PHASED ARRAY RADIOMETER CALIBRATION USING A RADIATED NOISE SOURCE

Karthik Srinivasan V. (1), Ashutosh S. Limaye (1), Charles A. Laymon (2) and Paul J. Meyer (2)

(1) Universities Space Research Association, Huntsville, Alabama
(2) NASA Marshall Space Flight Center, Huntsville, Alabama

1. INTRODUCTION

Electronic beam steering capability of phased array antenna systems offer significant advantages when used in real aperture imaging radiometers. The sensitivity of such systems is limited by the ability to accurately calibrate variations in the antenna circuit characteristics. Passive antenna systems, which require mechanical rotation to scan the beam, have stable characteristics and the noise figure of the antenna can be characterized with knowledge of its physical temperature [1],[2]. Phased array antenna systems provide the ability to electronically steer the beam in any desired direction. Such antennas make use of active components (amplifiers, phase shifters) to provide electronic scanning capability while maintaining a low antenna noise figure. The gain fluctuations in the active components can be significant, resulting in substantial calibration difficulties [3]. In this paper, we introduce two novel calibration techniques that provide an end-to-end calibration of a real-aperture, phased array radiometer system. Empirical data will be shown to illustrate the performance of both methods.

2. ONE DIODE TECHNIQUE

Fig 1 shows a simplified block diagram of a two load radiometer system [4] with a phased array antenna array. Fig 2 shows the configuration of each active antenna element and the center element of the array. The center element of the array radiates a Gaussian noise of known amplitude. A controller steps the radiometer between target scene observations (with the radiated source turned off), internal load observations and an observation of the target scene with the radiated noise source turned on. The difference between the emission temperature measured with the noise source turned on and off provides a method to compute the gain of the antenna electronics. Though the plane of reference for the calibration is the front-end of the radiometer, this technique can account for drifts in the gain of the antenna electronics, thus providing a quasi-end-to-end calibration.
3. TWO DIODE TECHNIQUE

Fig 3 shows a modified radiometer and antenna array system. The individual active antenna element is modified from the one diode method to include a front-end RF switch on each antenna element as illustrated in fig 4. The center element of the array is the same as the one diode method. In this setup, the two internal loads in the radiometer are replaced by a noise source injected directly into the antenna array through a feed network. The controller now steps between the target scene observation (with the radiated noise source turned off), an observation of the target scene with the radiated noise source turned on and the injected load. In this method, the plane of reference for the calibration is the antenna itself, providing an complete end-to-end calibration.
4. CONCLUSION

This paper presents two novel methods to calibrate real-aperture microwave radiometer systems with phased array antennas. The proposed techniques make use of mutual coupling between antenna elements to measure the instantaneous gain of the antenna electronics. The one diode technique uses three calibration loads (one radiated antenna load and two loads internal to the radiometer) to compute the gain of the antenna electronics and the receiver while using the radiometer input as the calibration plane of reference. The two diode method uses only two calibration loads (one load is radiated from the antenna and the second load is injected into the antenna electronics) to obtain the overall system gain. The plane of reference for this method is the input to the antenna. The performance benefits of the two methods will be shown using empirical results.

5. REFERENCES


Phased Array Radiometer Calibration Using a Radiated Noise Source

K. Srinivasan¹, A. Limaye², C. Laymon², P. Meyer²

¹Universities Space Research Association, Huntsville, Alabama
²George C. Marshall Space Flight Center, NASA, Huntsville, Alabama
Motivation

• Passive real-aperture microwave remote sensing systems have predominantly been ‘staring’ or mechanically steered systems.

• Phased arrays have been used for years in radar systems for electronic beamsteering but present enormous calibration challenges in passive systems.

Can we calibrate an NxN phased array antenna with active electronics in real-time?
Motivation

CHALLENGES

• The gain of active RF components can vary with time – short term (minutes) drift, component ageing.

• The noise figure can be expected to be fairly stable at least in the short term.

