**2011 IEEE Aerospace Conference**
Big Sky, MT, March 7, 2011
Session# 3.01 Phased Array Antennas Systems and Beam Forming Technologies
Pres #: 3.0102, Paper ID: 1198
Rm: Elbow 3, Time: 8:55am

# Design and Test of FPGA-based Direction-of-Arrival Algorithms for Adaptive Array Antennas

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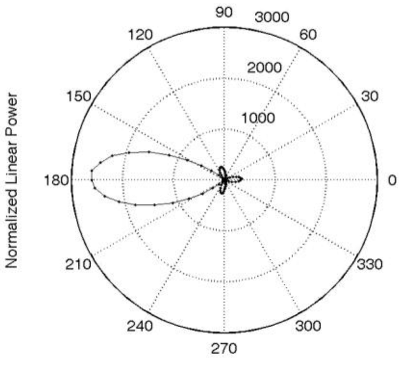
ADVANCED ACOUSTIC CONCEPTS

# Motivation

## Smart Antenna Systems

- **Directional radiation patterns used to:**
  - reduced transmit power
  - protect data from unwanted listeners
  - nullify interference

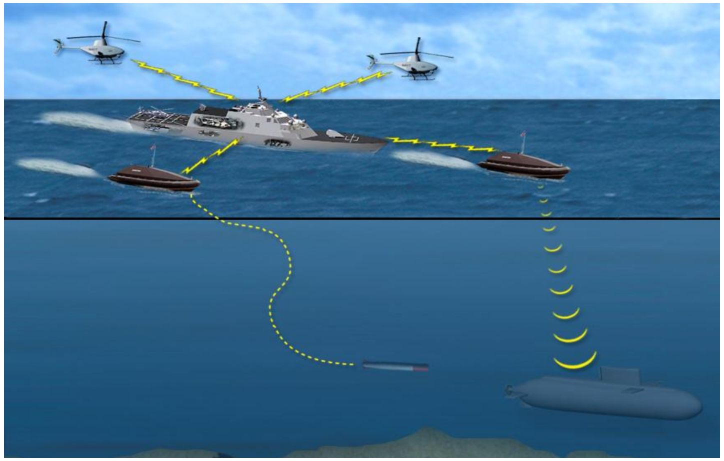
- **Attractiveness of Digital Systems**
  - complexity of DOA algorithms
  - reduced size and power
  - leverage advances in digital IC fabrication




*Directional Radiation Pattern*

*Courtesy Ericsson MW, Sweden*

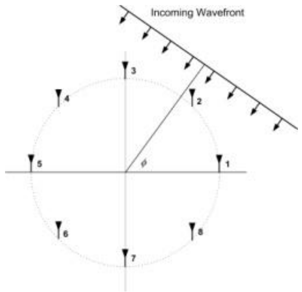
*Secure Wireless Communication with Airborne Web Server*



*Integrated Multi-Platform Sonar System LCS Application*

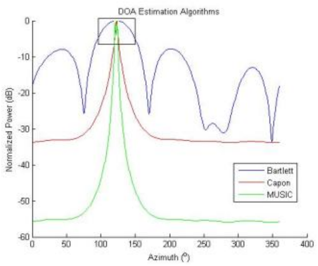
## Smart Antenna Components

1) **Antenna Array**



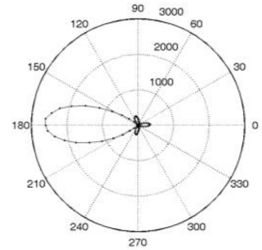

*8-element uniform circular array*

2) **Direction-of-Arrival (DOA) Estimation (Rx)**




*Rx Power vs. Incident Angle*

3) **Beam Forming (Rx/Tx)**




*Directional Radiation Pattern*

# Our Work

## Implementation & Bench Top Testing of DOA Algorithms

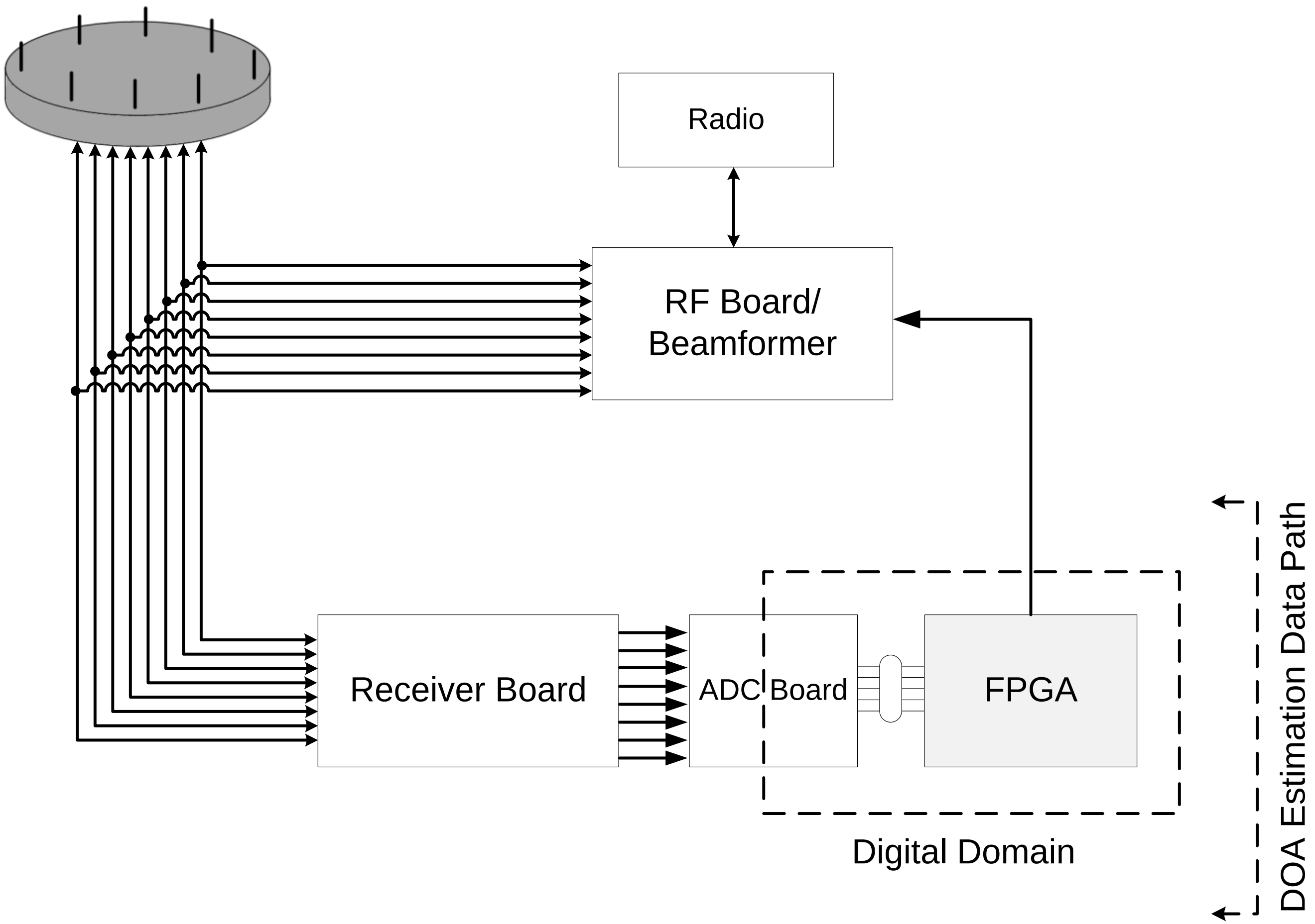
- **System Design of a Full Receiver Path with Digital Processing Backend**
- **Design of a Test Bed to Drive Phased Signals into the System**
- **Implementation of DOA Algorithms on a Virtex-5 FPGA**

