Nanosatellites for Earth Environmental Monitoring

The MicroMAS Project

(Micro-sized Microwave Atmospheric Satellite)

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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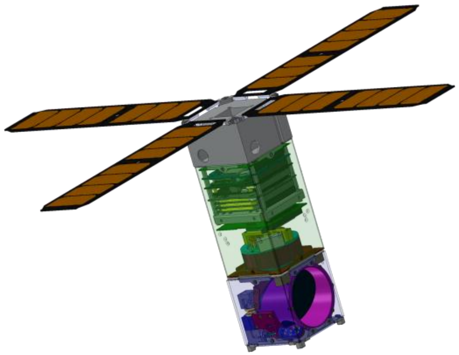
Outline

- Introduction and Motivation
- Mission Objectives
- Spacecraft Subsystems
  - Structures
  - Avionics
  - Communications
  - Power
  - ADCS
  - Thermal
- Payload: 118-GHz Microwave Spectrometer
- Path Forward



MicroMAS
3U CubeSat

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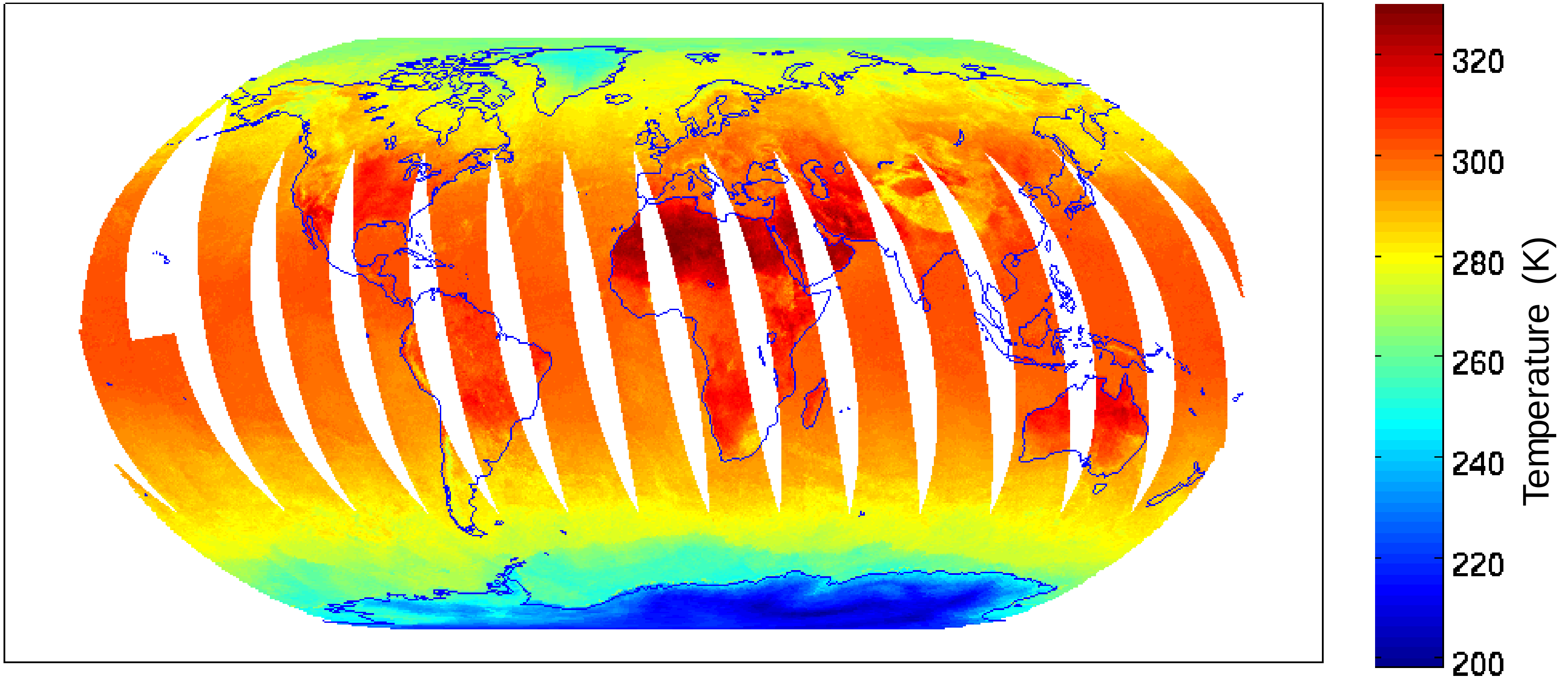
All-Weather, High-Resolution Observations of the Earth’s Atmosphere

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

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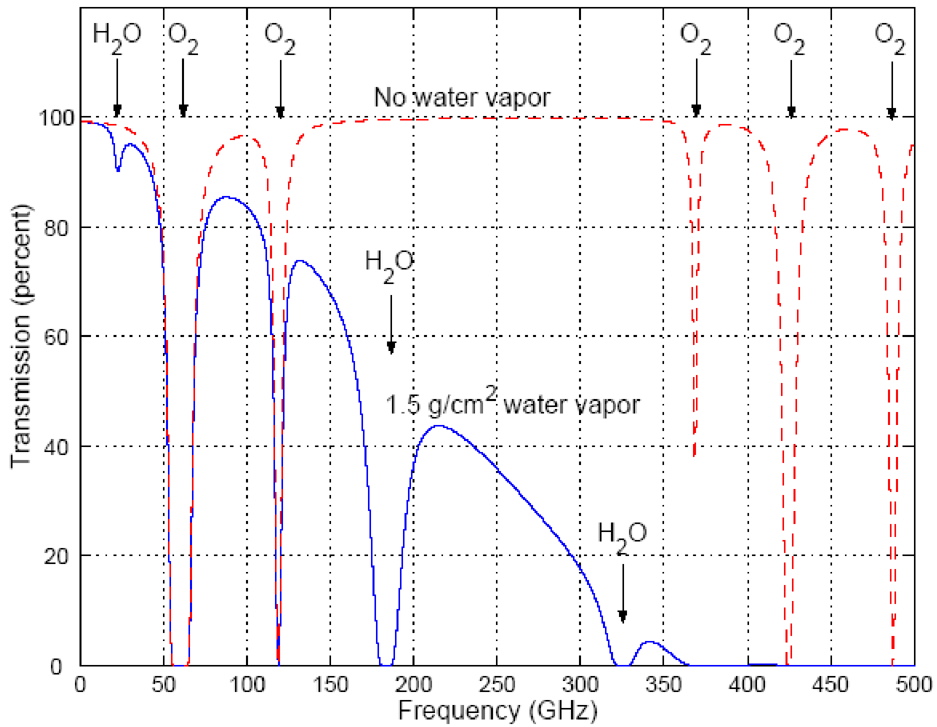
Cloud Penetration



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

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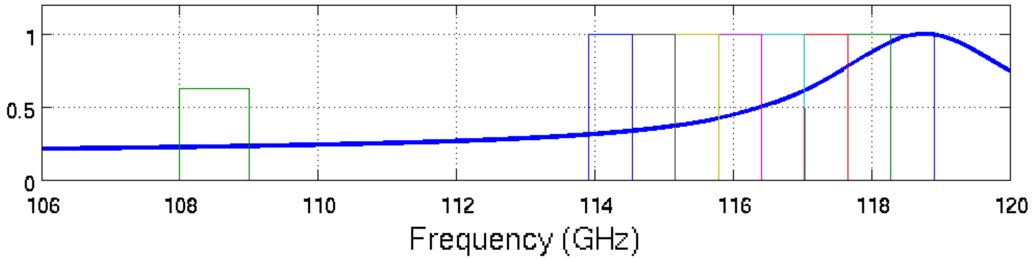
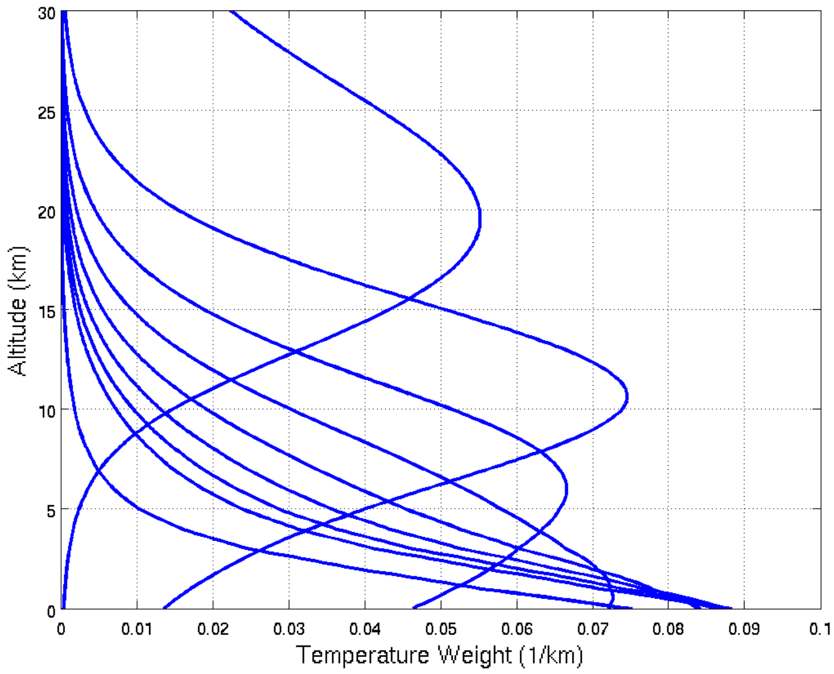
MicroMAS Channel Characteristics

