Nanosatellites for Earth Environmental Monitoring

The MicroMAS Project

(Micro-sized Microwave Atmospheric Satellite)


N. Erickson (UMass-Amherst)

13 August 2012

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Outline

- Introduction and Motivation
- Mission Objectives
- Spacecraft Subsystems
  - Structures
  - Avionics
  - Communications
  - Power
  - ADCS
  - Thermal
- Payload: 118-GHz Microwave Spectrometer
- Path Forward
All-Weather, High-Resolution Observations of the Earth’s Atmosphere

AIRS/AMSU (NASA Aqua)
Mosaic of Ascending Orbits on Sep 6, 2002

Drives Numerical Forecasting Models
Sentinel for Severe Weather and Hurricanes
Important Indicator for Trafficability
Microwave Atmospheric Sensing

The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines.

Cloud Penetration

The diagram shows the transmission of frequencies with and without water vapor. The transmission is given in percent and the frequency in GHz. The presence of water vapor reduces the transmission at specific frequencies, indicating different altitudes can be sensed.
MicroMAS Channel Characteristics

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Approximately 1 rev/sec
1-degree sample spacing (Nyquist)
+/- 50-degree swath
Preliminary MicroMAS Simulations
Super Typhoon Pongsona (Dec 8, 2002)
Recent Work & Enabling Technologies

- **Ultra-compact receivers**
  - MIT LL
  - UMass Amherst

- **Multiband antenna systems**
  - MIT LL
  - Northeastern U
  - UMass Amherst

- **Novel calibration methods**
  - MIT LL
  - MIT campus
  - Tufts U

- **Geophysical retrievals and performance analysis**
  - MIT LL
  - MIT Campus

- **Nanosatellite Space Systems Engineering**
  - MIT Campus
  - MIT LL

**Projects**

- DoD 2011/2012
- NASA & NOAA
- NASA & NOAA
- Beaver Works 2012+
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MicroMAS Mission Objectives

Demonstrate Core Element of a Transformative Environmental Monitoring Architecture

- Synoptic sensing with focus on hurricanes and severe weather
- Slightly inclined orbit; ~500-km orbit altitude
- 25-km pixel diameter at nadir (cross-track scan out to ±50°)
- Geolocation error less than 10% of pixel diameter
- 1 K absolute accuracy; 0.3 K sensitivity
- 1-year mission lifetime
- 20 kbps (avg) downlink
- 12 W (avg) power

3U CubeSat

WJB@LL.MIT.EDU
MicroMAS Mission Overview

1. Mission Planning/Pre-Launch Integration
2. Launch as secondary payload
3. On-orbit deployment and initialization
4. Mission Ops - 6 months nominal
5. Fault Recovery/Limited Ops
6. Mission Termination
MicroMAS Radiometer Objectives

- 8 channels near 118.75-GHz oxygen line
- 1 window channel
- Cross-track scan
- Spatial Nyquist sampling
- 2.4-degree FWHM antenna beam
- 95% beam efficiency
- 2 W (avg)
- 0.3 K NEDT
- 1 K calibration accuracy
- Noise diode, earth limb, and cold sky calibration
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MicroMAS 3U Spacecraft

- Deployable solar panels
- Reaction wheel assembly
- Avionics and communication
- Scanning assembly
- Passive microwave spectrometer

10x10x34 cm
4.5 kg, 12 W avg

Body-mounted solar panels not shown
MicroMAS Bus Design

- ADCS Interface Board
- Motherboard
- Battery
- Motor Controller
- Payload
- MAI-400 ADCS Unit
- Radio
- EPS
- Magnetometer
- Scanner Assembly Motor
- (Top) Custom Avionics Interface Board
Avionics Design

- **Bus**
  - **Bottom Interface Board**
    - PDU
    - Line Xcvrs
    - Sun Sensor IF
    - Alternate Gyro
    - Magnetometer
  - **EPS (Clyde Space)**
    - SD Card (2GB)
    - SPI flash (64Mb)
    - Real-time Clock
  - **PIC Motherboard**
    - Motor Controller (Elmo Hornet)
    - RTD Interface
  - **Radio (Espace PTS)**
    - Gyro
    - Magnetometer

- **Payload**
  - **Top Interface Board**
    - PDU
    - Line Xcvrs
    - Motor Controller
    - RTD Interface
  - **Spinner Assembly**
    - Slipring
    - Motor
    - Encoder

- **Legend**:
  - Custom Component
  - COTS Component

- **Reaction Wheels (MAI-400)**
- **Downlink Patch Antenna**
- **Uplink Patch Antenna**

SmallSat - 15
WJB 8/13/12
WJB@LL.MIT.EDU

LINCOLN LABORATORY
Massachusetts Institute of Technology
Thermal Analysis

Temperature [°C], Time = 0 sec
ADCS Block Diagram

Hardware Abbr.
CSS: Coarse Sun Sensor
EHS: Earth Horizon Sensor
MTM: Magnetometer
MTQ: Magnetorquer
RRS: Relative Rotation Sensors
RWA: Reaction Wheel Assy.
SAM: Scanner Assy. Motor

