Passive Wireless Sensing (PaWS™) in a High-Multipath, High-Doppler Environment

University partners:
- *ElectroScience Laboratory, OSU*
- *Experimental Mechanics of Materials Laboratory, OSU*
- *NanoTech West, OSU*

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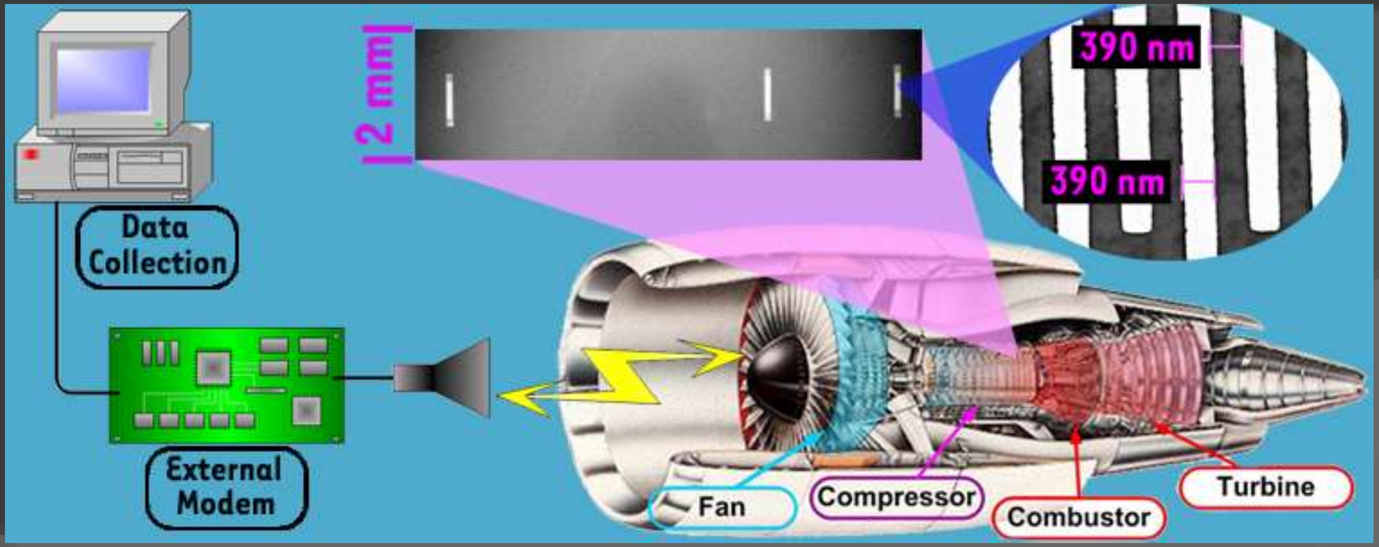
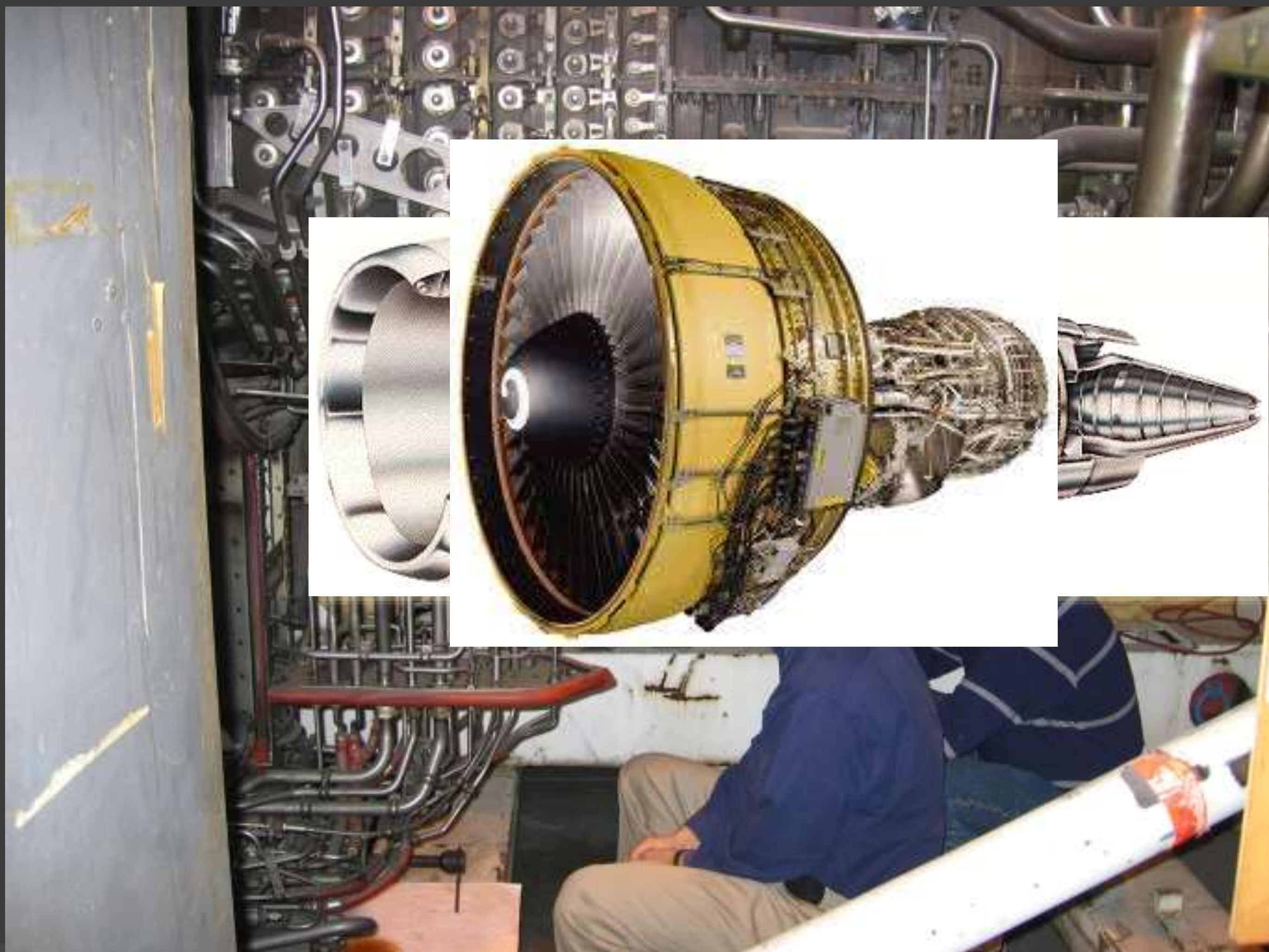
June 7, 2012
Syntonics LLC
Bruce G. Montgomery, President

PaWS enables valuable measurements inside moving or inaccessible machinery

- PaWS uses:
  - Small, conformal, surface-acoustic wave sensors that …
  - Operate without power up to and above 600C to …
  - Wirelessly measure strain, temperature, pressure, etc. …
  - On moving or stationary parts inside compressors, turbines, pumps, rotor heads, transmissions, etc.



RF Propagation in a Jet Engine



GE CF6-50 Jet Engine at National Museum of the U.S. Air Force, Whight Patterson AFB, Dayton OH

