Application of Software Radios for Sensing & Instrumentation at ORNL

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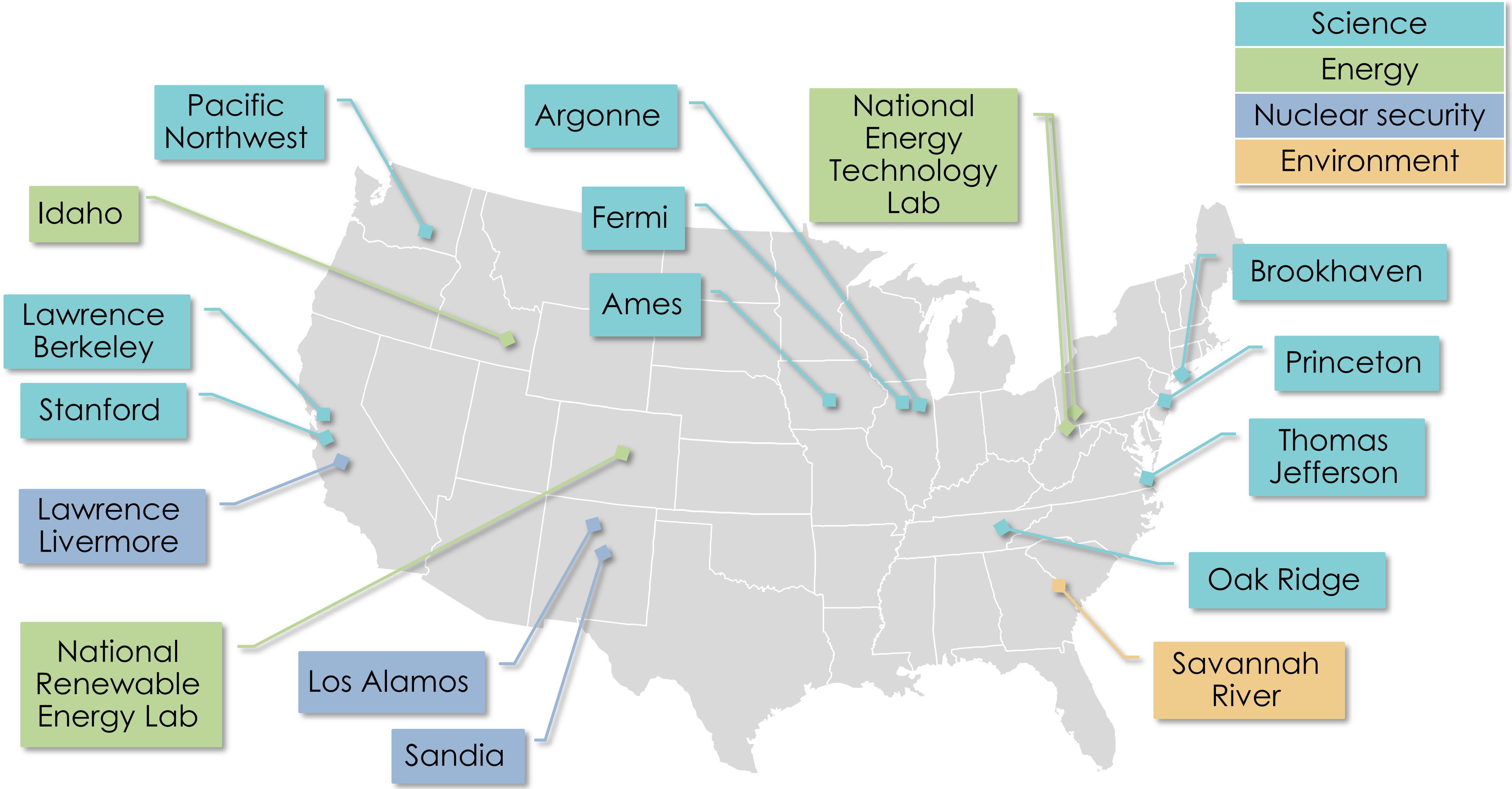


Oak Ridge National Laboratory (ORNL)

Deliver scientific discoveries and technical breakthroughs needed to realize solutions in energy and national security and provide economic benefit to the nation

$1.55B
FY17 expenditures

4,400
employees

$750M
modernization investment

Nation's largest materials research portfolio

3,200
research guests annually

Nation's most diverse energy portfolio

Forefront scientific computing facilities

World's most intense neutron source

World-class research reactor

2,261
journal articles published in CY17

Managing major DOE projects: US ITER, exascale computing

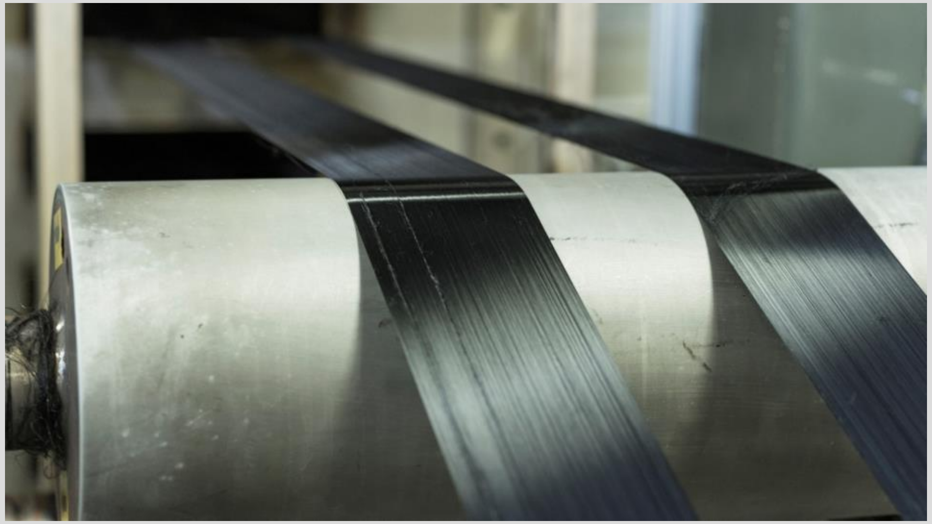
219
invention disclosures in FY17

74
patents issued in FY17

SDR for Sensing at ORNL

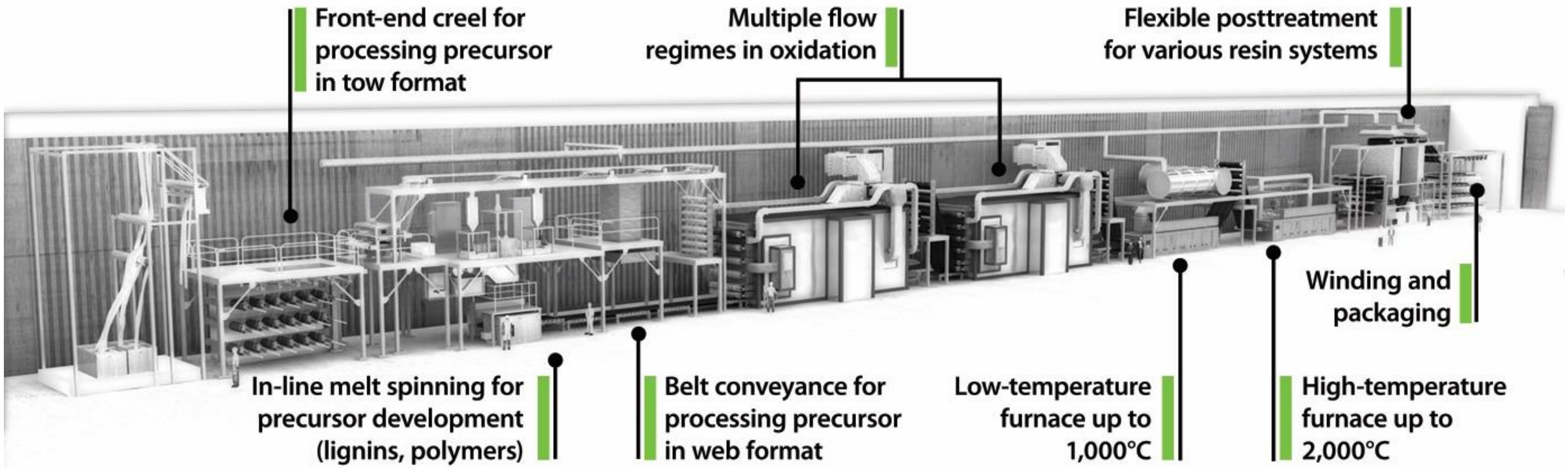
- Replace custom components and test equipment
  - Lower cost & effort to develop prototypes
  - Common hardware and software allows transfer of skills between multiple projects
- Current Projects in Sensors & Embedded Systems Group
  - Carbon Fiber Tow Measurement System **(Material Inspection)**
  - Surface Acoustic Wave (SAW) Sensor Interrogator System **(Wireless Sensors)**

