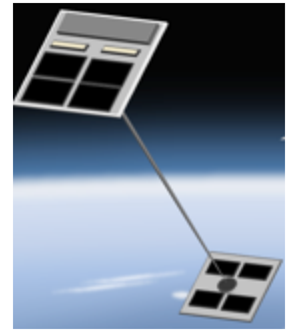


Exploring the Potential of Miniature Electrodynamic Tethers and Developments in the Miniature Tether Electrodynamics Experiment

Nikhil Shastri
University of Michigan

Abhishek Cauligi, Bret Bronner, Brent Pniewski, Abiodum Alao, Peter Rivera Alexandria Western, Roshan Radhakrishnan, Rupak Karnik, Siju Varughese, Nate Scott, Brian Gilchrist – University of Michigan

Jesse McTernan, Sven Bilen - Pennsylvania State University

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

PENNSTATE
1855

SSC14-WK-4

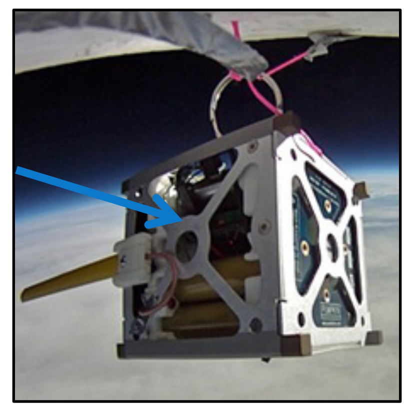
Picosatellites and Femtosatellites

- Picosats (0.1–1 kg) and femtosats (<100 g), are an emerging class of "ultra-small" satellites
  - Smartphone sized satellites with enhanced MEMS sensors
- Can fly low-cost constellations of satellites
  - Multi-point, simultaneous measurements

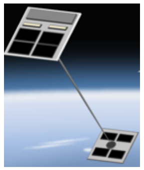
Sprite chipsat[1]
7.5 mg, 1×1×0.025 cm

PhoneSat 1.0[2]
~1 kg, ~10×10×10 cm

Google-HTC
Nexus 1

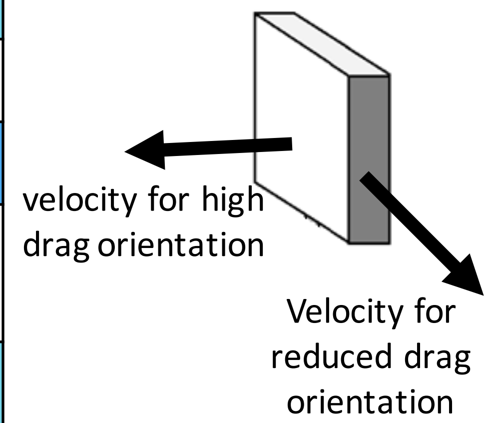


Challenges for Ultra-small Sats



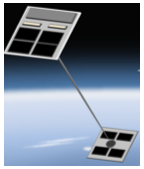
1. Missions **requiring** coordination and maneuverability (*fleets of s/c*)
2. Short orbital lifetime.
3. Limited power and size

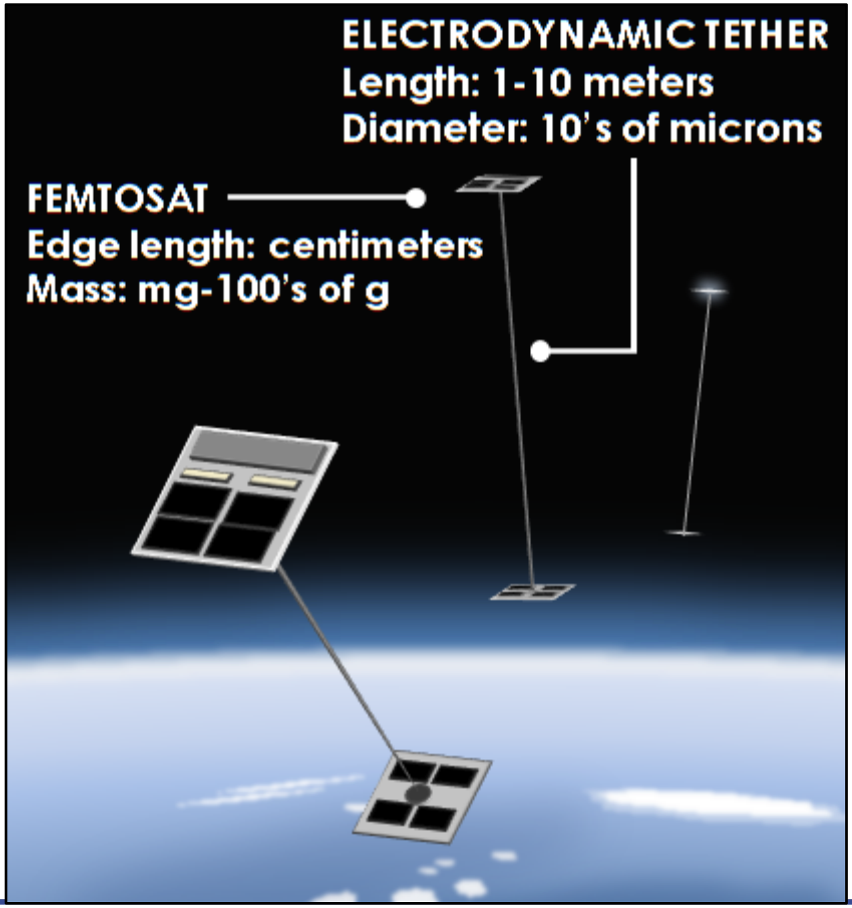
A *Rough* Estimate of Satellite Lifetime due to Atmospheric Drag					
Parameters	**1-kg CubeSat**	**200-g PicoSat**		**8-g FemtoSat**	
Dimensions	10x10x10 cm	10x10x2 cm		3.8x3.8x0.1 cm	
Configuration	1 face in ram direction	Low drag	High Drag	Low drag	High Drag
Ballistic Coeff. (kg·m^{-2})	45	45	9	95	2.5
Alt = 300 km	weeks	**weeks**	**days**	**a month**	**hours**
Alt = 400 km	months	**months**	**weeks**	**several months**	**days**
Alt = 500 km	~1 year or more	**~1 year or more**	**months**	**~years**	**weeks**



Early concepts have no propellant so the orbital lifetime is *short*

Motivation for using Miniature Electrodynamic Tethers (EDTs)





