Weather Sensing and Laser Communications for Nanosatellites

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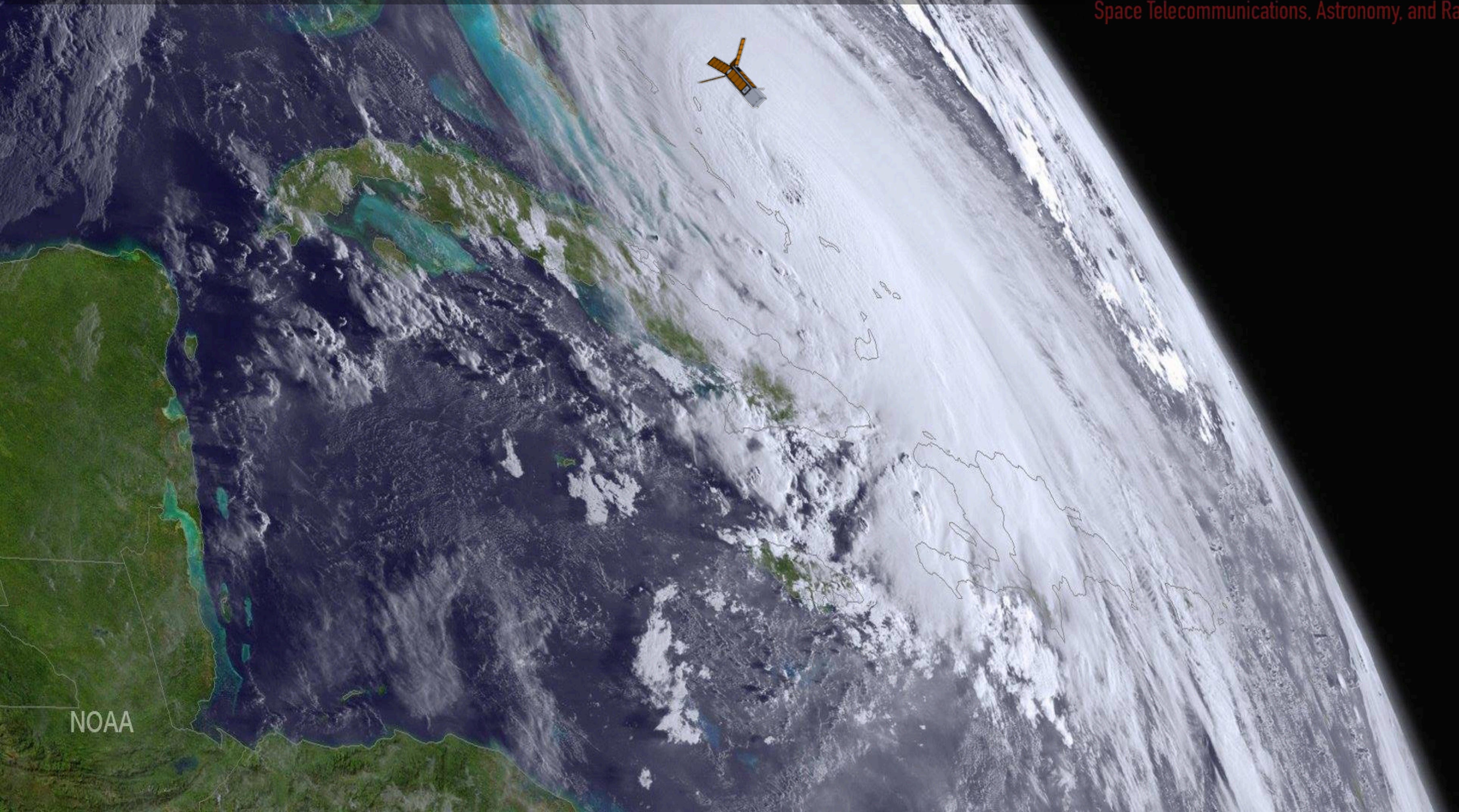
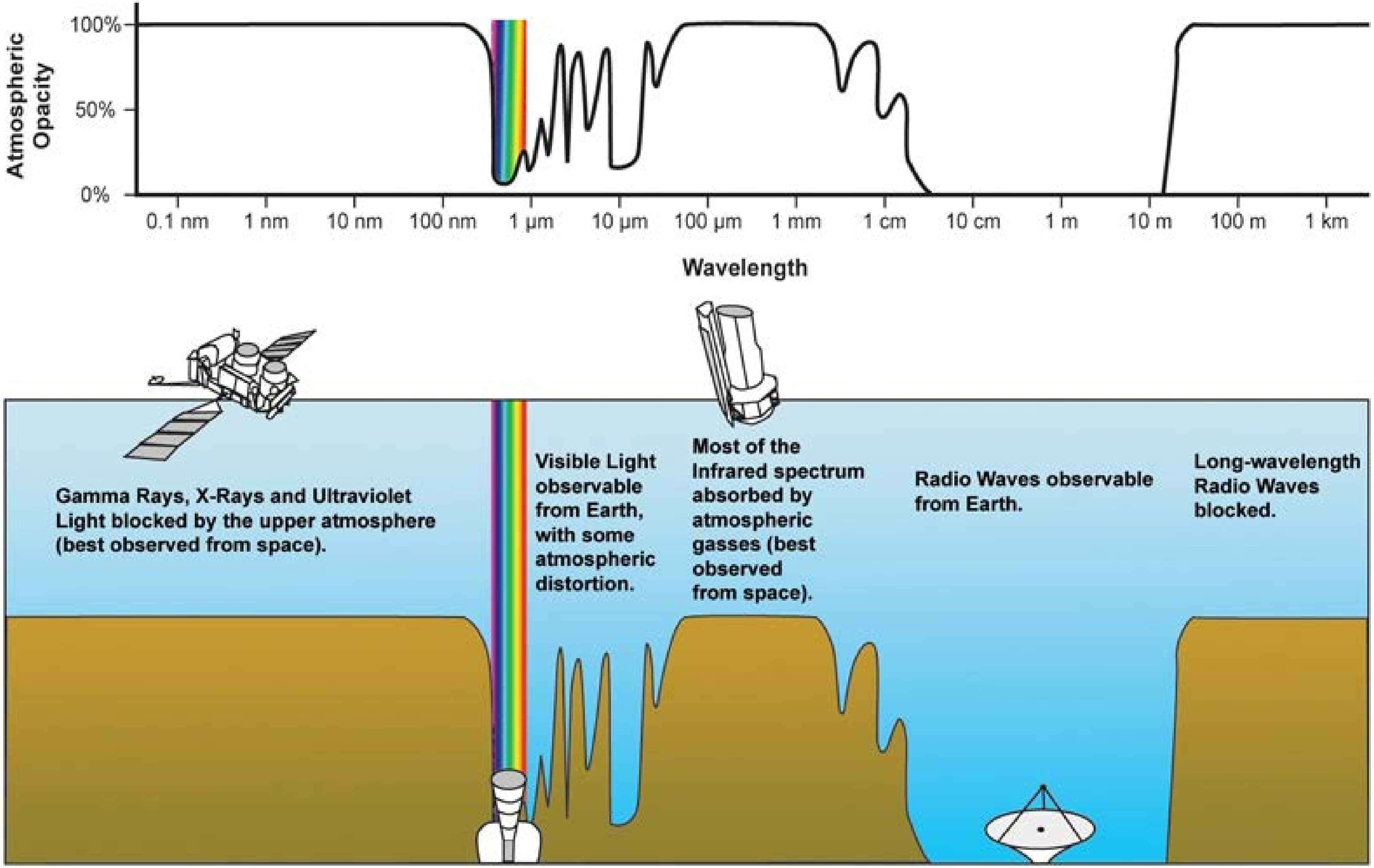
MIT STAR Lab

Space Telecommunications, Astronomy, and Radiation

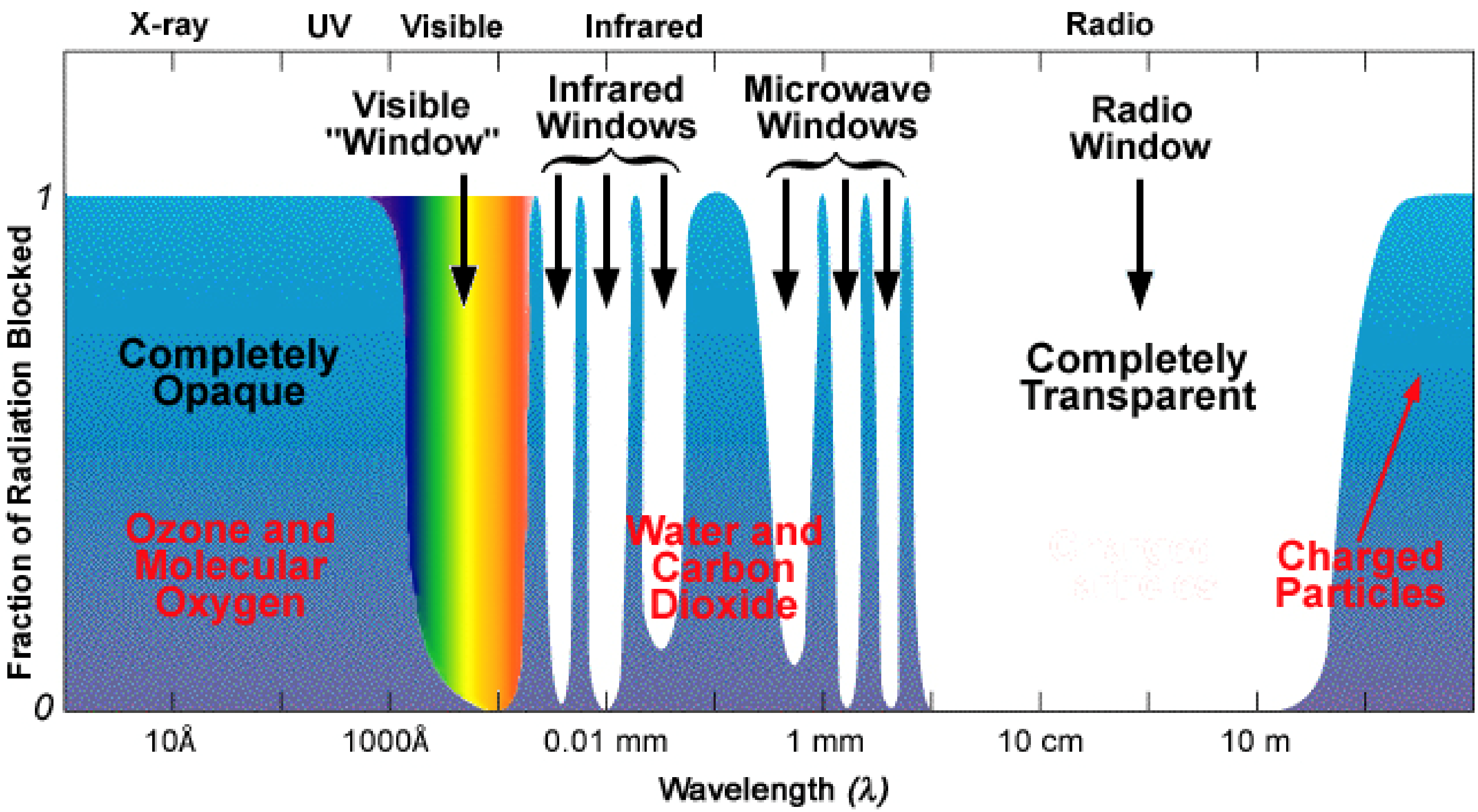


Why Space? Above the Atmosphere



[http://www.ipac.caltech.edu/outreach/Edu/Windows/irwindows.html]