SOLUTION

• Calibrate the antenna by observing a known source
  • Place a noise source in the field of view of the antenna
  • Use an injected noise source
  • Use a mirror to look at a cold sky target
  • Use mutual coupling between antenna elements to establish a calibration source
One Diode Calibration Method

Motivation: In-flight real-time continuous calibration

Features:
• One Antenna Diode Calibration
• Measure antenna electronics gain in real time
• Utilize mutual coupling between antenna elements as a calibration source
• Calibrate every scan angle in real time

Implementation:
• Radiate a noise source from the center element of the array
• Radiated Diode (ENR = 40 dB) used with a Hach radiometer

One Diode Method

Calibration Equations

\[ P_w = k B G_r (T_w + T_r) \]
\[ P_c = k B G_r (T_c + T_r) \]
\[ P_s = k B G_r (G_a (T_A + T_{ae}) + T_r) \]
\[ P_D = k B G_r (G_a (T_A + T_{ae} + T_D) + T_r) \]

\[ \hat{\gamma}_{\text{AD}} = \frac{\hat{P}_s - \hat{P}_c}{\hat{P}_D - \hat{P}_s} = \frac{\hat{G}_a (\hat{T}_A + \hat{T}_{ae}) - T_c}{\hat{G}_a T_D} \]
\[ \hat{T}_A = T_D \hat{\gamma}_{\text{AD}} + \frac{T_c}{\hat{G}_a} - T_{ae} \]

\[ \hat{G}_a = \frac{\hat{P}_D - \hat{P}_s}{\hat{P}_w - \hat{P}_c} \cdot \frac{T_w - T_c}{T_D} \]

- \( P_w \) – Power observed from the radiometer warm load at noise temperature \( T_w \)
- \( P_c \) – Power observed from the radiometer cold load at noise temperature \( T_c \)
- \( P_s \) – Power observed from the target scene (radiated diode off)
- \( P_D \) – Power observed from the target scene with the radiated diode \( (T_D) \) on
- \( k \) – Boltzmann’s constant
- \( G_r \) – Radiometer gain
- \( G_a \) – Antenna electronics gain
- \( T_r \) – Radiometer noise temperature
- \( T_{ae} \) – Antenna noise temperature
Measurement Precision

\[
\Delta T_A = \Delta \gamma_{1D} \cdot \frac{\partial T_A}{\partial \gamma_{1D}} + \Delta G_a \cdot \frac{\partial T_A}{\partial G_a}
\]

\[
\Delta \gamma_{1D} \cdot \frac{\partial T_A}{\partial \gamma_{1D}} = \sqrt{\frac{a_c^2}{\tau_c} + \frac{a_s^2}{\tau_s} + \frac{a_D^2}{\tau_D}}
\]

\[
\Delta G_a \cdot \frac{\partial T_A}{\partial G_a} = \sqrt{\frac{a_{gD}^2}{\tau_D} + \frac{a_{gs}^2}{\tau_s} + \frac{a_{gw}^2}{\tau_w} + \frac{a_{gc}^2}{\tau_c}}
\]

\[
a_c = \frac{T_c + T_r}{G_a \sqrt{B}}
\]

\[
a_s = \frac{(G_a T_A + T_r) - (G_a (T_A + T_D) - T_c)}{T_D G_a^2 \sqrt{B}}
\]

\[
a_D = \frac{(G_a (T_A + T_D) + T_r)(G_a T_A - T_c)}{T_D G_a^2 \sqrt{B}}
\]

\[
a_{gD} = \frac{T_c \cdot (G_a (T_A + T_{ae} + T_D) + T_r)}{T_D G_a^2 \sqrt{B}}
\]

\[
a_{gs} = \frac{T_c \cdot (G_a (T_A + T_{ae}) + T_r)}{T_D G_a^2 \sqrt{B}}
\]

\[
a_{gw} = \frac{T_c \cdot ((T_c + T_w)(T_w + T_c))}{G_a \sqrt{B} \cdot (T_w - T_c)^2}
\]

\[
a_{gc} = \frac{T_c \cdot ((T_c + T_w)(T_c + T_r))}{G_a \sqrt{B} \cdot (T_w - T_c)^2}
\]

\[
\tau = \tau_w + \tau_c + \tau_s + \tau_D
\]
### Measurement Precision

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Noise Temperature</td>
<td>400 K</td>
</tr>
<tr>
<td>Pre-detection Bandwidth</td>
<td>24 MHz</td>
</tr>
<tr>
<td>Antenna Noise Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Total Dwell Time</td>
<td>1 sec</td>
</tr>
<tr>
<td>Radiometer Warm Load</td>
<td>300K</td>
</tr>
<tr>
<td>Radiometer Cold Load</td>
<td>210K</td>
</tr>
<tr>
<td>Antenna Radiated Diode</td>
<td>300K</td>
</tr>
</tbody>
</table>

\( \text{Antenna Gain} = 3.5 \)

\( \Delta T \) due to:
- \( r \)
- \( G_s \)
- Total \( \Delta T \)

