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USRP based X-band Digital Beam Forming Synthetic Aperture Imaging Radar

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Presentation Outline

- Project goals
- System concept and aperture design
  - Conversion to X-band
  - Electronics module
- USRP waveform generation and reception
- MIMO and TDM timing and control
- Measurement scene
- Measurements produced by USRP
- Signal post processing and calibration
- Image formation
- Summary highlights and future work

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Project Goals

- Develop and demonstrate fundamental synthetic aperture radar (SAR) system performance with a USRP as the back end exciter/receiver.
- Demonstrate implementation of several key radar techniques
  - Virtual element antenna aperture formation
    - Multiple Input Multiple Output (MIMO) techniques
  - Time Domain Multiplexing (TDM) of radar waveform between elements
  - Up-conversion of USRP carrier to X-band for better resolution in area limited platforms
  - Digital Beam Forming (DBF) for image formation. No moving parts.
  - Mitigate transmit leakage while receiving radar return
  - Use USRP for digital pulse compression and as many signal processing functions as practical given academic semester time constraints
  - Use only COTs components

Imaging Radar Operational Concept

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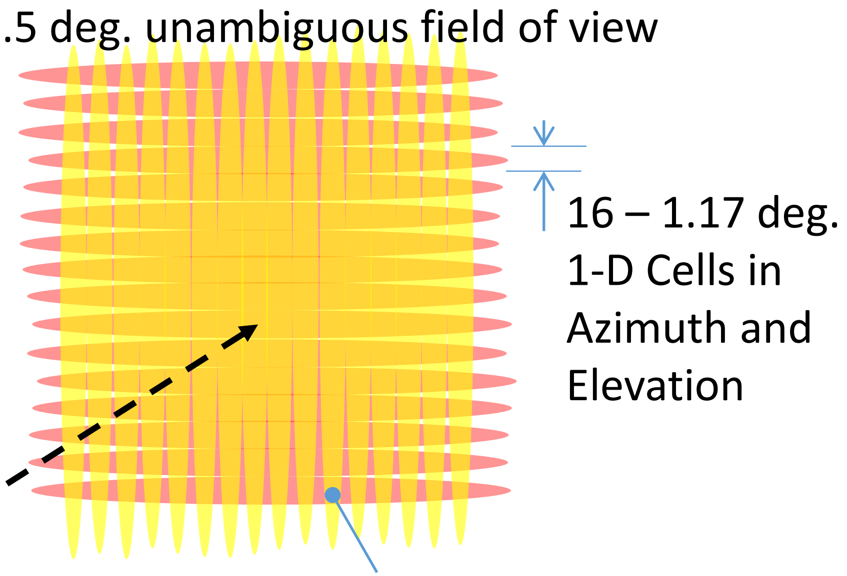
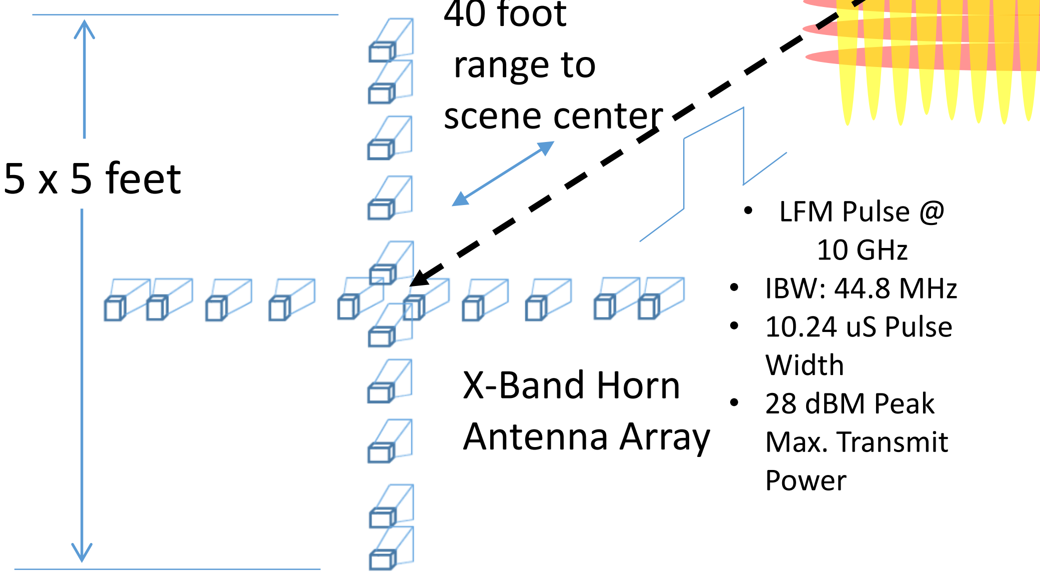
- Union of the orthogonal 1-D images forms 2-D cross-range image of scene
- Down-range resolved with pulsed linear frequency modulated (LFM) waveform

  - Center Freq.: 10 GHz
  - Pulsed LFM Transmit/Receive Waveform (44.8 MHz IBW)
  - Range Res. : 10 feet
  - No moving parts
  - Uses all COTs components
  - Uses digital beam forming



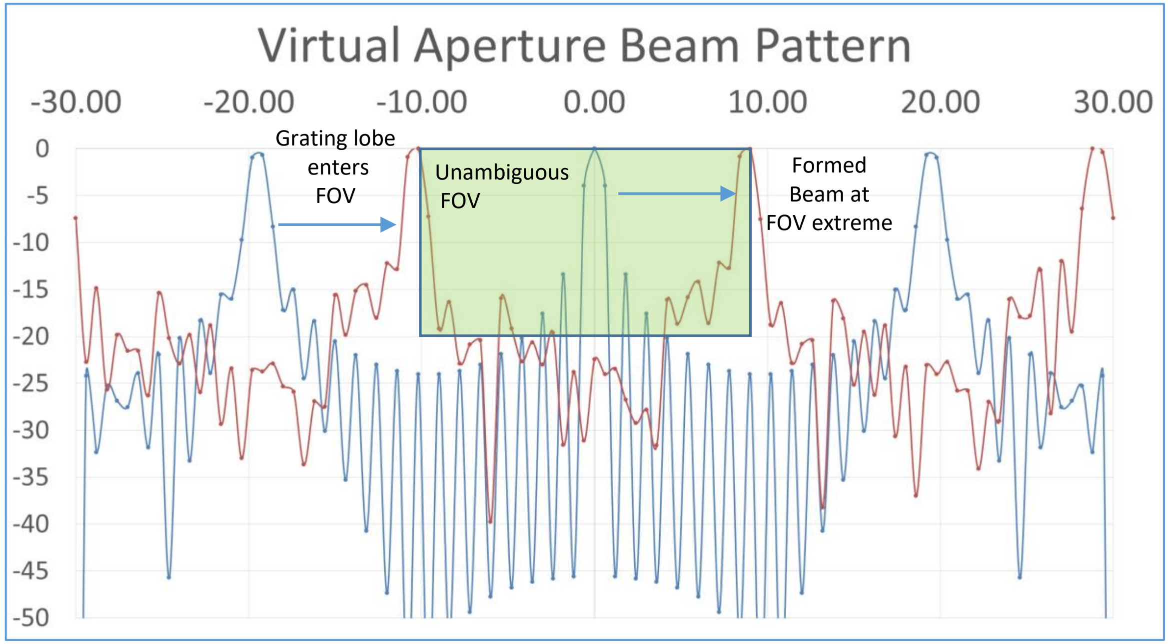


- LFM Pulse @ 10 GHz
- IBW: 44.8 MHz
- 10.24 uS Pulse Width
- 28 dBM Peak Max. Transmit Power