Engines Tested

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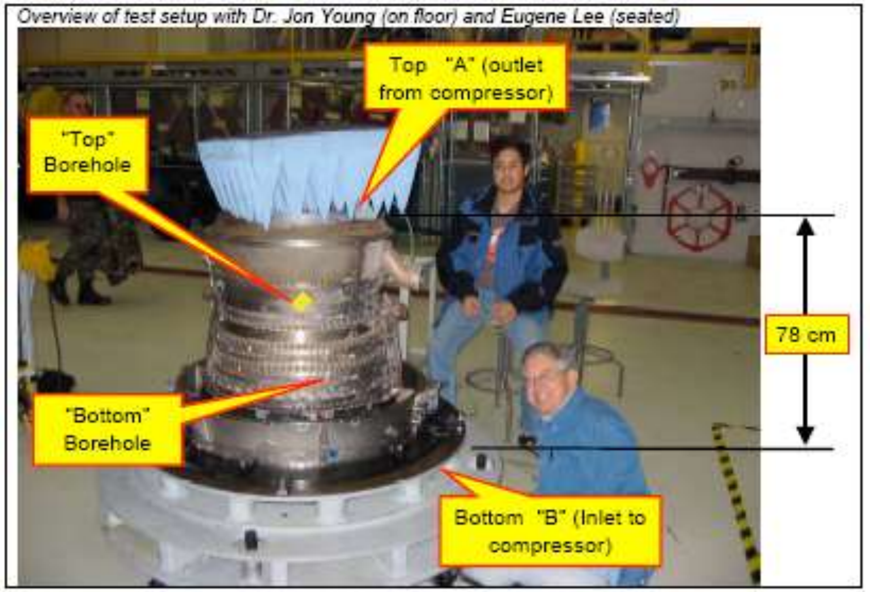
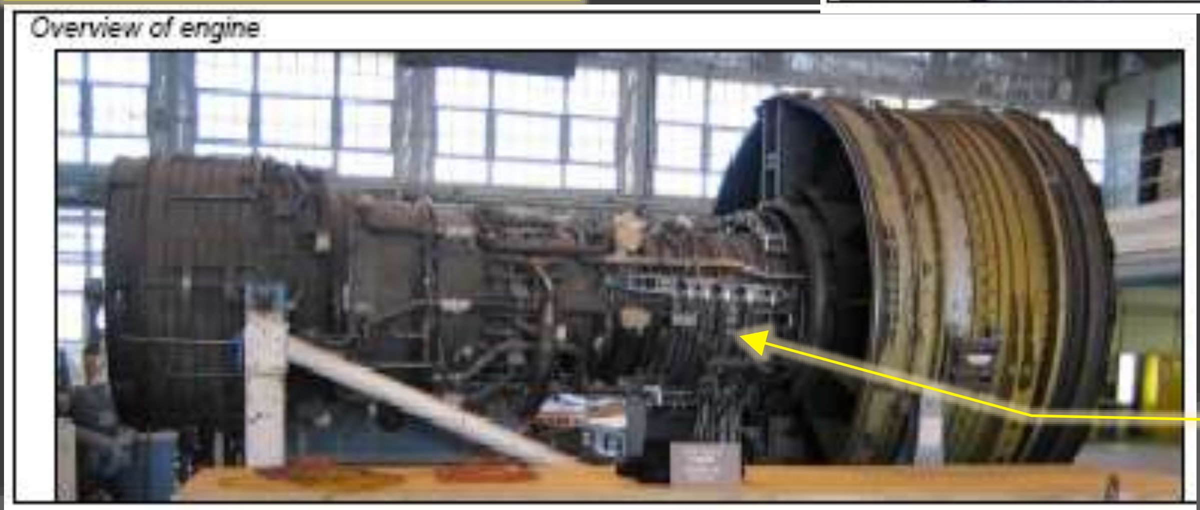
Small Jet Engine
- Compressor stage (only) used on GD F-16
- "B" = Inlet to Compressor (bottom in this photo)
- "A" = Outlet from Compressor (top in this photo)



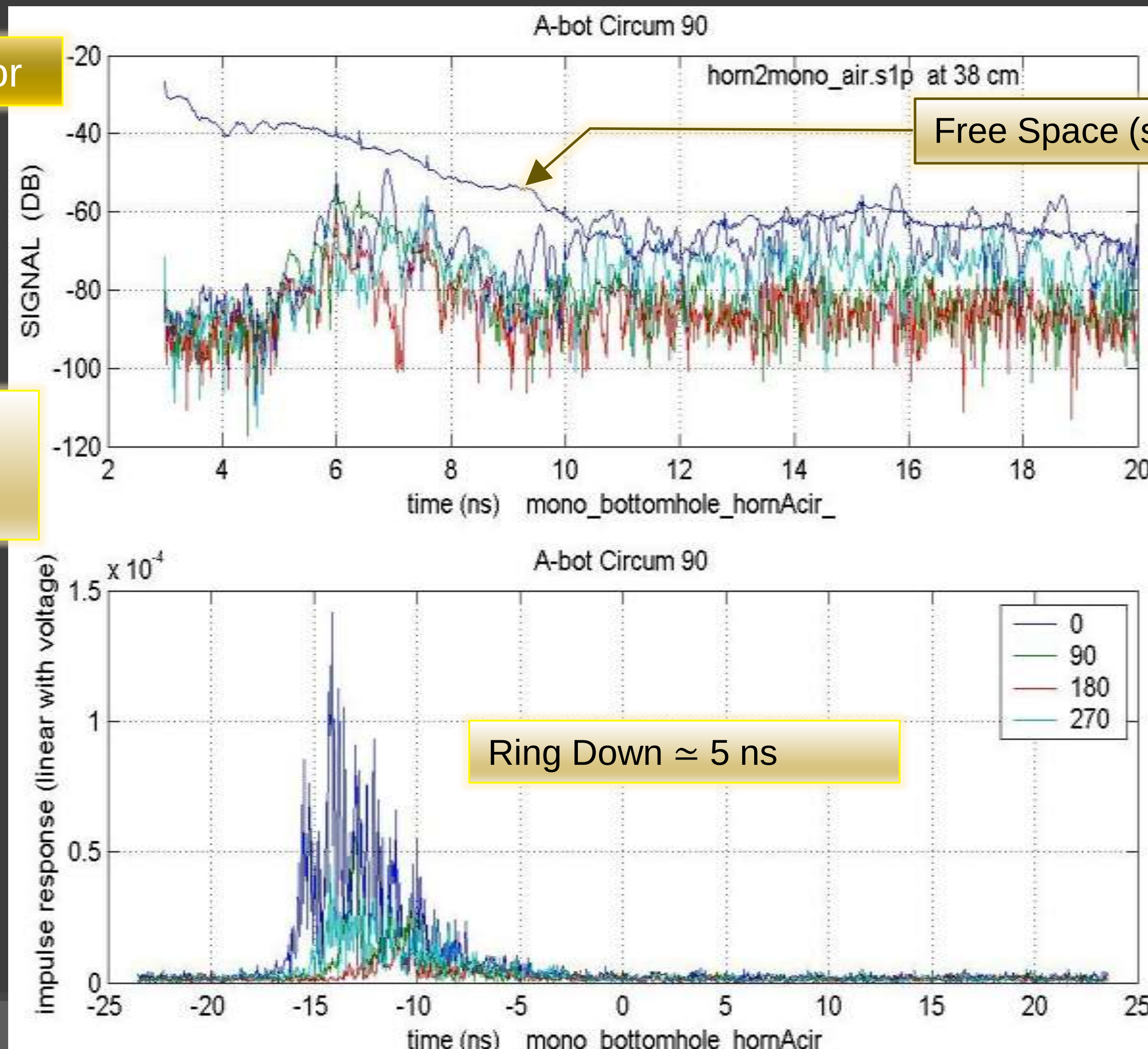
Large Jet Engine
- Engine used on Boeing 747



Transmission, Compressor Outlet to Bottom Borehole

F-16 Compressor

Circumferential polarization, 90˚ increments

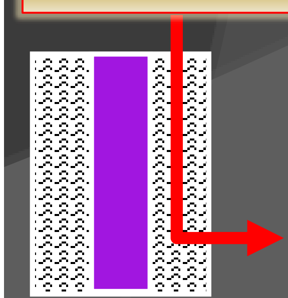


Free Space (same distance)

Ring Down ≃ 5 ns

Other data shows similar ripple pattern

Circumferential Polarization



Transmission, Compressor Inlet to Stage 1

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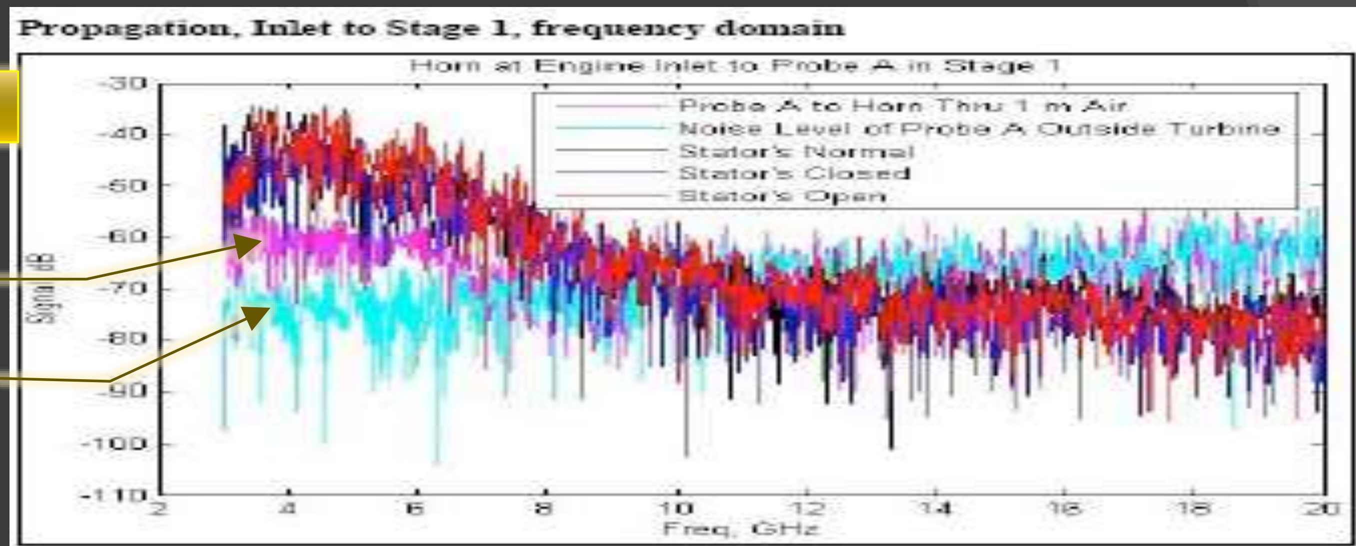
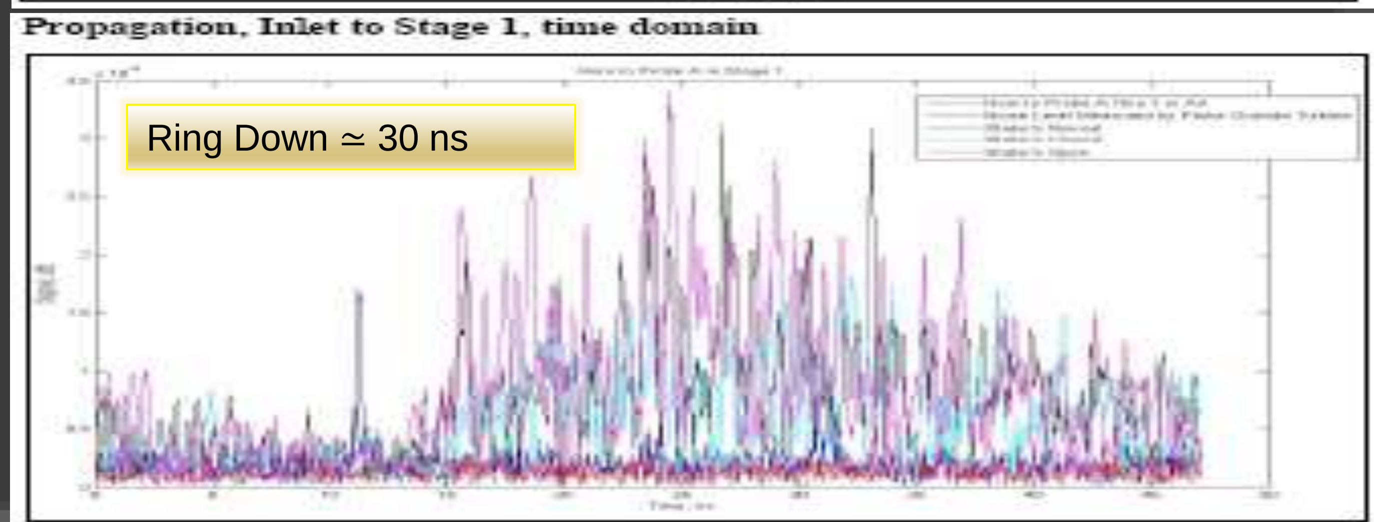
747 Compressor

