
W. Blackwell, MIT Lincoln Laboratory

J. Pereira, NOAA NESDIS

August 8, 2015

This work is sponsored by the National Oceanic and Atmospheric Administration under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
Outline

• Introduction and Motivation
• Foundational Work: MicroMAS-1, MicroMAS-2, and MiRaTA
• The Next Step: EON-MW
• Summary

MicroMAS = Microsized Microwave Atmospheric Satellite
MiRaTA = Microwave Radiometer Technology Acceleration
EON-MW = Earth Observing Nanosatellite-MicroWave
Global Observing System (GOS) For Environmental Monitoring

Source: World Meteorological Organization
Satellites Provide the Most Forecast Skill

Impact of GOS components on 24-h ECMWF Global Forecast skill
(courtesy of Erik Andersson, ECMWF)

- Microwave sounding
- Infrared sounding
- Airborne obs
- GPS radio occultation
- Weather balloon
- Radar
- Weather balloon
- Water vapor sounding
- Infrared imaging
- Infrared sounding
- Drifting buoy
- Airborne obs
- Infrared sounding
- Infrared imaging
- Water vapor sounding
- Microwave imaging
- Infrared imaging
- Microwave imaging
- Infrared imaging
- Microwave imaging
- Infrared imaging
- Infrared imaging
- Infrared imaging
- Infrared imaging
- Ozone

Passive microwave observations have the highest impact

Satellite data now account for most of the skill

Bigger is better
Need: All-Weather, High-Resolution, Persistent 3-D Observations of the Earth’s Atmosphere

Advanced Technology Microwave Sounder
Mosaic of Orbits on Nov 10, 2011

Drives Numerical Forecasting Models
Monitoring of Severe Weather and Hurricanes
Hydrologic and Climate Studies
Traditional Approach: Big Satellites

Suomi NPP Satellite
(Launched Oct 2011)

Visible/Infrared Imager Radiometer Suite (VIIRS)
Cross-track Infrared Sounder (CrIS)
Cloud and Earth Radiant Energy System (CERES)
Advanced Technology Microwave Sounder (ATMS)
Ozone Mapping and Profiler Suite (OMPS)

Current Approaches Unsustainable

- Expensive
- Long development cycles
- Very high failure impact

NPP: National Polar-orbiting Partnership

2100 kg

NASA/GSFC
Focus: Microwave Sounding

Suomi NPP Satellite (Launched Oct 2011)

23.8-GHz Brightness Temperature (K)

- Microwave sensor amenable to miniaturization (10 cm aperture)
- Broad footprints (~50 km)
- Modest pointing requirements
- Relatively low data rate

NPP: National Polar-orbiting Partnership

Advanced Technology Microwave Sounder (ATMS)

100 kg, 100 W

2100 kg

NASA/GSFC
**New Approach for Microwave Sounding**

Suomi NPP Satellite (Launched Oct 2011)

- **Advanced Technology Microwave Sounder (ATMS)**
  - 100 kg, 100 W

MicroMAS Satellite
(Launched Jul 2014)

- **4.2 kg, 10 W, 34 x 10 x 10 cm**

- Microwave sensor amenable to miniaturization (10 cm aperture)
- Broad footprints (~50 km)
- Modest pointing requirements
- Relatively low data rate

**Perfect fit for a cubesat!**
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MicroMAS = Microsized Microwave Atmospheric Satellite
MiRaTA = Microwave Radiometer Technology Acceleration

**MicroMAS-1**
- 3U cubesat with 118-GHz radiometer
- 8 channels for temperature measurements
- July 2014 launch, March 2015 release; validation of spacecraft systems; eventual transmitter failure

**MicroMAS-2**
- 3U cubesat scanning radiometer with channels near 90, 118, 183, and 206 GHz
- 12 channels for moisture and temperature profiling and precipitation imaging
- Two launches in 2016

**MiRaTA**
- 3U cubesat with 60, 183, and 206 GHz radiometers and GPS radio occultation
- 10 channels for temperature, moisture, and cloud ice measurements
- Nov 2016 launch on JPSS-1
Earth Observing “Nanosatellite” (EON-MW)

**MicroMAS-1**
- 3U cubesat with 118-GHz radiometer
- 8 channels for temperature measurements
- July 2014 launch, March 2015 release; validation of spacecraft systems; eventual transmitter failure