Carbon Fiber Tow Measurement System



Carbon Fiber Technology Facility (CFTF)

- Demonstrate low-cost carbon fiber technology
- Produce development quantities of low-cost carbon fiber for process evaluation and prototyping



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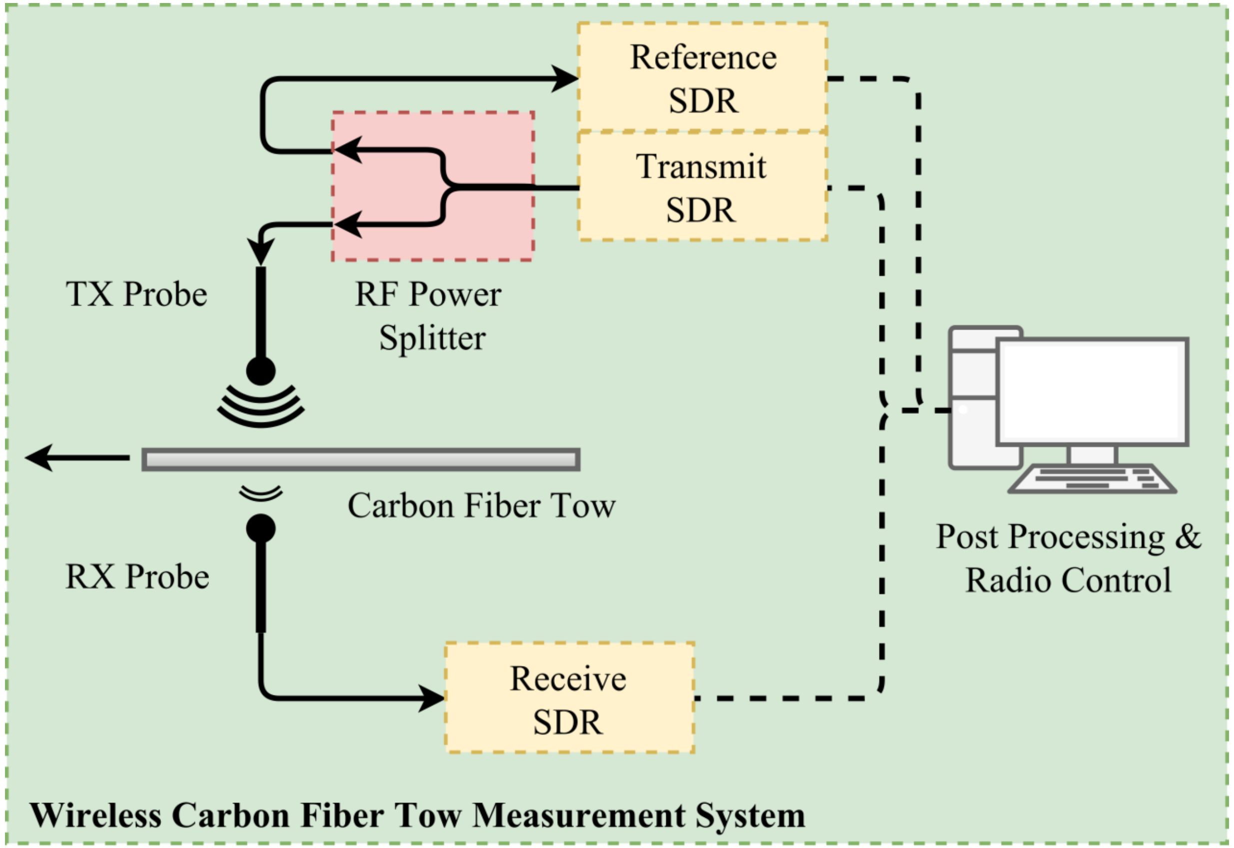
Challenges with Carbon Fiber Production

- 10-20% of carbon fiber ultimately ends up as waste
  - Significant portion due to production line start-up and process variability
- Currently, no in-line measurements exist to characterize fiber during manufacture
  - Analysis is performed off-line after carbon fiber is made
- **<u>Desire real-time feedback control for process variables</u>**
  - Non-contact (wireless) measurement systems
  - Provide direct or inferred observations of carbon fiber quality
    - Use to steer process line parameters (temp, tension, etc)

Measurement Concept

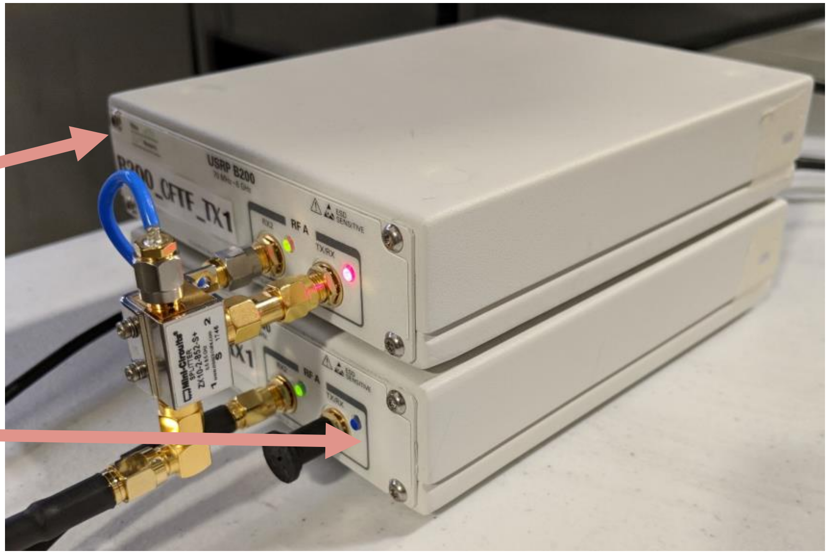
Concept

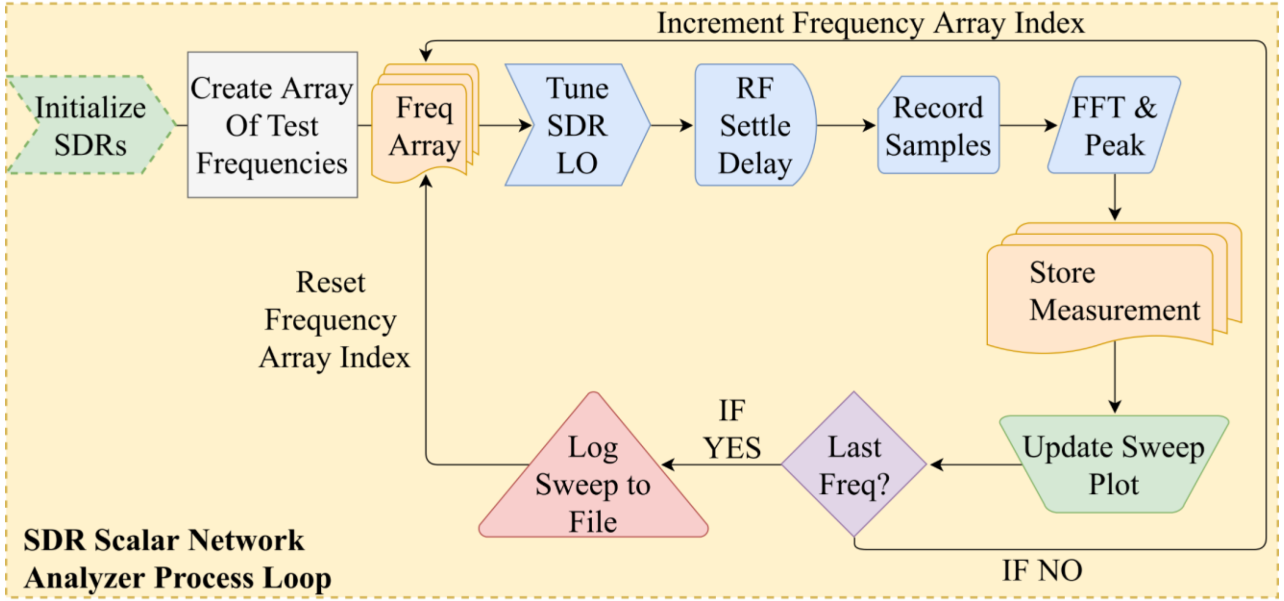
- Transmit high frequency (GHz) signals through tow and measure signal attenuation
- Use SDR to emulate scalar network analyzer
  - Lower cost than network analyzer
  - Easier to ruggedize for carbon fiber application*