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





Approximately 1 rev/sec
1-degree sample spacing (Nyquist)
+/- 50-degree swath

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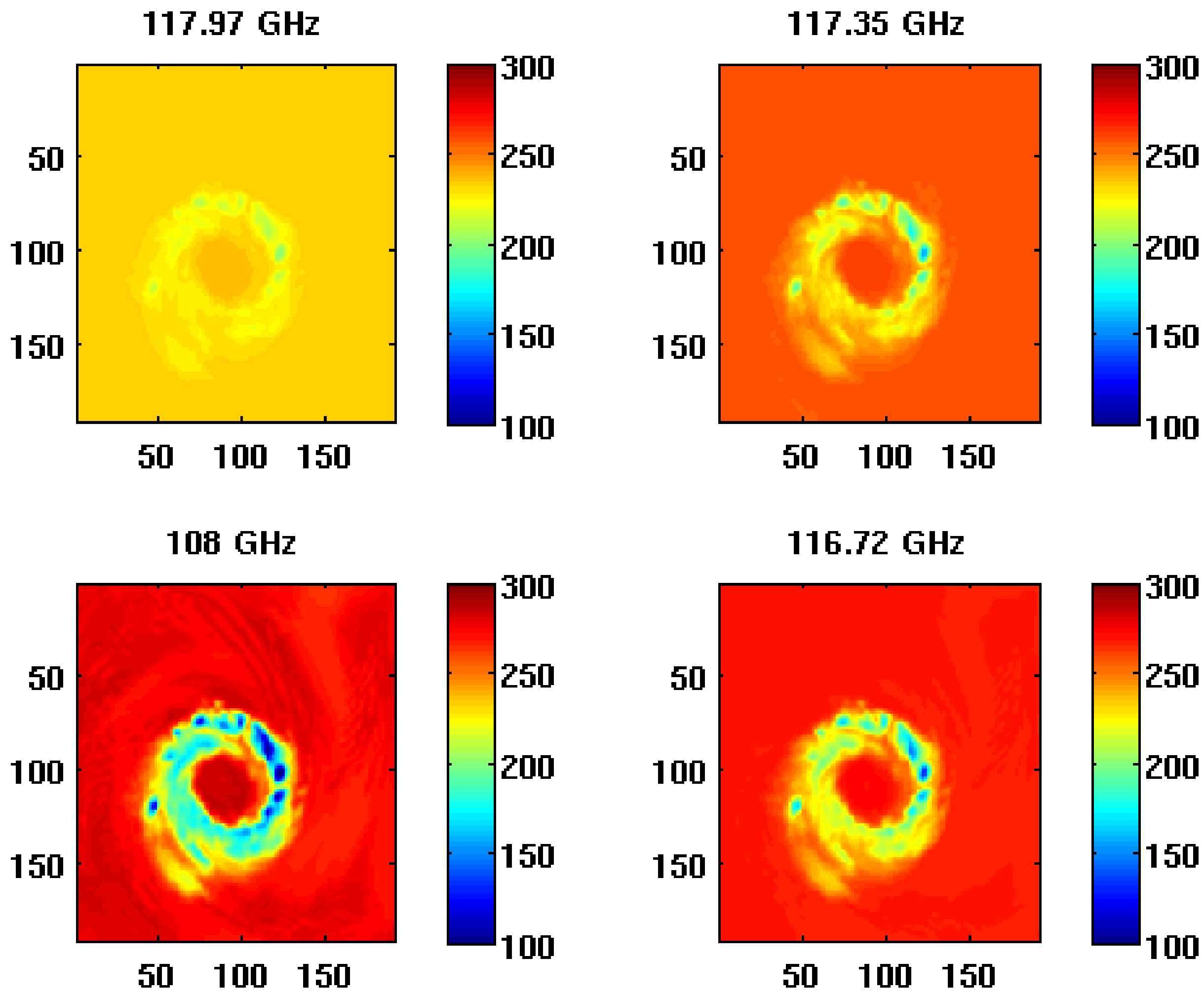
Preliminary MicroMAS Simulations
Super Typhoon Pongsona (Dec 8, 2002)



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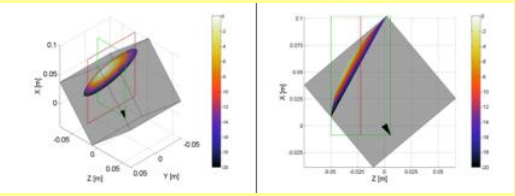
Recent Work & Enabling Technologies

Ultra-compact receivers

MIT LL
UMass Amherst

DoD 2011/2012

Multiband antenna systems



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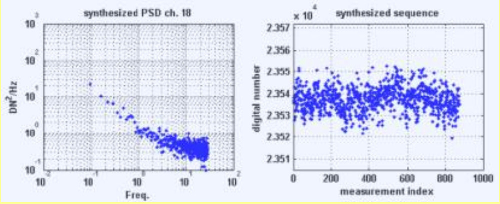
Northeastern U
UMass Amherst

Novel calibration methods



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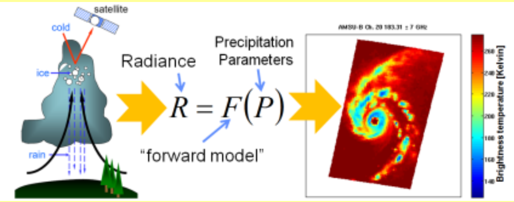
MIT campus
Tufts U

NASA & NOAA

Geophysical retrievals and performance analysis



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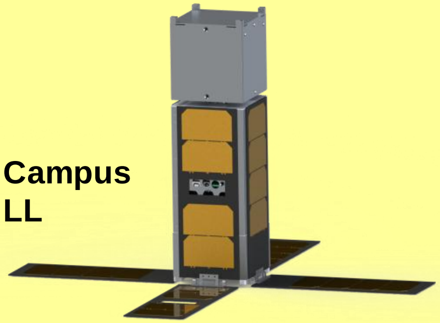
MIT Campus

NASA & NOAA

Nanosatellite Space Systems Engineering



MIT Campus
MIT LL

Beaver Works 2012+

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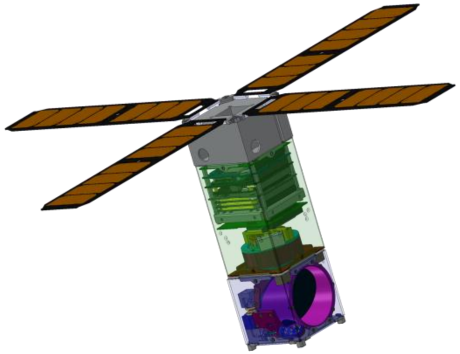
MicroMAS Mission Objectives

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

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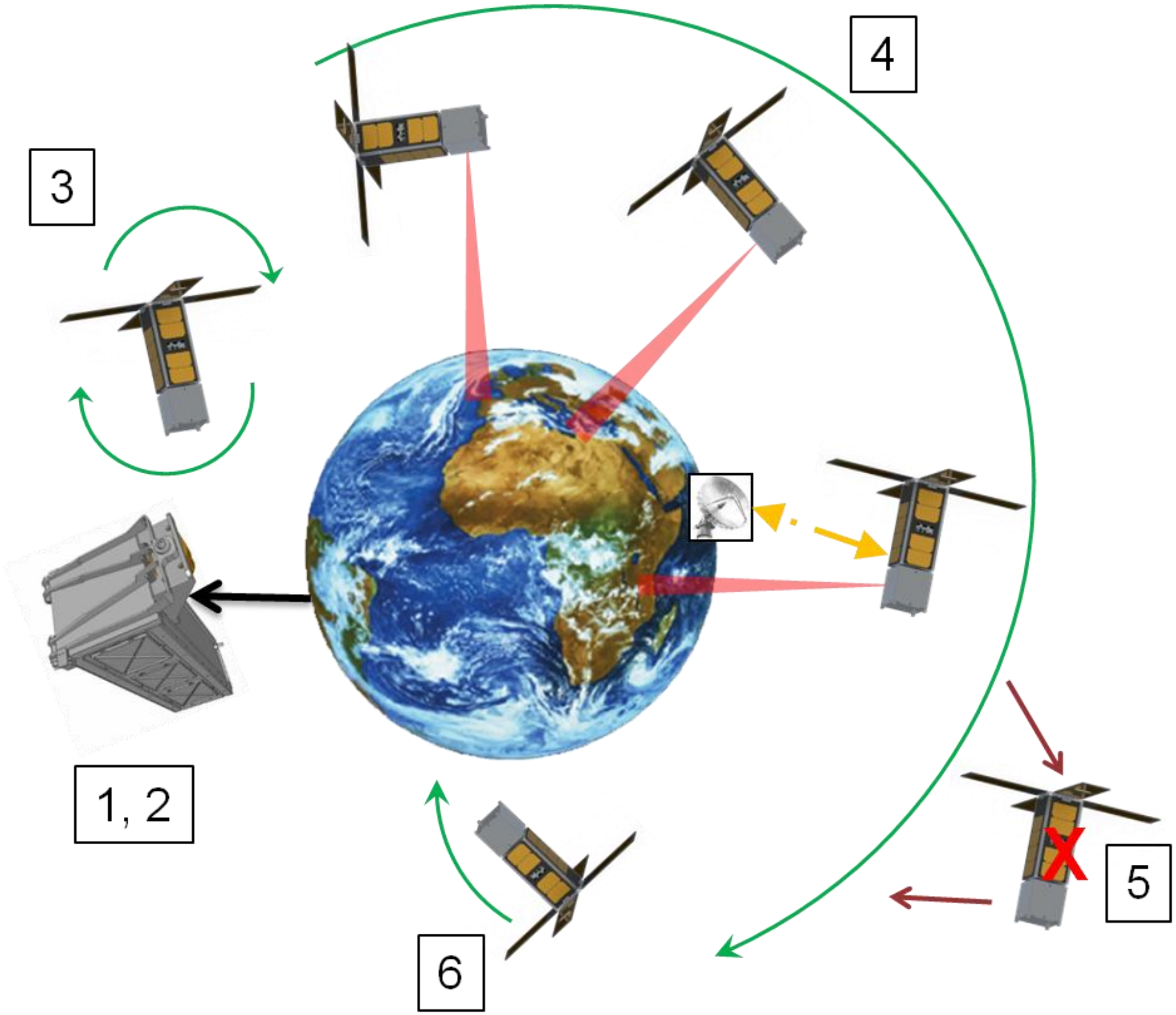
MicroMAS Mission Overview