Above the Atmosphere



[http://www22.homepage.villanova.edu/rex.saffer/SESAME/radiation_files/transatmos.jpg]

Overview

- **Introduction**
  - CubeSats 101
- Communications
  - NODE
    - Laser communication downlink
- Laser Occultation
  - Bending angle and T,P profile recovery
    - GPS Radio Occutlation for validation

NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks

Satellite Classification

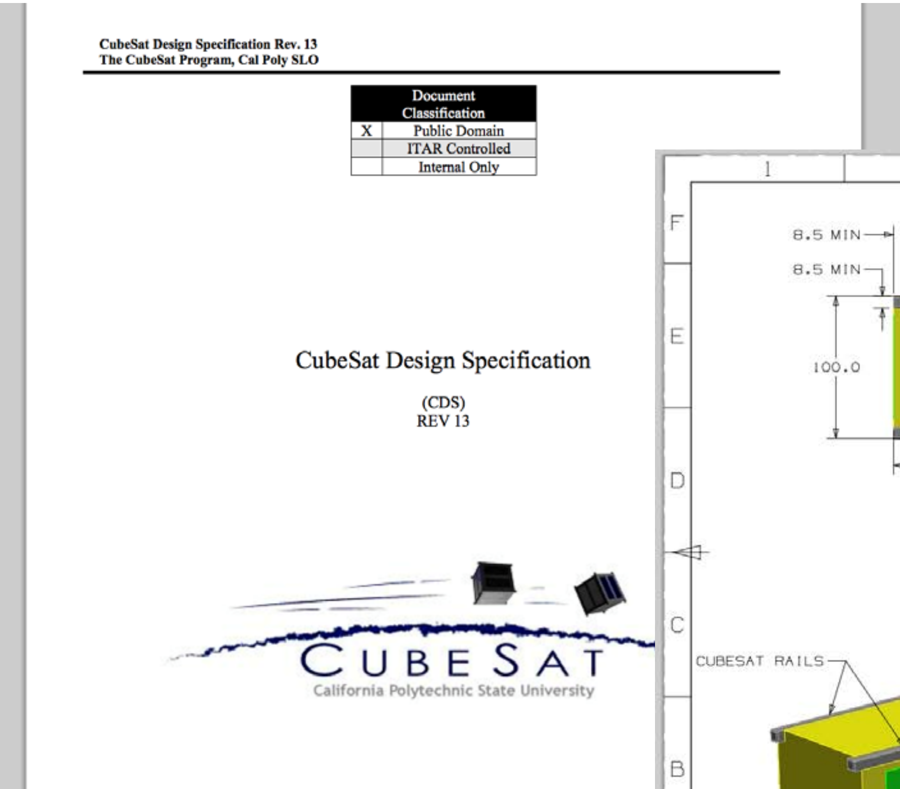
- Small Satellite < 500 kg (all wet mass)
- Microsatellite 10 –100 kg
- Nanosatellite 1 — 10 kg
- Picosatellite 0.1 kg – 1 kg
- Femtosatellite < 0.1 kg
- CubeSat 1U 10 cm x 10 cm x 10 cm cube
- 1U as a building block
- 1.5U, 2U, 3U, 6U, 12U…

CubeSats 101

- On the scene in 1999
  - Jordi Puig-Suari (Cal Poly SLO)
  - Bob Twiggs (Stanford)
  - “OPAL” Orbiting Picosatellite Automatic Launcher
  - *Too complicated*
  - “Beanie babies” vs. “Klondike bars”
- 1 standard CubeSat unit (1U)
  - Volume: 10 x 10 x 10 cm
  - Mass: < 1.33 kg
  - Common sizes: 1U, 1.5U, 2U, 3U…
  - Now 6U… 12U?
- Low cost and short development time
- Increased accessibility to space

https://directory.eoportal.org/web/eoportal/satellite-missions/o/opal, credit SSDL

CubeSat Design Specification


CubeSat Design Specification Rev. 13
The CubeSat Program, Cal Poly SLO

Document Classification	
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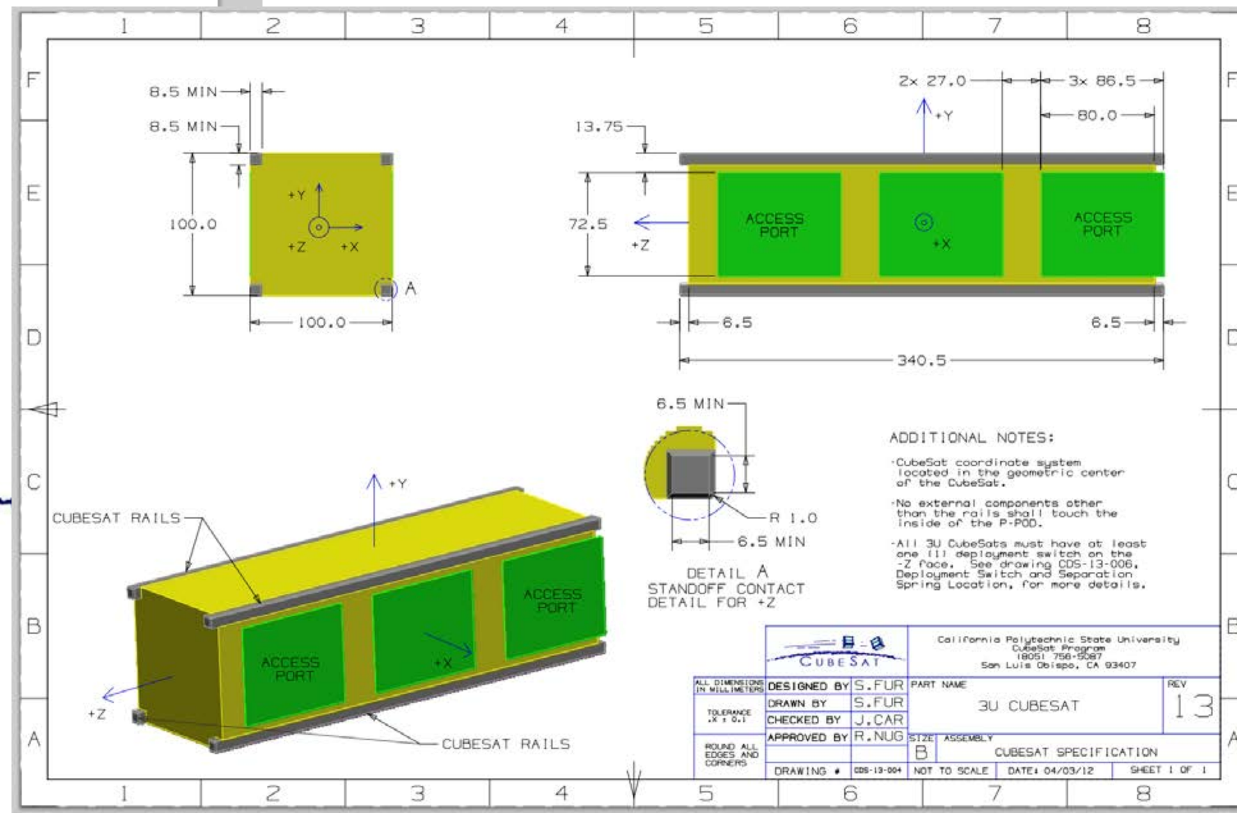
	Internal Only

CubeSat Design Specification

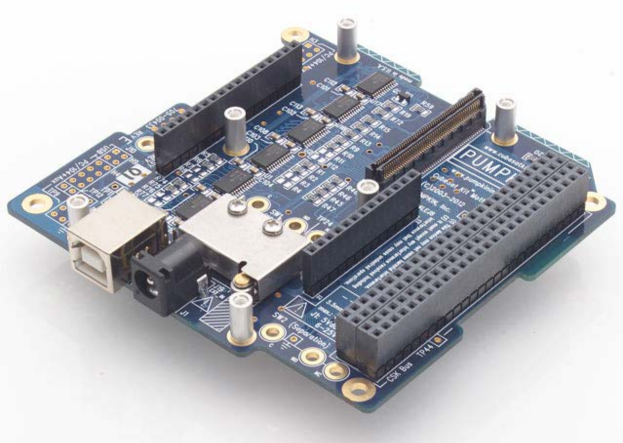
(CDS)
REV 13

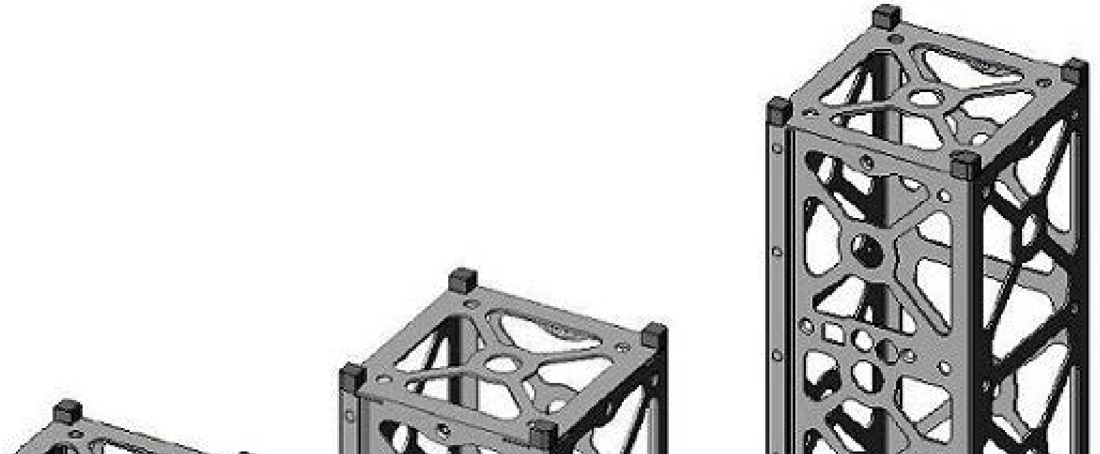
CUBESAT
California Polytechnic State University

