Millimeter-Wave Filter Bank Spectrometers

Kyle Massingill, Sean Bryan, Christopher Groppi, Philip Mauskopf, Bianca Pina, Philip Rybak, and Peter Wullen

***Abstract*—We present testing of a 180GHz prototype filter bank spectrometer and report on designs for larger channeled millimeter-wave filter banks at 50-183 GHz. This technology will be utilized in the development of a novel low-SWaP-C microwave sounding sensor. It works by amplifying the broadband signal with an LNA then channelizing with the millimeter-wave filter bank. Each channel of the filter bank is detected by a separate diode. The sensor system enabled by the millimeter-wave filter bank has a great potential for measuring 3D atmospheric water vapor and temperature by detecting the 183 GHz water line. We will report here our progress in utilizing the sensor for on the ground detections of humidity and preliminary designs for the use of the sensor on a small satellite. Satellite based microwave radiometers are the most important driver of global weather forecasting. Current sensors rely on high-Swap-C LO/mixer/RF components. We will demonstrate that the maturation and adoptions of our novel sensor system would greatly improve weather forecasting.**

The prototype millimeter-wave filter banks were fabricated using a micro milling CNC with a tolerance of 5-microns and is a waveguide coupled to five spectrometer channels. The spectrometer channels are resonant with a tuned center frequency. We tested a single channel prototype to determine sensitivity. Testing was performed by driving a VNA extender with a signal generator to input a sweeping signal into the prototype.

I. Introduction

DATA from microwave radiometers on large U.S. weather satellites is the single highest impact driver of global weather forecasting [1] [2]. These satellites carry instruments such the Advanced Technology Microwave Sounder (ATMS) and Advanced Microwave Sounding Unit (AMSU). These sensors use heterodyne mixer technology, followed by an RF filter bank and detectors. This effective approach comes with a relatively high cost in SWaP-C and system complexity. First, it requires a millimeter-wave local oscillator, which uses significant power and requires an additional temperature (and possibly frequency) stabilization system. After down conversion by a mixer, in existing systems the channels are separated with an RF filter bank which inherently limits instantaneous bandwidth and may be less compact due to longer RF wavelengths. Finally, existing mixers do not perform sideband-separation without additional complexity, meaning that signals from frequencies both above and below the line are combined. This complicates data analysis and increases the calibration and local oscillator stabilization requirements.

These disadvantages of existing spectrometer systems drove us to develop millimeter-wave waveguide filter bank technology [3] at Arizona State University, forming the heart of our novel approach. Our approach, as illustrated in the conceptual overview in Figure 1, is to first amplify the signal from the scene with a commercial millimeter-wave low noise amplifier (LNA). The signal then goes to a millimeter-wave filter bank that we fabricate at the ASU precision machining facility. The filter bank consists of resonant cavities that couple each frequency channel to a different output waveguide port. A millimeter-wave diode power detector at each output port detects the signal which a commercial instrumentation amplifier IC then amplifies before digitization, and storage. Our key enabling technology, the waveguide filter bank, has been successfully tested at 90 GHz [3] and 180 GHz [4] in the laboratory and in some integrated tests.

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K. Massingill, C. Groppi, P. Mauskopf, B. Pina, P. Rybak, and P. Wullen are with the School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287 USA (e-mail:kyle.massingill@asu.edu)

S. Bryan is with School of Electrical, Computer, and Energy Engineering, Arizona State University, Tempe, AZ USA

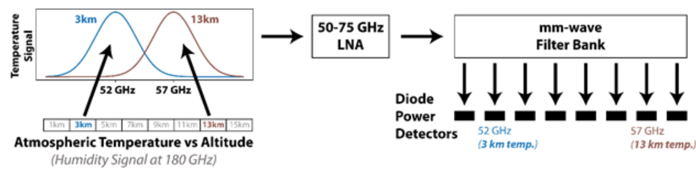

Fig. 1. Conceptual overview the spectrometer. Temperature (bottom left) and humidity signals from different atmospheric altitudes appear at different millimeter wave frequencies (top left) and are measured separately by diode detectors (bottom right) at each output of the filter bank.