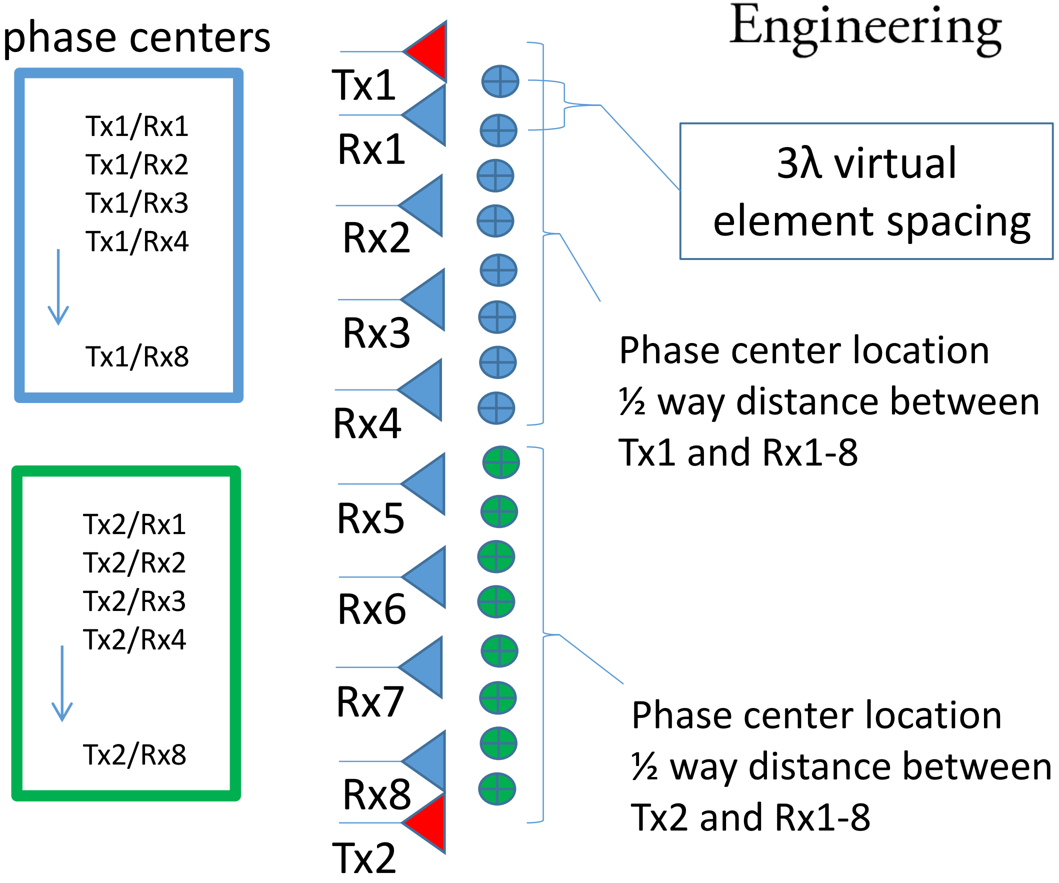
Beams are formed Digitally with Fourier Transform, 16 in Azimuth And 16 in Elevation

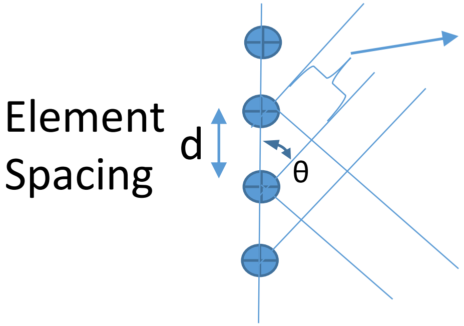
Sixteen Synthetic Aperture 1-D Virtual Elements at 3λ spacing formed for each axis

- Unambiguous field of view of +/- 8.75 deg., 1.17 deg. Spatial resolution



Generates 16 phase centers



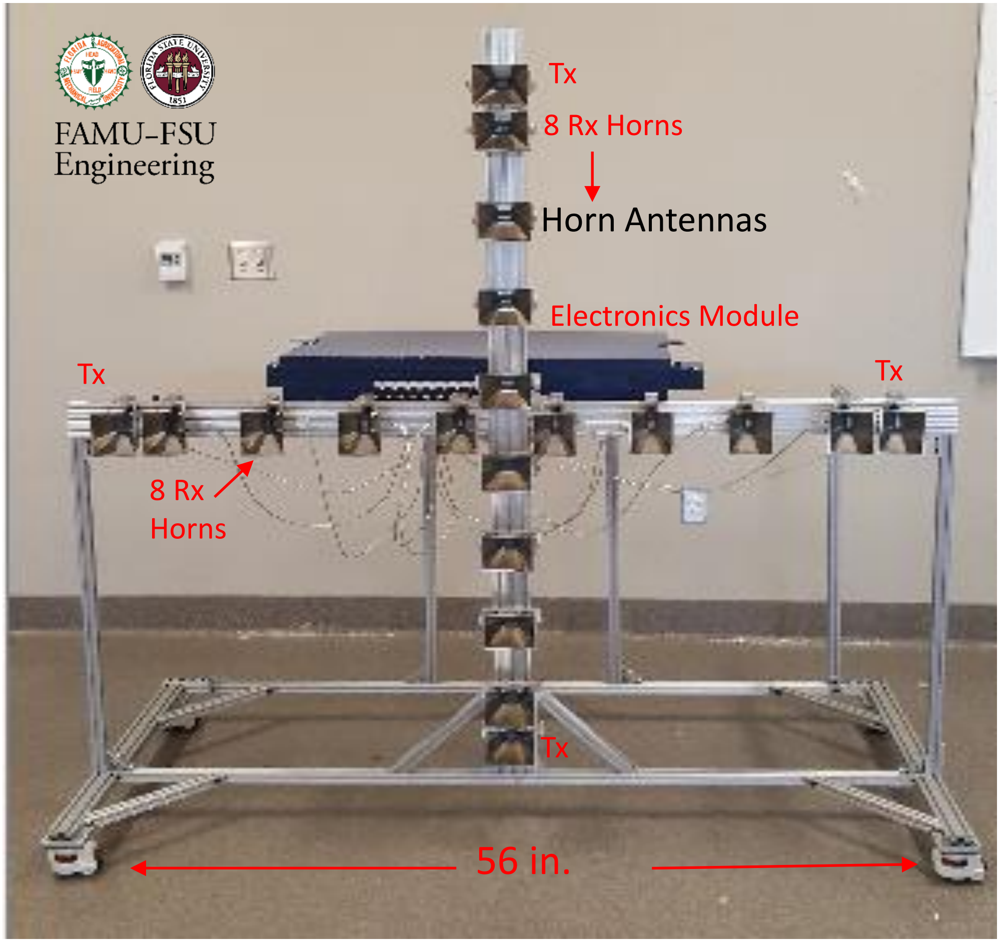


As spacing d increases, dsin(θ) goes through multiple 360 degree transitions as a function of angle creating ambiguous grating lobes.