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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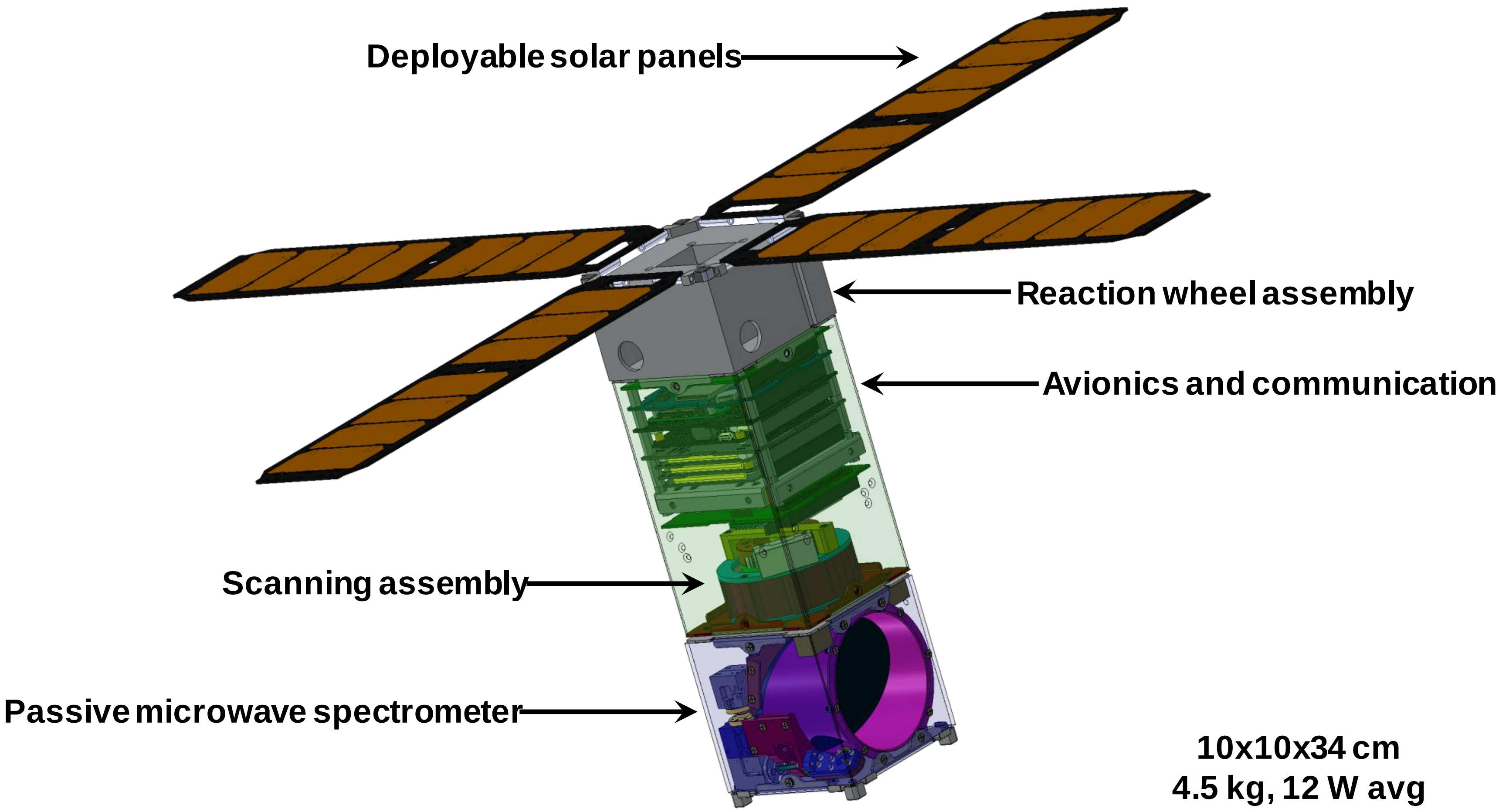
MicroMAS 3U Spacecraft



10x10x34 cm
4.5 kg, 12 W avg

Body-mounted solar panels not shown

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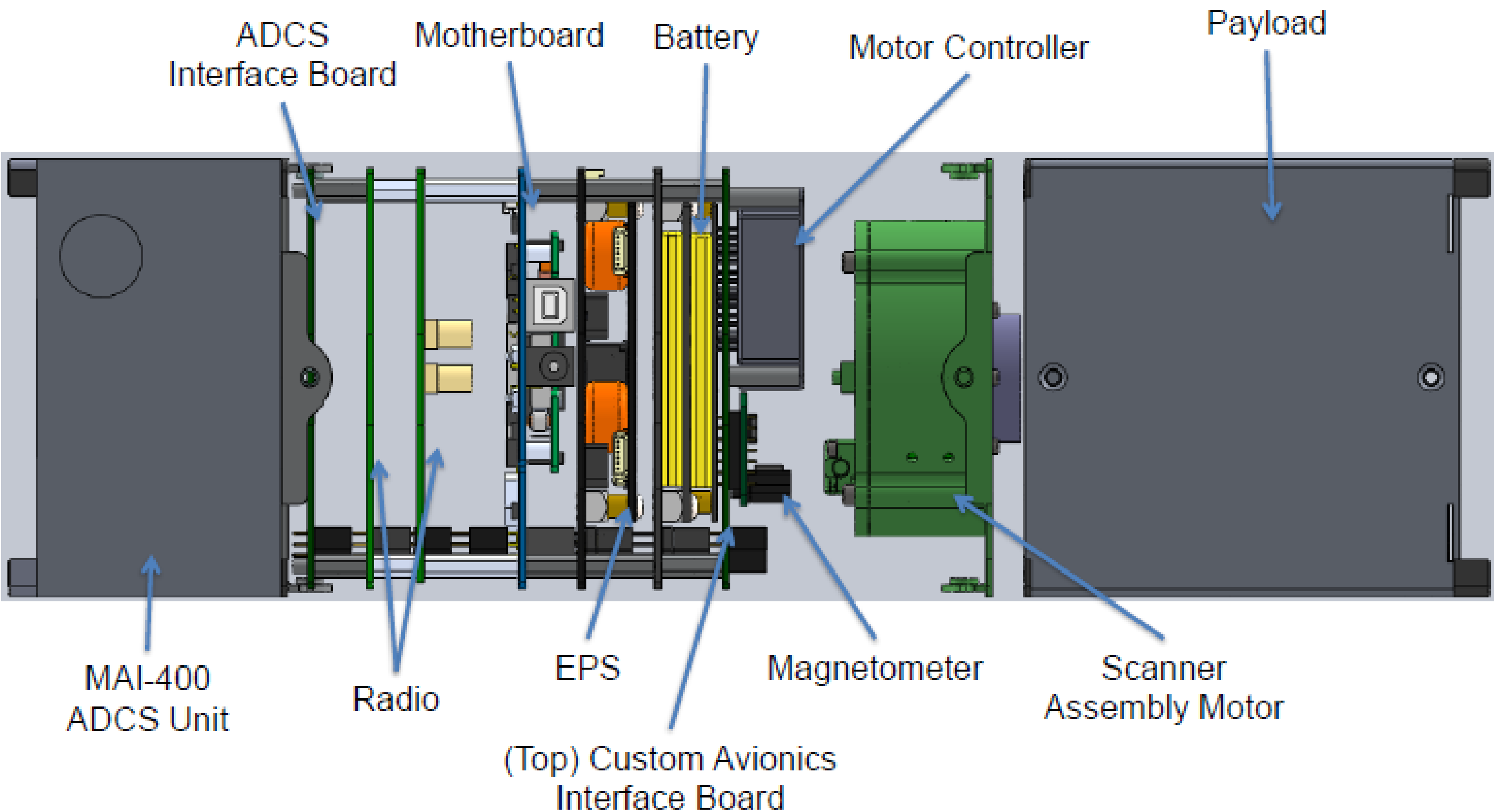
MicroMAS Bus Design



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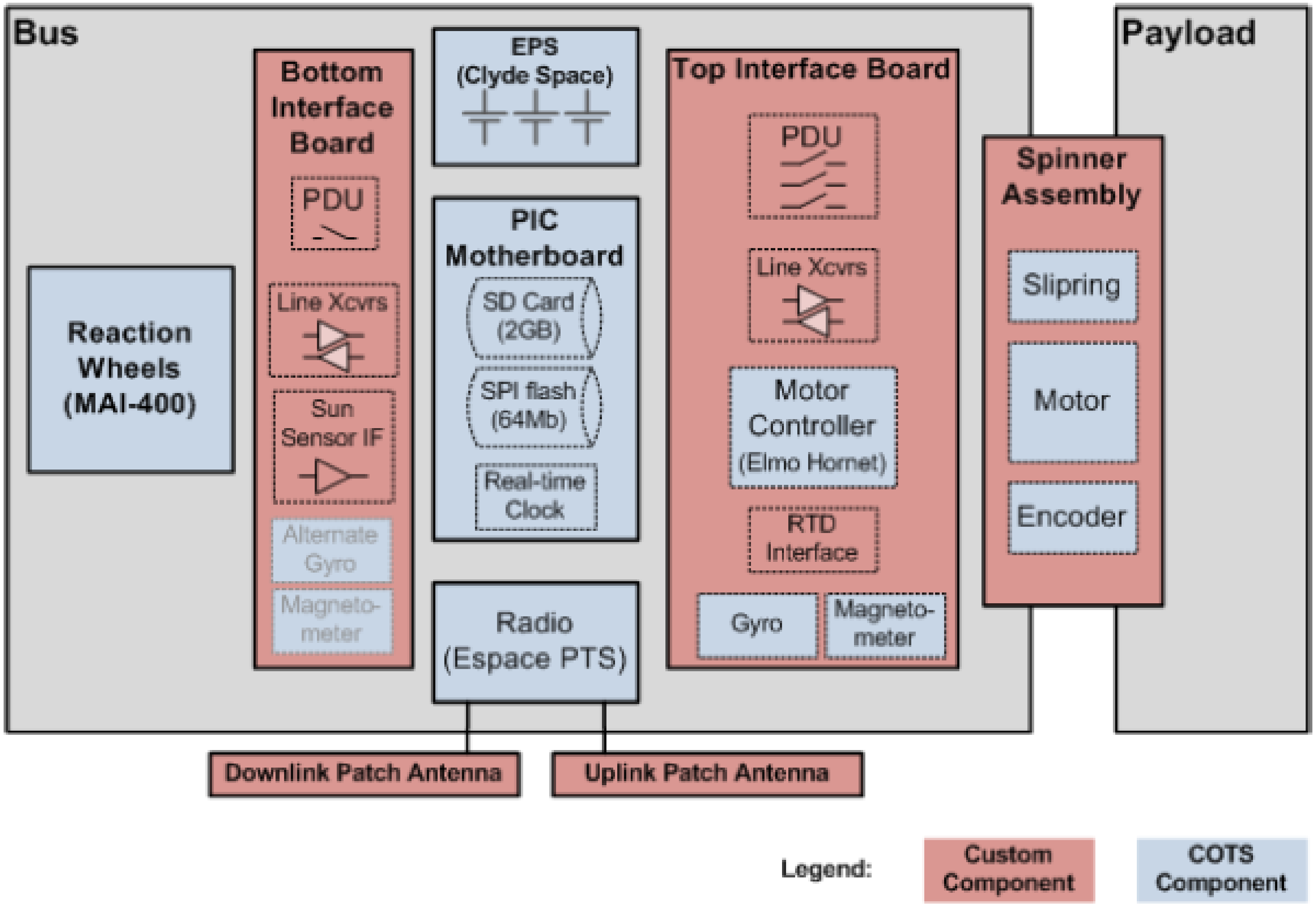
Avionics Design



