Detection, Identification, Location, and Remote Sensing Using SAW RFID Sensor Tags

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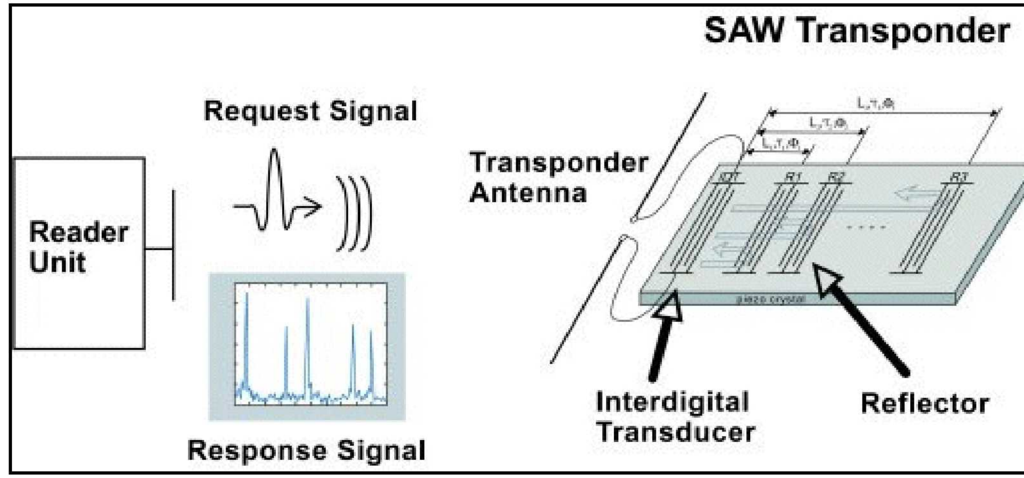
Outline

- Introduction to Surface Acoustic Wave (SAW) RFID tags
- Overview of the NASA JSC Passive Adaptive RFID Sensor EQuipment (PARSEQ) system
- PARSEQ simulated performance evaluation
- PARSEQ experimental performance evaluation
- PARSEQ field test
- Future Work

SAW RFID Tags



- RF interrogator signal (ISM Band: 2.40 – 2.48 GHz)
- InterDigital Transducer (IDT) converts RF signal at antenna to acoustic wave
- Piezoelectric substrate propagates acoustic signal
- Reflector spacing determines unique ID
- IDT converts acoustic wave back to RF at antenna

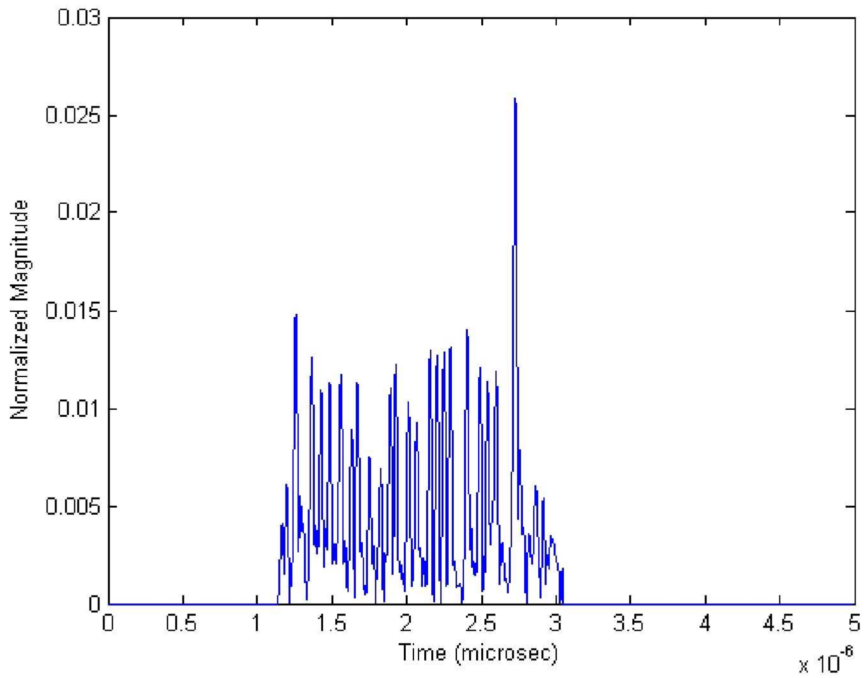
SAW RFID Tags – Advantages

- Completely passive wireless device
- Very rugged
  - Withstands extreme temperatures (~20° K to several hundred
  - Withstands extreme acceleration
  - Operates in vacuum
- Tag can be interrogated with extremely low power
  - Increased interrogation range
  - Reduced danger near pyrotechniques
- Provides remote sensing capability
  - Tag response modulated by tag temperature and tag strain
  - Can be interfaced with other passive sensors (load subset of reflectors with variable impedance device)

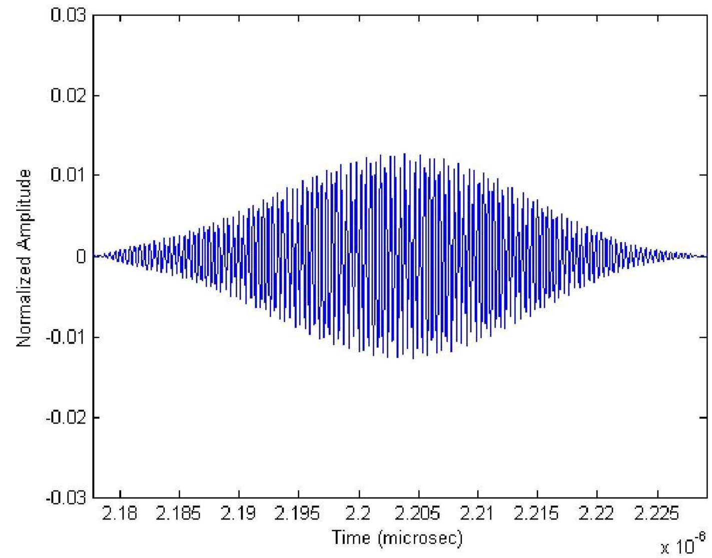
SAW RFID Tags – Disadvantages

- **High insertion loss and low-power response**
- **Must estimate temperature to read tag ID accurately**
- **Fabrication complexity and cost increase with frequency of operation**

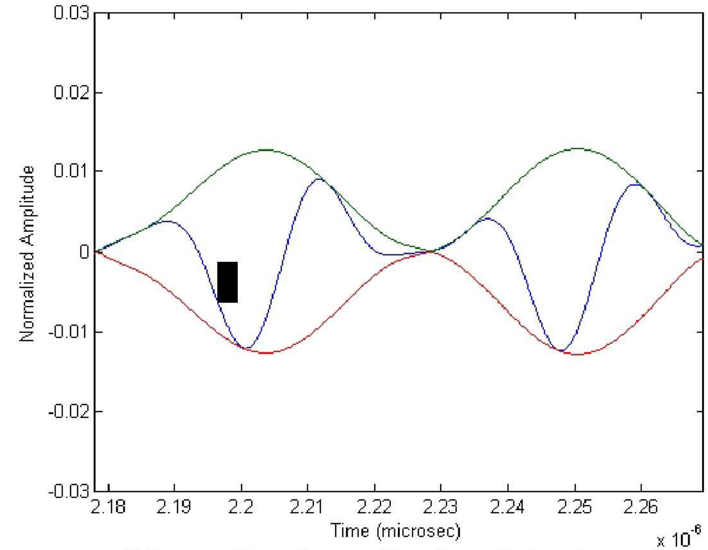
SAW RFID Tags –Example Impulse Response



Magnitude of normalized tag impulse response at -73° C



Normalized amplitude of single pulse



Normalized amplitude of single pulse

SAW RFID Tags –Temperature/Range Sensing

- Temperature

  Computed from estimated scale (compression/dilation) of received waveform

- Range

  Computed from estimated time delay of received waveform

- Estimation

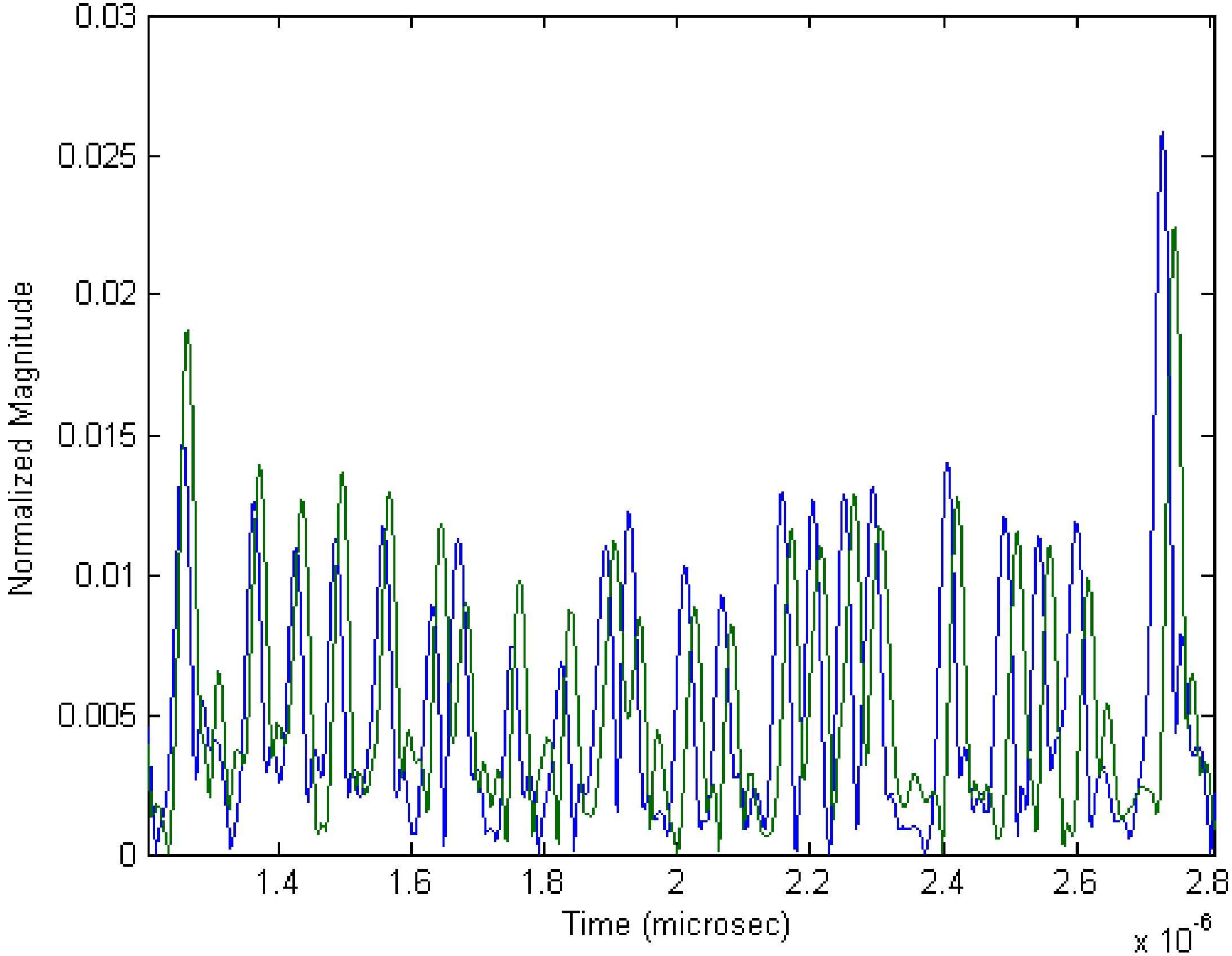
  Suboptimal and not robust to tag collision

  - Detect individual pulses
  - Estimate time of arrival (TOA) for each pulse directly
  - Use TOA of first pulse to compute waveform time delay and delay between pulses to compute waveform scale

  Optimal and robust to tag collision

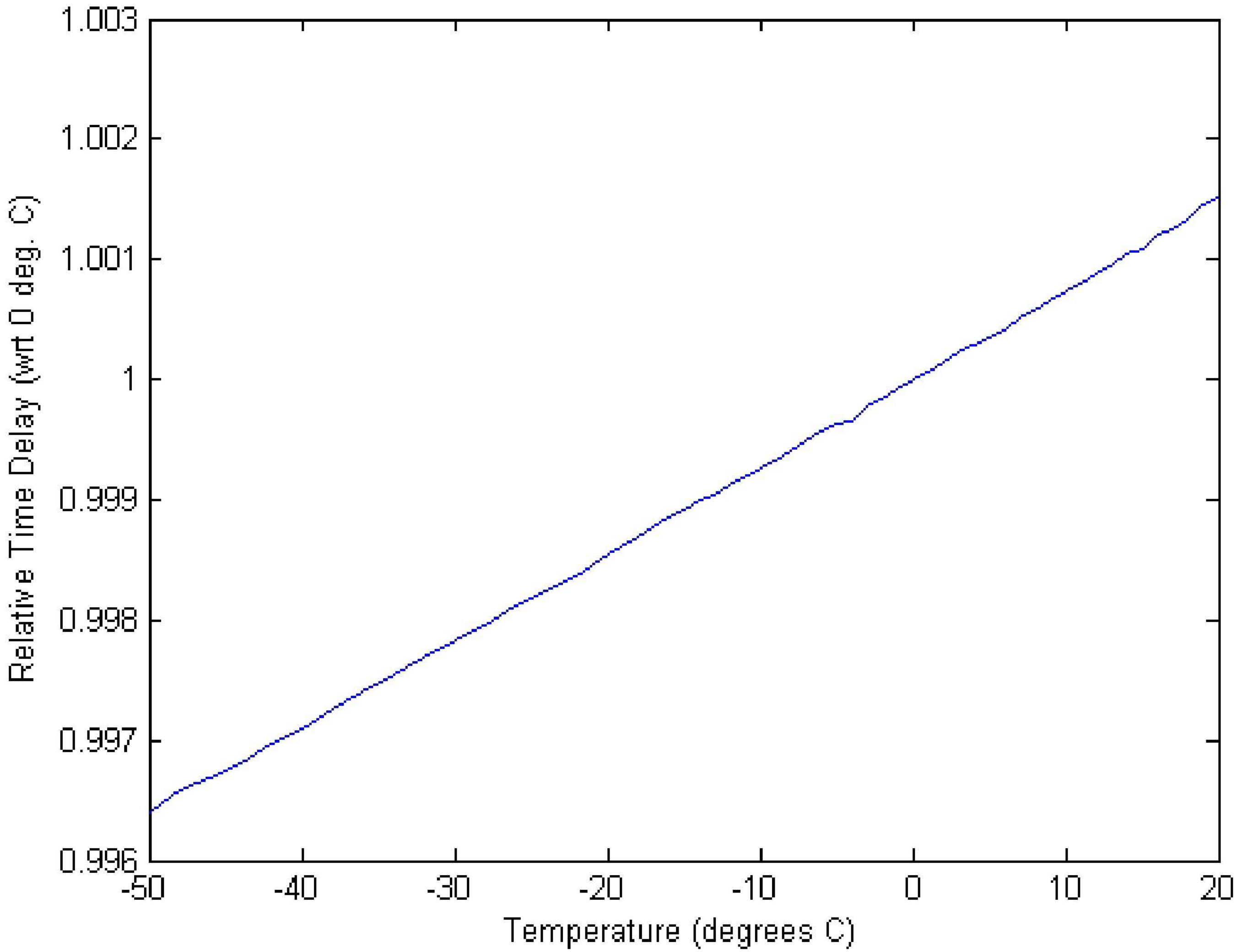
  - Estimate time scale and time delay of waveform simultaneously using wavelet transform

