

## A 6U CubeSat Constellation for Atmospheric Temperature and Humidity Sounding

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### ABSTRACT

We are currently developing a 118/183 GHz sensor that will enable observations of temperature and precipitation profiles over land and ocean. The 118/183 GHz system is well suited for a CubeSat deployment as ~10cm antenna aperture provides sufficiently small footprint sizes (~25km). This project will enable low cost, compact radiometer instrumentation at 118 and 183 GHz that would fit in a 6U CubeSat with the objective of mass-producing this design to enable a suite of small satellites to image the key geophysical parameters that are needed to improve prediction of extreme weather events. We will take advantage of past and current technology developments at JPL viz. HAMSR (High Altitude Microwave Scanning Radiometer), Advanced Component Technology (ACT'08) to enable low-mass and low-power high frequency airborne radiometers. The 35 nm InP enabling technology provides significant reduction in power consumption (Low Noise Amplifier + Mixer Block consumes 24 mW). In this paper, we will describe the design and implementation of the 118 GHz temperature sounder and 183 GHz humidity sounder instrument on the 6U CubeSat. In addition, a summary of radiometer calibration and retrieval techniques of the temperature and humidity will be discussed. The successful demonstration of this instrument on the 6U CubeSat would pave the way for the development of a constellation consisting of suite of these instruments. The proposed constellation of these 6U CubeSat radiometers would allow sampling of tropospheric temperature and humidity with fine temporal (on the order of minutes) and spatial resolution (~25 km).

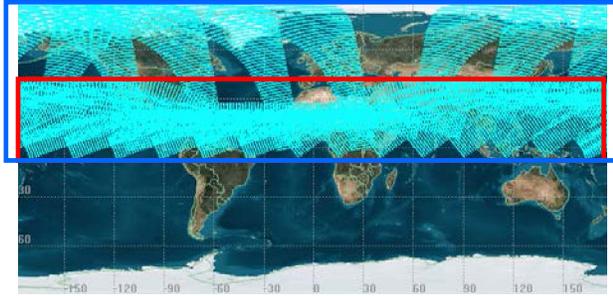
### INTRODUCTION

Extreme weather forecasting is currently limited by the paucity of observations of thermodynamic variables in the troposphere, including water vapor. Most climate models predict an increase in extreme events with a doubling of carbon dioxide [2]. However, to accurately predict how the distribution of extreme events may change in the future we need to be able to understand the mechanisms that influence our current climate. This includes understanding how modes of natural climate variability, such as the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO) impact the weather extremes [3]. Our current observing system is not well-suited for observing extreme events globally due to the sparse sampling and in-homogeneity of ground-based in-situ observations and the infrequent revisit time of satellite observations [4]. For example, sun-synchronous polar orbiting weather satellites that observe weather at a given location at discrete times during the day miss events that have a strong diurnal component, such as precipitation and thunderstorms. Observations of weather extremes, such as extreme precipitation events, temperature extremes, tropical and extra-tropical cyclones among others, with temporal resolution on the order of minutes and spatial resolution on the order of few kms (<10 kms), are required for

improved forecasting of extreme weather events. We envision a suite of low-cost passive microwave sounding sensors and imaging sensors on CubeSats that work in concert with traditional flagship observational systems, such as those manifested on large environmental satellites (i.e. JPSS, WSF, GCOM-W), to monitor weather extremes. The flagship sensors, operating at the same time (e.g. ATMS, SSMIS, AMSR-2), will be used for inter-satellite calibration.

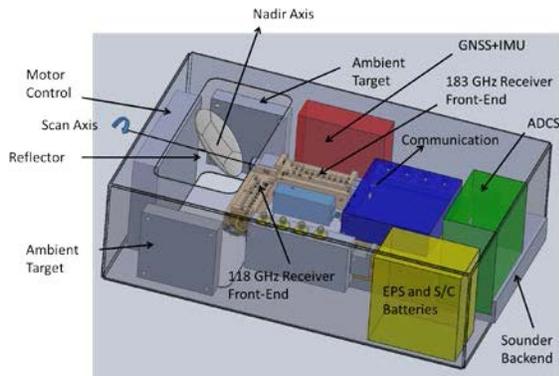
Potential orbit scenarios have been investigated to deploy sensors as a constellation enabling near-continuous global coverage. Observations of weather at time scales of variability (<30 mins) are needed to improved weather prediction. Four polar sensors provide less than 3 hour revisit time in mid-latitudes. In comparison, fifteen low-inclination satellites can provide 15 min revisit times in hurricane sector as shown in figure 1.

In this paper we address the development of smaller, cheaper and low power passive microwave radiometer instrument for agile deployment in a constellation or as a stand-alone free-flyer configured to meet a targeted science need.