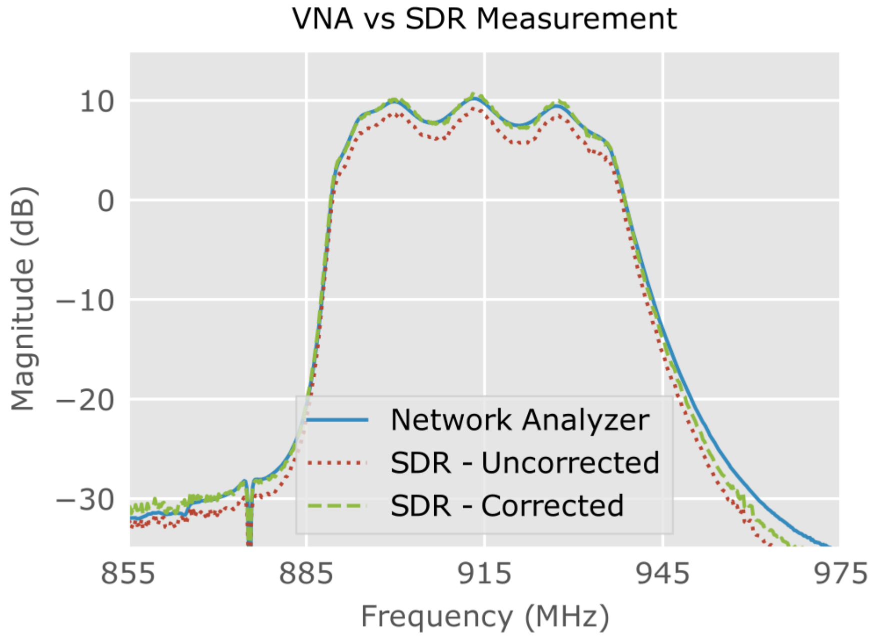


System Prototype

- Two B200 SDR's
  - One to generate TX signal and RX reference signal
  - One to RX signal after sent through tow
- GNU Radio to generate tone and interact with radios via Python







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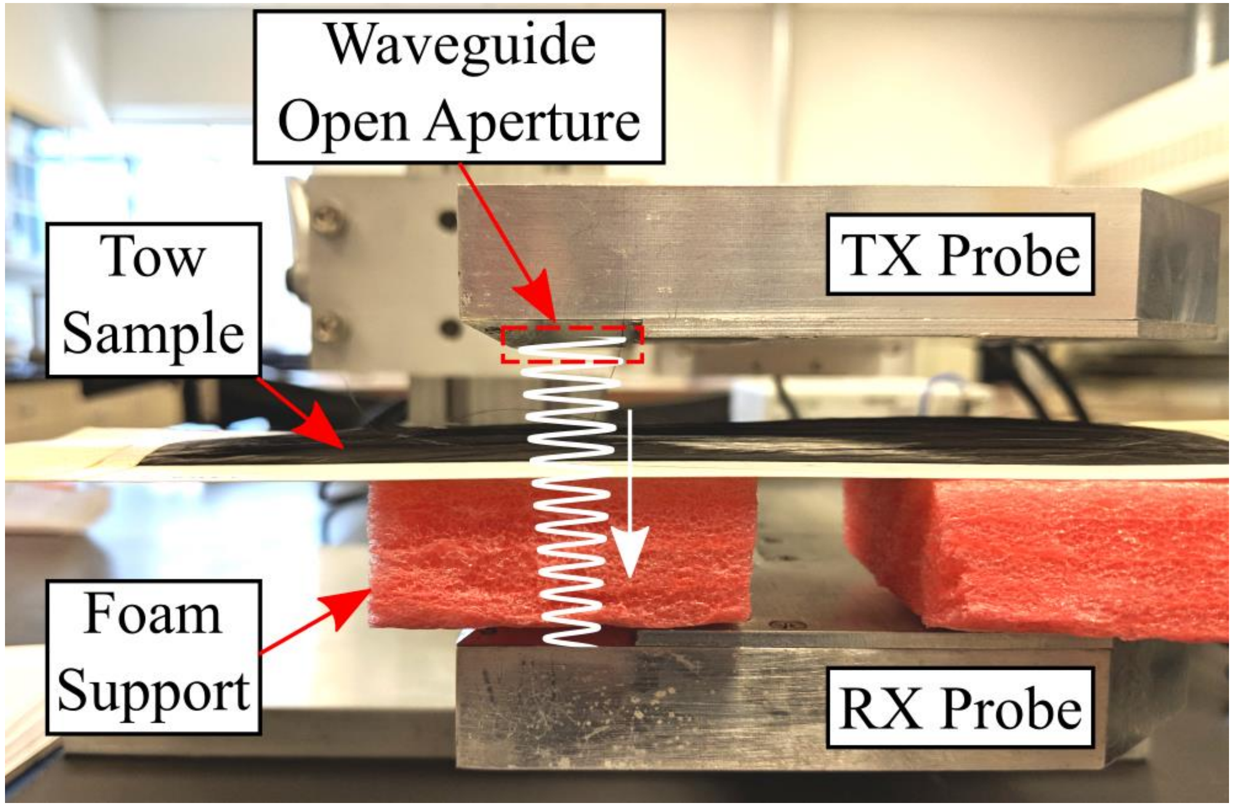
Experiment

- Tow samples obtained that have undergone different processing conditions
  - Furnace temperatures, line tension, etc.
  - Process conditions prescribed to exaggerate changes in material properties, not to achieve specific target properties
- Open-ended waveguide to direct energy through tow
  - Could also use antennas



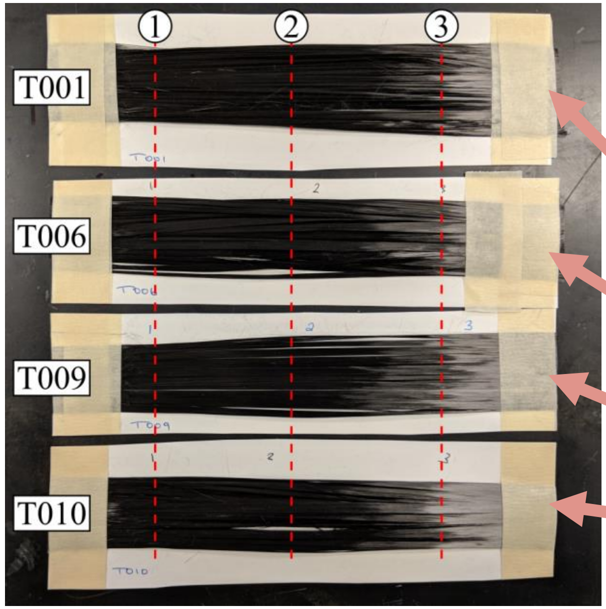


TABLE 1. Samples processing conditions.

Sample ID	Sample Processing Conditions
T001:	Default Start Up Conditions
T006:	Line Tension, Line Speed, Oxidation Furnace Adjustments
T009:	Increase HT Furnace Set Point (Add 100°)
T010:	HT Furnace Reached Set Point

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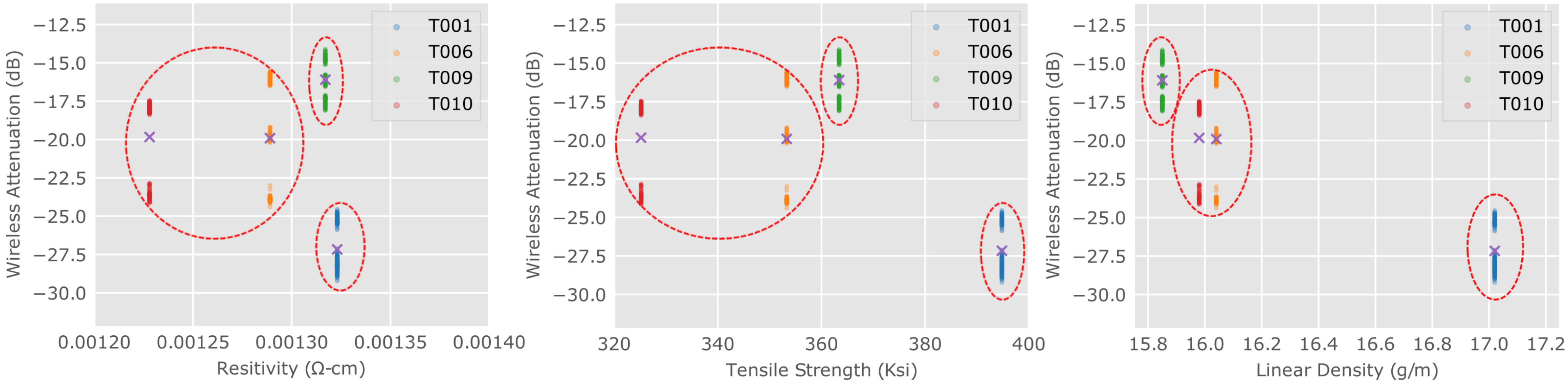
Measurement Results

- Averaged measurements over frequency to observe any trends
- Correlations show potential properties that can be detected with RF attenuation