SAW RFID Tags –Example Response vs. Temperature



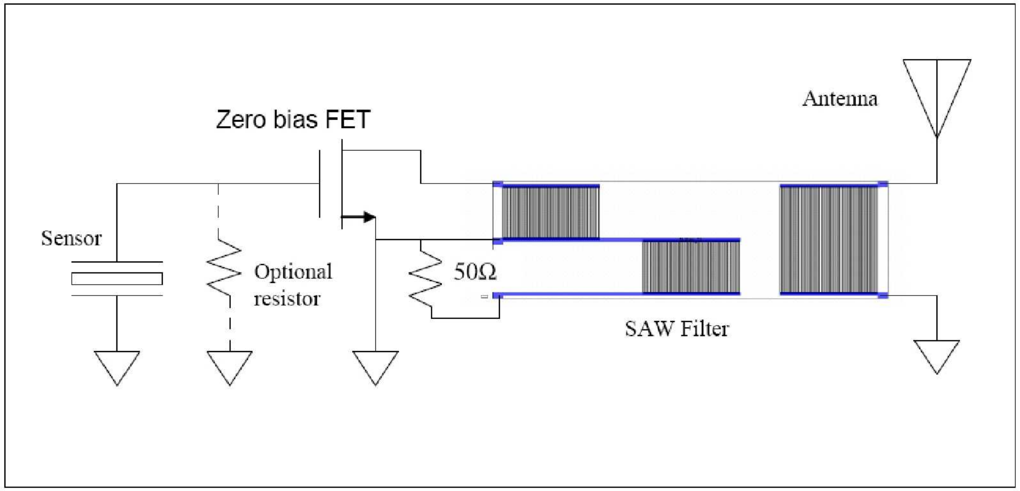
Tag impulse response magnitude at -73° C (blue) and 21° C (green).

SAW RFID Tags –Temperature Coefficient of Delay (TCD)



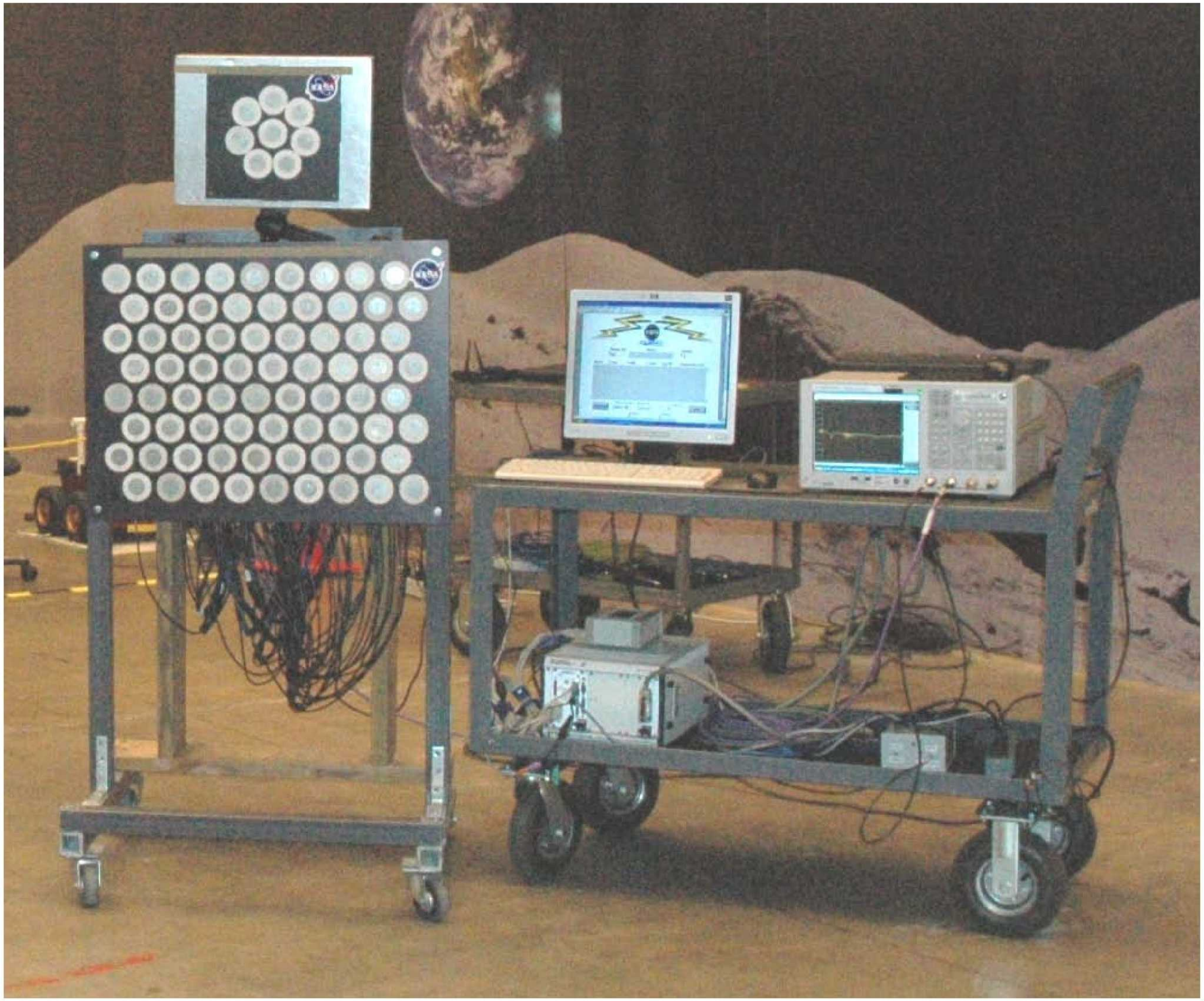
SAW RFID Tags –Other Sensing Modalities

- **Pressure sensors**
  - **Stress/strain on crystal causes change in propagation velocity (same as response to temperature)**
- **Incorporation of commercial sensors**
  - **Sandia National Laboratory (SNL) concept: FET-loading of SAW IDT with passive sensor driving FET**
  - **Passive sensor types under evaluation: accelerometer, acoustic emission**



SNL SAW Sensor Concept

NASA JSC PARSEQ System



PARSEQ – Goals and Challenges

- **Goals**

  Simultaneous detection, identification, location, and remote sensing of multiple objects with passive SAW RFID tags

- **Challenges**

  For NASA sensor applications, often want many tags within interrogator field-of-view

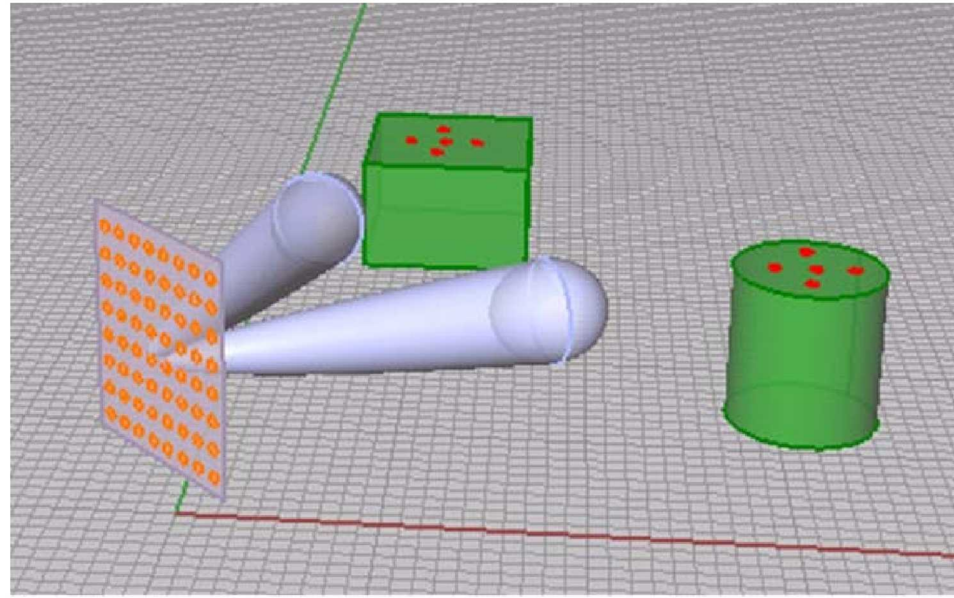
  Ranges > 100 feet are desired for many applications

  Primary SAW material in use is very sensitive to temperature

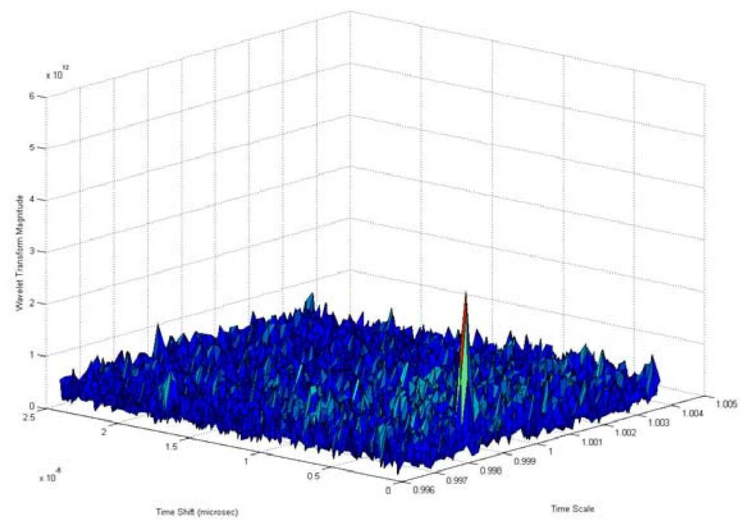
  - **Good for temperature sensing, but makes other sensors more challenging**

PARSEQ – Approach

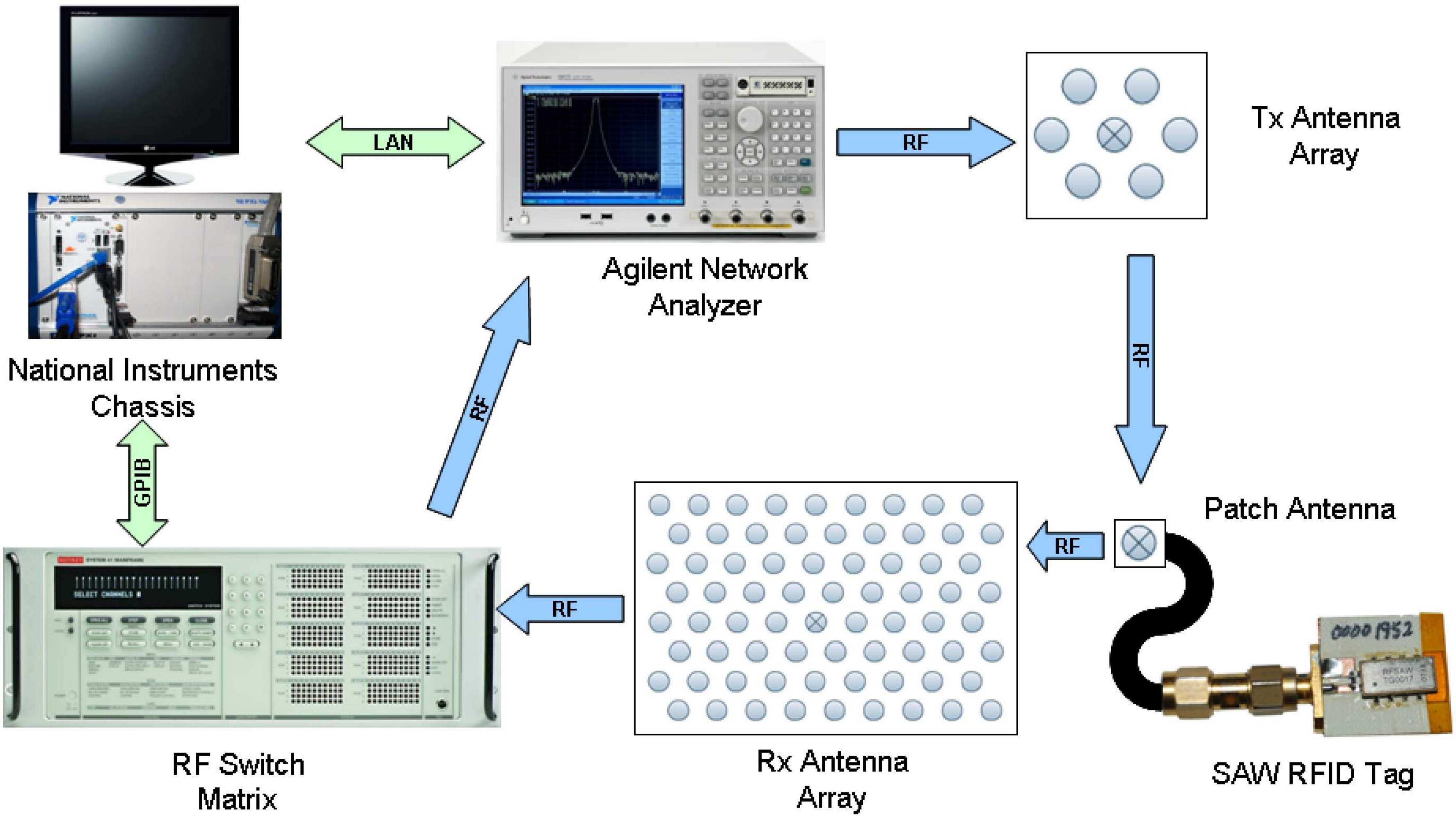
- **Fully exploit spatial diversity**
  - Larger aperture interrogators
  - Adaptive digital beamforming



