# Aerospace Applications for Surface Acoustic Wave Devices


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# Outline

- Motivation
- Introduction to SAW Sensors
- SAW Sensor Examples
- Aerospace Applications for Passive Wireless Sensors
- Conclusions
- Funding/Partnership Opportunities

# Motivation

VSST

## Need for Improved Aviation Safety
## Can we detect changes in the structure before this happens?

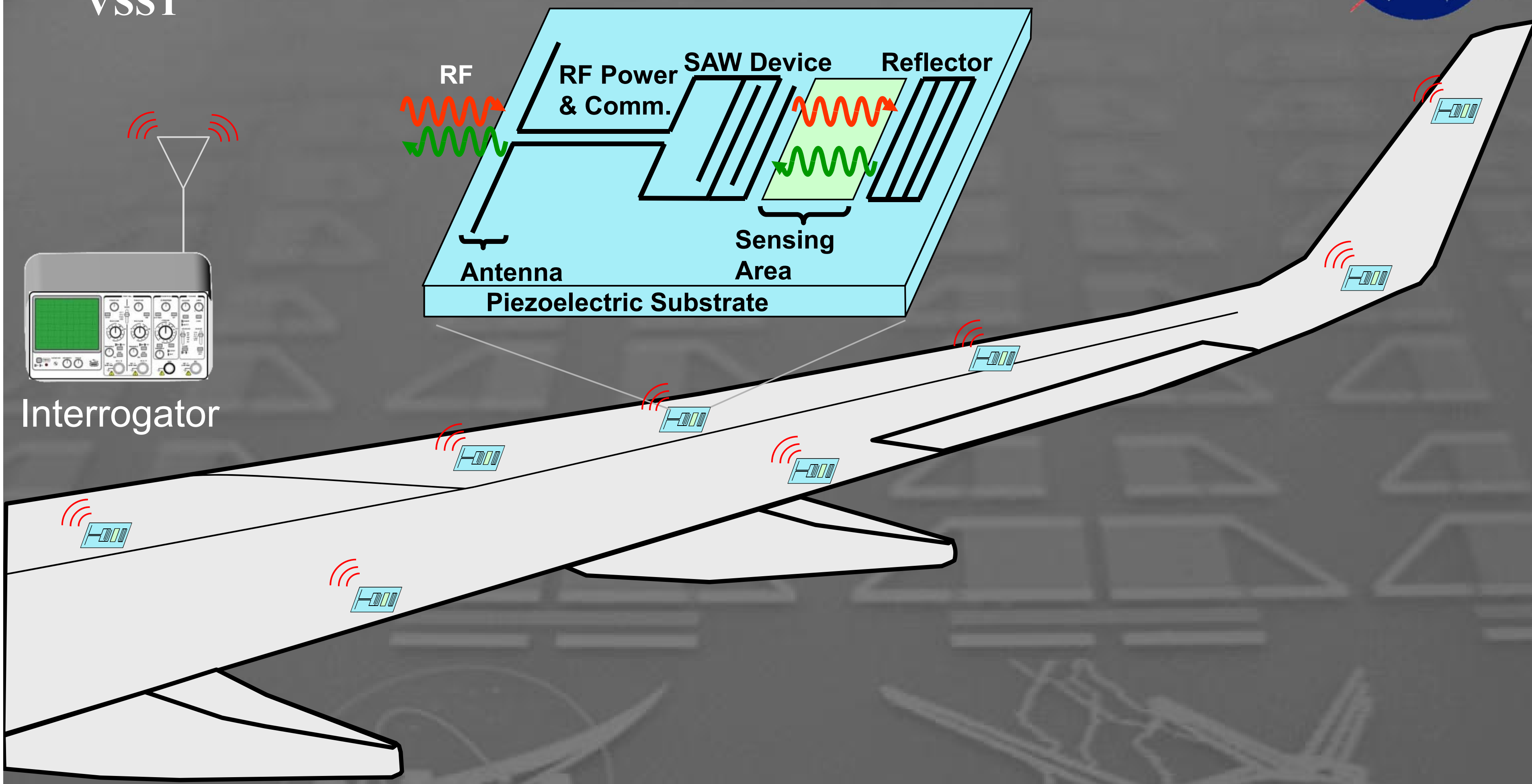

Forward fuselage, Aloha Airlines (1 person killed)

Vertical Tail, American Airlines Flt 587 (265 killed)

Engine, Delta Flight 1288 (2 people killed)

U.S. Forest Service C-130, near Walker, CA (3 killed)

# Wireless OFC SAW Sensor Goal




- Goal is to develop a passive wireless sensors for Aerospace Applications
  - (temperature, strain, load, fatigue, fastener failure, impact sensors, etc.)
- OFC allows for many uniquely coded sensor to be interrogated at once.
- Envision hundreds of SAW devices mounted directly to the structure (mostly internally).

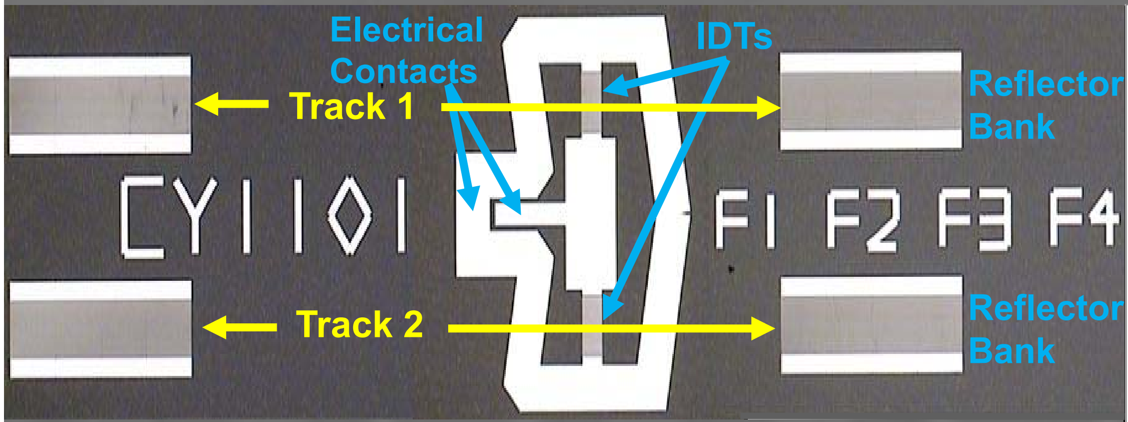
# SAW Sensor Sensitivity[1]

