Advanced Component Development to Enable Low-Mass, Low-Power High-Frequency Microwave Radiometers for Coastal Wet-Tropospheric Correction on SWOT

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Abstract — **Current satellite ocean altimeters include a nadir-viewing, co-located 18-37 GHz multi-channel microwave radiometer to measure wet-tropospheric path delay. Due to the area 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. In order to meet the needs of the NRC Decadal-Survey recommended SWOT mission, higher-frequency microwave channels will need to be added to the Jason-1 and Jason-2 radiometers in order to improve retrievals of wet-tropospheric delay in coastal areas and to increase the potential for over-land retrievals.**

Critical microwave component and receiver technologies are under development to reduce the risk, cost, volume, mass, and development time for such a high-frequency microwave radiometer. This project focuses on the design and fabrication of a prototype system consisting of (1) a low-power, low-mass and small-volume direct-detection millimeter-wave radiometer with integrated calibration sources covering frequencies from 90 to 170 GHz that fits within the overall SWOT mission constraints, and (2) a multi-frequency feed horn covering the same frequency range. Three key component technologies are under development to scale the design of the Advanced Microwave Radiometer (AMR) on the OSTM/Jason-2 altimetry mission from 18-34 GHz to 90-170 GHz. They are a PIN-diode switch for calibration that can be integrated into the receiver front end, a high-Excess Noise Ratio (ENR) noise source and a single, tri-frequency feed horn. These new components will be integrated into a MMIC-based low-mass, low-power, small-volume technology-demonstration radiometer with channels at 92, 130 and 166 GHz.

Index Terms — **Atmospheric measurements, humidity measurement, microwave radiometry, monolithic microwave and millimeter-wave integrated circuits (MMICs), multichip modules (MCMs), remote sensing.**

I. Introduction

Conventional satellite altimeters, including TOPEX/Poseidon, Jason-1, Jason-2/Ocean Surface Topography Mission (OSTM), Geosat and the Geosat follow-on (GFO), include a nadir-viewing, 18-37 GHz microwave radiometer to measure wet-tropospheric path delay over the oceans [1]. However, due to their relatively large instantaneous fields of view for practical antenna apertures, they have reduced accuracy within approximately 40 km of the coasts. In addition, they do not provide wet path delay estimates over land. In 2007, the NRC Earth Science Decadal Survey recommended a Tier-2 mission entitled Surface Water and Ocean Topography (SWOT). The primary objective of SWOT is to characterize ocean mesoscale and submesoscale processes (on a 10-km scale and larger) in the global oceans, for the first time, and to measure the global water storage in inland surface water bodies, including rivers, lakes, reservoirs, and wetlands.

An important new science objective of SWOT is to transition satellite radar altimetry into the coastal zone, requiring a novel microwave radiometer to provide fine-spatial resolution wet-tropospheric path delay corrections near land. A viable approach to meet this need is the addition of high-frequency microwave window channels (90-170 GHz) to the baseline low-frequency channels (18-37 GHz). For a maximum antenna aperture size, the high-frequency microwave radiometer channels have inherently finer spatial resolution. In addition, the high-frequency microwave channels in the atmospheric transmission windows are sensitive to the water-vapor continuum and therefore can be used to improve the retrieval of wet-tropospheric path delay in coastal regions. Over the open ocean, low-frequency brightness temperatures (T_Bs) are expected to yield path-delay retrieval performance similar to that of current space-based altimeters, better than 1 cm RMS [1]. As the radiometer approaches land, the low-frequency T_Bs will be contaminated by the coastline, and the high-frequency T_Bs will be used to extrapolate the path delay toward the coast from the last uncontaminated ocean pixel.

As part of a related mission-concept study, a radiative transfer simulator, coupled with a high-resolution Weather Research and Forecasting (WRF) model, has been implemented to assess retrieval performance and determine instrument requirements. Results of this study indicated that the addition of three high-frequency radiometer channels centered at 92, 130 and 166 GHz could yield path delay retrievals with an RMS error of less than 1 cm to within 3 km from the coast, in the acceptable range of errors for SWOT.

In addition, the performance of a 183-GHz sounding radiometer for over-land retrievals was assessed using a Bayesian retrieval algorithm over land and over ocean. NOAA's National Center for Environmental Prediction (NCEP) model fields were used to generate simulated global 183 GHz brightness temperatures, and errors were binned as a function of path delay (PD). RMS errors over land ranged from 1.5 to 3.0 cm, and over ocean or large water bodies varied from 0.5 cm at low PDs to 2.0 cm at high PDs. Therefore, channels near the 183-GHz water vapor absorption line are expected to yield useful retrievals over land.