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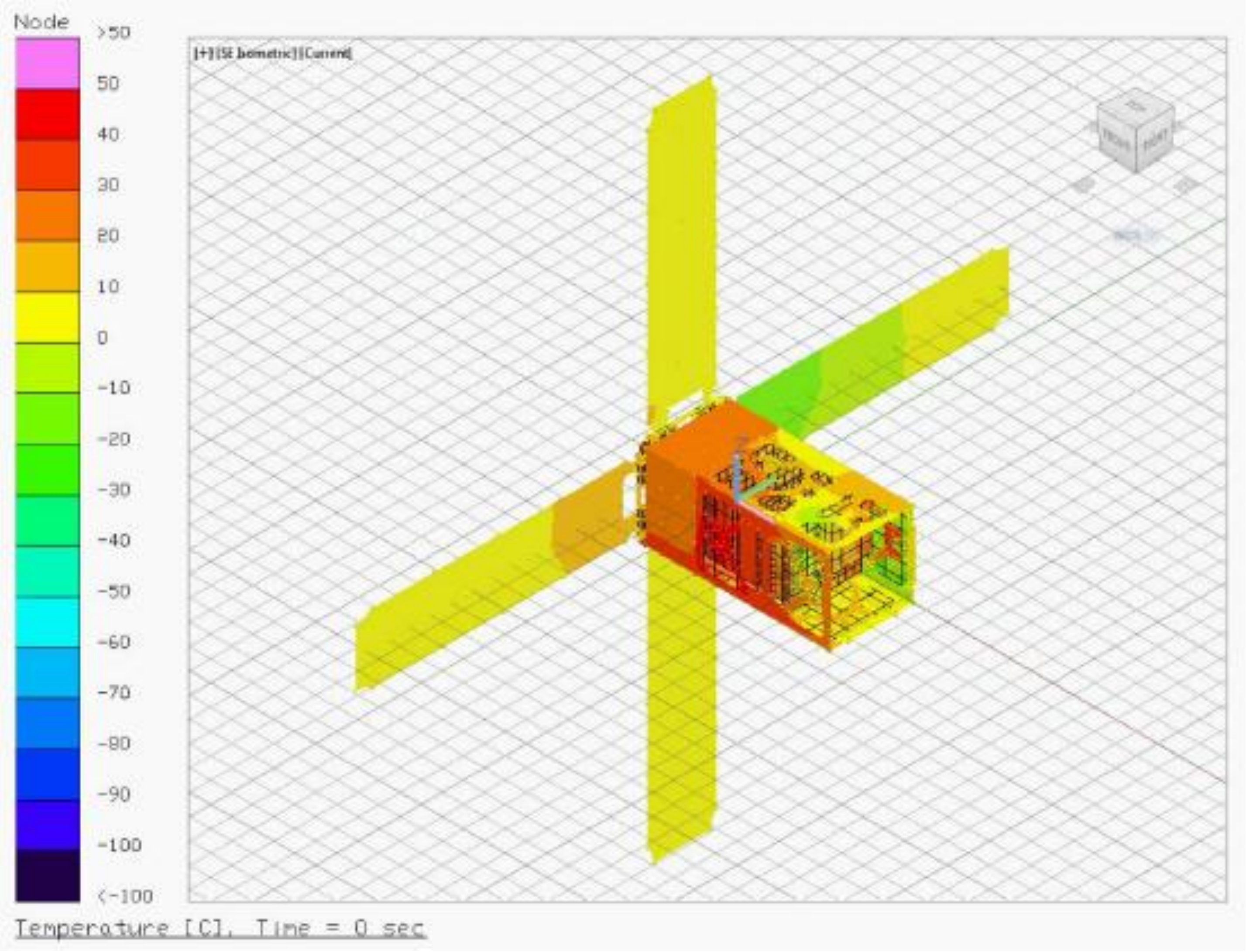
Thermal Analysis



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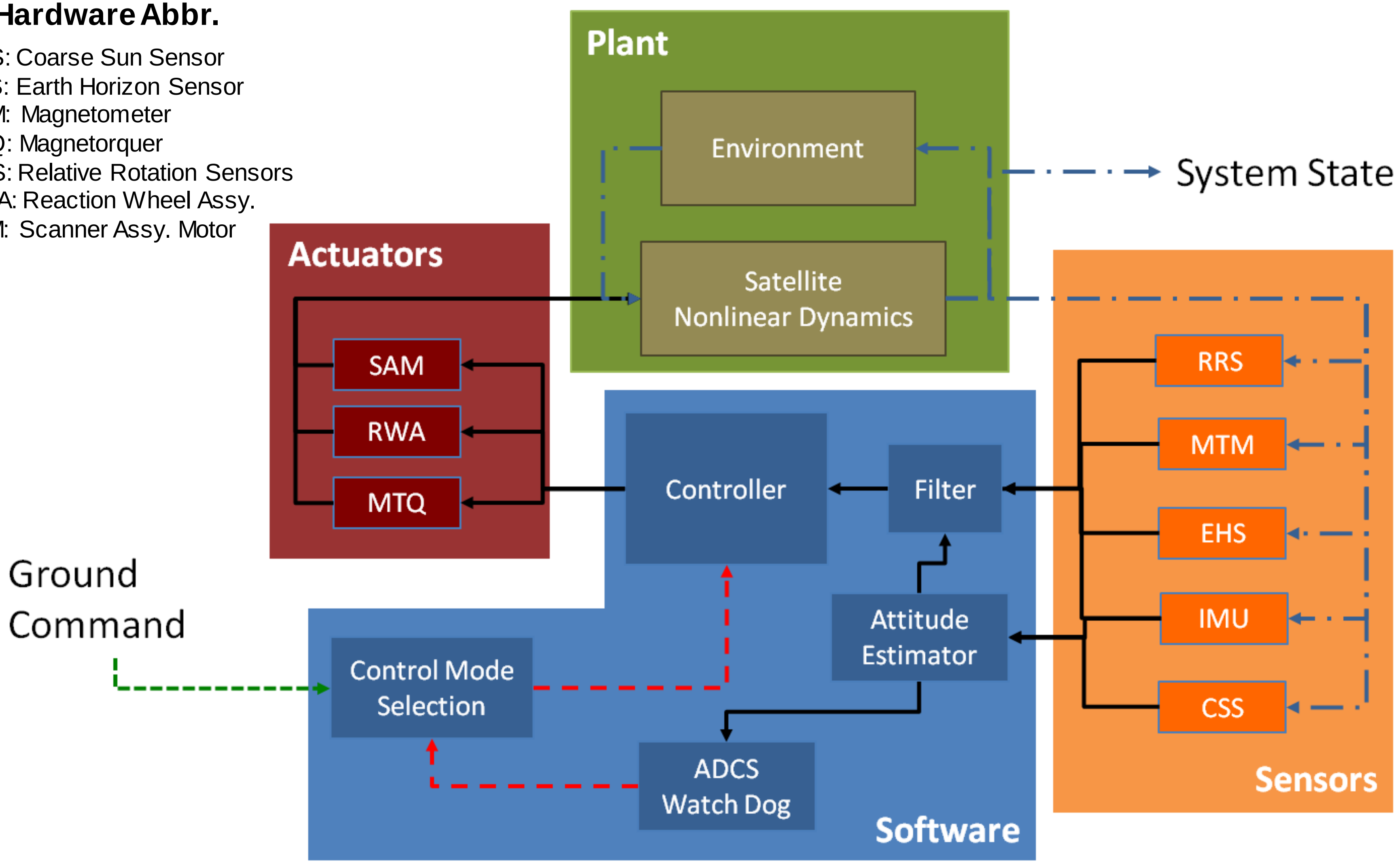
ADCS Block Diagram

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



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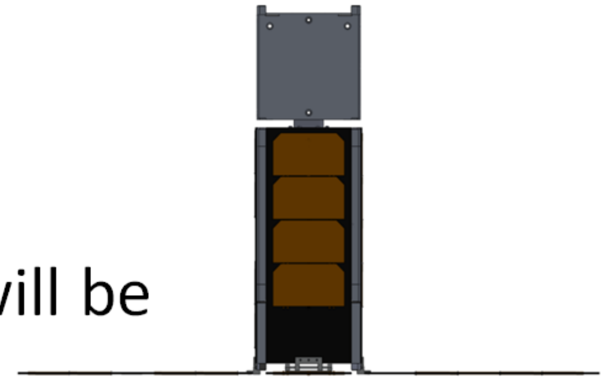
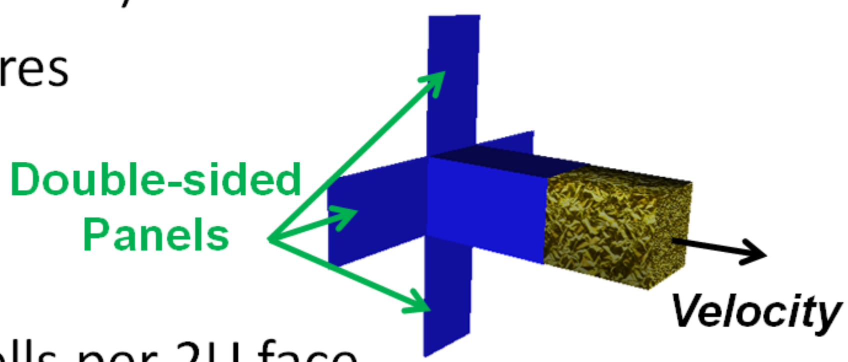
Power Subsystem