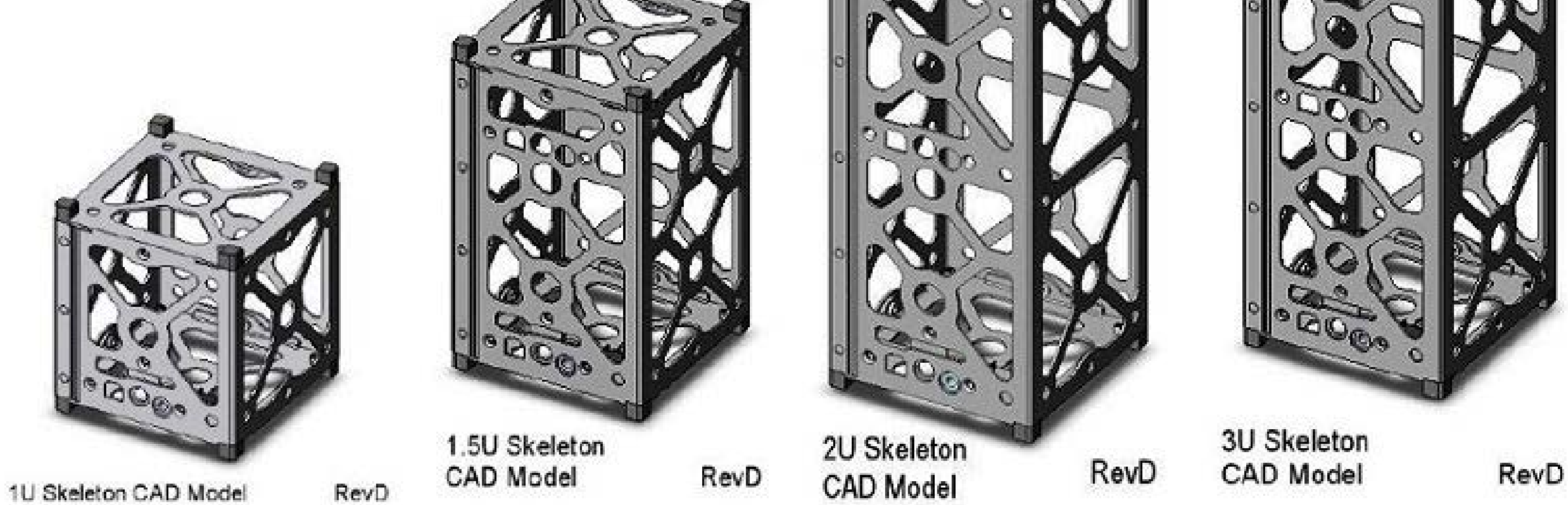


Tall, Grande, Venti…

Pumpkin, Inc. Motherboard

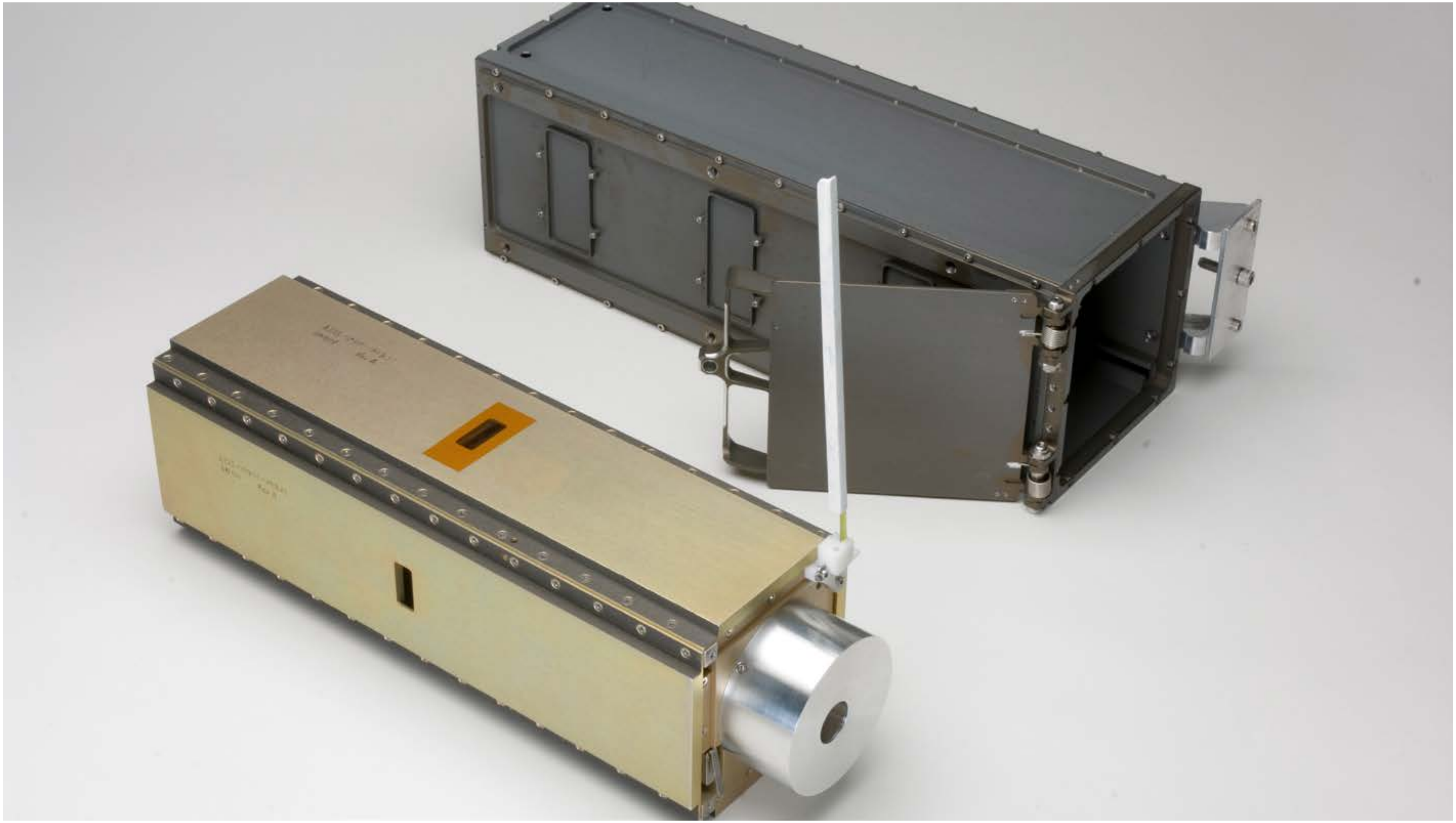






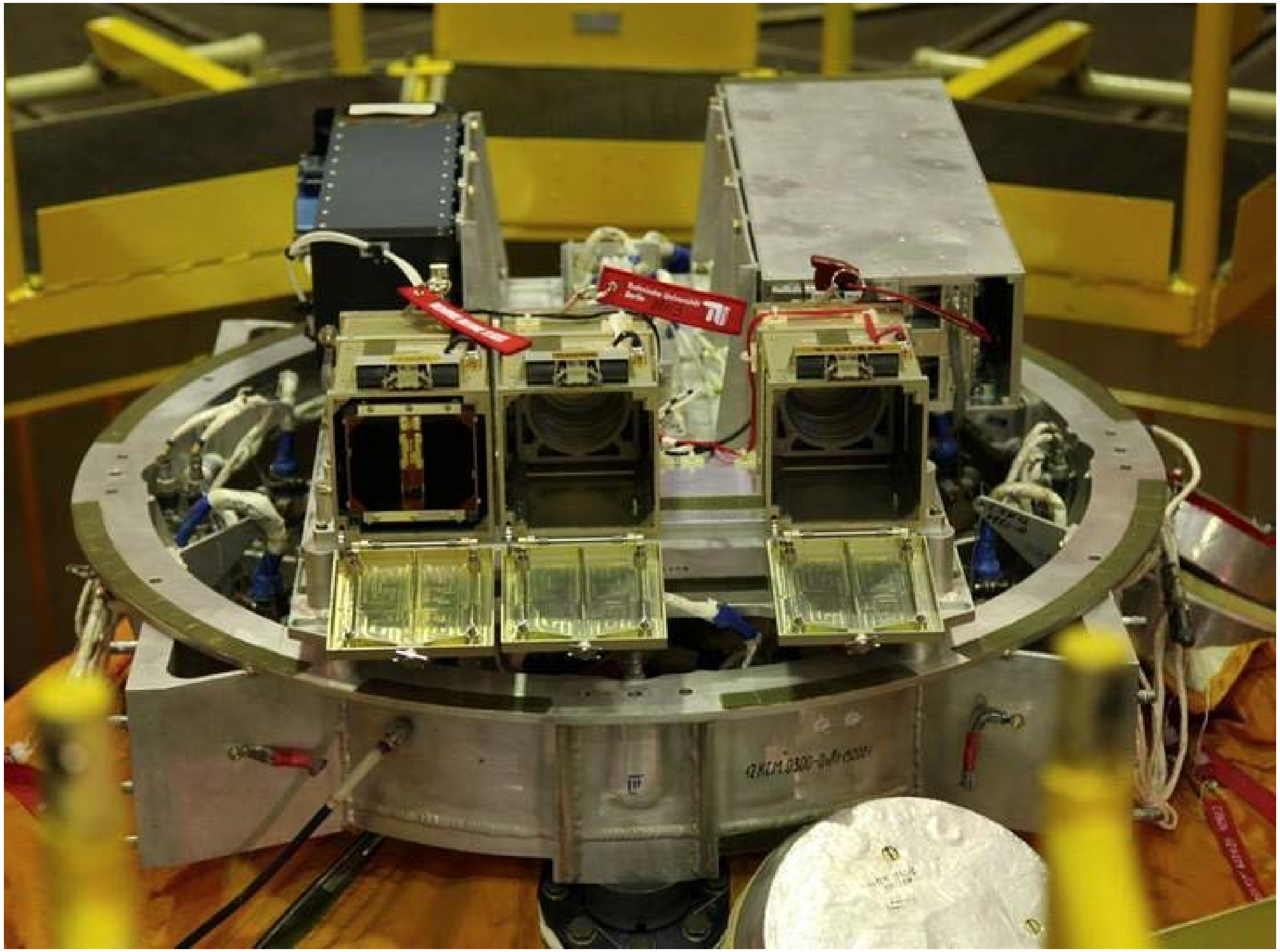
http://ccar.colorado.edu/asen5050/projects/projects_2013/Naik_Siddhesh/Cubesat.JPG

Poly-Picosatellite Orbital Deployer



http://www.nasa.gov/centers/ames/images/content/152693main_genebox-015.jpg

Launch integration on Rocket



CubeSat deployment pods on top of the Bion-M1 spacecraft: BeeSat-2, BeeSat-3 and SOMP in front; OSSI-1 (1U) in a 3U-Pod back left; DOVE-2 (3U) in back right. *http://amsat-uk.org/tag/beesat-2*