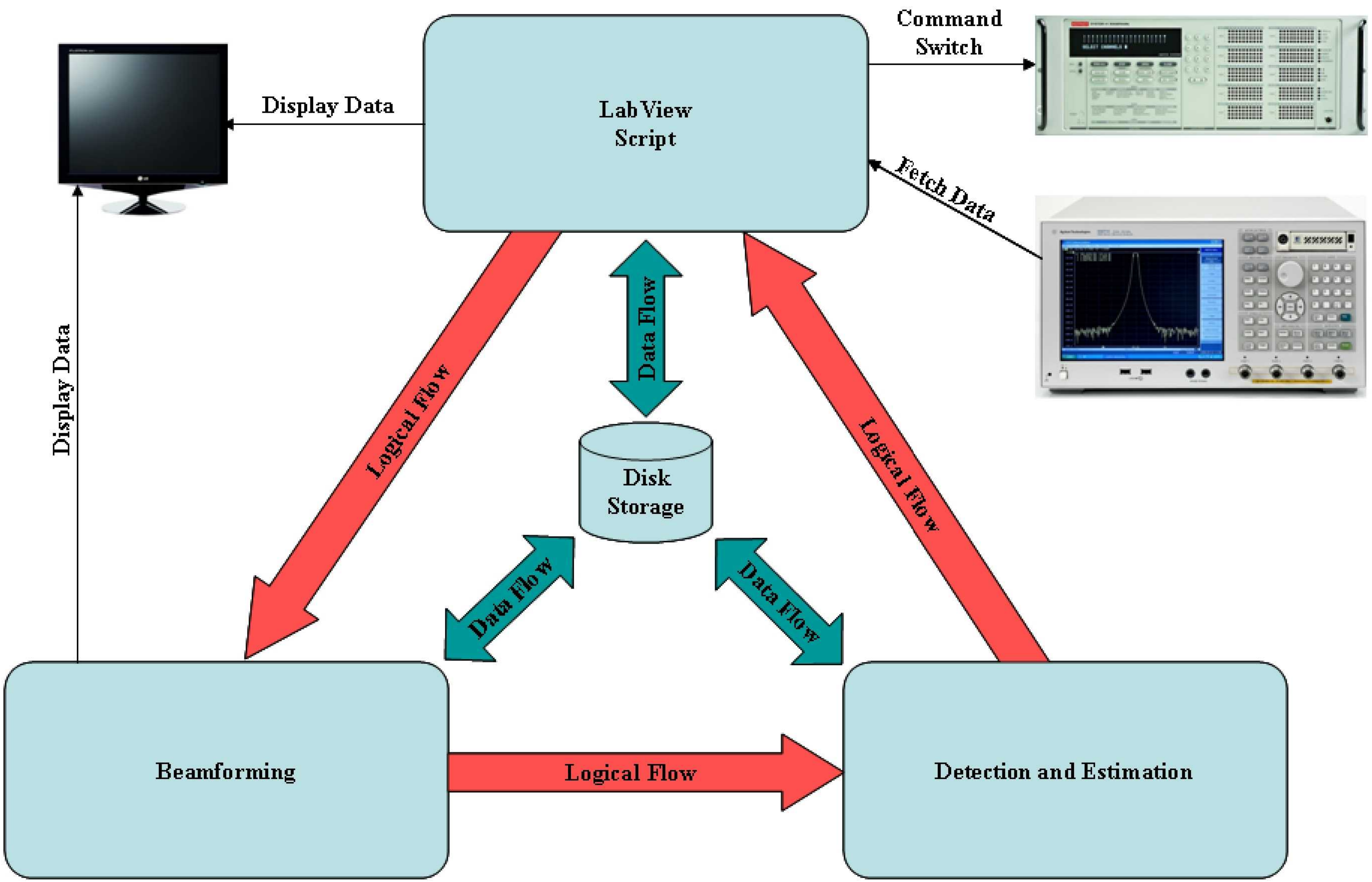
- **Fully exploit time and frequency diversity**
  - Wideband processing
  - Wavelet transform



PARSEQ – Hardware Architecture



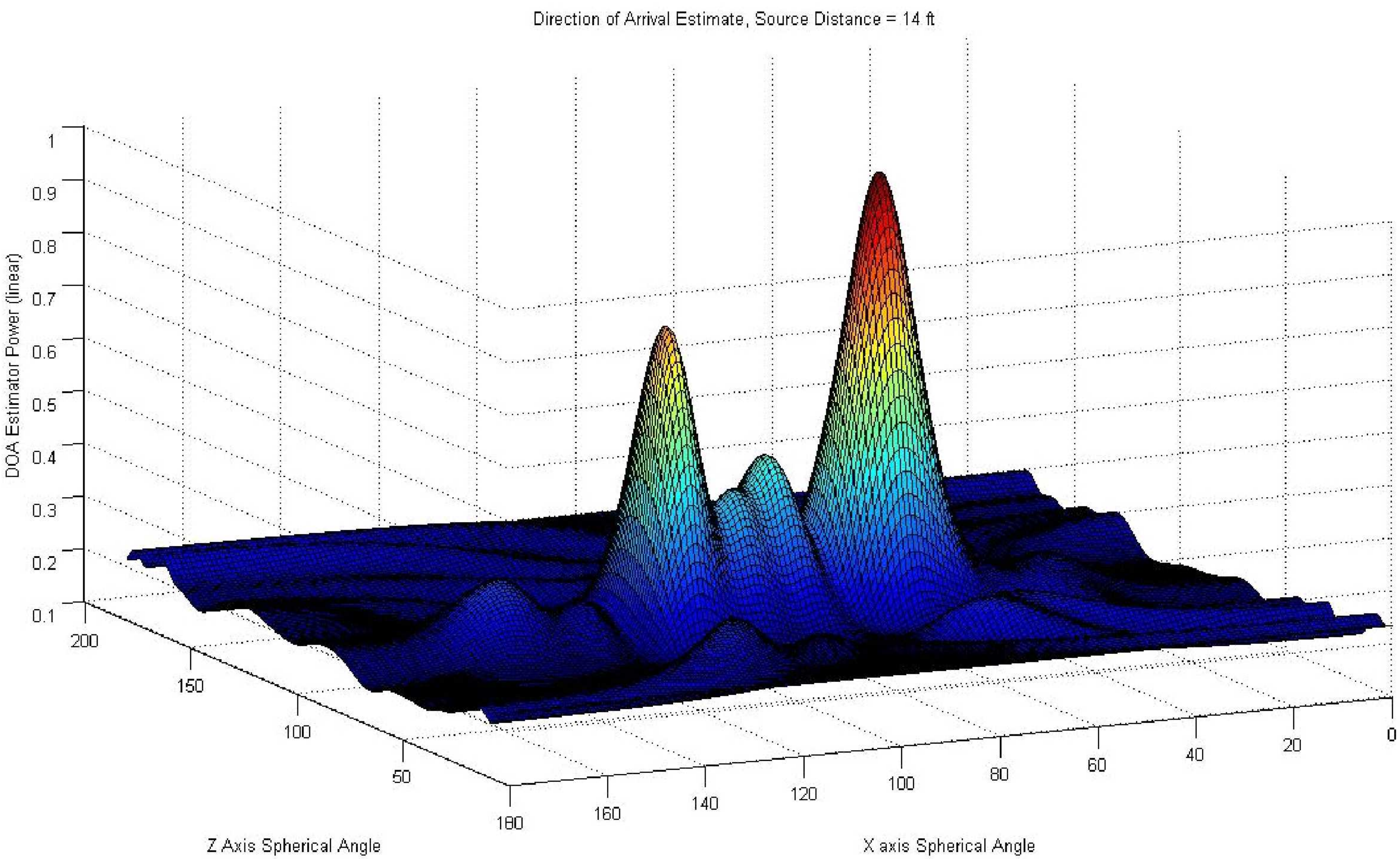
PARSEQ – Software Architecture



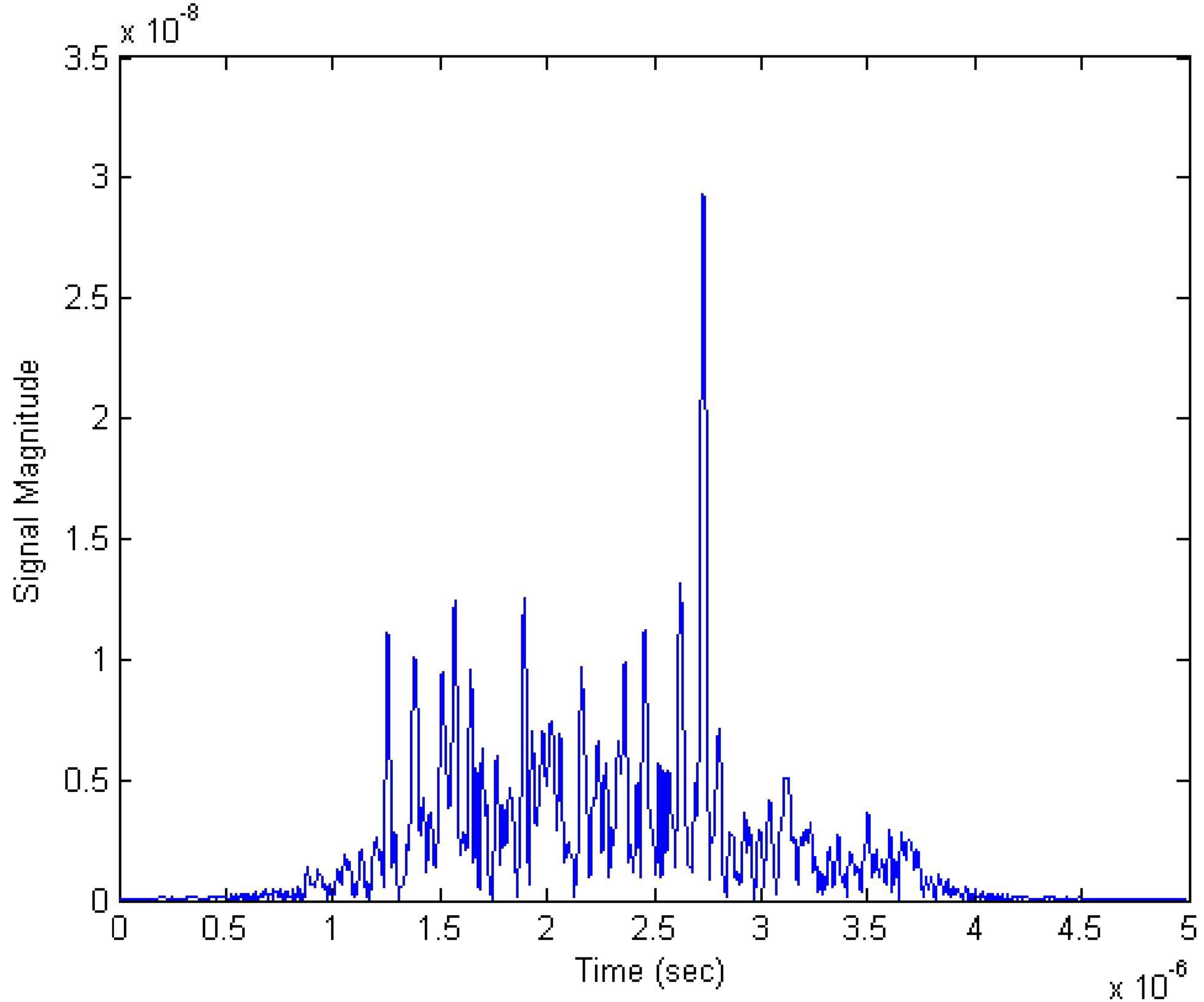
PARSEQ – Array Processing

- **Sample channel frequency response at each receiving antenna**
  - Stepped CW sweep with network analyzer for each antenna
  - Step through receiving antennas with RF switch matrix
- **Signal preconditioning to remove initial transients in channel impulse response**
  - Early reflections, transmitter/receiver cross-talk, etc.
  - Tag response delay ~1 μsec
- **Form pre-determined beams in Fourier domain**
  - Adaptive beam-forming performed at initialization to determine beam coefficients
  - Beams can be re-computed as desired
- **Process beam-formed data to detect/estimate tags**
  - Current processing sequential with single processor
  - Can be fully parallelized

