Nanosatellites for Earth Environmental Monitoring: The MicroMAS Project

W. Blackwell, G. Allen, C. Galbraith,
T. Hancock, R. Leslie, I. Osaretin,
L. Retherford, M. Scarito, C. Semisch,
M. Shields, M. Silver, D. Toher, K. Wight
Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, MA 02420
Email: WJB@LL.MIT.EDU

D. Miller and K. Cahoy
Space Systems Laboratory
Massachusetts Institute of Technology
Cambridge, MA 02139

N. Erickson
Department of Radio Astronomy
University of Massachusetts
Amherst, Massachusetts 01003

***Abstract*—The Micro-sized Microwave Atmospheric Satellite (MicroMAS) is a 3U cubesat (30x10x10 cm, 4kg) hosting a passive microwave spectrometer operating near the 118.75-GHz oxygen absorption line. The focus of the first MicroMAS mission (hereafter, MicroMAS-1) is to observe convective thunderstorms, tropical cyclones, and hurricanes from a near-equatorial orbit at approximately 500-km altitude. A MicroMAS flight unit is currently being developed in anticipation of a 2014 launch. A parabolic reflector is mechanically rotated as the spacecraft orbits the earth, thus directing a cross-track scanned beam with FWHM beamwidth of 2.2-degrees, yielding an approximately 25-km diameter footprint from a nominal altitude of 500 km. Radiometric calibration is carried out using observations of cold space, the earth's limb, and an internal noise diode that is weakly coupled through the RF front-end electronics. A key technology feature is the development of an ultra-compact intermediate frequency processor module for channelization, detection, and A-to-D conversion. The antenna system and RF front-end electronics are highly integrated and miniaturized. A MicroMAS-2 mission is currently being planned using a multi-band spectrometer operating near 118 and 183 GHz in a sun-synchronous orbit of approximately 800-km altitude. A HyMAS-1 (Hyperspectral Microwave Atmospheric Satellite) mission with approximately 50 channels near 118 and 183 GHz is also being planned. In this paper, the mission concept of operations will be discussed, the radiometer payload will be described, and the spacecraft subsystems (avionics, power, communications, attitude determination and control, and mechanical structures) will be summarized.**

I. Introduction

The need for low-cost, mission-flexible, and rapidly deployable spaceborne sensors that meet stringent performance requirements pervades the NASA Earth Science measurement programs, including especially the recommended NRC Earth Science Decadal Survey missions. The challenge of data continuity further complicates mission planning and development and has historically been exacerbated by uncertain and sometimes substantial shifts in national priorities, launch failures, and budget availability that have degraded and delayed critical Earth Science measurement capabilities. The importance of millimeter wave sounding has been highlighted by the Decadal Survey and subsequent recommendation of a PATH mission [3]. New technologies [1, 2, 7] have enabled a novel approach toward this science observational goal, and in this paper we describe recent technology develop efforts to address the challenges above through the use of CubeSat radiometers, as CubeSat capabilities are rapidly progressing [5, 6, 8, 9].

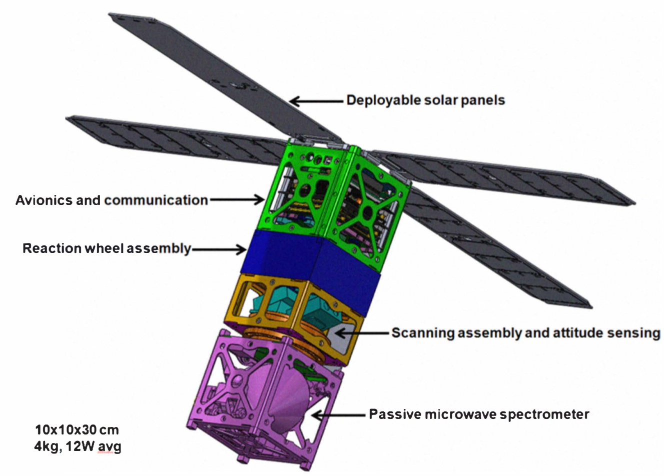

Fig. 1. The MicroMAS 3U cubesat spacecraft. The complete spacecraft has been designed to meet the following requirements: Mass ¡ 4kg, Power ¡ 12W, Volume = 10x10x30 cm^3. Highly integrated electronics and the lack of an internal blackbody calibration target help reduce the required mass, power, and cost substantially relative to current systems.