Free space

Noise level

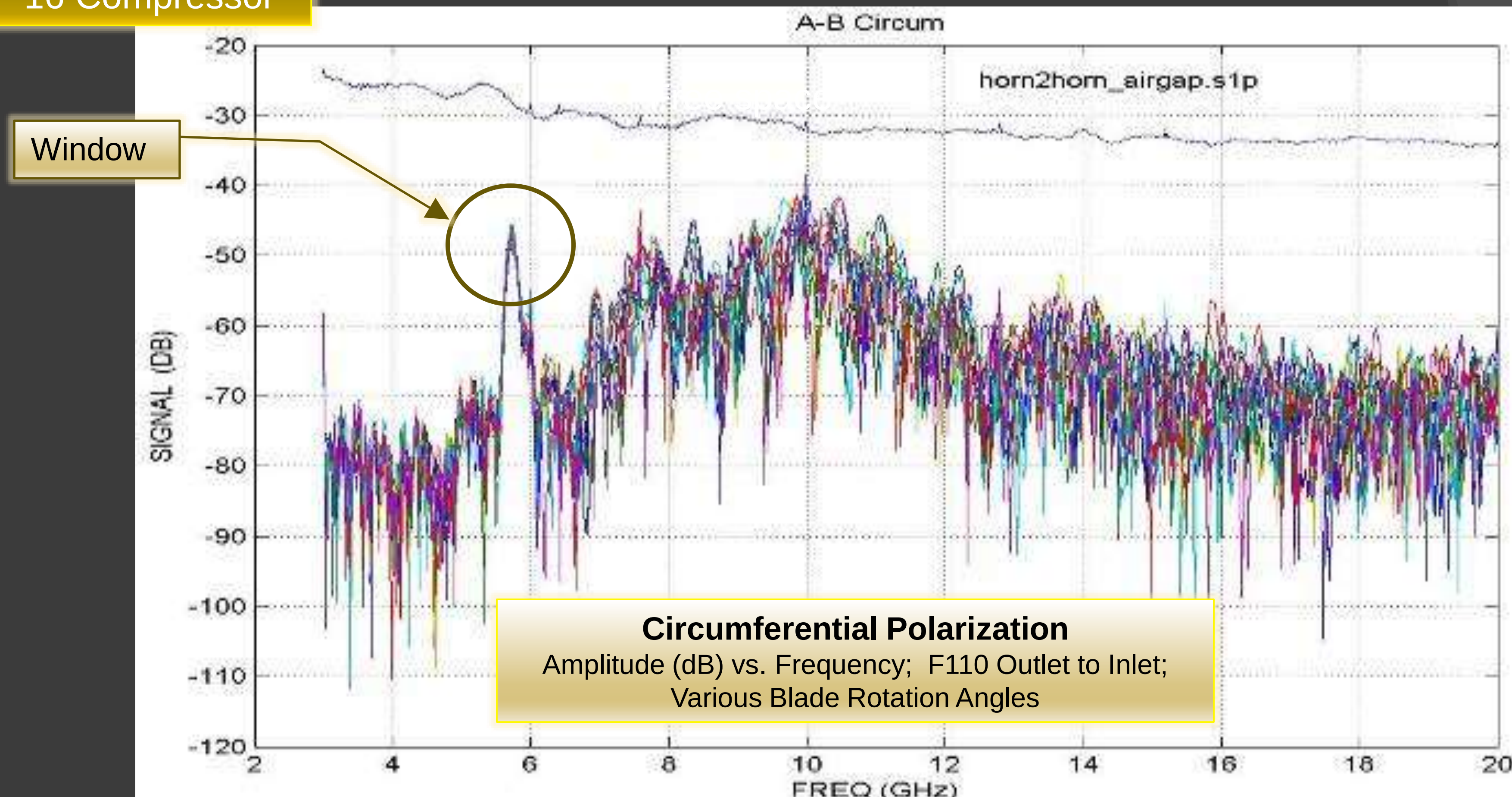




Ring Down ≃ 30 ns

Transmission, Outlet to Inlet, Circular Polarization

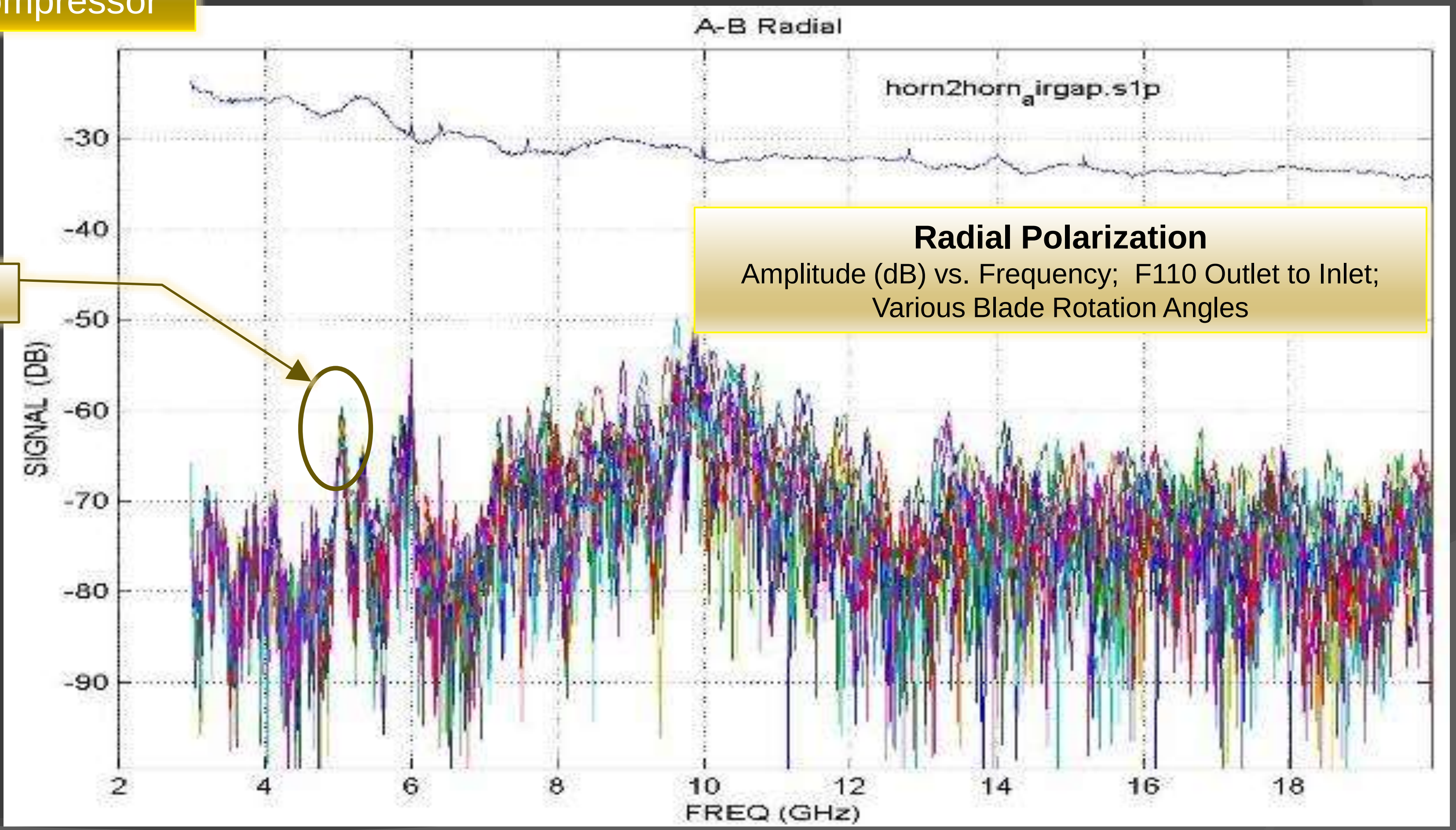
F-16 Compressor



Transmission, Outlet to Inlet, Radial Polarization