**Figure 1. Coverage of four polar sensors (blue box) with ~3 hr revisit time in mid-latitudes compared with 15 Low-inclination satellites (red box) providing 15 min revisit time.**

In this effort, we are developing a low-cost compact multi-frequency CubeSat microwave radiometer system, leveraging recent developments in MMIC receiver technology and digital back ends at JPL. The CubeSat platform, which is based upon a standard 10x10x10 cm architecture (1U), has been becoming increasingly capable over the past several years where it is now possible to envision medium to large scale science missions that utilize them. This has also been recognized by NASA through the selection of the CHARM mission, a 183 GHz CubeSat radiometer led by Dr. Boon Lim at JPL. NASA also just selected a micro-sat constellation project for the first Ventures mission. To advance a CubeSat based radiometer to a full science mission, we need to extend the radiometer system to other bands for observations of precipitation, temperature, wind vector, water vapor, clouds and sea ice among others.



**Figure 2: Drawing of the CMSR payload including important avionics components inside a 6U CubeSat.**

#### INSTRUMENT DESCRIPTION

The CubeSat Microwave Sounding Radiometer (CMSR) – is a passive microwave radiometer, which measures the thermal radiation emitted from the atmosphere and the surface below. It has two receivers,

which detect part of this emission in three spectral bands. Each receiver is attached to a spectrometer – a filter bank, which essentially tunes the receiver to 4 narrow spectral channels simultaneously. The actual spectrum observed at any given time and location is determined by the vertical distribution of temperature and the density of certain molecules in the atmosphere, which both absorb and emit thermal radiation. This relationship can be formulated mathematically with the so-called Radiative transfer equation, which expresses what the spectrum should look like for a given distribution of the molecules and the temperature (along with the surface temperature and emissivity). The molecular species used by CMSR are oxygen, which has a spectral line near 118 GHz; and water vapor, which has a spectral line near 183 GHz. Thus, one CMSR receiver operates in the 118-GHz region (with 4 spectral channels); and one operates in the 183-GHz region (with 4 spectral channels). The vertical resolution of the profiles is related to the distribution of the so-called weighting functions. These are vertical contribution profiles, which indicate how much each part of the atmosphere contributes to the radiation measured in each channel.

The CMSR instrument is shown in Fig. 2. The instrument is a downward-looking cross-track scanner with the scan axis that is oriented along the flight path. A system diagram is shown in Fig. 3.

The antenna system of CMSR consists of a reflector that rotates at 30 rpm via a stepper motor. A single full rotation includes the swath below the CubeSat followed by observations of ambient (roughly blackbody calibration target and cold space which is viewed at the top of the rotation). An FPGA is used to read the digitized radiometer counts and receive the reflector position from the scan motor encoder, which are then sent to a microprocessor and packed into data files. The micro-processor additionally reads telemetry data from onboard housekeeping channels (containing instrument temperatures) and receives packets from an onboard navigation unit, which provides GPS time and position, as well as independent attitude information. The raw data files are accessed through an Ethernet port. The CMSR data rate is at ~200 kb/s, allowing for real-time access using a S-band communication system. Once on the ground, the raw data will be unpacked and processed through two levels of processing. The Level 1 product will contain geolocated time-stamped calibrated brightness temperatures for the earth scan. These data will then be input to a 1-D variational retrieval algorithm to produce temperature and water-vapor profiles as Level 2 products.

### Antenna/Calibration Subsystem

The CMSR scanning antenna system consists of a rotating reflector which is mechanically connected to a common scan motor. Figure 4 shows the optical elements and a ray-trace. A single feed horn and diplexer are required to maintain acceptable antenna performance with coincident beams. The reflector is fed by single circular corrugated tri-frequency horn, shown in figure 5, that was custom developed for NASA Earth Science Technology Advanced Component Technology program (ACT'08) [5]. The block contains a corrugated horn with WR-10, WR-8 and WR-5 waveguide ports.

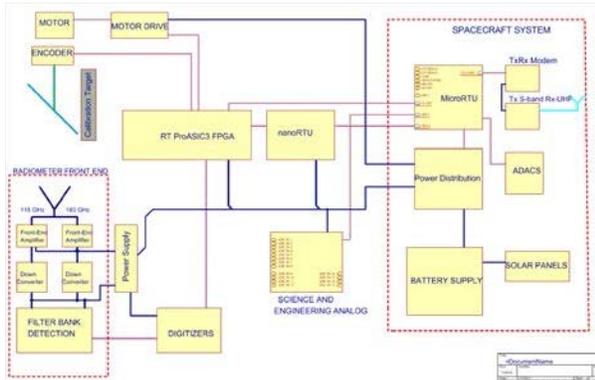


Figure 3: CMSR System-level block diagram

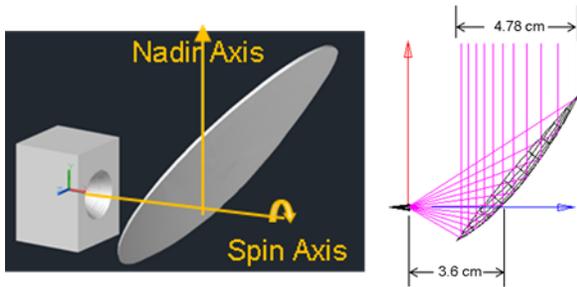


Figure 4: Reflector and feed-horn optical layout. The antenna is an offset paraboloid sized to -20dB contours of the best-fit Gaussian feed. The horn boresight and scan axis coincide.