II. MicroMAS Overview

Recent work has involved the development and testing of ultra-compact radiometer component technologies that would enable the realization of a high-performance, multi-band sounder that would conform to the 1U CubeSat size, weight, and power requirements. A notional Micro-sized Microwave Atmospheric Satellite (MicroMAS, 30x20x10 cm3) is shown in Fig. 1.

A. Antenna System

The MicroMAS antenna system uses an offset parabolic reflector to focus a conical scalar feed horn toward the Earth. The antenna reflector system has been extensively designed

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Left edge	Center	Right edge	Bandwidth
113.9135	114.2260	114.5385	0.625
114.5375	114.8500	115.1625	0.625
115.1615	115.4740	115.7865	0.625
115.7855	116.0980	116.4105	0.625
116.4095	116.7220	117.0345	0.625
117.0335	117.3460	117.6585	0.625
117.6575	117.9700	118.2825	0.625
118.2815	118.5940	118.9065	0.625
108.0000	108.5000	109.0000	1.0000

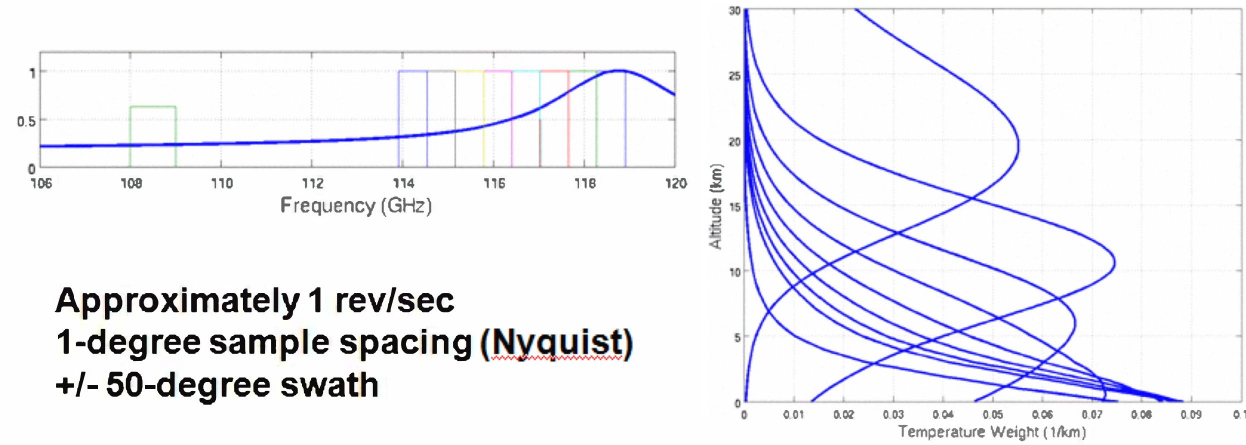

Fig. 2. The MicroMAS radiometer measures upwelling thermal emission in nine channels, shown in the table above. A window channel near 108 GHz is included. The channel bandwidths are shown with a notional atmospheric attenuation curve. The weighting functions are shown in the lower right panel in the figure. The reflector rotates at approximately 60 RPM while Nyquist sampling in the cross-track dimension.

and analyzed, indicating a worst-case beam efficiency of 95 percent and a full-width at half-maxium beamwidth of approximately 2.2 degrees. Recent measurements of the fabricated antenna flight assembly in a compact antenna test range have confirmed that all antenna design requirements have been met.