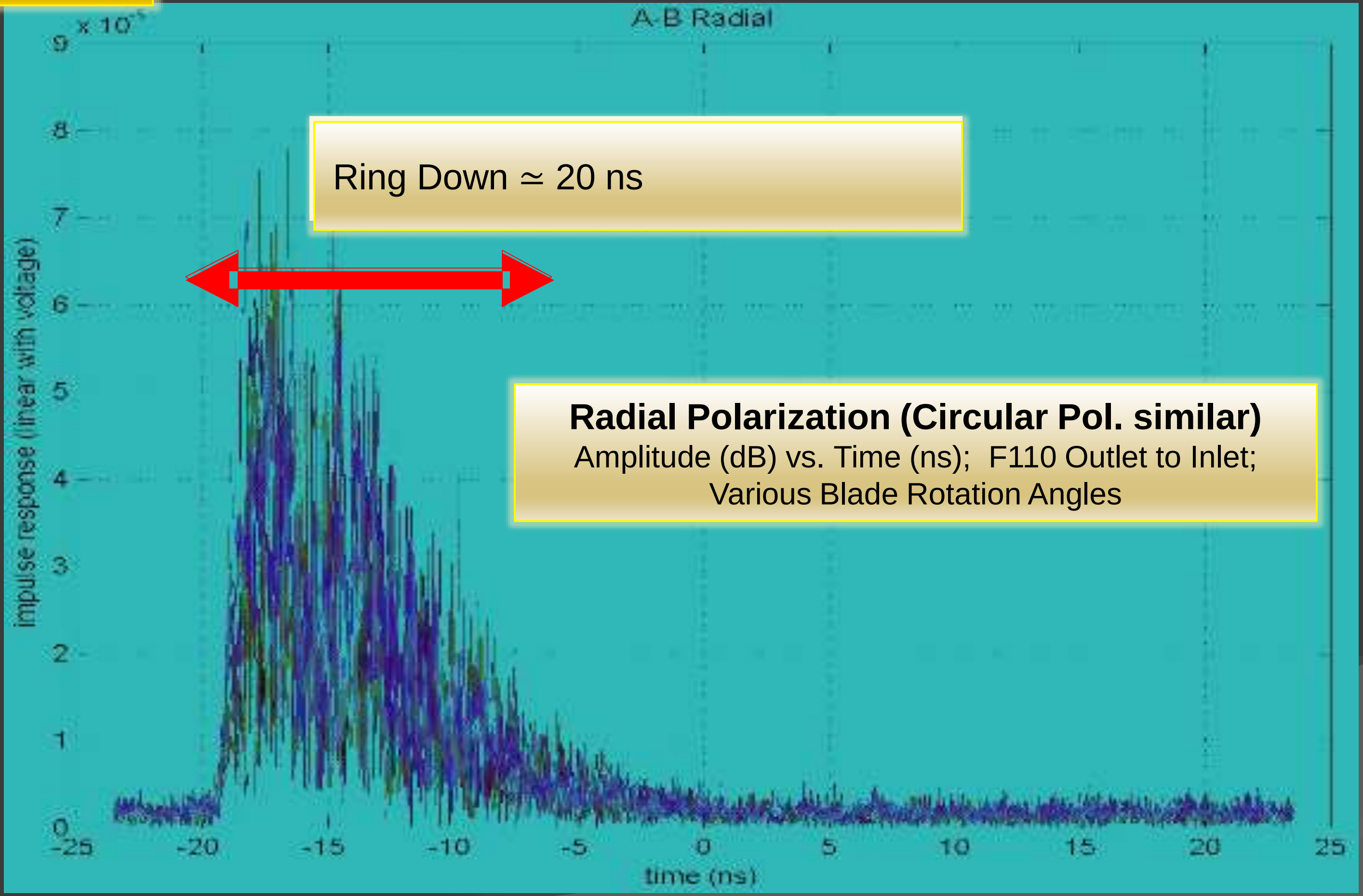
F-16 Compressor

Window



Ring Down

F-16 Compressor



Waveguide Cutoff

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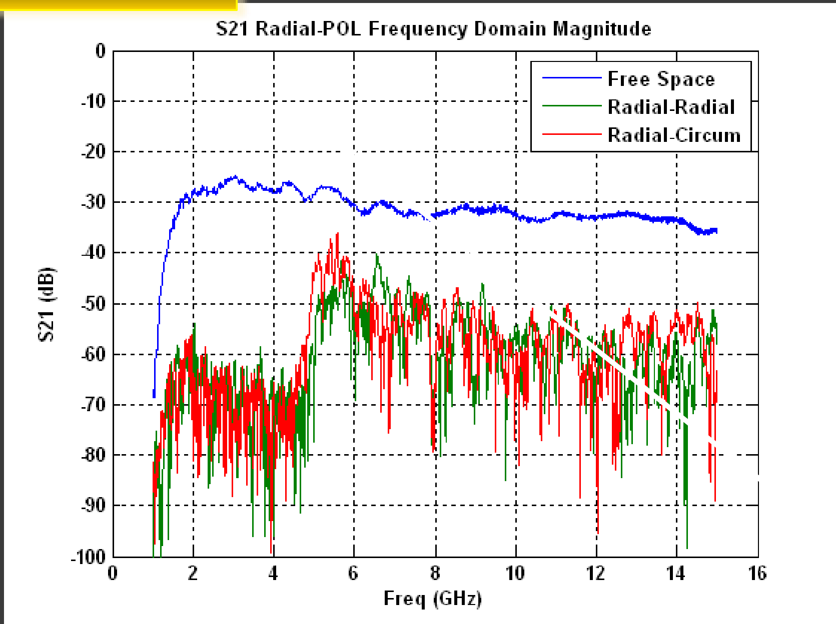
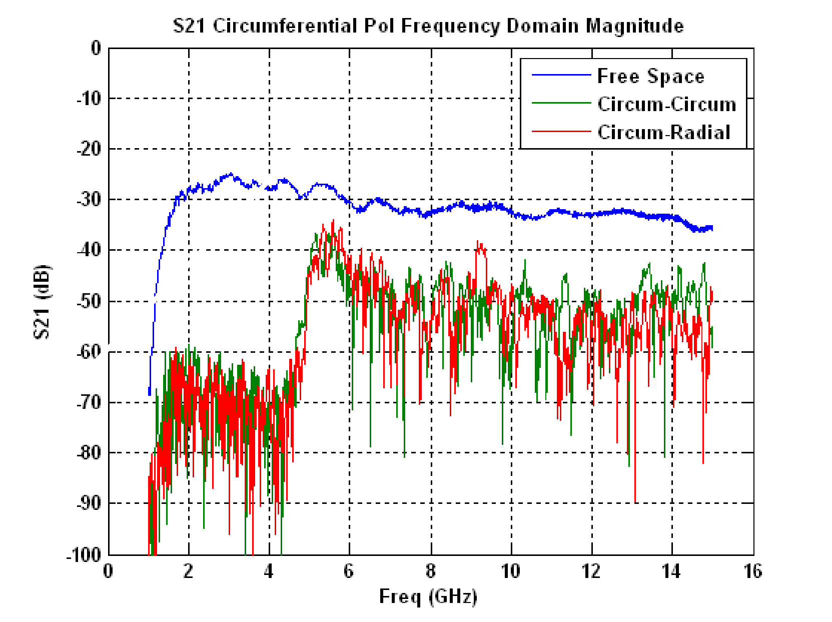
F-16 Compressor