Figure 5: Tri-Frequency feed horn and integrated triplexer.

Rings were machined separately and fitted stably into the split block. The key design specification for the

feed-horn is 10 GHz bandwidth in each of the bands with 15 dB return loss or better. The H-plane and E-plane feed-horn patterns of the horn for the 118 GHz and 183 GHz are shown in figure 6. The antenna patterns for entire optics assembly including the feed-horn and reflector are shown in figure 7.

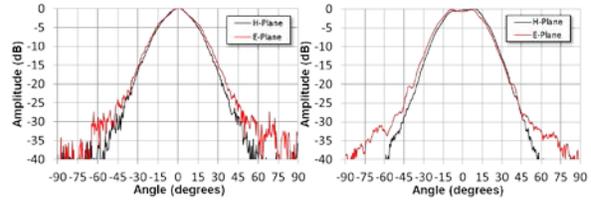


Figure 6: H-plane and E-plane feed-horn pattern for WR-8 (left) and WR-5 (right)

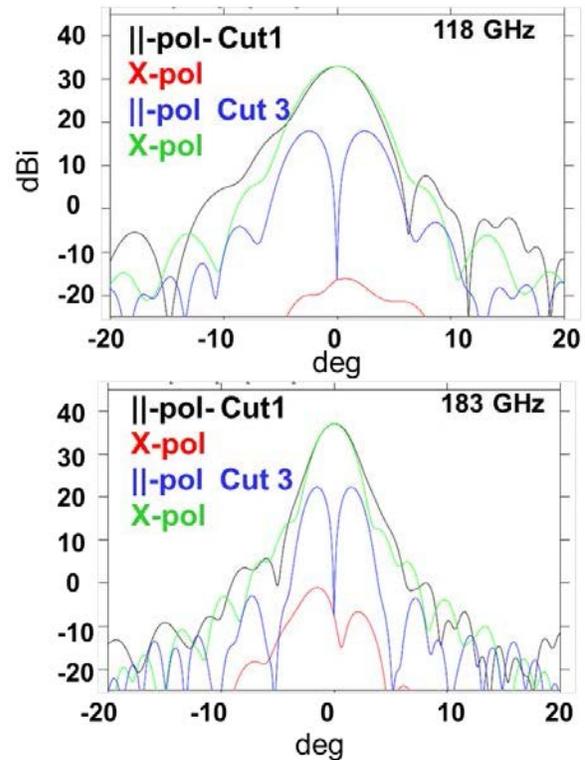
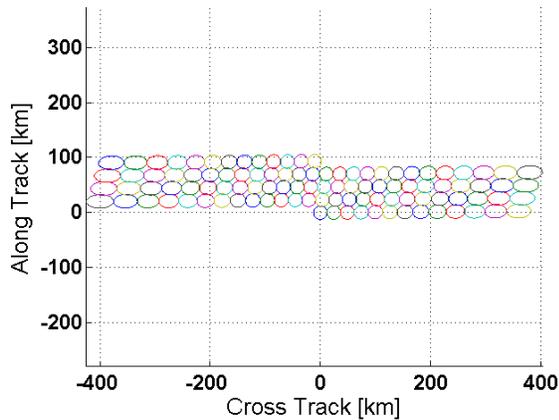


Figure 7: H-plane and E-plane antenna (include feed horn and reflector) pattern for 118 GHz (top) and 183 GHz (down)

This design provides matched and coincident antenna beams in all RF bands. The size of the beam is  $4.1^\circ$  and  $3.5^\circ$  half power full width (HPFW) at 118 GHz and 183 GHz bands respectively. The side lobes for all beams for angles greater than  $10^\circ$  off bore-sight are well below 30 dB with a beam efficiency of  $>95\%$  (defined as the fraction of power received within 2.5 times the main beamwidth), providing minimal footprint contamination. From an orbit altitude of 400 km, the

eamwidth corresponds to a 28-km footprint on the ground at nadir for 118 GHz and 25-km for 183 GHz.