A. Pressure Broadening

The 183GHz water molecule spectral line is commonly used in weather satellites to observe vertical profiles of water vapor in the atmosphere. Pressure broadening causes the emission of water vapor in lower (and higher pressure) parts of the atmosphere, to be ”broadened” several GHz away from the 183GHz rest frequency. While emission from water vapor in the higher (and lower pressure) parts of the atmosphere stays close to 183GHz. The broadening is caused as a resulted of molecular collisions that are more likely at higher pressure and temperature. As illustrated in figure 3, observations several GHz away from the 183GHz line has emission only from the lower part of the atmosphere while observation from near 183GHz has emission from both the higher and lower parts of the atmosphere. Retrieving the humidity profile from the measured spectrometer data is a non-linear fitting problem, or inverse problem [5]. Pressure broadening, analyzed with careful radiative transport simulations of the atmosphere, allows the radiometer measurements to be converted to measurements of atmospheric temperature. This is demonstrated in existing codes such as the am code [6].

II. Design

A. Spectrometer

To meet the goal of delivering a low volume, low power, and high channel count millimeter-wave atmospheric spectrometer,

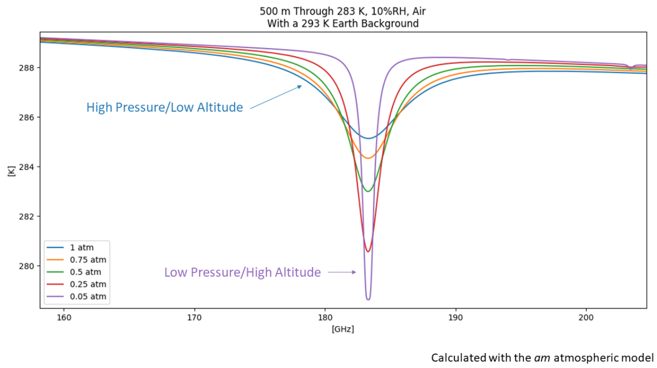

Fig. 2. Demonstration of pressure broadened signal from water vapor 183GHz spectral line as determined by atmospheric simulation. [6]

we have designed the following system. As illustrated in figure 3, light enters through a pyramidal feed horn, then is amplified at broadband by two LNAs. Frequencies are then selected off as the light travels through the filter-bank. Each channel of the filter-bank terminates on a diode detector. The LNAs are the only part of the spectrometer that require power, and the instrument can be made exceedingly compact.

Fig. 3. Drawing of spectrometer system. Broadband signal enters the feed horn, is then amplified by LNAs and finally divided by filter-bank. The filter-bank is a passive component of directly milled metal based on a novel design.

B. Filter-Bank

The primary novel technology of our mm-wave spectrometer is the filter-bank. The design for mm-wave filter-banks presented here was developed at the ASU Astronomical Instrumentation Lab and are described in more detail in [3] and [4]. The filter-bank consists of a primary rectangular waveguide and tee coupling channels tuned to specific frequencies. The channels are tuned by narrow coupling section then a half-wavelength resonating cavity. A second narrow section on the other end of the resonant cavity, defines the length of resonance. The channel is then terminated by a detector. The narrow sections have a cutoff frequency 50% higher than the center frequency of the channel. The center frequency of each channel is defined by the length of the resonant cavity, while the bandwidth is defined by length of the narrow cutoff sections. An example filter-bank is shown in figure 4. Multiple five channel examples of this filter-bank have been designed and modeled in HFSS with full 3D simulation, that include effects from machining such as rounded corners on channels. Larger channeled filter-banks have been modeled using a cascading S-matrix approach. This is achieved by 3D simulating each channels individually to get the 3 port S-matrix then cascading the S-matrix of all the channels. This has been done for a 54 channel filter with pass bands 135-170GHz and 190-245GHz. Two prototypes of five channel filter-bank designs have been fabricated and tested. The prototypes were drilled in aluminum on a 5-micron tolerance CNC mill. One was made in WR10 with for 80-105GHz [3], the other was made in WR5 for 156-203GHZ [4]. Testing was completed by sweeping over injected frequency using a signal generator and recording the voltage induced on diodes terminating the channels. The results show broad agreement between simulation and testing.

Fig. 4. An example of the waveguide filter-bank concept. Broadband light propagates through the waveguide and different frequency bands are selected off of the main waveguide by the five channels.