Actuators
- SAM
- RWA
- MTQ

Controller
- Attitude Estimator
- Filter

Control Mode Selection
- ADS Watch Dog

Environment

Satellite Nonlinear Dynamics

System State

Ground Command

Software

Sensors
- RRS
- MTM
- EHS
- IMU
- CSS
Power Subsystem

- Four 2U solar arrays will be mounted on the cubesat bus.
  - PCB Substrate
  - Connected to the EPS via wires.
- Four double-sided 2U solar arrays will be deployed out at a 90 degree angle.
  - PCB Substrate (1.6 mm thickness)
  - Connected to the EPS via wires
- Solar cells
  - GaAs UTJ, 28.3% BOL
  - 22.6 cm^2 for each cell, 4 cells per 2U face
PIC24 MCU Utilization

Microchip PIC24FJ256GA110 on Pumpkin PPM D1
- 32 MHz system clock, 16 MIPS
- Program Memory: 256 kB Flash
  - 24% currently used
- Data Memory: 16 kB SRAM
  - 54% currently used
- I/O Pins Used: 35 / 49
  - ADCS control algorithm included, estimation not included

I2C
1: EPS
2: RTCC
3: Gyro

UART
1: Payload
2: USB Serial Debug
3: Motor Controller
4: Reaction Wheels

SPI
1: SD Card
2: Radio
3: Serial Flash

ADC
1: Temp Sensors
2-10: Unused

Timers
1: Solar Panel Deploy
2: OS Sys Tick
3: Payload Timestamp
4-5: Unused
Communications

- Espace Payload Telemetry System
- Cubesat Form Factor
- RF Board & Digital Processing Board
- On Order: Delivery: November 2012

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<tr>
<td>Standby Power</td>
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</table>
Communications: Ground Segment

- Open Systems of Agile Ground Stations
  - Originally HETE2-dedicated system of three stations around the equator
  - Developed through SBIR effort managed by NASA Ames
  - Available to support cubesat and nanosat missions at low cost

Lat: 8.7167° N  
Long: 167.7333° E

Lat: 4.9347° N  
Long: 52.3303° E

Lat: 1.3667° N  
Long: 103.7500° E
Spacecraft Bus Status

• Engineering Development Model (EDM) complete in Oct 2011
  – Functional testing
  – Vibration testing
  – Thermal testing
  – TVAC testing
  – Air bearing testing

• Flight Model under development
  – Long-lead parts ordered
  – Program at CDR maturity with 10% margin on mass, power, and budget
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MicroMAS – RF Front End

First Stage

Second Stage

To IF (K-conn.)
MicroMAS Tripler, Mixer, and RF Low-noise Preamplifier Modules
MicroMAS second stage EM assembly

Fabrication of flight units underway
Path Forward

- Launch to be provided in late 2013 / early 2014 by NASA

- Concept demonstration illuminating new regions of architecture trade space for future Earth Science missions
  - All-weather sounding of highly dynamic phenomena, including convective storms, hurricanes, etc.
  - Studies of the hydrologic cycle
    - Vapor, liquid, ice; precipitation
  - Studies of the diurnal cycle
Backup Slides
The Nanosatellite Advantage

• Proliferation of the CubeSat standard (10x10x10 cm, 1 kg, 1W cubes)
  – Inexpensive COTS subsystems readily available
  – Launch opportunities on a variety of vehicles
  – Expanding base of prior art from the academic community

• Several successful missions with non-trivial science return
  – Radio Aurora Explorer (RAX), UofM, space weather mission (NSF)

• Sensor systems now practical at CubeSat scales
  – Driven in some cases by communication/consumer electronics
  – Passive microwave systems particularly well-suited

• New nanosatellite capabilities/infrastructure rapidly emerging
  – Space-to-ground communications exceeding 1Mbps
  – Sophisticated solar arrays
  – Propulsion systems
Beaver Works III: Micro-sized Microwave Atmospheric Satellite

- Micro-sized Microwave Atmospheric Satellite
  - Spacecraft bus developed by campus
  - Payload developed by Lincoln-led team

- New Technology Development
  - Ultra-compact receivers (Lincoln)
  - CubeSat spacecraft bus (campus)

- Lead: Professor David Miller
  - 2010 Fall (Design focus): 16.851 Satellite Engineering
    - 13 on MicroMAS team
  - 2011 Spring (Build focus): 16.89 Space Systems & 16.83 (undergrad capstone)
    - Six on MicroMAS team, plus post-doc and staff

Pico-satellite remote sensing of hurricanes severe weather

- 30x10x10 cm
- ~10 W average
- ~30kbps
- ~4 kg
System Block Diagram
Power Subsystem