- 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

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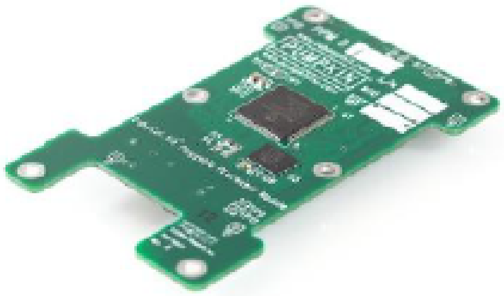
PIC24 MCU Utilization

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

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Communications

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

	Uplink	Downlink
Frequency	2.025-2.120 GHz	2.20-2.30 GHz
Data Rate	0.01 – 0.1 Mbps	0.01-1.0 Mbps
Power	2.0 W	3.6 W
Output Power	N/A	1.0 W
Modulation	BPSK, QPSK, **OQPSK**, CPFSK	
Standby Power: 0.75W		

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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

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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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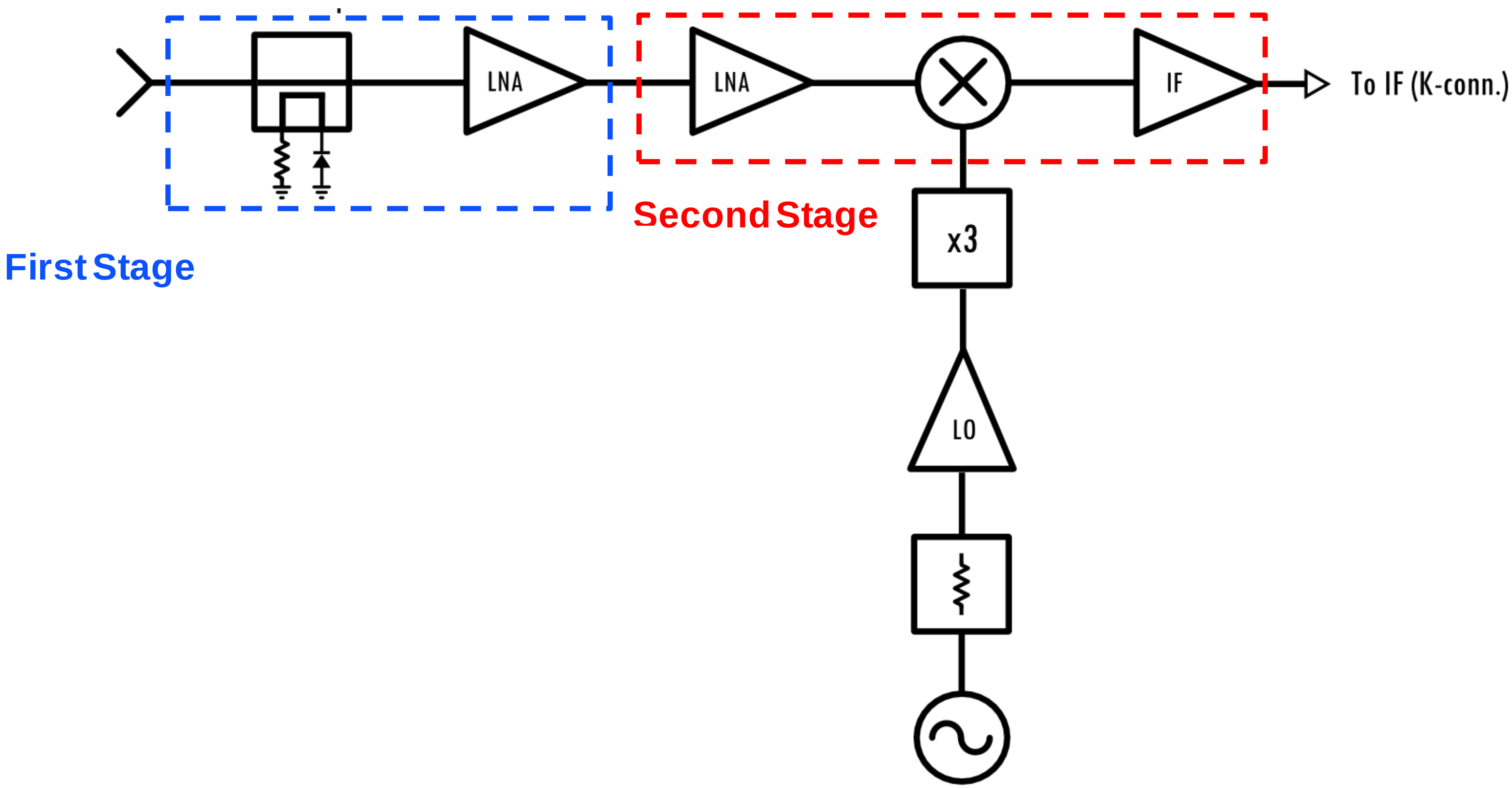
MicroMAS – RF Front End



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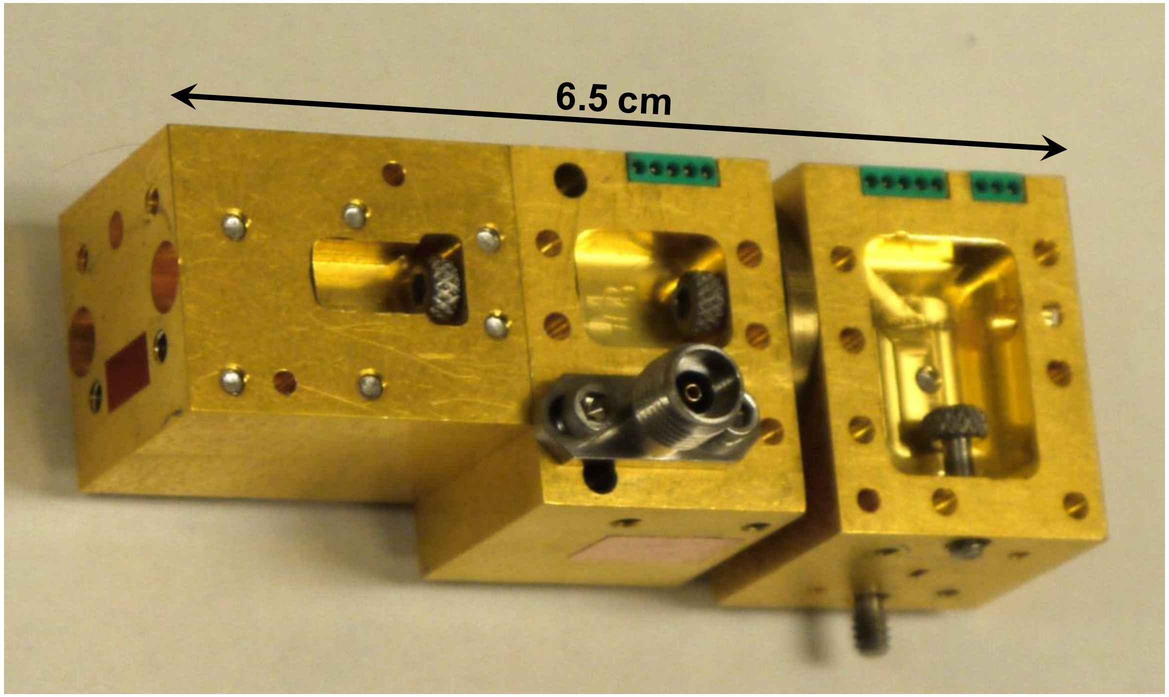
MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department