**MicroMAS-2**
- 3U cubesat scanning radiometer with channels near 90, 118, 183, and 206 GHz
- 12 channels for moisture and temperature profiling and precipitation imaging
- Two launches in 2016

**MiRaTA**
- 3U cubesat with 80, 183, and 206 GHz radiometers and GPS radio occultation
- 10 channels for temperature, moisture, and cloud ice measurements
- Nov 2016 launch

**EON-MW**
- 12U satellite with 22 channels to replicate ATMS
- High-performance, radiation tolerant design; >two-year mission life
- 2018/2019 launch
- 20 kg; 50 W
Successful MicroMAS Release
March 4, 2015

Micro-sized Microwave Atmospheric Satellite
(Released from ISS 3/4/2015)

4.2 kg, 10 W, 3U (34 x 10 x 10 cm)

MicroMAS provides high-resolution radiometric imagery for improved weather forecasting

Collaborative mission between MIT LL and MIT Campus (Aero/Astro)
MIT Campus: Spacecraft bus
MIT LL: Payload and system I&T

MicroMAS transmitter fault occurred two weeks into mission.
No payload data downloaded to date.
The MicroMAS CubeSat

- 4.25 kg total mass
- 10 W avg power
- 16 kbps max data rate
- 0.5° pointing accuracy
Timely development of COTS parts was a major program challenge
MicroMAS Payload (Side View)
118-GHz Spectrometer

IF Processor
Dielectric Resonator
Oscillator
Frequency Tripler
Mixer
Preamplifier/Noise-diode Module
Waveguide
Feed-horn

10x10x10 cm, <1 kg, <2 W

Approximately a factor of 100 reduction in size, weight, and power relative to the current state of the art
MicroMAS Flight Unit
Radiometer Performance (Accuracy and Precision) is State-of-the-ART

ATMS equivalent spot size; 250 K payload temperature
Successful Checkout of Avionics, Power, Attitude Determination, Thermal, and Communications Subsystems

Magnitude of tumble: approx. 7 deg/sec or 52 sec/rev
Earth Horizon Sensor Readings

Side-looking EHS is on the same side as panel YN

Room Temp ~1400 counts

EHS A (Side) Measurements

EHS B (AntiRam) Measurements

Sun

Space
MicroMAS-2
Late 2016 Launch

Spacecraft

- 3.8 kg total mass
- 9.1 W avg power
- 16 kbps max data rate
- 0.2° pointing accuracy

Payload

- 12 Channel (90-206 GHz)
- Scanning Radiometer
- Payload Cube (30 RPM)
- <3 W avg power
## MicroMAS-2 Design Changes

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Delta from MicroMAS1</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>Next gen payload 12 channel, quad-band</td>
<td>Better science</td>
</tr>
<tr>
<td>Avionics</td>
<td>More flexible executive code Bug fixes in ADCS code</td>
<td>Improved performance and stability</td>
</tr>
</tbody>
</table>
| Comm          | - Next gen Cadet high-rate radio  
- Backup low-rate radio on motherboard (MB)                                            | Backup for Cadet radio failure  
- Recover ADCS anomaly  
- Partial data option  
- Use as beacon                                                                 | Improved reliability |
| Power         | 4@ 3U panels, Deploy to 135 °                                                      | Supplies more power             |
| Launch        | ISRO PSLV ISIS Quad pack                                                            | Schedule availability           |
|               |                                                                                     | Survive higher launch loads     |
| Orbit         | ~ 500 km, 98° sun synch                                                            | Longer orbit life               |
|               |                                                                                     | Operate in different thermal conditions |
| Ground segment| Beacon Improved ground station code                                                 | Better performance and reliability |
|               |                                                                                     | Beacon freq approval            |
MicroMAS-2 Payload

**Ultracompact W/F/G band Radiometer**
- Window 2 ch (90, 207 GHz)
- F band 9 ch (115-119 GHz)
- G band 3 ch (183±1, 3, 7 GHz)
MicroMAS-2 Flight Unit

Receiver Temperature

- 700 K near 183 GHz
- 2000 K at 207 GHz
Microwave Radiometer Technology Acceleration (MiRaTA)

- 3U (10 cm x 10 cm x 34 cm) tri-band radiometer
  - Temperature, water vapor, and cloud ice
  - Absolute calibration better than 1 K
- Calibration proof of concept using limb measurements and GPS-RO
  - 60, 183, and 206 GHz; OEM628 GPS
- Funded by NASA Earth Science Technology Office (ESTO)
- $3.6M
- Launch in late 2016