- **Signal energy distribution in cluttered environment**



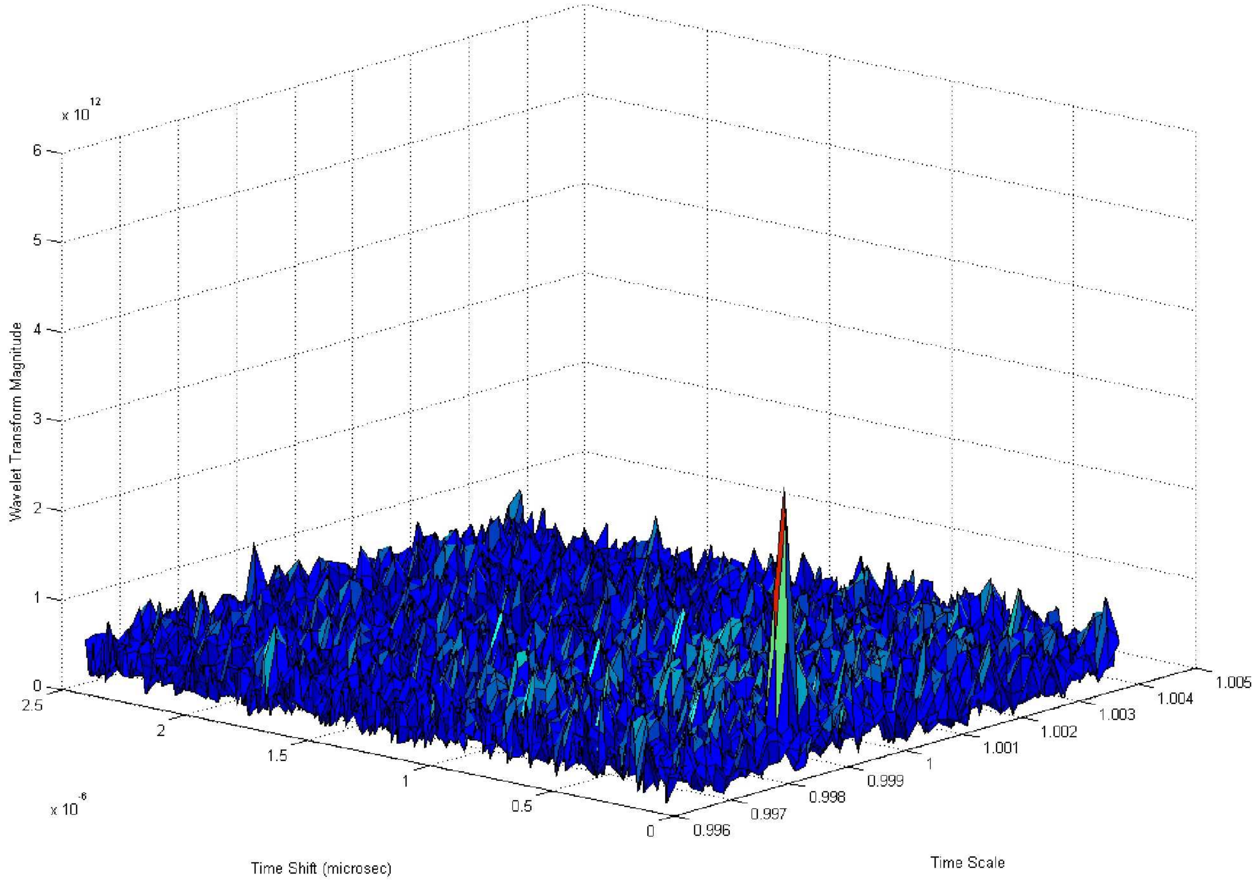
- **Example beam data with five tags**



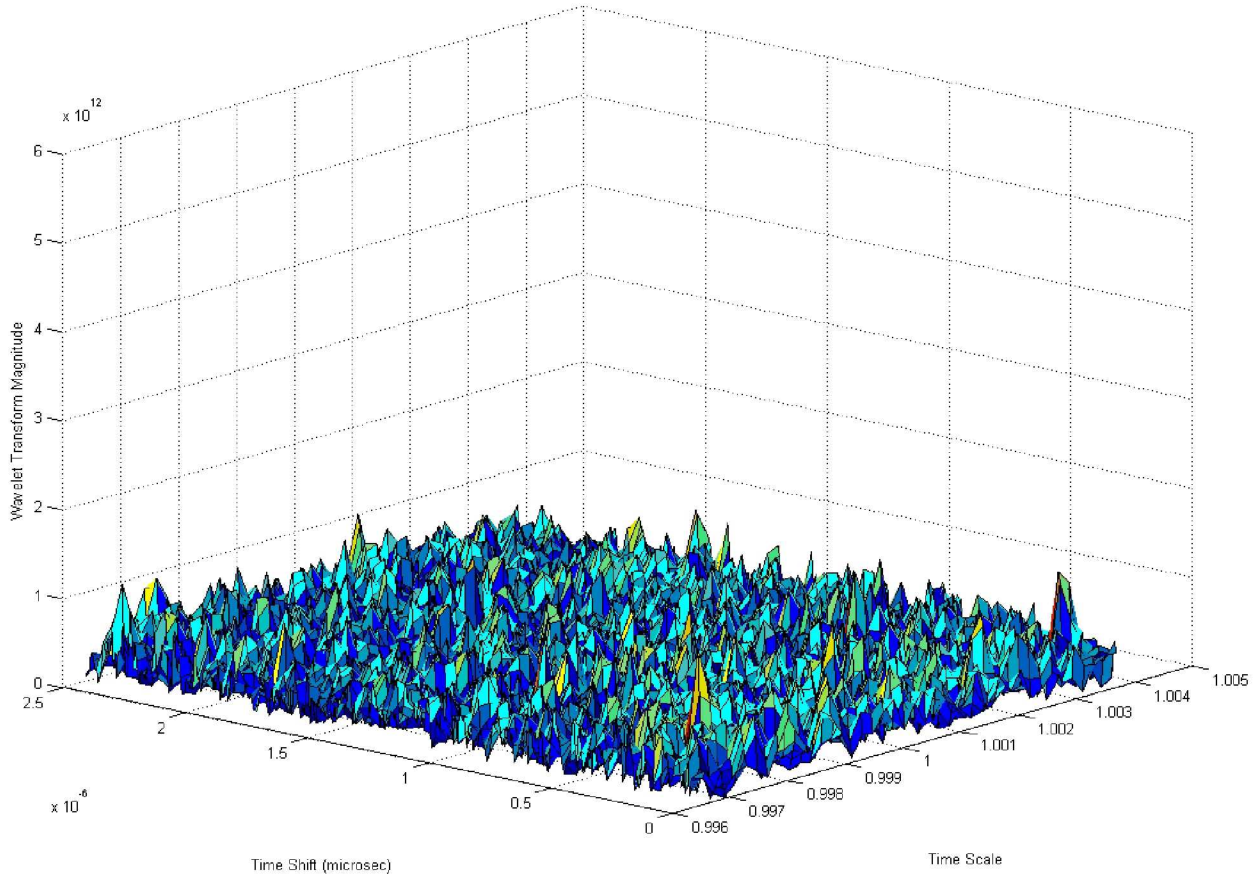
PARSEQ – Beam-Level Processing

- **Compute sampled 2-D correlation surface (wavelet ambiguity function) for each tag template**
  - Scaled tag templates pre-computed
  - Minimal computational burden to compute correlations
- **Determine maximum correlation peak**
  - Nothing above threshold: no tags detected in beam
  - Maximum peak over threshold: corresponding tag detected
- **Estimate range and temperature for detected tag**
  - Nonlinear optimization to maximize correlation value in vicinity of detected correlation peak
  - Optimization represents nearly all of computational burden: $O(N^3)$
- **Successive interference cancellation (SIC)**
  - Project residual signal on detected, scaled template
  - Remove projection to form new residual

- **Correlation surface with wavelet matched to single tag response**

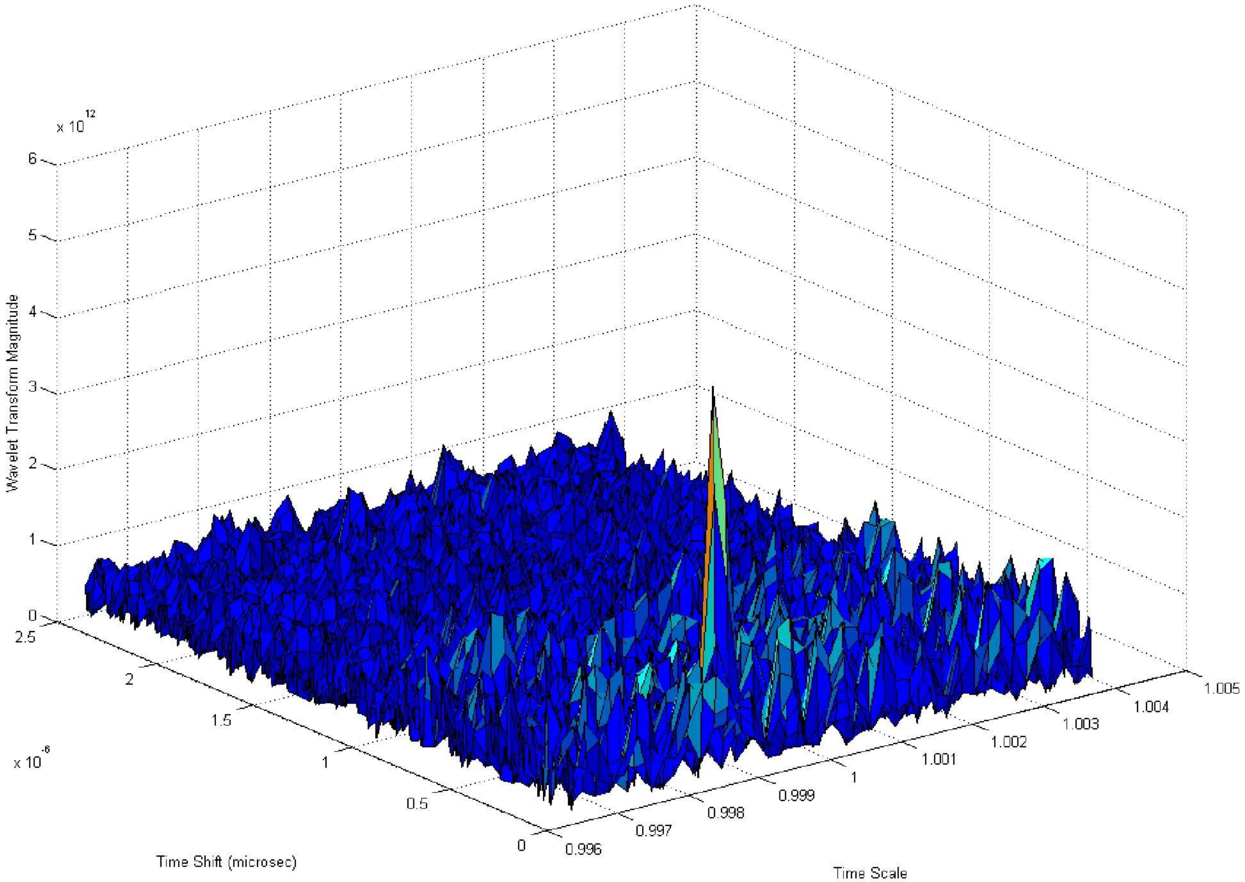


- **Correlation surface with wavelet not matched to single tag response**

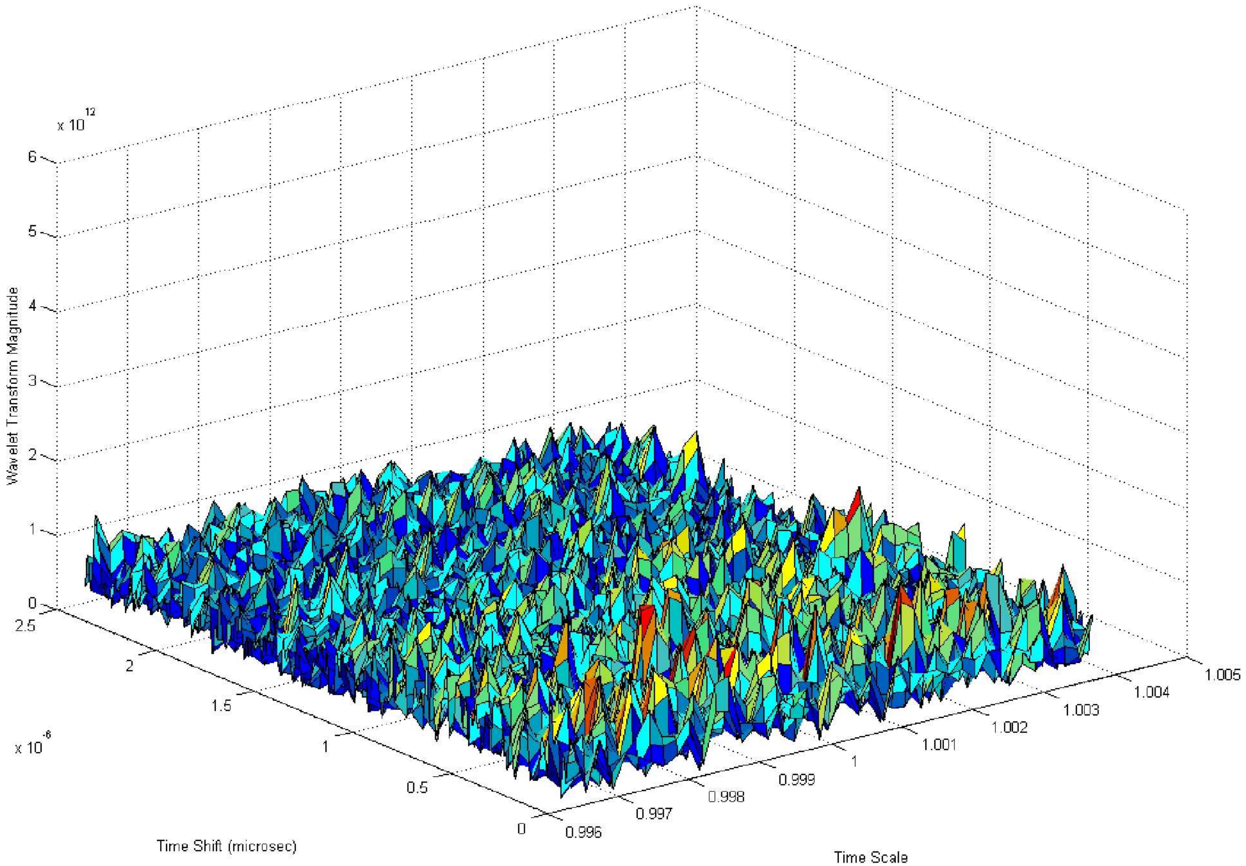


PARSEQ – SIC Processing

- **Correlation surface with strongest response prior to SIC processing for two-tag superposition signal**

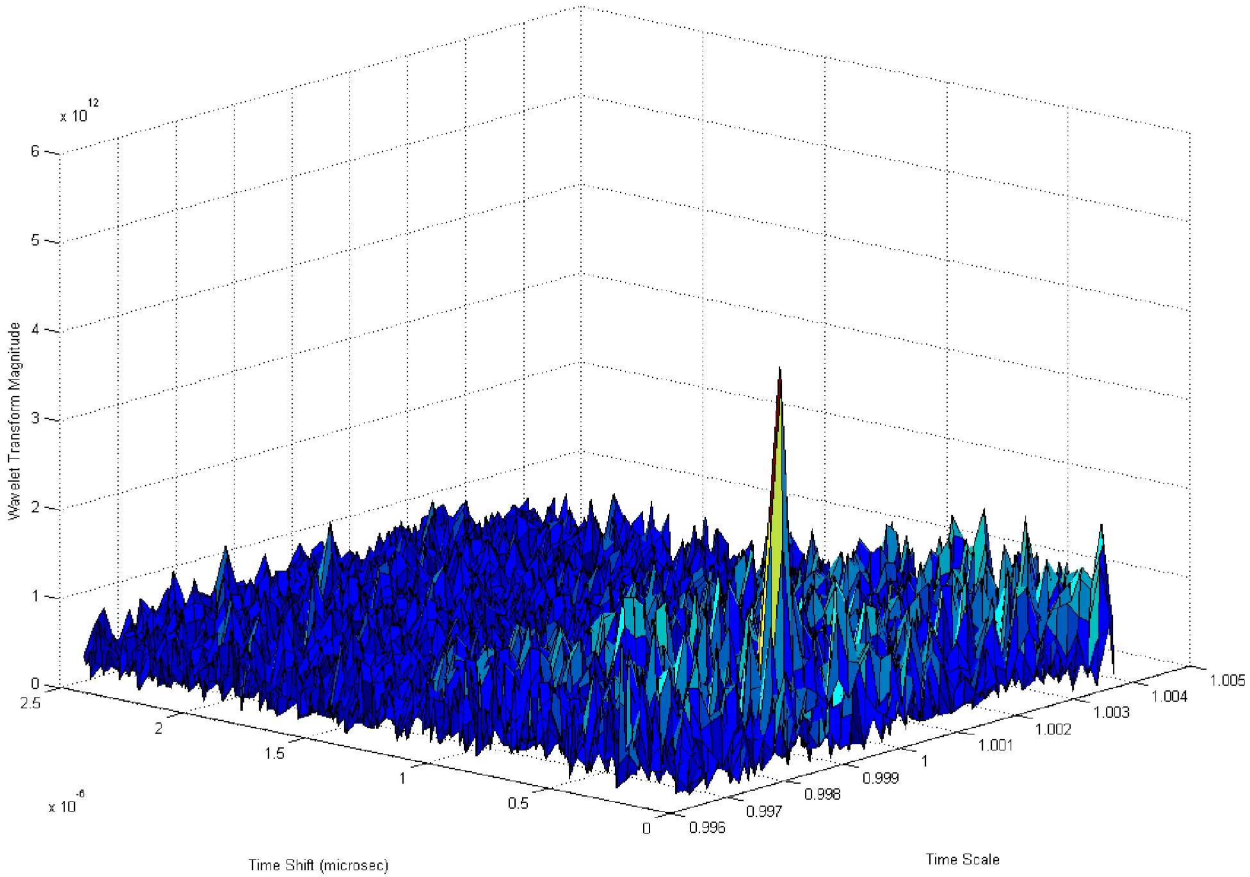


- **Correlation surface with strongest response after SIC processing for two-tag superposition signal**