Measurement Correlation Matrix

	RF	D	LD	T	M	E	R
RF1	1.0	-0.39	-0.97	-0.61	0.39	-0.56	-0.24
RF2	1.0	0.97	-0.96	0.69	-0.34	0.73	0.73

−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00



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Next Steps

- Better statistical analysis of data
  - Averaging data masks features
  - Good opportunity to apply machine learning techniques
- Frequency sweep analysis
- In-situ measurements
  - Install the system on the manufacturing line
- Integrate embedded processing for stand-alone measurement system
- Add phase to measurement
- Improved wireless probes

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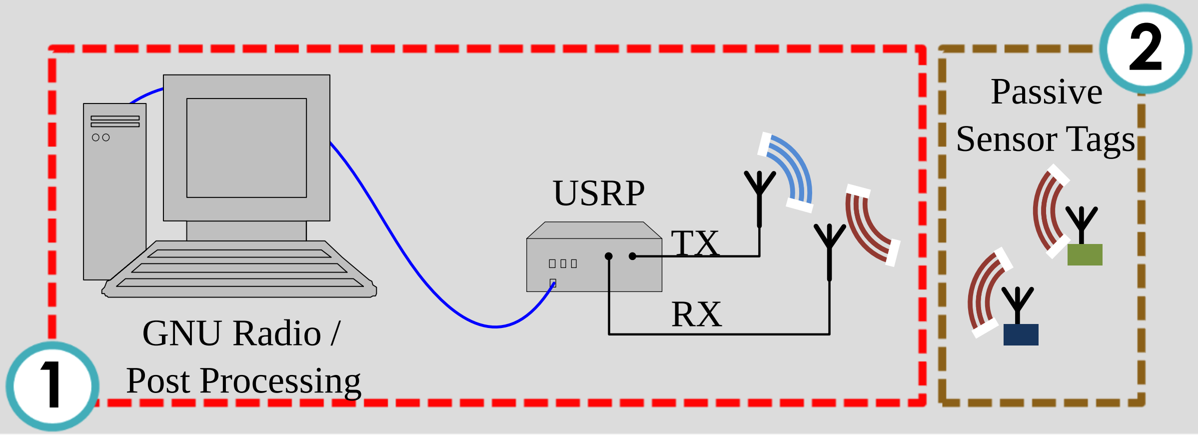
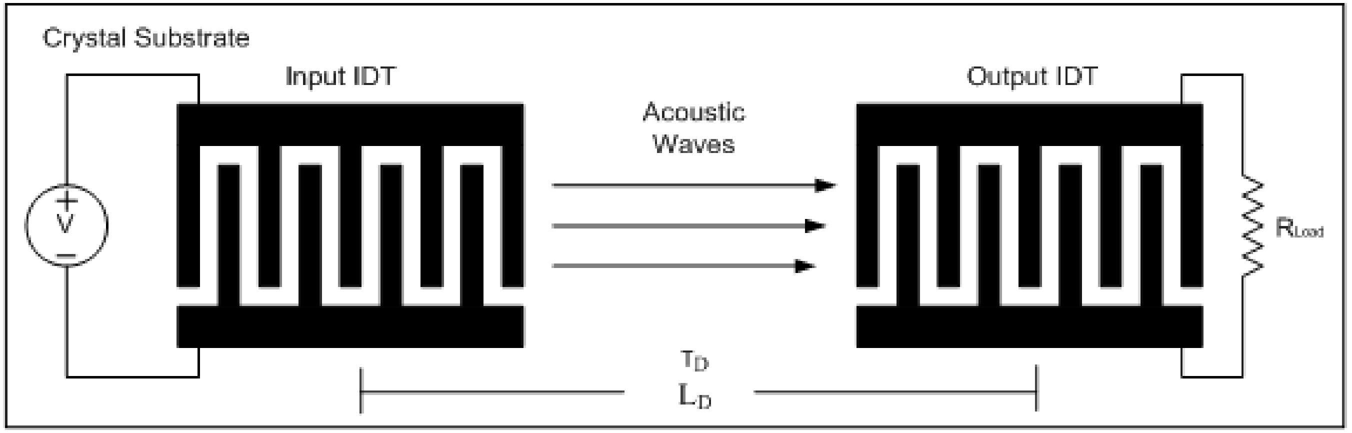
SAW Sensor Interrogation System



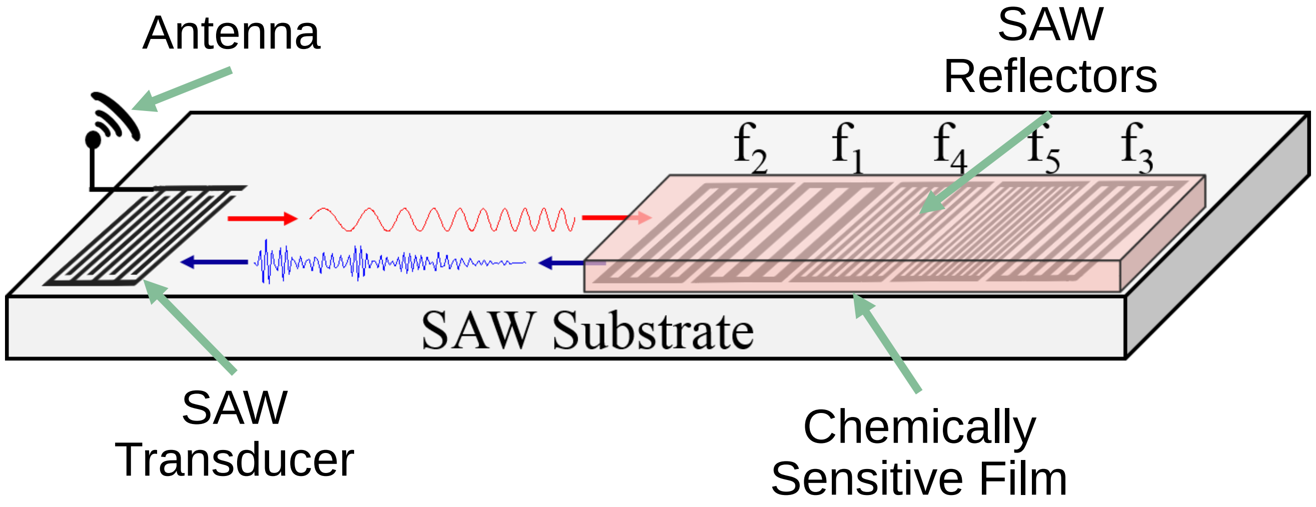
Surface Acoustic Wave (SAW) Devices

- Solid state devices
  - Converts electrical energy into mechanical wave (and vice versa) on piezo-electric substrate
  - Very complex signal processing in small size **(Spatial mapping of time function)**
  - Acoustic Wave Velocity: ~3000-4000 m/s
- 4-5 Billion SAW devices produced each year (Probably More…)
  - Filters, Delay Lines, Resonators
  - **Sensors**, RFID



SAW Sensors

- One Port Device
  - **Measure reflected interrogation signal** (S_{11}); passive operation
  - Post-processing to determine how frequency, phase, delay of reflected signal is changing
  - "Cooperative RADAR target"
- 10MHz-3GHz Operation
  - Fabrication tolerances limit; sensor size dominated by antenna in wireless config.
  - Common to operate at **915 MHz or 2.4 GHz**
- Variety of Device Embodiments
  - Temperature, strain (pressure), chemical and gas detection
  - Resonant, delay line (narrow or wideband)
  - Radiation hard



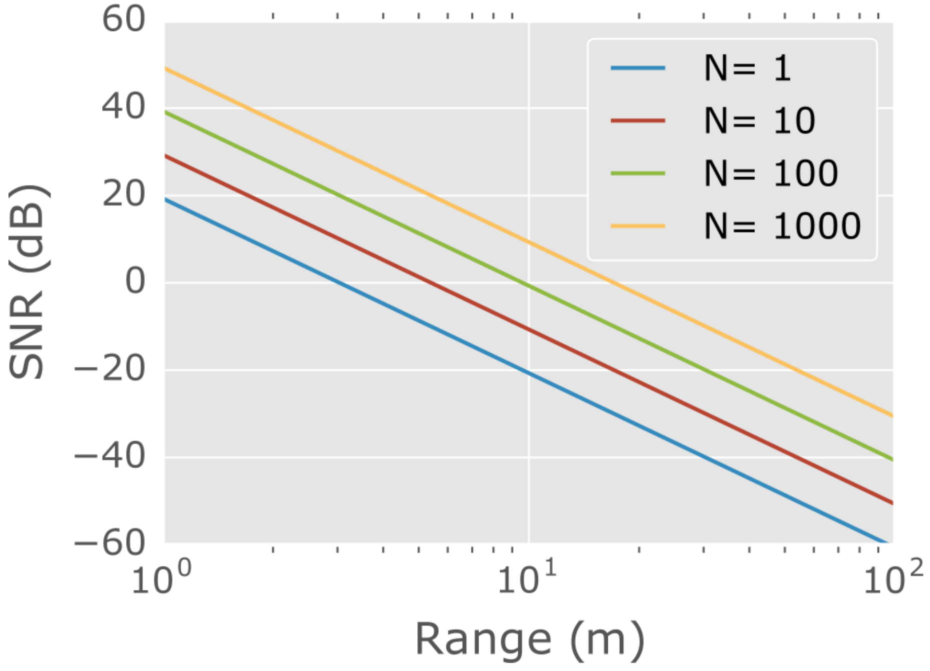
SAW Sensor Efforts @ ORNL

- HF Gas Dosimeter
  - Silica (SiO_2) film deposited on SAW reflectors
  - Frequency shift tracked as silica is etched by HF (visco-elasticity and mass loading)
- Methane Gas (Transformer dissolved gas analysis)
  - Cryptophane-A molecule to trap methane on SAW surface (mass-loading)
- Temperature
  - Wireless, remote temperature monitoring of grid equipment