  - Bartlett
  - MVDR
- **Parametric Testing**

  - Detected Angle Calculation & Power Spectra
  - Bartlett vs. MVDR Accuracy
  - Single vs. Dual Beams
  - Input Signal Levels:  Full range of ADC vs. Minimum detectable

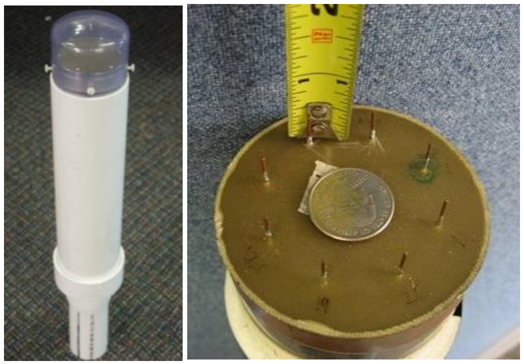
# System Design

## Architecture of our Smart Antenna System

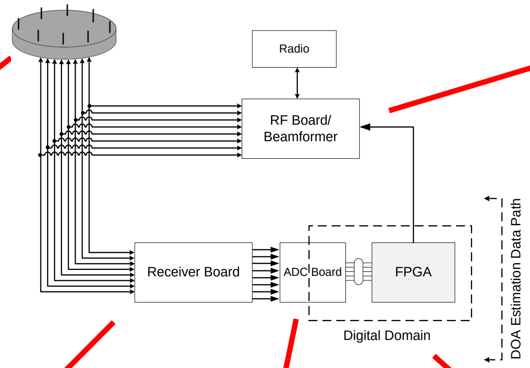


# System Design

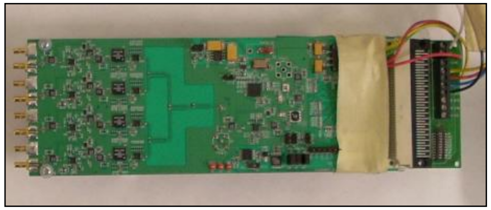
### 5.8 GHz, 8-element Circular Array Antenna



- Diameter = 76mm (3”)
- Inter-element spacing = 0.37λ = 19mm (0.75”)




### Custom 8-Channel RF Beam Former



- Uses Analog Phase Shifters
- Pre-Calculated, Switched Beam Coefficients
- No Digital, Real-Time Processing

### Custom 8-Channel Receiver Board

- Down converts 5.8GHz to 1-10MHz IF

### Custom 8-Channel A/D Board

- 25MSa, Analog Devices AD9287,
- SPI control, 200Mb/s LVDS Serial Outputs

### Xilinx Virtex-5 FPGA Eval Board (ML507)

- Virtex-5, FX70 FPGA
- System Clock = 100MHz, 200Mb/s LVDS Serial Inputs

## Bartlett Algorithm (Theory)

- A Fourier Spectrum Analysis

- A set of weights are created which model what the signal power would look like from a particular angle a(φ). These depend on the physical properties of the antenna head *(i.e., circular, linear, size...)*

$$\boldsymbol{a}(\varphi) = \left[ 1, e^{j\beta\rho\cos\left(\varphi - \frac{2\pi}{m}\right)}, \ldots, e^{j\beta\rho\cos\left(\varphi - \frac{(m-1)\times 2\pi}{m}\right)} \right]^T$$

- The total signal vector received at the array can be described as follows:

$$\boldsymbol{x}(t) = \sum_{k=1}^{K} \boldsymbol{a}_k(\varphi) s_k(t) + \boldsymbol{n}(t)$$

**K = # of sources**
**$s_k$ = the signal at each element**
**n(t) = noise**

- The autocorrelation (or covariance matrix) of this information gives provides information about signal strength.

$$\hat{\boldsymbol{R}} = \frac{1}{T} \sum_{t=1}^{T} \boldsymbol{x}(t) \boldsymbol{x}(t)^H$$

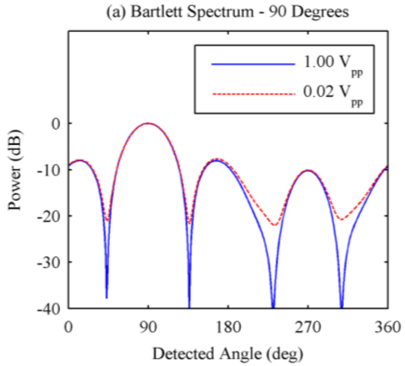
**H denotes the conjugate transpose (or hermetian transpose)**

## Bartlett Algorithm (Theory cont…)

- The normalized power at each angle φ can then be described as:

$$P = a^{H}(\phi)\hat{R}a(\phi)$$

- This gives us the traditional power spectra plots (power vs. angle) of the antenna.