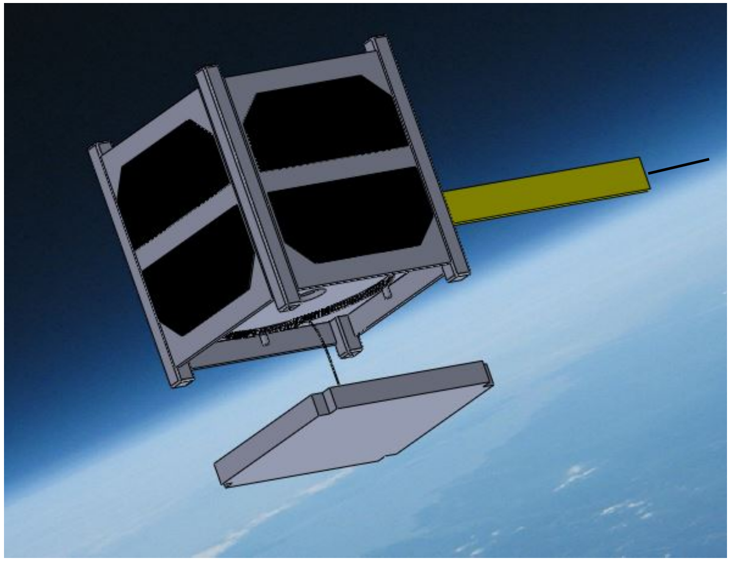
- EDT can provide propulsion
  - Drag make-up
  - Change inclination, altitude, etc.
  - No consumable propellant
- Additional benefits of tether:
  - Provided gravity gradient stability
  - Tether as antenna
  - Ionospheric plasma probe

Research questions:

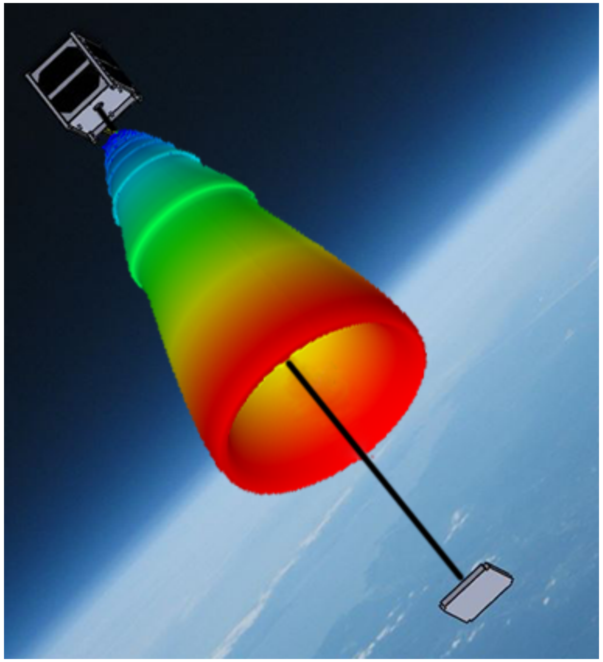
Can electrodynamic tethers provide ultra-small satellites with lifetime enhancement and maneuverability? Can it provide additional benefits?

MiTEE System Concept

MiTEE: Miniature Tether Electrodynamics Experiment



- Technology demonstration mission
- Primary mission: verify a 10 meter long tether can provide drag makeup for a femtosatellite (smartphone sized satellite)



- Secondary mission: Can the tether be used as an antenna?
- Use as a plasma probe

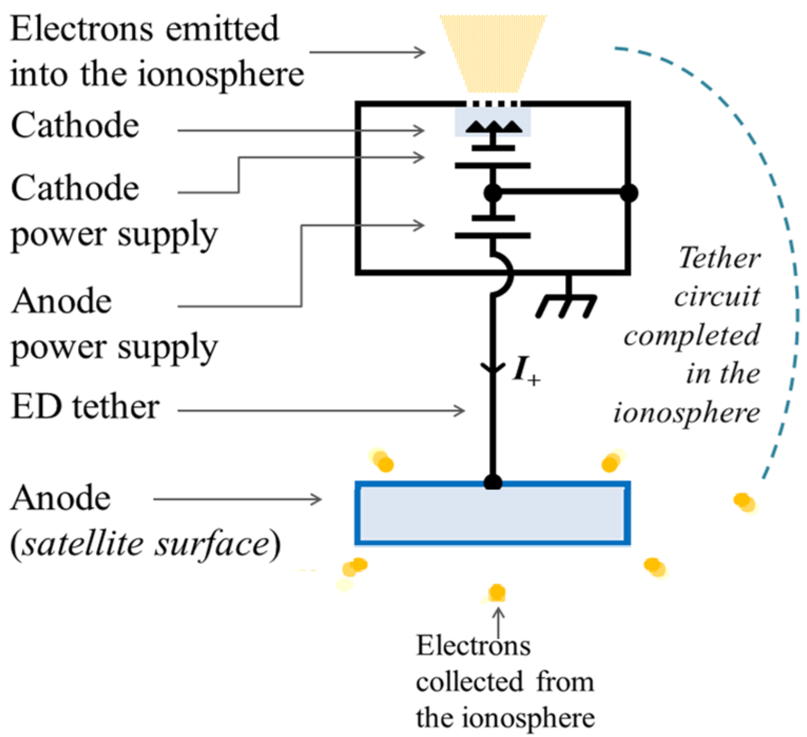
MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Electrodynamic Tether Propulsion

- Exploits the Lorenz force generated by current flow in a magnetic field

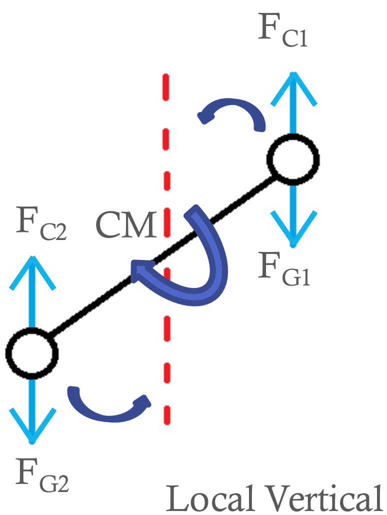
$$\mathbf{F}_{\mathrm{Electrodynamic\,Tether}} = \int_{0}^{Tether\_Length} \left(I_{\mathrm{tether}}\, d\mathbf{L}\right) \times \mathbf{B}_{\mathrm{Earth}}$$