---

1. Two radiometer loads – Goodberlet et al, 2006
2. Two Diode method

---

Two Diode Calibration Method

Motivation: In-flight real-time continuous calibration

Features:
• Two Diode Calibration
• End-to-end calibration for a phased array system
• Calibrate every scan angle in real time
• Utilize mutual coupling between antenna elements as a calibration source
• Requires fewer calibration loads than the One Diode Method

Implementation:
• Radiate a noise source from the center element of the array
• Radiated Diode (ENR = 40 dB) and an injected noise source (~300 K)
Two Diode Method

Calibration Equations

\[
\overline{P_i} = kBG_r (G_a (T_i + T_{ae}) + T_r) \\
\overline{P_s} = kBG_r (G_a (T_A + T_{ae}) + T_r) \\
\overline{P_D} = kBG_r (G_a (T_A + T_{ae} + T_D) + T_r)
\]

\[
\gamma_{2D} = \frac{\hat{P}_i - \hat{P}_s}{\hat{P}_i - \hat{P}_s} = \frac{(T_i + \hat{T}_A)}{T_i - (\hat{T}_A + T_D)}
\]

\[
\hat{T}_A = T_i + T_D \left( \frac{\gamma_{2D}}{1 - \gamma_{2D}} \right)
\]

- \(P_i\) – Power observed from the injected noise source at noise temperature \(T_i\)
- \(P_s\) – Power observed from the target scene (radiated diode off)
- \(P_D\) – Power observed from the target scene with the radiated diode \(T_D\) on
- \(k\) – Boltzmann’s constant
- \(G_r\) – Radiometer gain
- \(G_a\) – Antenna electronics gain
- \(T_r\) – Radiometer noise temperature
- \(T_{ae}\) – Antenna noise temperature

Independent of system parameters!
\[ \Delta T_A = \Delta \gamma_{2D} \cdot \frac{\partial T_A}{\partial \gamma_{2D}} \]

\[ \Delta \gamma_{2D} \cdot \frac{\partial T_A}{\partial \gamma_{2D}} = \sqrt{\frac{a_i^2}{\tau_i} + \frac{a_s^2}{\tau_s} + \frac{a_D^2}{\tau_D}} \]

\[ a_i = \frac{G_a T_i + T_r}{G_a \sqrt{B}} \]

\[ a_s = \frac{(G_a T_A + T_r)(T_i - T_A - T_D)}{T_D G_a \sqrt{B}} \]

\[ a_D = \frac{(G_a (T_A + T_D) + T_r)(T_A - T_i)}{T_D G_a \sqrt{B}} \]

\[ \tau = \tau_i + \tau_s + \tau_D \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Noise Temperature</td>
<td>400 K</td>
</tr>
<tr>
<td>Pre-detection Bandwidth</td>
<td>24 MHz</td>
</tr>
<tr>
<td>Antenna Noise Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Total Dwell Time</td>
<td>1 sec</td>
</tr>
<tr>
<td>Antenna Injected Load</td>
<td>300K</td>
</tr>
<tr>
<td>Antenna Radiated Diode</td>
<td>300K</td>
</tr>
</tbody>
</table>
Measurement Precision

\[ T_{\text{inj}} = 300K \]

\[ T_{D} = 300K \]
Phased Array Antenna

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L-band (2 passbands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Type</td>
<td>Real aperture planar phased array</td>
</tr>
<tr>
<td>Array</td>
<td>81 element (9x9) electronic beam steering</td>
</tr>
<tr>
<td>Dimensions</td>
<td>102 x 102 x 18 cm</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>15° (3dB at nadir)</td>
</tr>
<tr>
<td>Polarizations</td>
<td>Horizontal, Vertical</td>
</tr>
<tr>
<td>Beams</td>
<td>2 simultaneous acquisition</td>
</tr>
<tr>
<td>Scan Type</td>
<td>Push-broom, Conical, Staring at any angle</td>
</tr>
<tr>
<td>Control</td>
<td>In-flight reprogrammable scan mode</td>
</tr>
<tr>
<td>Electronics</td>
<td>Programmable Integrated circuit (PIC)</td>
</tr>
</tbody>
</table>

The front side comprises passive antenna elements.

Each antenna element has a circuit board that steers the beam and switches RF polarization.

Behind the antenna elements are the electronic control components.

