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

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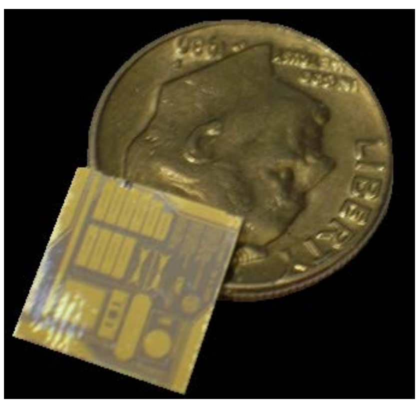
Picosatellites and Femtosatellites

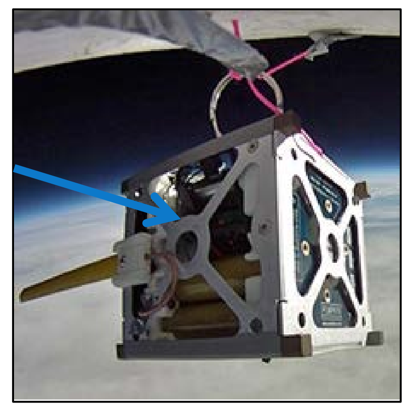
- Picosats (0.1–1 kg) and femtosats (<100 g), are an emerging class of "ultra-small" satellites
  - Smartphone sized satellites with enhanced MEMS sensors
- Can fly low-cost constellations of satellites
  - Multi-point, simultaneous measurements

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



PhoneSat 1.0[2]
~1 kg, ~10×10×10 cm

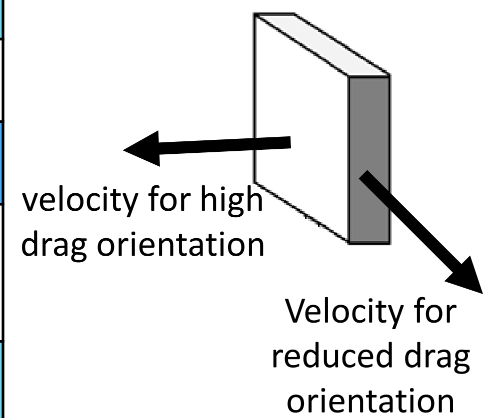
Google-HTC Nexus 1



Challenges for Ultra-small Sats

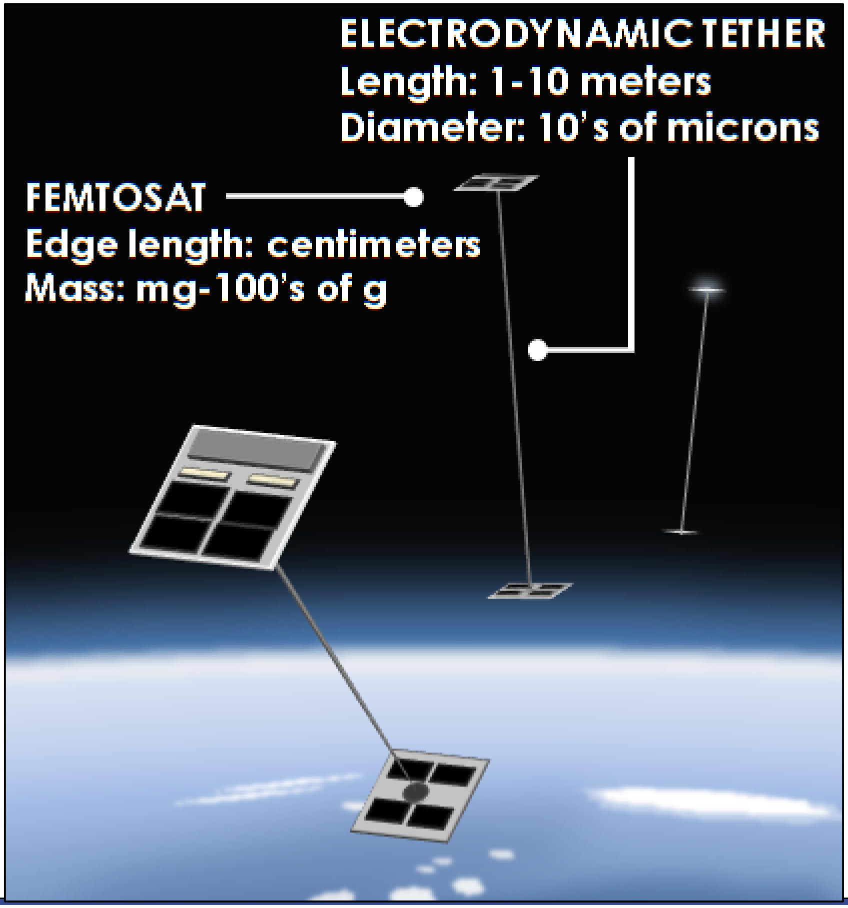
1. Missions **requiring** coordination and maneuverability (*fleets of s/c*)
2. Short orbital lifetime.
3. Limited power and size

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. ($kg \cdot m^{-2}$)	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)