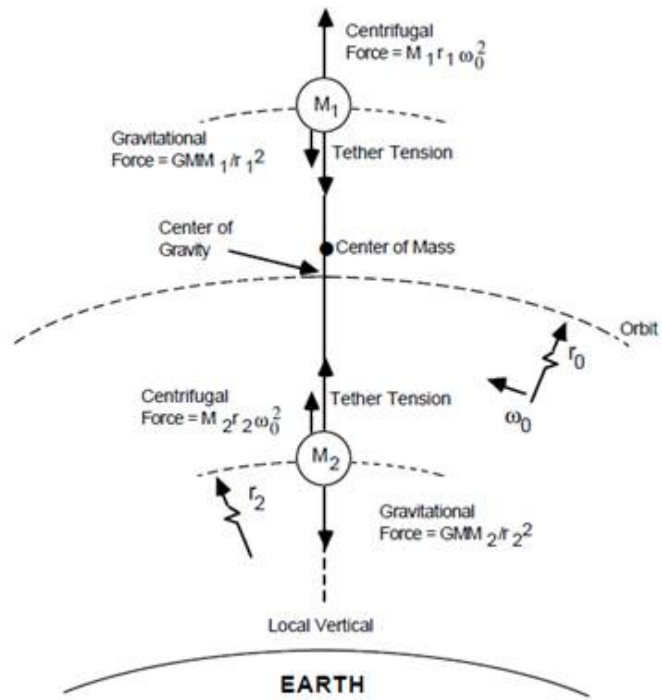


MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Gravity Gradient Stabilization

- The gravity gradient force generates tension in the tether
- The gravity gradient torque helps align the tether along the local vertical



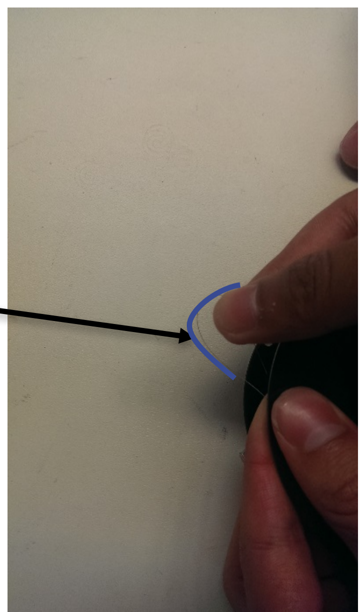


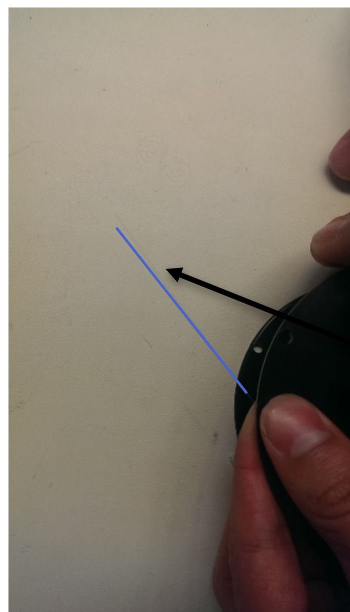
Gravity Gradient Forces[3]

Tether Overview

- Requirements for Tether Material
  - High tensile strength to prevent tether from breaking
  - Conductive with insulating overlay
  - Semi-rigid
- Investigating various materials for use
  - Conducting testing on gold plated Nitinol as main material base

Bent Nitinol





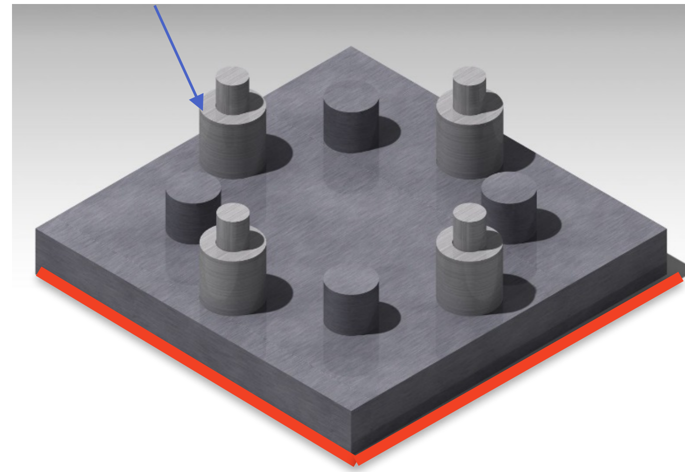
Springs back to original shape

MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

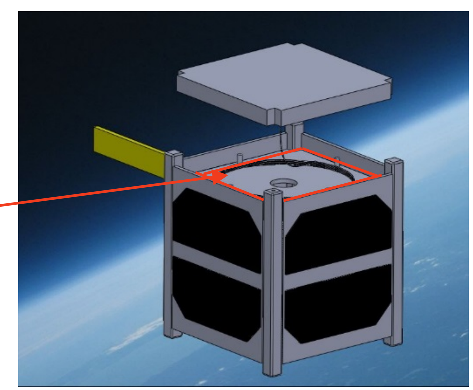
Deployment System

- Tether Storage
  - Coiled in a figure 8 pattern in spool to minimize tip off dynamics
- Deployment
  - Thermal knife cuts fiber that holds back end body
  - Spring loaded pegs push end body away
  - Investigating methods to prevent bounce back at end of tether
- Micro-Gravity Testing
  - Initial testing conducted in house
  - Constructed drop chamber to deploy tether
  - Will conduct further testing on parabolic flight