Aperture and Component Module Hardware Photos

- All COTs component used

Antenna Aperture



USRP Interconnections with Electronics module and PC

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All Commercial Components Used In Electrical Design

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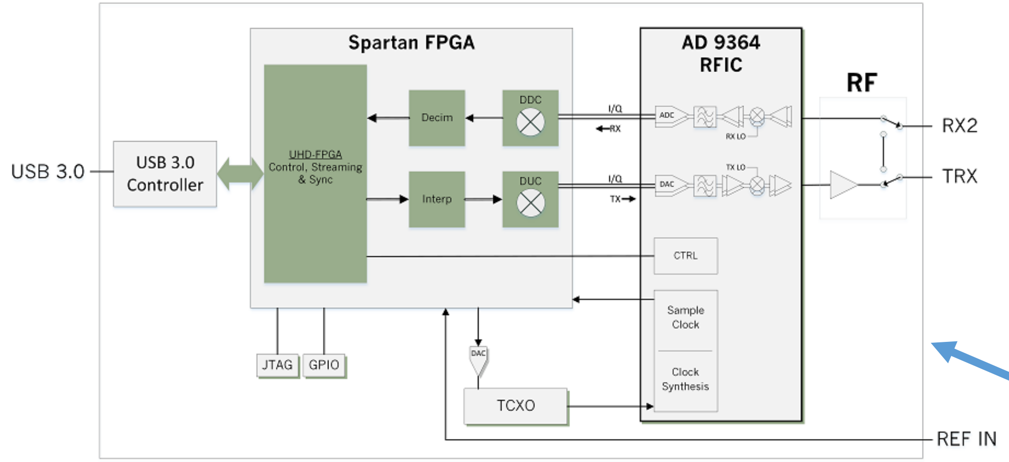
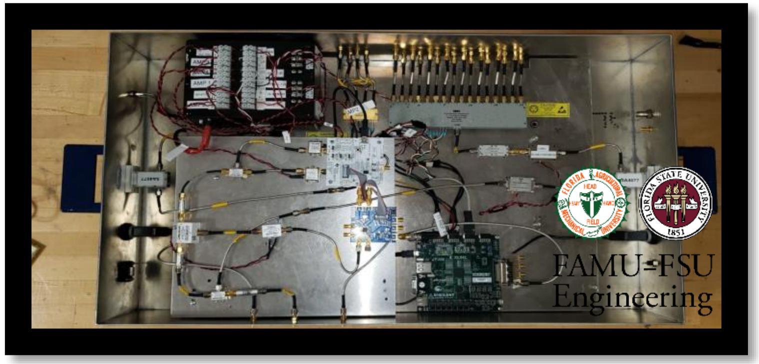
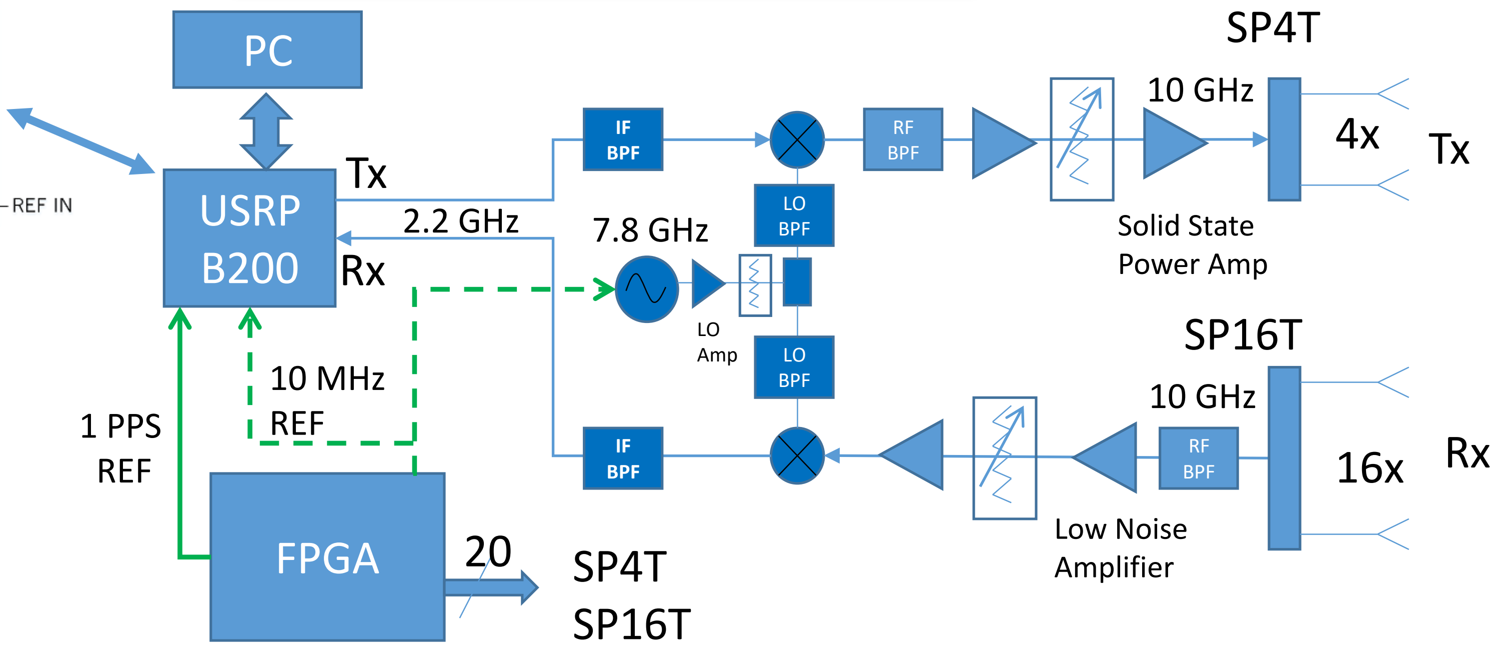
B200 USRP Block Diagram