- 4.5 kg total mass
- 10 W avg power
- 10 kbps max data rate
- 0.5° pointing accuracy
MiRaTA Radiometer System

- Antenna Reflector
- V-band feed-waveguide assembly
- V-band Receiver Front End
- Dielectric Resonant Oscillator
- G-band Calibration Module
- G-band Mixer Module
- G-band feed-waveguide assembly
- Reflector Shroud
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Earth Observing Nanosatellite

- All the features of MicroMAS (wide swath) and MiRaTA (sensitivity)
- 12U cubesat (21x21x34 cm)
- Larger aperture (improved spatial resolution)
- 23/31 + 50-60/88 + 166/183 GHz 22 ATMS-equivalent channels
- 2-3 year mission lifetime
- Data downlink using S-band
EON Spacecraft Requirements

• Pointing
  – 0.1-degree (3-sigma) pointing knowledge
  – 0.5-degree (3-sigma) pointing control
  – Expected performance: ~Five times better than requirement

• Power
  – 48 W (avg) power required
  – Solar array to provide 60 W (avg) at end of life (three years)

• Communications
  – Average data rate 50 kbps
  – S-band radio downlinks all data at 100 seconds per orbit

• Lifetime
  – Two years (threshold); >three years (goal)
  – Rad hard/tolerant parts used; TID below 10 krad at three years
  – Scanning assembly lifetime tested to >50M revs (>three years)
EON Payload

- G-Band Antenna Feed
- V-Band Receiver Front End
- Reflect Shroud
- K-ka Band Antenna Feed
- K-Ka/W Band RFE
- Scanner Assembly
- DRO
- K-Ka/W Band IFP
EON Scanning Assembly Motor

Space Qualified Aeroflex Zero-Cogging Brushless DC Motor

- Part no: Z-0250-050-3-104
- 2.5in O.D., 1.5in I.D., 1in height
- Mass: 163g
- Nominal operating power: 0.020 W
- Lifetime tested to >50M rotations (> 3yr EON life)
- Redundant windings

Image courtesy of Aeroflex, Inc

Note: Image of generic Aeroflex BLDC motor
## EON Avionics

### Andrews Space 100 Series

<table>
<thead>
<tr>
<th>Model 160 Flight Computer</th>
<th>Processor</th>
<th>Xilinx Virtex 4FX with dual PPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>64 MB of SDRAM, 2 GB of Flash, 1 Mb of EEPROM (x3)</td>
<td></td>
</tr>
<tr>
<td>Operating System</td>
<td>Real Time Linux</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model 140 Communication Card</th>
<th>Supported Interfaces</th>
<th>Ethernet, SPI, I2C, RS-232, RS-422, RS-485, 1553B, JTAG</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Model 130 Electrical Power System</th>
<th>Solar Panel Interface</th>
<th>6 Battery Control Regulators, Peak Power Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Interface</td>
<td>7.2 V Lithium Ion</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model 120 Instrumentation Card</th>
<th>A/D Converter</th>
<th>16-bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/O</td>
<td>16 Analog Inputs, 2 Analog Outputs, 8 Opto-Isolated Digital I/O</td>
<td></td>
</tr>
</tbody>
</table>

| Model 110 Motor/Valve Driver Cards | Driver Circuit | 36 Channels/ 12 per card (2A/channel) |
EON GNC Components

Sinclair star tracker
Attitude, pointing & Angular Rates

Sensonor IMU
Angular Rates & Linear Accelerations

140 serial interface
Control Software - Avionics Suite 160 Processor

120/130 analog interface

110 Driver Card

Pointing and Position Commands

Sinclair reaction wheels
Vehicle stabilization & Pointing
Torque: > 5 mNm @ 28 V
Momentum: 60 mNm-sec @ 6500 RPM

Millenium Space Systems reaction wheel
Vehicle stabilization & Pointing
Torque: > 100 mNm @ 28 V
Momentum: 1000 mNm-sec @ 6500 RPM