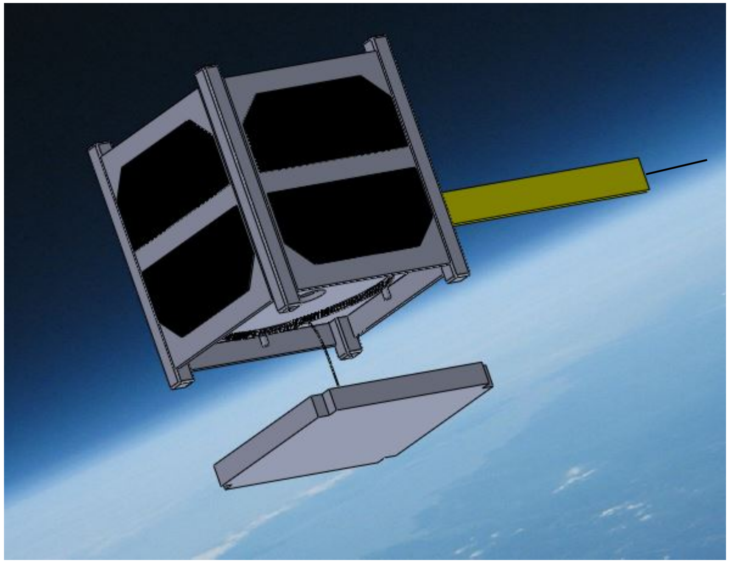
- EDT can provide <u>propulsion</u>
  - Drag make-up
  - Change inclination, altitude, etc.
  - No consumable propellant
- <u>Additional benefits</u> of tether:
  - Provided gravity gradient stability
  - Tether as antenna
  - Ionospheric plasma probe

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

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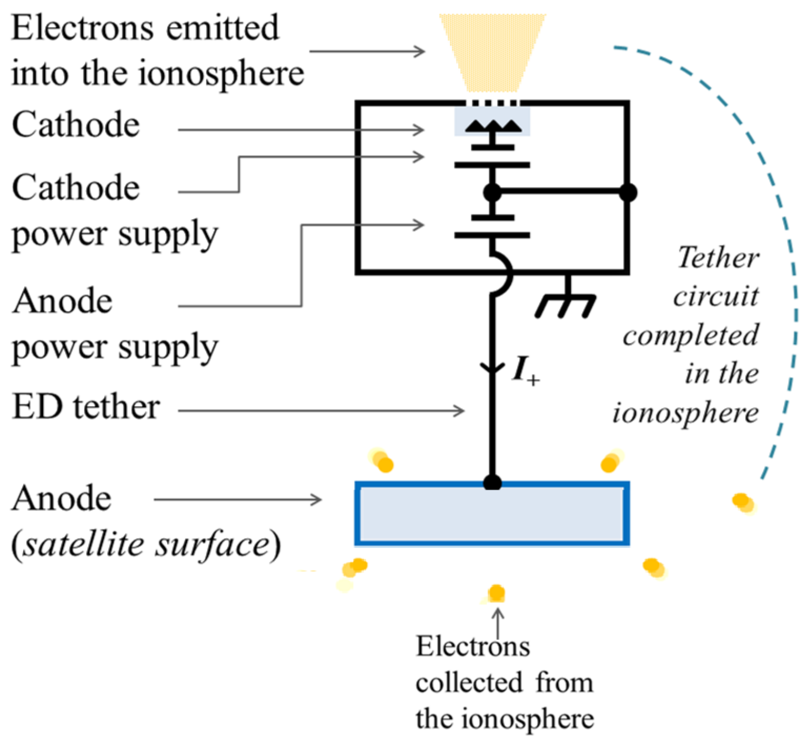
Electrodynamic Tether Propulsion

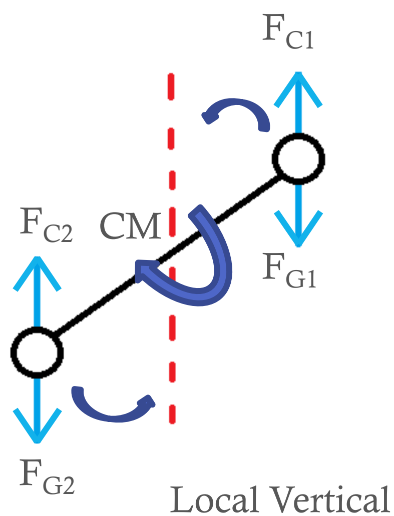
- Exploits the Lorenz force generated by current flow in a magnetic field