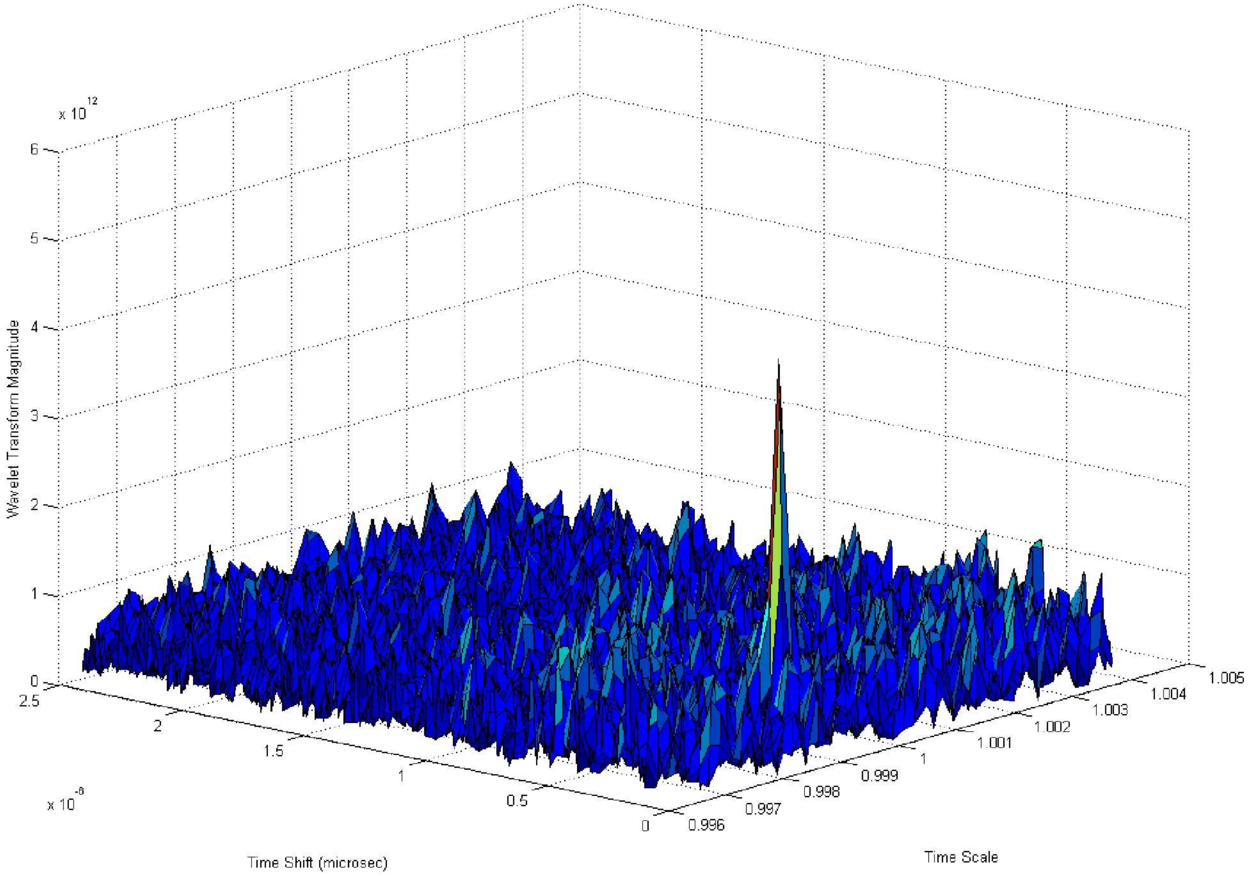


PARSEQ – SIC Processing

- **Correlation surface with second strongest response prior to SIC processing for two-tag superposition signal**



- **Correlation surface with second strongest response after SIC processing for two-tag superposition signal**

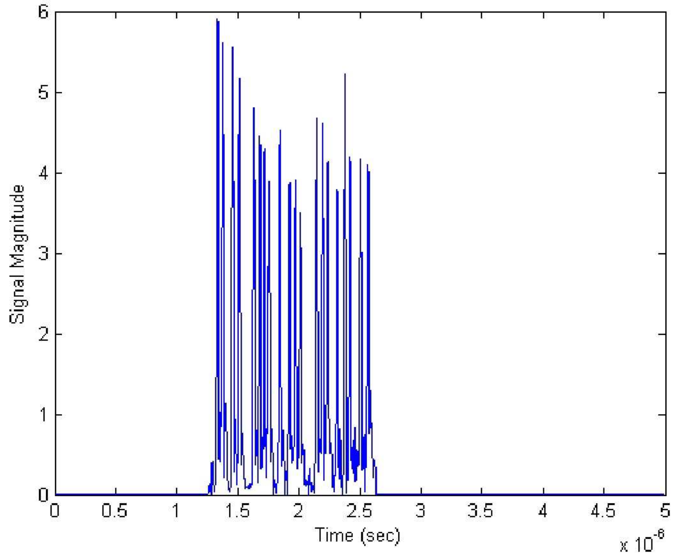


PARSEQ Performance Evaluation - Simulations

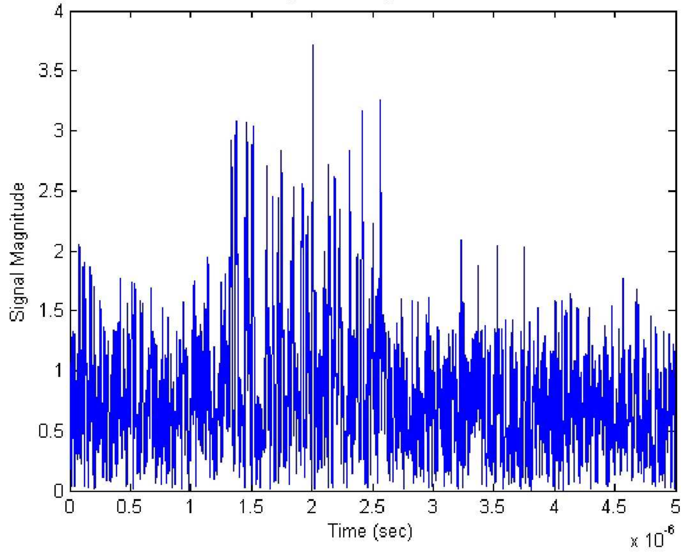
- **40-bit SAW Tag**
  - Tag IDs selected at random
  - 11 Total tags in simulation
- **Simulations based on measured tag responses with simulated additive white Gaussian noise**
  - Multiple SNRs
  - Multiple levels of tag interference
- **Composite signals formed by summing scaled and shifted tag responses**
  - All tags at different ranges and temperatures
  - All tags with same energy (worst case overall)
- **Simulation metrics**
  - Detection probability
  - False alarm probability
  - Mean-squared temperature and range error