- EPS connected to battery via headers and connected in the CubeSat bus.
- EPS:
  - Contains 3.3V, 5V, 12V, and Unregulated V buses.
- Battery:
  - Li-Ion
  - 20 Wh
Software

• **Salvo Real Time Operating System**
  - Designed for minimal memory use
    • Program: 1665 Bytes (0.6 % on PIC24)
    • Data: 46 Bytes (small)
  - Event-driven cooperative multitasking RTOS
    • 16 separate priority levels supported
  - Task intercommunication & resource management
    • Semaphores
    • Messages
    • Message queues
    • Event flags
  - Timer functions
    • Delays
    • Timeouts
    • Cyclic timers
Software

- **Green Transition**: Nominal Concept of Operations
- **Red Transition**: Fault induced
- **Blue Transition**: Explicit ground station command
## Communications Data Budget

### Max P/L Data Rate to Bus & Required Storage Onboard Bus

#### Assume Constant 19.2 kbps

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<td>104.50</td>
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<td>102.50</td>
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</table>

*Req P/L Rate is the information rate output by the P/L assuming a constant 19.2 kbps output rate from the P/L.*

**Max P/L (bps) is the maximum amount of payload data (information) per second that can be continuously sent to the bus and downloaded without interruption.

***Req. Storage (MB) is the maximum amount of payload mission data that needs to be held for download at any given time assuming continuous payload operation at the Max P/L Rate.

**Assumptions:**
- MicroMAS Information Downlink Rate: 347 kbps // Collection occurs during downlink time // NO COMPRESSION
- Analysis shown is for 30 day period // Link Constraint: Eb/No > 7.5 dB, Elevation > 5°
# Mass Summary

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<th>CBE (g)</th>
<th>Margin (g)</th>
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**Total CBE Mass** 3980

**Maximum without waiver** 4000

**Margin without waiver** 0.5%

**Maximum with waiver*** 4500

**Margin with waiver** 13.1%

*Based on understood maximum P-POD rating; depends on launch vehicle selection*
## Power Summary

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<th>Eclipse (W)</th>
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<tbody>
<tr>
<td>ADCS</td>
<td>2.324</td>
<td>2.324</td>
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<tr>
<td>Comm</td>
<td>0.933</td>
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<tr>
<td>EPS</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>Scanner Assembly</td>
<td>0.880</td>
<td>0.880</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.004</td>
<td>0.282</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.385</td>
<td>0.385</td>
</tr>
<tr>
<td>Payload</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Battery Charging*</td>
<td>3.761</td>
<td>--</td>
</tr>
<tr>
<td>Total CBE Average Nominal Power Draw (W)</td>
<td>9.8 W</td>
<td>6.5 W</td>
</tr>
<tr>
<td>Total Required at Source**</td>
<td>10.9 W</td>
<td>3.2 W-hr</td>
</tr>
<tr>
<td>Average Available at Source*** (EOL)</td>
<td>11.9 W</td>
<td>4.0 W-hr</td>
</tr>
<tr>
<td>Mission Allowable Cost Growth Over CBE (W)</td>
<td>1.1 W</td>
<td>0.7 W-hr</td>
</tr>
<tr>
<td>Mission Allowable Cost Growth Over CBE (%)</td>
<td><strong>10%</strong></td>
<td><strong>24%</strong></td>
</tr>
</tbody>
</table>

*Factor of 1.1 for battery charge inefficiency

**90% efficiency between panel and BCR, assuming 32-minute eclipse

***Max 20% battery depth of discharge
MicroMAS – IF Processor

Multiplexer 9-ch, 18-30 GHz
MIT-LL
LTCC

To RF Front-end (K-conn.)
MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department

First stage: RF preamplifier and noise diode
1.01” x 0.80” x 0.75”

Second stage: RF amplifier, mixer, and IF preamp
0.96” x 0.76” x 0.75”

RF in: 108-119 GHz
IF out: 18-29 GHz
MicroMAS LTCC SIW Filters

- Substrate Integrated Waveguide (SIW) filters offer lower insertion loss and better filter shape factor than stripline interdigital filters due to their higher $Q (> 500)$ resonators
  - Filters are realized in two-layer LTCC stack with via “fences” creating the waveguide side walls
  - Via “posts” control coupling in between resonator cavities

[HFSS Model with diagram]

[HFSS Simulation with graphs]

SmallSat - 40
WJB 8/13/12
WJB@LL.MIT.EDU
Radiometer Status

- Antenna subassembly complete and tested
  - Performance requirements achieved

- Receiver front-end engineering model complete
  - Prof. Neal Erickson (UMass-Amherst)
  - High-performance RF LNA
  - Electronic calibration
  - Very low size, weight, and power

- Receiver IF processor in development
  - Design complete
  - Ultra-compact, high-performance

- Radiometer control and data handling prototype complete