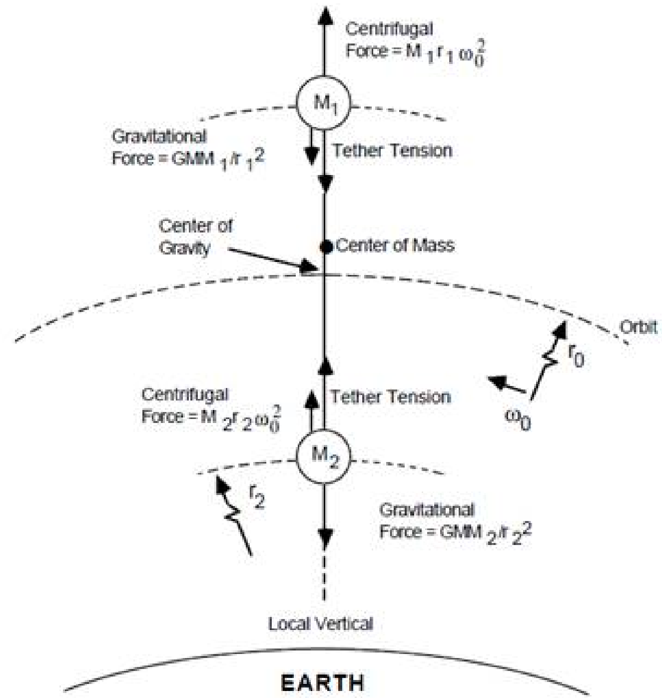
$$\mathbf{F}_{\text{Electrodynamic Tether}} = \int_0^{Tether\_Length} \left(I_{\text{tether}}\, d\mathbf{L}\right) \times \mathbf{B}_{\text{Earth}}$$



Gravity Gradient Stabilization

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



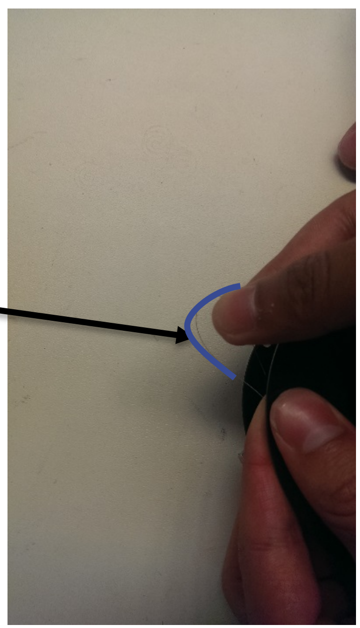


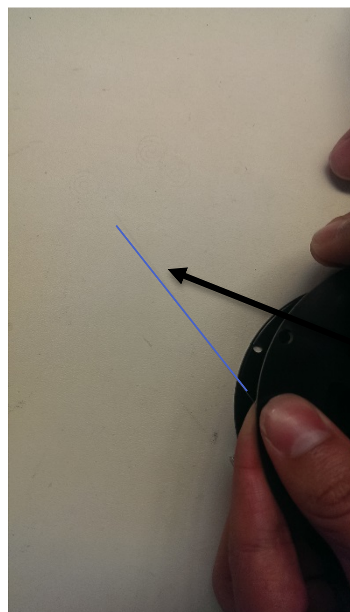
Gravity Gradient Forces[3]