II. HIGH-FREQUENCY RADIOMETER TECHNOLOGY DEVELOPMENT

Development of a new high-frequency radiometer measurement technique for SWOT requires technology developments in both: (1) a low-power, low-mass and small-volume direct-detection millimeter-wave radiometer with integrated calibration sources covering frequencies from 90 to 180 GHz that fits within the overall SWOT mission constraints, and (2) a multi-frequency feed horn covering the same frequency range. This requires essentially a frequency scaling of the design of the Advanced Microwave Radiometer (AMR) flying on the OSTM/Jason-2 altimetry mission that was launched in 2008. The MMIC-based AMR receiver has three integrated radiometer channels at 18.7, 23.8 and 34.0 GHz fed by a single tri-frequency feed horn. The AMR design was optimized for low mass, volume and power, consuming less than half of the power of the heritage Jason-1 microwave radiometer launched in 2001 and much less than half of the volume and mass. Three key component technologies are needed to scale the design of the AMR to the 90 to 180 GHz frequency range. The first is a calibration noise source with sufficient excess noise ratio (ENR) up to 170 GHz. The second is a PIN-diode switch that can be integrated into the receiver front end. Finally, a linearly-polarized multi-frequency feed horn is needed to cover the high-frequency radiometer channels at 92, 130, and 166 GHz.

The new components developed under this program will be integrated into a MMIC-based, low-mass, low-power, small-volume radiometer with channels centered at 92, 130 and 166 GHz. This radiometer will serve as a laboratory technology demonstrator and provide realistic mass, power and volume estimates to feed into the SWOT mission concept study. A block diagram of the radiometer system is shown in Figure 1.

III. TRI-FREQUENCY FEED HORN ANTENNA

The tri-frequency feed horn antenna needs to accept electromagnetic energy in all three radiometer frequency bands and triplex to three waveguide outputs, i.e., WR-10 for the 92-GHz radiometer, WR-08 for the 130-GHz radiometer, and WR-05 for the 166-GHz radiometer. The key design specifications for the feed horn are 10-GHz bandwidth in each of the three bands, 20-dB port-to-port isolation and better than

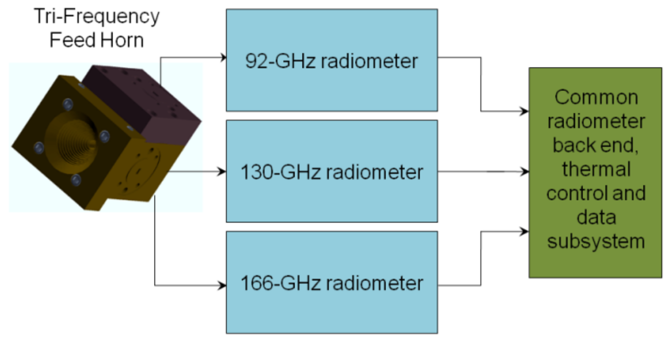

Figure 1. Block diagram of a technology-demonstration system to serve as risk reduction for a high-frequency microwave radiometer intended for deployment on the SWOT mission.

15-dB return loss across each band. A tri-frequency feed horn was designed in a split-block waveguide, with a corrugated horn and all three waveguide ports inside the block. A CAD rendering of the antenna design is shown in Figure 2, and an exploded view of the assembly is provided in Figure 3. Simulations indicate that this design will meet all necessary antenna specifications. The next steps are antenna fabrication and testing.

IV. PIN-DIODE SWITCH AND NOISE SOURCE FOR INTERNAL CALIBRATION

Microwave radiometers for wet-tropospheric path delay corrections in radar altimetry satellite missions are nadir-viewing, so they do not regularly view cosmic background radiation or blackbody sources for radiometric calibration, as conically scanning satellite radiometers do. Consequently, internal calibration sources are essential for radiometric calibration. For this purpose, switching sources with known equivalent temperature into the receiver using a PIN-diode switch is currently the most efficient method to meet the

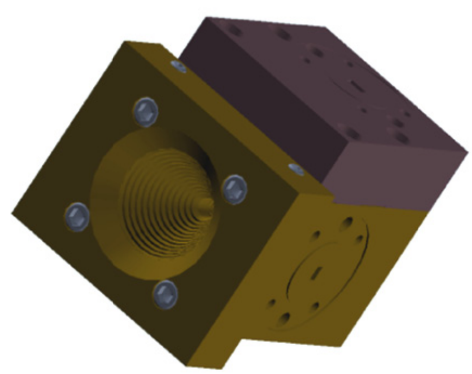

Figure 2. CAD rendering of of tri-frequency feed horn design, with corrugated horn (left) and three waveguide outputs: WR-10 for 92-GHz radiometer (upper right), WR-08 for 130-GHz radiometer (lower right) and WR-05 for 166-GHz radiometer (on back side of split block, not shown).