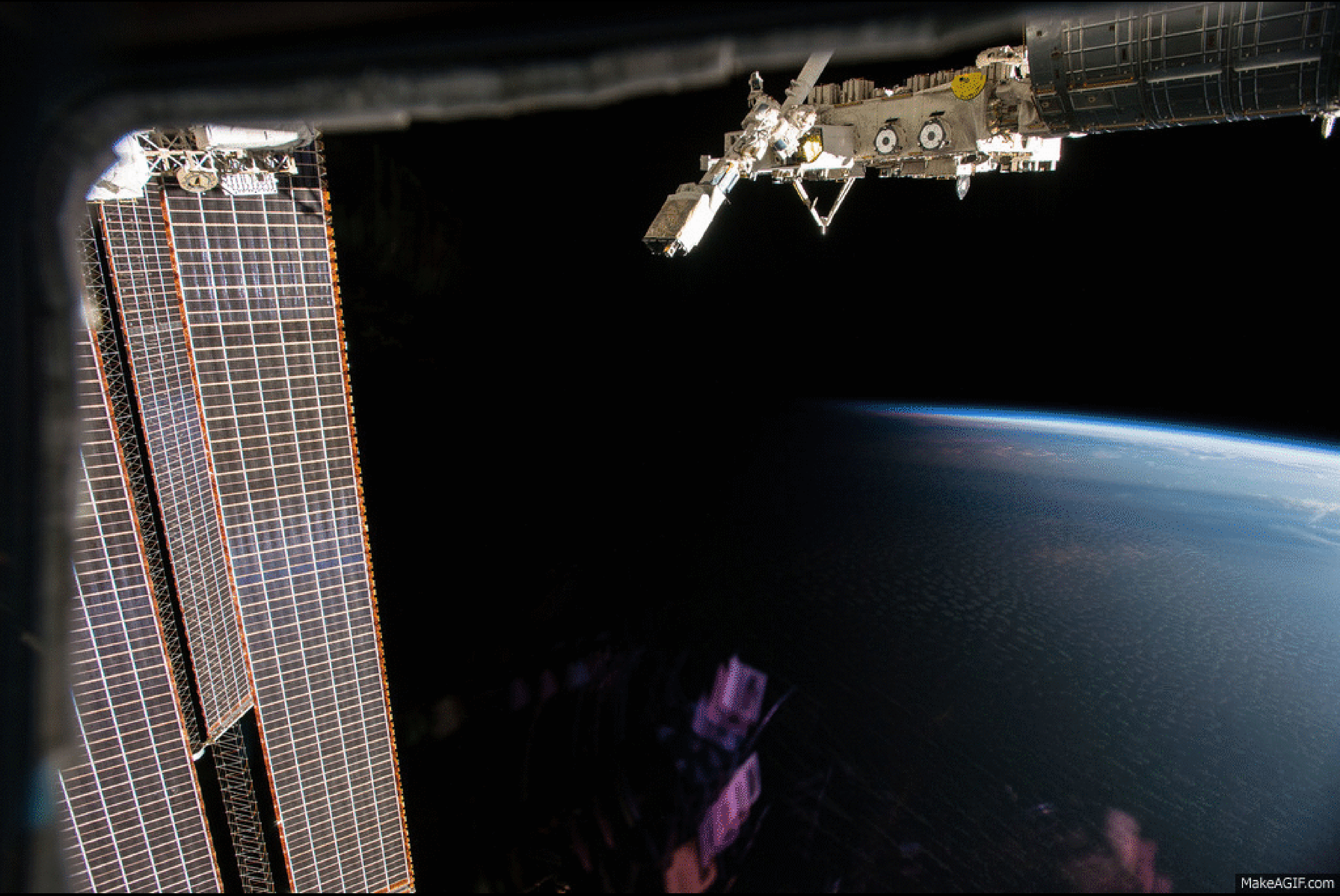
Launch from Space Station

- Deliver to NanoRacks
- Get integrated into NRCSD
- Get integrated into Cargo
- Cargo integrated into Cygnus
- Cygnus shipped to launch site
- Cygnus integrated into rocket
- Antares launch
- Cygnus separation
- Cygnus rendezvous with ISS
- Cygnus unpacked
- Cargo unpacked
- NRCSD integrated to slide table
- Slide table through airlock
- NRCSD onto JEMRMS
- Deployment

Cygnus being unberthed from Harmony module

http://www.flickr.com/photos/nasa2explore/12644390754/


DESCO


MakeAGIF.com

- Space is hard
  - Rocket acoustic/phys vibe
  - Rockets can fail/explode
  - It’s far away
  - Vacuum
  - Microgravity
  - Hot / cold temp. swings
  - Radiation / solar storms
  - Things break – *a lot*
  - Hard to find small objects
  - Lots of safety paperwork
  - Expensive to get there
  - Expensive ground staff

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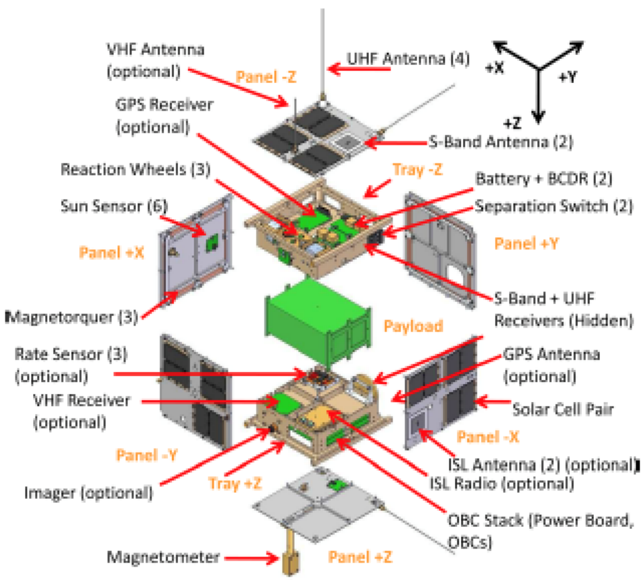
- Space is also awesome
  - Helps us answer “why are we here?”
  - Incredible ability to observe Earth

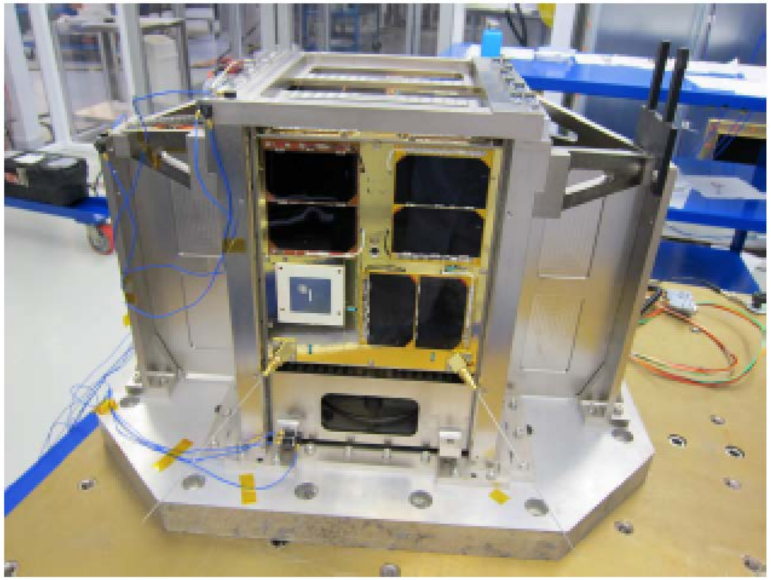
CubeSat Formation Flying Demonstration

- CanX-4 and CanX-5 have demonstrated relative navigation **using carrier-phase differential GPS**
  - *Newman et al., SmallSat 2015*
  - Separations from 1 km to 50 m
    - Sub-meter position accuracy
  - ATO: along track orbit
  - PCO: projected circular orbit

Table 5: Summary of formation control results

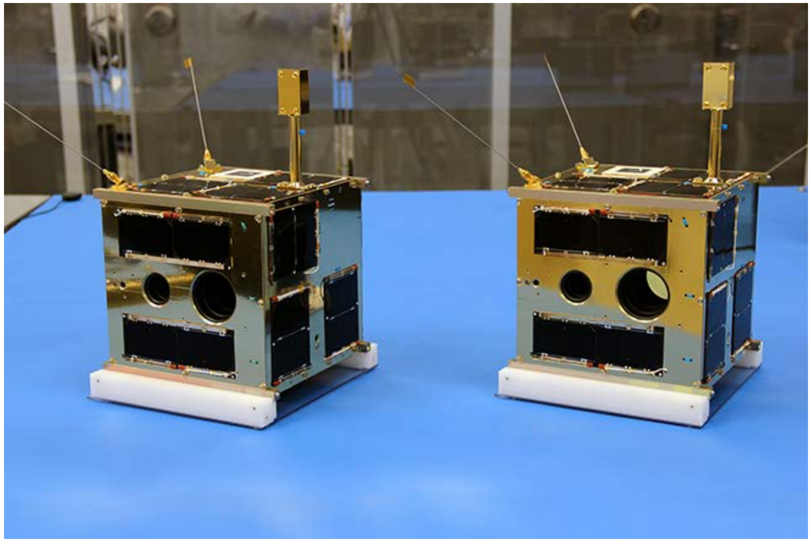
Formation	$\Delta v_{expected}$ [cm/s/orbit]	Δv_{actual} [cm/s/orbit]	Δr_{actual} 3D-RMS [m]	Δr_{actual} 3D-RMS [m]
ATO 1000	3.65	5.55	0.590	0.453
ATO 500	1.71	1.62	0.345	0.513
PCO 100	0.99	1.63	0.517	0.602
PCO 50	3.07	1.27	0.554	0.594





CubeSat Inertial Pointing Capability

- A study of variability of massive, luminous stars and supernova
- BRITE (BRIght Target Explorer) Constellation
  - 7 kg, 20 cm cube nanosatellites
  - University of Toronto and collaborators
- Multiple satellites help with continuous viewing
- Different filters on satellites
- Demonstrated **up to 12 arcsec RMS pointing over 15 min**