Spring Loaded Pegs

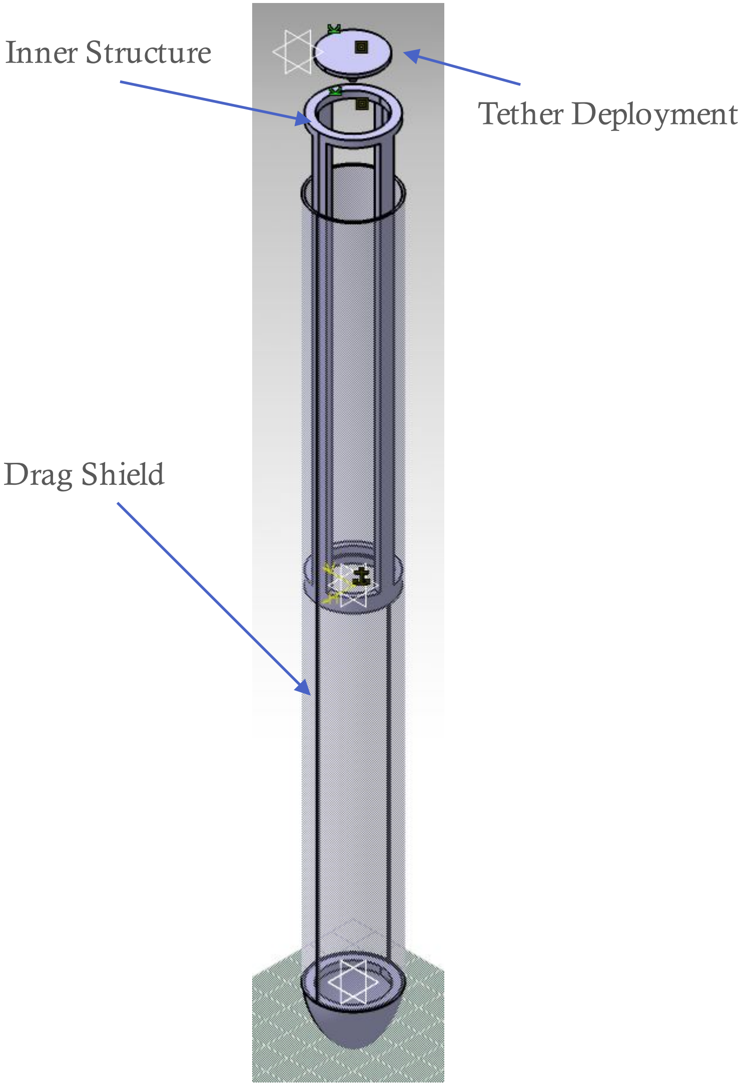


Tether Deployment System



Deployment System

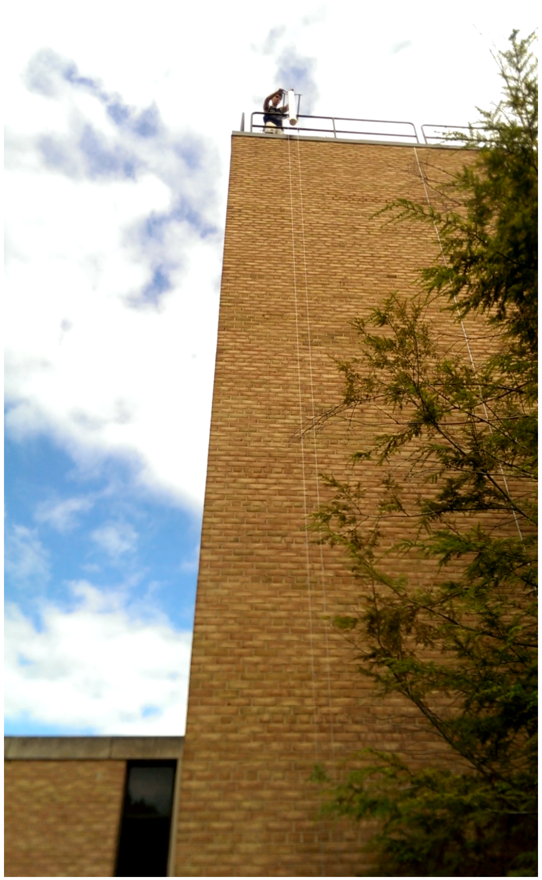
- Tether Storage
  - Coiled in a figure 8 pattern in spool to minimize tip off dynamics
- Deployment
  - Thermal knife cuts fiber that holds back end body
  - Spring loaded pegs push end body away
  - Investigating methods to prevent bounce back at end of tether
- Micro-Gravity Testing
  - Initial testing conducted in house
  - Constructed drop chamber to deploy tether
  - Will conduct further testing on parabolic flight



MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

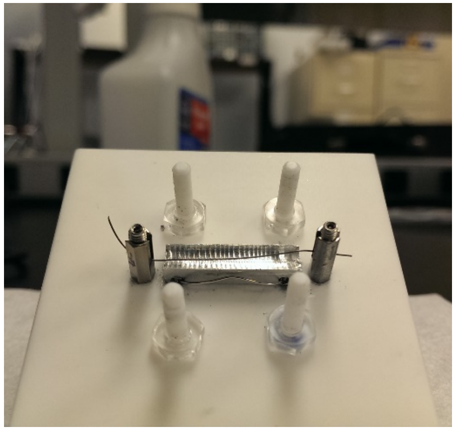
Deployment System

- Tether Storage
  - Coiled in a figure 8 pattern in spool to minimize tip off dynamics
- Deployment
  - Thermal knife cuts fiber that holds back end body
  - Spring loaded pegs push end body away
  - Investigating methods to prevent bounce back at end of tether
- Micro-Gravity Testing
  - Initial testing conducted in house
  - Constructed drop chamber to deploy tether
  - Will conduct further testing on parabolic flight

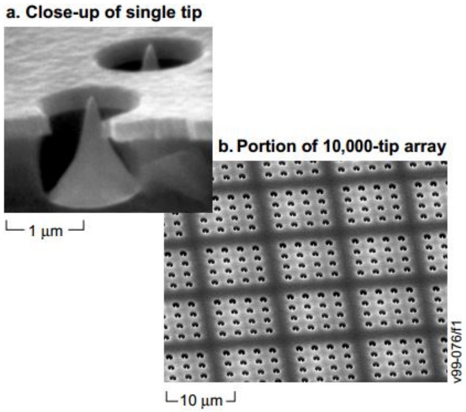


Cathode

- Emits electrons from main body of satellite
- Flying two types of cathodes
  - Thermionic cathode
    - Hot cathode for primary emission
  - Field emission array cathode
    - Low TRL, cold cathode for demonstration and redundancy



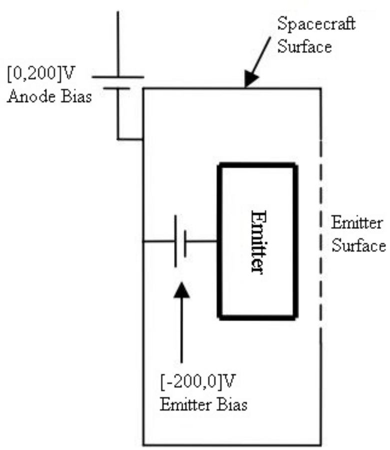
Thermionic cathode



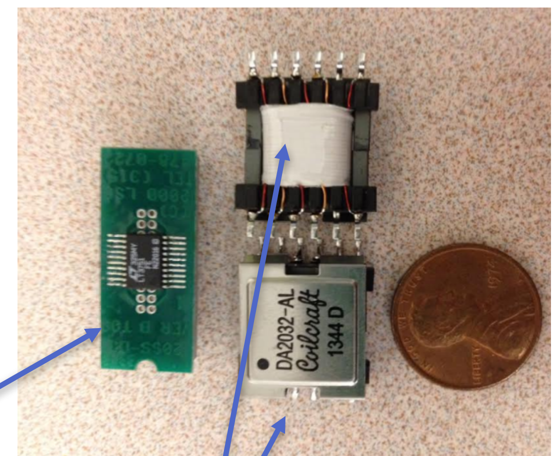
FEAC Cathode[4]