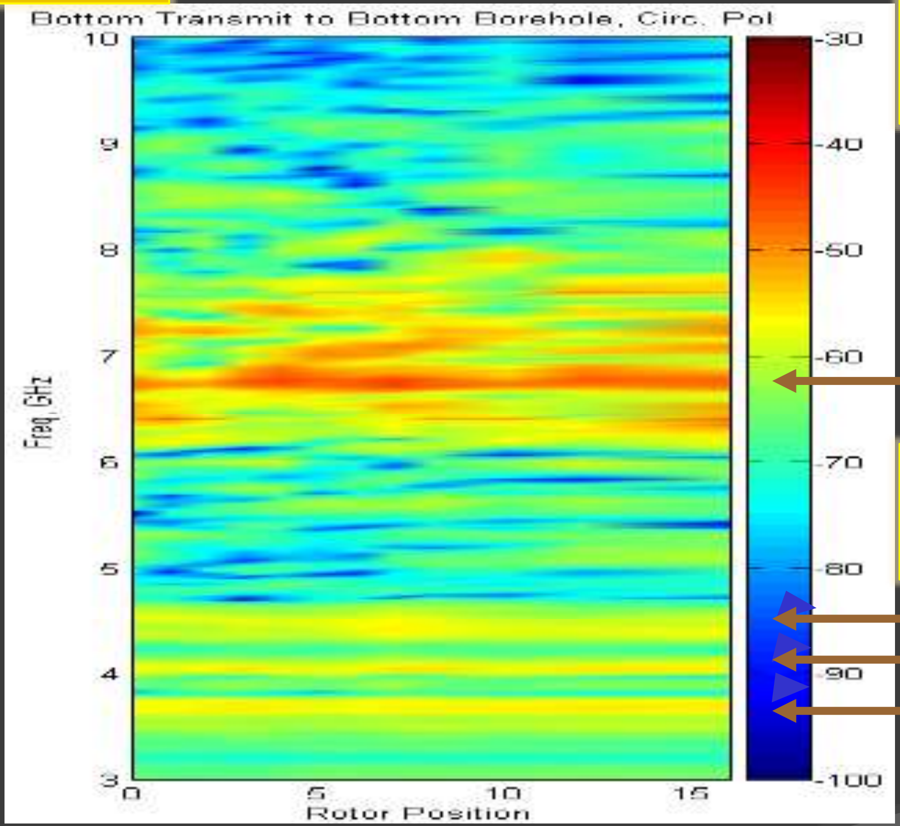
Waveguide Cut-off

- **Similar propagation characteristics observed for four polarization measurements**
- **In all cases, cut-off frequency of ≈ 5.2 GHz is observed**

- **1000 times (30 dB) more power is required to communicate with sensor at frequencies lower than cutoff**
- **Two way comms are twice as bad: 1,000,000 times more power!**

EM "Windows" in Jet Engine Turbines

F-16 Compressor



- Amplitude (dB) vs. Frequency and Rotation
- Propagation to Farthest Borehole (circumferential polariz)

"Windows" = No variation with rotation!

Conclusions from Propagation Measurements

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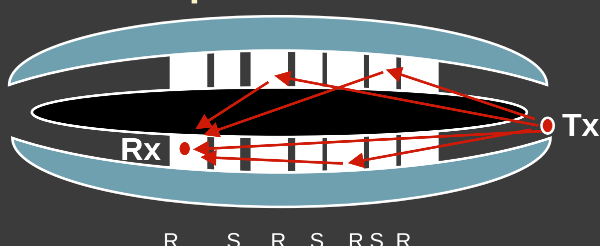
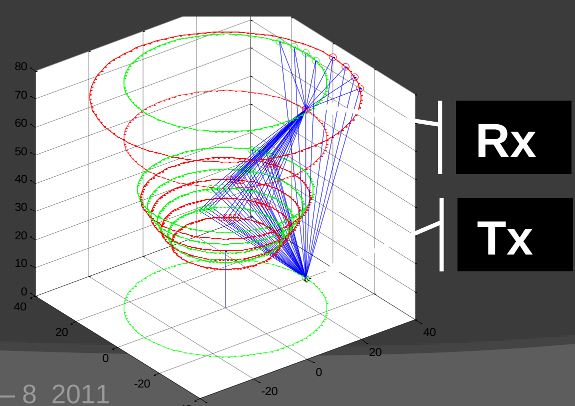
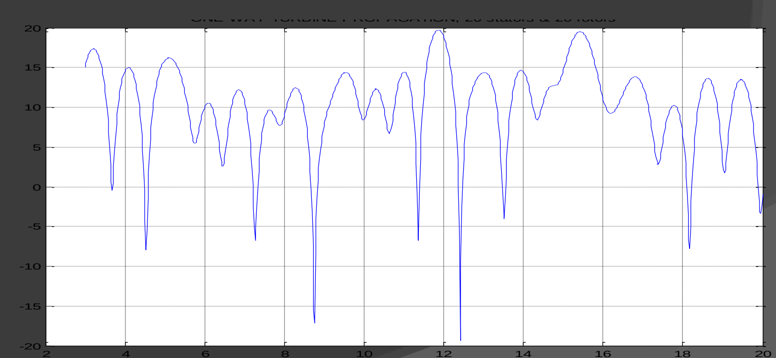
- Signal loss can be less than in free space's 1÷R2
- There is no isolated initial time domain term
  - Signal is spread out in time, so initial direct term is as small as the multiple reflection terms
- Multiple reflection terms spread out over a duration that corresponds to ⪅3 times the physical size of the compressor
- In the time domain:
  - Individual stages can be discerned
  - But not individual turbine blades
  - This indicates that internal compressor propagation:
    - Is axial
    - With multiple reflections
    - But not circumferential or spiral
- PaWS must operate above the "cutoff" frequency

Propagation Modeling

- Modeled propagation as a transmitter and receiver with “point” scatterers in between
  - “Point scatterer” is a point in space where the scattering is centered
  - The scatterer has no frequency, angle, or polarization dependence

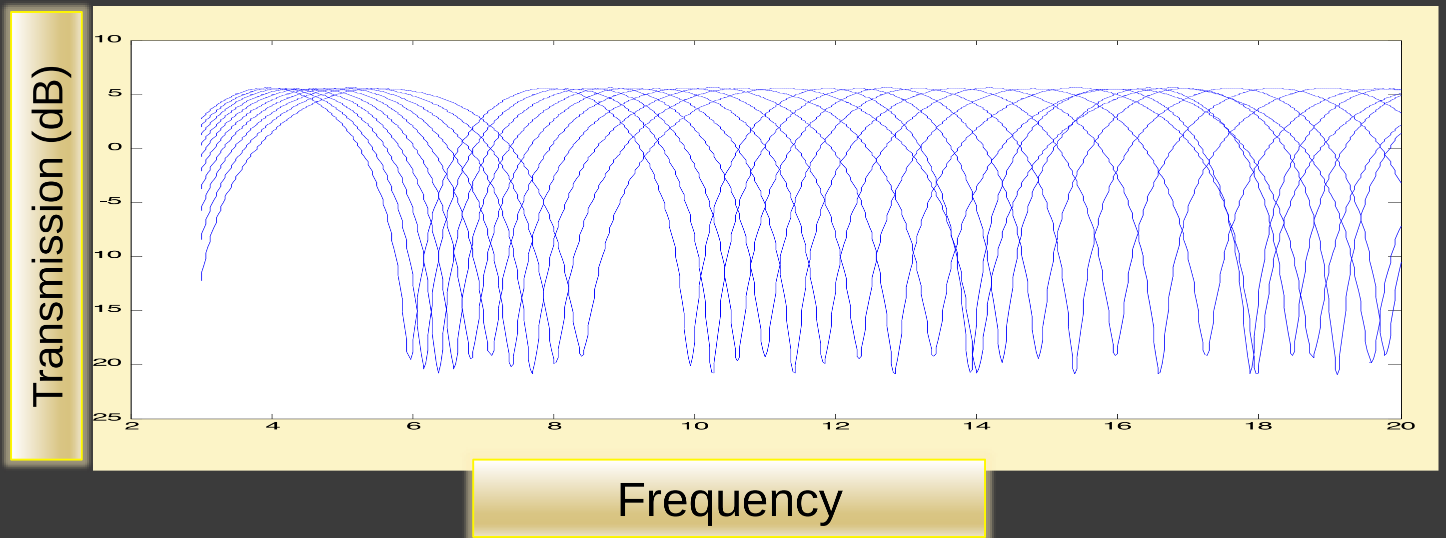






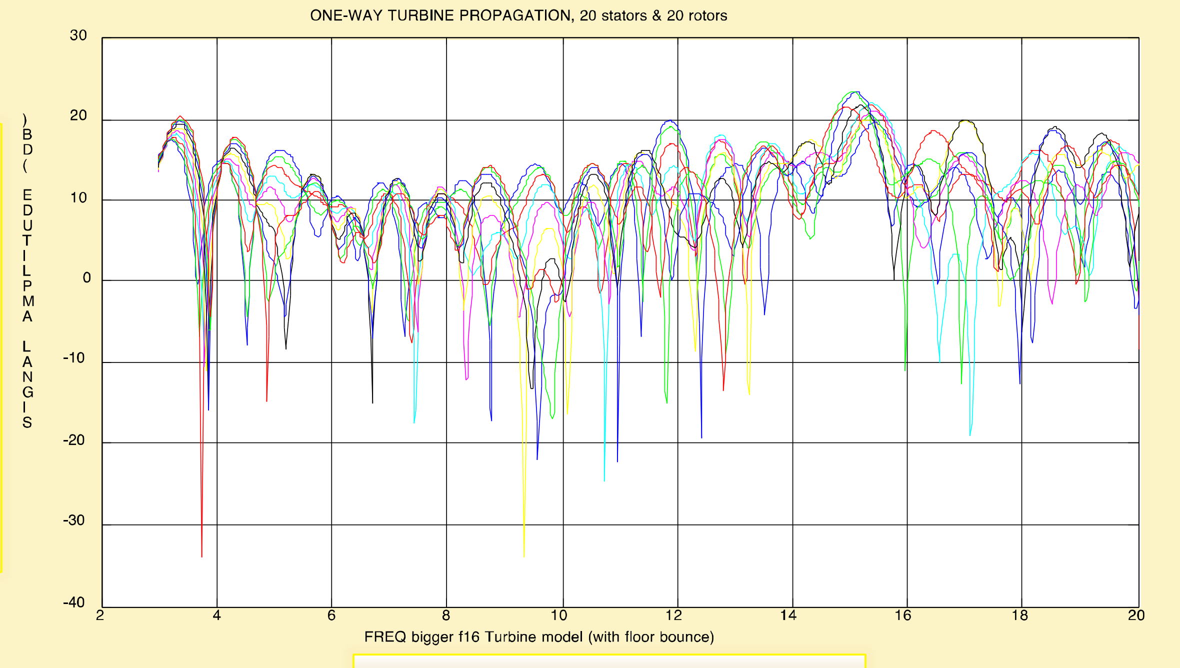
Model results closely correlated with the measured data