Simulated Performance – Example Waveforms

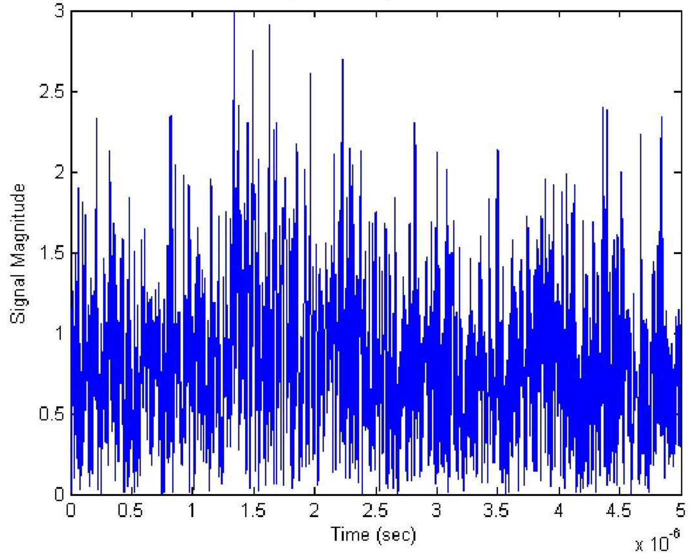
Single Tag – No AWGN



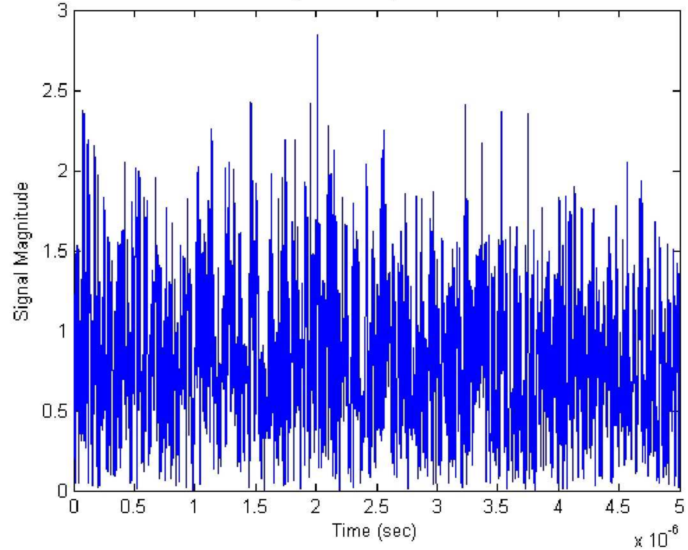
Single Tag – 25 dB



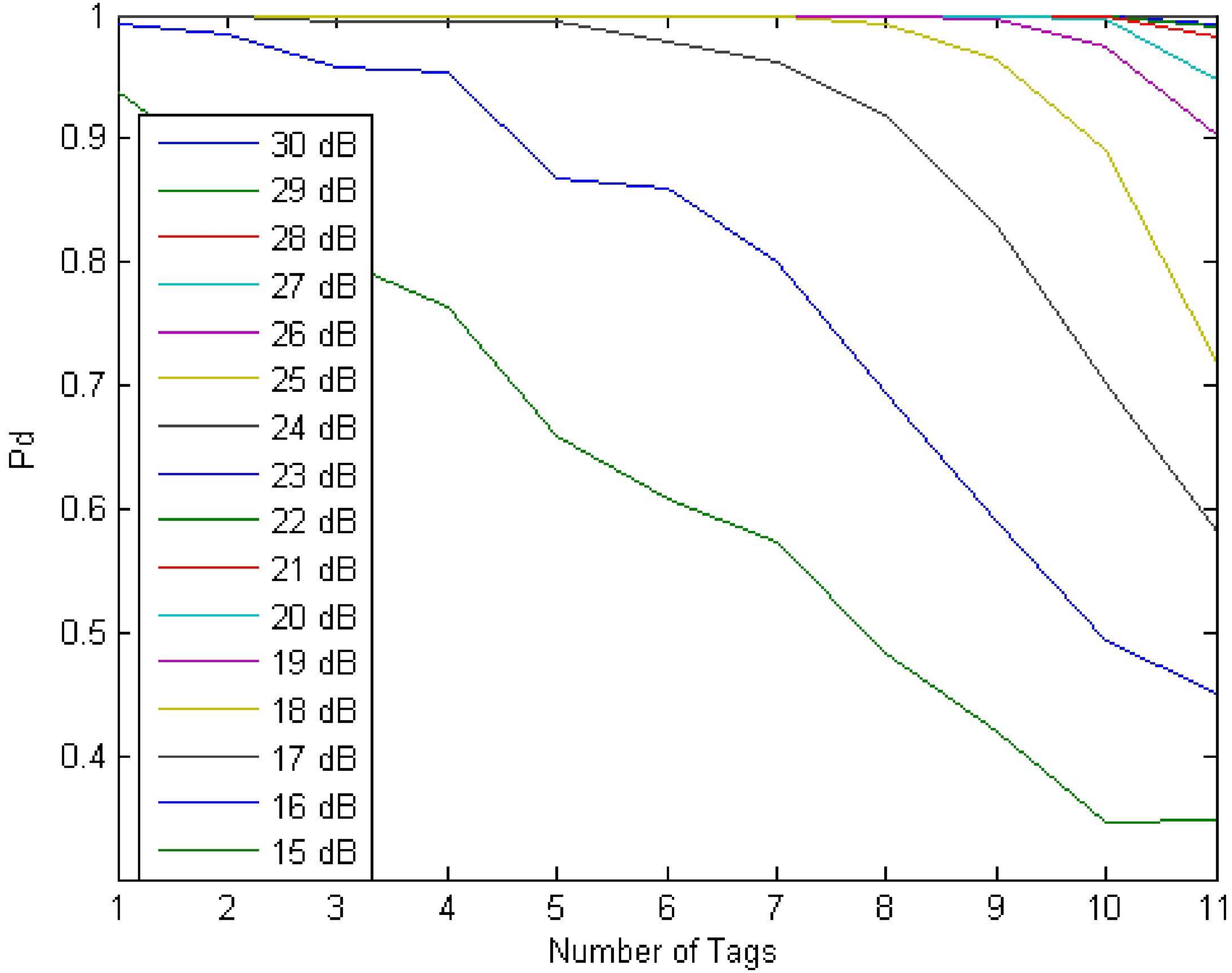
Single Tag – 20 dB



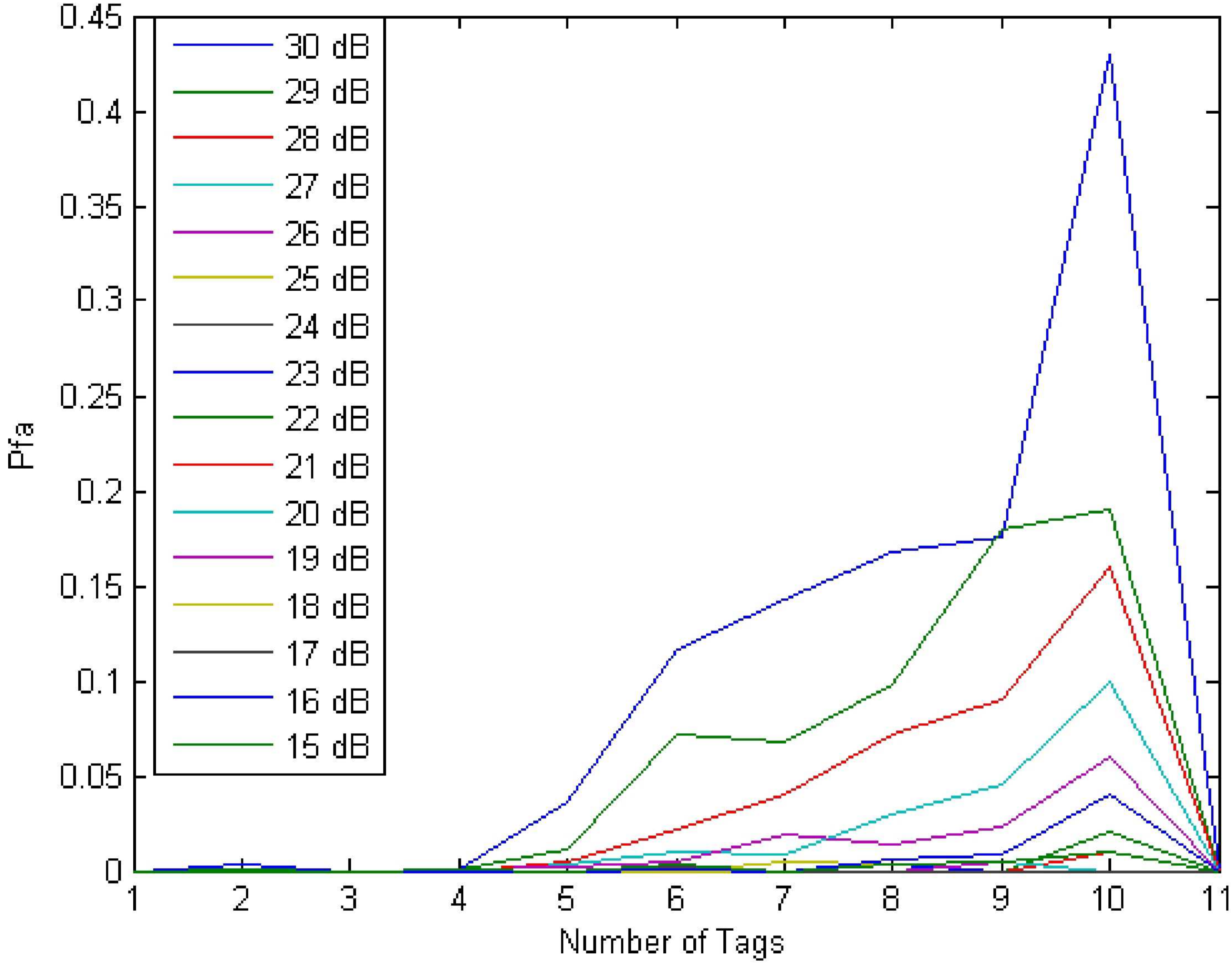
Single Tag – 15 dB



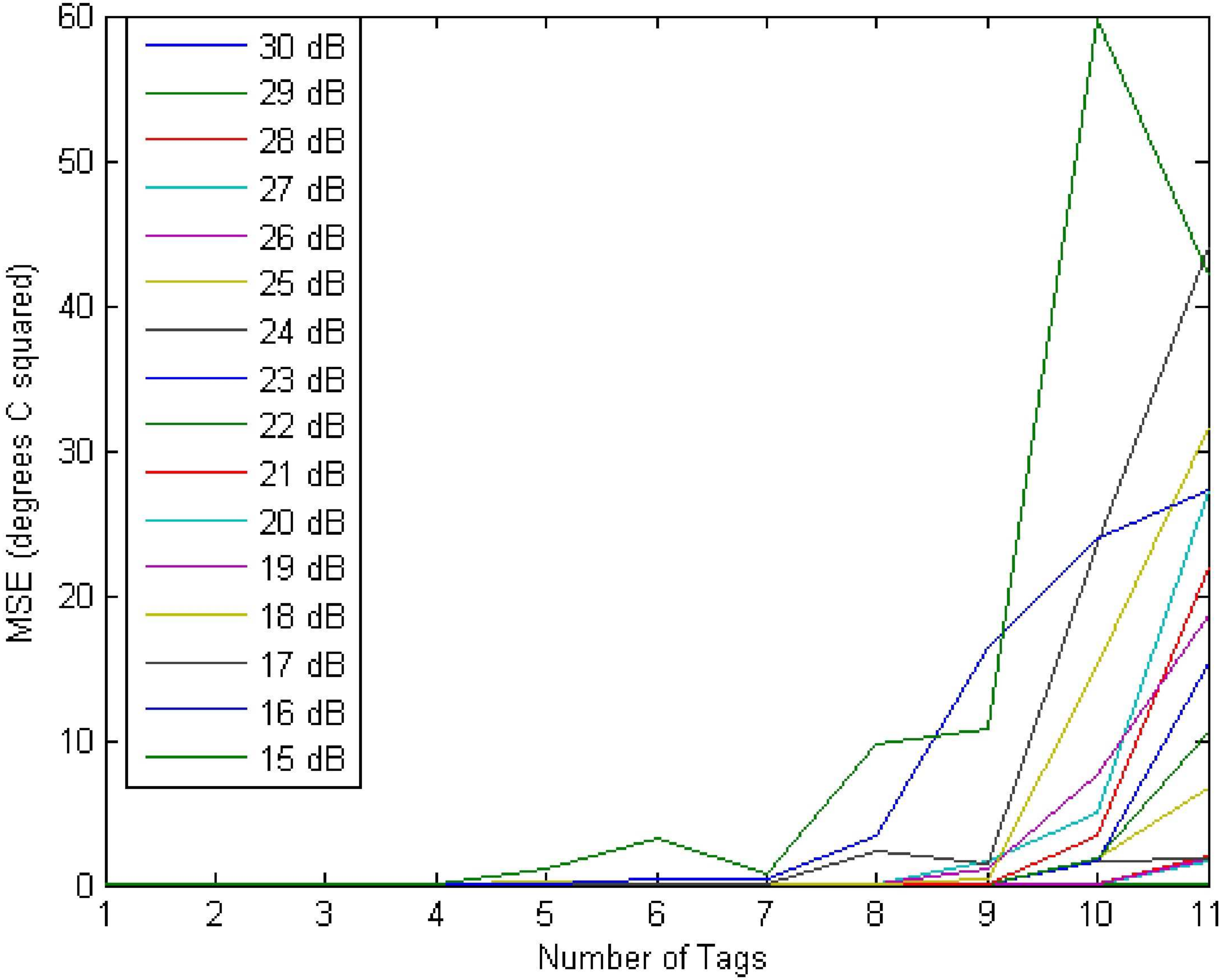
Simulated Performance – Probability of Detection



Simulated Performance – Probability of False Alarm



Simulated Performance – Temperature Estimation



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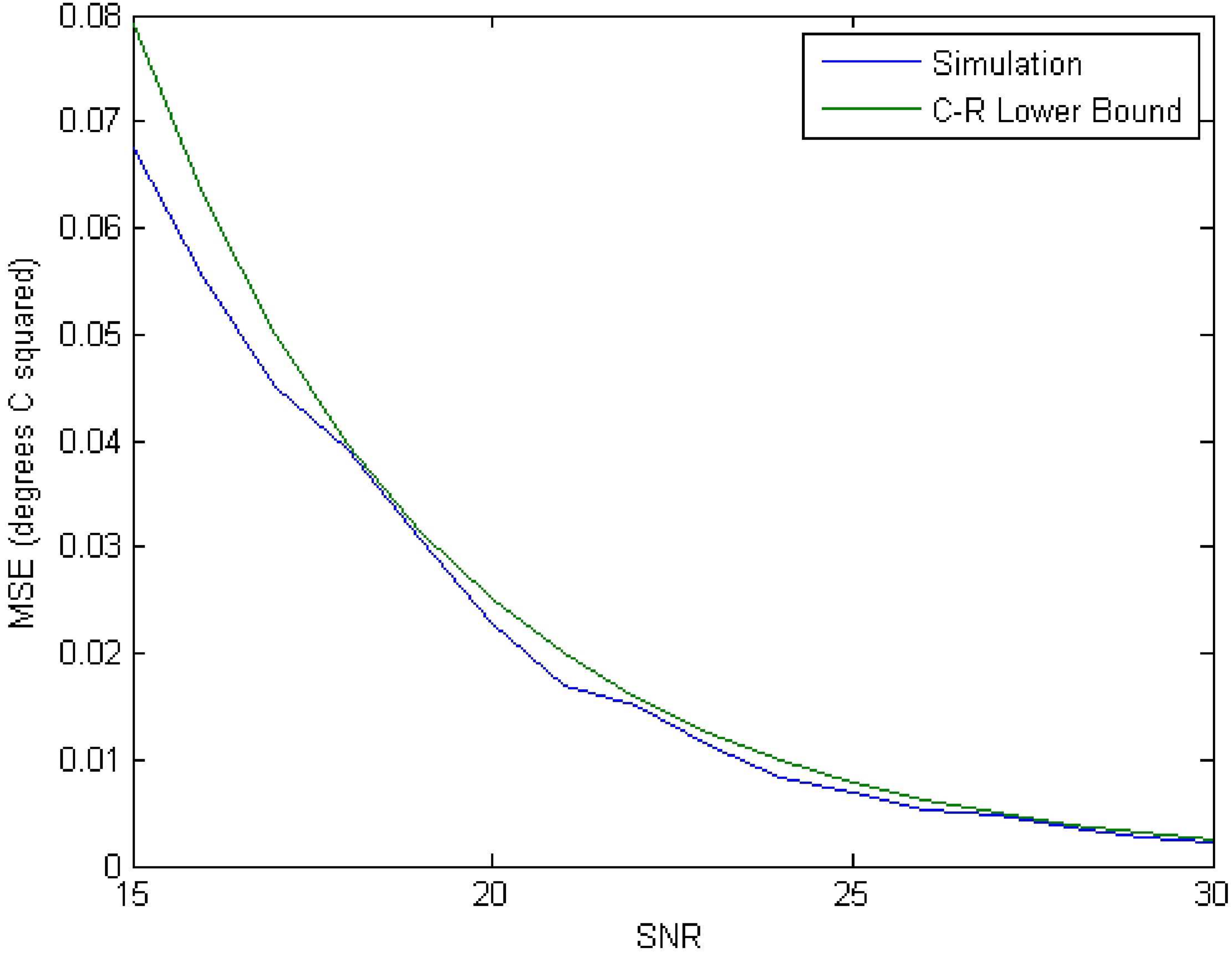
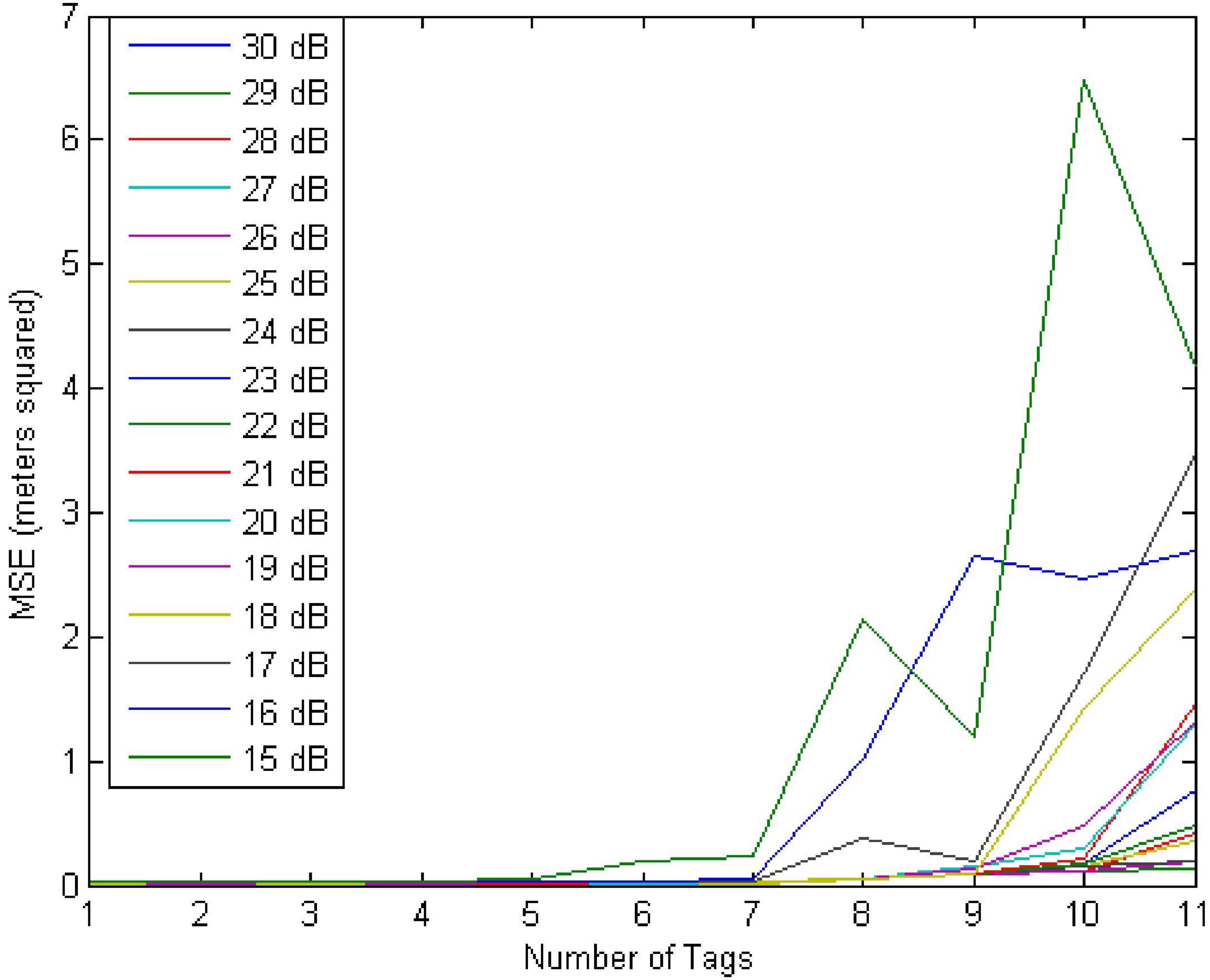
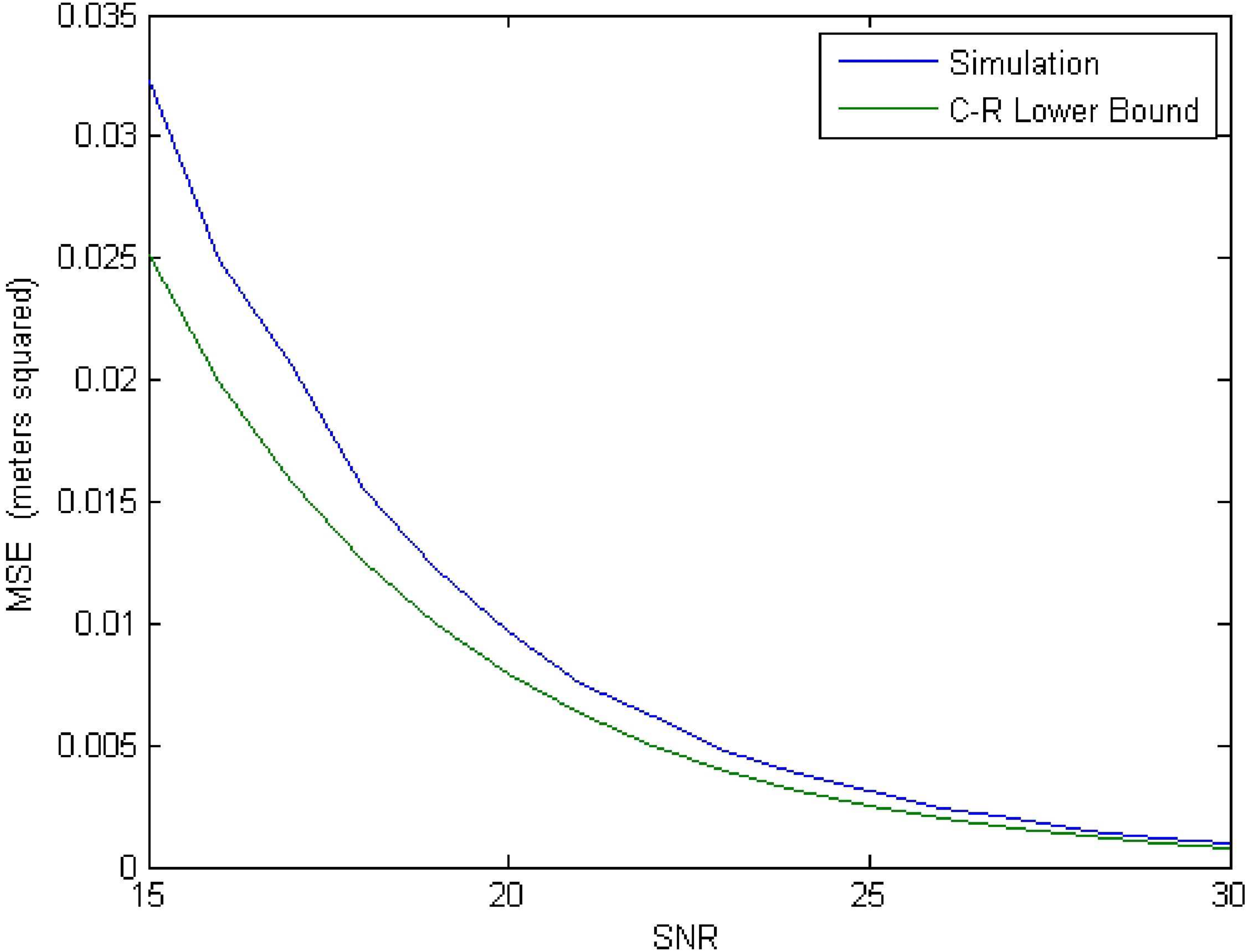


