MAPIR: An Airborne Polarimetric Imaging Radiometer in Support of Hydrologic Satellite Observations

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Science Motivation

Earth Science
Vision 2030
March 2004

NASA Science Plan
2007

National Research Council
Earth Science and
Applications from Space
January 2007

GPM
Global Precipitation Mission
2013-

SMAP
Soil Moisture Active Passive
2014-

ICESat-2
2015-

DESDynI
Deformation, Ecosystem
Structure, Dynamics of Ice
2017-

SWOT
Surface Water
Ocean Topography
2020-

Reports contain common theme of need for measurements of precipitation, soil moisture, and sea ice and provide measurement goals.

Shortage of available airborne simulators and instruments to produce data for algorithm development, validation, and for applied science activities.
Science Applications

Supported NASA Missions:
- SMAP
- DESDynI
- HyspIRI
- NPOESS
- GPM

Human Health & Air Quality
- Landslides
- Biomass & Ecosystem Health

National Defense Applications

L-band RFI Surveillance

Irrigation Scheduling
Agricultural Productivity

Precipitation Validation

Drought Detection

Flood Water Monitoring

Weather Forecasting

Hydrologic Modeling

L-band Instrument Performance Capabilities

Observed Brightness Temperature

Water Temperature Algorithms

Soil Moisture Data Processing

Vegetation Water Content Algorithms

Veg. Canopy Temperature Data Processing

Ocean Salinity Algorithms

Data Processing Algorithms
System Architecture
Phased Array Antenna

The front side comprises passive antenna elements.

<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>Weight</td>
<td>57 kg</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>15 deg (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>
<tr>
<td>Calibration</td>
<td>Emitted Gaussian noise source, 50 ohm termination</td>
</tr>
</tbody>
</table>

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 ea.</td>
<td>2 ea.</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 5 cm</td>
</tr>
<tr>
<td>Internal Cal. Loads</td>
<td>Warm: 300 K Cold: 210 K</td>
<td>Warm: 300 K Cold: 210 K</td>
</tr>
<tr>
<td>Down Convert Freq.</td>
<td>8-32 MHz</td>
<td>10-110 MHz</td>
</tr>
</tbody>
</table>

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

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

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**
- 1.625 MHz (narrowband receiver)
- 7.8125 MHz (wideband receiver)

**Clock**
- 125 MHz 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

---

#### Subband 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>1401.7</td>
<td>1338.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1403.2</td>
<td>1346.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1404.7</td>
<td>1354.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1406.3</td>
<td>1362.3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1407.8</td>
<td>1370.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1409.4</td>
<td>1378.0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1411.0</td>
<td>1385.8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1412.5</td>
<td>1393.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1414.1</td>
<td>1401.4</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1415.7</td>
<td>1409.2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1417.2</td>
<td>1417.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1418.8</td>
<td>1424.8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1420.3</td>
<td>1432.7</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1421.9</td>
<td>1440.5</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1423.5</td>
<td>1448.3</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1424.6</td>
<td>1456.1</td>
<td></td>
</tr>
</tbody>
</table>

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*Developed by Univ. of Michigan, Space Physics Research Lab*
Command and Control

### Key

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

### Parameters

- **Platform Altitude & Speed**
- **No. Beams & Scan Angles**
- **Minimum Allowable Integration Time**
- **Maximum Allowable Integration Time**
- **Antenna Switch Time**
- **DBE Clock Speed**

### Diagram Components

- **Controller**
- **Antenna**
- **Radiometer**
- **Correlator**
- **Control PC**
- **Operator PC**
- **Aircraft Data / Nav**
- **External GPS**

### Connections

- **Antenna Status**
- **Rack**
- **DBE Clock Speed**
- **Radiometer Temp.**

### Integration Time Indicators

- **DBE**
- **Corr. Data**
- **Corr. Cmd.**
- **T.M.**
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

Implementation:
- Radiate a noise source from the center element of the array
- Radiated diode (ENR = 40 dB) and an injected noise source (~300 K)
Calibration

- Receiver Noise Temperature: 400 K
- Pre-detection Bandwidth: 24 MHz
- Antenna Noise Temperature: 300 K
- Total Dwell Time: 1 sec
- Radiometer Warm Load: 300K
- Radiometer Cold Load: 210K
- Antenna Injected Load: 300K
- Antenna Radiated Diode: 300K

Notes:
1. Two radiometer loads – Goodberlet et al, 2006
2. Two Diode method
Performance Evaluation

- TB time series, 10 azimuth angles
- Shows system stability relative to range of Earth observations
- RMSE at 10 msec = 2.5 K
- No system-generated RFI observed

Observations sorted by angle along with diode measurements

- TB observations sorted by angle
- Larger variability at 60°, and 160° can be attributed to lack of separation of scene obs from either or both calibration diodes