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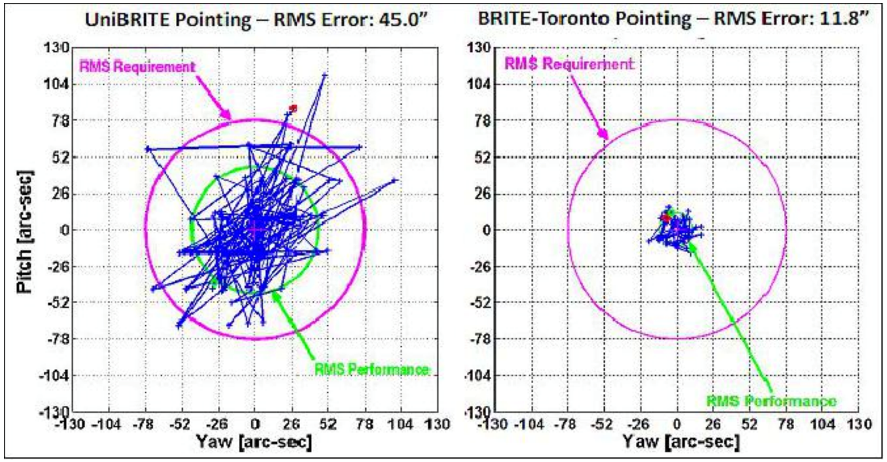
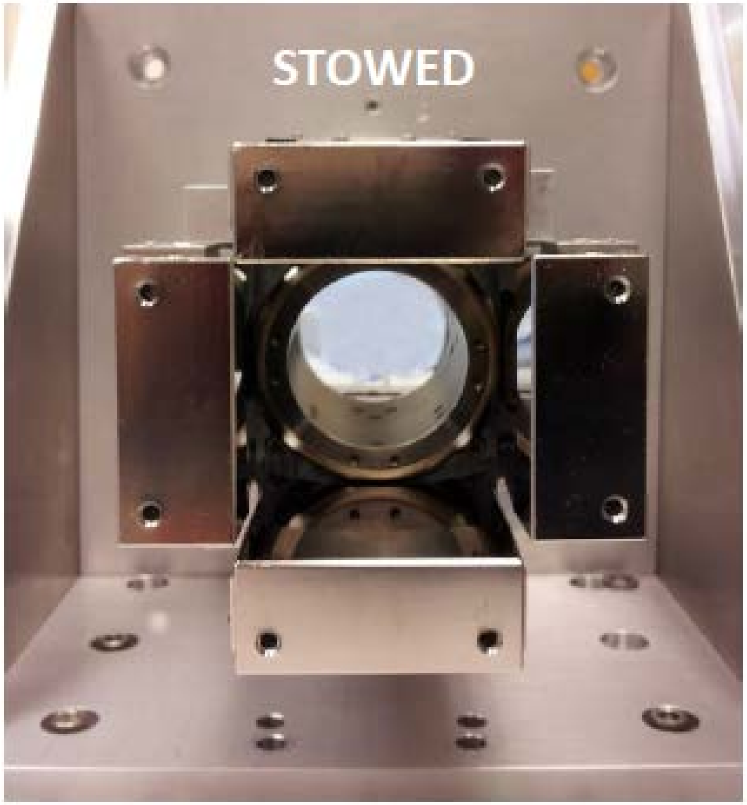
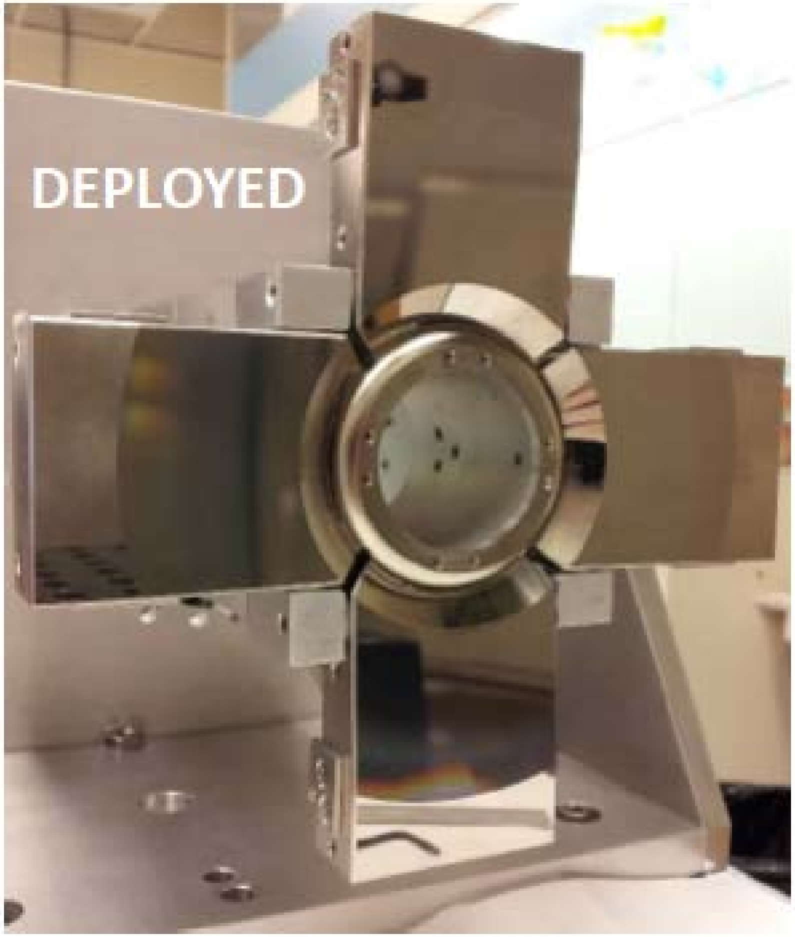


Fighting the "but, the tiny aperture" issue

- Utah State University Space Dynamics Laboratory "Petal"
  - Deployable Petal Telescope

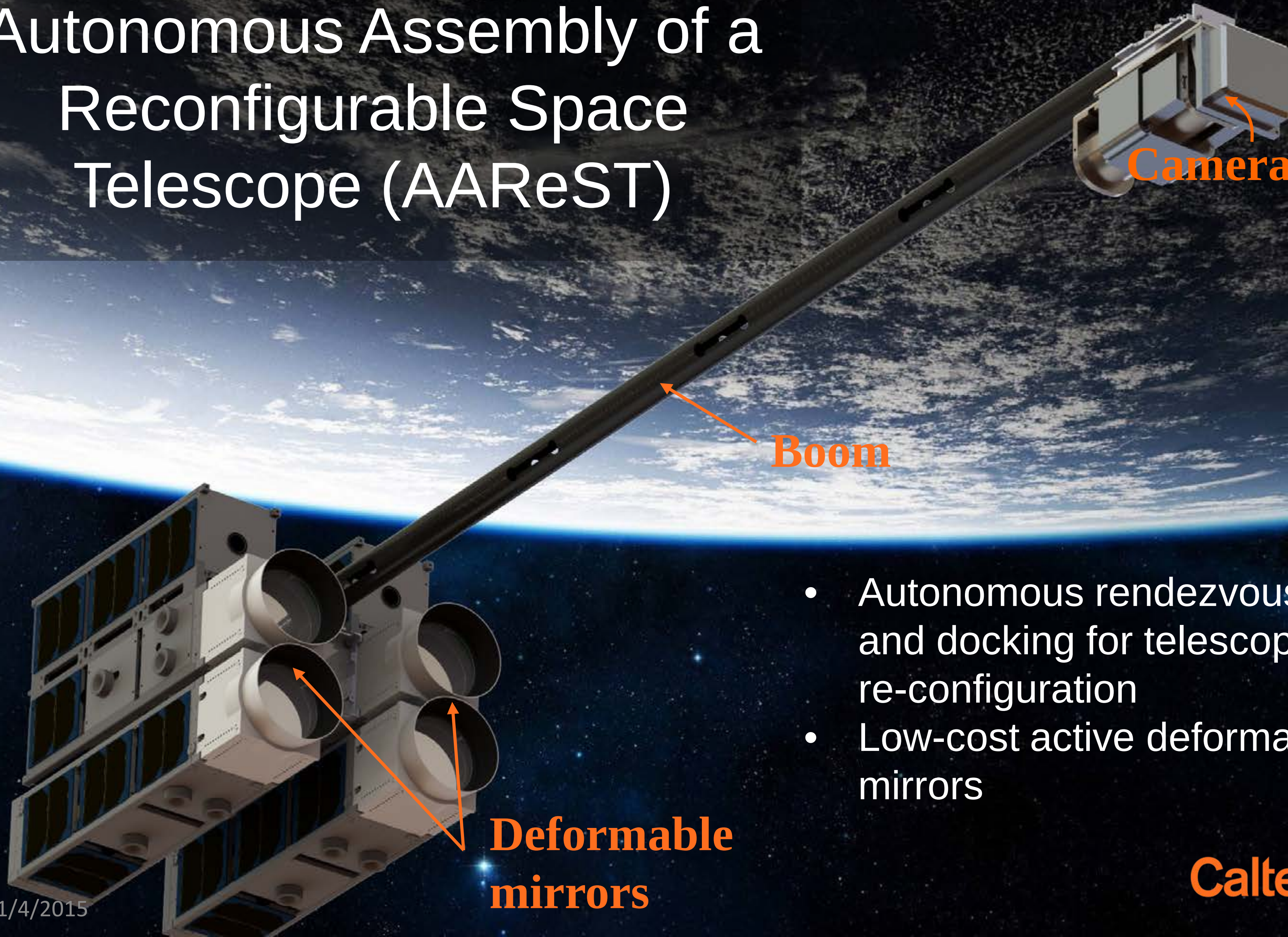




http://www.sdl.usu.edu/downloads/petal-telescope.pdf

Deployed/Distributed Apertures

Autonomous Assembly of a Reconfigurable Space Telescope (AAReST)

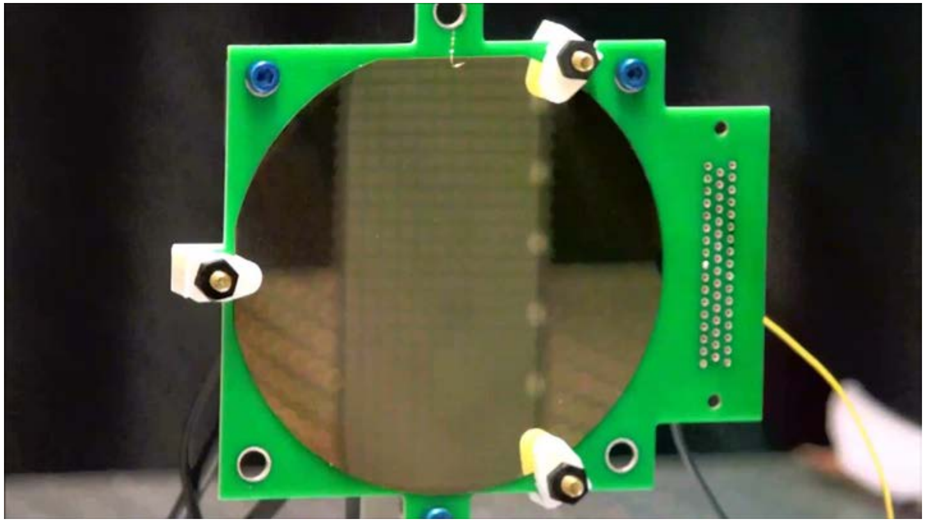


- Autonomous rendezvous and docking for telescope re-configuration
- Low-cost active deformable mirrors

Caltech

Improved optical quality of apertures

- AAReST deformable mirrors for on deployables



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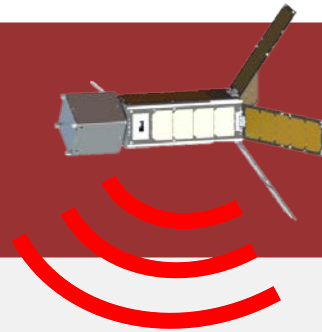
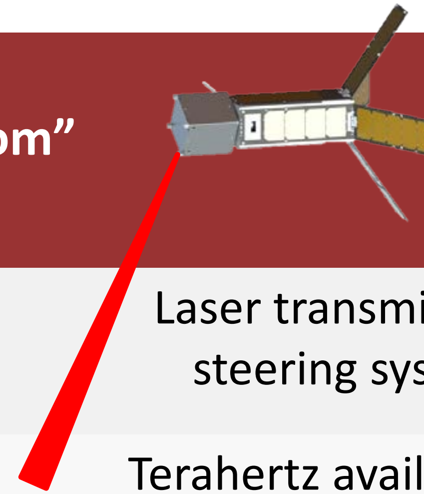
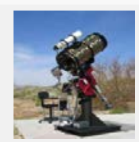
NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks

Optical vs. RF

	Radio	Optical "Lasercom"
Space Segment	Radio modem, patch antenna	Laser transmitter, steering system
Spectrum / License	~Megahertz Heavily regulated	Terahertz available Unregulated
Ground Segment	Large dish (20+ ft) and facility $1M and up	1 ft amateur astronomy telescope $100k







Lasercom offers **superior link efficiency** (less power per bit) due to its ability to better direct signal to receiver.