Simulated Performance – Range Estimation



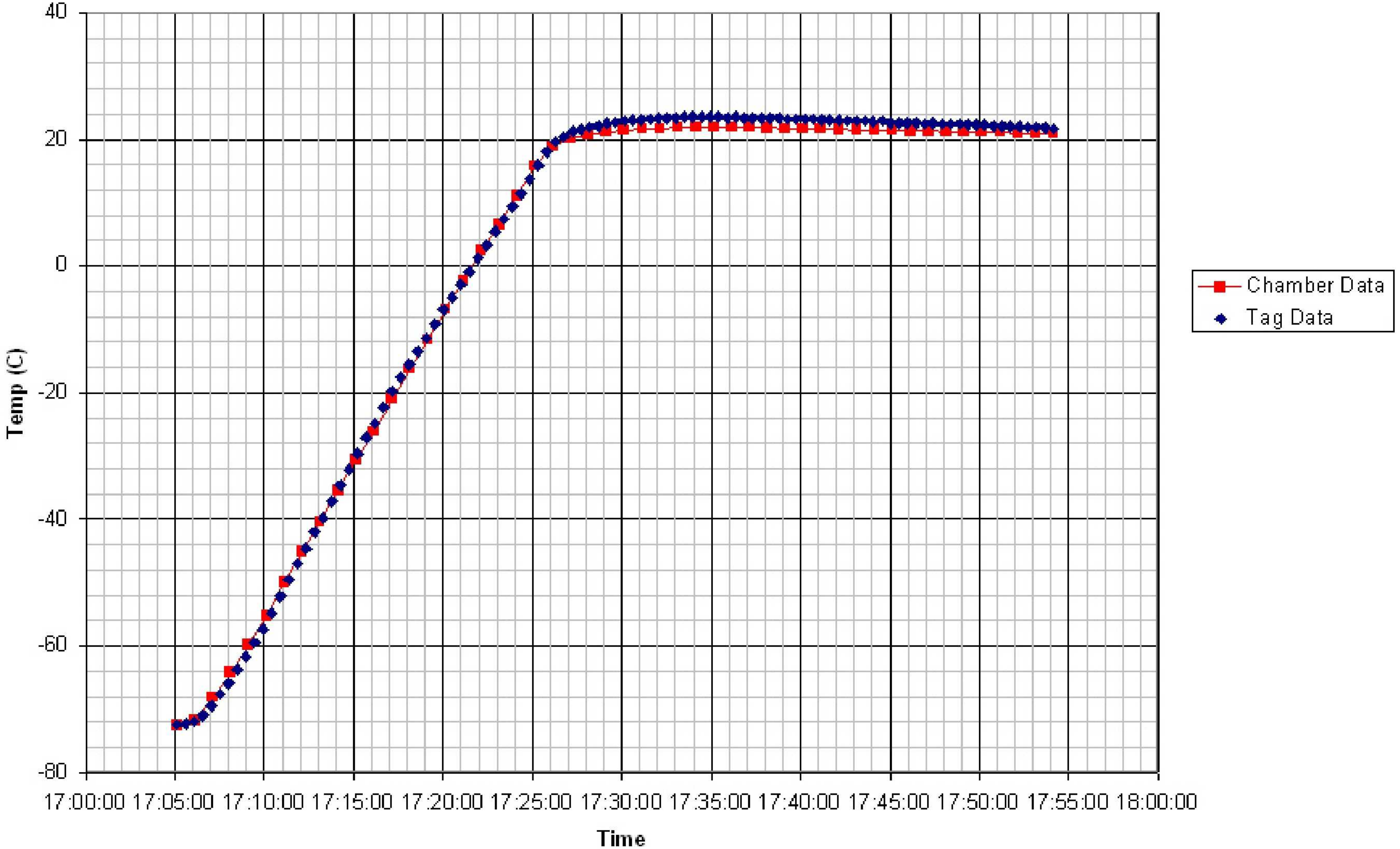
Simulated Performance – Range Estimation



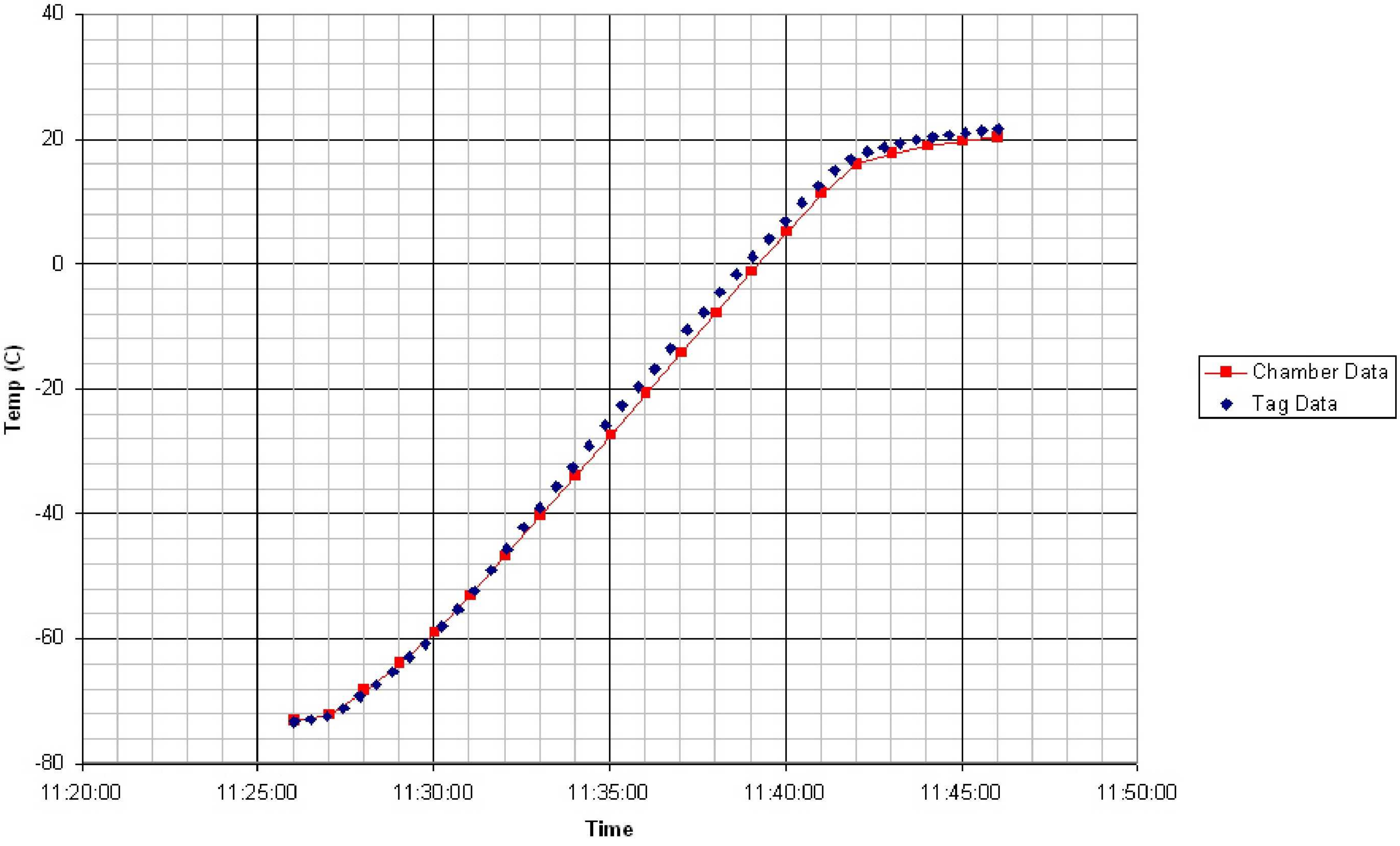
PARSEQ Performance Evaluation - Experimental

- **Connectorized tag placed in thermal chamber**
  - **Cable to external patch antenna**
  - **Chamber cycled from -72° C to 20° C and back**
- **System configuration**
  - **8-element Tx antenna array**
  - **72-element Rx antenna array**
  - **10 mW transmit power**
  - **~3 m cable run and ~2 m antenna range**

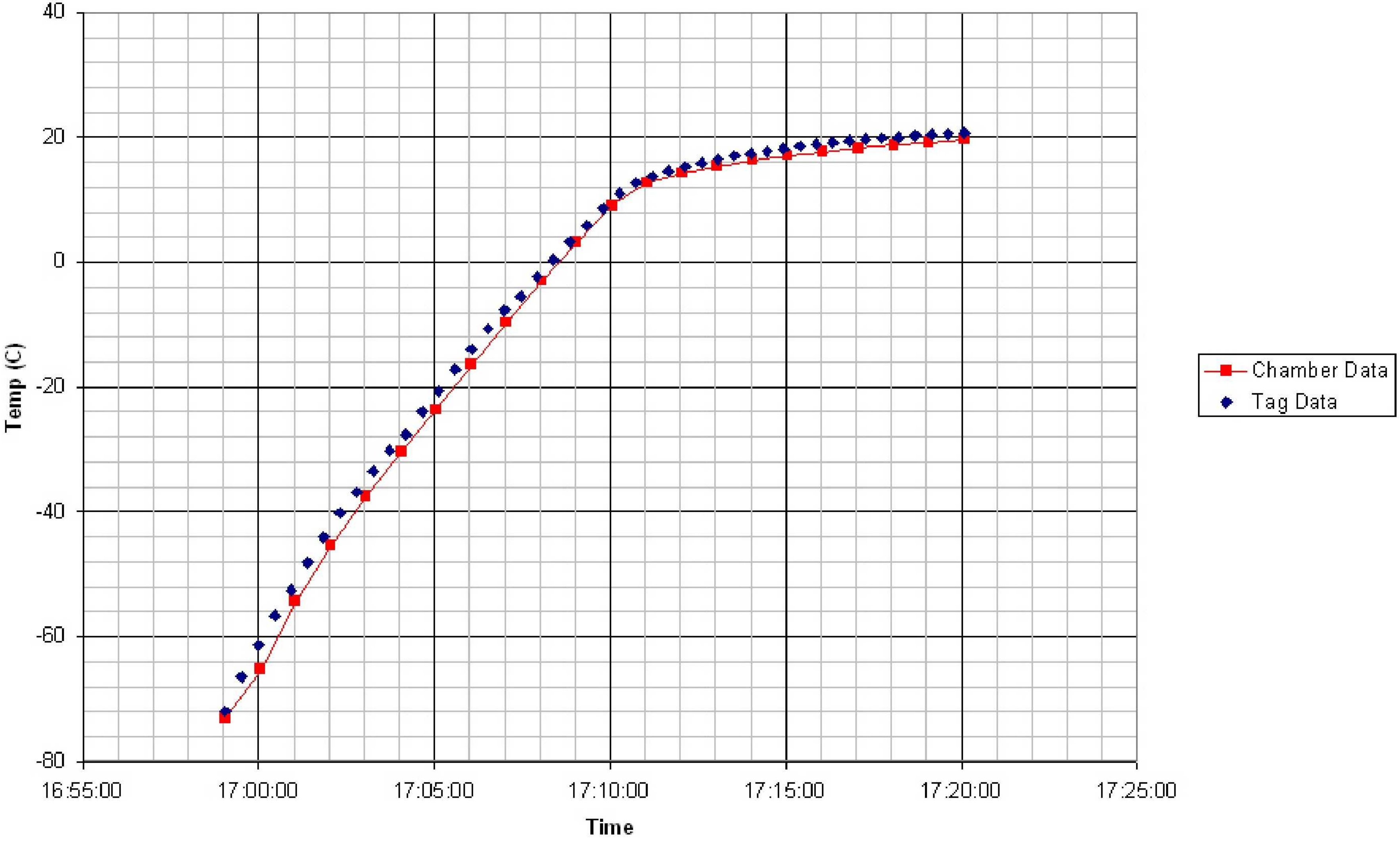
Experimental Performance – Temperature Estimation @ 4.5° C/min