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
**Performance Evaluation**

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam patterns</td>
<td>Symmetric</td>
</tr>
<tr>
<td>3 dB nadir beamwidth</td>
<td>15 degrees</td>
</tr>
<tr>
<td>Side lobe characterization</td>
<td>1st side lobe: -20 dB</td>
</tr>
<tr>
<td>Functionality of scan modes</td>
<td>Functionality of all modes confirmed</td>
</tr>
<tr>
<td>Cross polarization isolation</td>
<td>30 dB</td>
</tr>
</tbody>
</table>

---

**Graphs:**

- Top graph: Normalized Amplitude (dB) vs. Angle (deg) for different beam patterns.
- Bottom graph: Normalized Amplitude (dB) vs. Angle (deg) for different polarization configurations.
Aircraft Integration

NASA P3-B Orion

Forklift raises antenna into bomb bay

UTSI Piper Navajo, PA-31

Adapter box provides interface between antenna and aircraft

Characteristics | P-3B Orion | Piper Navajo |
--- | --- | --- |
Range (nm) | 3,800 | 1,000 |
Payload (lbs.) | 16,000 | 350 |
Cruise Speed (kts) | 330 | 150 |
Max. Altitude (ft.) | 30,000 | 10,000 |
Capacity (crew) | 15 (4) | 2 (2) |

Structural interface for antenna inside bomb bay

Single GN2 tank installed in left wing locker

Belly pod fairings fabricated in-house at UTSI
Airborne Platform Configuration

**Piper Navajo PA-31 (N11UT)**

### Instrumentation

- **MAPIR**
  - *L-band brightness temperature*
- **Infrared Pyrometer**
  - *Surface temperature*
- **Laser Altimeter**
  - *Precise platform altitude*
  - *Vegetation canopy height*
- **PAR (Up, Down)**
  - *Photosynthetically active radiation*
- **Total Solar Radiation Pyrometer**
  - *Downwelling solar radiation*

### Supporting Equipment

- **GPS Antenna**
  - *Platform position and attitude*
- **Nitrogen Source Tank with Electronic Controller**
  - *Humidity control inside MAPIR antenna enclosure*
- **Forward and Nadir Digital Video**
- **Data Acquisition System**
Flight Mission Profile

Study area in central Tennessee

<table>
<thead>
<tr>
<th>Date</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-May</td>
<td>Normandy Lake, abort</td>
</tr>
<tr>
<td>19-May</td>
<td>CHESS, abort</td>
</tr>
<tr>
<td>20-May</td>
<td>CHESS, Crossville, Normandy L.</td>
</tr>
<tr>
<td>25-May</td>
<td>Crossville</td>
</tr>
<tr>
<td>26-May</td>
<td>Crossville, abort</td>
</tr>
</tbody>
</table>

Normandy Lake used for water calibration

Typical Climate Reference Network station configuration

Four flight lines intersect over instrument station

<table>
<thead>
<tr>
<th>Scan Mode</th>
<th>Altitude (ft. MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normandy</td>
</tr>
<tr>
<td>Conical, dual beam</td>
<td>6500</td>
</tr>
<tr>
<td>Conical, dual beam</td>
<td>4700</td>
</tr>
<tr>
<td>Nadir, single beam</td>
<td>3180</td>
</tr>
<tr>
<td>Nadir, single beam</td>
<td>2850</td>
</tr>
<tr>
<td>Nadir, single beam</td>
<td>2550</td>
</tr>
<tr>
<td>Nadir, single beam</td>
<td>2100</td>
</tr>
</tbody>
</table>
Demonstrated Performance

Vertical polarization; single beam conical scan at 40° look angle; 4600 ft AGL; raw observed TB data, not gridded.

Landscape is gently rolling with a mix of woodland, pasture and cropland.

Vertical polarization; Nadir at 3540 ft. msl

Watts Bar Reservoir

Vertical polarization; conical scan mode at 5500 ft. msl
RF Interference Characterization

No. of Subband with RFI Detected
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

Horizontal Polarization

Vertical Polarization

625 m AGL

533 m AGL

442 m AGL
Conclusions & Future Work

Conclusions

• Results indicate successful performance of beam forming radiometer
• Successful implementation of real-time calibration with emitted and injected Gaussian noise
• Opportunities for improvement

Future Work

• Improve calibration method
• Implement angle (phase) specific calibration
• Refine gridded product production
• Conduct additional performance tests
  • In situ observations
  • Mapping
  • Instrument intercomparisons
• Conduct more RFI analysis

FR2.L07.2 (10:45, Nautilus) *Phased array radiometer calibration using a radiated noise source; Srinivasan, Limaye, Laymon, and Meyer*