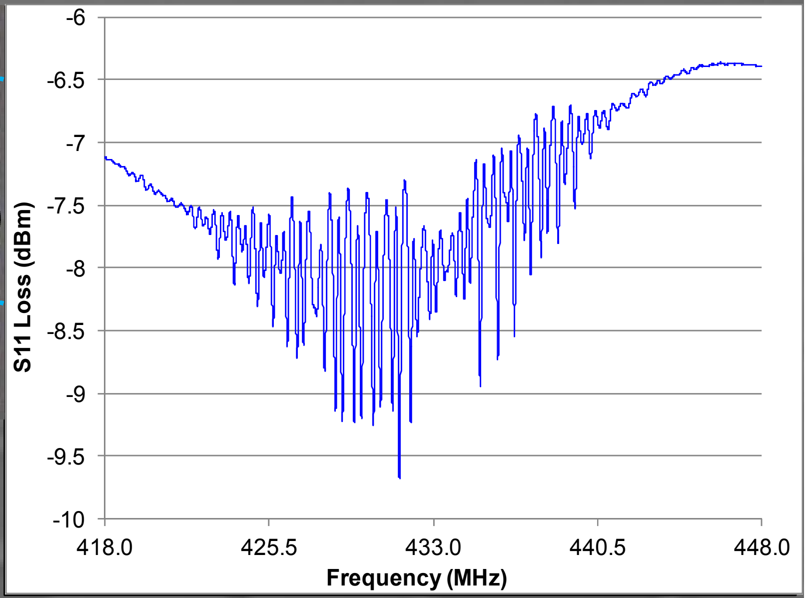
VSST

| Measurand | Device | Freq. (MHz) | Substrate | Sensitivity | (Value/Unit) |
|---|---|---|---|---|---|
| Pressure | DL | 105 | Quartz | 3.8 | ppm/kPa |
| | DL | 90 | AlN/Si | 27.0 | ppm/kPa |
| Force | DL | 8.3 | $LiNbO_3$ | 10.8 | ppm/kN |
| Strain | R | 140.2 | Quartz | 1.28 | ppm/$10^{-6}$ |
| | DL | 10.9 | PZT | 21 | ppm/$10^{-6}$ |
| Position (linear) | DL | 8.3 | $LiNbO_3$ | 120.5 | ppm/µm |
| Position (angular) | R | 434 | Quartz | 2.86 | ppm/mrad |
| Acceleration | DL | 251 | Quartz | 45 | ppm/(m/$s^2$) |
| | DL | 10.9 | PZT | 8.7 | ppm/(m/$s^2$) |
| Rotation rate | DL | 10.9 | PZT | 25.7 | ppm/$s^{-2}$ |
| Flow rate (gas) | DL | 73 | $LiNbO_3$ | 204 | ppm/($cm^3$/s) |
| Flow rate (liquid) | DL | 68 | $LiNbO_3$ | 105 | ppm/($mm^3$/s) |
| Liquid viscosity | DL | 30 | $LiNbO_3$ | 2.7 | ppm/cP |
| Liquid density | DL | 6 | $ZnO/Si_xN_y$ | 30000 | ppm/(g/$cm^3$) |
| Electric field (normal) | DL | 900 | LiNbO | 3141 | ppm/(V/µm) |
| | R | 85 | $Li_2B_4O_7$ on piezoceramic | 300 | ppm/(V/µm) |
| Electric field (transverse) | DL | 1000 | $LiNbO_3$ | 120 | ppm/(V/µm) |
| Voltage | DL | 900 | $LiNbO_3$ | 0.93 | ppm/V |
| Liquid conductivity | DL | 51 | $LiTaO_3$ | 13400 | ppm/(S/m) |
| Magnetic field | DL | 140 | Fe-B/Quartz | 0.38 | ppm/(A/m) |
| Temperature | DL | 43 | $LiNbO_3$ | 92.13 | ppm/° C |
| Radiation dose | R | 199 | Quartz | 0.48 | ppm/$(J/kg)^{0.5}$ |
| Thin film thickness | DL | 75 | $LiNbO_3$ | 9.25 | ppm/nm |

[1] G. Fischerauer, "Acoustic Wave Devices," in: W. Göpel, et al (Eds.), Sensors A Comprehensive Survey, Vol. 8. Weinheim: VCH, 1995.
DL – Delay Line, R – Resonator, Sensitivity is the fractional frequency shift in ppm / delta measurand in ppm

# Prototype SAW Sensor



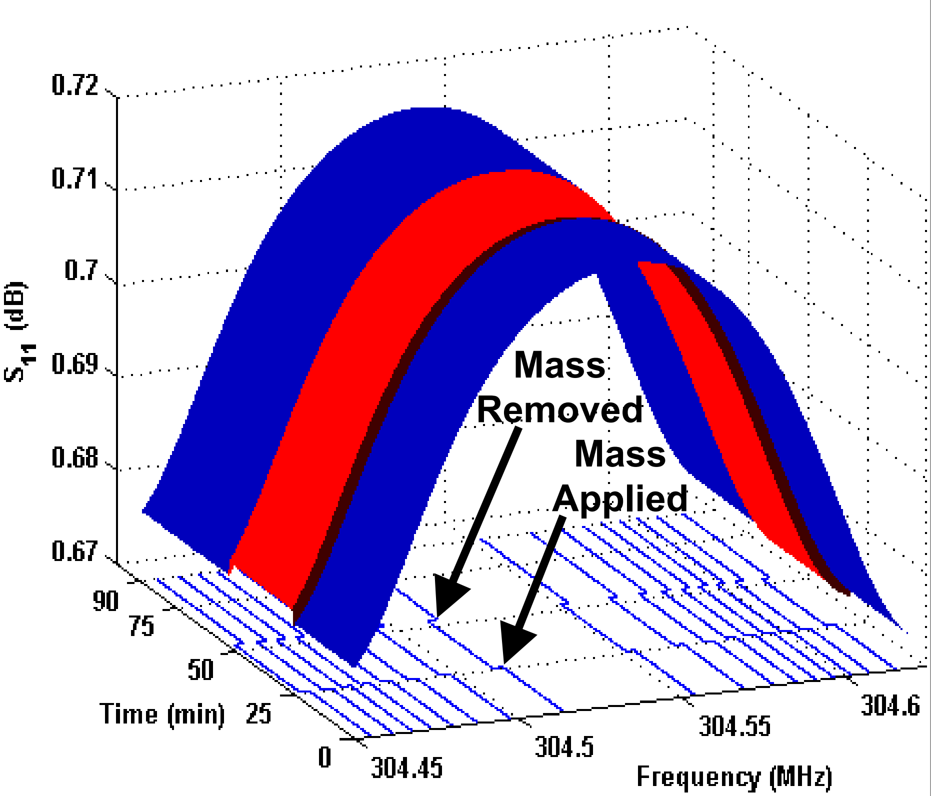



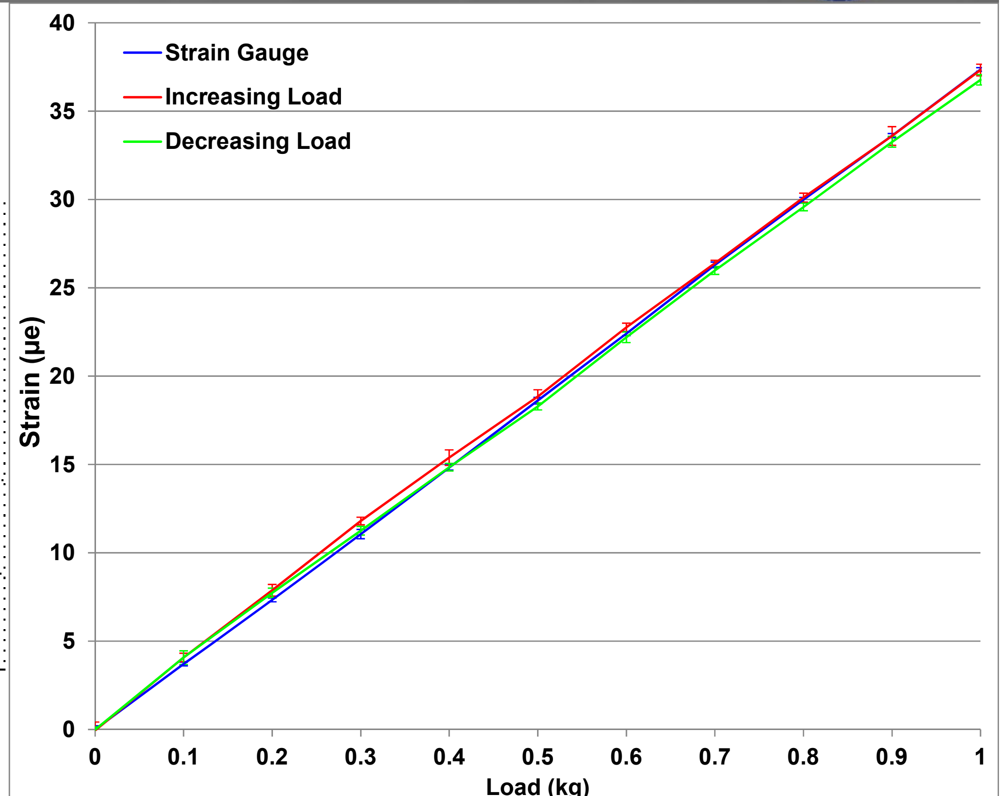

$f_0$= 433 MHz
$\lambda$= 6.319 µm
finger widths = 1.055 µm

$S_{11}$ Response of SAW Sensor

- Orthogonal Frequency Coded Devices
  - Spread spectrum (multiple frequencies) for communications
  - Unique identifier for each sensor
  - Improves range and code collision avoidance
- OFC SAW Devices have been fabricated in partnership with the University of Central Florida.