Interrogation Systems

- Often approached from a RADAR perspective (very similar)
- Transmit a pulse, listen for delayed echo from SAW
- Exploit pulse compression gain, averaging, and others

$$SNR = N \frac{P_t \cdot G_{SAW}^2 \cdot G_{INT}^2 \cdot \lambda^2 \cdot \sigma' \cdot \tau\beta}{(4\pi)^3 \cdot L_S \cdot F \cdot L_{SAW} \cdot R^4 \cdot kT_0B}$$

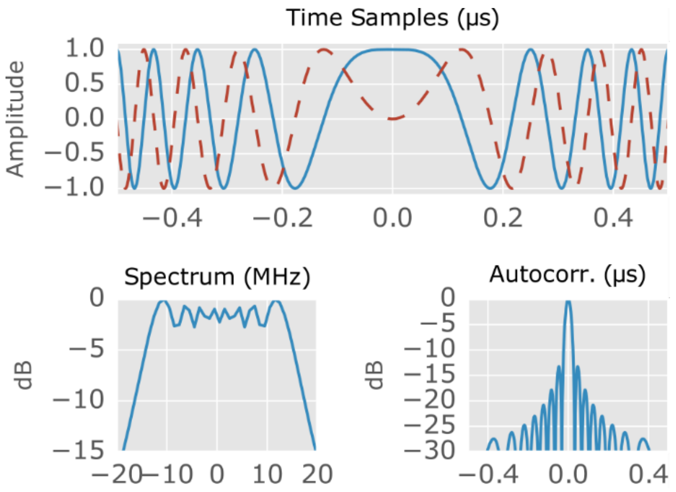


Interrogation Signal Considerations

- Excite sensor bandwidth (and possibly more as sensor frequency shifts with applied stimulus)
- Consider waveform pulse compression properties (sidelobe suppression)
- Time length (SAW Response typically <5μs)

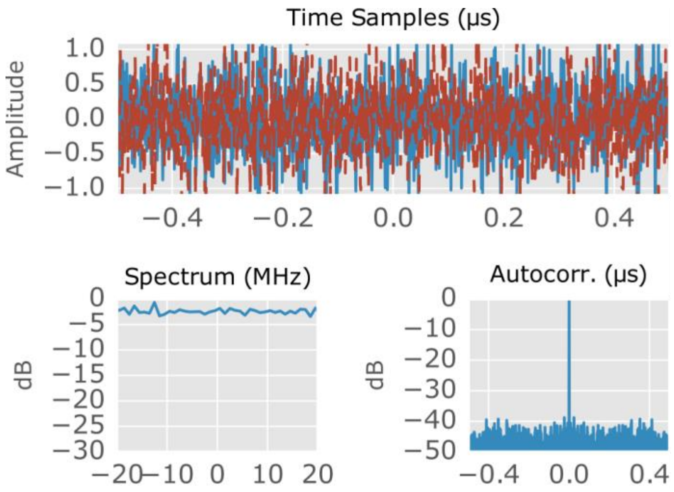
Chirp (Swept Frequency)

- Advantages:
  - Consistent frequency spectrum
  - Many options for design (BW, windowing, chirp rate)
- Disadvantages:
  - Spreading of range bins in time
  - High autocorrelation sidelobes



Noise (Random Modulation)

- Advantages:
  - Suppressed range ambiguity (multi-sensor environments)
  - Reduced mutual interference (multi-interrogator environments)
- Disadvantages:
  - Many interrogation cycles for ‘complete picture’
  - Deconvolution of different TX signal for every cycle (slower processing)



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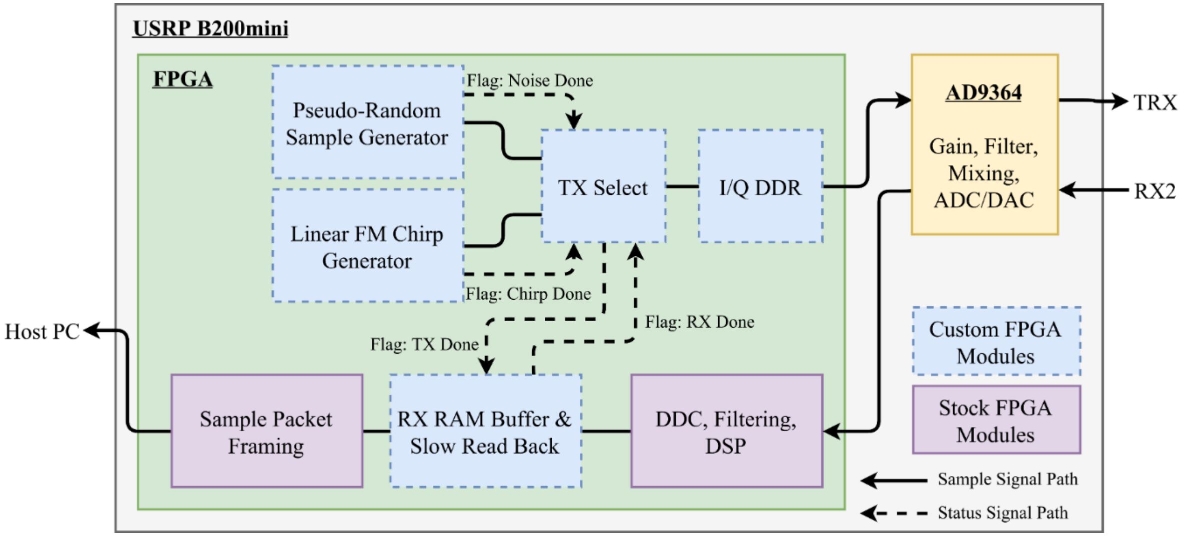
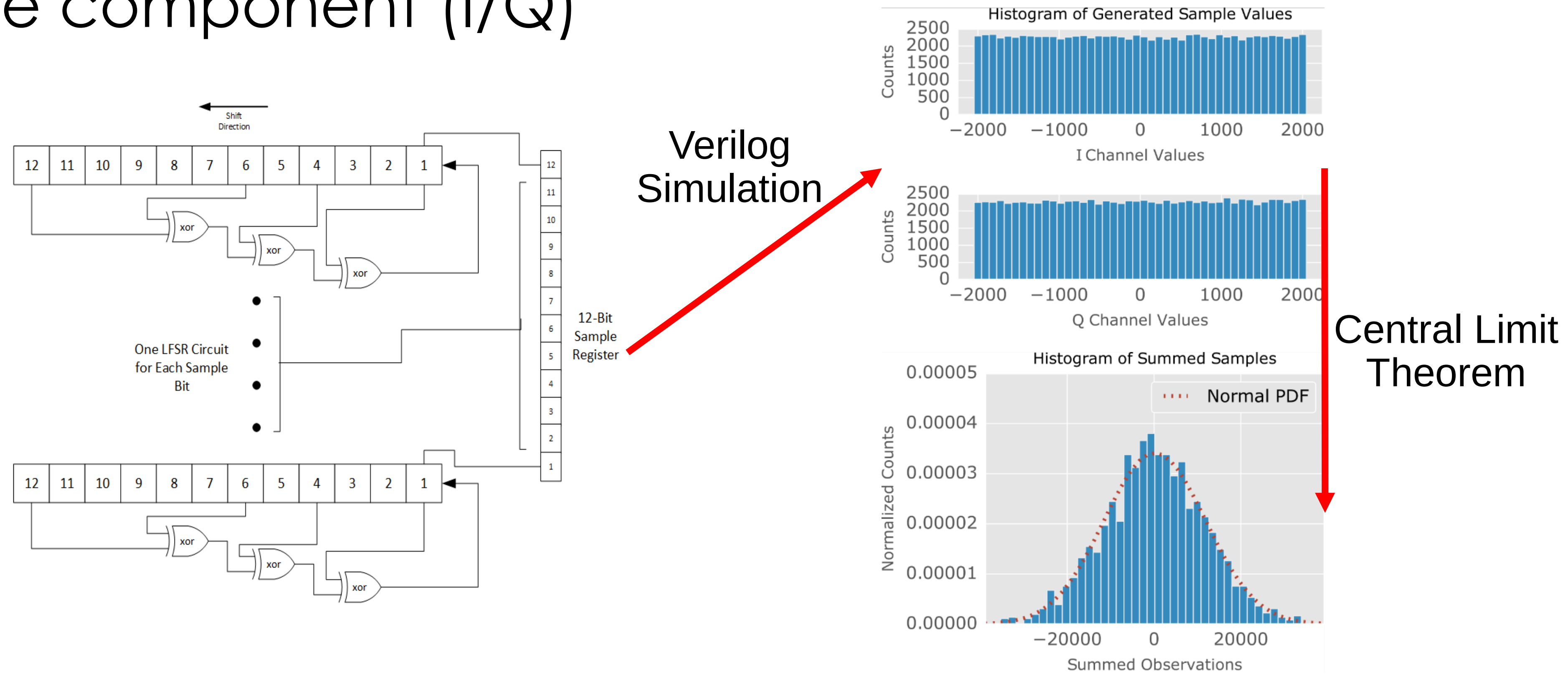
B200mini FPGA Modifications