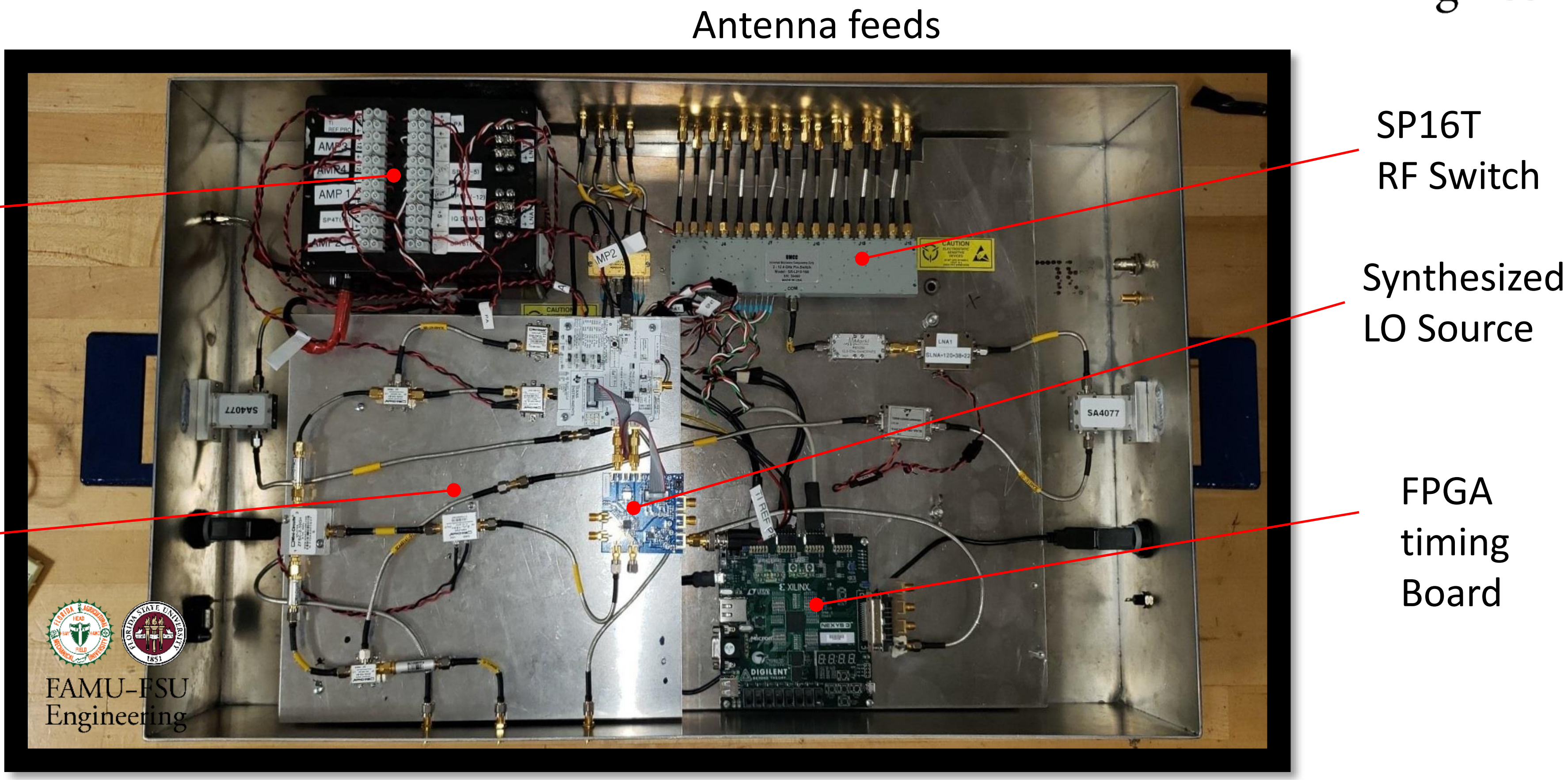
Electronic Component Module





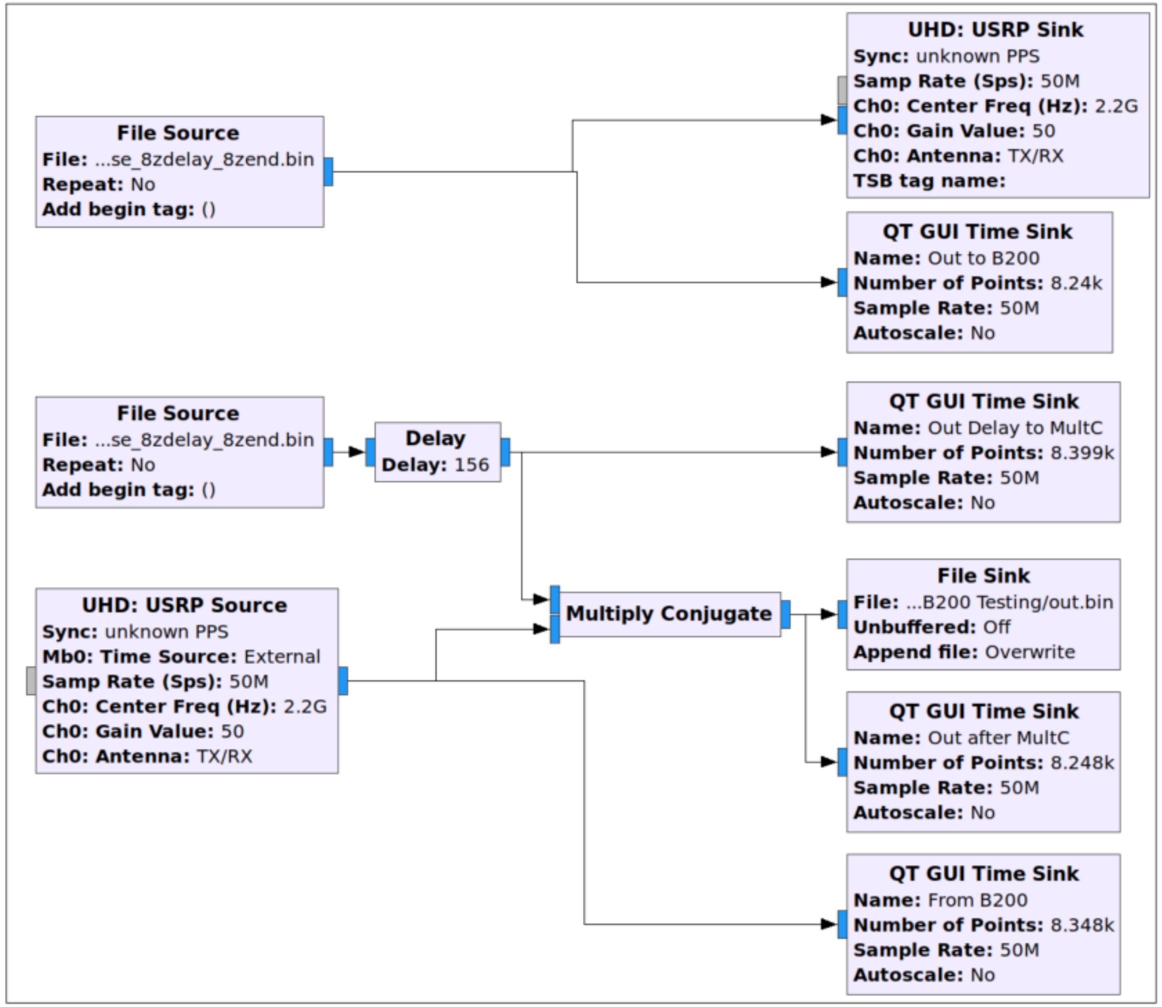
Electronics Module Detail

- Hardline coax cable interconnects components



Pulsed FMCW Flow Graph

- Fs = 50 MHz sample rate
- 2.2 GHz IF
- 44.8 MHz IBW LFM
- Digital Pulse Compression
- 8,192 complex samples define 16 pulse data collect
- Non-streaming
  - Tried but could not eliminate dropouts at the 50MHz sample rate over USB 3.0