# Measured SAW Response

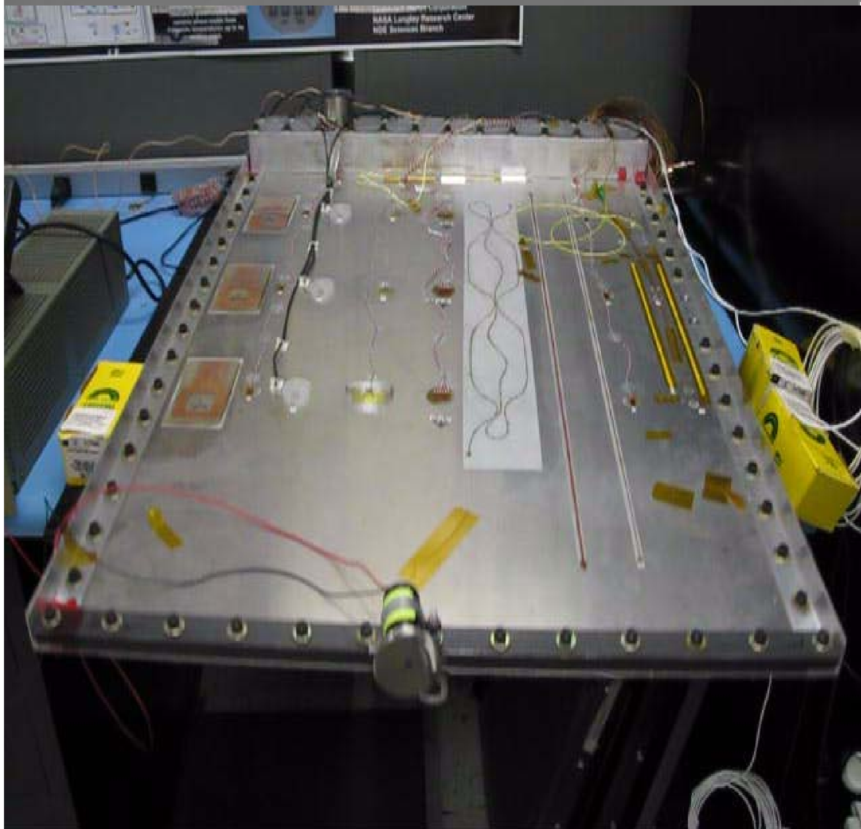


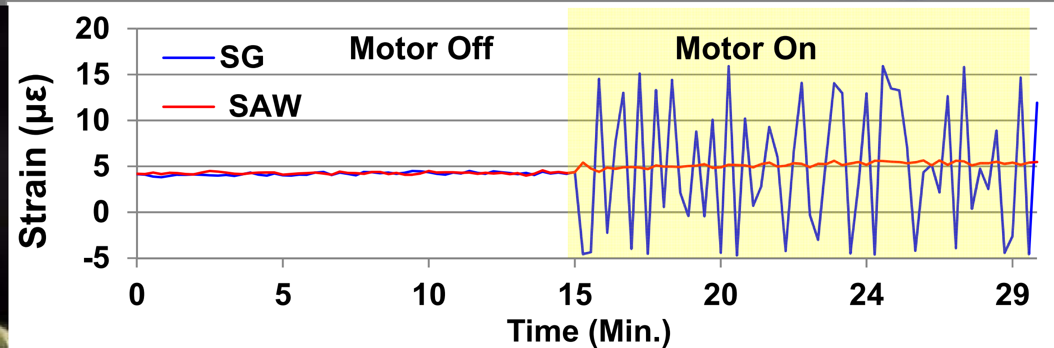



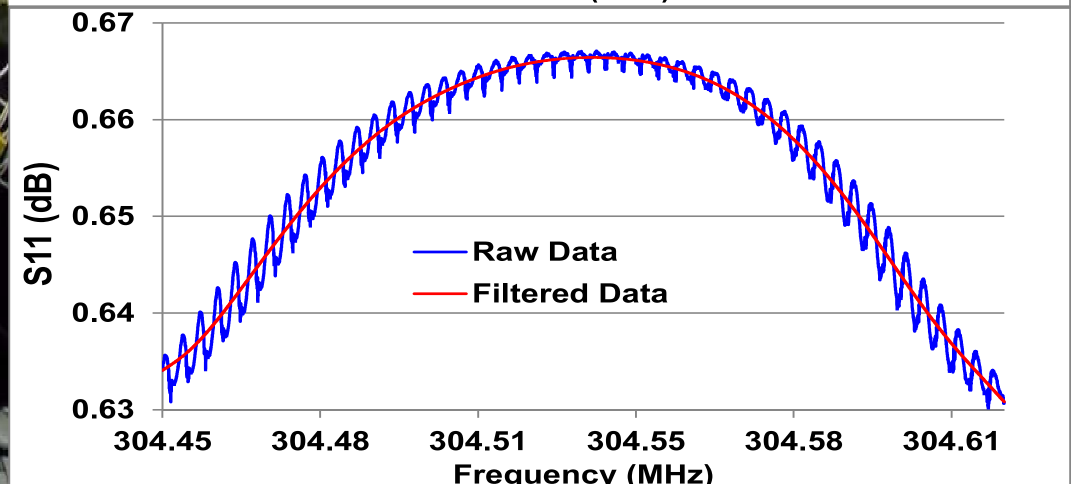

- The time and frequency response of a SAW sensor with and without strain from a 0.5kg mass.
  - The data was taken for 25 minutes without any strain.
  - SAW device was strained (7.6 με) for 25 minutes and then the strain was removed.
- The step function of strain application and removal is clearly observable. (2874.4Hz)

- Strain measurements: SAW vs Strain Gauge.
- The load was increased from 0Kg to 1Kg in 100g increments.
- The load was decreased from 1Kg to 0Kg in 100g increments

# SAW $S_{11}$ Response to Vibrations



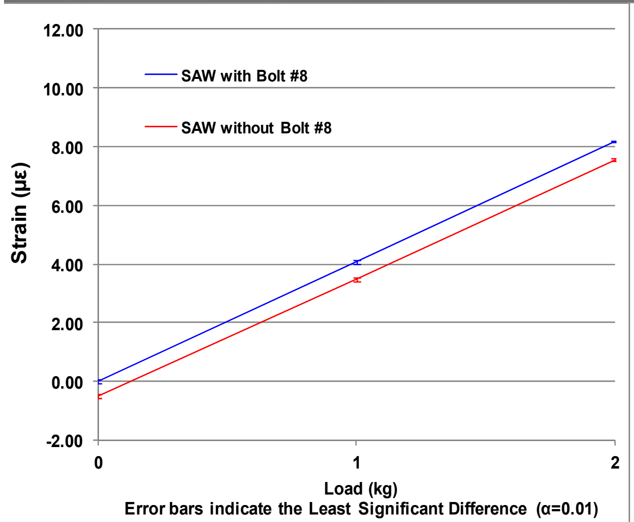


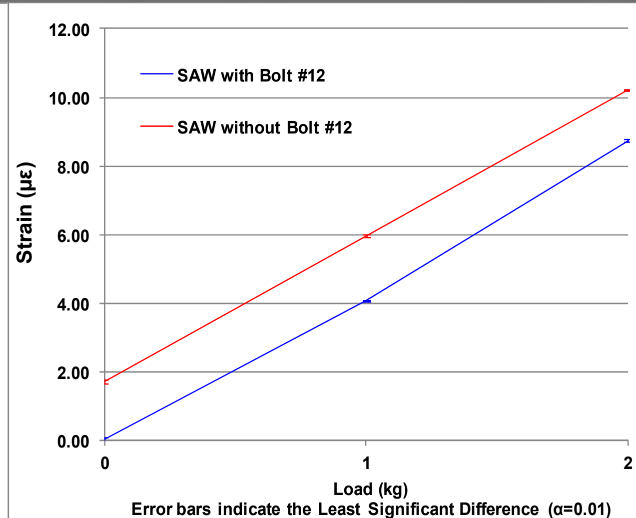



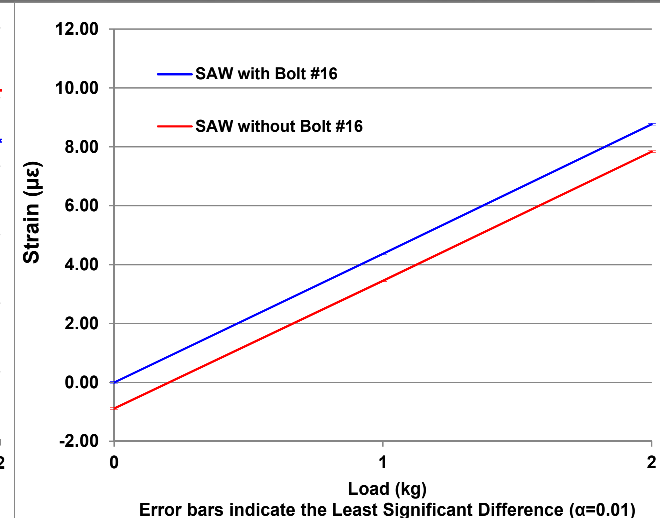

- Strain vibrational noise from electric motor when panel has 1kg load.
- The strain gauge vibrational noise from the motor increased from ±1 με to a range of ±10 με.  At the same time the SAW strain measurements increased from ±1 με to ±1.49 με.