- Transmit
  - Generate interrogation signal
    - Pseudo-Random Sample Generator
    - Linear FM Chirp
  - Indicate to receive to start buffering after TX
- Receive
  - Buffer 512 samples in block RAM
  - Trickle samples back to host at slow rate (utilize more BW than USB can handle in real time)
  - Inject reference pulse for time sync (post-processing will use to time align interrogation cycles)



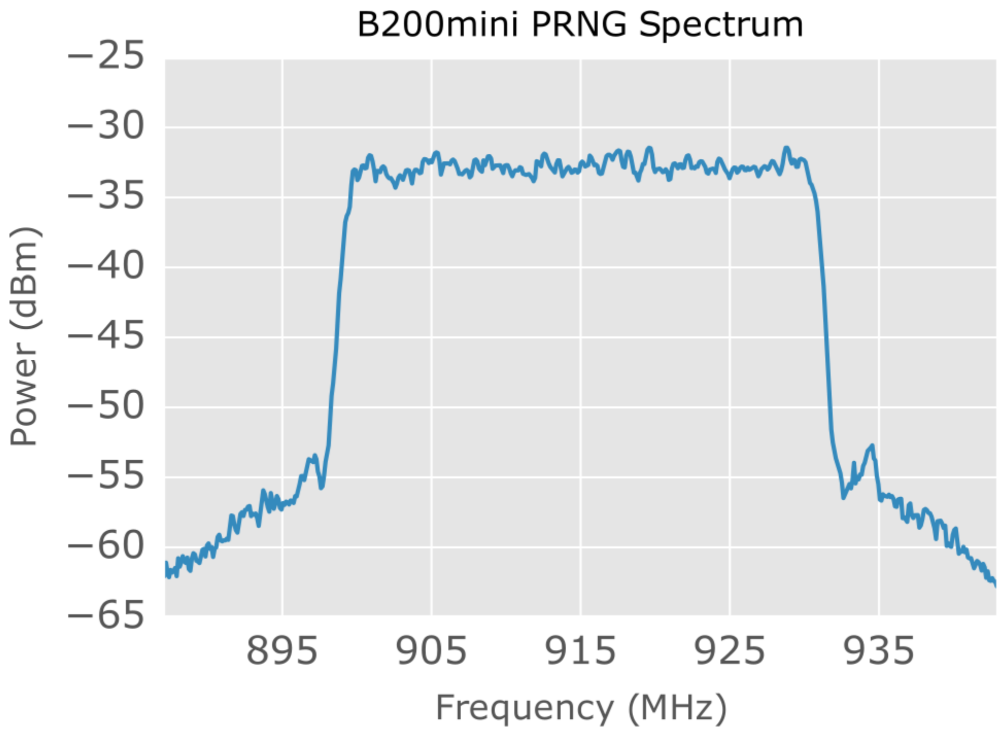
Pseudo-Random Sample Generator

- Utilize linear-feedback-shift-registers to generate sample bits
- Each sample bit has independent LFSR, 12 LFSR's for each sample component (I/Q)



LFSR Array RF Spectrum

- Spectrum measured over long time interval
- Uniform magnitude over excitation bandwidth (given enough observations)
- 32 MHz Sample Rate



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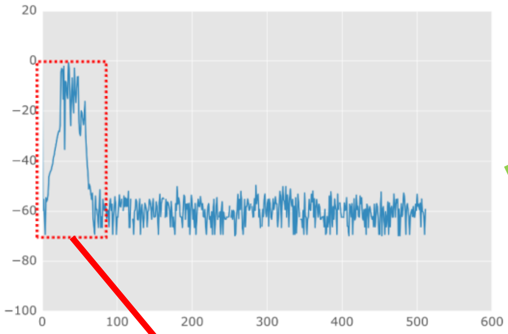
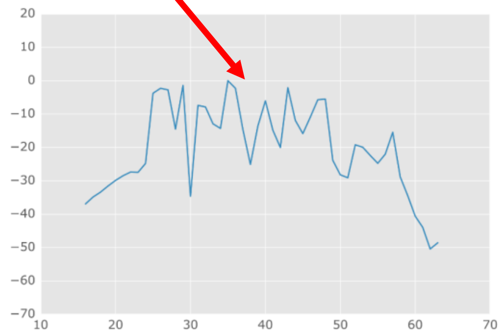
Post-Processing Signals

$$H_R(f) = [H_{TX}(f) \cdot H_{Tag}(f)] \cdot e^{-j2\pi f \tau_{EM}} + H_G(f) + H_J(f)$$

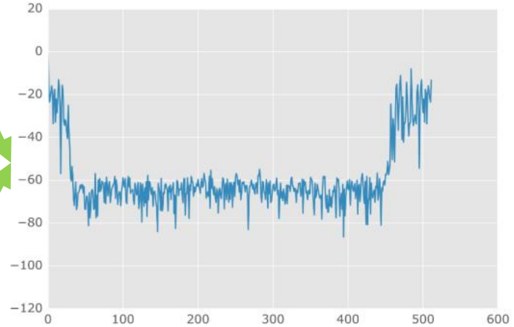
Raw Data





Gated TX Burst (TX→RX Leakage)

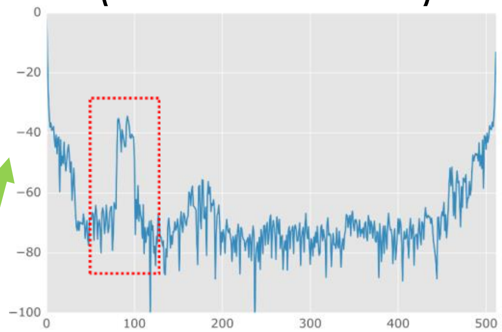
Deconvolve TX Signal

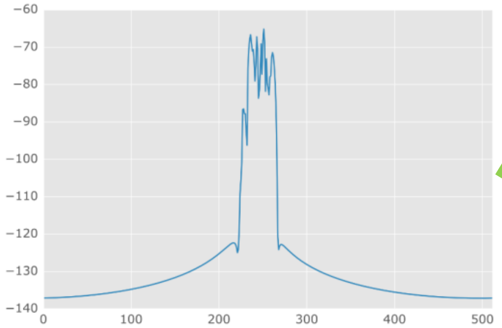


$$H_{dec} = H_R(f) \cdot H^*_{TX}(f)$$

$$H_{Ave}(f) = \frac{\sum_{i=0}^{N} H_{Rpp_i}(f)}{N}$$

Average Sweeps (100's – 1000's)