Timing Critical Between USRP Waveform and FPGA Discrete Switching Signals

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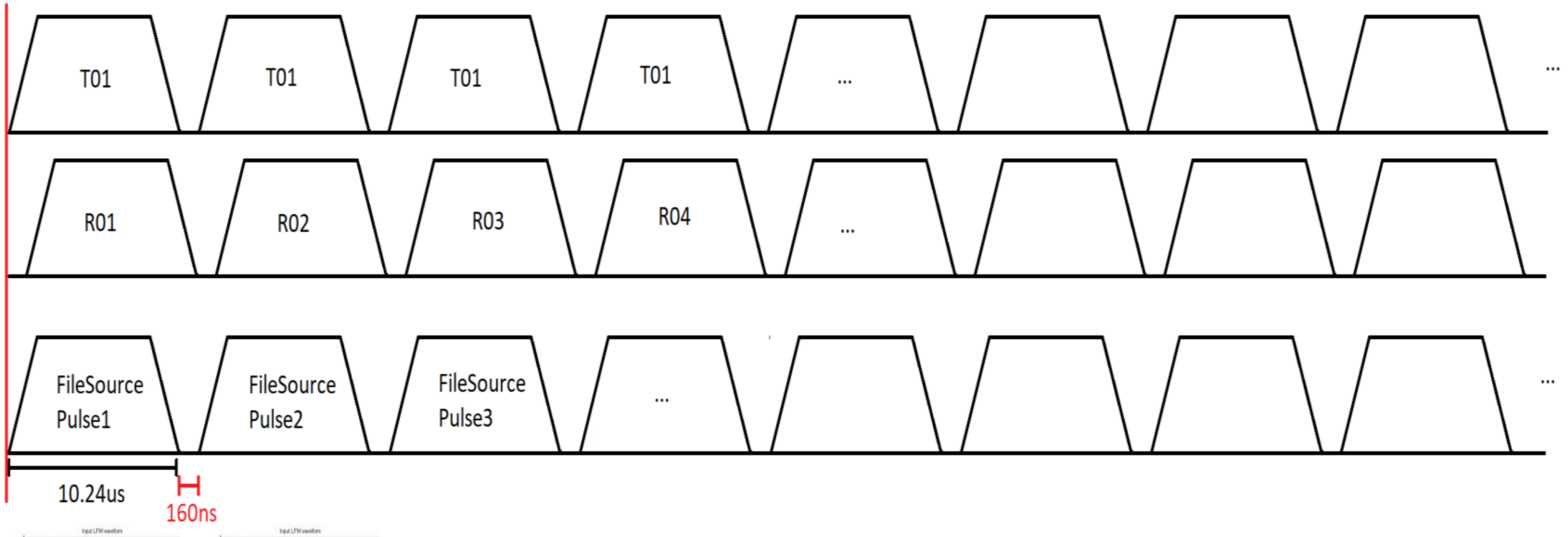
- FPGA generates discrete signals for MIMO operation
- Delay in USRP output relative to 1PPS ref signal was a challenge to synchronize switching MIMO elements

Transmit Horns

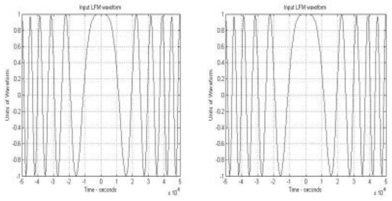
Receive Horns

USRP LFM Waveform



16 pulses per data collect

Fs=50 MHz
IBW=44.8 MHz



Each data collection dwell contains 8,192 complex samples capturing the 16 pulses

Full Thread Radar Performance GRC Output

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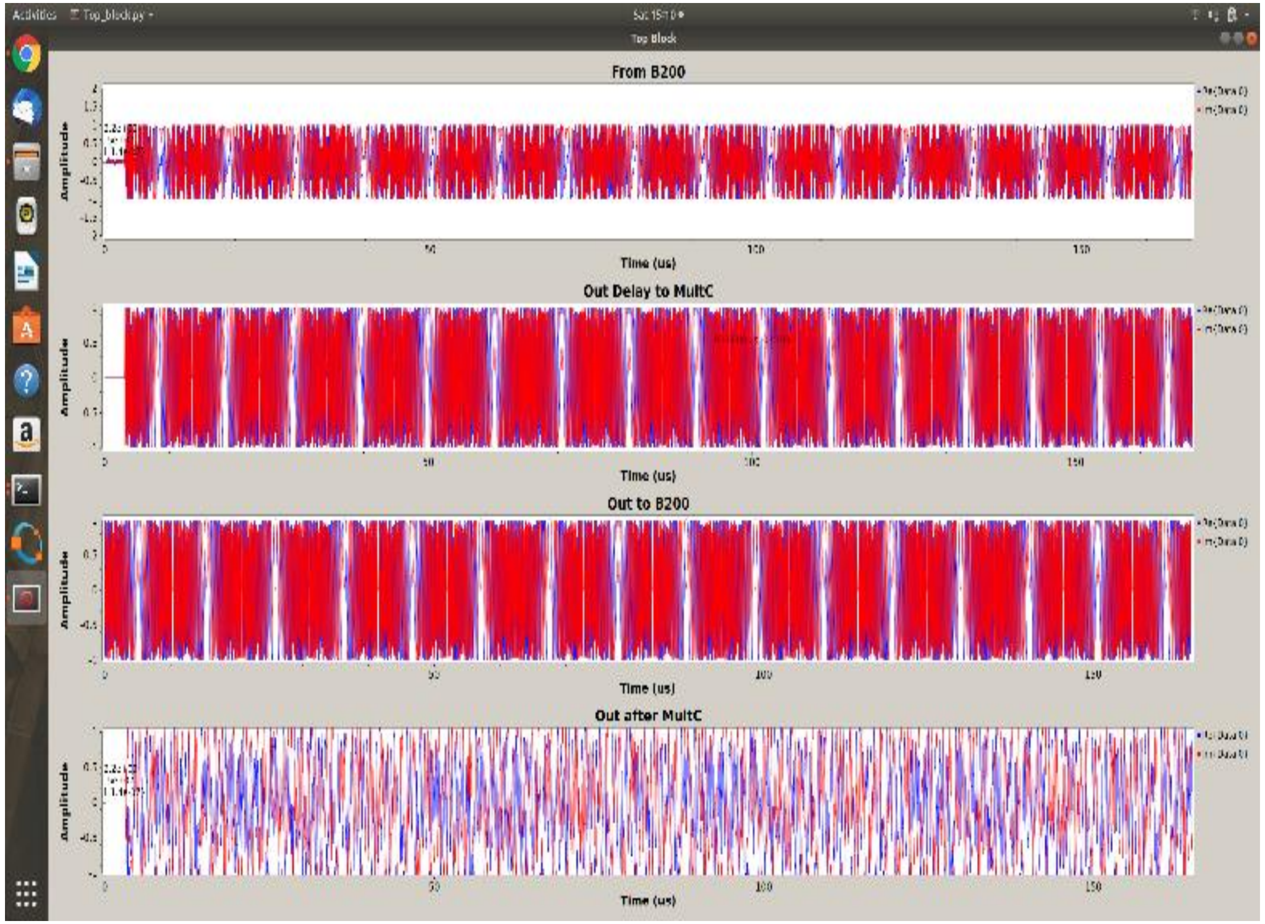
- 16 LFM pulses form one coherent data collect interval

Clear scene + Transmit leakage

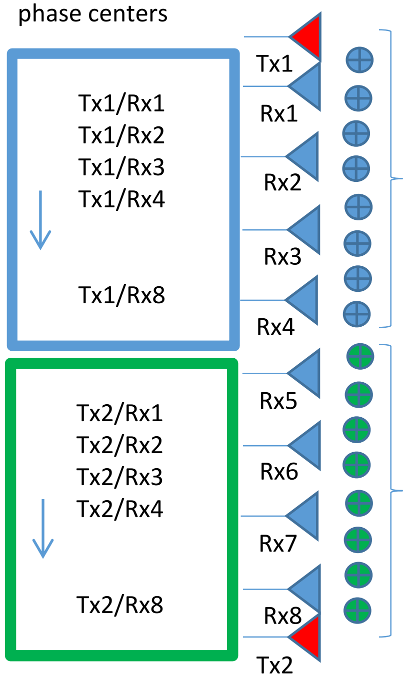


Demodulated transmit leakage signal after digitizing in USRP

Baseband modulation Generate by USRP

Pulse compressed output From USRP containing transmit leakage

Generates 16 phase centers



Phase center location ½ way distance between Tx1 and Rx1-8

Phase center location ½ way distance between Tx2 and Rx1-8

Simple Scene With Corner Reflectors Used to Verify Fundamental System Performance