Simple Scatterer Case



- Set of frequency scans for rotating turbine (simple scatterer case)
- Basically the phase of the scatterer varies with the rotation, as expected

More Complex Scatterer Case



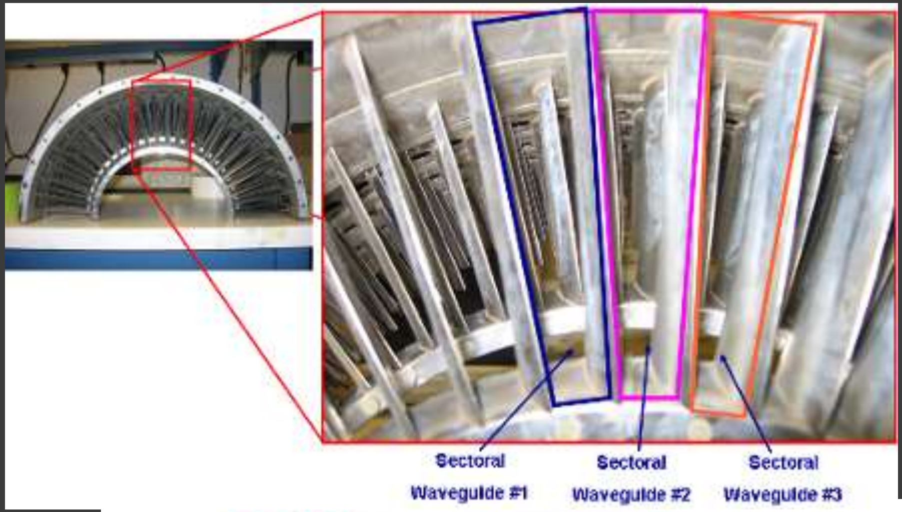
Transmission (dB)

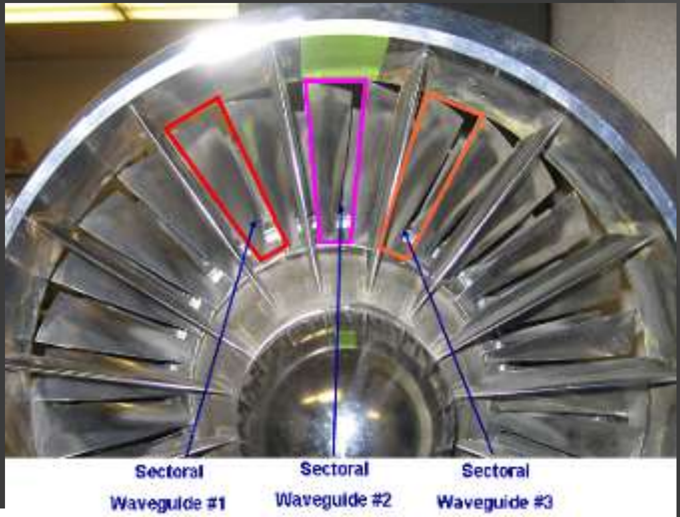
Frequency

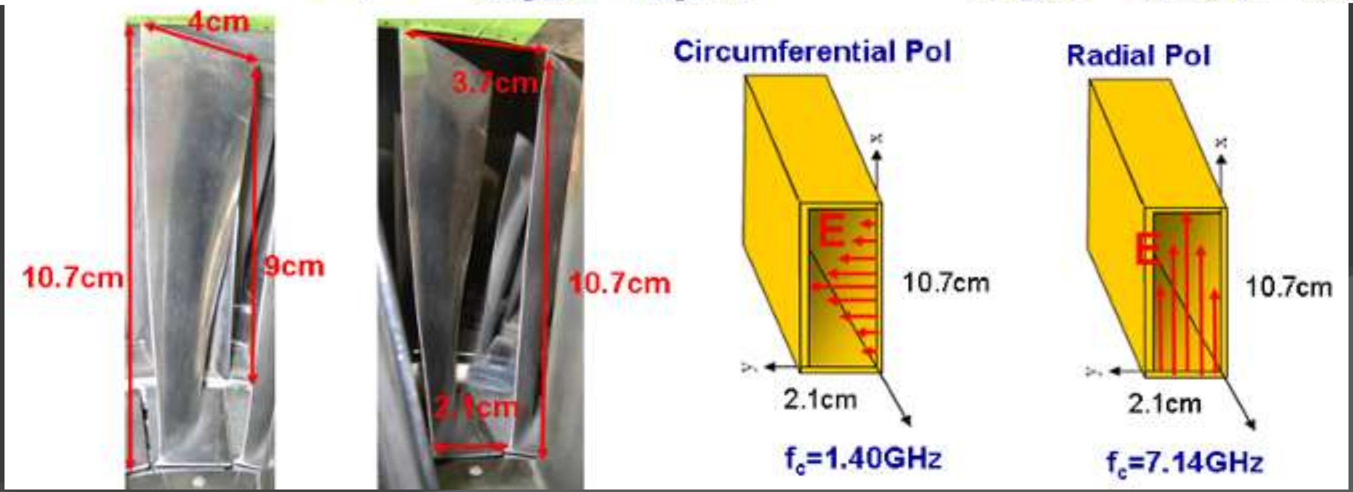
Example results from the model data for various blade rotation angles