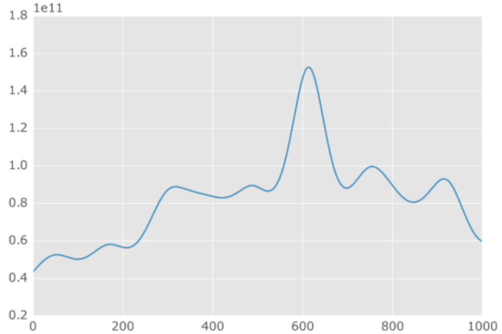


Apply Matched Filter Bank to Data

$$\begin{bmatrix} H_{R_{MF_1}}(f) \\ H_{R_{MF_2}}(f) \\ \cdot \\ \cdot \\ H_{R_{MF_N}}(f) \end{bmatrix} = H_{Ave}(f) \cdot \begin{bmatrix} H_{MF_1}(f) \\ H_{MF_2}(f) \\ \cdot \\ \cdot \\ H_{MF_N}(f) \end{bmatrix} \quad (2)$$

$$E_{Corr_i} = \int_{-BW/2}^{+BW/2} H_{R_{MF_i}}(f)df$$

Integrate and Find Closest Match

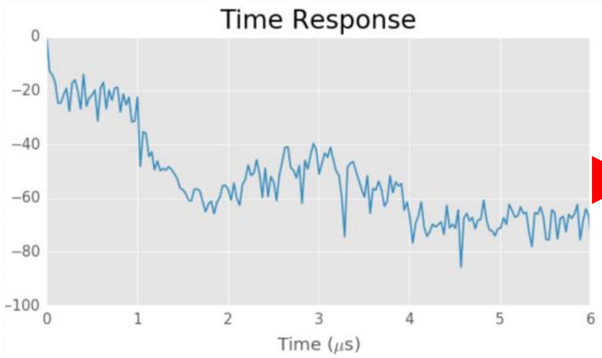


Relate Frequency/Time Shift to Sensing Measurement

Averaging Sweeps (Noise Interrogation Pulse)

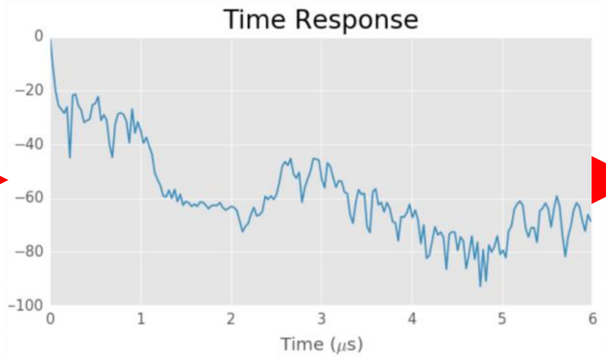
N = 1

- Entire frequency band is not excited with 1 pulse from noise source
- Cannot easily extract SAW sensor response
- Measurements will look random



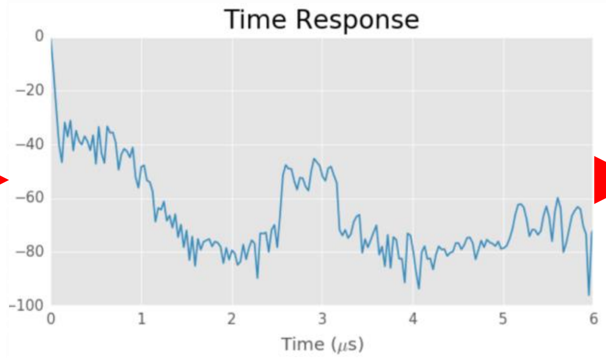
N = 10

- SAW response starts to look better
- Measurements will begin to track if SNR is good
- Measurement variation may still be large



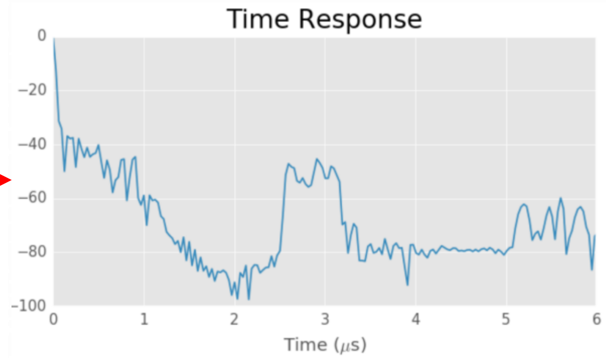
N = 100

- SAW device response is well formed
- Measurements track nicely
- Measurement variation starts to become very small



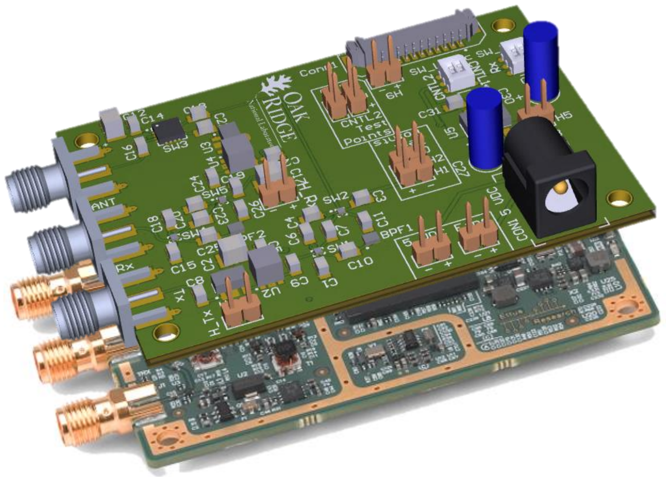
N = 1000

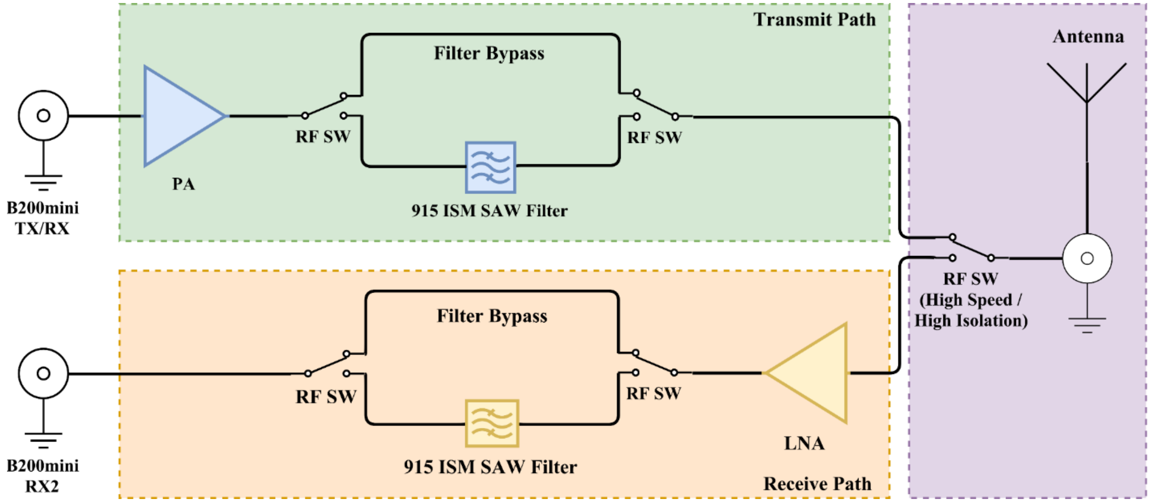
- Further reduction of noise floor
- Main response & double transit easily seen
- Very small variation in measurements (High precision)



B200mini RF Daughterboard

- For SAW sensing application, measurement range/precision driven by SNR
- B200mini Performance Can be Improved with External RF Hardware
  - Power amplifier → Increase output power
  - Low Noise Amplifier → Improve NF; amplify SAW response
  - TX/RX Switch → Single antenna; reduce self-jamming effects
  - Filters → TX harmonic suppression; RX out-of-band suppression