B. 118-GHz Receiver System

A single receiver will be developed to cover 108-119 GHz, based partly on the UMass development of the SEQUOIA focal plane array (85-116 GHz) for the Large Millimeter Telescope. The radiometer will be built in two parts: 1) a noise source and preamplifier, and 2) a module with additional gain at 118 GHz (if needed), a mixer, and an IF amplifier. The local oscillator (LO) for the mixer will be at 90 GHz, produced by a tripler housed in a separate block. The RF gain will exceed 40 dB and the IF gain will exceed 30 dB. Frontend receiver noise figure is not expected to exceed 5 dB. Total power consumption of all 118-GHz receiver components is not expected to exceed 2 W and total mass is not expected to exceed 500 g.

C. LO and IF/Baseband Electronics

The millimeter wave receiver front-ends covering the 118-GHz band are downconverted to K/Ka-band covering 18-29 GHz. The wideband IF will be amplified by two GaAs pHEMT MMICs before the channelizing filter. In the 118-GHz band, 18-19 GHz is used for surface sensing while the atmospheric channels fall between 23.5-28.5 GHz where they will be channelized into 8 x 625 MHz channels (see Fig. 2) requiring filters with 2.2-2.6 percent bandwidth. At the output of each channel there will be a diode detector optimized for stable and linear response with a broadband resistive match for accurate power measurement. The detected signal will be amplified by a low-power CMOS op-amp and sampled by a 16-bit ADC. Each channel will be read into a small FPGA to aggregate the data into a single data stream and interface it to the payload microprocessor.

III. MICROMAS SPACECRAFT AND MISSION CONCEPT OF OPERATIONS

MicroMAS is a nanosatellite compatible with the 3U CubeSat specification. It is designed to autonomously collect microwave radiometry data and transmit the data through an RF link to a ground station for subsequent processing, analysis, and use in weather forecast models. The concept of operations (shown in Fig. 3) is broadly similar to previous CubeSat remote sensing demonstration missions, but is intended to demonstrate several capability enhancements not previously implemented on a CubeSat. 1U of the 3U structure is allocated to the radiometer payload module, which is attached to the remainder of the structure with a motorized rotating coupling and bearing assembly, as shown in Fig. 4. The spacecraft will launch to a stable orbit with inclination between 20 and 30 degrees and initial altitude between 475 and 600 km. Once separated from the launch vehicle, the satellite will deploy solar panels and establish a stable attitude. It will then spin up

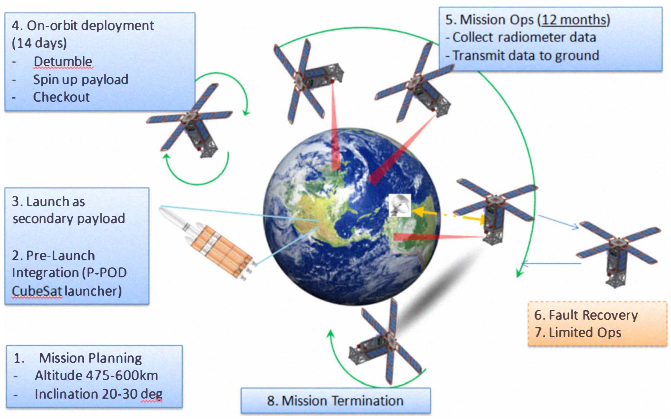

Fig. 3. The MicroMAS concept of operations is shown. Nominal mission lifetime is planned to exceed one year.