- Filtering removes the low frequency structural vibrations.  Similar to comparing an

# Single Fastener Failure Detection with Noise



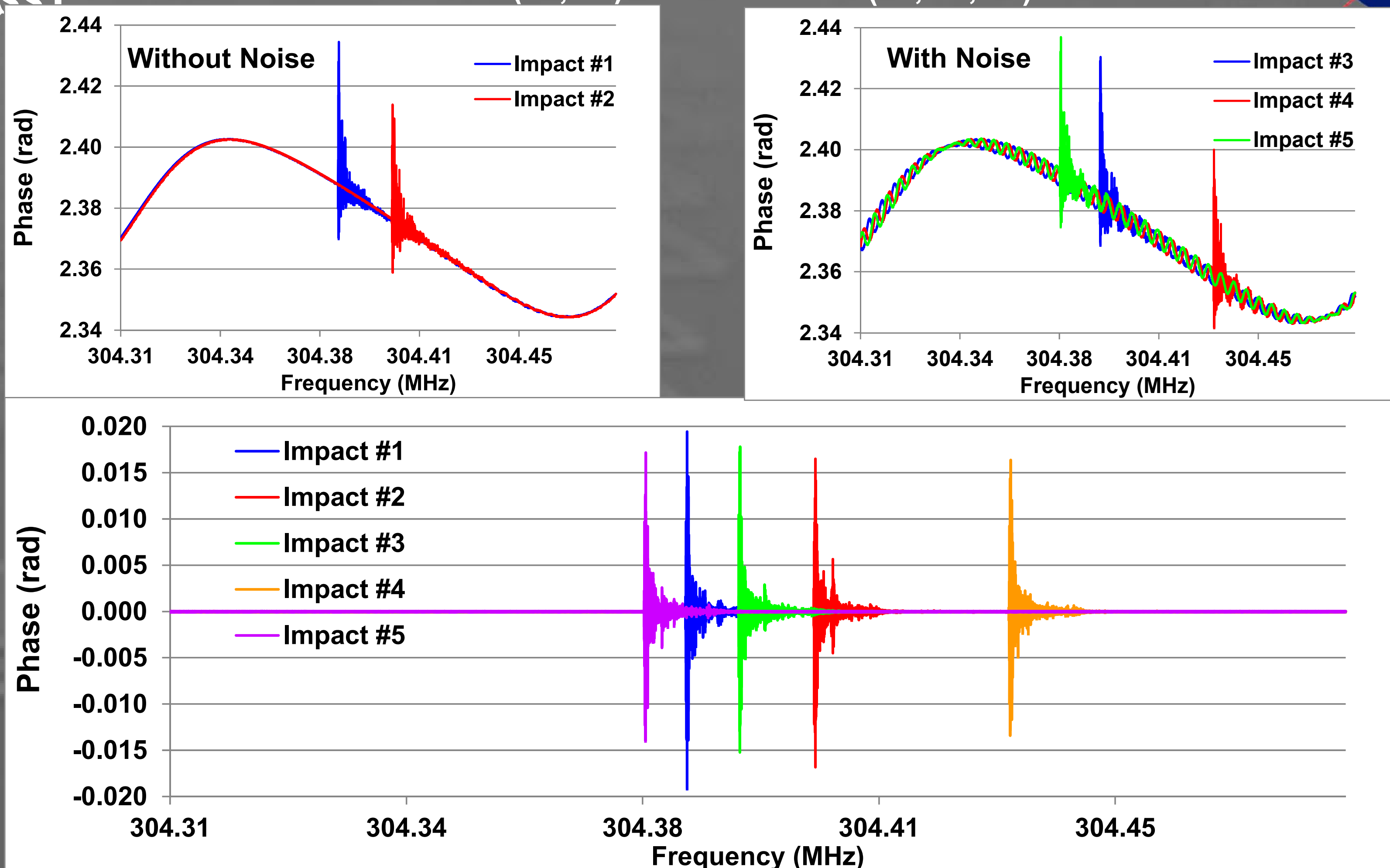




- Surface Acoustic Wave Data (micro strain) with loading (0kg, 1kg, 2kg) and with all of the bolts tightened and with a single bolt removed.

- Note that the error bars do not overlap. Therefore, the SAW device detects a single bolt being removed for all three loading conditions with noise and for all three distances 52 cm, 65 cm and 80 cm.

# Impact Detection with Noise

Filtered phase response from $S_{11}$ of SAW sensor during impacts without noise (#1, #2) and with noise (#3, #4, #5).




- High pass filtering of the phase data removes all of the vibrational noise and the natural shape of the phase data.
- SNR = 51.0db average, 51cm from impact with noise!!
- Compare to AE #1 SNR = 29.3 dB at roughly the same distance.

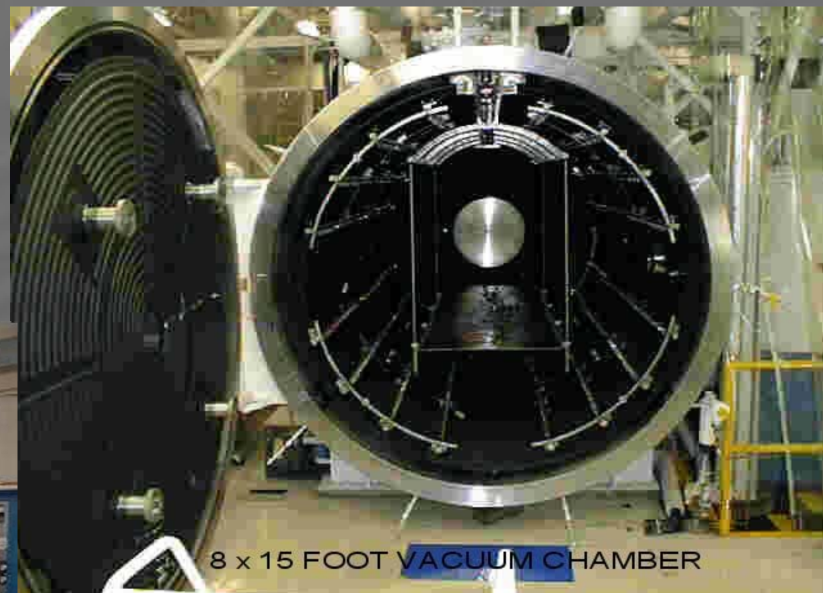
# Applications

- Passive wireless sensors are sought for many NASA Aerospace applications
  - Ground Tests
  - Wind Tunnels
  - Flight tests
- The applications are not limited to SAW sensors, other technologies may be needed.