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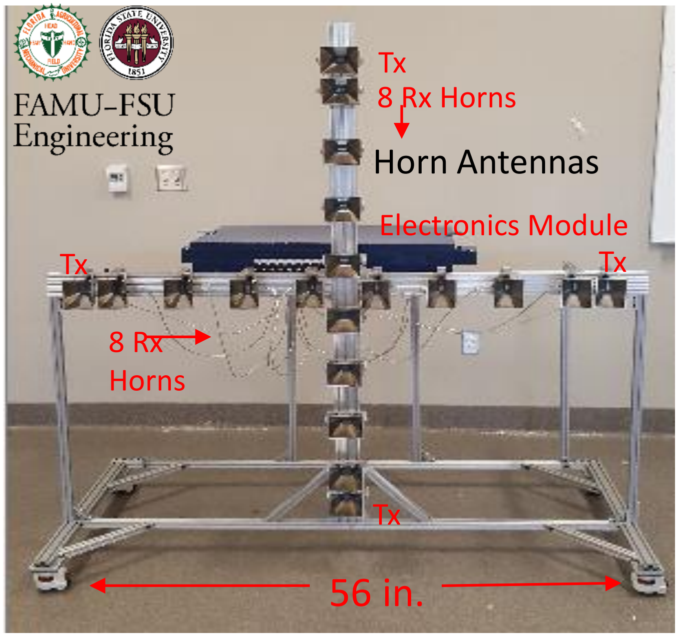
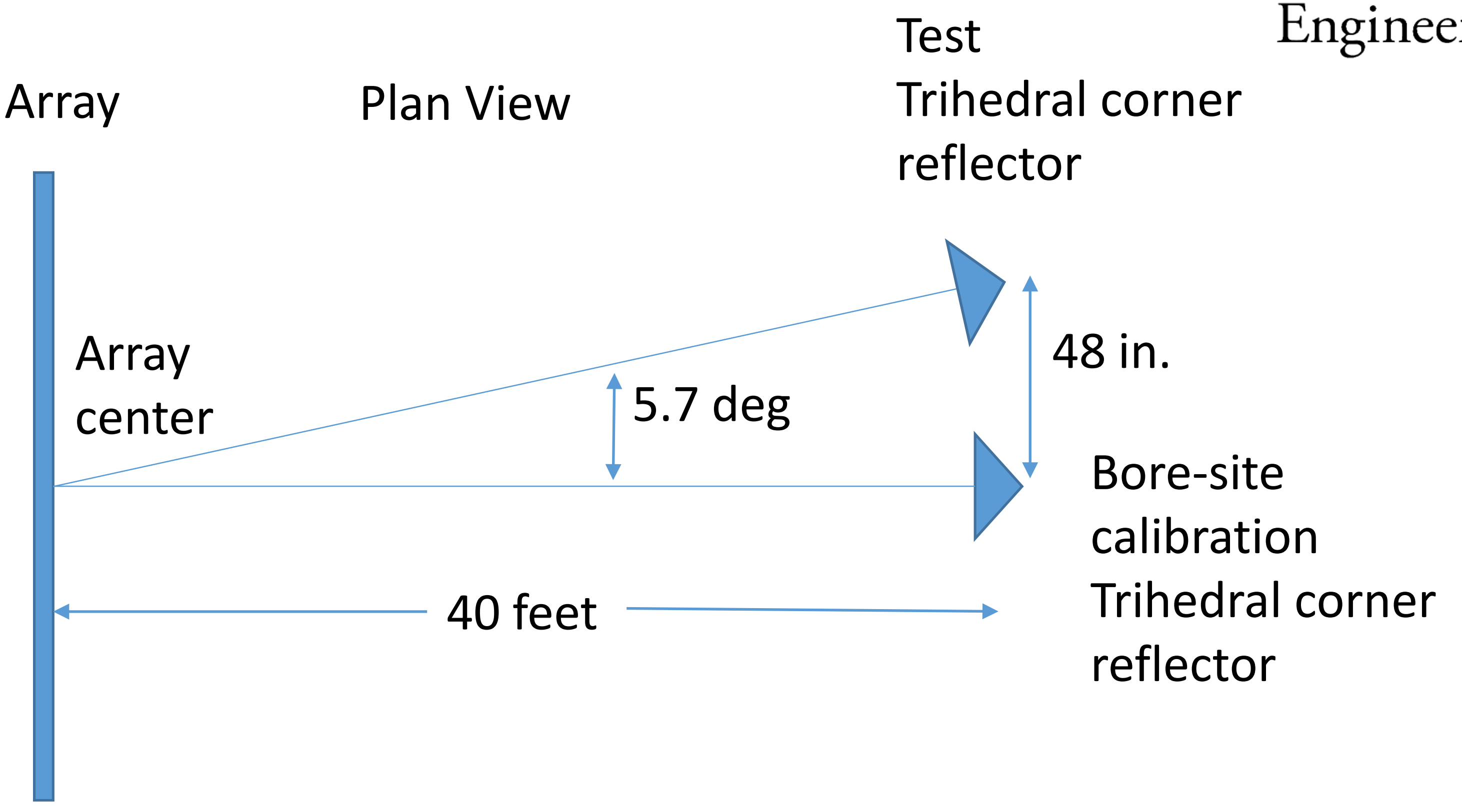
- Corner reflectors at same range with minimal scattering variables in scene



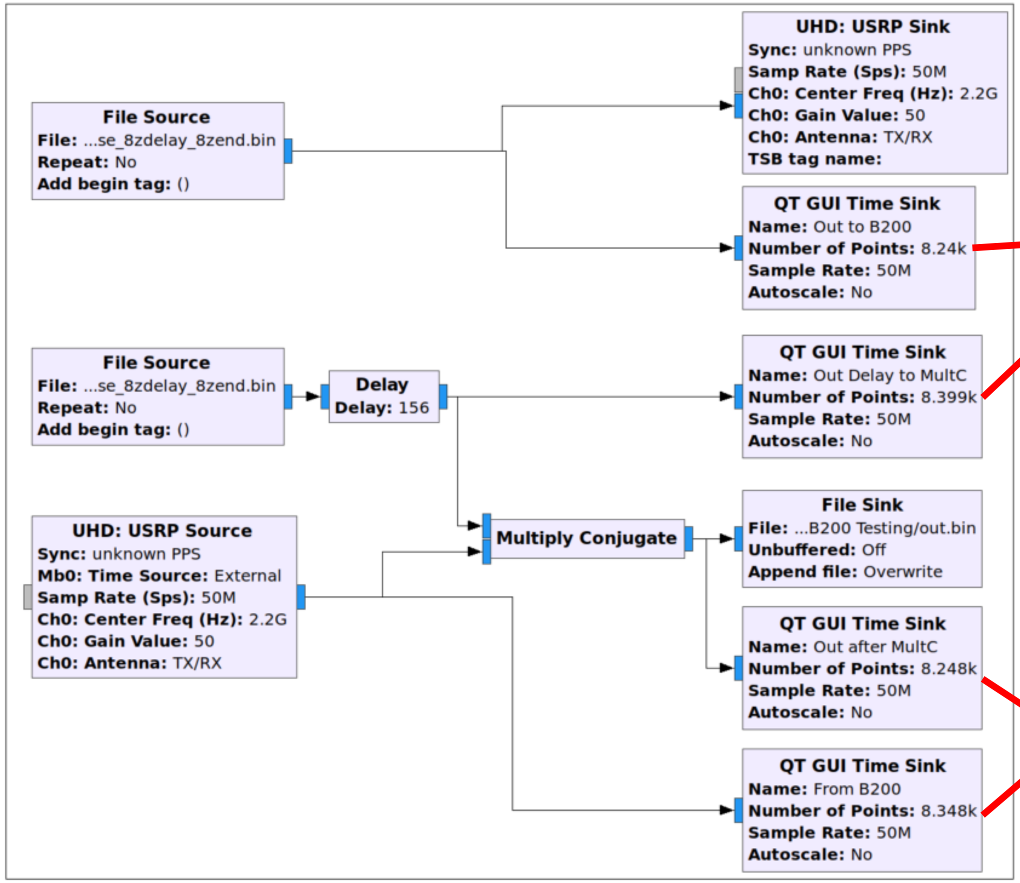


Scene Viewed From Aperture

- Trihedral reflectors used for broad angle response avoiding precision alignment challenges
- Flat plate or dihedral reflector specular response requires careful alignment

