Development of Low-Mass, Low-Power, High-Frequency Microwave Radiometers with Internal Calibration to Provide High-Resolution Wet-Tropospheric Path Delay Measurements for the SWOT Mission

Steven C. Reising, Alexander Lee, and Darrin Albers
Microwave Systems Laboratory, Colorado State University, Fort Collins, CO

Pekka Kangaslahti, Shannon T. Brown, Douglas E. Dawson, Oliver Montes, Todd C. Gaier, Daniel J. Hoppe, and Behrouz Khayatian
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
Surface Water and Ocean Topography (SWOT) Mission

Accelerated Tier-2 U.S. National Research Council Earth Science Decadal Survey Mission planned for launch in 2020 (NASA/CNES partnership)

• **Oceanography Objectives:**
  – Characterize ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 10 km and larger (1-cm ht. precision required)
    • Kinetic energy / Heat and carbon air-sea fluxes
    • Climate change and ocean circulation
    • Coastal and internal tides

• **Hydrology Objectives:**
  – To provide global height measurements of inland surface water bodies with area greater than 250 m² and rivers with width greater than 100 m
  – To measure change in global water storage in these inland water bodies and river discharge on sub-monthly to annual time scales

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Scientific Motivation

- Current satellite ocean altimeters include a nadir-viewing, co-located 18-34 GHz multi-channel microwave radiometer to measure wet-tropospheric path delay. Due to the large diameters of the surface instantaneous fields of view (IFOV) at these frequencies, the accuracy of wet path retrievals begins to degrade at approximately 40 km from the coasts.
- Conventional altimeter-correcting microwave radiometers do not provide wet path delay over land.
- In order to meet these needs, higher-frequency microwave channels (90-170 GHz) are part of the trade space of the SWOT mission to improve retrievals of wet-tropospheric delay in coastal areas and to increase the potential for over-land retrievals.
High-resolution WRF model results show reduced wet path-delay error using both low-frequency (18-34 GHz) and high-frequency (90-170 GHz) radiometer channels.
Objectives

• Develop low-power, low-mass and small-volume direct-detection high-frequency microwave receivers with integrated calibration sources covering frequencies from 90 to 170 GHz

• Design and fabricate a tri-frequency feed horn with integrated triplexer covering 90 to 170 GHz

• Design and fabricate PIN-diode switches and noise diodes for internal calibration from 90 to 170 GHz that can be integrated into the receiver front end

• Integrate and test components in MMIC-based low-mass, low-power, small-volume radiometer at 92, 130 and 166 GHz with the tri-frequency feed horn
Requirements

Key Antenna Subsystem RF Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequencies</td>
<td>92, 130 and 166* GHz</td>
</tr>
<tr>
<td>Bandwidths</td>
<td>10 GHz</td>
</tr>
<tr>
<td>Port-to-port isolation</td>
<td>&gt; 20 dB</td>
</tr>
<tr>
<td>Return loss</td>
<td>&gt; 15 dB</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>&lt; 0.75 dB</td>
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</tbody>
</table>

Key Receiver RF Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequencies</td>
<td>92, 130 and 166 GHz</td>
</tr>
<tr>
<td>Bandwidths</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Noise Temperature</td>
<td>&lt; 1300 K</td>
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<tr>
<td>Return loss</td>
<td>&gt; 15 dB</td>
</tr>
<tr>
<td>Calibration stability</td>
<td>0.1 K over 30 – 60 s</td>
</tr>
</tbody>
</table>

*Note: We will attempt to push all 166 GHz component designs to accommodate 183 GHz sounding channels as closely as possible.*
A single, tri-band feed horn and triplexer are required to maintain acceptable antenna performance, since separate feeds for each of the high-frequency channels would need to be moved further off the reflector focus, degrading this critical performance factor. The tri-frequency horn was custom designed and produced at JPL, with an electroform combiner from Custom Microwave, Inc. Measurements show good agreement with simulated results.
Example of a Ring to Produce Horn Corrugation
Comparison of measured and simulated return loss, shown in blue and red, respectively, for the WR-10 waveguide port used for the 92-GHz radiometer. The bandwidth is 11 GHz with 15-dB return loss or better.
Measured return loss for the WR-8 waveguide port used for the 130-GHz radiometer. The bandwidth is 18 GHz with 15-dB return loss or better.
Comparison of measured and simulated return loss, shown in blue and red, respectively, for the WR-5 waveguide port used for the 166-GHz radiometer. The bandwidth is 26 GHz with 15-dB return loss or better, including the 183-GHz band.
Horn Antenna Pattern at 92 GHz

Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 92 GHz.

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Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 130 GHz.
Measured E-plane and H-plane radiation patterns of tri-frequency horn antenna at 166 GHz.
Noise Diodes for Internal Calibration

• Nadir-pointing radiometers are flown on altimetry missions with no moving parts, motivating two-point internal radiometric calibration, as on Jason-2. Highly stable noise diodes will be used to achieve one of these two points.

• Radiometric objectives
  • Provide an electronically-switchable source for calibrating the radiometer over long time scales, i.e. hours to days.