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



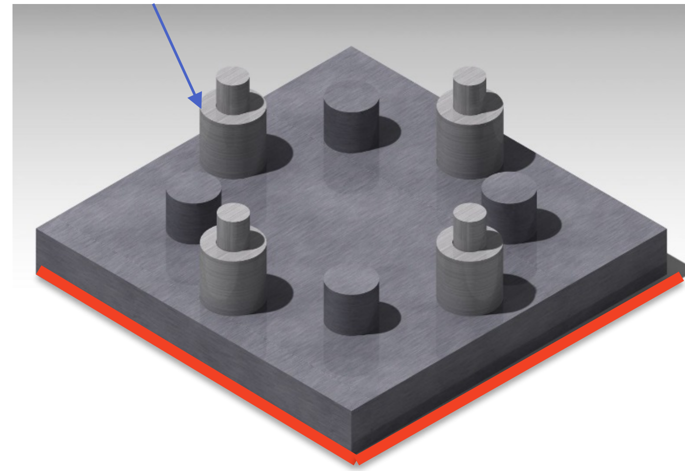


Springs back to original shape

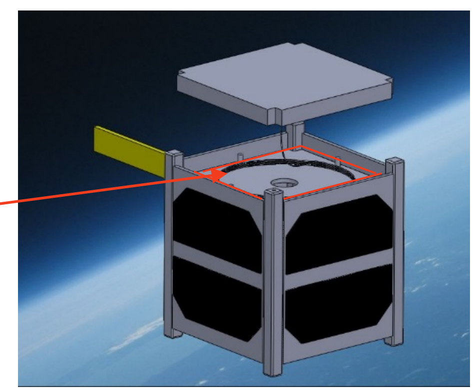
Deployment System

- 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



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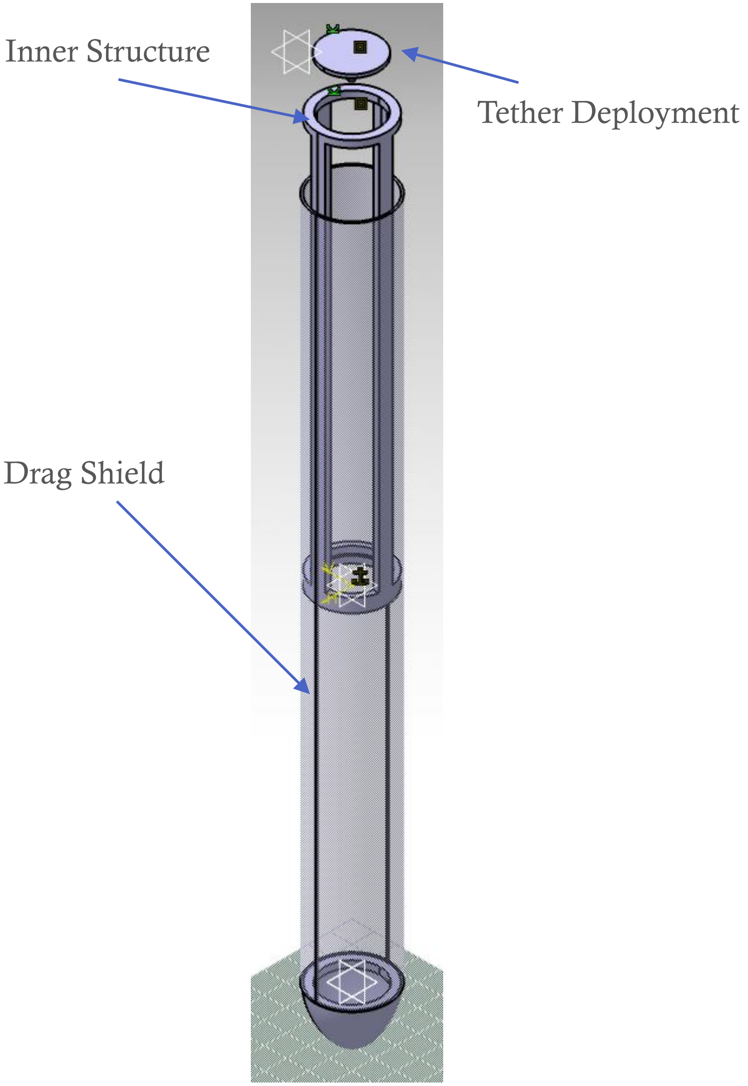

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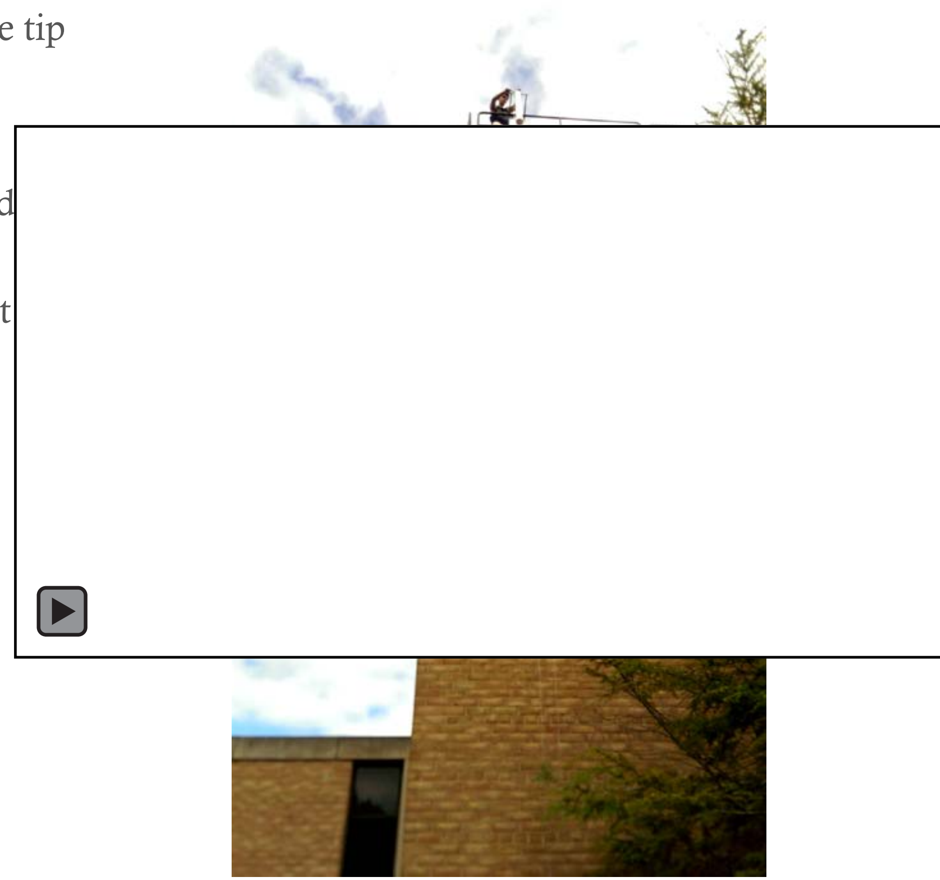
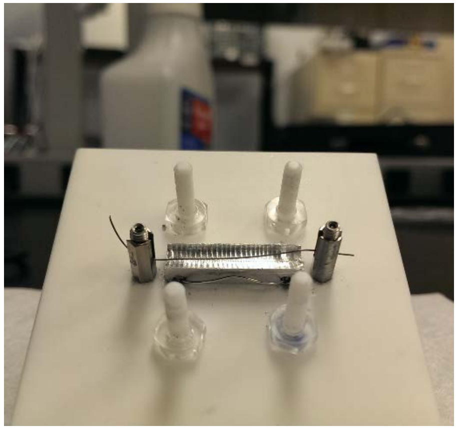
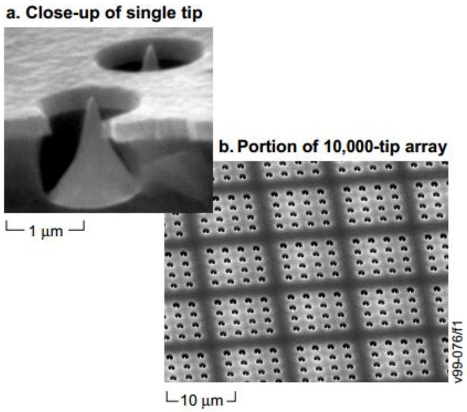