Experimental Performance – Temperature Estimation @ 6° C/min



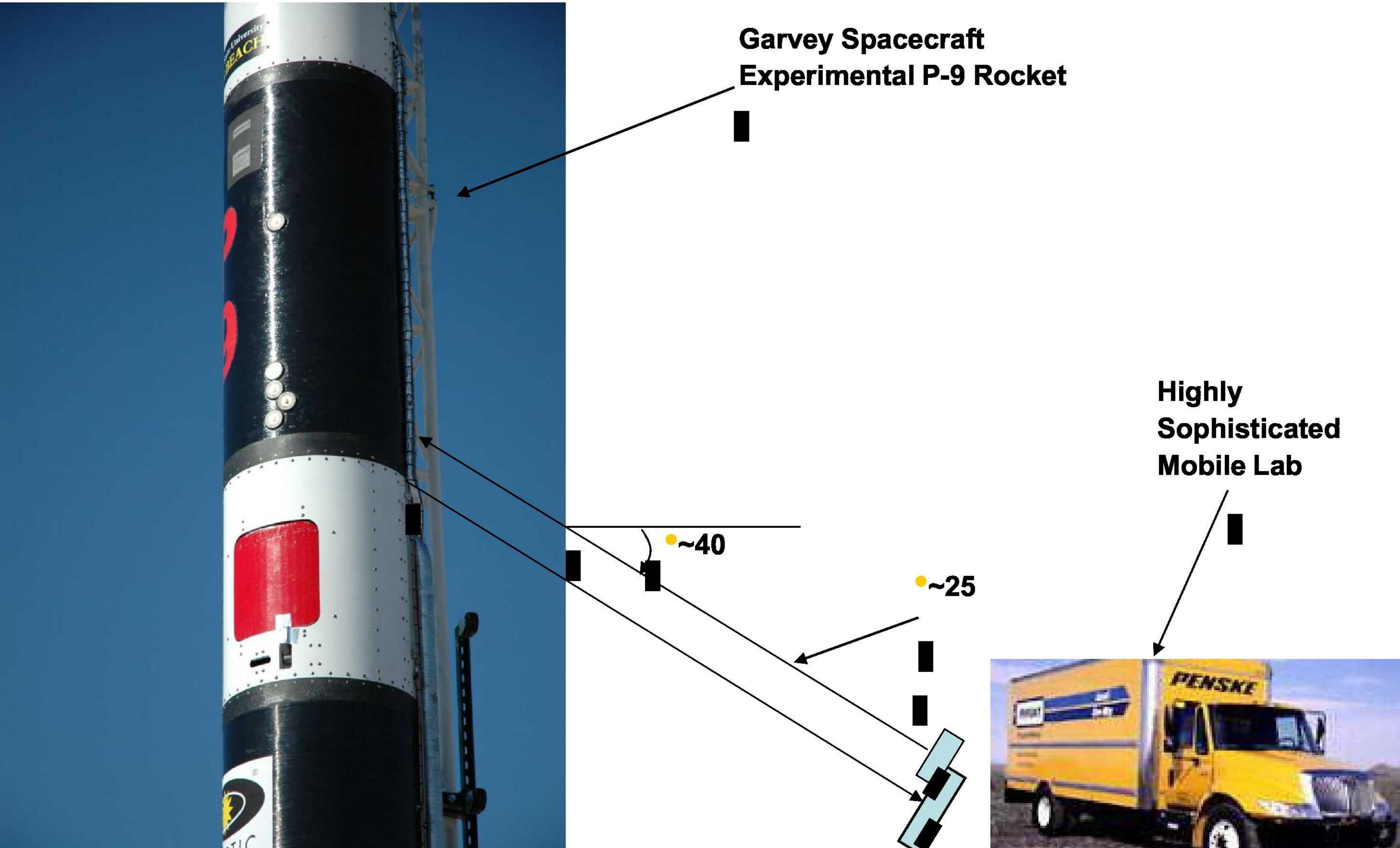
Experimental Performance – Temperature Estimation @ 11° C/min



PARSEQ Field Test – Garvey Rocket Test

- **Monitor temperature of experimental LOX tank wirelessly**
  - **5 tags placed on exterior of tank**
  - **Tags placed at same level as wired internal temperature sensors**
- **System configuration**
  - **8-element Tx antenna**
  - **64-element Rx antenna**
  - **~19 ft. baseline range**
  - **~25 ft. tag range**
  - **Azimuth: tag boresight**
  - **Elevation: ~40° off tag bore-sight**

Garvey Spacecraft P-9 Rocket


Garvey Spacecraft
Experimental P-9 Rocket
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Mobile Lab
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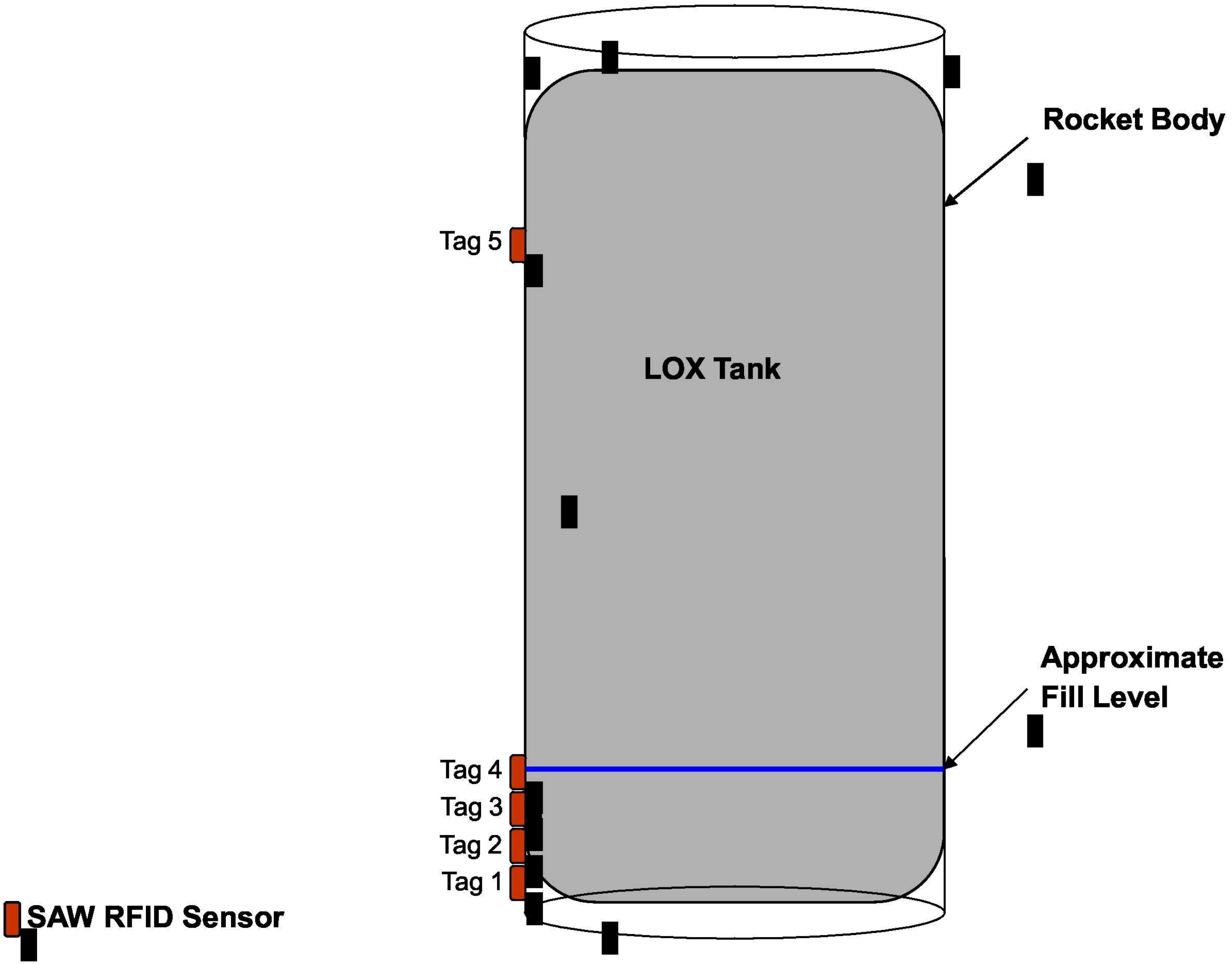
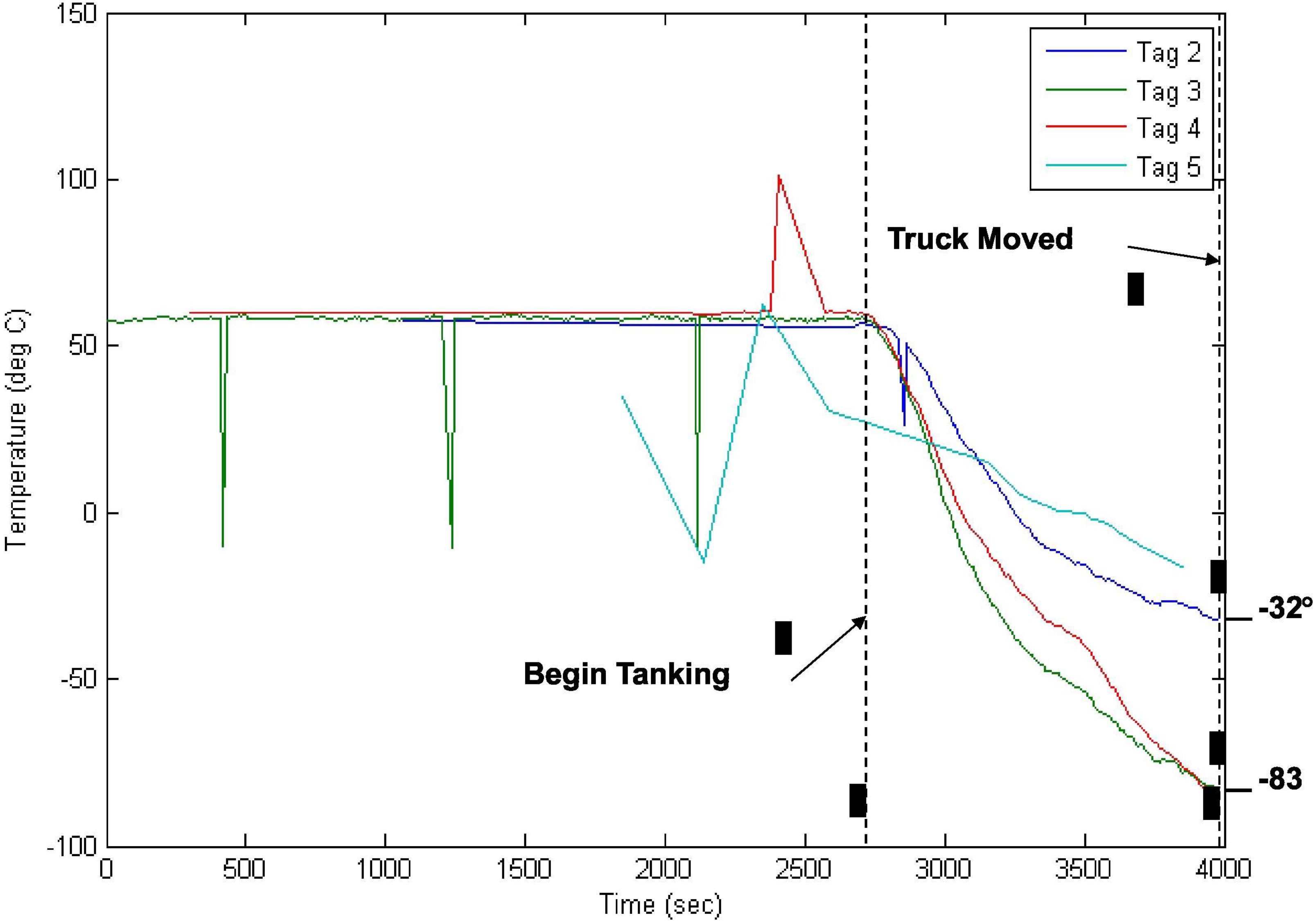
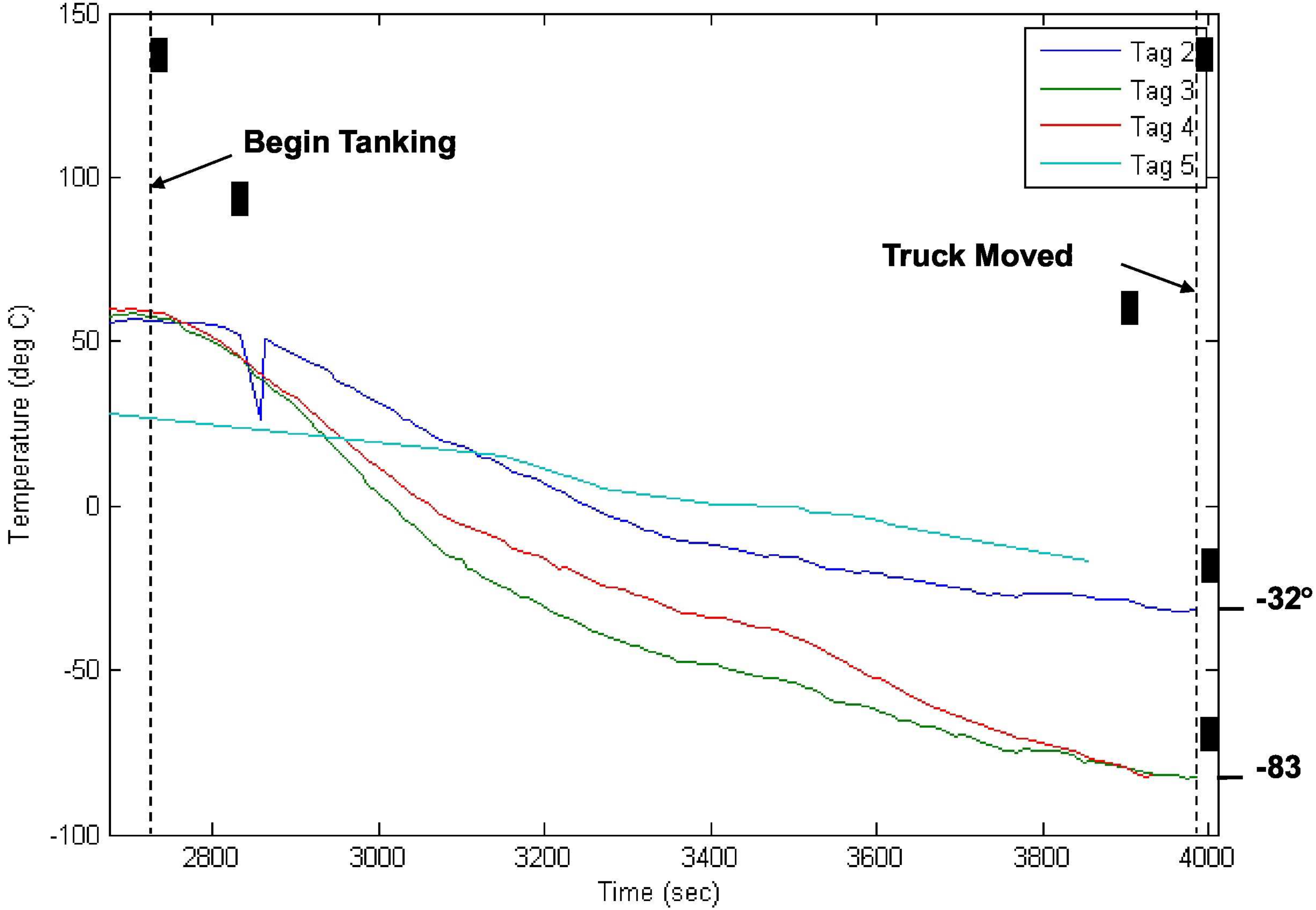
Garvey Test – Tag Placement



Garvey Test – Test Results



Garvey Test – Results During Tanking



Future Work

- **Integrate calibrated, passive commercial sensors with SAW devices**

  Primary targets: accelerometers, acoustic emission sensors

- **Longer Ranges and higher tag density**

- **Sample rates significantly higher than current temperature applications: > 10 kHz, compared to 1-3 Hz**