# Ground Testing Applications (Aero)


The cabling required to connect 466 foil strain gages to the stitched/resin film infused graphite-epoxy wing box

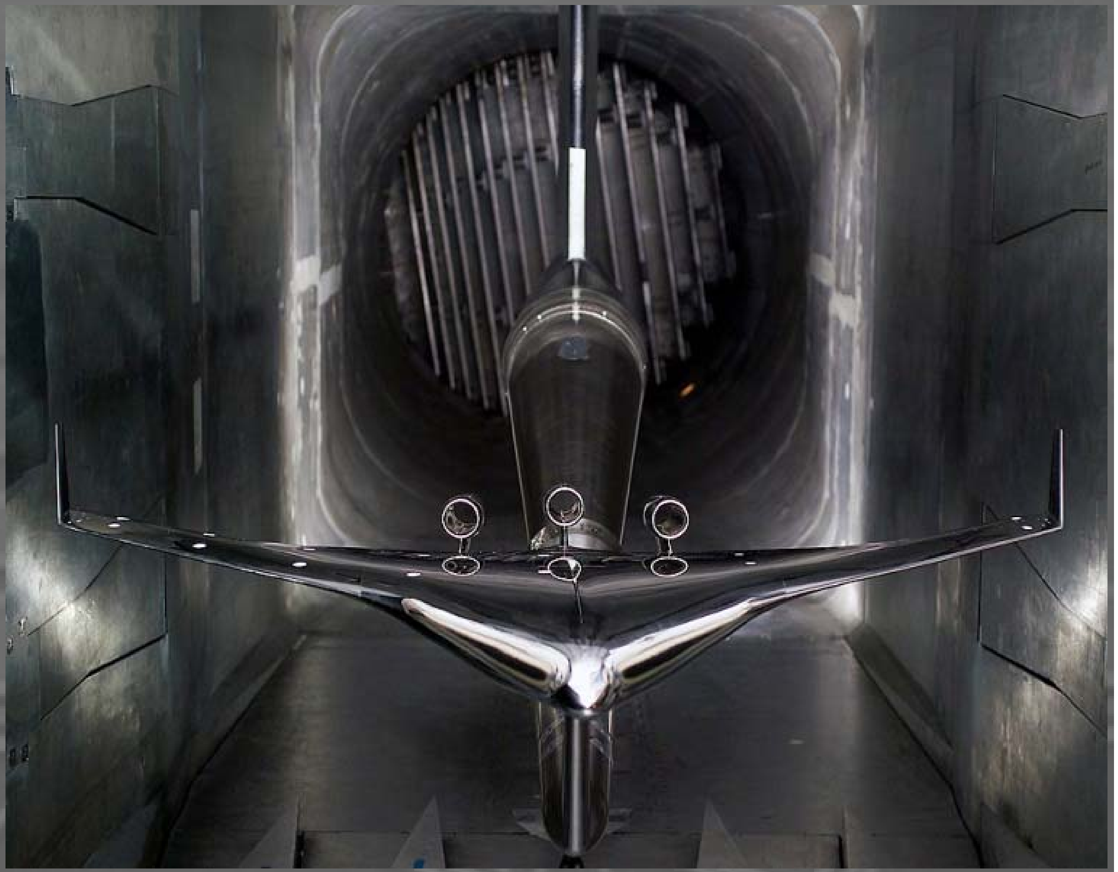
# Ground Testing Applications (Space)




Testing within Thermal Vacuum Chambers.

# Cryogenic Wind Tunnel Environment

- **National Transonic Facility wind tunnel**
  - **-157° C to -101° C**
  - **Pressures 101kPa to 896kPa**
  - **Mach 0.1 to 1.2**
  - **Medium Nitrogen or Dry air**
- **0.3 Meter Cryogenic Tunnel**
  - **-195° C to 54.4° C**
  - **Pressures 101kPa to 607kPa**
  - **Mach 0.1 to 0.9**
  - **Medium Nitrogen or Dry air**
- **Researchers prefer that nothing crosses the balance block which connects the model to the sting.**
- **Wireless sensors could eliminate wiring crossing the model balance.**



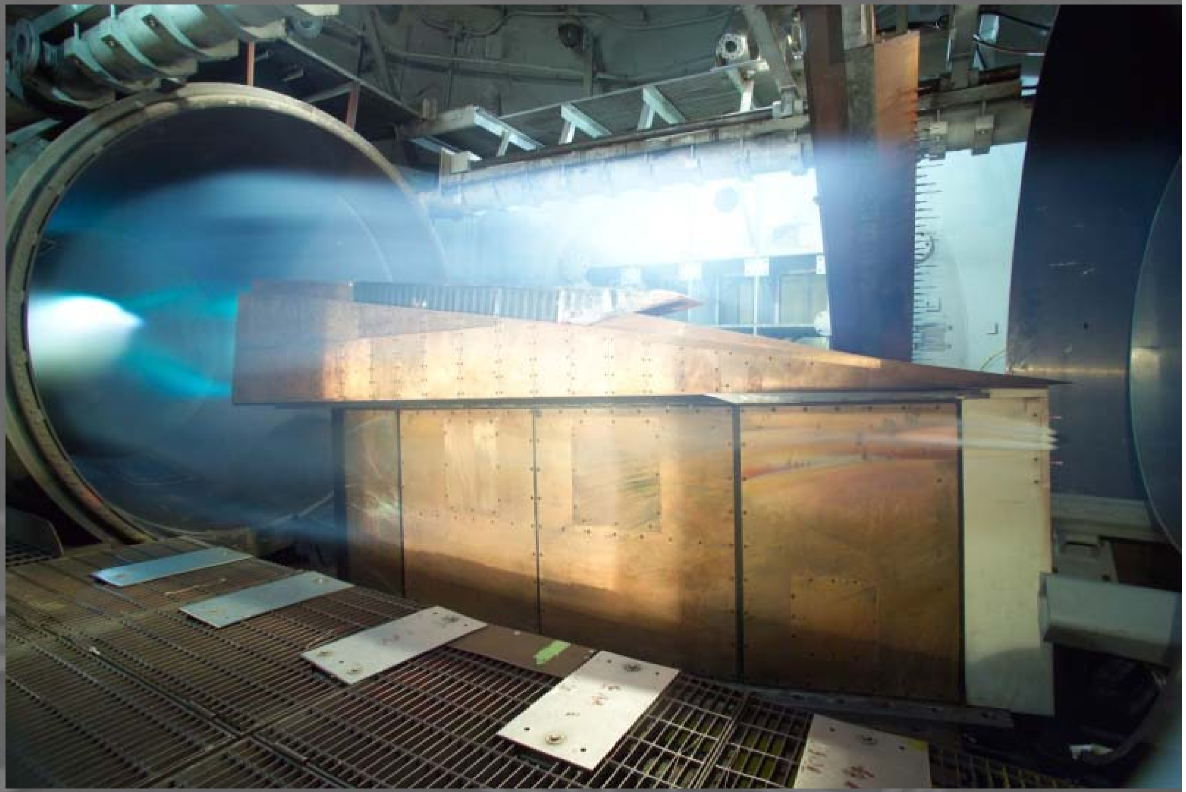
Blended Wing Body model in the test section of the National Transonic Facility wind tunnel, where temperatures can drop to -157 ° C during testing

# Wind Tunnel High Temp Environments

- Arc Heated Scramjet Facility
  – 838° C to 2616° C
  – Mach 4.7 to 8
  – Medium Dry air

- 20-Inch Mach 6 CF4 Tunnel
  – 338° C to 549° C
  – Mach 6
  – Medium CF4 Tetrafluoromethane

- 8Ft High Temp Tunnel
  – 482° C to 1927° C
  – Mach 3,4,5 and 7
  – Medium Burning methane, air, oxygen



**X-51 Engine Test in 8Ft High Temp Tunnel**
**Testing can reach 1927° C**

**The X-51 skin temperature reached 1480° C during flight.**

# Spacecraft Applications

- The Max Launch Abort System (MLAS) was launched on July 8, 2009 from Wallops Island in Virginia.
- The main objective of the launch was to test for a stable trajectory during an unpowered portion of the flight.
- To monitor the capsule during flight ~176 sensors were flown.
  - 87 pressure sensors
  - 52 strain gauges
  - 23 accelerometers
  - 13 thermistors

# Spacecraft Applications

- The ARES 1-X rocket launched on Oct. 28, 2009, equipped with over 906 sensors on board; 689 of the 906 sensors were low data rate sensors:
    - 112 temperature sensors
    - 98 strain gauges
    - 108 accelerometers
    - 371 pressure sensors.

# Space Habitat Applications

Habitat sensors will have to operate in the harsh environments.

Lunar equatorial temperature ranges between 100K and 400K, with a radiation dosage of 0.025 MRad (Si) protected with 2.54 mm of aluminum. The lunar dust becomes charged positively during the day and negatively during the lunar night, causing dust plumes from the surface as the moon rotates.