Cathode

- 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



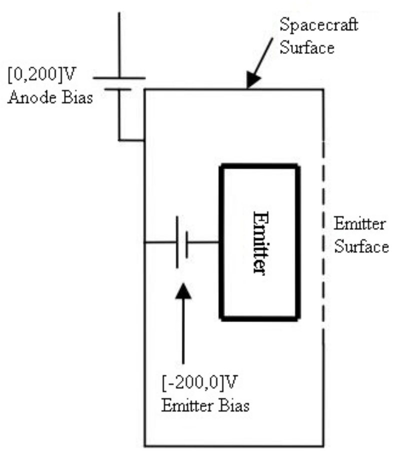
Thermionic cathode



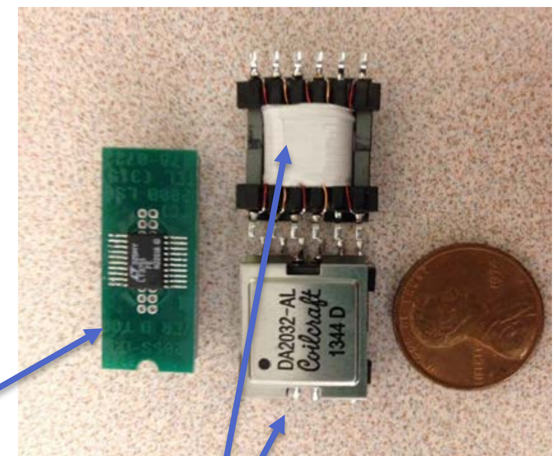
FEAC Cathode[4]

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

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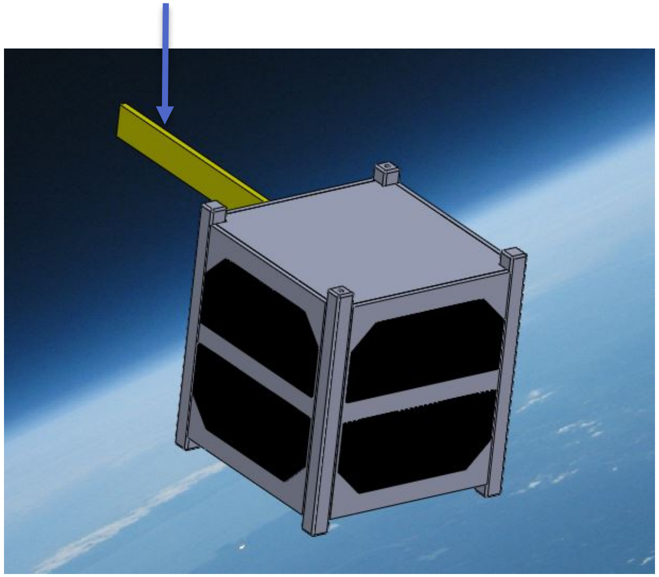
Communications Overview

- 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



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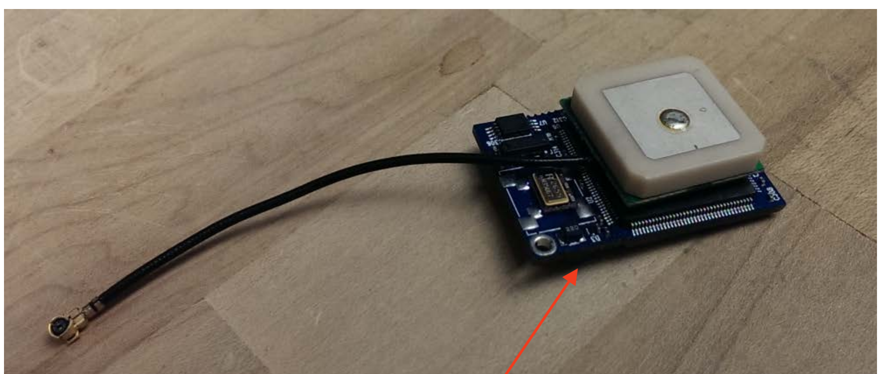
Diagnostics Tools