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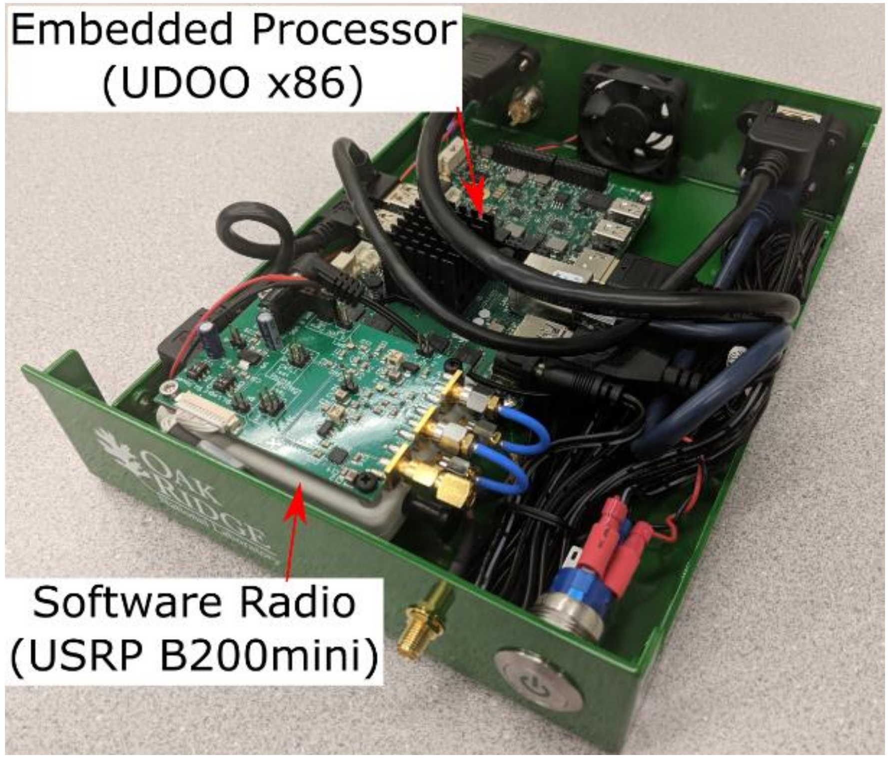
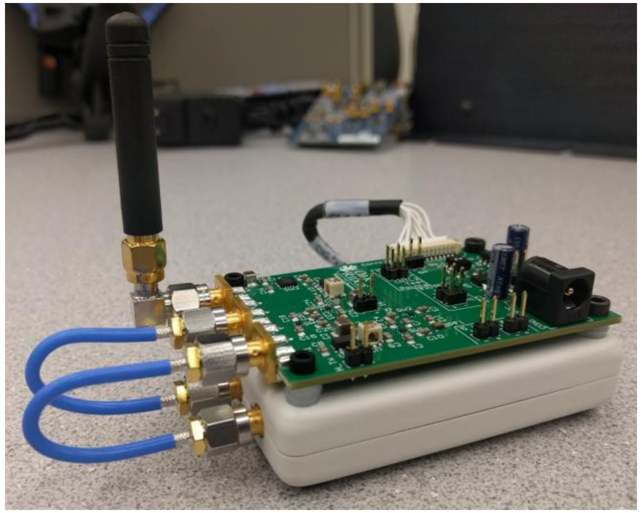
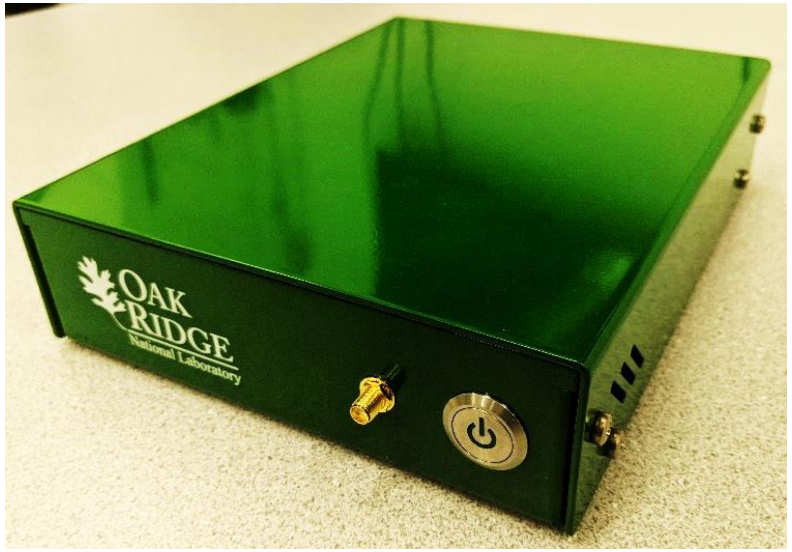
Portable Interrogation System

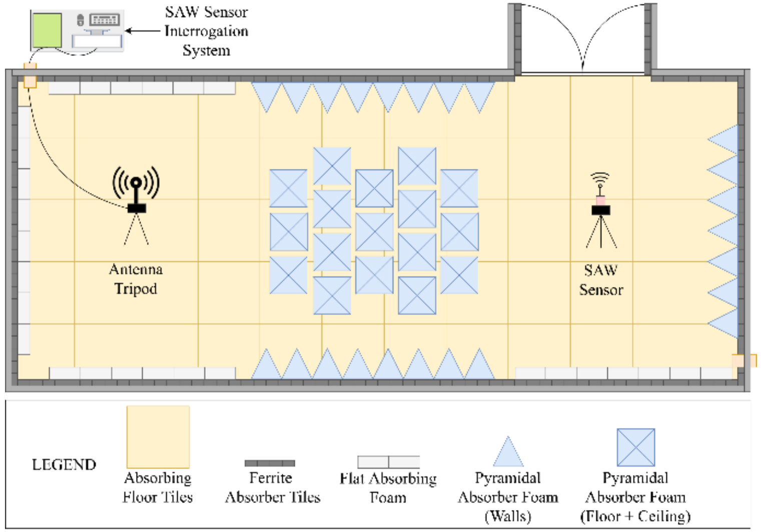
- Integrates Udoo x86 embedder system
  - Intel Celeron N3160 (2.24 GHz)
  - 4 GB RAM
  - 32 GB EMMC
  - Ubuntu
- B200mini + ORNL Daughterboard
- 225×175×50 mm (9×7×2 in.)
- 1.2 kg (2.6 lbs)



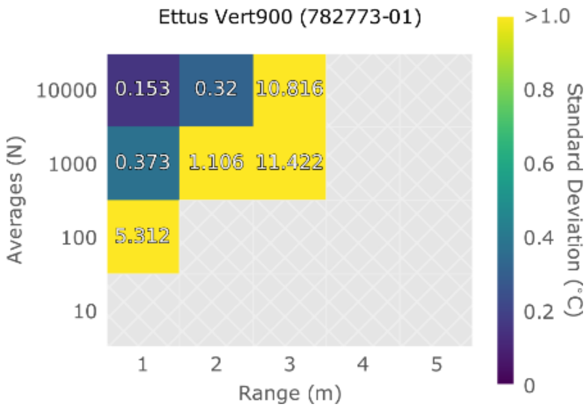


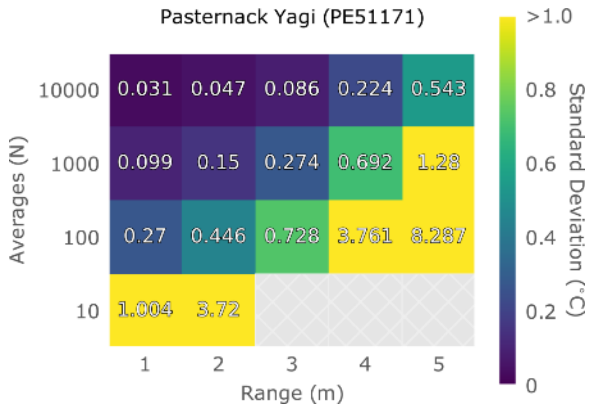


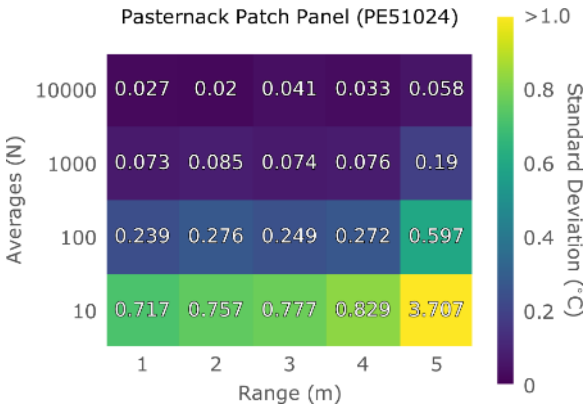
Anechoic Chamber Measurements (Temp. Sensor)



- Monopole, Yagi, and Patch Panel antennas tested
- Sensor can operate up to 5 meters (Limited by chamber length)
- Measurement precision down to 0.027°C observed
- Best performance observed with Patch Panel antenna







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Next Steps

- Ruggedize interrogator system for outdoor use
  - Planning to test system with power utility
- Improve B200mini daughter-board design
  - Higher output power, better filters, tunable LNA gain
- Remote control and central data collection

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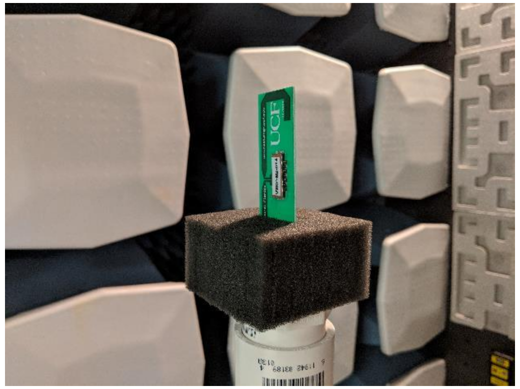
Conclusion

- SDR a great asset for sensing and instrumentation
- Common hardware platforms and software interface allow experience to transfer between projects
  - Rapid prototyping
- GNU Radio + Python allows rapid prototyping of signal processing blocks and data acquisition



Shout-Out

- Wednesday, 4:15PM
  - “An Over-The-Air Trainable Machine Modem for Resilient Communications”
  - Adam Anderson

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GNURadio

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

Henderson, NV

2018