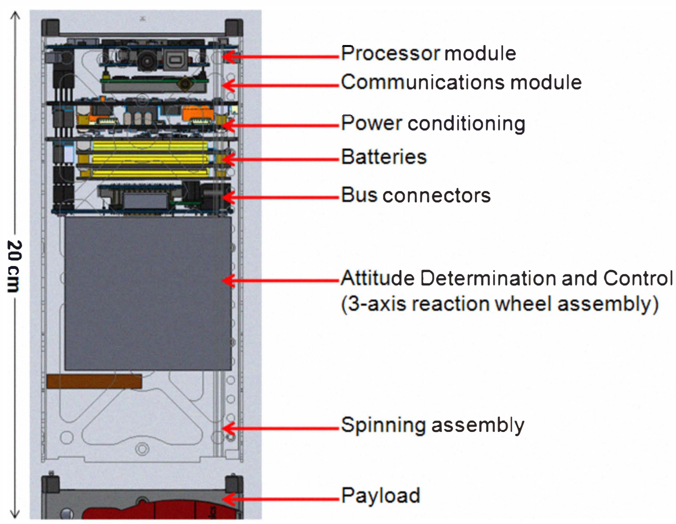

Fig. 4. The MicroMAS spacecraft bus is shown. Commercial parts are used whenever possible to reduce cost and schedule.

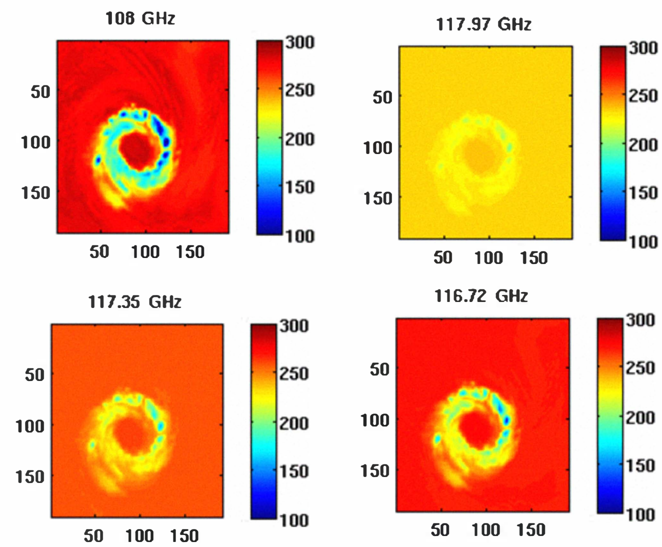

Fig. 5. Simulation of representative MicroMAS channels for Super Typhoon Pongsona (Dec. 8, 2002). The 108-GHz window channel reveals strong brightness temperature depressions due to ice scattering.

the payload module so the payload field of view sweeps across the ground track at a rate of approximately 1 Hz. With no propulsion on board, the orbit will eventually decay until the spacecraft re-enters the atmosphere after an expected lifetime of at least 12 months.

IV. MicroMAS Science Objectives

Weather forecasting and warning applications rely increasingly on integrated observations from a variety of systems that are asynchronous in time and are nonuniformly spaced geographically. Critical observing system features include rapid update and full volumetric coverage. On regional scales, the combination of satellite data with automated meteorological measurements from aircraft and with a network of ground-based radars and meteorological instruments reporting in real time has been shown to provide enhanced nowcasting and short-term forecasting capabilities. Such capabilities improve severe local storm warnings (including forecasts of storm initiation, evolution, and decay), and they support activities such as construction, road travel, the needs of the aviation system (both civil and military), and recreation. The MicroMAS work focuses on improved rapid-update capabilities provided by a low-earth-orbit satellite constellation.

Oxygen band channels measure blackbody radiation emanating from atmosphleric layers which are many kilometers thick and are centered at altitudes ranging between the surface and the stratosphere, depending on the observed radio frequency [4, 10, 11]. Both the 60- and 118-GHz resonant bands of oxygen exhibit similar ranges of atmospheric transmittances and have corresponding altitude responses, while also having a usefully different response to hydrometeors. The larger particles at the top of any precipitating column reflect the cold radiance of space into the antenna beam, thereby revealing the altitude of the reflecting layer since only frequencies for which the atmosphere is transparent to those altitudes will respond to the precipitation. Cell-top altitude retrievals using 118-GHz oxygen band spectral images were described in [3], where rms accuracies approaching 1 km was suggested; cell-top altitude is related in part to vertical winds and precipitation rates.