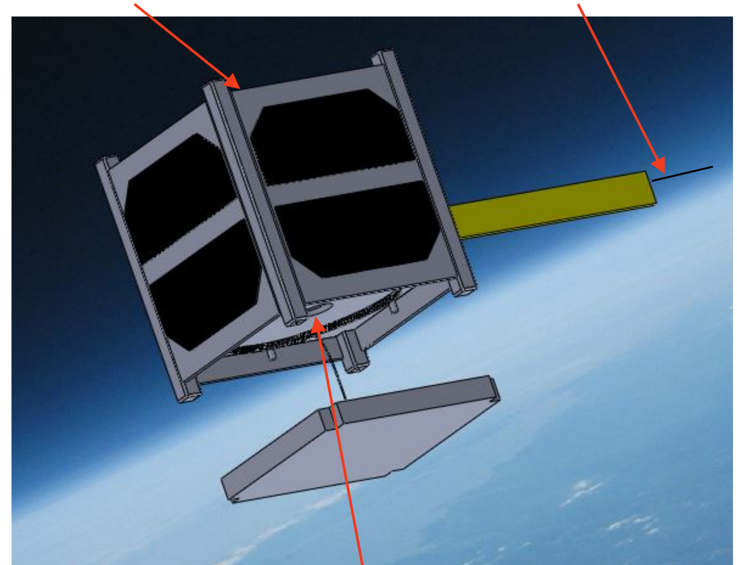
- Langmuir Probe
  - Plasma diagnostics tool to measure ambient plasma characteristics
  - Deployed off of primary antenna boom
- Camera
  - Verifies deployment, end body location
- GPS
  - Position data



GPS Receiver and Patch Antenna

GPS

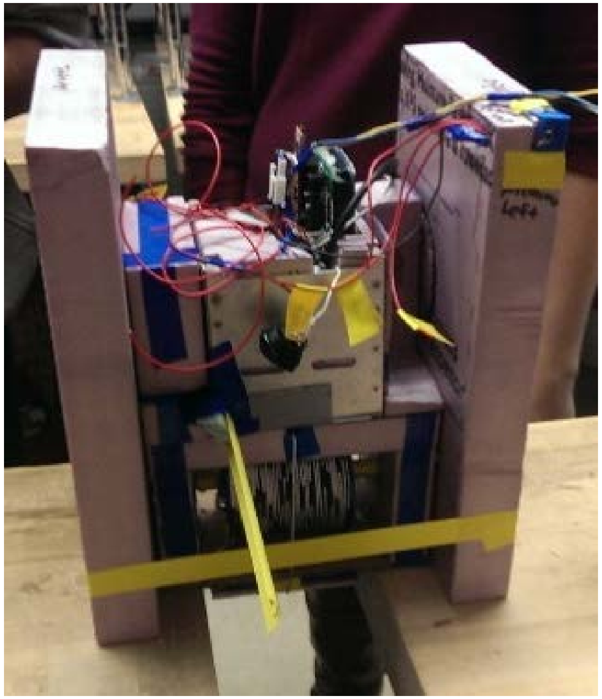
Langmuir Probe



Camera Location

Summer Progress Summary

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



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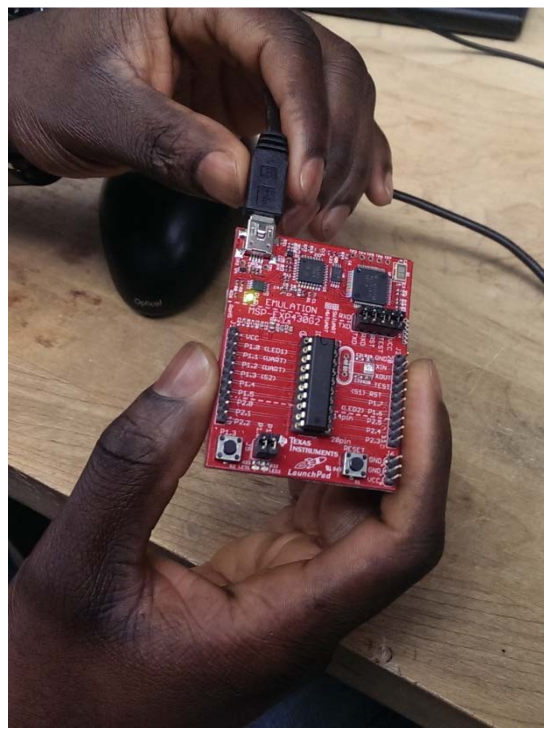
- Successfully completed a high-altitude balloon flight
  - Tested communications and integration of components
- Decision to have distributed network of MSP430s control CubeSat

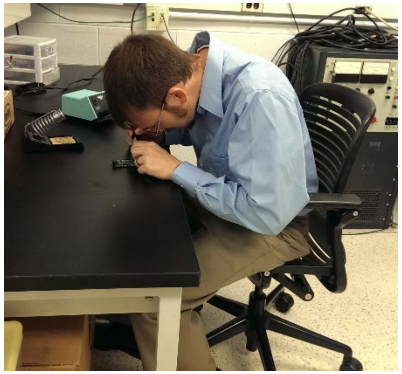


Summer Progress Summary

- 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

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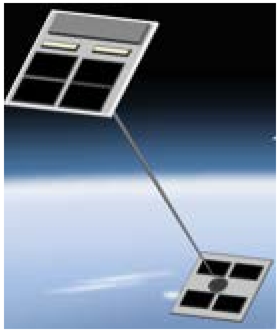

Questions?

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Thank you for your time!