EPS - HVPS

- High-Voltage Power Supply (HVPS) supplies voltage bias for anode and cathode
- Low TRL item never tested in a CubeSat
- Requirements
  - 200 V drop, supplying up to 5 mA
  - Low power (< 2 W)
  - Small form factor
- Powered by on-board battery/solar cells



HVPS Anode/Cathode System Application[5]



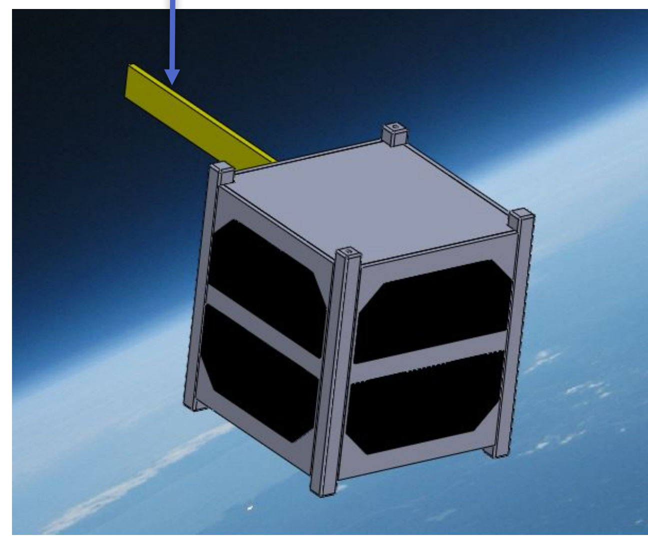
LT3751 IC

Coilcraft DA2032 Flyback Transformer

Communications Overview

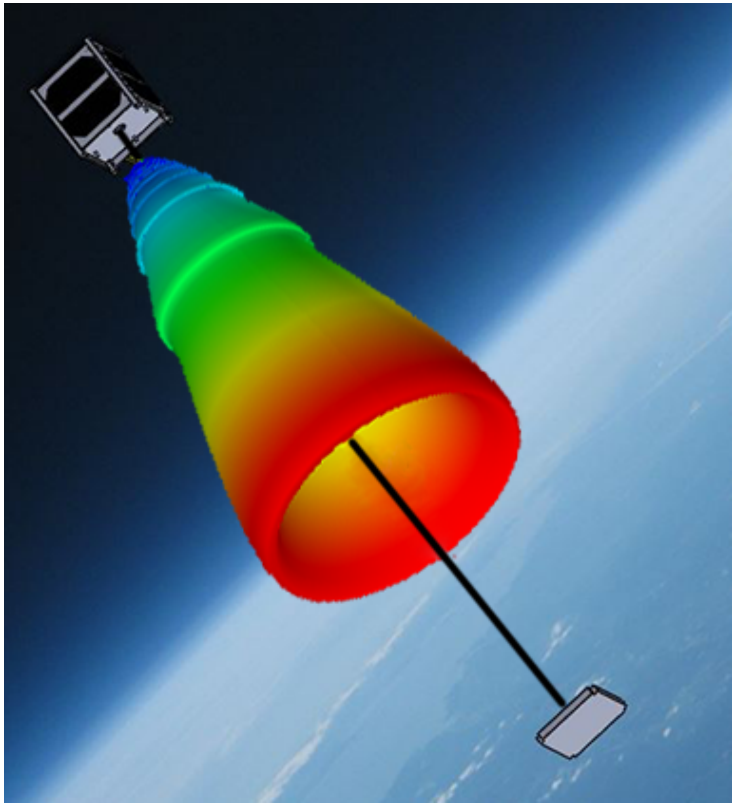
- Primary Antenna
  - Monopole antenna
  - Omnidirectional in azimuth plane
  - 90° beamwidth in elevation plane
- Secondary Antenna
  - Travelling wave antenna
  - Gain 8 dBi at 435 MHz
  - Doughnut shaped radiation pattern directed towards nadir
- Ground stations
  - Ann Arbor, MI
  - TBD backup station
  - HAM community

Primary Antenna



Communications Overview

- Primary Antenna
  - Monopole antenna
  - Omnidirectional in azimuth plane
  - 90° beamwidth in elevation plane
- Secondary Antenna
  - Travelling wave antenna
  - Gain 8 dBi at 435 MHz
  - Doughnut shaped radiation pattern directed towards nadir
- Ground stations
  - Ann Arbor, MI
  - TBD backup station
  - HAM community

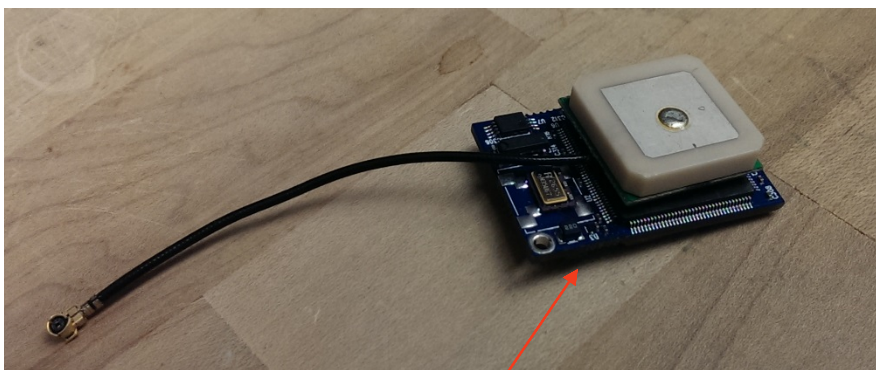


MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Diagnostics Tools

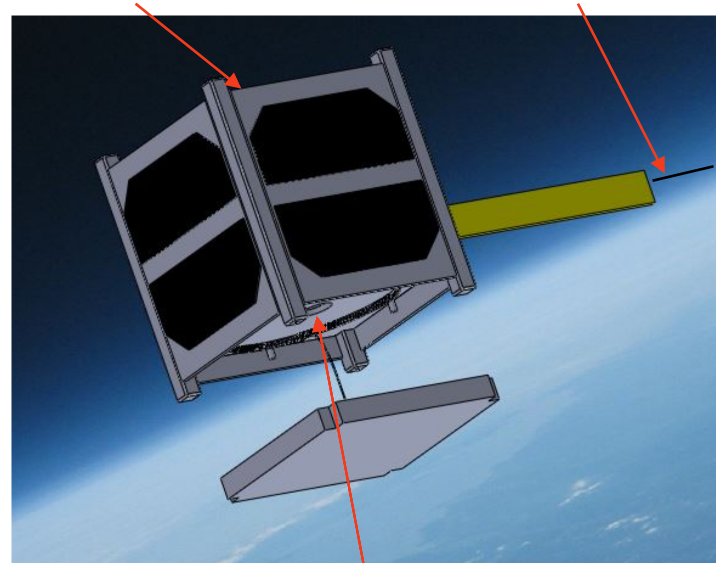
- Langmuir Probe
  - Plasma diagnostics tool to measure ambient plasma characteristics
  - Deployed off of primary antenna boom
- Camera
  - Verifies deployment, end body location
- GPS
  - Position data