**Figure 8: Scan pattern on earth's surface from 400 km and 7 km/s speed using 3.5° HPBW**

The unobstructed cross-track swath spans  $\pm 45^\circ$  from nadir, giving a 800-km swath from a 400-km flight altitude. A diagram of a typical set of scans, for 4 revolutions, is shown in figure 8. The scan system is designed for a nominal ground track speed of 7 km/s at 400 km. An integration time of 30 ms is used to obtain contiguous samples cross tack. The reflector observes two pyramidal blackbody calibration targets during each scan that are located on the sizes of the scan arc. Both targets are at the ambient air temperature. The ambient and hot targets are identical for the 118 and 183-GHz sides. The temperature of each target will be measured with temperature sensors embedded within the target near the tips.

### Receiver Subsystem

The receiver sub-systems employ a super-heterodyne approach. A receiver block diagram is presented in figure 9. The receivers consist of an InP (35 nm) MMIC LNA based front-end [6, 7]. The 118 GHz is a double-side band receiver and measures both sides of the oxygen line at 118 GHz. The 183 GHz receiver front-end has an RF image-reject waveguide filter that rejects the 166 GHz channel upper sideband by  $\sim 25$  dB. A Sub-Harmonic InP mixer downconverts the signal to the intermediate frequency (IF) ranging from 1 to 8 GHz. A passive multiplier is used to provide a source of local oscillator (LO) power and is driven by a dielectric resonator oscillator (DRO). The IF is amplified and spectrally resolved into four channels using an analog filter-bank at both 118 GHz and 183 GHz. The output of the filter-bank is amplified using low power SiGe amplifiers and detected using Schottky detector diodes. The detected output is amplified and fed into the digitizer board that has voltage-to-frequency converter.

The data is then accumulated using an FPGA and microprocessor that will perform on-board integration and combine the science data with engineering and housekeeping measurements to format a data-packet which will then be transmitted to the ground-station using an S-band communication system. The instrument characteristics are summarized in table 1.

**Table 1: Instrument Requirements**

Parameter	118 GHz	183 GHz
System noise temperature	< 500 K	< 500 K
No. of Channels	4 ( $\pm 1, \pm 3, \pm 5, \pm 7$ GHz)	4 (-1, -3, -5, -7 GHz)
Bandwidth	170 MHz, 320 MHz, 250 MHz and 362 MHz at 1,3,5 and 7 GHz respectively	
Spatial Resolution	35 km at Nadir Orbit: 500 km	25 km at Nadir Orbit: 500 km
Mass	<3 kg	
Power	<10 W	
Volume	20 x 20 x 10 cm	

### CONCLUSIONS

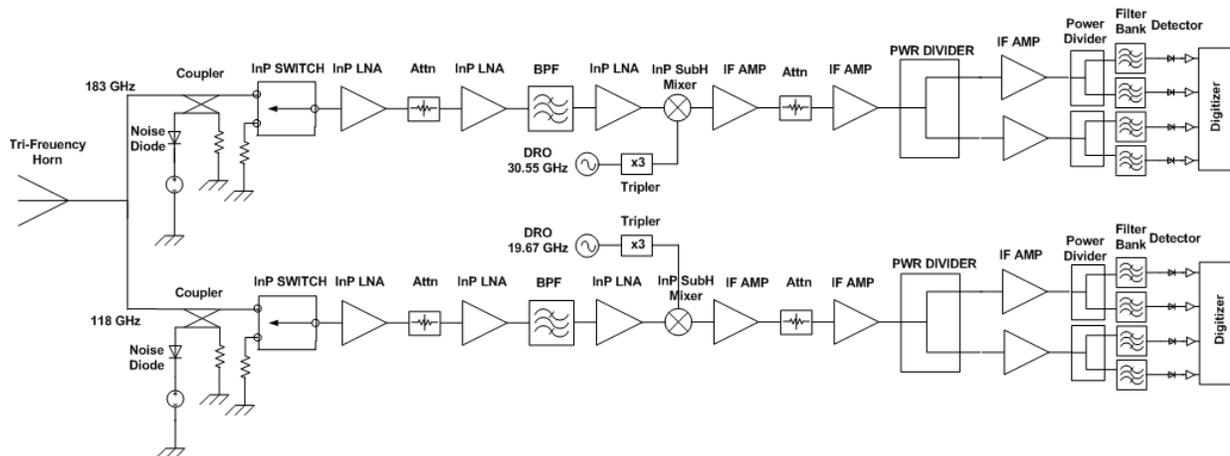
The CubeSat microwave sounding radiometer is designed to provide millimeter wave temperature and humidity sounding. It utilizes the current state of the art technology to enable substantially reduced size, mass, power and volume compared with existing instruments such as ATMS.

### Acknowledgments

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**Figure 9. 118 GHz and 183 GHz receiver chain with four channel outputs.**

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