References

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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
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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

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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]

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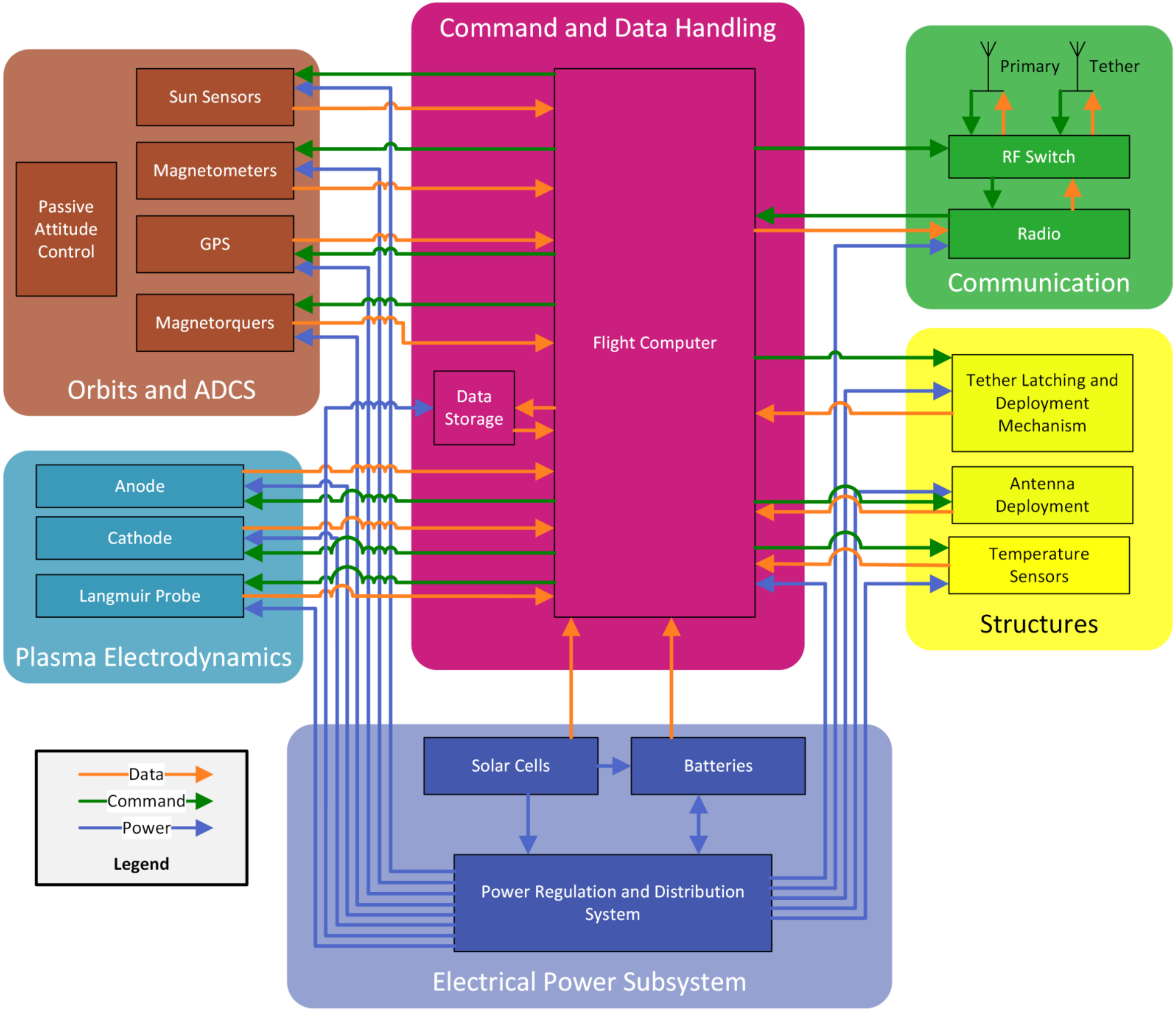
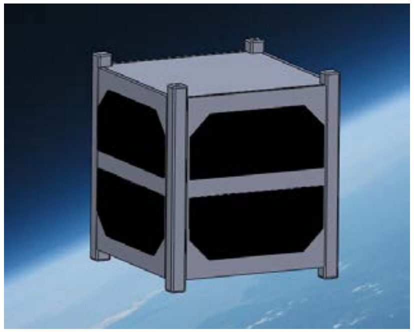
System Block Diagram