- Peak power detection is then used to estimate the angle of arrival (i.e., DOA)

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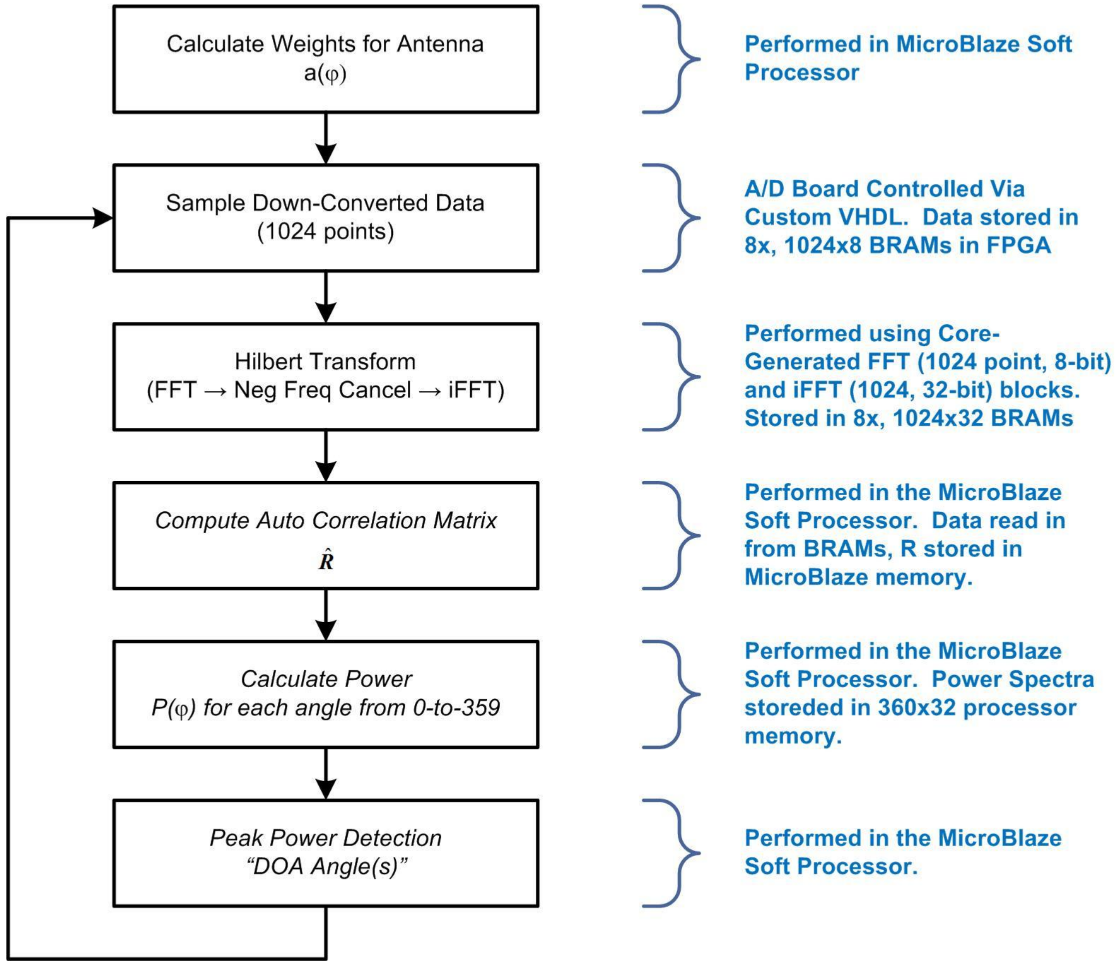
## Bartlett Algorithm (FPGA Implementation)



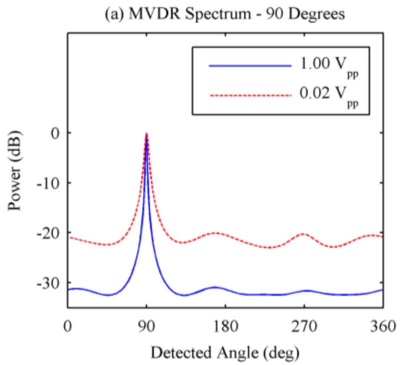
## MVDR Algorithm (Theory)

- A Fourier Spectrum Analysis, but uses an inversion of the covariance matrix for better accuracy.

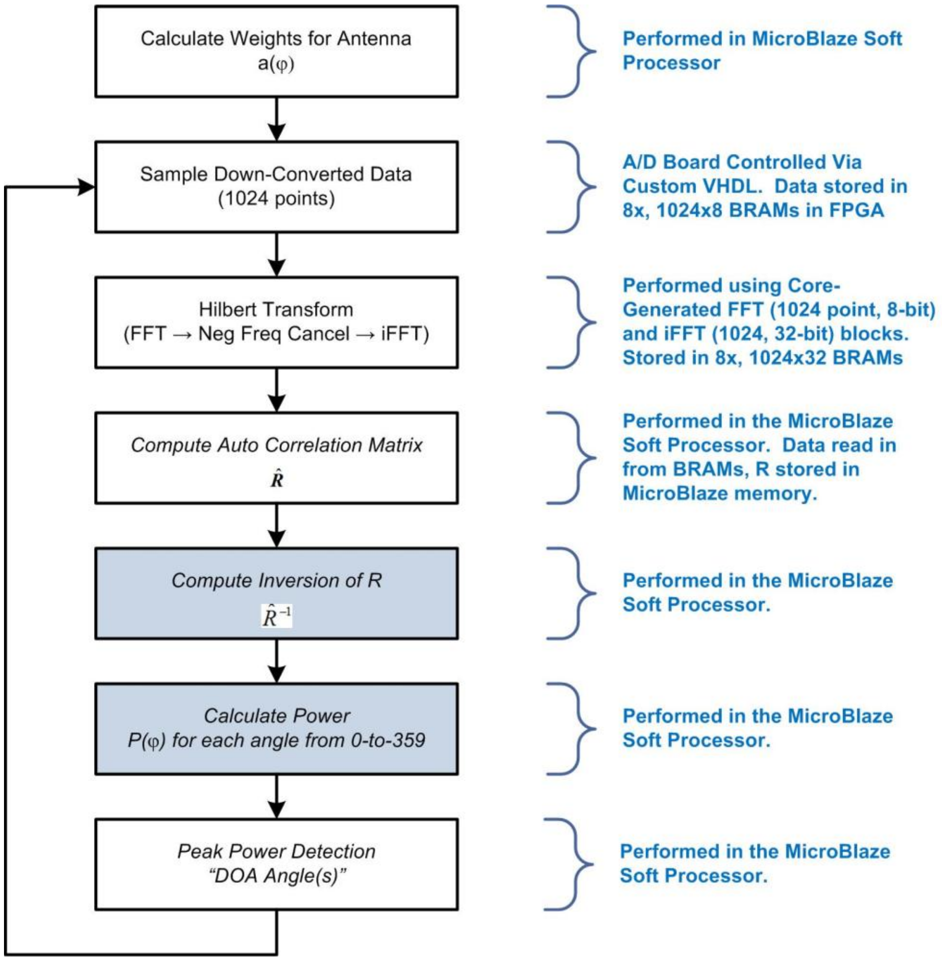
- The algorithm is identical to Bartlett up through the auto correlation computation.  The R matrix is then inverted and used in the final power calculation as follows:

$$P = \frac{1}{a^{H}(\varphi)\hat{R}^{-1}a(\varphi)}$$

- This leads to greater accuracy but increased computation time.