MicroMAS Tripler, Mixer, and RF Low-noise Preamplifer Modules

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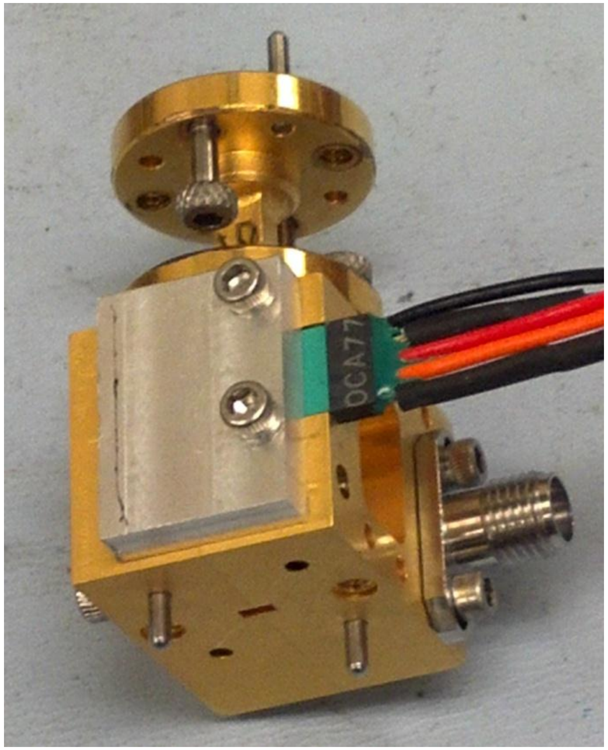
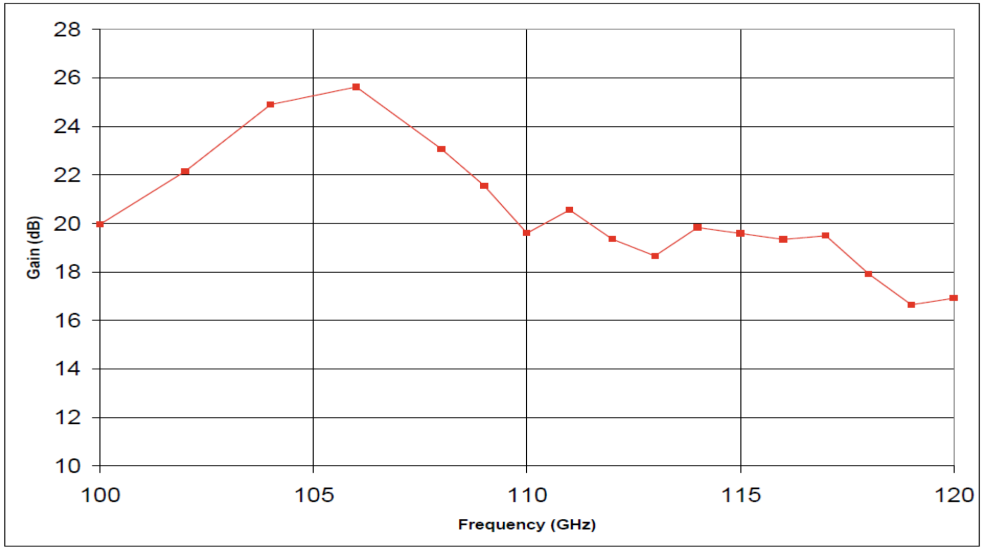
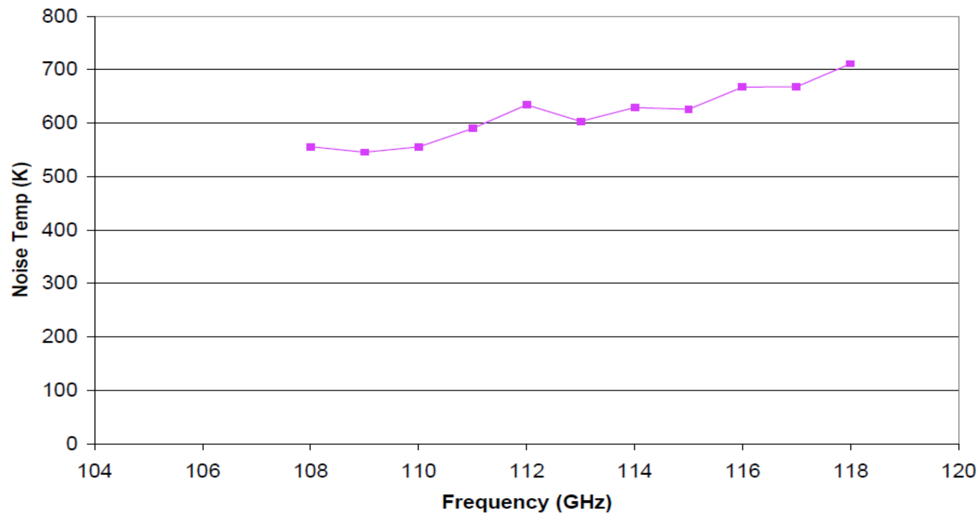
MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department



MicroMAS second stage
EM assembly

Fabrication of flight units underway





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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**

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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

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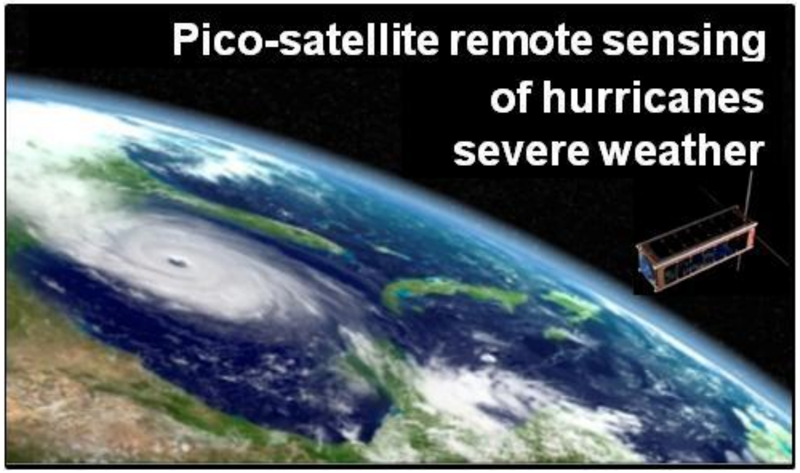
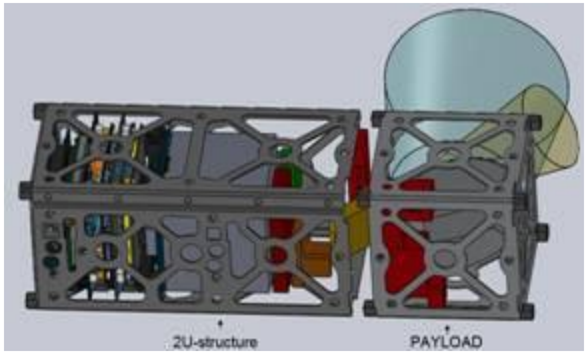
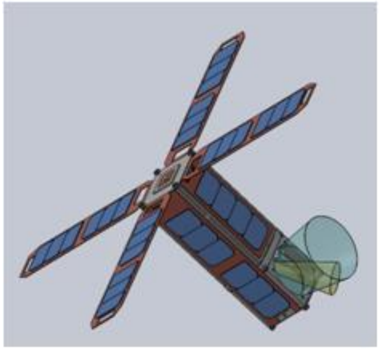
Beaver Works III:
Micro-sized Microwave Atmospheric Satellite



- 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)

30x10x10 cm
~10 W average
~30kbps
~4 kg





- 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

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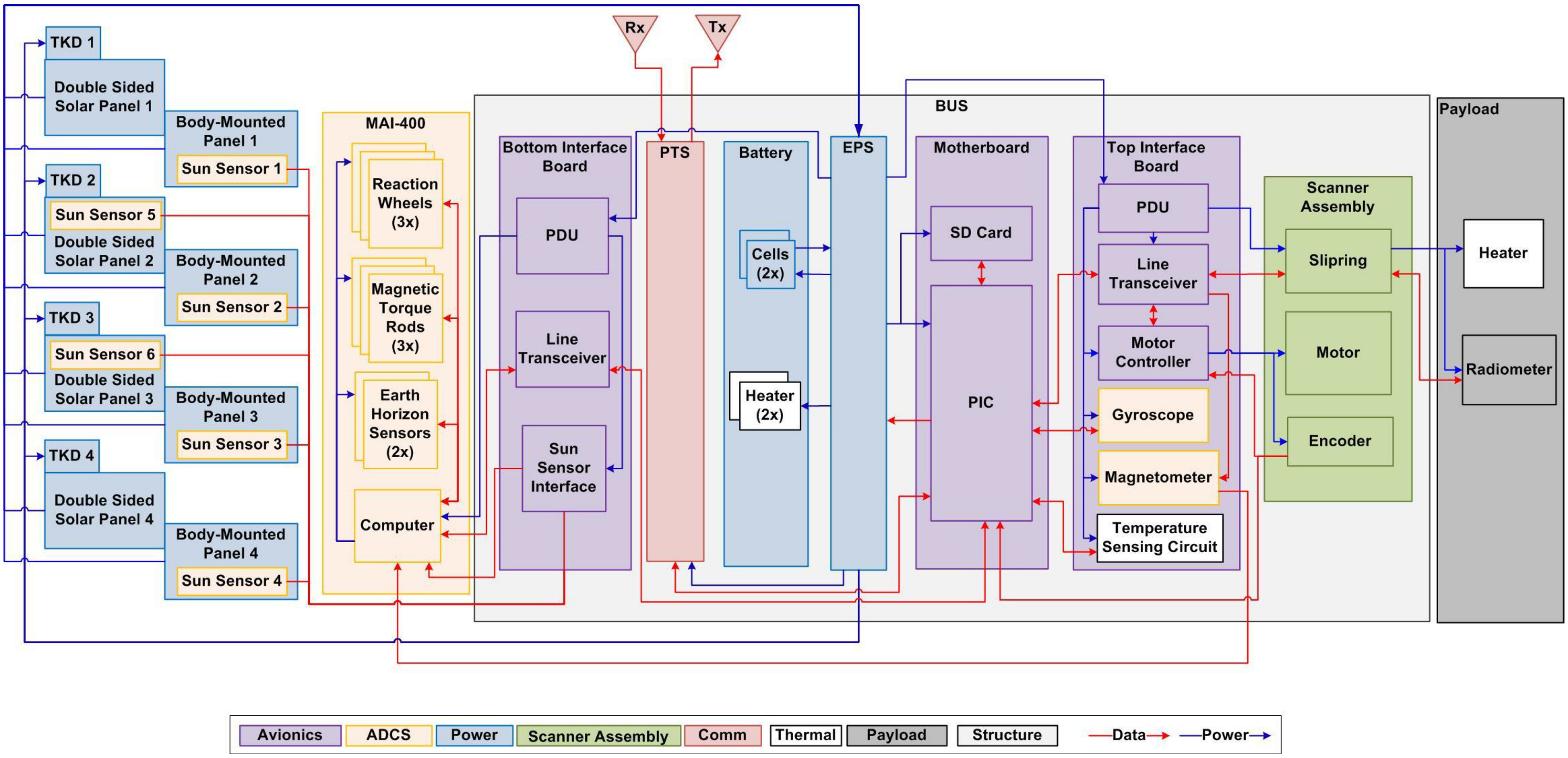
System Block Diagram



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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

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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