- 1-way propagation
- 20 stators, 20 rotors

Adding Wave Guide Cutoff to Model



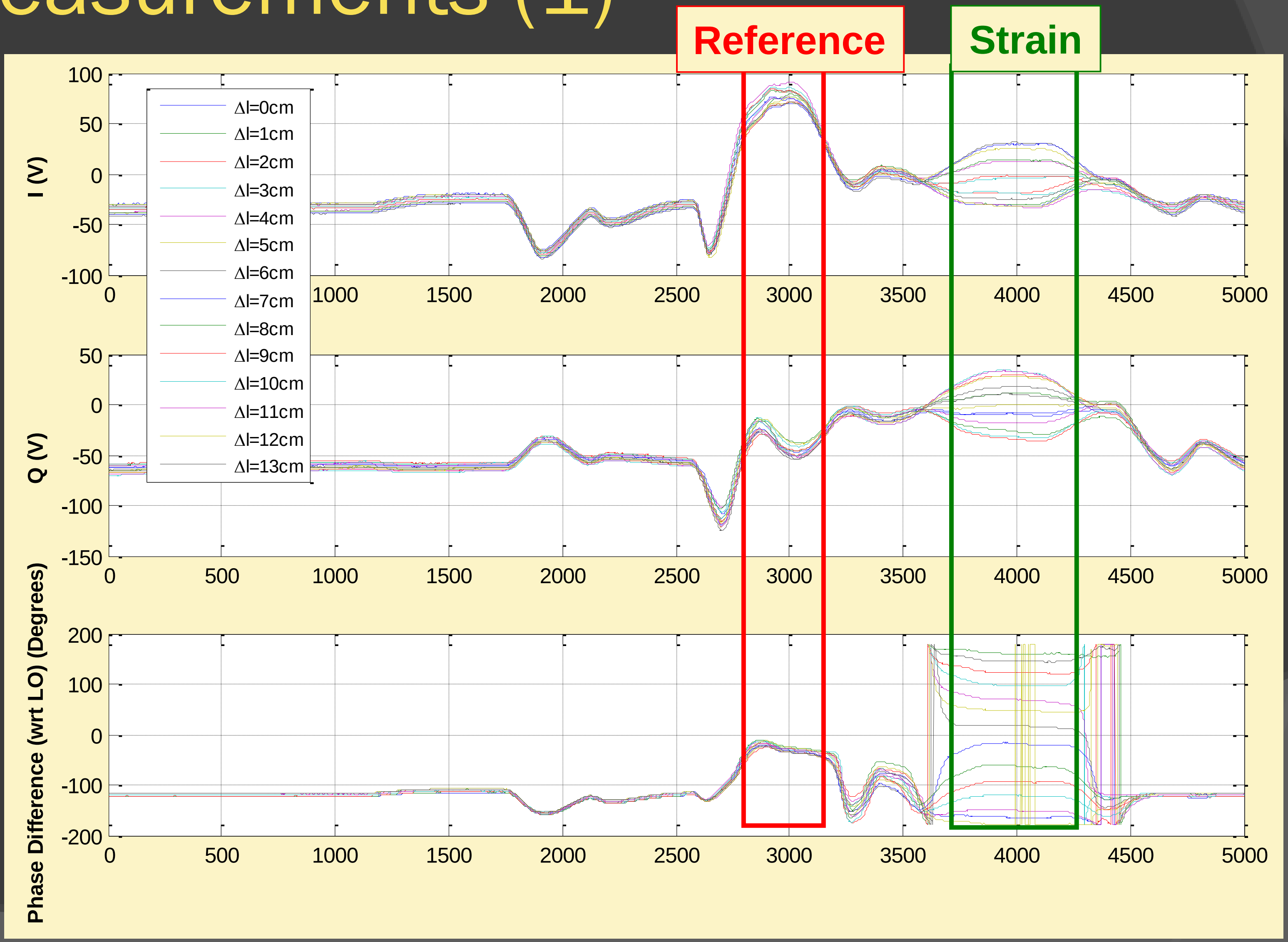




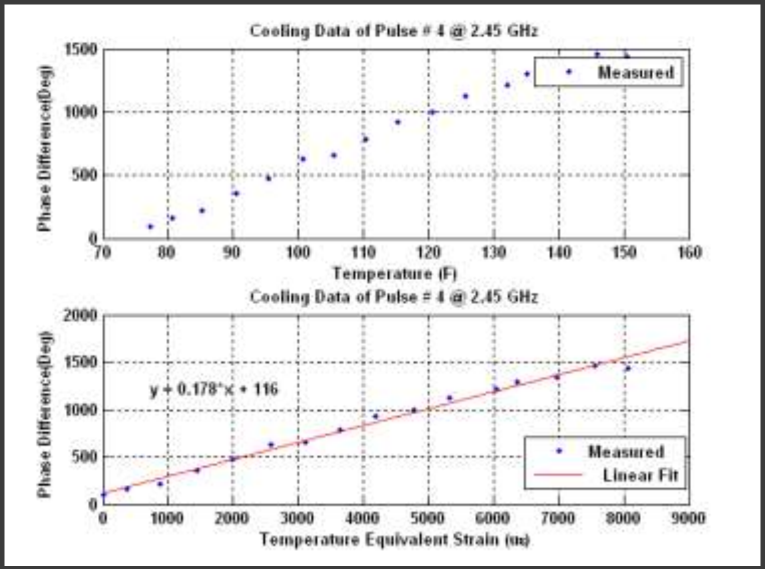
Analytical Results for Cutoff Frequency of Several Stages

STAGE	L1 [cm]	L2 [cm]	w [cm]	S_{top} [cm]	S_{bottom} [cm]	f_c[GHz] Circum (L1)	f_c[GHz] Circum (L2)	f_c[GHz] Radial (S_{top})	f_c[GHz] Radial (S_{bottom})
Rotor 1	9.0	10.7	4.0	3.7	2.1	1.67	1.40	4.05	7.14
Stator 1	8.0	9.0	2.3	2.5	1.27	1.88	1.67	6.00	11.81
Rotor 2	6.9	7.7	2.0	2.0	1.20	2.17	1.95	7.50	12.50
Stator 2	6.1	7.2	1.8	1.7	1.10	2.46	2.08	8.82	13.64
Rotor 3	5.4	6.0	1.5	1.4	1.00	2.78	2.50	10.71	15.00
Stator 3	4.7	5.2	1.2	1.3	0.95	3.19	2.88	11.54	15.79
Rotor 4	4.2	4.8	1.2	1.1	0.90	3.57	3.13	13.64	16.67
Stator 4	3.8	4.3	1.2	1.1	0.90	3.95	3.49	13.64	16.67

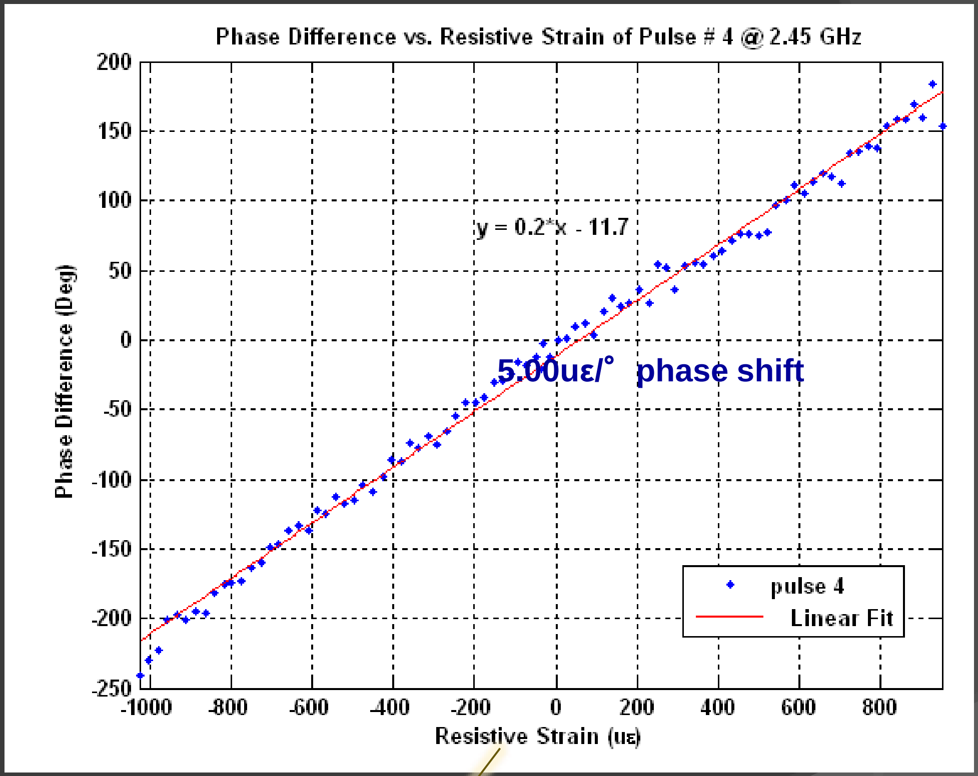
Quasi-Static Cantilever Measurements (1)



Quasi-Static Cantilever Measurements (2)