GPS Receiver and Patch Antenna

GPS

Langmuir Probe



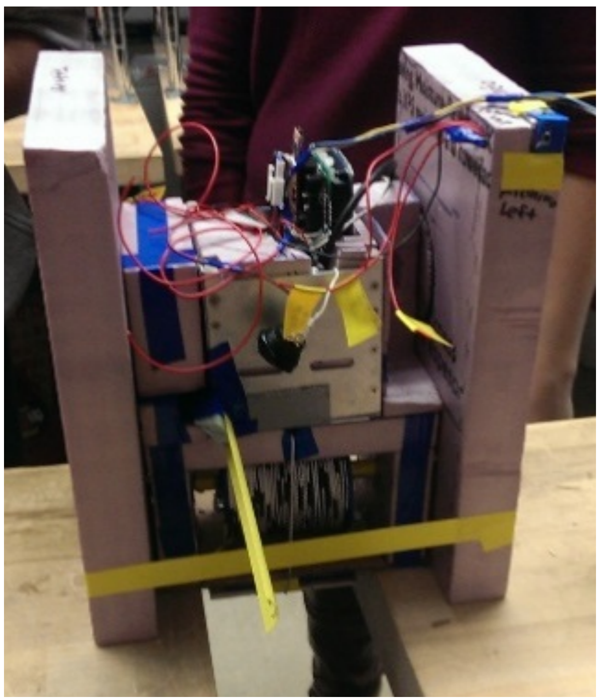
Camera Location

MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

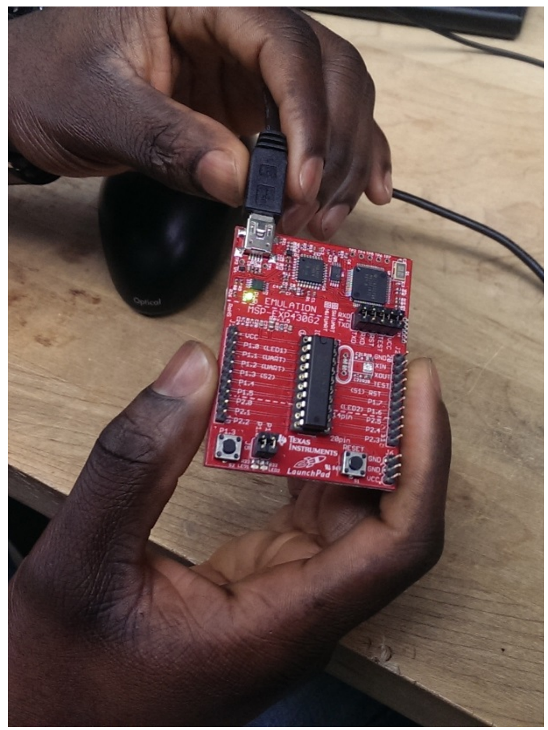
Summer Progress Summary

- Successfully completed a high-altitude balloon flight
  - Tested communications and integration of components



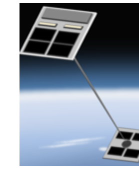
Summer Progress Summary

- Successfully completed a high-altitude balloon flight
  - Tested communications and integration of components
- Decision to have distributed network of MSP430s control CubeSat



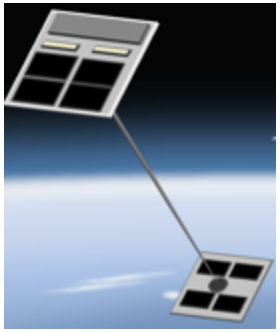
Summer Progress Summary

- Successfully completed a high-altitude balloon flight
  - Tested communications and integration of components
- Decision to have distributed network of MSP430s control CubeSat
- In-house microgravity chamber and thermionic cathode testing system



Future Plans

- Heading towards a Preliminary Design Review in Fall 2014
- Plan to submit a proposal for launch position
- Submit proposal for reduced gravity flight with NASA

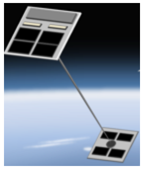


Questions?

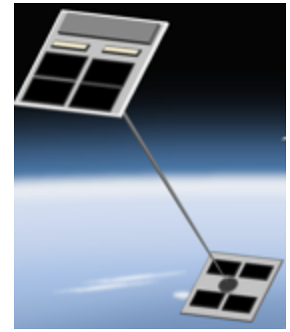
• • •

Thank you for your time!

References



1. Atchison, J.A. and M.A. Peck, “A Passive, Sun-Pointing, Milimeter-Scale Solar Sail,” Acta Astronautica, Vol. 67, No. 1-2, July-August 2010, pp. 108-121
2. Twiggs, R.J. and R.A. Deepak, “Thinking Outside the Box: Space Science Beyond the CubeSat,” Journal of Small Satellites, Vol. 1. No. 1, 2012, pp. 3-7
3. Cosmo, M. L. *Tethers in Space Handbook*. 3rd ed. 1997. Print.
4. V.M. Aguero and R.C. Adamo, "Space applications of Spindt cathode field emission arrays," in *6th Spacecraft Charging Technology Conf.* 2000, pp347-352
5. Morris, D.P., "Optimizing space-charge limits of electron emission into plasmas with application to in-space electric propulsion," Ph.D dissertation, The University of Michigan, Ann Arbor, MI, 2005.