Comparison of RF and Optical

- TX aperture is 30 cm
- RX aperture is 30 cm
- Link range is 700 km (LEO)
- Receiver sensitivities typical for 1 Gbps link

	Optical λ = 1000 nm	RF (10 GHz) λ = 3 cm	Units
TX Power (P_t)	0	0	dBW
TX Losses (L_t)	-2	0	dB
TX Aperture (G_t)	119	30	dB
Path Loss (L_{path})	-259	-169	dB
RX Aperture (G_r)	119	30	dB
RX Power (P_r)	-23	-109	dBW
RX Sensitivity	-97	-114	dBW
Margin	**74**	**5**	**dB**

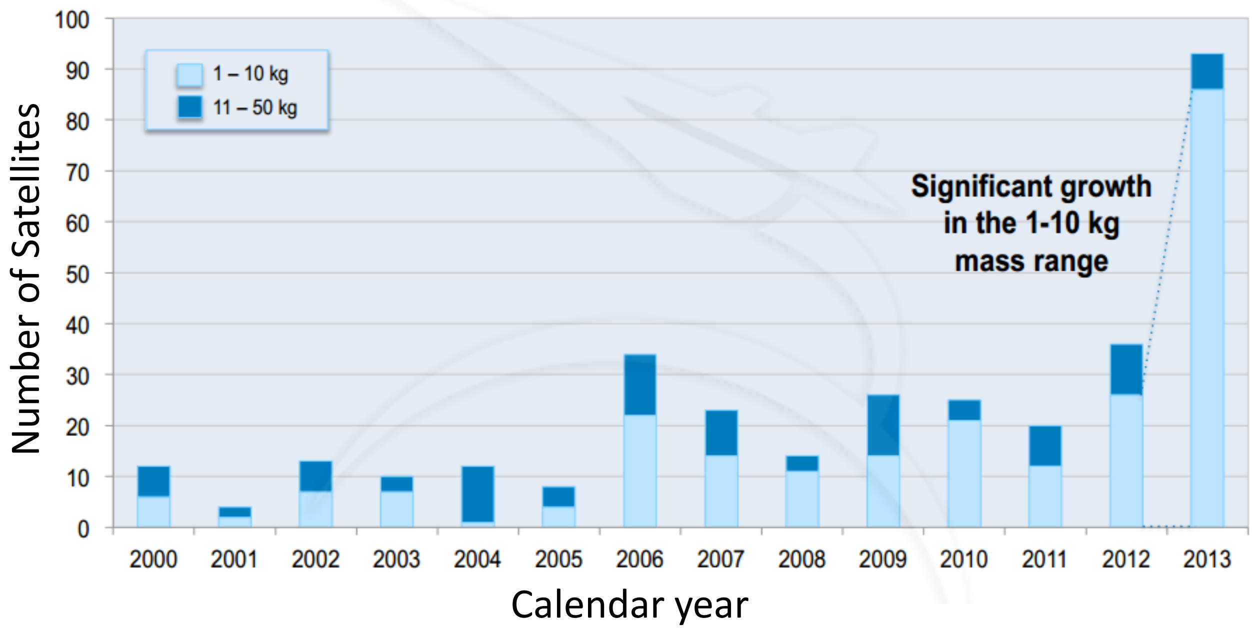
Adapted from: Caplan, D. "Free-Space Laser Communications", 2008

All system parameters are matched, except wavelength

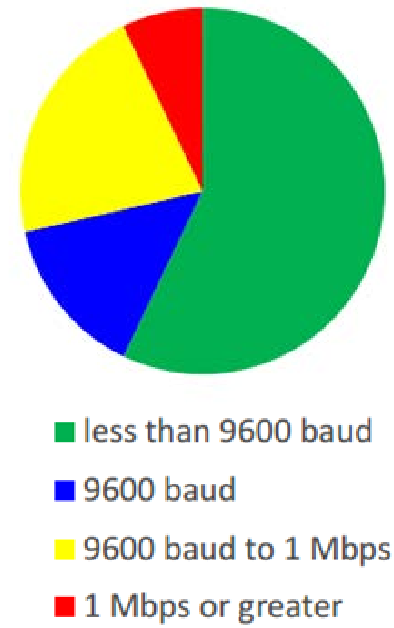
Optical system has a **70 dB advantage**

Motivation

- Rapid growth of small satellite market
- Increasing downlink demand from science payload
- Limited capability from CubeSat RF systems



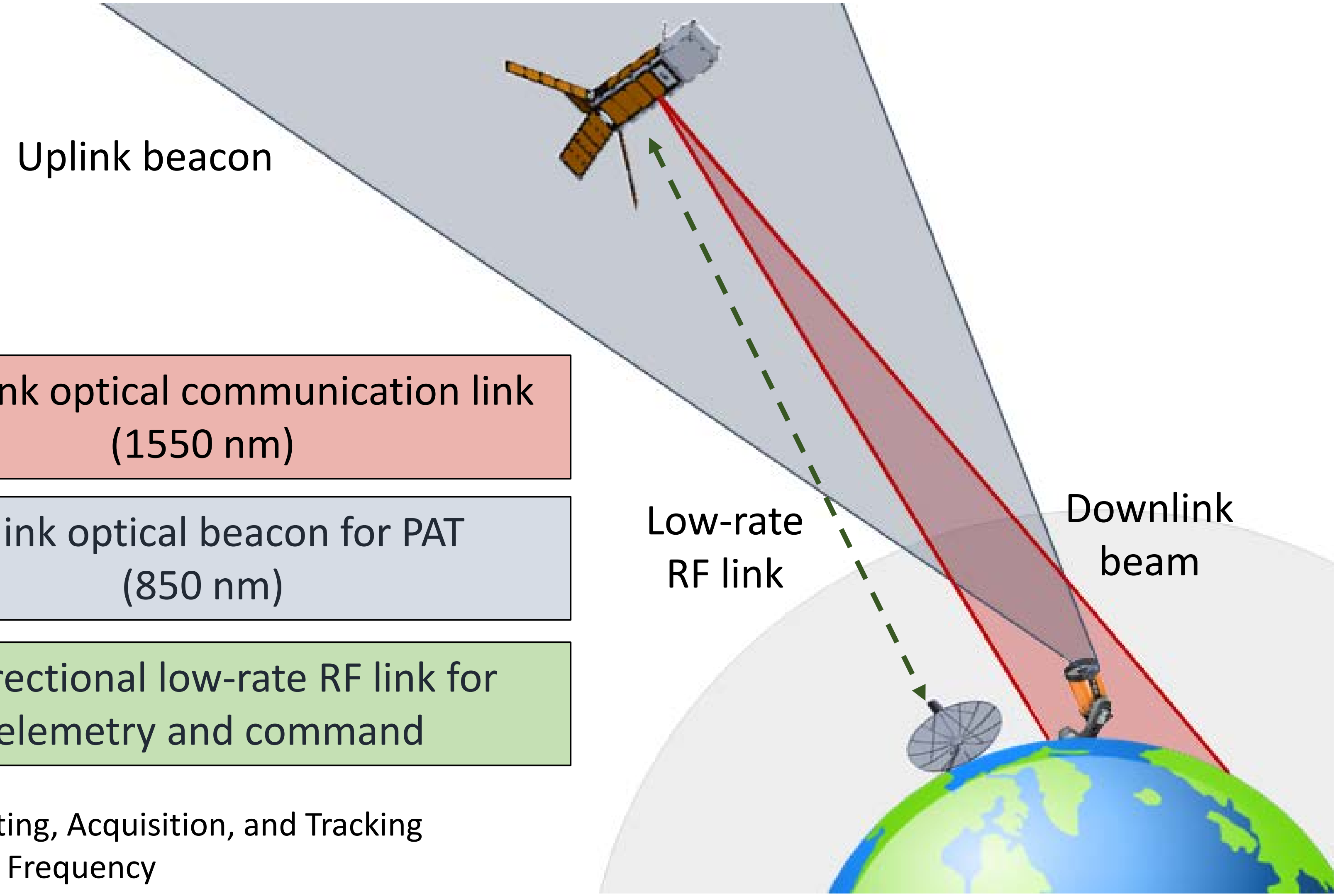
Number of small satellites (1-50 kg) launched per year[1]



CubeSat communication capabilities[2]

Nanosatellite Optical Downlink Experiment (NODE)

NODE Architecture



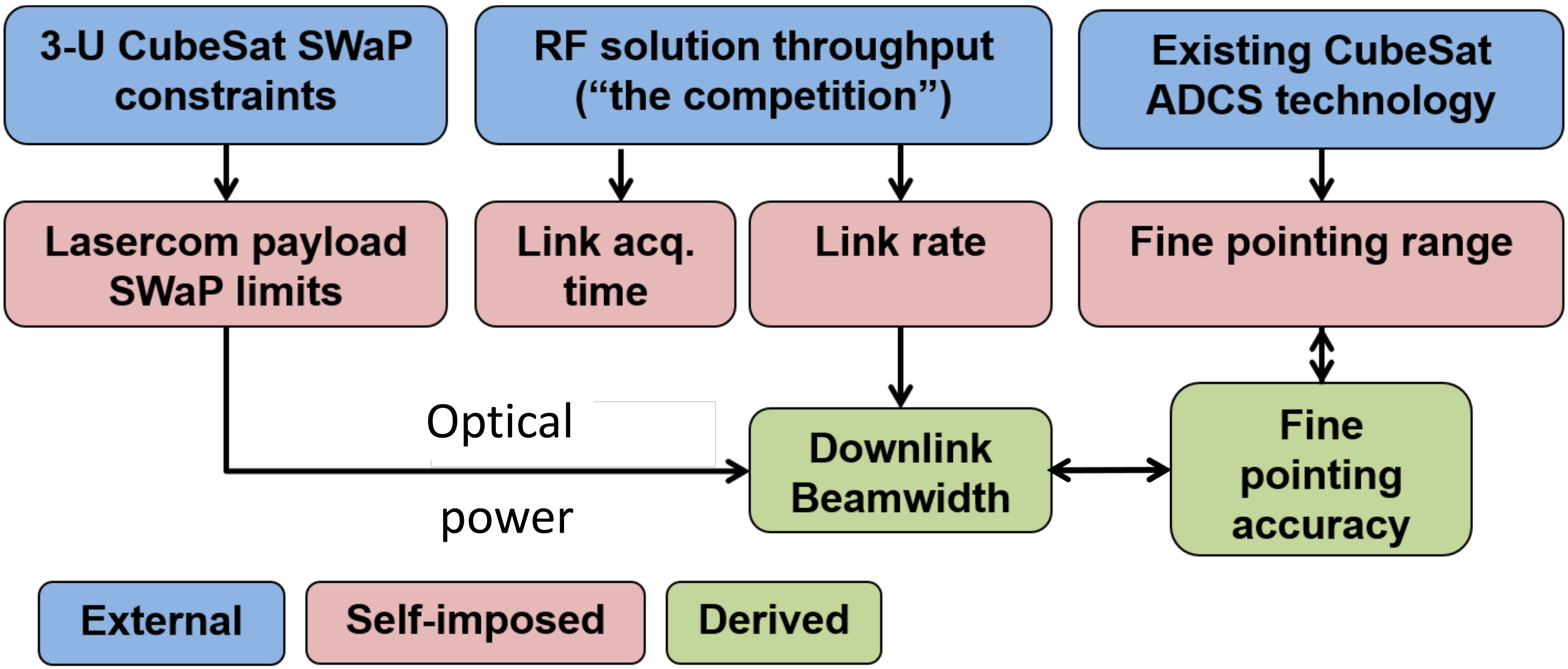
Downlink optical communication link (1550 nm)

Uplink optical beacon for PAT (850 nm)