Martian environment has temperatures that vary from 145K to 293K, and radiation dosage of 0.01 Mrad (Si) protected with 2.54 mm of aluminum.

Shape, strain, humidity, chemical, pressure, and temperature sensors are required.

VSST

# Wireless Sensor Implementation Issues

- Power
  - No Batteries (due to temperature extremes and accessibility issues)

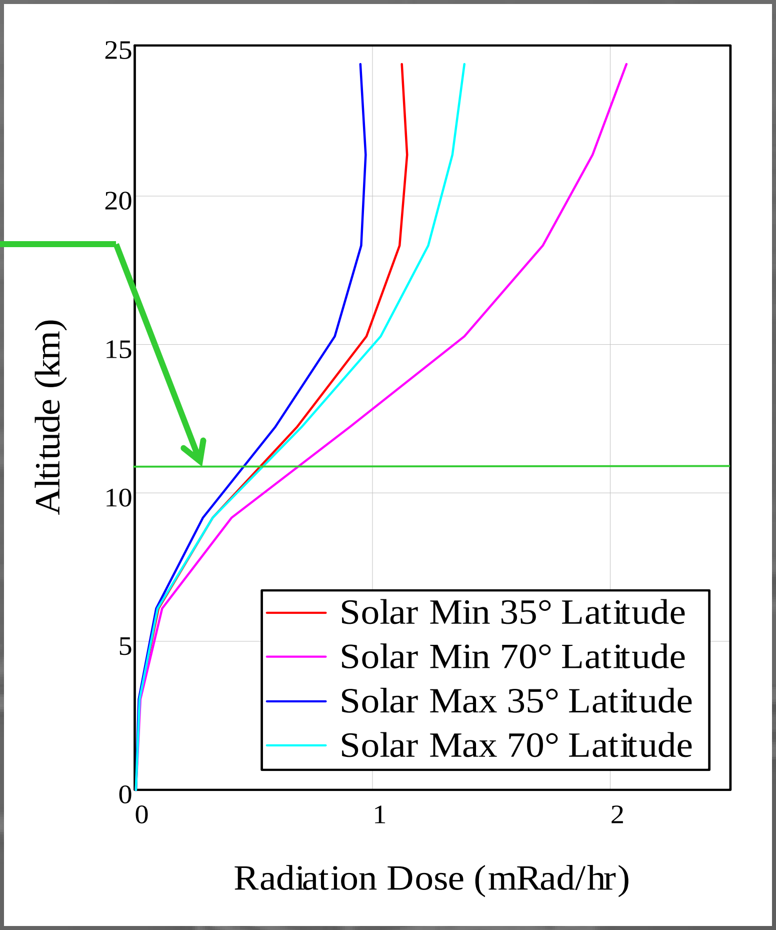
- Harsh Environments
  - Radiation hardened, radiation tolerant
  - Extreme temperatures (high and low)
  - Shock and vibration
  - High Pressure and vacuum

- Reduced: volume and mass

- RF/Communication Issues
  - Higher data rates
  - Modulation techniques (interference single and multipath, multiple sources)
  - Frequency Allocation and RF power levels
  - Certification for flight
  - RF nulls and availability in enclosed metal areas such as in wings/tunnels

# Atmospheric Ionizing Radiation

- Autopilot memory in a modern commercial airliner was found to have 1 upset every 200 hours due to radiation.
- Newer electronics have smaller feature sizes and are more susceptible to single event upsets.
- Ionizing radiation increases with altitude so hypersonic aircraft will require more radiation tolerant electronics.




Radiation dosage vs. altitude for the Solar minimum (10/86) and the Solar maximum (7/89) for 90 degrees west longitude.

# Conclusions

- NASA's Aerospace projects have many applications that could benefit from passive wireless sensor networks, however some are very harsh environments.
  - Propulsion systems 1538° C
  - Hypersonic skin heating 1282° C
  - Wings & Structure -60° C ~ 190° C
  - Fuel Tanks cryogenic -190° C
  - Wind tunnel testing -195° C ~ 2616° C
  - Ionizing Radiation
  - Vibration
- Despite the challenges new technologies may be the answer
  - SAW?
  - MEMS?
  - RFID?
  - Backscatter?

X-51 Engine Test in 8Ft High Temp Tunnel
Testing can reach 1927° C

# Funding/Partnership Opportunities

- NASA does not have the resources to develop all of the sensors it needs for its applications, therefore, we are looking for partners!

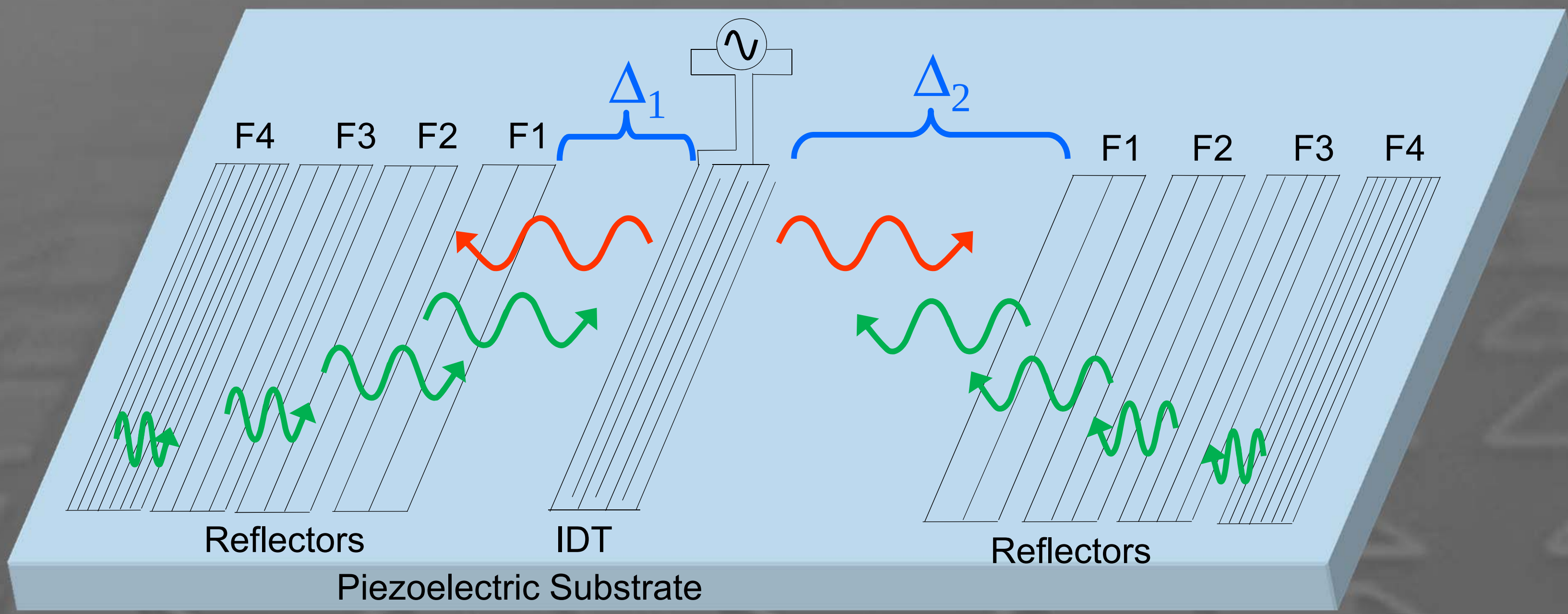
- NASA Research Opportunities (NRAs) Grants & Contracts
  - http://nspires.nasaprs.com/

- Small Business Innovation Research (SBIR) Small Business Technology Transfer (STTR)
  - http://sbir.gsfc.nasa.gov/