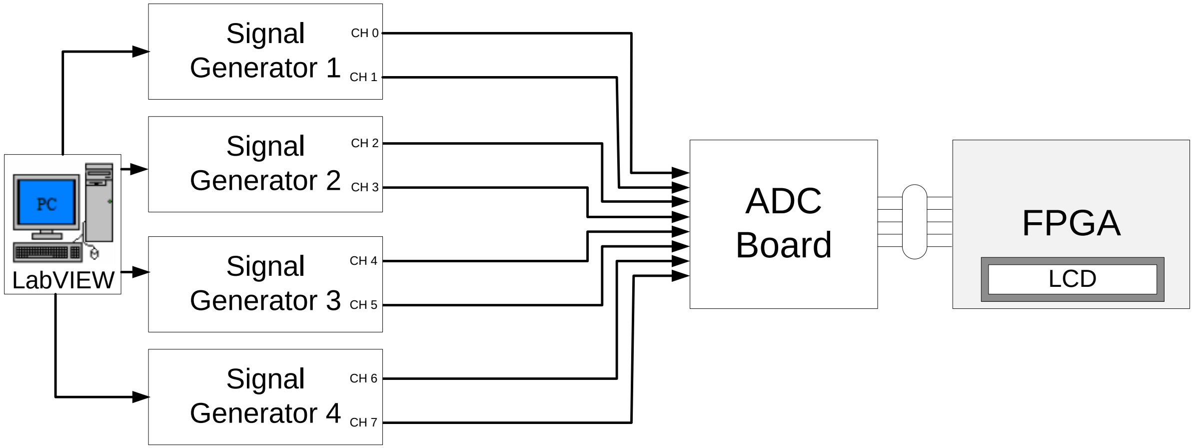
## MVDR Algorithm (FPGA Implementation)



# Test Bed Setup

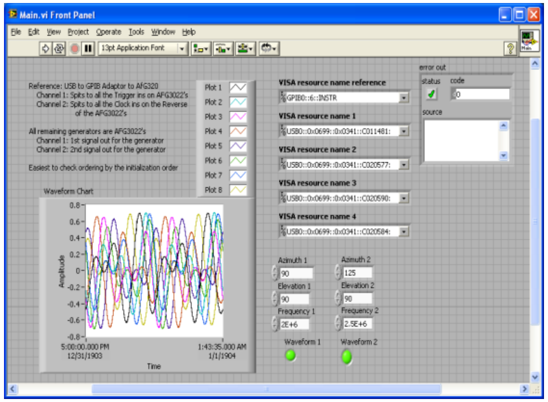
## Phased Signal Emulation

- A signal generator system was created to drive phased signals directly into the A/D converter.
- This isolates the DOA algorithm computation as much as possible from the RF front-end.
- Controlled signal levels can test sensitivity of algorithms to % of A/D inputs range (i.e., 100%, 50%, etc…)

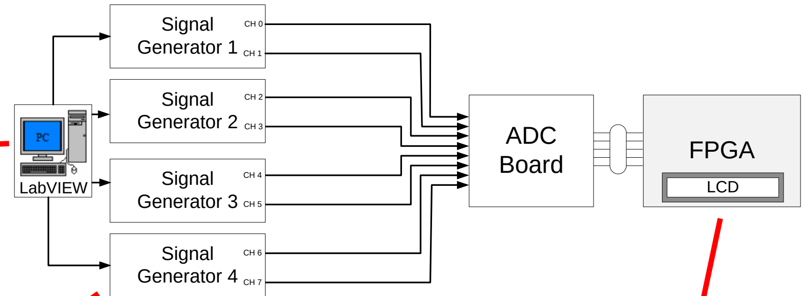


# Test Bed Setup

## Lab View Instrument Controller Interface




- Controls 8-Channels of Signal Generator.
- AWG allows any frequency and phase to be programmed
- This allows emulation of 1 or 2 beams at any angle

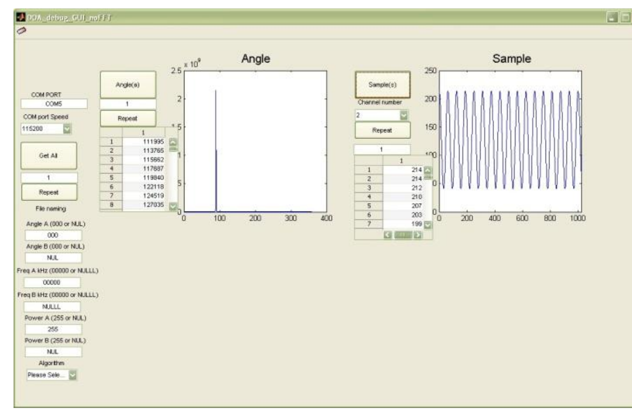



## Tektronix AFG3022 Dual Channel Generators (4x)

- Receives AWG data from Lab View.
- Can produce phased waveforms up to 10MHz.

