Airborne Radar Testbed
Radio Frequency Calibration:
WPI MQP 2016

Alexander Corben & Jamie Wang

Advisors: Edward Clancy & Andy Messier

© 2016 Massachusetts Institute of Technology.

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

This material is based upon work supported under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Air Force.

Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work.
Presentation Outline

• Presentation Outline
• Problem Statement
• Design
• Verification Results
• Experimental Results
• Conclusion
Presentation Outline

• Presentation Outline
• Problem Statement
• Design
• Verification Results
• Experimental Results
• Conclusion
• **AESA’s** utilize **phase shifters** for beam steering as opposed to **time delay circuits**
  – More appealing: size, complexity, cost
  – Side effect: **beam squint**

• The antenna system is divided into a series of **sub-arrays**
  – Each sub-array driven with a **unique RF waveform generator** allows for **time delay beam steering**
Phase Stability & Calibration Concern

- Realize the **effective time offset** between channels
- Achieve a **known phase** at the input to the sub-arrays
**Concern:** How consistent and accurate is the calibration system?

**Goal:** Characterize the calibration system under operational conditions.
How calibration works
Detecting amplitude and phase

“Test” Channel

“Reference” Channel

Detect 4 DC voltages at each sample frequency

\[ A = \frac{1}{2} \sqrt{(V_3 - V_1)^2 + (V_4 - V_2)^2} \]

\[ \phi = \tan^{-1} \frac{V_4 - V_2}{V_1 - V_3} \]

Source: Jerry Benitz
Presentation Outline

• Presentation Outline
• Problem Statement
• Design
• Verification Results
• Experimental Results
• Conclusion
Test System: High Level Diagram

Master FPGA: Waveform Storage, Phase Shift and Time Delay

Slave FPGA: Waveform Storage, Phase Shift and Time Delay

Up Converter

** Calibration Module **

** Device Under Test (DUT) **

Power Receiver

PicoScope

Up Converter
FPGA Design Overview for Both FPGAs

- **Synchronized** transmission between multiple waveform generators
- **Time delay** for subsample resolution and continuous **phase control**
- **Single sample control** given DAC sampling frequency of 2.8 Gsps
RF Design: Upconversion

**Purpose:** Convert from intermediate frequency to Ku band RF output

- **Solution** because actual upconversion hardware was not ready
- **Range:** 400-800 MHz to 16.6-17.0 GHz
- **Test Frequency:** 700 MHz --> 16.7 GHz
Final Product
Presentation Outline

• Presentation Outline
• Problem Statement
• Design
• Verification Results
• Experimental Results
• Conclusion
FIR Filtering

- Control **phase, delay and gain**
  - allows for **subsample delay control** (1/3, 1/12, etc.)
  - Also supports **continuous phase control**
Interferometer: Broadside Null

- Interferometer: 1 antenna 180° out of phase --> destructive interference
- Simulated expected antenna pattern in MATLAB
- In lab, interferometer antenna pattern worked for producing nulls
- Multi-path effects from test environment visible in measurements
  - However, broadside null is consistent
Presentation Outline

- Presentation Outline
- Problem Statement
- Design
- Verification Results
- Experimental Results
- Conclusion
Test Setup

- Transmit waveform data
- Utilize antennas and receiver as feedback loop
- Analyze data in Matlab
Test Protocol: Step 1

**Step 1:** Established a baseline null position and phase difference
- Tuned test channel
- Examined consistency

![Baseline Interference Pattern](image1)

![Baseline Phase Detector Output](image2)
**Test Protocol: Step 2**

**Step 2:** Used phase shifter to intentionally put the system out of calibration

- Measured resulting null position and phase difference

---

**Uncalibrated Interference Pattern**

---

**Uncalibrated Phase Detector Output**

---

**Post Phase-Shift Power Measurement**

---

**Phase Detector Output (1000 Measurements)**

---

Incorrect Null position

Baseline Null position
Test Protocol: Step 3

Step 3: Used new phase difference measurement to change the phase of the test channel input signal

- Measured resulting null position and phase difference

Interference Pattern After Re-Calibration

Restored Phase Detector Output After Re-Calibration

Figure of Merit: How close was the recalibrated null to the original baseline null?
Measurement Repeatability

Over 1000 measurements for a set of 5 full system resets, the phase detector output was determined to be reliable within \( \sim 1^{\circ} \).
Accuracy of Calibration Module

Digitally steering back to a baseline position using the calibration module output to revise waveforms achieves accuracy within 0.15° at OBA.
Presentation Outline

- Presentation Outline
- Problem Statement
- Design
- Verification Results
- Experimental Results
- Conclusion
Conclusion

- Main concern: accuracy and consistency of calibration module
- Developed test system simulating transmission side of ARTB with calibration module as DUT
- Utilized power receiver and horn antennas as feedback loop
- Ran statistical analysis of calibration and received power data

The ARTB calibration module can consistently and accurately provide calibration data to revise waveforms within 0.15° of the baseline beam angle.
Future Work

- Run in near-field chamber
- Test at full 1 GHz bandwidth
- Examine effects of temperature changes on calibration consistency and accuracy
Acknowledgements

Andy Messier
Edward Clancy
Jeffery Blanco
Tasadduq Hussain
Matt Calderon
Gerald Benitz
Questions?
Additional Detail
Additional Information:
Beam Squint

• Using phase shifters for beam steering induces beam squint over wide bandwidths

• Wave must travel an additional $dsin(\theta)$ for each successive antenna element

• Phase shift is frequency dependent, but time delay is not

\[
\Delta t = \frac{dsin(\theta)}{c} \quad \Delta \phi = 2\pi f \Delta t = \frac{2\pi dsin(\theta)}{\lambda}
\]
Additional Detail:
Horizontal Linear Scan

- Use of a horizontal linear scan results in additional path length as the scan angle moves away from broadside
- Additional phase shift not relevant for power measurement
- From Friis Equation, additional power loss is 0.1dB at the scan edges

Friis Equation:

\[ Pr = Pt + Gt + Gr + 20 \log \left( \frac{\lambda}{4\pi \Delta r} \right) \]
Additional Information: Full 1GHz Bandwidth

- Slope indicates delay
  - Example: Test signal is exactly 1 DAC sample ahead
- Midband phase may require correction
  - Example: Phase is lagging 40° vs 1 DAC sample advance
Additional Information: Synchronization

- Master board **triggers** slave board for **synchronization**
  - **Deterministic**: able to use filtering to align phase of waveforms
Additional Information: Full Upconverter

Upconversion from 600 MHz to 16.8 GHz

Center Frequency: 17.4 GHz

Span: 5 GHz