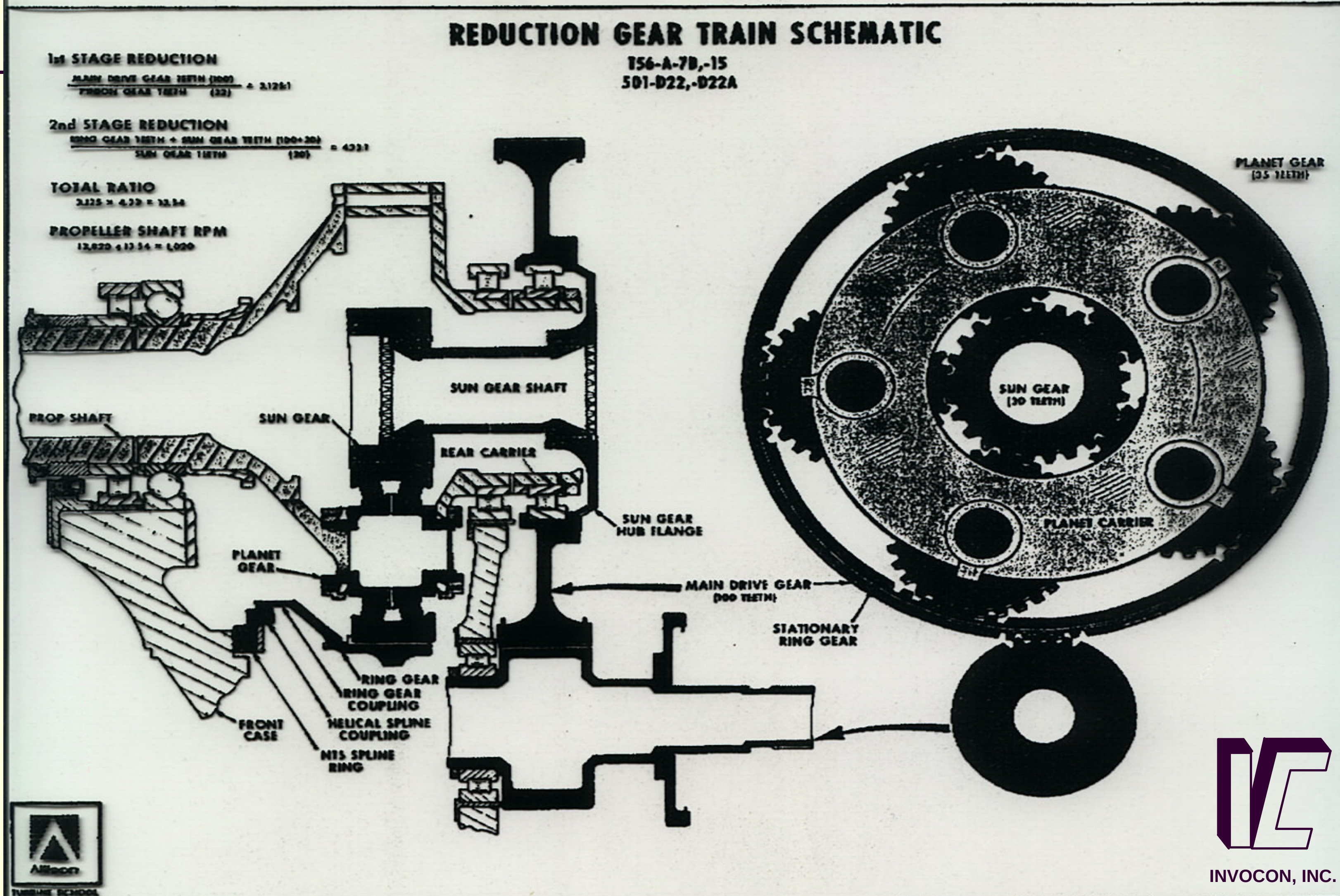
REDUCTION GEAR TRAIN SCHEMATIC
T56-A-7B,-15
501-D22,-D22A
1st STAGE REDUCTION
2nd STAGE REDUCTION
TOTAL RATIO
PROPELLER SHAFT RPM
SUN GEAR SHAFT
PROP SHAFT
SUN GEAR
REAR CARRIER
SUN GEAR HUB FLANGE
PLANET GEAR
MAIN DRIVE GEAR
(100 TEETH)
STATIONARY RING GEAR
RING GEAR
RING GEAR COUPLING
HELICAL SPLINE COUPLING
FRONT CASE
NTS SPLINE RING
PLANET GEAR
(35 TEETH)
SUN GEAR
(30 TEETH)
PLANET CARRIER
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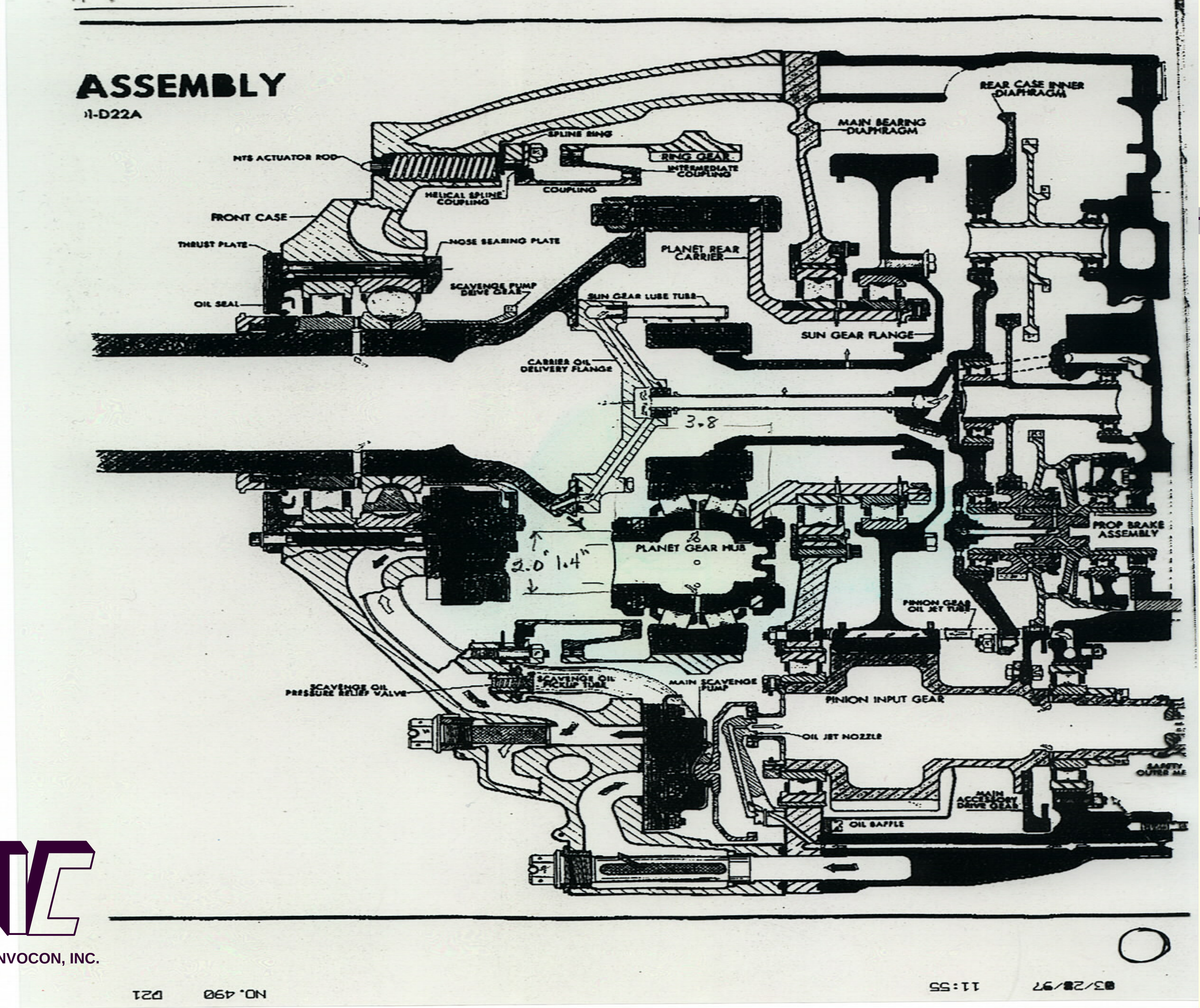
ASSEMBLY
-D22A
NTS ACTUATOR ROD
SPLINE RING
RING GEAR
INTERMEDIATE COUPLING
COUPLING
HELICAL SPLINE COUPLING
FRONT CASE
THRUST PLATE
NOSE BEARING PLATE
OIL SEAL
SCAVENGE PUMP DRIVE GEAR
SUN GEAR LUBE TUBE
PLANET REAR CARRIER
MAIN BEARING DIAPHRAGM
REAR CASE INNER DIAPHRAGM
SUN GEAR FLANGE
CARRIER OIL DELIVERY FLANGE
3.8
2.0" 1.4"
PLANET GEAR HUB
PROP BRAKE ASSEMBLY
PINION GEAR OIL JET TUBE