III. Testing

We have demonstrated our spectrometer technology with a single-channel prototype system in a laboratory environment. For this demonstration, we connected two commercial Radiometer Physics LNAs to the input port of the prototype spectrometer tested in [4], and connected a Pacific Millimeter Products GD diode detector to the 156 GHz output port. We used laboratory SRS amplifiers to measure the detector signal. We viewed ambient temperature and 77 K liquid nitrogen loads to calibrate the system, then took over a minute of data viewing the ambient temperature load to measure the noise. We clearly observed the temperature signal in the radiometer, and the measured noise performance shown in Figure 5. This shows that the system is stable with no excess (i.e. 1/f) noise detected down to the lowest clearly resolvable audio frequency ($\sim$ 50 mHz, or $\sim$ 20 seconds). This demonstrates that our novel spectrometer maintains calibration and stability over the long timescales required in microwave sounding observation.

Motivated by this successful laboratory demonstration, and to set requirements for the amplifiers, detectors, and other components, we developed a noise budget for the full sensor system. First considering only the channel bandwidth and the system temperature, the per-channel sensitivity $NE(\triangle)T$ is set by the radiometer equation

$$NE(\triangle)T = (T_{\mathsf{scene}} + T_{\mathsf{sys}})/\sqrt{BW}, \qquad (1)$$

where T_{scene} is the incident signal and BW is the channel bandwidth. Including noise contributions from other system elements the noise is calculated to be $30.5\ \mathrm{mK}\sqrt{\mathrm{s}}$, close to the fundamental limit. For the 60 GHz channels, the forecast is $40.5\ \mathrm{mK}\sqrt{\mathrm{s}}$. Our measured noise level of $230\ \mathrm{mK}\sqrt{\mathrm{s}}$ is close to the $80\ \mathrm{mK}/\sqrt{\mathrm{s}}$ level our model forecast for our prototype, with the difference due to insufficient gain in the prototype amplifiers. This will be corrected easily in the fielded instrument. Our laboratory demonstration proves the feasibility of a radiometer based on waveguide filter bank technology.

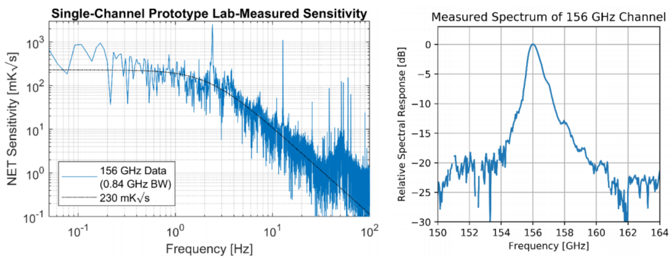

Fig. 5. Measured sensitivity (left) and passband (right) of a single-channel prototype. This demonstrates the feasibility of our approach, and has excellent noise stability ($< 50\ \mathrm{mHz}, > 20\ \mathrm{s}$).

IV. Conclusion

The CubeSounder mission was recently selected by the NASA flight opportunities program to mature and flight test this technology. We will fly a prototype spectrometer system on a suborbital balloon platform to demonstrate the ability of the technology to detect water vapor in the relevant environment.

At the start of the program, we will use our atmospheric simulation pipeline to finalize the selection of frequency channels and bandwidths to achieve optimum temperature and humidity sensitivity. This will in turn let us finalize the design of the detector readout electronics, and finalize the design of the 60 GHz filter bank. This will lead to final circuit designs and mechanical drawings of the payload, concluding with an internal design review before fabrication. We will build the flight control, power, and detector readout electronics. We will also write flight control software for the embedded control PC, and integrate the payload. Our first flight will use an existing 183 GHz spectrometer and LNAs to enable our first flight to come relatively early in the program. The second flight will re-use the recovered flight and detector readout systems, and we will then integrate the 60 GHz sensor.

System testing in the laboratory will consist of using an ambient temperature/liquid nitrogen calibration target to measure radiometer sensitivity and responsivity. At ASU, we already have several Vector Network Analyzers (VNAs) and VNA extensions up to 210+ GHz which we will use to measure the optical efficiency of the spectrometer and the spectral passband of each channel. Similar test results from our single-channel prototype are shown in Figure 5. After verifying the sensitivity of the integrated sensor payload, we will conclude the testing by observing the atmosphere above the ASU campus. To verify that our system will operate in the balloon environment, ASU has a large thermal vacuum testing facility that has been successfully used to test space and near-space hardware.

Flight testing is the key next step for CubeSounder technology. While laboratory testing has already shown the high performance of our sensor technology, ground testing has significant limitations. Crucially, ground testing does not enable us to conclusively show that our technology performs well in the balloon flight environment, and only permits limited testing of system integration and autonomous operation. Also, ground testing only permits imaging of a small part of the atmosphere, limiting our ability to verify our sensor data by comparing with known weather conditions.

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