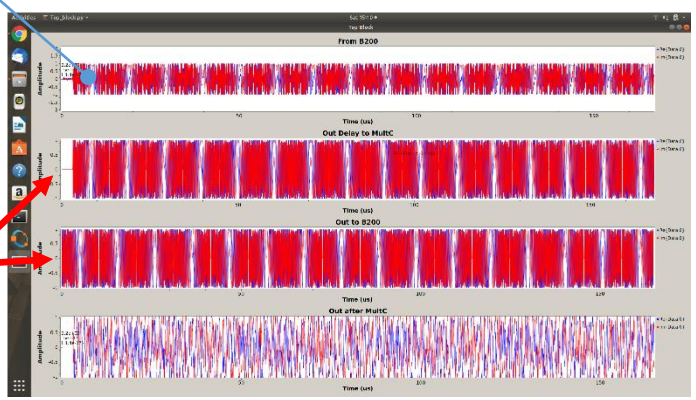
Displayed data from the USRP in the GRC

- Sixteen LFM pulses at key points in the signal thread



Demodulated transmit leakage signal after digitizing in USRP

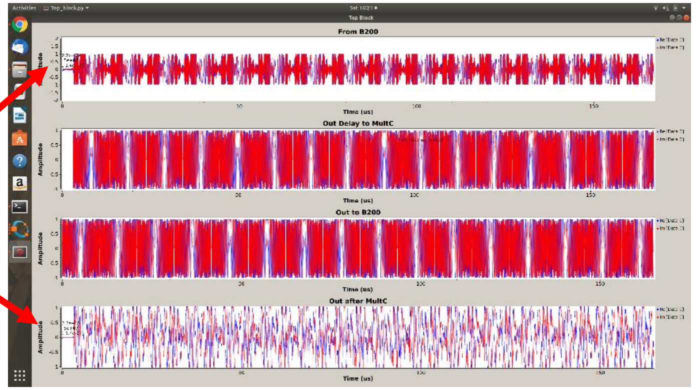
Clear scene + Transmit leakage



Baseband modulation Generate by USRP

Pulse compressed output From USRP containing transmit leakage

Two Corner Reflectors (CRs) + Transmit leakage



Demodulated return Signal after digitizing in USRP. CR returns adding in with transmit leakage.

Pulse compressed output From USRP containing transmit leakage and CR returns (the input to MATLAB processing)

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Processing Flow in MATLAB After Digital Pulse Compression in USRP

- Complex baseband data is obtained from the USRP
- Starting phase is different for each data collect requiring post processing phase if integration of pulses is required for sufficient SNR

Import time domain .bin file from GRC into MATLAB → Convert .bin file into complex domain → Reshape data into 16 pulses → FFT each pulse after forming vector for each of 16 pulses

→ Extract complex value for each of 16 pulses at selected FFT range bin → Apply calibration to 16 complex values from bore-site data → Perform 16 point spatial DFT

Time Domain FFT of Each Transmit Receiver Pair Pulse Resolves Range of Corner Reflector

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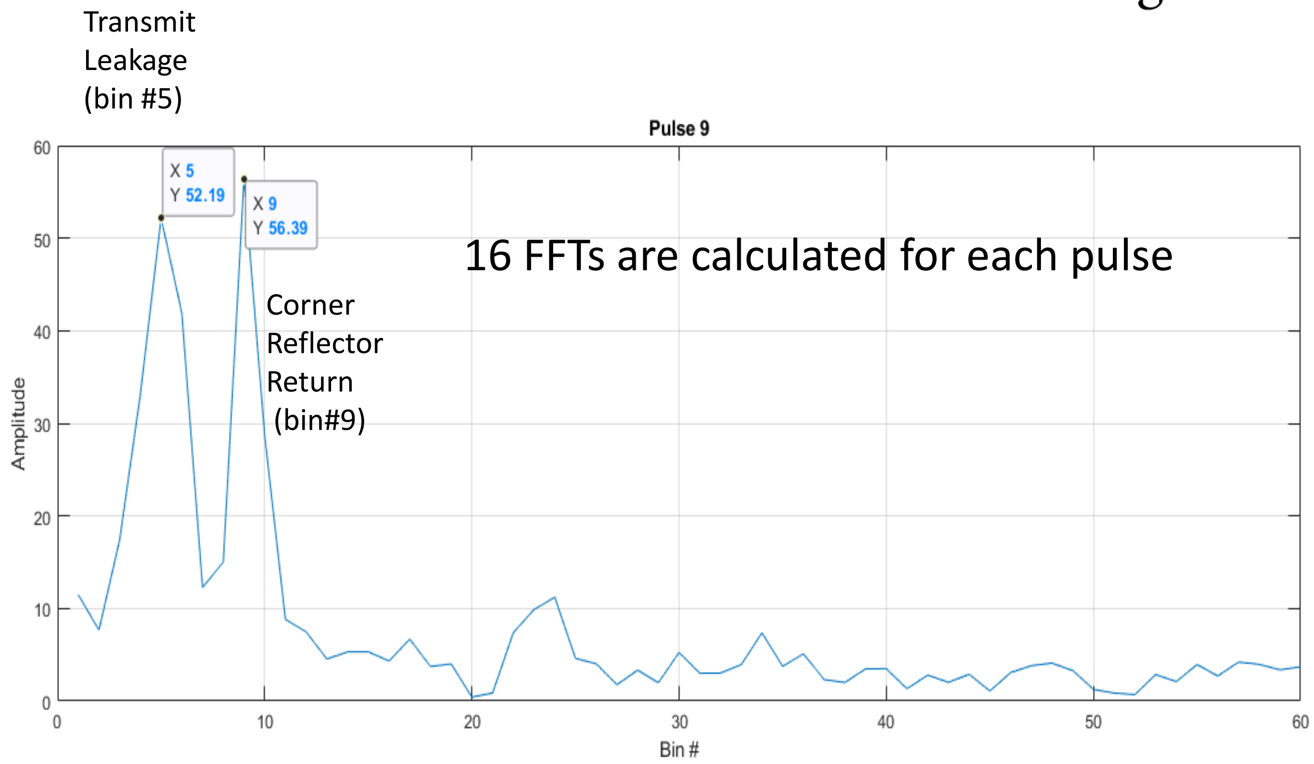
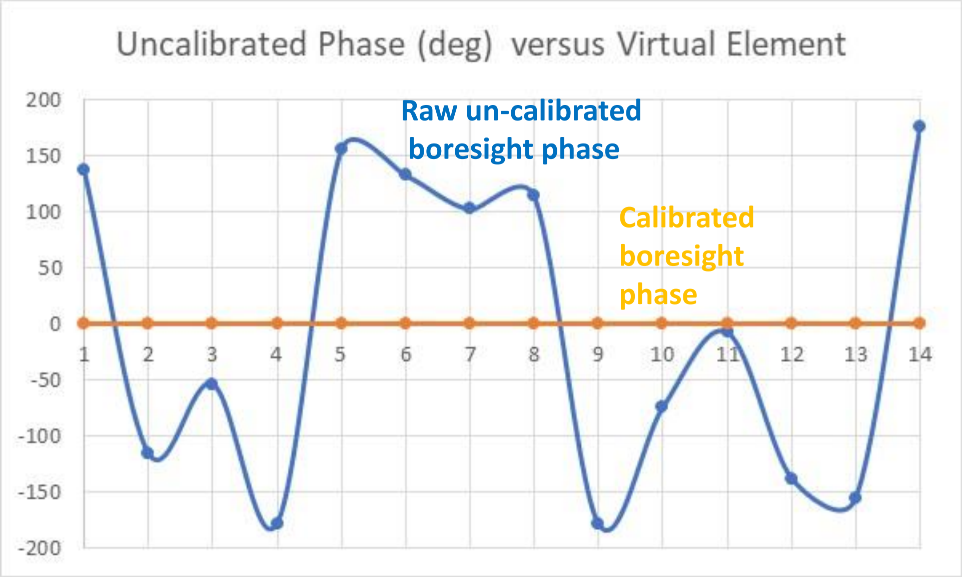
- Complex signal values of desired bin #9 are obtained for image formation.