• RF design objectives from radiometer requirements
  • Noise diode output will be coupled into the radiometer using a commercially-available waveguide-based coupler.
  • Stable excess noise ratio (ENR) of 10-dB or greater, yielding equivalent noise of ~600 K for a 10-dB coupler.
## Noise Diode Measurements

<table>
<thead>
<tr>
<th>Package Style</th>
<th>Manufacturer</th>
<th>ENR @ 92 GHz (dB)</th>
<th>ENR @ 135 GHz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Lead*</td>
<td>M-Pulse</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>Bare Die (substrate bypass)</td>
<td>M-Pulse</td>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>Bare Die (wire bypass)</td>
<td>M-Pulse</td>
<td>10</td>
<td>--</td>
</tr>
</tbody>
</table>

*Noise diode manufactured for NASA/GSFC
This direct-detection Dicke radiometer uses two LNAs and a single bandpass filter for band definition.

Direct-detection architecture is the lowest power and mass solution for these high-frequency receivers. Keeping the radiometer power at a minimum is critical to fit within the overall SWOT mission constraints, including the power requirements of the radar interferometer.
92-GHz Bandpass Filter: Modeled and Measured on Die

- Insertion Loss (dB)

Frequency (GHz)

HFSS
S21

- Return Loss (dB)

Frequency (GHz)

S11
HFSS S11

- 5-mil (125-µm) thick polished alumina substrate
- Measured using a probe station with WR-10 waveguides
- Modeled and measured in open air
92-GHz Multi-Chip Module

92-GHz direct-detection radiometer with Dicke switching and integrated matched load
92-GHz Multi-chip Module (Close-up)

Matched Load
PIN-Diode Switch
Low-Noise Amplifier #1
Band Pass Filter
Low-Noise Amplifier #2
Waveguide to Microstrip Transition
92-GHz Radiometer Performance Analysis

NEΔT (K)

Integration time (s)

- Microwave Humidity Sounder on Orbit at 89 GHz
- Advanced Microwave Sounding Unit on Orbit at 89 GHz
• These Dicke radiometers use four LNAs to provide sufficient signal level at the input to the detector.

• Direct-detection architecture is the lowest power and mass solution for these high-frequency receivers. Keeping the radiometer power at a minimum is critical to fit within the overall SWOT mission constraints, including the power requirements of the radar interferometer.
166-GHz Predicted Performance

Microwave Humidity Sounder on Orbit at 89 GHz
Advanced Microwave Sounding Unit on Orbit at 89 GHz
166-GHz Band Pass Filter: Return Loss

- Return Loss (dB)
- Frequency (GHz)

HFSS Enclosed
HFSS Air
Measured Return Loss

0.94” (2.4 mm)
166-GHz Band Pass Filter: Insertion Loss

HFSS Enclosed
HFSS Air
Measured Insertion Loss
The passive high-frequency microwave components were designed and fabricated in microstrip technology on 3-mil (75 µm) thick alumina substrates.
166-GHz Low-Noise Amplifier

- 35-nm process InP HEMT
- Three-stage design with separate gate bias for the first stage to optimize low-noise performance
- Record low noise temperature of 300 K from 150 - 160 GHz
- Chip area of 900 x 560 $\mu$m$^2$
- The LNA was mounted in optimized WR-08 and WR-05 waveguide housings to test over a broad bandwidth.
166-GHz Multi-Chip Module

0.093" (2.4 mm)
130-GHz Predicted Performance

\[ \text{NE}_{\Delta T} \text{ (K)} \]

\[ \text{Integration Time (s)} \]

- Microwave Humidity Sounder on Orbit at 89 GHz
- Advanced Microwave Sounding Unit on Orbit at 89 GHz
130-GHz Band Pass Filter: Return Loss

The passive high-frequency microwave components were designed and fabricated in microstrip technology on 3-mil (75 µm) thick alumina substrates.
130-GHz Band Pass Filter: Insertion Loss

Note: Correction for CPW losses included.
• MMIC LNA was packaged in WR-8 and WR-10 housings for characterization over a broad bandwidth.
130-GHz Multi-Chip Module
130-GHz Multi-Chip Module
Compact Airborne Microwave Radiometer

• Under a new NASA IIP-10 award, CSU and JPL will develop, demonstrate and fly the Compact Airborne Microwave Radiometer to combine low-frequency wet-delay correction channels (18-34 GHz) with high-frequency mm-wave window (90-170 GHz) and sounding (118 and 183 GHz) channels. It will be capable of deployment on the NASA King Air, Ikhana and Global Hawk.

• Migrate 34 GHz of the Jason-2’s Advanced Microwave Radiometer to 31 GHz to avoid frequency cross-talk with KaRIn radiometer

• Assess variability of wet-tropospheric path delay on 10-km and smaller spatial scales

• Demonstrate high-frequency radiometry to improve both coastal and over-land retrievals of wet path delay

• Provide a calibration and validation instrument to support of the SWOT mission.
Summary

• Conventional altimeters include a nadir-viewing 18-37 GHz microwave radiometer to measure wet-tropospheric path delay. However, they have reduced accuracy within 25-50 km of land.

• The potential addition of higher-frequency microwave channels to SWOT’s Jason-2 baseline radiometer is expected improve retrievals in coastal regions and may enable retrievals over land.

• We have developed PIN-diode switches, noise sources and a tri-frequency feed horn for wide-band performance near 92, 130 and 166 GHz.

• To demonstrate these components, we are producing a three-frequency-band, millimeter-wave MMIC-based low-mass, low-power, small-volume radiometer with internal calibration sources integrated with the tri-frequency feed horn.
Thanks to NASA ESTO for their continued support!