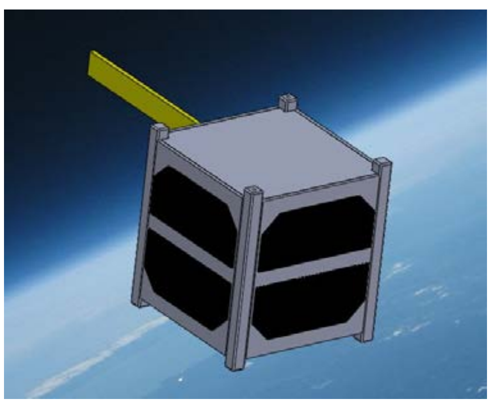


Operations Overview

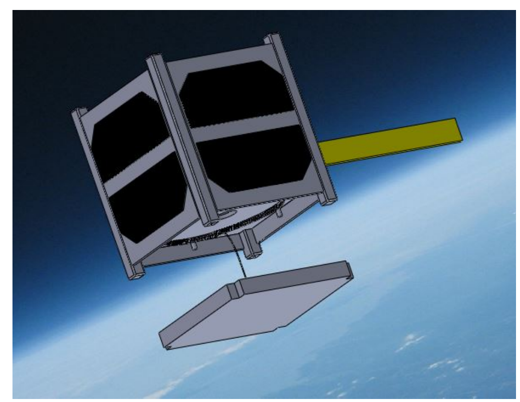
Launch from PPOD



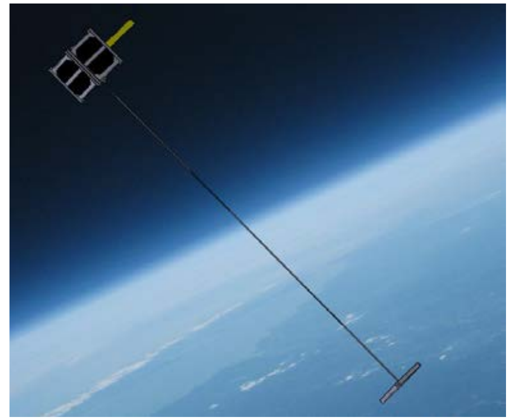
Primary Antenna Deployment and De-tumble



Tether Deployment when Nadir Facing



Science Mission Starts



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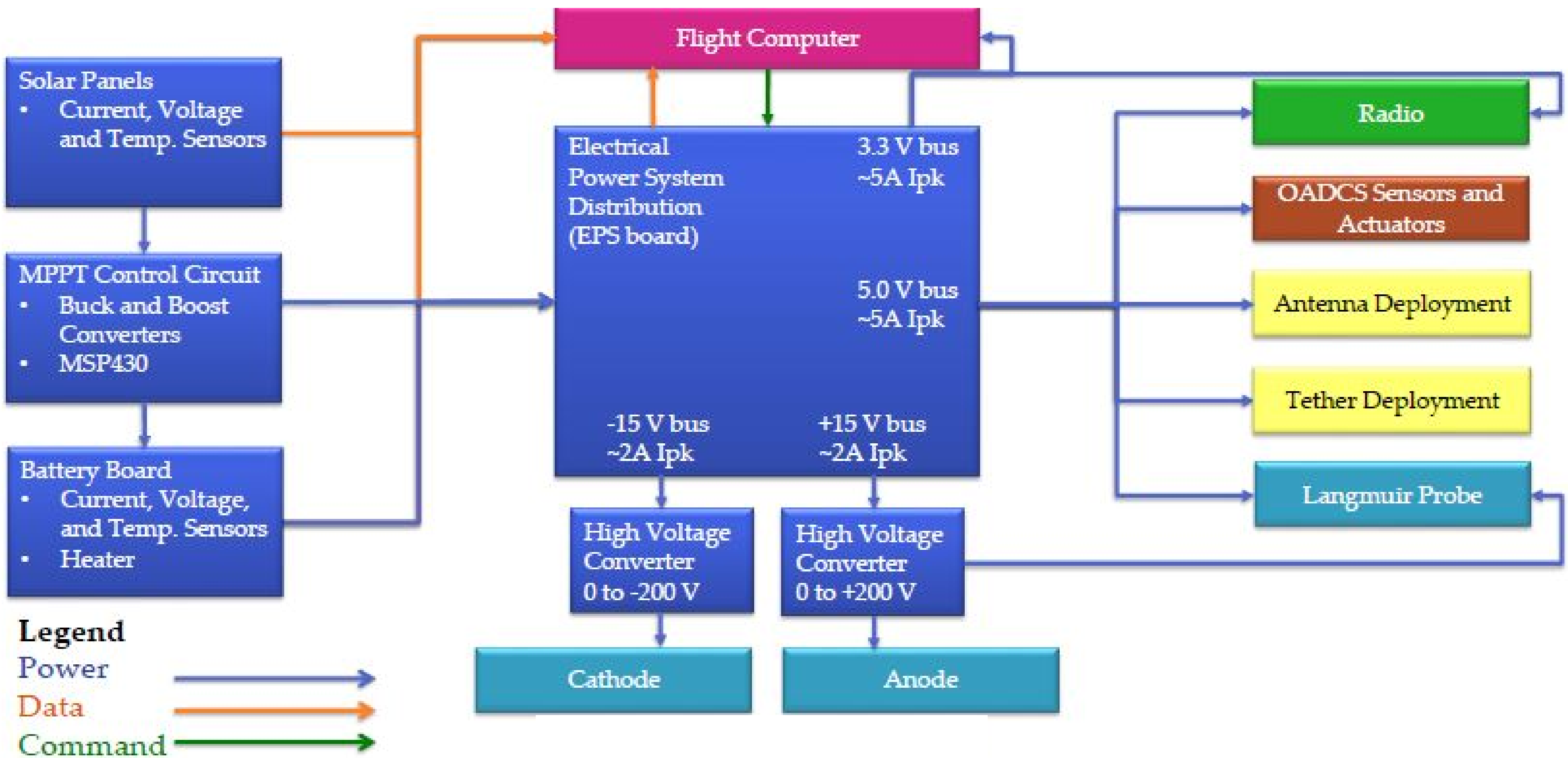
EPS Block Diagram



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

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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