A MicroMAS brightness temperature simulation for Super Typhoon Pongsona (Dec. 8, 2002) is shown in Fig. 5. Altitude slicing as elaborated above is revealed in the figure, and intense scattering from cloud ice particles is clearly evident as indicated by marked brightness temperature depressions (deep blue color in the images).

V. Summary

Passive microwave radiometers hosted on CubeSat platforms hold great potential to provide high-fidelity earth science measurements at relatively low cost. Furthermore, constellation architectures enabled by low-cost CubeSats could offer performance substantially surpassing current state-of-the-art.

The MicroMAS-1 mission is on schedule to launch in 2014 on a launch to be provided by NASA.

Acknowledgment

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References

[1] Iturbide-Sanchez, F., S. C. Reising and S. Padmanabhan, "A Miniaturized Spectrometer Radiometer Based on MMIC Technology for Tropospheric Water Vapor Profiling", IEEE Trans. Geosci. Remote Sensing, vol. 45, pp. 2181-2194, Jul. 2007.

[2] Kangaslahti, P., S. T. Brown, T. C. Gaier, D. E. Dawson, D. Harding, L-L. Fu, D. Esteban-Fernandez, "Radiometer Testbed Development for SWOT," NASA Earth Science Technology Forum, Arlington, VA, Jun. 2010.

[3] Lambrigtsen, B., Tanner, A., Gaier, T., Kangaslahti, P., "A Baseline for the Decadal-Survey PATH Mission," IEEE Proc. IGARSS, 2008.

[4] R. Vincent Leslie and David H. Staelin, "NPOESS Aircraft Sounder Testbed – Microwave: Observations of Clouds and Precipitation at 54, 118, 183, and 425 GHz," IEEE Trans. Geosci. Remote Sensing, Vol. 42, No. 10, pg. 2240-2247, October 2004.

[5] "Naval Postgraduate School CubeSat Launcher (NPSCuL)," Naval Postgraduate School Space Systems Academic Group, Nov. 30, 2008.

[6] Pong, C. M., Lim, S., Smith, M. W., Miller, D. W., Villasenor, J. S., and Seager, S., "Achieving high-precision pointing on ExoplanetSat: Initial feasibility analysis," Proc. SPIE 7731(68), 2010.

[7] Reising, S. C., S. T. Brown, P. Kangaslahti, T. C. Gaier, D. E. Dawson, D. J. Hoppe, O. Montes, B. Khayatian, A. Lee and D. Albers, "Advanced Component Development to Enable Low-Mass, Low-Power High-Frequency Microwave Radiometers for Coastal Wet-Tropospheric Correction on SWOT," NASA Earth Science Technology Forum, Arlington, VA, Jun. 2010.

[8] Smith, M. W., Seager, S., Pong, C. M., Villasenor, J. S., Ricker, G. R., Miller, D. W., Knapp, M. E., Farmer, G. T., and Jensen-Clem, R., "ExoplanetSat: Detecting and monitoring exoplanets using a low-cost, CubeSat platform," Proc. SPIE 7731(78), 2010.

[9] Smith, M. W., Miller, D. W., Seager, S., "Enhancing undergraduate education in aerospace engineering and planetary sciences at MIT through the development of a CubeSat mission," Proc. SPIE 7731(171), 2010.

[10] Staelin, D. H. and C. Surussavadee, "Precipitation Retrieval Accuracies for Geo-Microwave Sounders," IEEE Trans. Geosci. Remote Sens., 45(10), 3150-3159, 2007.

[11] Surussavadee, C. and D. H. Staelin, "Global Precipitation Retrievals Using the NOAA/AMSU Millimeter-Wave Channels: Comparisons with Rain Gauges," J. Appl. Meteor. and Climate, 49, 124-135, 2010.