Bi-directional low-rate RF link for telemetry and command

PAT = Pointing, Acquisition, and Tracking
RF = Radio Frequency

Requirements Derivation

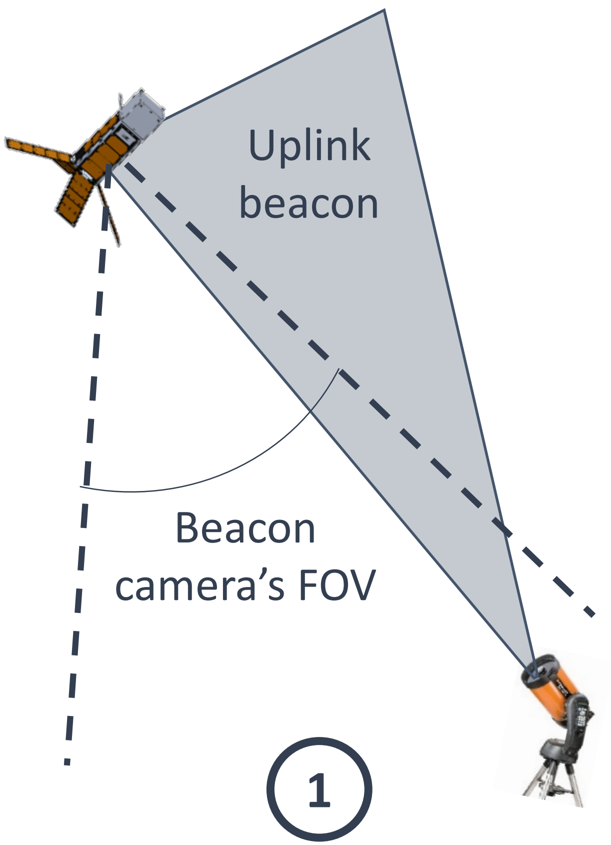


SWaP = Size, Weight, and Power
ADCS = Attitude Determination and Control System

Design Parameters

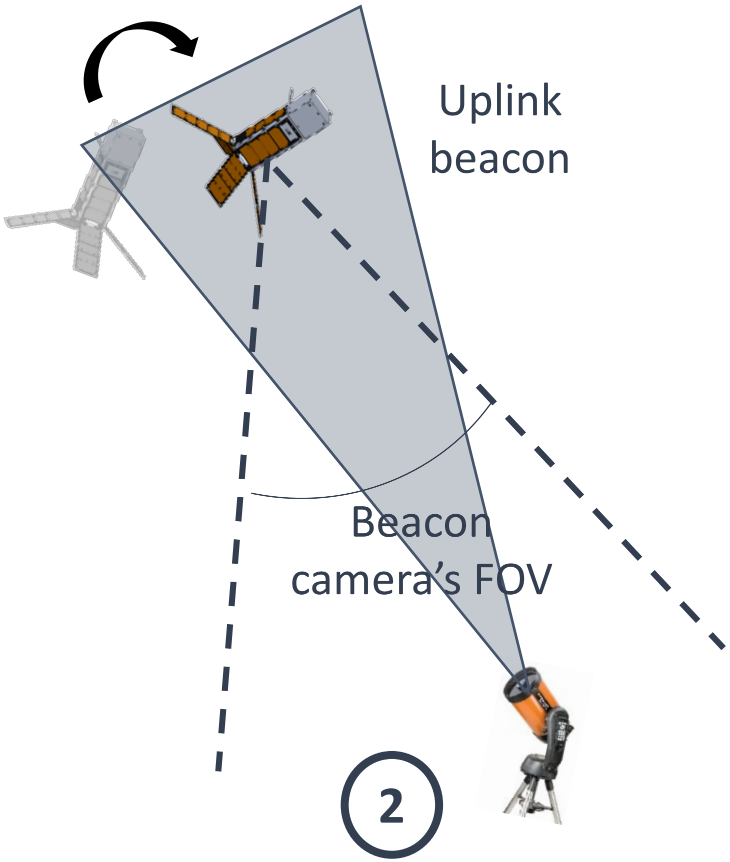
Link parameters		
Data rate	10 – 50 Mbps	User data rate
Bit error rate	10^{-4} (no coding)	Conservation baseline
Path length	1000 km (at 20° elevation)	LEO orbit at 400 km altitude
NODE module		
Size, weight	10 x 10 x 5 cm, 1 kg	0.5U CubeSat
Power	10 W (transmit)	CubeSat constraints
Downlink beam	0.12° FWHM	Provide required data rate
Coarse pointing	**3° (3-σ)**	**Host CubeSat ADCS**
Fine pointing	**0.03° (3-σ)**	**Fast-steering mirror**

Concept of Operations – I



1	CubeSat slews toward ground station	
	Sensors	CubeSat coarse sensors
	Actuators	CubeSat reaction wheels
	Pointing accuracy	3°
2	CubeSat closes loop around beacon offset	
	Sensors	Beacon camera
	Actuators	CubeSat reaction wheels
	Pointing accuracy	1.25°
3	Fine steering mechanism is activated	
	Sensors	Beacon camera
	Actuators	Fast-steering mirror
	Pointing accuracy	0.03°

Concept of Operations - II



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	Sensors	Beacon camera
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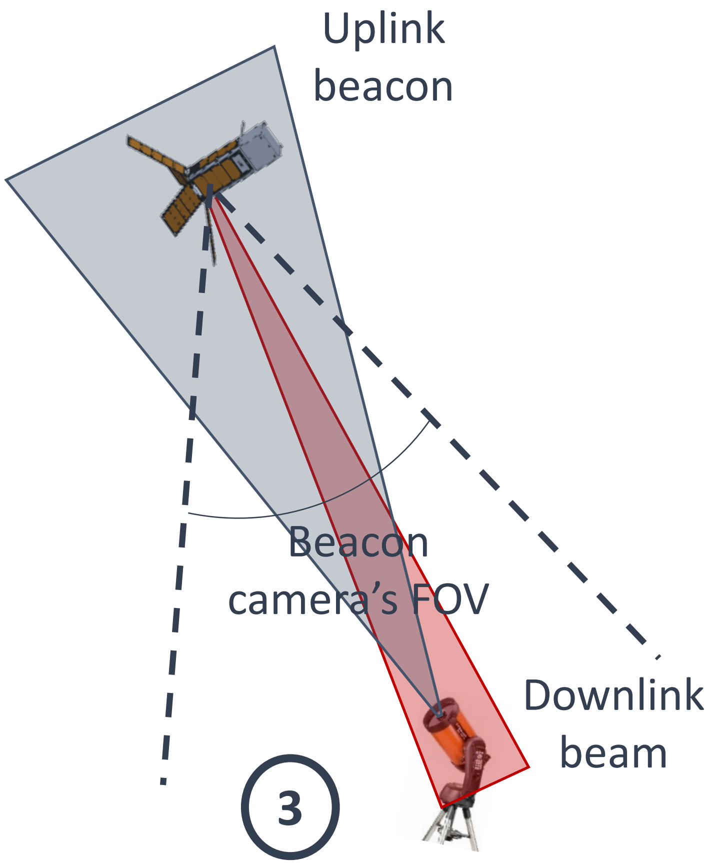
3	Fine steering mechanism is activated	
	Sensors	Beacon camera
	Actuators	Fast-steering mirror
	Pointing accuracy	0.03°

Concept of Operations - III



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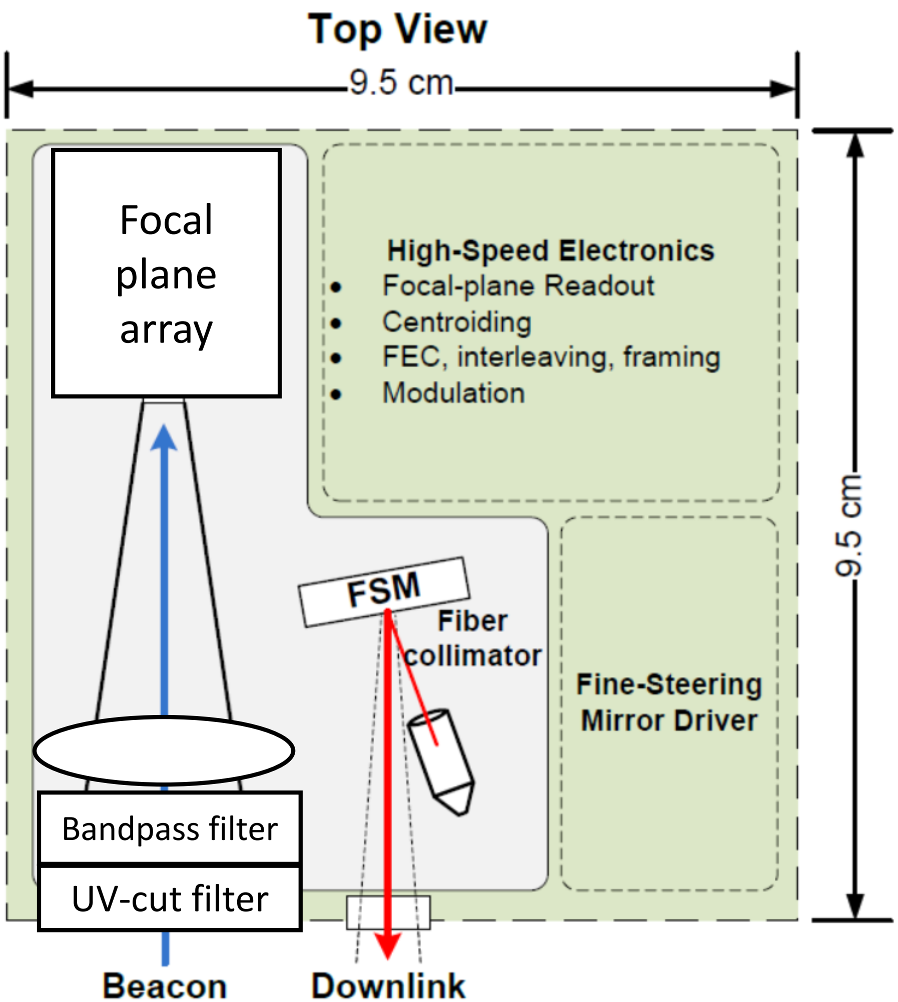
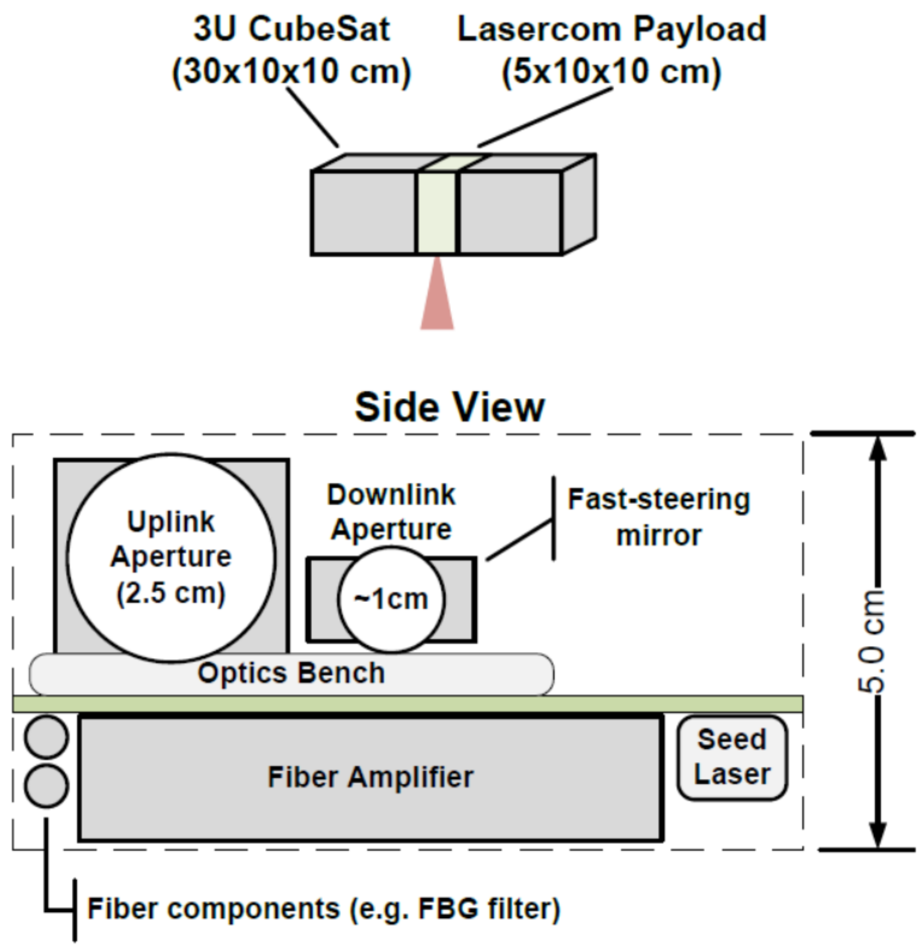
NODE System Layout