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

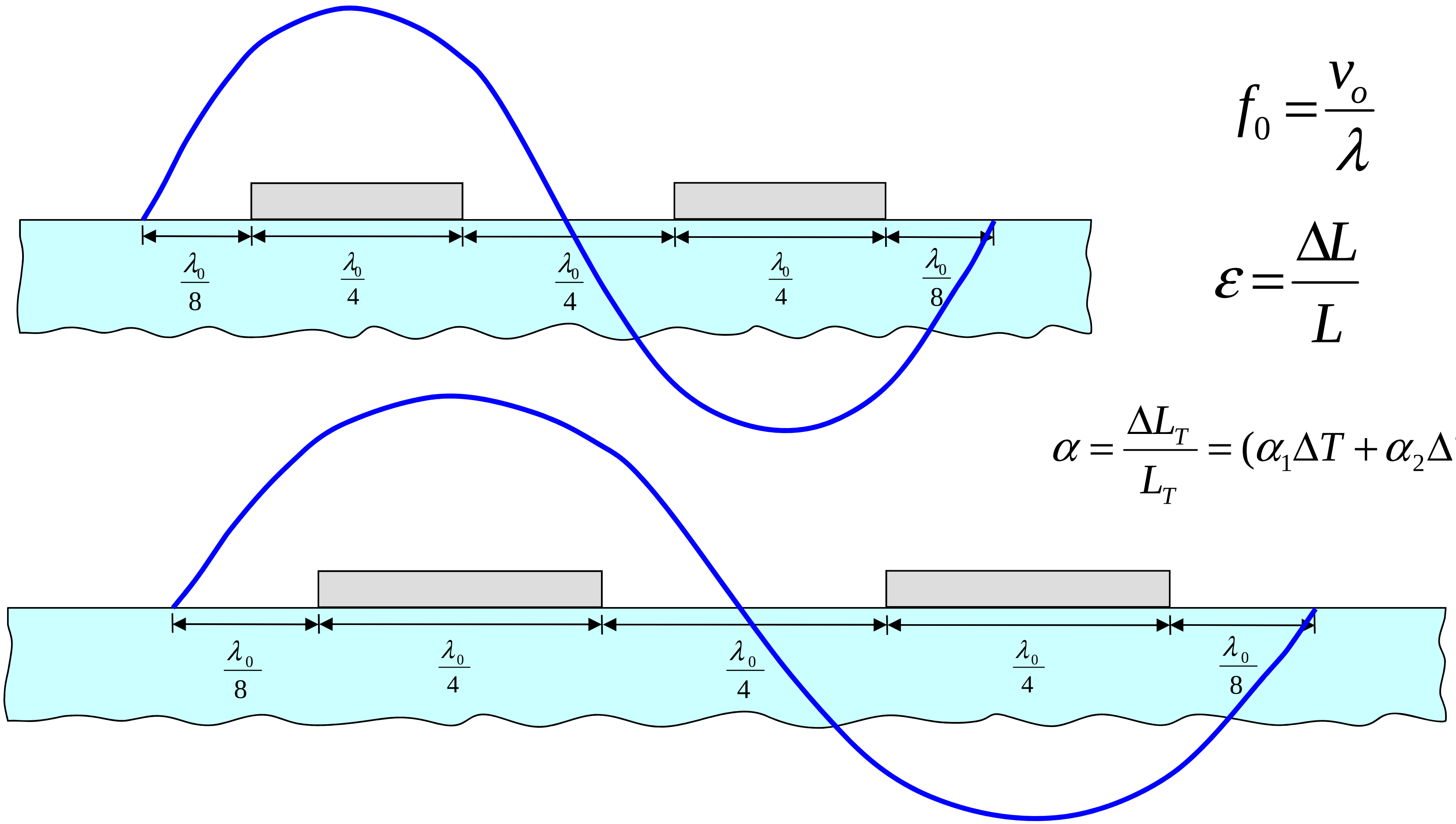
# Auxiliary Slides

# Single IDT OFC SAW Sensor




- SAW sensor that employs four orthogonal frequency coded (OFC) reflectors in two banks.
- Broadband signal generates SAW waves from the IDT (red arrows).
- Each reflector grating reflects a single frequency back (green arrows).
- $\Delta_1$ and $\Delta_2$ are the spacings between the reflector banks and the IDT.
- $\Delta_2 > 2\Delta_1$ so ensure the reflector banks responses do not overlap in time.
- The reflected signals change frequency in response to physical changes.
- OCF uniquely codes each sensor and is Spread Spectrum (multiple frequencies).

# Effects of Strain on SAW Device




$$f_0 = \frac{v_o}{\lambda}$$

$$\varepsilon = \frac{\Delta L}{L}$$

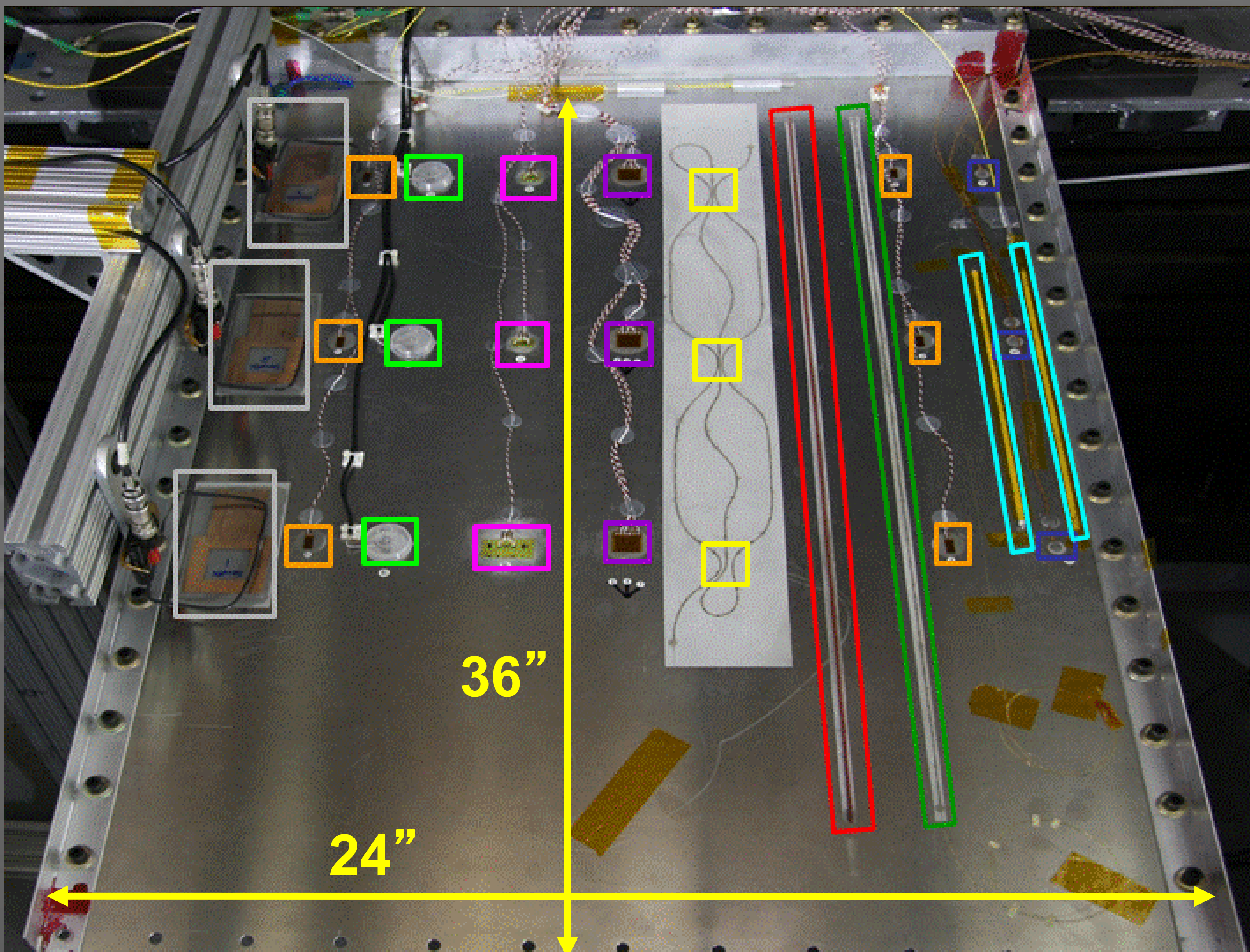
$$\alpha = \frac{\Delta L_T}{L_T} = (\alpha_1 \Delta T + \alpha_2 \Delta T^2)$$

# Material Selection

- Single crystal Langasite ($La_3Ga_5SiO_{14}$) (LGS) was chosen for the substrate, Euler orientation of (0, 138.5, 26.6) .
- Advantages: Curie temperature ~1470° C
  - Potential -196.15° C (Malocha) – 1470° C (900° C Da Cuhna)
- Disadvantage: more expensive material.