Receivers

<table>
<thead>
<tr>
<th>Type</th>
<th>Hach</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Channels</td>
<td>4</td>
</tr>
<tr>
<td>Array</td>
<td>81 element (9x9) electronic beam steering</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Narrow</th>
<th>Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Receivers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Antenna Inputs</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Passbands</td>
<td>1401-1425 MHz</td>
<td>1350-1450 MHz</td>
</tr>
<tr>
<td>Integration Time</td>
<td>10 ms (min.)</td>
<td>10 ms (min.)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>7.6 x 7.6 x 7.6 cm</td>
<td>8.9 x 8.9 x 3.8 cm</td>
</tr>
<tr>
<td>Down Convert Freq.</td>
<td>8-32MHz</td>
<td>10-110 MHz</td>
</tr>
</tbody>
</table>

The wide band receivers developed in-house observe a wider spectrum for possible RFI that may effect observations.

Four receivers acquire data at two narrow bands and two wide bands simultaneously.

All four receivers are integrated into a common enclosure with required splitters, filters and amplifiers.

Theses radiometers are a byproduct of a Phase I and Phase II SBIR.
Correlator & Digital Back End

Dimensions: 48 cm x 69 cm x 22 cm
Filters: 16 subbands for each channel
Subchannel Bandwidth: 2.65 MHz (narrowband receiver)
7.8 MHz (wideband receiver)
Clock: 10 ms oscillator
Digitizer: 12 bit ADC; internal processing to 7 bit
Correlator: Nallatech BenADC-V4 with Xilinx FPGA
RFI Processing: ADD method: Computes I & Q moments
Control: RTD PC/104-Plus stack
Storage: 11 Mb packets

**Control Computer:** RTD PC/104-Plus Stack

**Correlator Module:** Nallatech BenADC-V4 firmware with Xilinx Spartan FPGA

Developed by Univ. of Michigan, Space Physics Research Lab

---

**Table:**

<table>
<thead>
<tr>
<th>Subband Number</th>
<th>Center Freq. (MHz)</th>
<th>Narrow</th>
<th>Wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140.17</td>
<td>1338.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>140.32</td>
<td>1346.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>140.47</td>
<td>1354.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>140.63</td>
<td>1362.3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>140.78</td>
<td>1370.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>140.94</td>
<td>1378.0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>141.10</td>
<td>1385.8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>141.25</td>
<td>1393.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>141.41</td>
<td>1401.4</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>141.57</td>
<td>1409.2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>141.72</td>
<td>1417.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>141.88</td>
<td>1424.8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>142.03</td>
<td>1432.7</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>142.19</td>
<td>1440.5</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>142.35</td>
<td>1448.3</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>142.46</td>
<td>1456.1</td>
<td></td>
</tr>
</tbody>
</table>

---

Command and Control

Antenna Status

Controller

Rack

Docking Bag End (DBE)

Correlator

Control PC

Operator PC

T.M.

Aircraft Data / Nav

External GPS

DBE Clock Speed

Antenna Switch Time

Minimum Allowable Integration Time

Maximum Allowable Integration Time

No. Beams & Scan Angles

Platform Altitude & Speed

Operational Integration Time

Corr. Data


Radiometer Temp.

Key

Command Lines
RF Pathway
Correlator / T.M. Data
Status Lines
Ethernet

Calibration Performance Evaluation

Experimental Set-up

- NASA EMI chamber
- Antenna on table looking at ceiling
- Scanning forward half only (0-160° azimuth) in 20° increments at 40° look angle
- Control system in adjoining room

Observations sorted by angle along with diode measurements

Radiometer Loads

Insufficient separation between radiated diode and scene
Performance Evaluation

### Table: Comparison of Calibration Methods

<table>
<thead>
<tr>
<th>Cal Method</th>
<th>NEDT @10ms</th>
<th>Meas Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometer Loads only</td>
<td>9.8</td>
<td>9.87</td>
</tr>
<tr>
<td>One Diode</td>
<td>9.1</td>
<td>9.74</td>
</tr>
<tr>
<td>Two Diode</td>
<td>2.08</td>
<td>2.67</td>
</tr>
</tbody>
</table>

### Graphs:

- **Radiometer Loads only**
- **One Diode Method**
- **Two Diode Method**

Challenges

• The amplitude of the mutually coupled signal is a function of scan angle – results in different radiated diode observations at each scan angle

• Impact of the difference in system noise temperature due to front-end antenna switch loss as a function of switch position

• Efficiency of the radiated diode as a function of antenna size? Can this be overcome by using multiple radiating elements embedded within the array?
Conclusions

- Use of a radiated noise diode as a calibration source for an antenna array can be (relatively) simple to implement and significant applications
- First results are promising and indicate good potential for beam forming radiometers
- Opportunities for improvement

Future Work

- Address scan angle dependent mutual coupling issues
- Analyze efficiency of calibration as a function of antenna size
- Improve the injected feed network