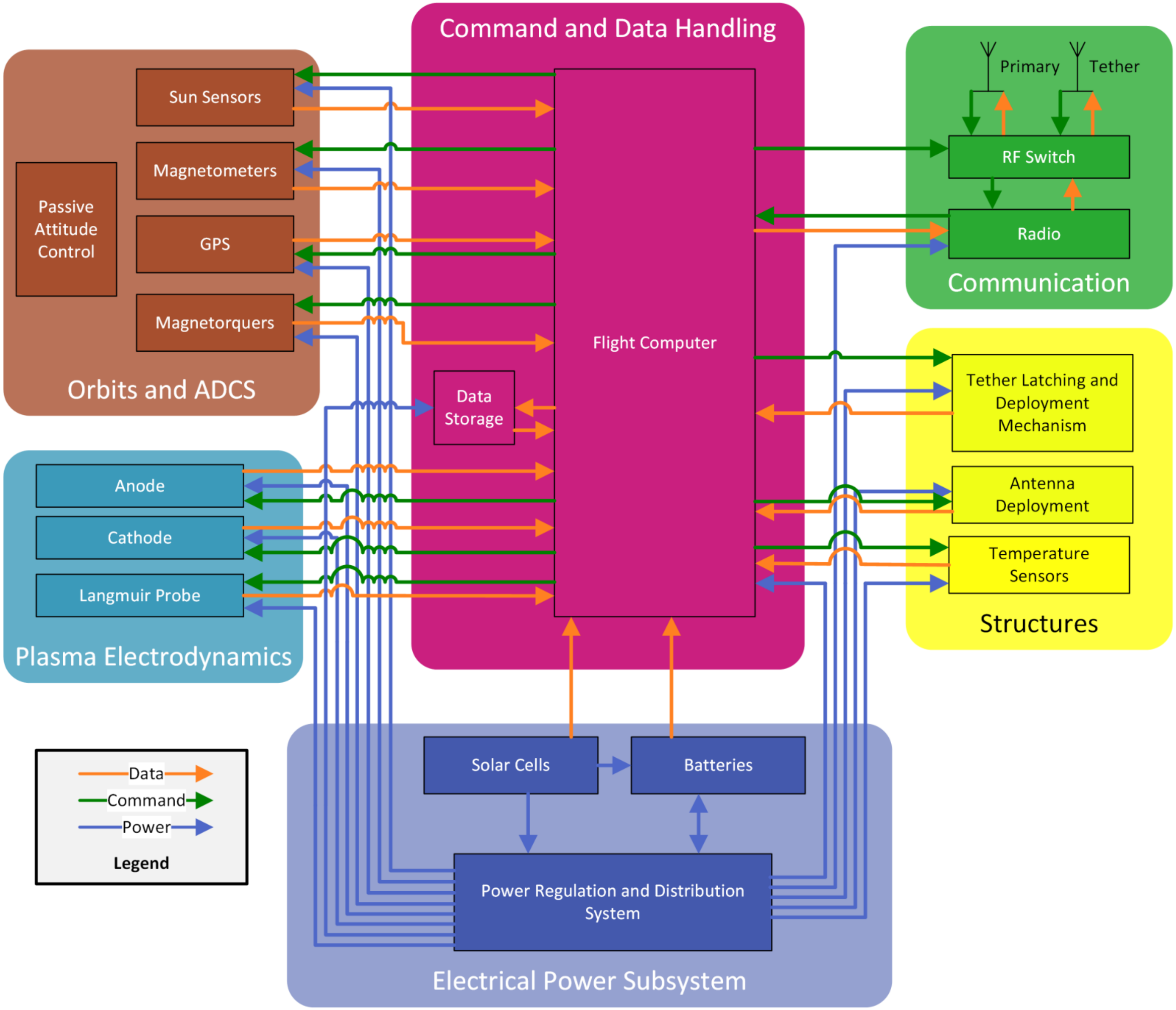
Backup Slides

Picosatellites and Femtosatellites

- Can be launched to form low cost constellations if propulsion source was on board
  - Multi-point, simultaneous measurements
  - Take *in-situ* measurements

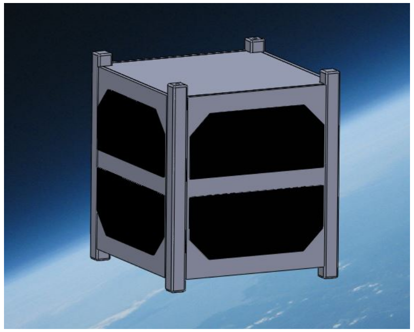
DARPA System F6 Constellation Concept[3]

System Block Diagram

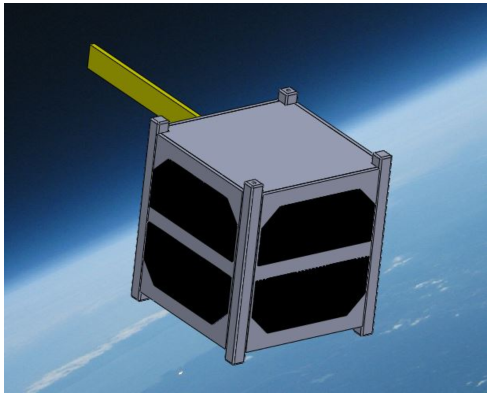


Operations Overview

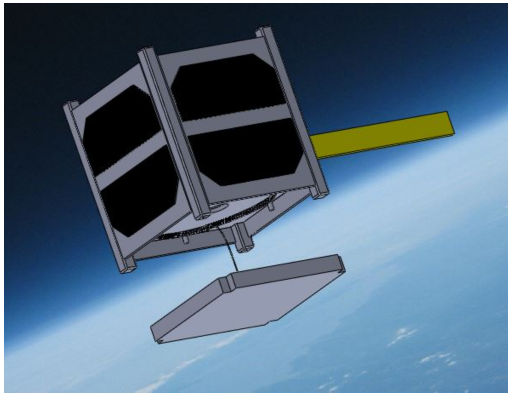
Launch from PPOD



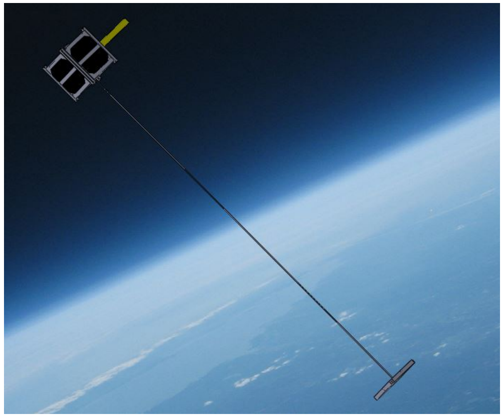
Primary Antenna Deployment and De-tumble