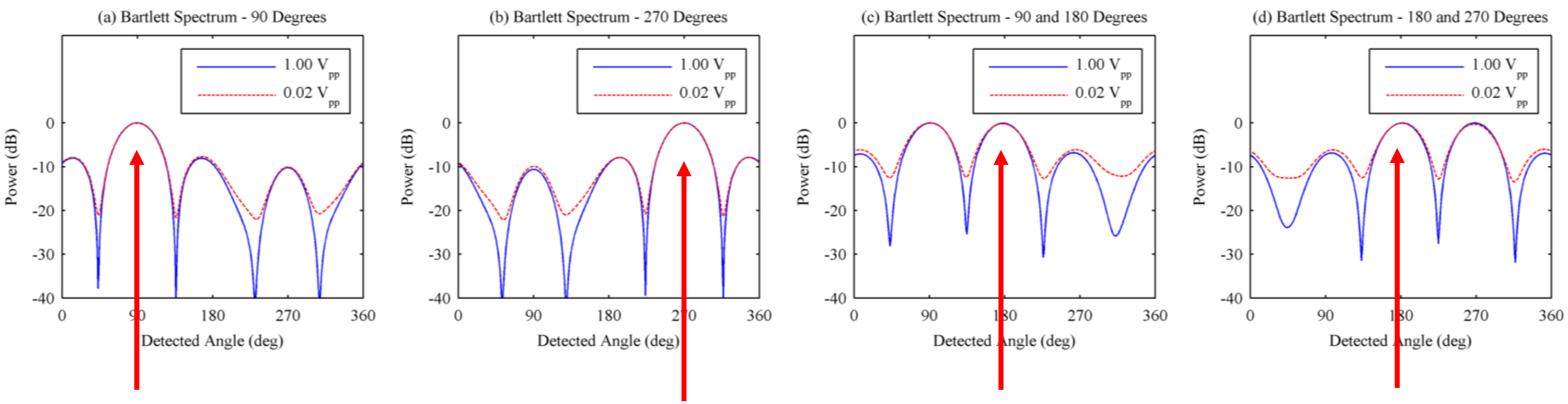
## Custom Matlab Interface to Readout FPGA Data

- RS232 Interface to FPGA
- Shows contents of:
  - *sampled data of each channel*
  - *Power spectra vs. Angle Calculation*
  - *Power spectra vs. Angle Calculation*
- Can Start/Stop Acquisition & DOA



## Bartlett Spectrum

- 1 vs. 2 Incident Wave Fronts
- 1Vpp *(8-bits of digitization)* vs. 20mVpp *(3-bits of digitization)*




Single Beam Incident at 90°

Single Beam Incident at 270°

Multiple Beams Incident at 90° and 180°

Multiple Beams Incident at 180° and 270°

# Test Results (Bartlett)

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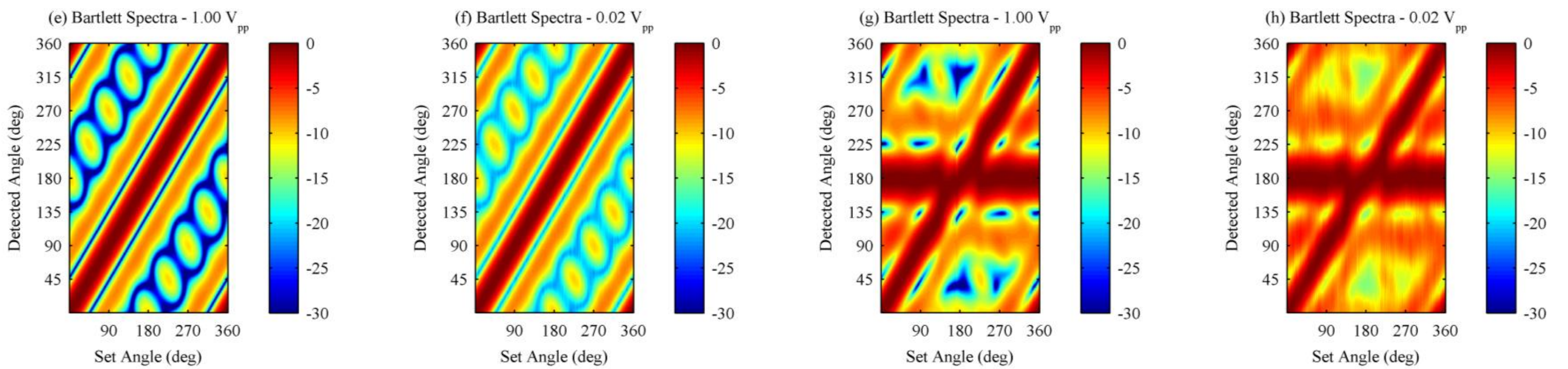
## Bartlett Spectrograph (Output Power vs. Incident Wave front Angle)

- Set Angle = Angle of the Incoming Wave Front (swept from 0 to 359)
- Detected Angle = Power Spectrum Plotted Against That Angle