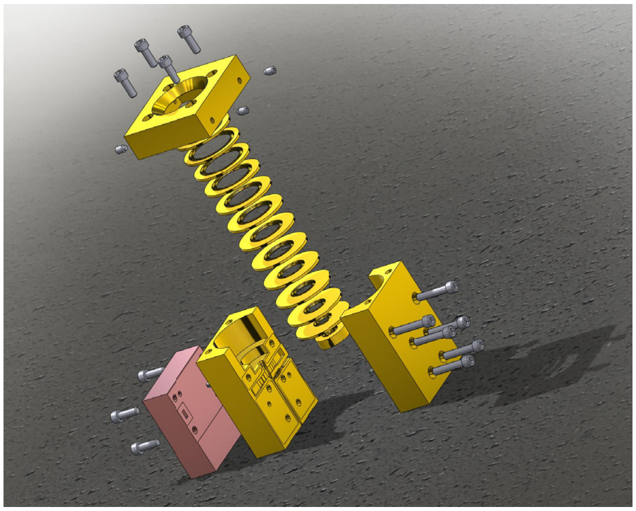

Figure 3. CAD rendering of exploded assembly of tri-frequency feed horn and triplexer.

requirements of low insertion loss, high return loss, high isolation and high stability. As part of this work, single-pole, double throw (SPDT) switches have been designed in an InP PIN-diode process for the 90 GHz to 180 GHz frequency range. Modeling results indicate less than 1-dB insertion loss as well as both return loss and isolation of greater than 25 dB. A fabrication run has recently been completed, and both on-wafer and on-chip/die tests will be performed to verify that the specifications are met. Afterward, the switches will be integrated into the MMIC-based multi-chip modules (see Section V).

Two well-characterized noise-equivalent temperature references are needed for internal calibration. The "warm" reference is typically accomplished by switching the receiver from viewing the external scene to viewing a matched load. The noise-equivalent temperature is then equal to the physical temperature of the load, which is easily measured. The "hot" reference is usually achieved by coupling the output of a stable noise source into the receiver. This requires a noise source of sufficient power (expressed in excess noise ratio, ENR), that is stable over a sufficiently long time period.

To achieve the "hot" reference, commercial noise diodes are available in bare die or in beam-lead packages to facilitate a variety of packaging approaches. The ENR of commercially-available diodes was measured by mounting them on existing substrates and integrating them into available WR-10 waveguide-band (75 to 110 GHz) waveguide-to-microstrip chassis. The required power output level of noise sources in current high-frequency microwave radiometer architectures is at least 10-dB ENR to enable coupling thru a coupler to the radiometer. As shown in Figure 4, tests under these conditions showed that a beam-lead noise source can produce at least 13-dB ENR over the 92-GHz radiometer band and 12-dB ENR at 120 GHz, the highest frequency measured. A simple, empirical model of the noise diode ENR and reflection in the chassis reflects the basic features of the measurements from 85 to 120 GHz, as shown in Figure 4.

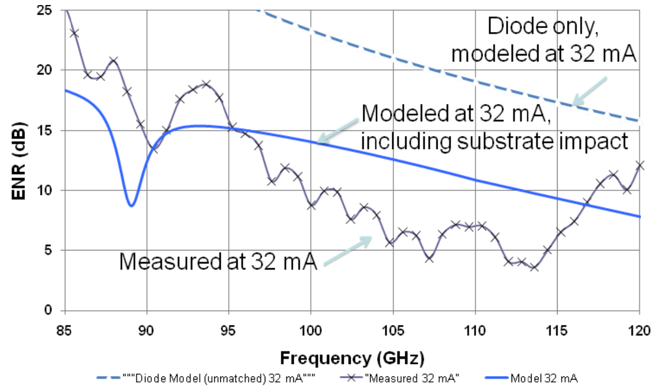

Figure 4. Measured and modeled beam-lead noise source excess noise ratio (ENR) at 32-mA bias current.

V. MMIC-Based Multi-Chip Module

Passive components were custom designed for the 92-GHz radiometer. These include RF band-definition filters, attenuators, and matched loads, as well as probes to couple energy received from the waveguide-based antenna input onto MMIC-compatible microstrip transmission lines. Performance simulations using Ansoft HFSS shows that the specifications are met or exceeded over the radiometer design bandwidth of 5 GHz.

In order to minimize both receiver noise temperature and power consumption, direct-detection architecture was chosen over the more-common mixer-based superheterodyne architecture. Recent measurements at room temperature with new InP LNAs, developed collaboratively by JPL and Northrup Grumman, demonstrated a noise temperature of 300 K at 160 GHz, more than a factor of two below the previous state of the art [2],[3]. This reduces the receiver noise temperature below that of recent mixer-based receivers [4]. These new InP LNAs will be used in the 130 and 166-GHz radiometers. In the 92-GHz radiometer band, a commercially-available LNA was found to meet performance specifications.