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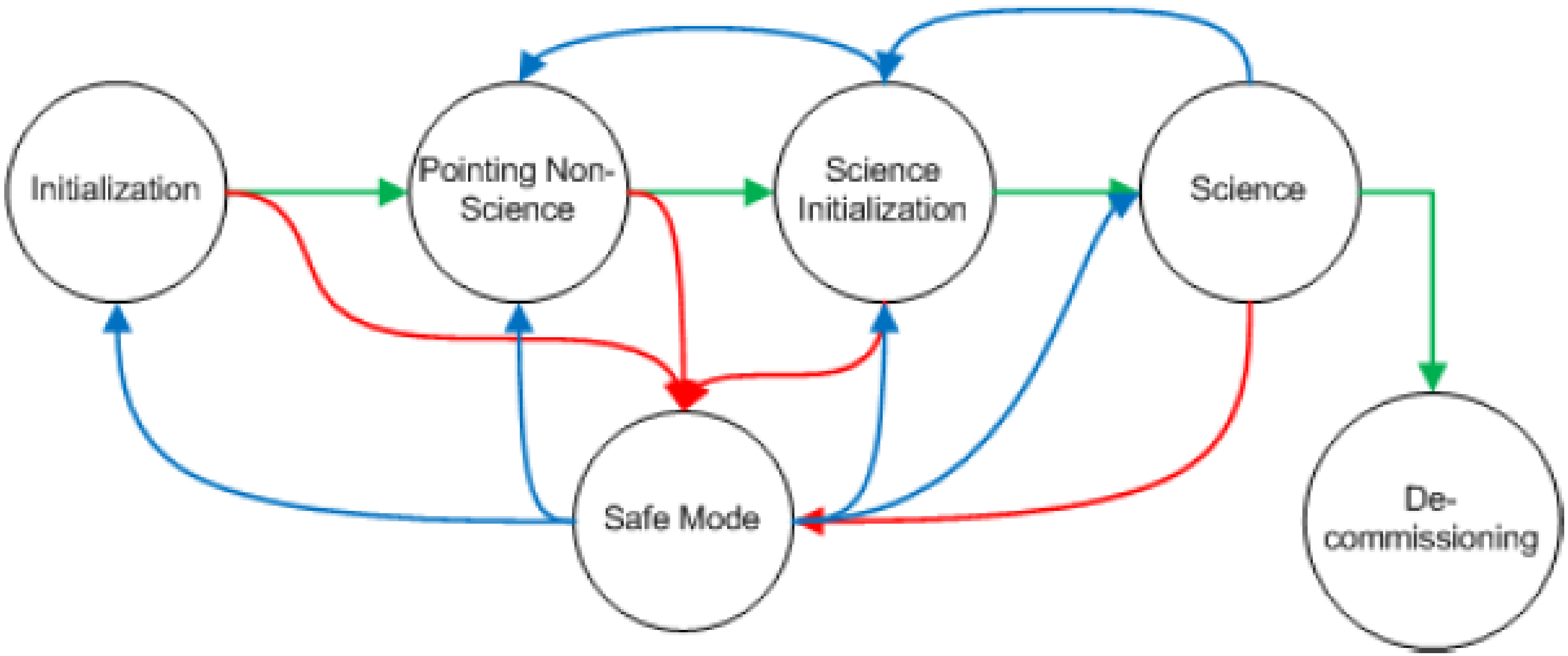
Software



Green Transition: Nominal Concept of Operations
Red Transition: Fault induced
Blue Transition: Explicit ground station command

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Communications Data Budget

Max P/L Data Rate to Bus & Required Storage Onboard Bus — ASSUME Constant 19.2 kbps — 7/20/2012 CBC

	0°			30°			42°			60°			90°		
300km	h = 300km, i = 0°	Gap	Access	h = 300km, i = 30°	Gap	Access	h = 300km, i = 42°	Gap	Access	h = 300km, i = 60°	Gap	Access	h = 300km, i = 90°	Gap	Access
	Mean (s)	2256.4	332.1	Mean (s)	6442.2	282.3	Mean (s)	8648.7	280.1	Mean (s)	10953.0	273.7	Mean (s)	12289.7	267.3
	Max (s)	2904.1	384.3	Max (s)	30314.9	412.0	Max (s)	30457.6	408.9	Max (s)	30476.2	402.7	Max (s)	30421.8	390.3
	Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*	
	Max P/L Rate (bps)	*44000*		Max P/L Rate (bps)	*14500*		Max P/L Rate (bps)	*10750*		Max P/L Rate (bps)	*8250*		Max P/L Rate (bps)	*7750*	
	Req. Storage (MB)	*18.50*		Req. Storage (MB)	*63.00*		Req. Storage (MB)	*58.00*		Req. Storage (MB)	*49.25*		Req. Storage (MB)	*41.13*	
400km	h = 400km, i = 0°	Gap	Access	h = 400km, i = 30°	Gap	Access	h = 400km, i = 42°	Gap	Access	h = 400km, i = 60°	Gap	Access	h = 400km, i = 90°	Gap	Access
	Mean (s)	2396.4	425.9	Mean (s)	5579.3	346.5	Mean (s)	7486.1	342.4	Mean (s)	9589.5	337.3	Mean (s)	10858.1	326.6
	Max (s)	3057.9	479.7	Max (s)	25229.3	501.7	Max (s)	31255.9	497.8	Max (s)	31241.6	490.1	Max (s)	41864.1	474.6
	Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*	
	Max P/L Rate (bps)	*52000*		Max P/L Rate (bps)	*20250*		Max P/L Rate (bps)	*15100*		Max P/L Rate (bps)	*11750*		Max P/L Rate (bps)	*10000*	
	Req. Storage (MB)	*22.25*		Req. Storage (MB)	*79.88*		Req. Storage (MB)	*72.75*		Req. Storage (MB)	*60.25*		Req. Storage (MB)	*46.38*	
500km	h = 500km, i = 0°	Gap	Access	h = 500km, i = 30°	Gap	Access	h = 500km, i = 42°	Gap	Access	h = 500km, i = 60°	Gap	Access	h = 500km, i = 90°	Gap	Access
	Mean (s)	2528.6	510.3	Mean (s)	4921.2	398.7	Mean (s)	6823.4	403.4	Mean (s)	8374.6	365.1	Mean (s)	9701.7	377.5
	Max (s)	3204.6	566.6	Max (s)	25842.9	584.8	Max (s)	26050.6	580.0	Max (s)	31984.8	570.8	Max (s)	37043.6	552.3
	Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*	
	Max P/L Rate (bps)	*58000*		Max P/L Rate (bps)	*26000*		Max P/L Rate (bps)	*19400*		Max P/L Rate (bps)	*14600*		Max P/L Rate (bps)	*13100*	
	Req. Storage (MB)	*25.63*		Req. Storage (MB)	*104.50*		Req. Storage (MB)	*105.88*		Req. Storage (MB)	*161.00*		Req. Storage (MB)	*91.00*	
600km	h = 600km, i = 0°	Gap	Access	h = 600km, i = 30°	Gap	Access	h = 600km, i = 42°	Gap	Access	h = 600km, i = 60°	Gap	Access	h = 600km, i = 90°	Gap	Access
	Mean (s)	2653.0	588.1	Mean (s)	4170.2	414.4	Mean (s)	5765.4	414.8	Mean (s)	7290.7	404.6	Mean (s)	8435.5	401.9
	Max (s)	3347.1	648.1	Max (s)	23049.7	663.1	Max (s)	26736.2	657.5	Max (s)	26835.6	646.7	Max (s)	29547.7	625.3
	Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*	
	Max P/L Rate (bps)	*62000*		Max P/L Rate (bps)	*31100*		Max P/L Rate (bps)	*23000*		Max P/L Rate (bps)	*18100*		Max P/L Rate (bps)	*15800*	
	Req. Storage (MB)	*28.13*		Req. Storage (MB)	*97.38*		Req. Storage (MB)	*92.63*		Req. Storage (MB)	*83.38*		Req. Storage (MB)	*96.75*	
700km	h = 700km, i = 0°	Gap	Access	h = 700km, i = 30°	Gap	Access	h = 700km, i = 42°	Gap	Access	h = 700km, i = 60°	Gap	Access	h = 700km, i = 90°	Gap	Access
	Mean (s)	2755.8	642.7	Mean (s)	4452.9	497.6	Mean (s)	6205.4	499.4	Mean (s)	7719.5	478.9	Mean (s)	8967.5	478.2
	Max (s)	3463.1	702.1	Max (s)	20865.7	715.5	Max (s)	27392.3	709.2	Max (s)	30099.6	697.5	Max (s)	27540.7	673.9
	Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*		Req P/L Rate (bps)	*19200*	
	Max P/L Rate (bps)	*65000*		Max P/L Rate (bps)	*34800*		Max P/L Rate (bps)	*25800*		Max P/L Rate (bps)	*20200*		Max P/L Rate (bps)	*17700*	
	Req. Storage (MB)	*30.63*		Req. Storage (MB)	*104.50*		Req. Storage (MB)	*102.50*		Req. Storage (MB)	*93.88*		Req. Storage (MB)	*82.75*	

* Req. P/L rate is the information rate output by the P/L assuming a constant 19.2kbps 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 downlinked without interruption.