  - Sufficient bandwidth (BW) of 44.8 MHz in each pulse enables mitigating transmit leakage
  - Resolution of 1/2BW = 11 nS or around 10 feet
  - Note from data (9-5)*10 feet = 40 feet which is range difference between transmit leakage and corner reflector range



Calibration of Single Corner Reflector Boresight Measurement Needed

- 10 GHz insertion phase and amplitude hardware differences in each path need to be compensated for
- Multiply by measured boresight conjugate and normalizing amplitude forces boresight to amplitude of ‘1’ and phase of 0 deg. This calibration is applied to all data.
- Elements 1 and 16 (closest to the transmit elements) suffered to much transmit leakage not allowing receive measurement



- Un-calibrated response symmetry indicates hardware insertion phase similar between paths
- Antenna aperture was mechanical aligned to corner reflector
- Alignment slightly off since symmetric around 6:7 rather than 7:8.

Final Spatial Beam Forming DFT Resolves Corner Reflectors in Cross-range

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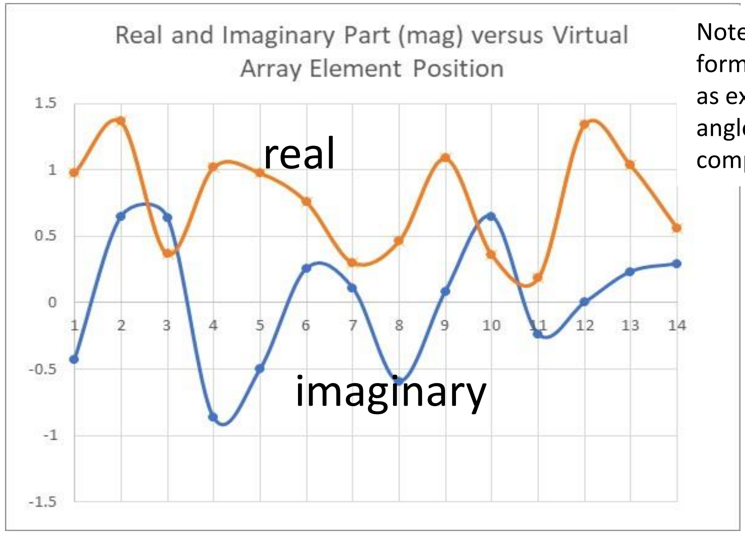
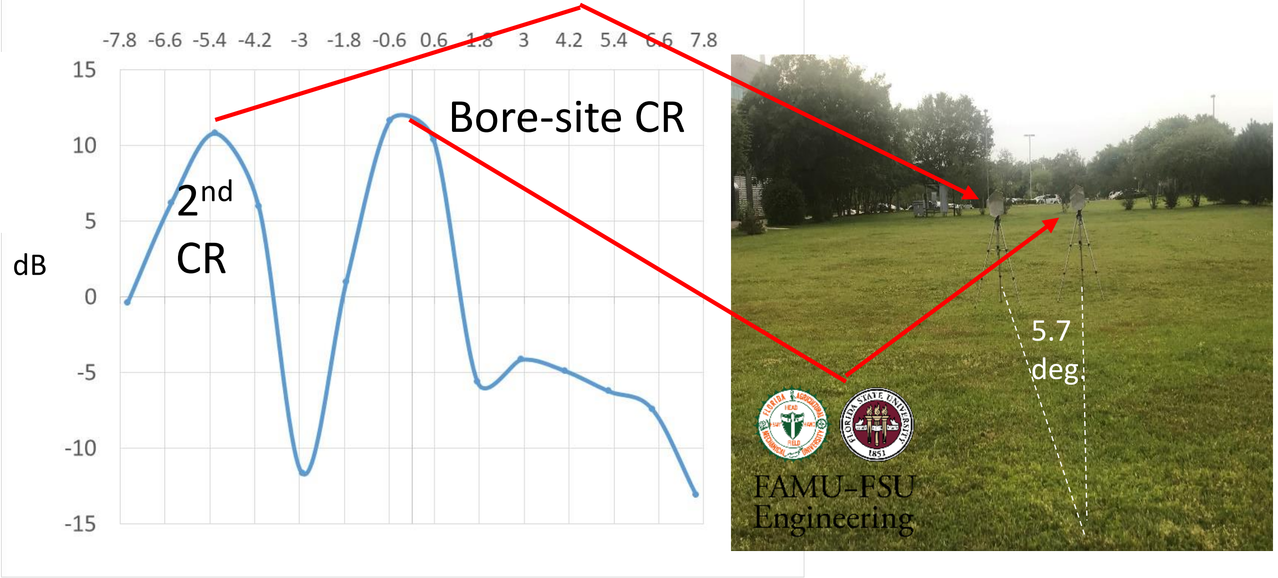
- Measured results of final spatial FFT beam forming code with Taylor weighting producers angle of arrival in image plane for both reflectors in scene
- 2nd CR is measure at -5.4 degrees off bore-site. This was very close to the off bore-site mechanical angle of -5.7 degrees.

Complex values after calibration applied to two corner reflector measured data



Note: real and imaginary parts form sinusoidal response as expected representing angle of arrival difference compared to boresight

Amplitude (dB) versus Angle (degrees)



Summary Highlights and Future Work

- Commercial USRP RF carrier was sufficiently phase stable to do digital beam forming
- Streaming was not possible at the 50 MHz sample rate over USB 3.0
- USRP phase starts at different value during each data collect requiring phase alignment in post processing if pulse integration required for SNR improvement
- Sufficient IBW needed to separate transmit leakage from minimum range.
- Isolating transmit element to nearest receive element so that receive path can linearly receive return signal
- Delay in USRP output relative to 1PPS signal from FPGA could be mitigated by RF detecting coupled off path and using that as a reference for FPGA switching
- Collect data over additional RF frequencies with same IBW and stitch together to increase range resolution
- Move signal processing functions from MATLAB into the custom GRC modules

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