Since the isolator and directional coupler are not available in MMIC-compatible form factors in the 90 to 180-GHz frequency band, commercially-available waveguide-based alternatives will be used for this technology demonstration system. All front-end components after the isolator, including the power detector, will be mounted in a custom-designed MMIC-based, low-mass, small-volume multi-chip module (MCM), an extension of prior successful design experience at both CSU and JPL [5]-[7].

The custom-designed passive components and MCM have been fabricated for the 92-GHz radiometer. The commercially-available isolator, directional coupler and LNA have been acquired and tested using a network analyzer. A commercially-available PIN-diode switch operating at 92 GHz has been tested at JPL and shown to meet the performance goals for the 92-GHz radiometer. The commercially-available beam-lead noise source has been mounted in a split-block waveguide housing. The 92-GHz radiometer and tri-frequency horn antenna assembly are shown as a CAD rendering in Figure 5.

The next steps in the radiometer fabrication include assembly and testing of the multi-chip module, as well as integration with the waveguide-based components. The 130-GHz and 166-GHz radiometers are in the preliminary design phase, based on the 92-GHz radiometer results to date.

V. Conclusion

Critical microwave component and receiver technologies are under development to reduce the risk, cost, volume, mass, and development time for a high-frequency microwave radiometer needed to enable wet-tropospheric correction in the coastal zone on the NRC Decadal Survey-recommended Surface Water and Ocean Topography (SWOT) Mission. This work focuses on the development of a low-power, low-mass and small-volume direct-detection millimeter-wave radiometer with integrated calibration sources centered at 92, 130 and 166 GHz, as well as a single, tri-frequency feed horn covering the same frequency range. Three key component technologies are under development to scale the design of the Advanced Microwave Radiometer (AMR) on the OSTM/Jason-2 altimetry mission from 18-34 GHz to 90-170 GHz. They are a PIN-diode switch for calibration that can be integrated into the receiver front end, a high-Excess Noise Ratio (ENR) noise source and a single, tri-frequency feed horn. A PIN-diode switch fabrication run for all three frequencies has recently been completed. Commercially-available noise diodes have been shown to provide 13-dB ENR in a WR-10 waveguide-to microstrip chassis. The design and fabrication of all custom components at 92 GHz is complete, and the design of a single, tri-frequency feed horn is complete, with fabrication scheduled to begin soon.

Acknowledgement

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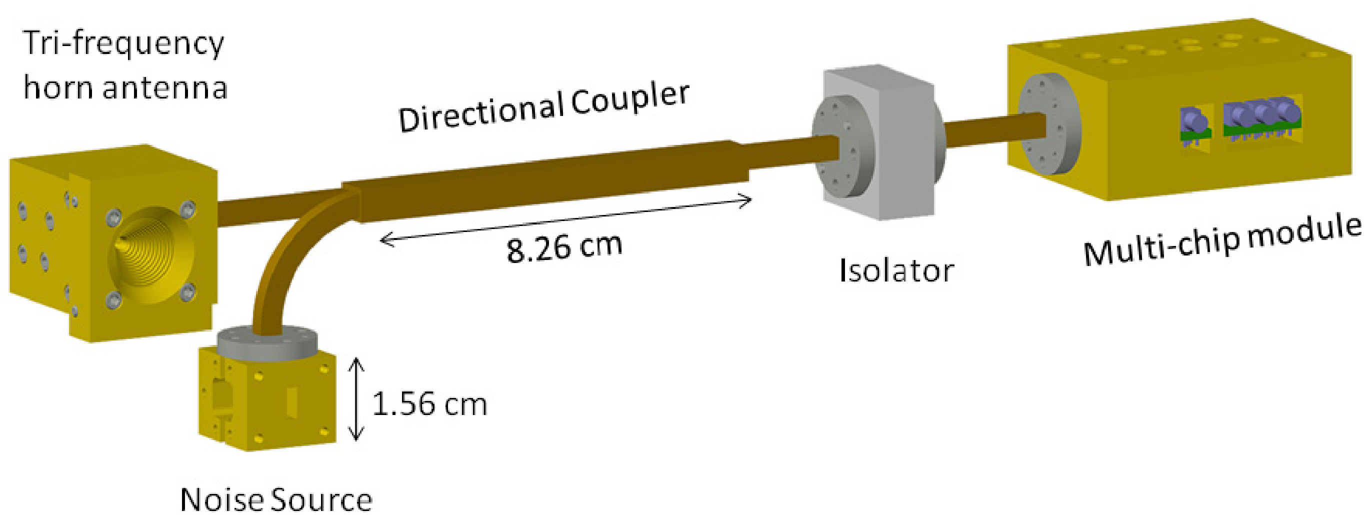

Figure 5. CAD rendering of the 92-GHz radiometer integrated with the tri-frequency feed horn antenna (left).