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

Assumptions:

MicroMAS Information Downlink Rate: 347kbps // Collection occurs during downlink time // NO COMPRESSION

Analysis shown is for 30 day period // Link Constraint: Eb/No > 7.5 dB, Elevation > 5°

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Mass Summary

Subsystem	Allocated (g)	CBE (g)	Margin (g)
Structures	250	232	18
Scanner Assembly	500	441	59
Avionics	300	344	(44)
Comm	150	174	(24)
Power	750	1010	(260)
ADCS	700	708	(8)
Thermal	50	72	(22)
Payload	1000	1000	-
Unallocated	300	-	300
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

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Power Summary

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

*Factor of 1.1 for battery charge inefficiency

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

***Max 20% battery depth of discharge

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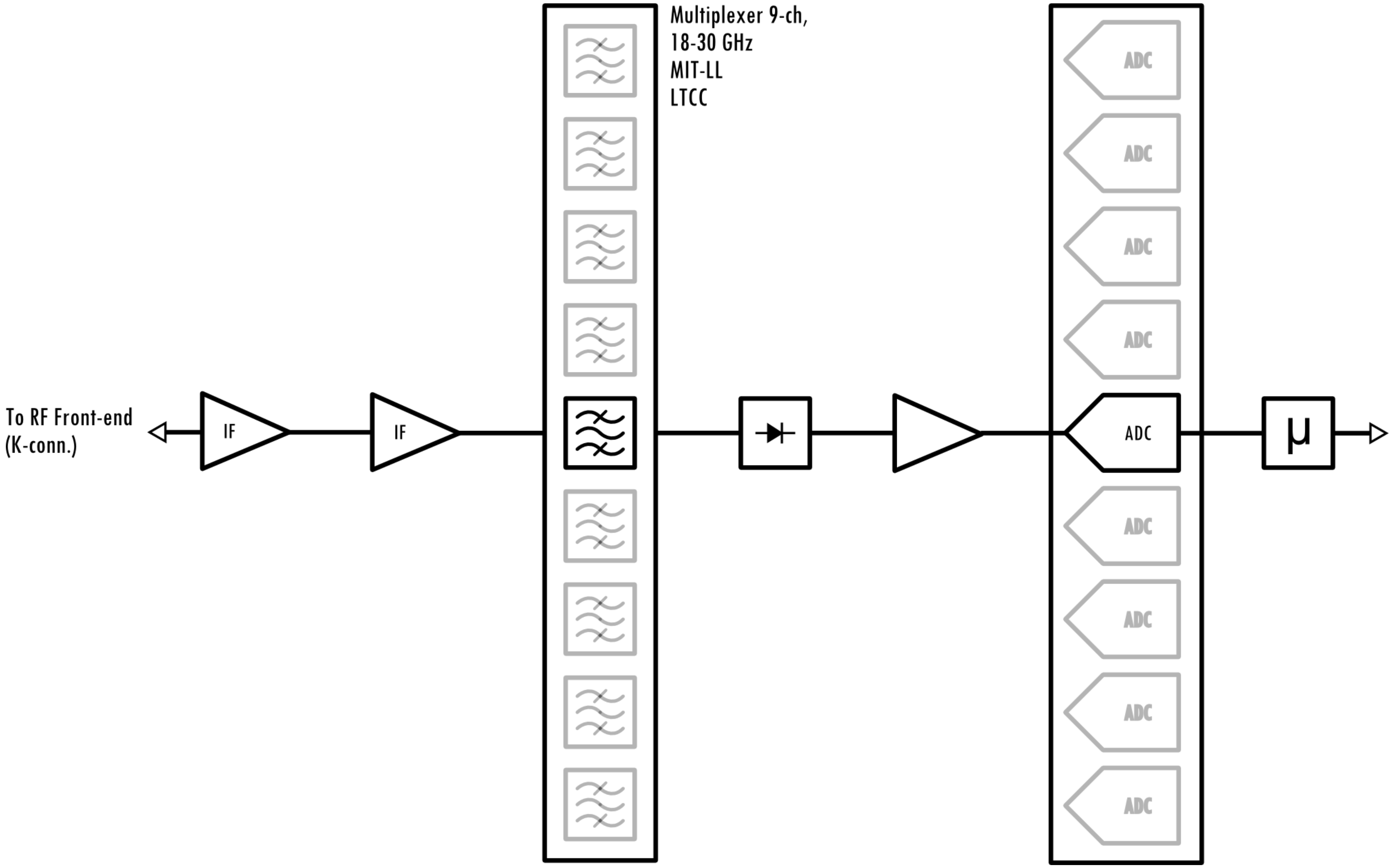
MicroMAS – IF Processor



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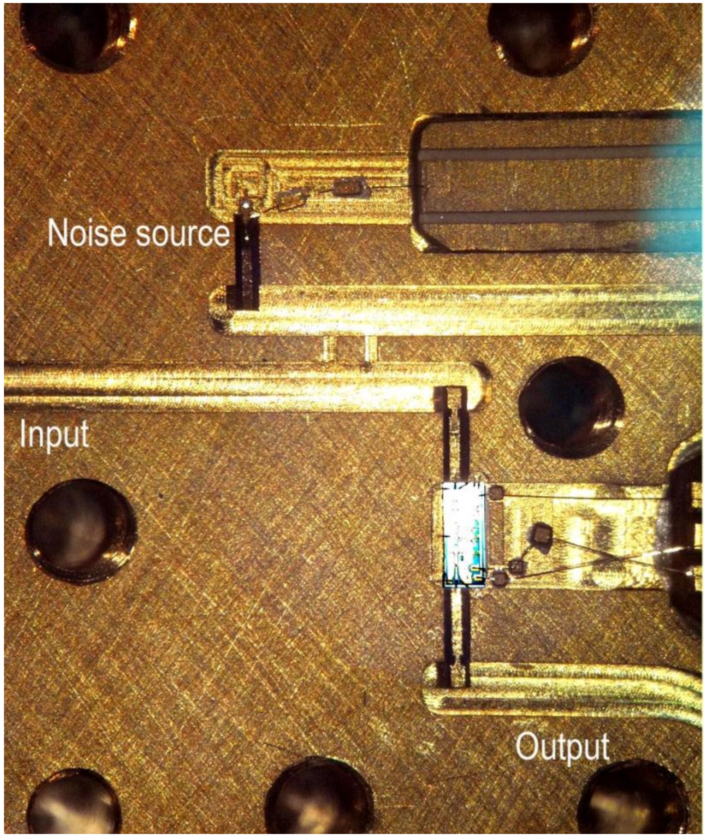
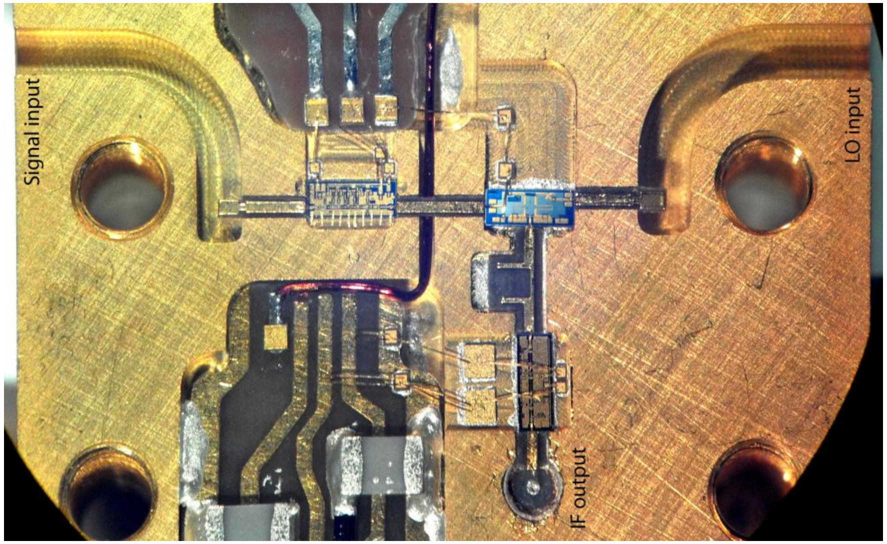
MicroMAS Receiver Engineering Model UMass Radio Astronomy Department

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

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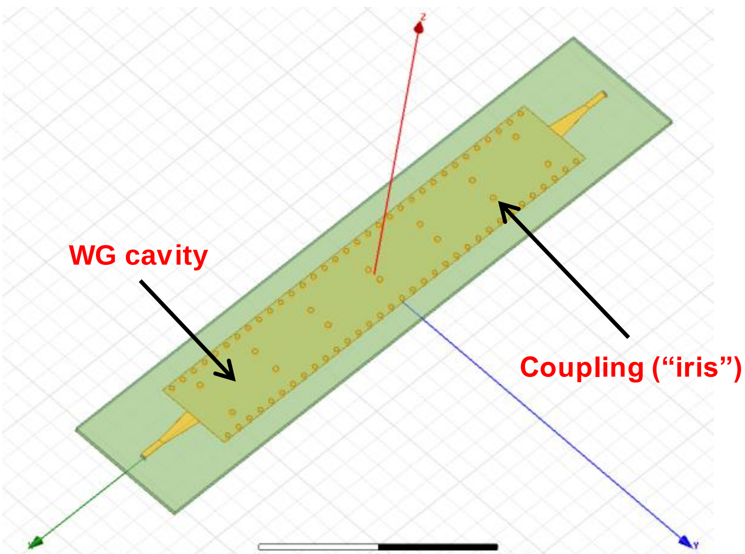
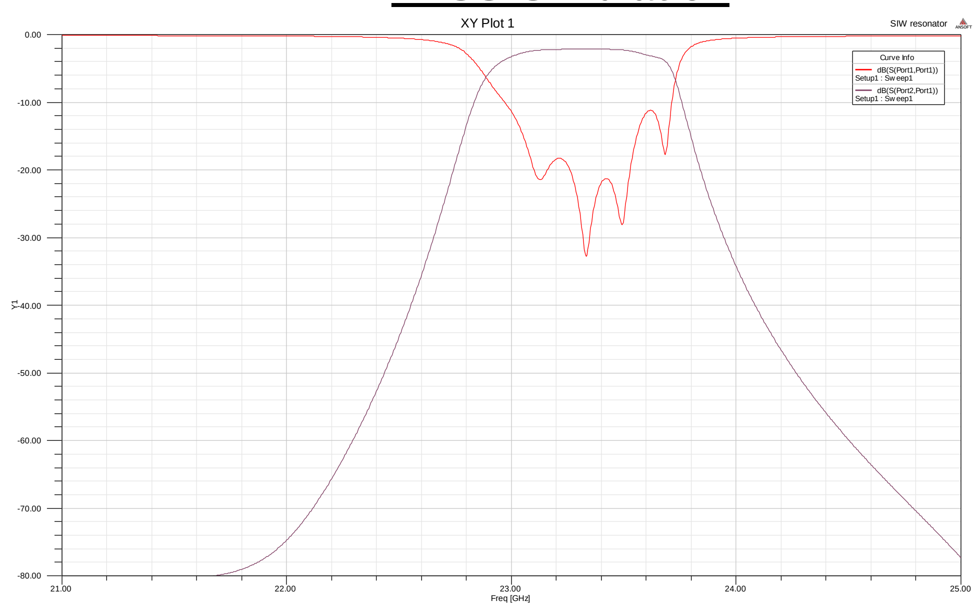
MicroMAS LTCC SIW Filters

- **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



HFSS Simulation



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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**

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