SCAVENGE OIL PRESSURE RELIEF VALVE
SCAVENGE OIL PICKUP TUBE
MAIN SCAVENGE PUMP
PINION INPUT GEAR
OIL JET NOZZLE
MAIN ACCESSORY DRIVE GEAR
OIL BAFFLE

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# INTERESTING QUESTIONS STILL TO BE ANSWERED

- WILL WIRELESS SYSTEMS BECOME ACCEPTED REPLACEMENTS FOR WIRED TEST INSTRUMENTATION?
- WHAT ARE THE “REAL” ROLES FOR WIRELESS?
- WHAT ARE THE DECIDING FACTORS FOR PERIODIC DATA SAMPLING AS OPPOSED TO CONTINUOUS SAMPLING AND ANALYSIS?
- WHAT ARE THE BEST APPROACHES TO MAKING “WIRELESS” A UNIVERSALLY ACCEPTABLE TOOL THAT HAS A MARKET VOLUME TO REDUCE PRICES TO COMPETITIVE LEVELS?
- IF THE POTENTIAL FOR A LARGE INSTALLED BASE IS ACHIEVED, WILL THE AVAILABLE SPECTRUM STAND THE STRAIN?
- WHAT ARE THE INDUSTRIAL MARKETS THAT WILL PRODUCE THE NECESSARY “COMMON DENOMINATOR REQUIREMENTS” FOR VOLUME PRODUCTION?
- HOW MUCH DOES WIRELESS CONTROL REALLY “BUY” IN A NOMINAL PERFORMANCE ENVIRONMENT