**Single, 1Vpp Beam Sweep**

**Single, 20mVpp Beam Sweep**

**Dual, 1Vpp Beam Sweep with one front held at 180° while other is swept**

**Dual, 20mVpp Beam Sweep with one front held at 180° while other is swept**

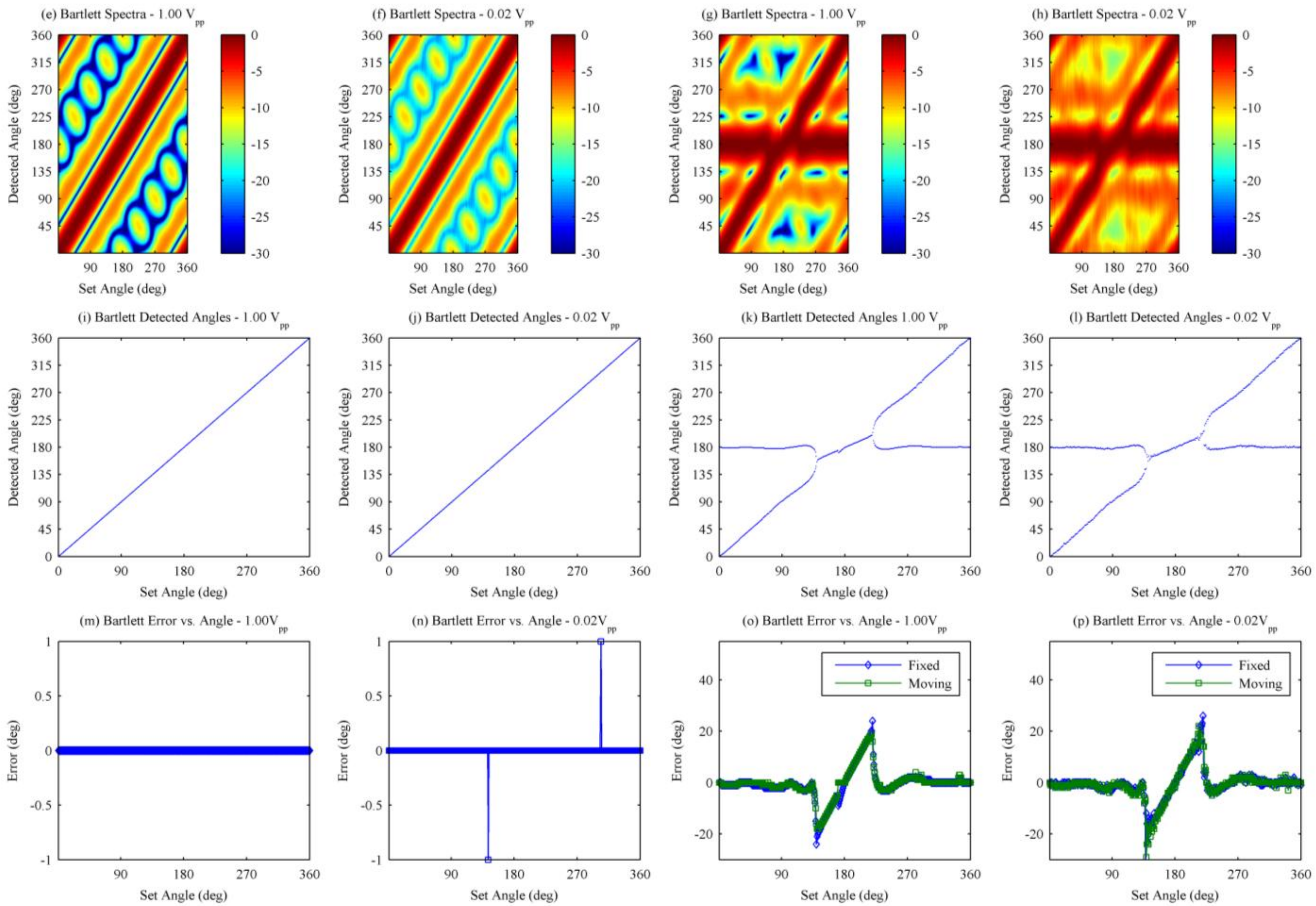
# Test Results (Bartlett)

## Detected Angle (Peak Detect vs. Incident Set Angle)

Spectrograph →

Detected Angle (Peak Power) →

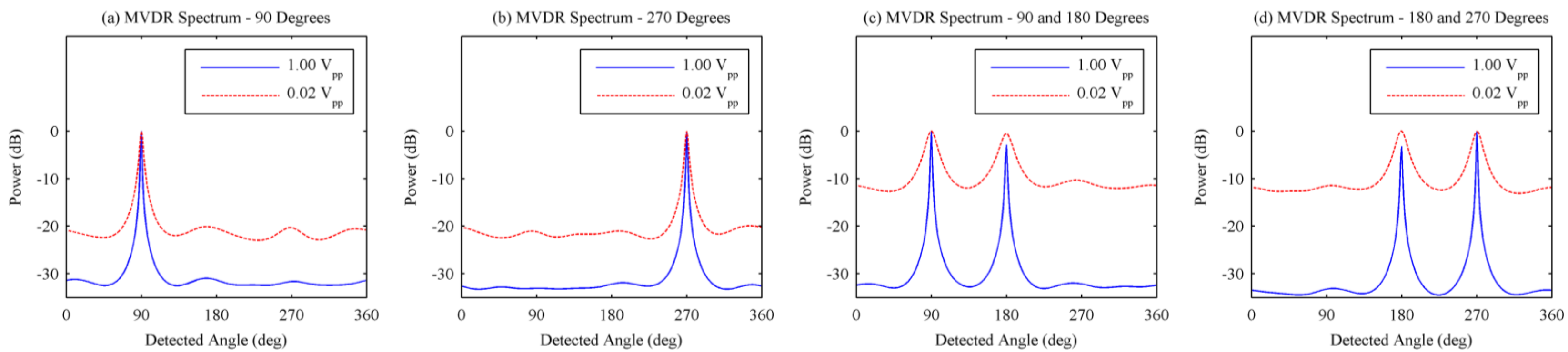
Detected Angle (Detected against Set) →



# Test Results (MVDR)

## MVDR Spectrum

- 1 vs. 2 Incident Wave Fronts
- 1Vpp *(8-bits of digitization)* vs. 20mVpp *(3-bits of digitization)*




**Single Beam Incident at 90°**

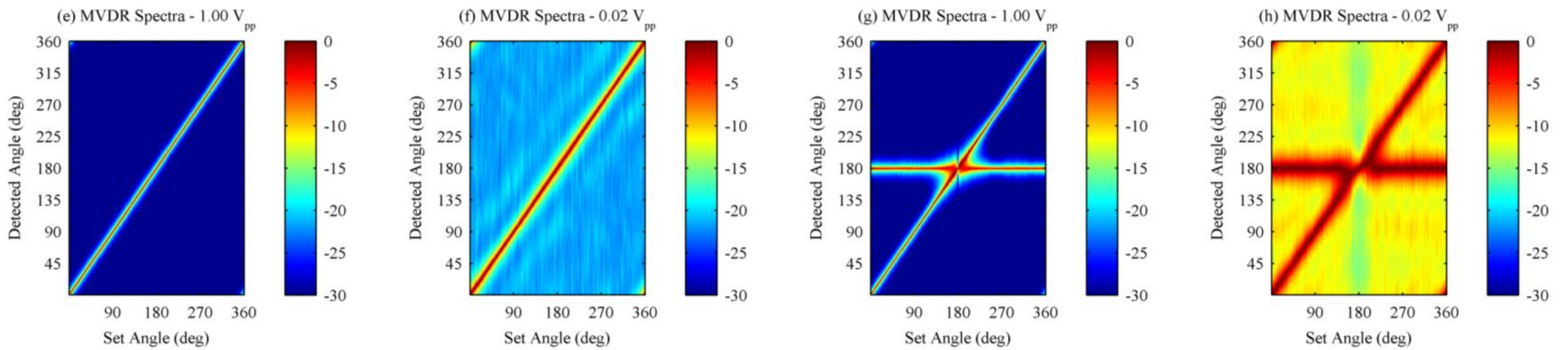
**Single Beam Incident at 270°**

**Multiple Beams Incident at 90° and 180°**

**Multiple Beams Incident at 180° and 270°**

## MVDR Spectrograph (Output Power vs. Incident Wave front Angle)

- Set Angle = Angle of the Incoming Wave Front (swept from 0 to 359)
- Detected Angle = Power Spectrum Plotted Against That Angle