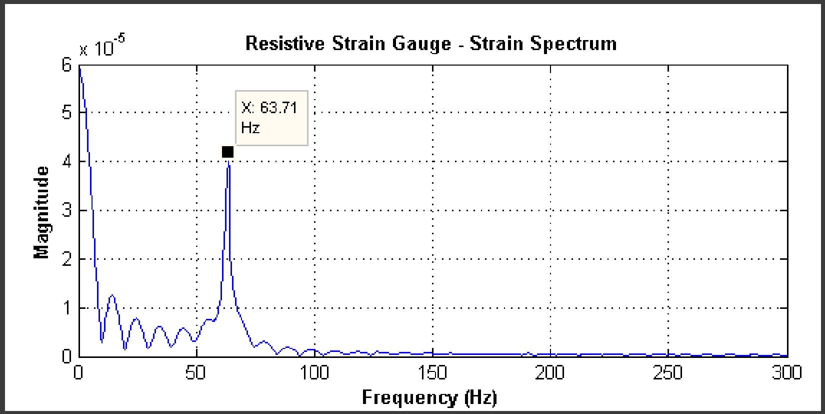
5.62uε/° phase shift

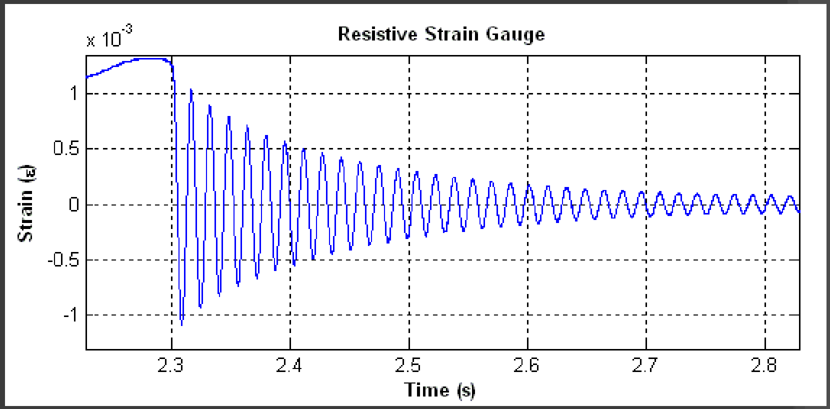


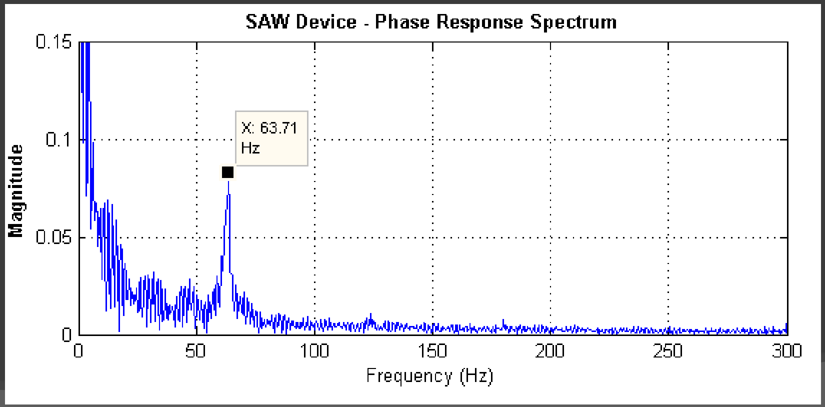
Strain based on resistive gage reading

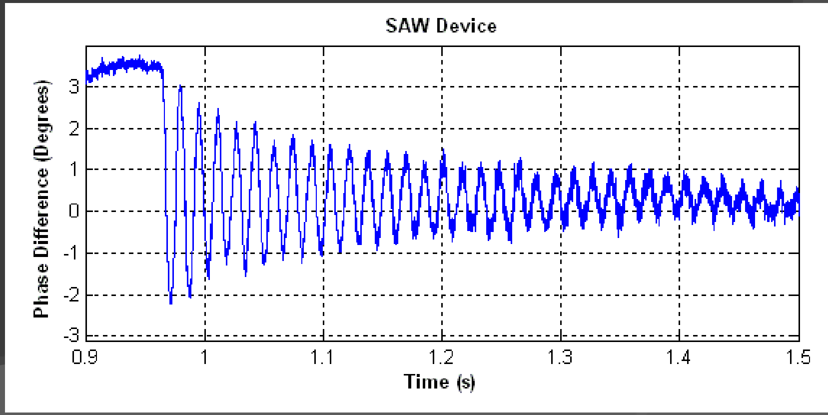
Oscillating Cantilever Measurements

- Cantilever beam was manually strained and released, free to vibrate at its resonant frequency
- SAW device and resistive strain gauge measured the same strain!



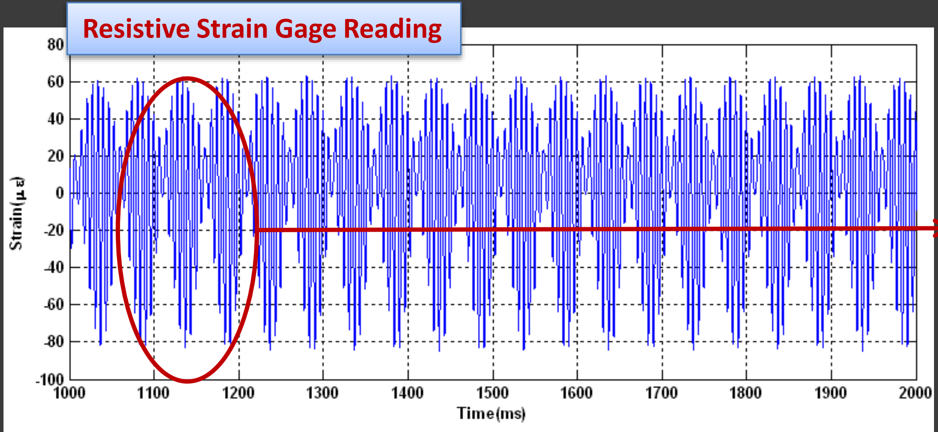


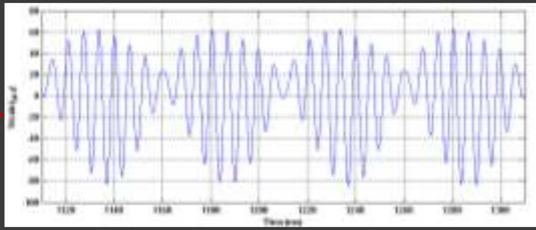


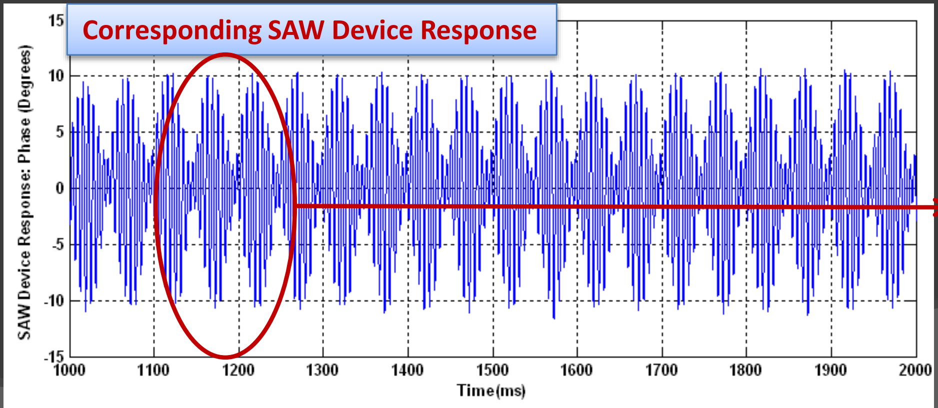


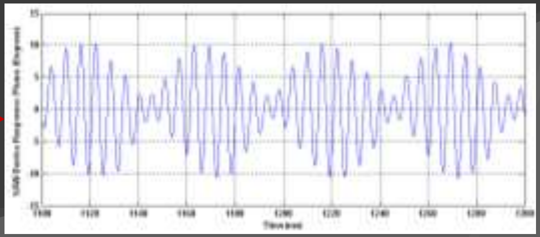
Harmonically Driven Cantilever Measurements

- Cantilever beam driven with frequency-modulated displacement
- Excellent correlation between strain gauge and SAW device!



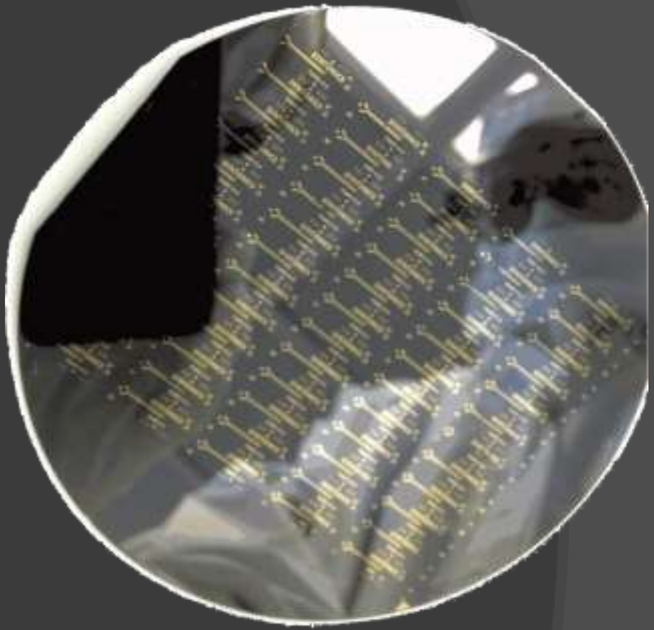


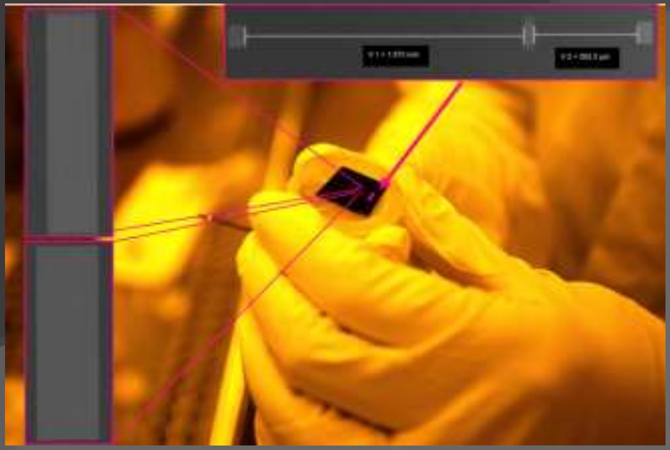




PaWS™ Development

- Prototype strain sensors designed, fabricated and demonstrated
  - Sensors use 300C and 600C materials
- Prototype RF Interrogation System developed and demonstrated
  - Upgrading to real-time data reduction





Syntonics is a technology-driven RF solutions company

- Founded 1999
  - Average 45% annual revenue growth (2007-2011)
- Established supplier to DoD with appropriate credentials
  - SECRET clearances (DSS)
  - COMSEC traditional account (NSA)
  - ISO 9001:2008 Quality Management System (since 2002)
  - DCAA-approved accounting system

BSI
ISO 9001
FM 69168

- Products
  - Highly capable RF-over-Fiber communications systems
    - FORAX™
    - FORAX-HARC
  - Handheld Tactical Antennas
- R&D on new RF innovations
  - Passive Wireless Sensing (PaWS™) for hostile environments
  - PARCA Software-Defined Antenna™