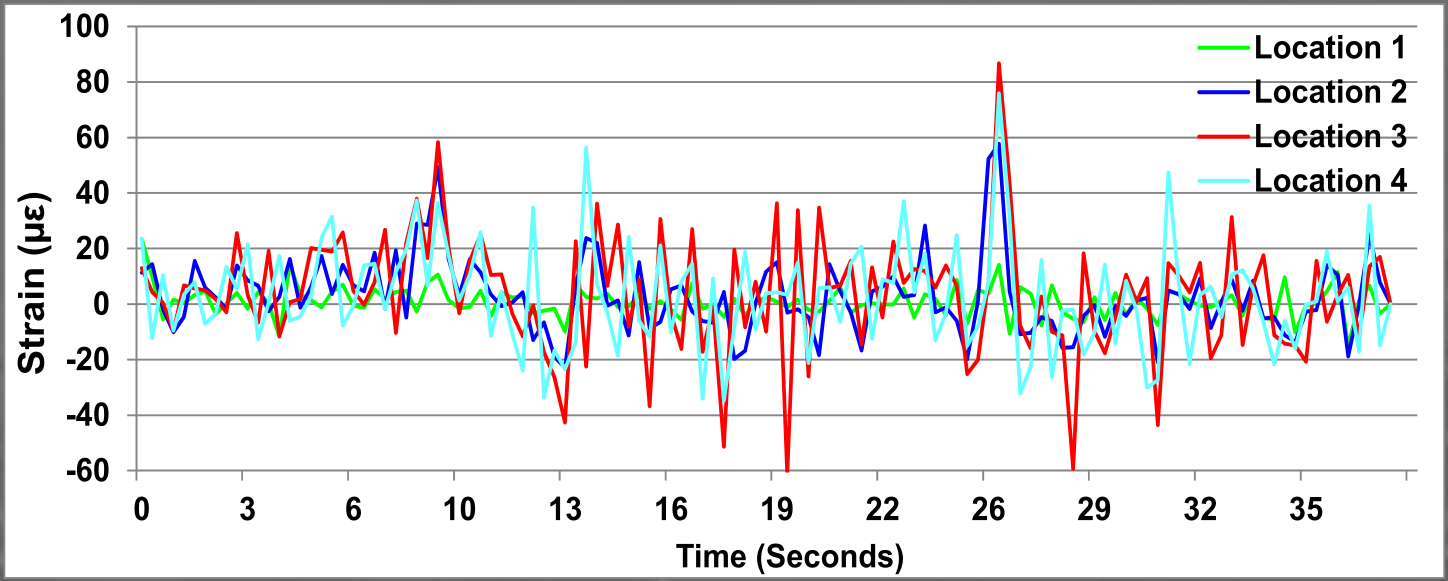
| | LGS | LiNb | Quartz | AlN | GaP |
|---|---|---|---|---|---|
| Temp Melting ° C | 1470 | 1253 | 1610 | 2200 | 1300 |
| Temp Curie ° C | ~1470 | 1150 | 573 | 950 | 970 |
| Coupling (k) | 0.0032 | 0.45 | 0.0016 | 0.026/0.06 | 0.092 |
| SAW Velocity (v) m/s | 2741 | 3992 | 3158 | 5600 | 2539 |
| Critical Temp ° C | ~1470 | 600 | 573 | ~950 | ~930 |
| Degradation mechanism | | Oxygen loss | Twinning | Oxidization | |

# Sensor Technologies




- Rosette Strain Gage
- Strain Gage
- FO Strain Gage
- FO Rosette
- FO Thermography
- SAW Device
- Nanotubes
- Shape Sensing
- SansEC
- Thermocouple

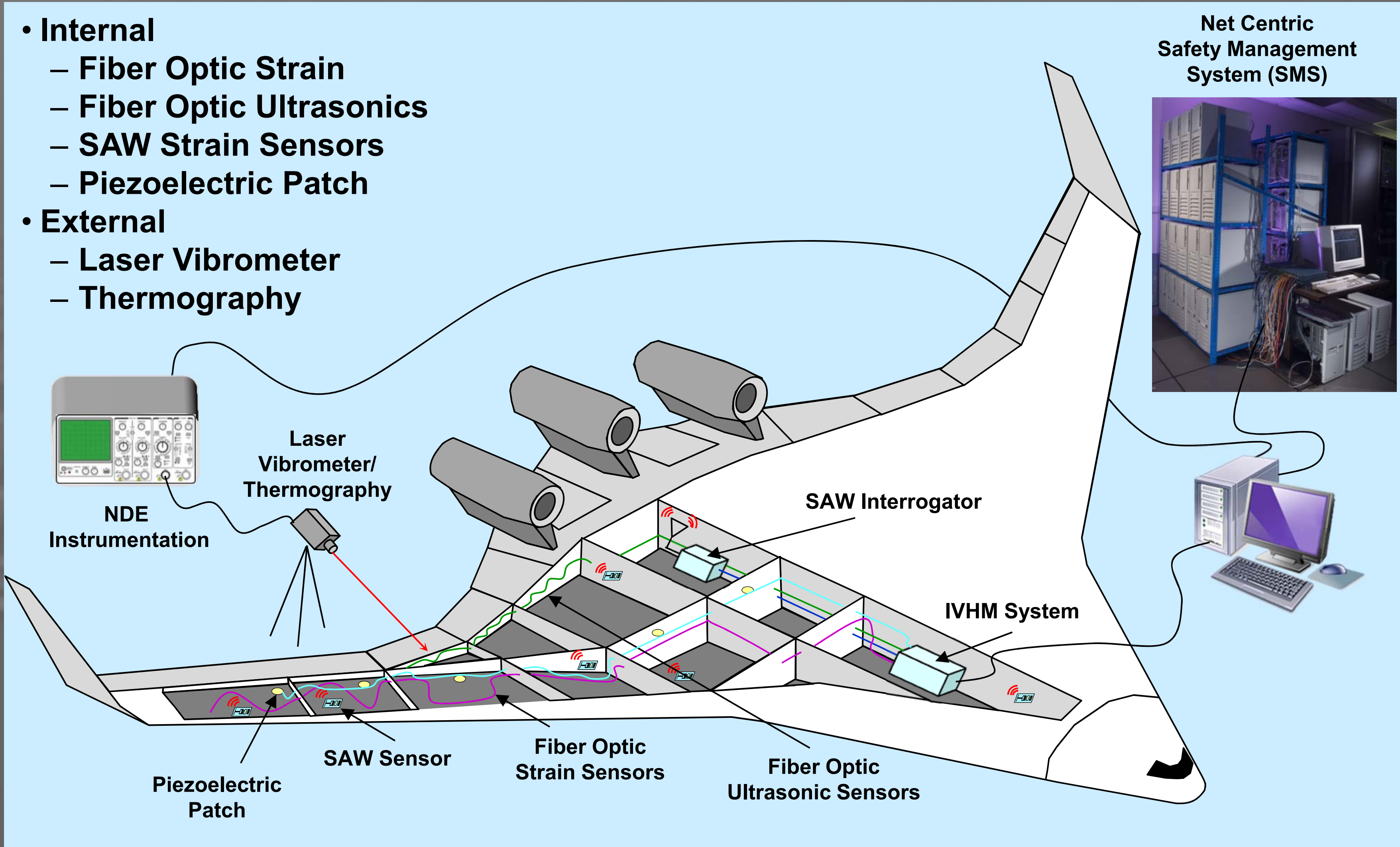
# Aircraft Vibrational Noise




- Strain sensor vibrational noise from four locations on the wing leading edge during takeoff.
- The raw sensor data was filtered with a two point moving average. The moving average was subtracted from the original data leaving the vibrational noise only.
- The structural noise, which is mostly due to vibrations of the aircraft, is -60 με to +85 με.

# Hybrid NDE/SHM

- Internal
  - Fiber Optic Strain
  - Fiber Optic Ultrasonics
  - SAW Strain Sensors
  - Piezoelectric Patch
- External
  - Laser Vibrometer
  - Thermography




**Aircraft in the Loop concept connects the onboard IVHM system to external NDE instrumentation and a Net-centric Safety Management System (SMS)**