Tether Deployment when Nadir Facing



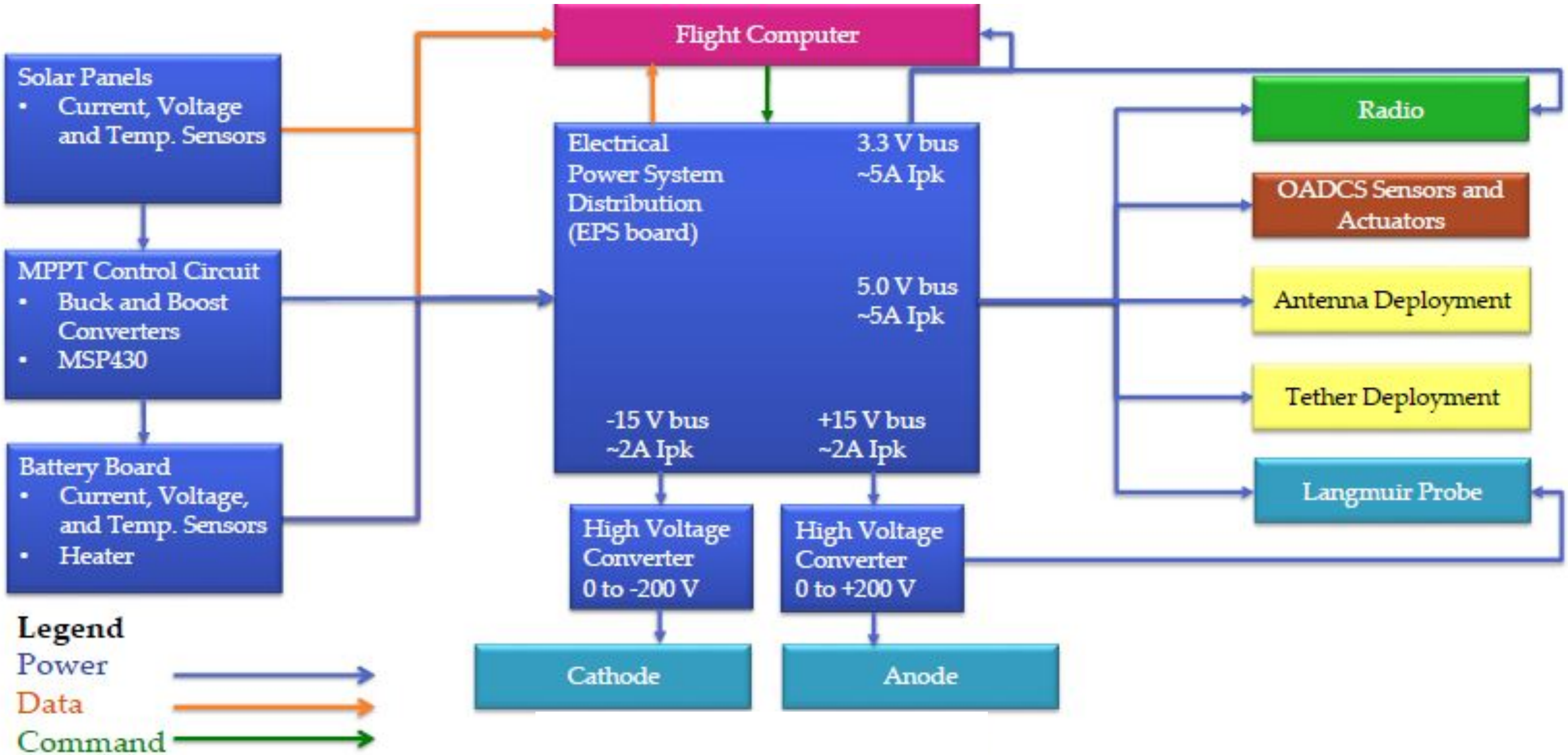
Science Mission Starts



MICHIGAN ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

EPS Block Diagram



MICHIGAN ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Link Budget

- Assumptions – UHF downlink at 435Mhz Reception using 436CP2UG Antenna from M2inc at ground station, 10dB Eb/No requirement to get a BER of 1e-06 using FSK modulation from an orbit of 500km altitude.

Item	Symbol	Units	Source	Spacecraft to Ground
Frequency	f	GHz	Input Parameter	0.44
Transmitter Power (DC)	P	Watts	Input Parameter	1.50
Transmitter Power Amplifier Efficiency	h^p	--	Input Parameter	0.30
Transmitter Power (RF)	P	Watts	P*h^p	0.45
Transmitter Power (RF)	P	dBW	10 log(P)	-3.468
Transmitter Line Loss	L^l	dB	Input Parameter	-2.000
Transmit Antenna Beamwidth	θ^t	deg	Input Parameter	48.276
Transmit Antenna Efficiency	h^t	--	Input Parameter	0.80
Peak Transmit Antenna Gain	G^{pt}	dBi	Eq. (13-18b)	12.21
Transmit Antenna Diameter	D^t	m	Input Parameter	1.0
Transmit Antenna Pointing Error	e^t	deg	Input Parameter	10.000
Transmit Antenna Pointing Loss	L^{pt}	dB	Eq. (13-21)	-0.515
Transmit Antenna Gain (net)	G^t	dBi	G^{pt} + L^{pt}	11.70
Equiv. Isotropic Radiated Power	EIRP	dBW	P + L^l+ G^t	6.23
Propagation Path Length	S	km	Input Parameter	5.000E+02
Space Loss	L^s	dB	Eq. (13-23a)	-139.19
Propagation & Polarization Loss	L^a	dB	Fig. 13-10	-0.5
Receive Antenna Diameter	D^r	m	Input Parameter	2.0
Receive Antenna Efficiency	h^r	--	Input Parameter	0.55
Peak Receive Antenna Gain	G^{rp}	dBi	Eq. (13-18b)	16.60
Receive Antenna Beamwidth	θ^r	deg	Eq. (13-19)	24.138
Receive Antenna Pointing Error	e^r	deg	Input Parameter	0.130
Receive Antenna Pointing Loss	L^{pr}	dB	Eq. (13-21)	0.000
Receive Antenna Gain (net)	G^r	dBi	G^{rp} + L^{pr}	16.60
System Noise Temperature	T^s	K	Table 13-10 or DSN table	135
Data Rate	R	bps	Input Parameter	9600
Modulation Rate	--	--	Input Parameter	1.0
Computer Implementation Efficiency	--	--	Input Parameter	0.90
Effective Data Rate	R	bps	*See cell	10667
E^b/N^o (1)	E^b/N^o	dB	Eq. (13-13)	50.16
Carrier-to-Noise Density Ratio	C/N^o	dB-Hz	Eq. (13-15a)	90.44
Bit Error Rate	BER	--	Input Parameter	1.000E-07
Required E^b/N^o (2)	Req E^b/N^o	dB	Fig. 13-9	12.0
Implementation Loss (3)	---	dB	Input Parameter	-2.0
Rain Attenuation (4)	--	dB	Fig. 13-11	-1.0
Margin	---	dB	(1) – (2) + (3) + (4)	35.161

OADCS Overview

- Pre-Deployment nadir pointing accuracy of 10°
- Post-Deployment will rely on gravity gradient for nadir pointing stability
- Rotational stability in-plane to less than 0.2 rad/s
    - Out of plane rotation should be less than 0.01 rad/s
- Actuator
    - Magnetorquers with active control
- Position and attitude determination sensors
    - GPS
    - IMU
    - Magnetometer
    - Sun sensor