**Single, 1Vpp Beam Sweep**

**Single, 20mVpp Beam Sweep**

**Dual, 1Vpp Beam Sweep with one front held at 180° while other is swept**

**Dual, 20mVpp Beam Sweep with one front held at 180° while other is swept**

# Test Results (MVDR)

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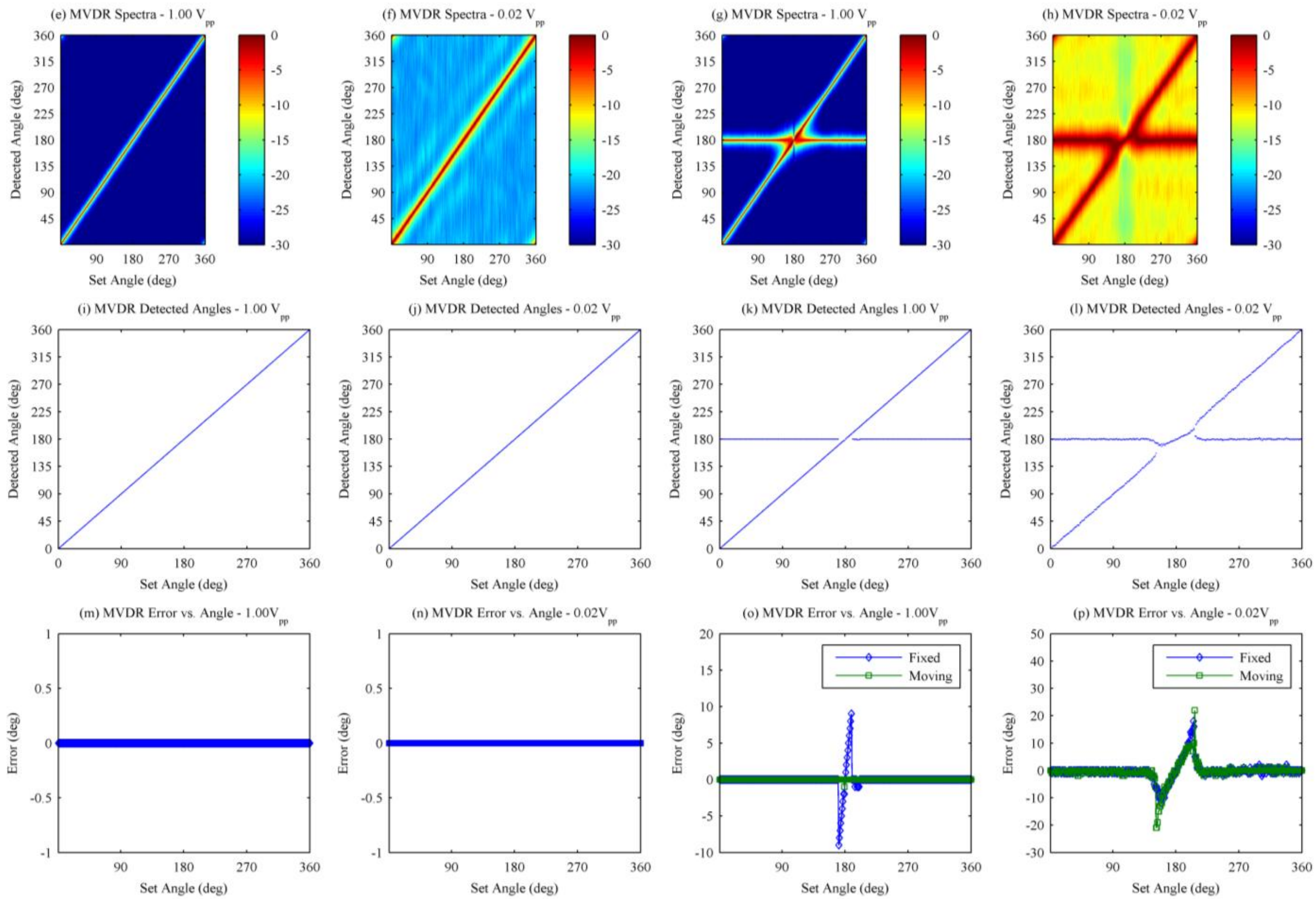
## Detected Angle (Peak Detect vs. Incident Set Angle)