Sun Sensor
120 deg FOV

Torque Rods
Vehicle stabilization
Momentum dumping
Summary and Path Forward

- Nanosatellite sounders could provide unprecedented performance at relatively low cost and risk
- MicroMAS missions demonstrate core technologies
- Pre-launch testing has indicated excellent performance
  - 40 RPM scanning; 2W payload power consumption
  - Accuracy and NEDT meet requirements
- MicroMAS-2: Commercially procured launch for Fall 2016
- Microwave Radiometer Technology Acceleration (MiRaTA)
  - Next generation follow-on with multiple bands (temp. and water)
  - 2016 launch on JPSS-1
- EON-MW could potentially demonstrate ATMS-like quality on a low-cost CubeSat
  - If proven, this would be a revolutionary advancement!
Backup Slides
### EON Mass Budget
(Mostly Measured Values)

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave payload</td>
<td>4</td>
</tr>
<tr>
<td>Rotary motor/slipring</td>
<td>0.47</td>
</tr>
<tr>
<td>GPS antennas</td>
<td>0.5</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.472</td>
</tr>
<tr>
<td>Batteries</td>
<td>1.8</td>
</tr>
<tr>
<td>Small reaction wheels</td>
<td>0.45</td>
</tr>
<tr>
<td>Large wheel</td>
<td>0.97</td>
</tr>
<tr>
<td>Torque bars</td>
<td>1</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>0.2</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>0.05</td>
</tr>
<tr>
<td>Star Tracker</td>
<td>0.085</td>
</tr>
<tr>
<td>Deployable solar array</td>
<td>2.45</td>
</tr>
<tr>
<td>Structure (Bus)</td>
<td>5</td>
</tr>
<tr>
<td>Cables and connectors</td>
<td>1</td>
</tr>
<tr>
<td>GPS receiver</td>
<td>0.25</td>
</tr>
<tr>
<td>Radio (L-3 Cadet)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18.997</strong></td>
</tr>
</tbody>
</table>

20% Margin (24 kg max)
Dose depth curve for a 5 year LEO polar mission (800km, 98deg)

Designing for 10 krad TID

# EON Payload Power Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
<th>Duty Cycle (%)</th>
<th>Avg Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G RFE</td>
<td>2.4</td>
<td>100</td>
<td>2.4</td>
</tr>
<tr>
<td>V RFE</td>
<td>1.9</td>
<td>100</td>
<td>1.9</td>
</tr>
<tr>
<td>K/Ka RFE</td>
<td>2.125</td>
<td>100</td>
<td>2.125</td>
</tr>
<tr>
<td>W RFE</td>
<td>0.375</td>
<td>100</td>
<td>0.375</td>
</tr>
<tr>
<td>V Digital</td>
<td>4.375</td>
<td>50</td>
<td>2.188</td>
</tr>
<tr>
<td>V PDRO</td>
<td>2.875</td>
<td>100</td>
<td>2.875</td>
</tr>
<tr>
<td>Thermal control</td>
<td>6.25</td>
<td>100</td>
<td>6.25</td>
</tr>
<tr>
<td>PIM</td>
<td>1.25</td>
<td>100</td>
<td>1.25</td>
</tr>
<tr>
<td>IFP</td>
<td>2.8125</td>
<td>100</td>
<td>2.8125</td>
</tr>
<tr>
<td>GPSRO</td>
<td>2.5</td>
<td>20</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>22.675</strong></td>
</tr>
</tbody>
</table>

Power regulation inefficiencies included above.
# EON Bus Power Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
<th>Duty Cycle (%)</th>
<th>Avg Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortex 110</td>
<td>1.3</td>
<td>100</td>
<td>1.3</td>
</tr>
<tr>
<td>Cortex 120</td>
<td>1.5</td>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>Cortex 130</td>
<td>3.3</td>
<td>100</td>
<td>3.3</td>
</tr>
<tr>
<td>Cortex 150</td>
<td>2</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Cortex 160</td>
<td>10</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>ST-16</td>
<td>0.5</td>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>RW3-0.60</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>RW3-1.0</td>
<td>2</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>Scanning assembly</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Comm</td>
<td>10</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>IMU</td>
<td>1.5</td>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>24.6</strong></td>
</tr>
</tbody>
</table>

Power regulation inefficiencies included above.
EON Power Budget

- Payload: 22.7 W
- Bus: 24.6 W
- Total: 47.3 W

- Available from solar array at end-of-life (11:30 orbit): 55 W

- Margin: 16 %
Solar Array Based on ISARA Design
Available from Pumpkin, Inc.

Stowed Configuration

Deployed Configuration

Triple folded side panels flip out

Panels fully unfolded

Solar Array Flips up