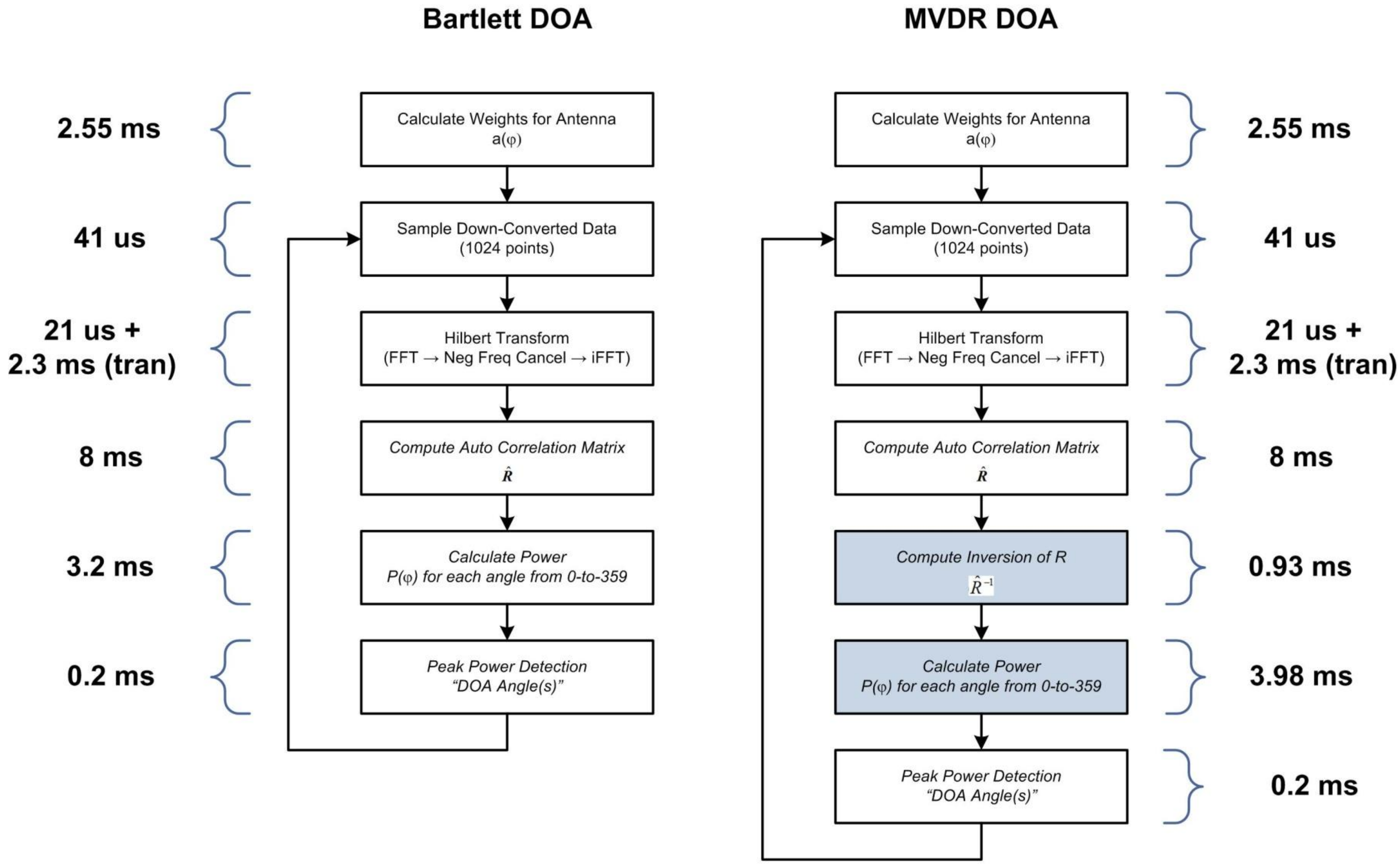
Spectrograph →

Detected Angle (Peak Power) →

Detected Angle (Detected against Set) →



# Computation Time




**DOA Computation = 14 ms**

**DOA Computation = 15 ms**

Note: Cal of 2.3ms in included in the 8ms for R computation.

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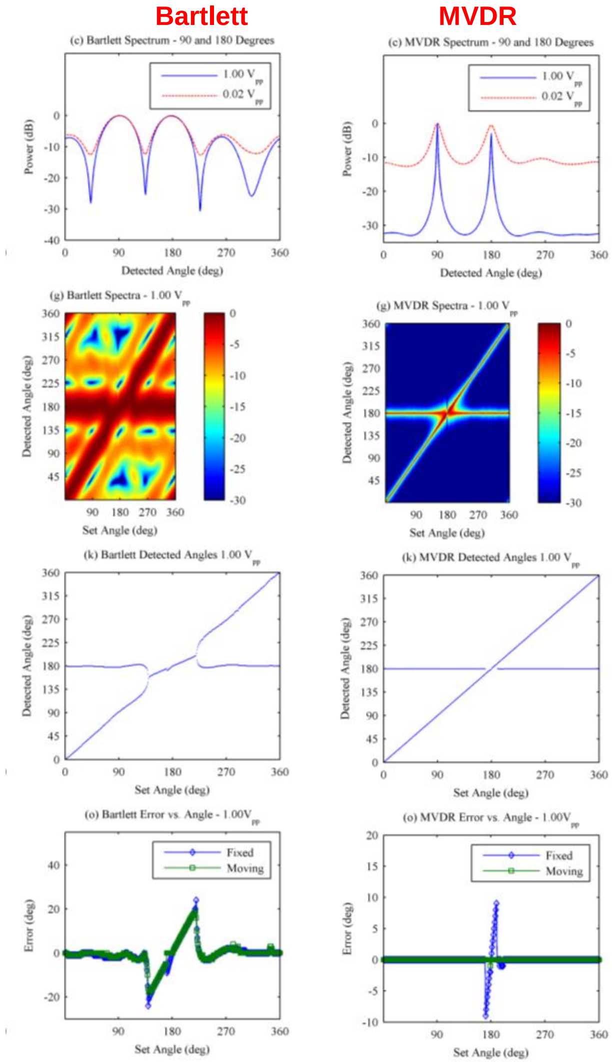
## Overview

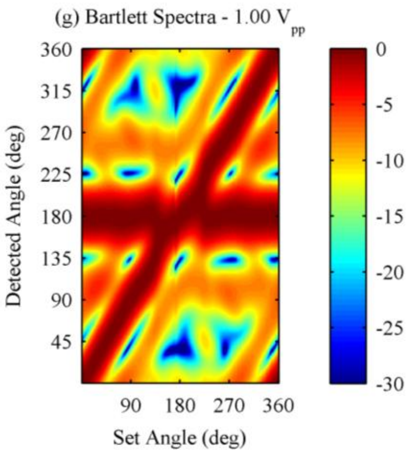
- Bartlett & MVDR DOA Algorithms were implemented on an Xilinx Virtex-5 FPGA.

- The accuracy of the calculations were measured across a variety of parameters.

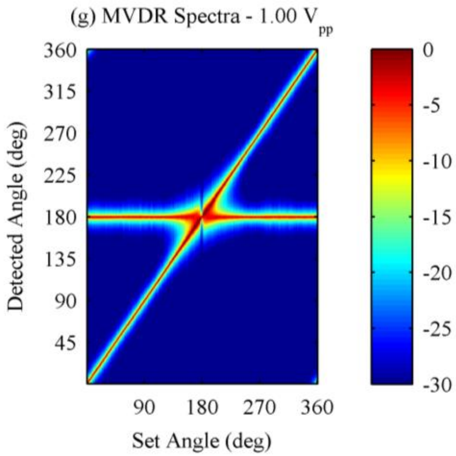
- The computation time was reported for both algorithms (Bartlett = 14ms, MVDS = 15ms)

- The MVDR algorithm is clearly more accurate but with a slightly larger computation time.





(g) Bartlett Spectra - 1.00 V pp
360
315
270
225
180
135
90
45
Detected Angle (deg)
90
180
270
360
Set Angle (deg)
0
-5
-10
-15
-20
-25
-30

(g) MVDR Spectra - 1.00 V pp
360
315
270
225
180
135
90
45
Detected Angle (deg)
90
180
270
360
Set Angle (deg)
0
-5
-10
-15
-20
-25
-30


# Questions