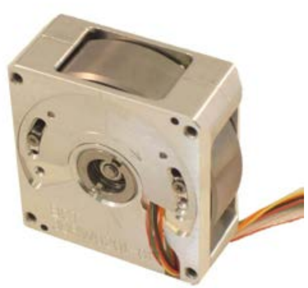




Coarse Control Stage

- Three-axis stabilized CubeSat ADCS
- Common pointing capability: 1 – 5° RMS [2,4]

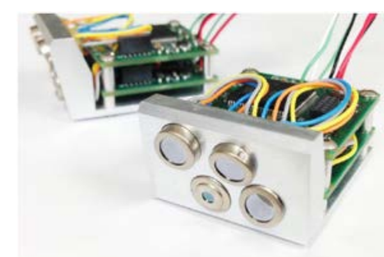
Attitude Sensors	Attitude Actuators
Sun sensors Magnetometers Earth horizon sensors Gyroscopes	Reaction wheels Magnetorquers



Miniaturized reaction wheels

[credit: Blue Canyon Tech].

Magnetorquers

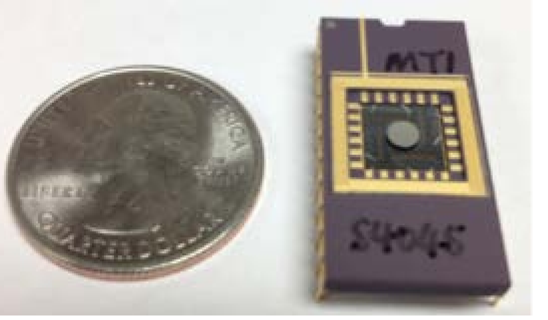


Earth horizon sensors

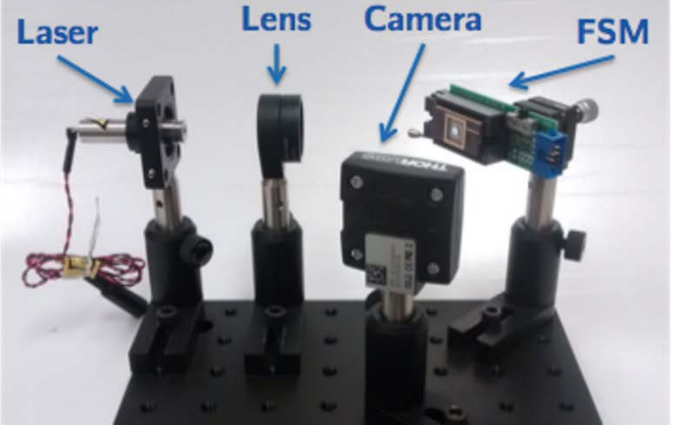
[credit: Maryland Aerospace Inc.]

Fine Control Stage

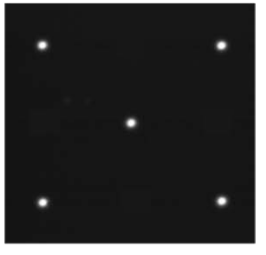
- MEMS fast steering mirror
  - Mirrorcle Tech. Inc.
  - 2-axis tip/tilt
  - Range: ±1.25°
  - No integrated feedback



Fast-steering mirror from Mirrorcle Tech.



Lab bench setup for FSM characterization



Test pattern

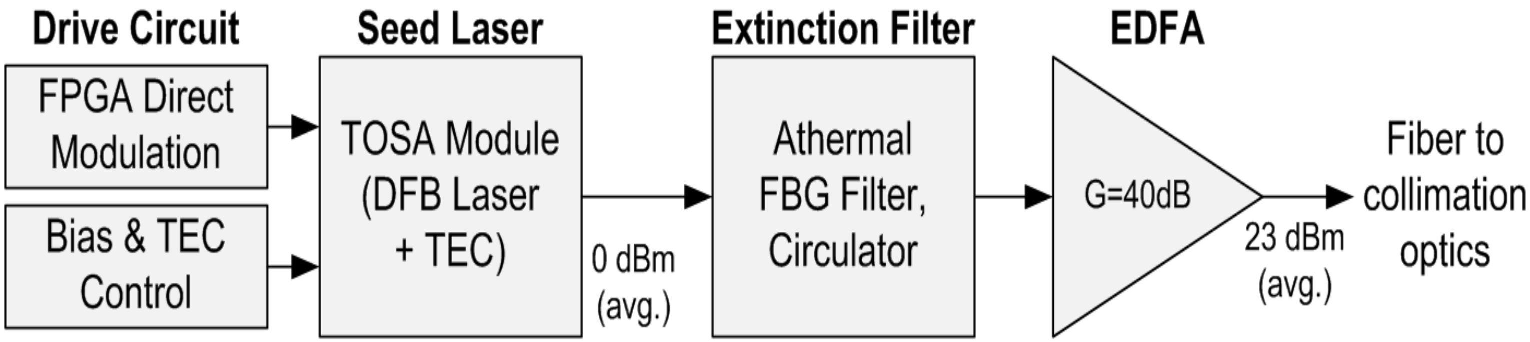
Repeatability Test Results	
RMS error (best device)	0.0007° (12 μrad)

Pointing requirement	0.03° (525 μrad)

Transmitter Design Parameters

Parameter	Value	Notes/Justification
Size	10 x 10 x 2 cm	Allocation to the transmitter portion of the lasercom terminal.
Mass	<300 g	
Electrical Input Power	< 8 W	
Operating Temp. Range	0-40 C	Typical CubeSat values
Optical Output Power	>200 mW avg.	Link budget, PPM-16 assumed
Modulation Type	PPM, M=[8-64]	ER implications, “power robbing”
Modulation BW	> 1 GHz desired	Future pointing improvements
Wavelength stability	+/- 1 nm	Ground receiver filter

Transmitter Design Overview

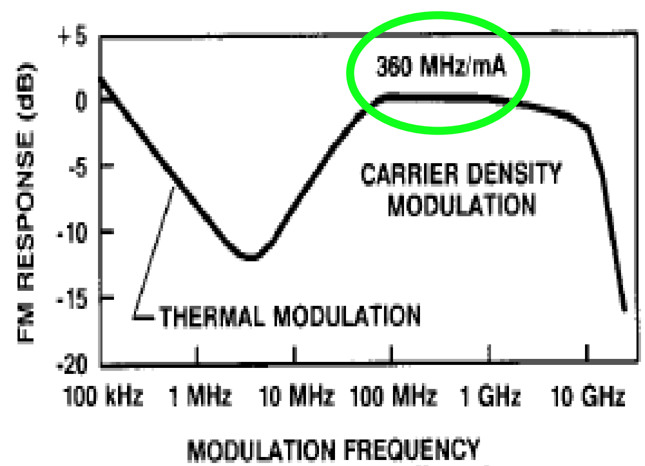


- Challenge: achieving **ER > 33dB** with directly modulated laser (DML)
  - Needed to prevent "power robbing" in EDFA

- DML ER can be improved with narrow-band optical filtering via FM-AM conversion

  Shirasaki, EL 1988; Vodhanel, JLT 1989 & 1990; Lee, PTL, 1996; Mahgerefteh, CLEO 1999 & PTL 2006; Caplan, JOFCR 2007, CLEO 2011 & 2014

- Typical DML FM response vs modulation frequency:



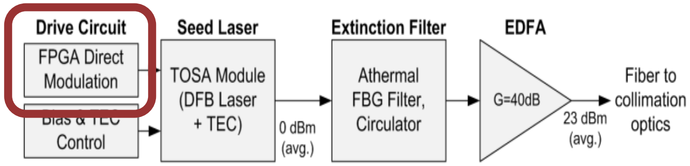
From Vodhanel, JLT 1990

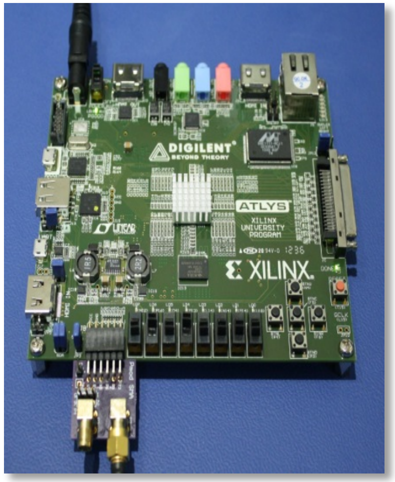
FPGA Modulation

- Electro-optic modulator not feasible in this design due to power constraints

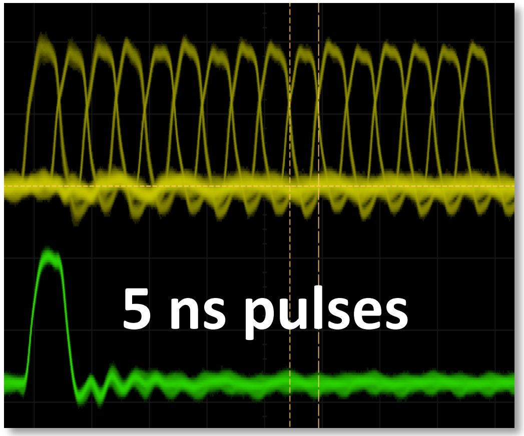
- Direct FPGA drive demonstrated with Xilinx Spartan 6 FPGA evaluation board
  - Adjustable: duty cycle, slot rate
  - GPIO drives 50 mA into 50 ohms

- SelectIO SERDES enables >600 MHz rates while maintaining low fabric clock rates
  - **Not using RocketIO/GTP interfaces**
    → power savings

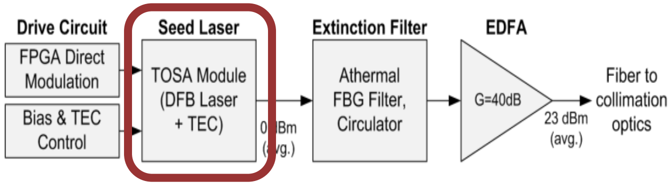




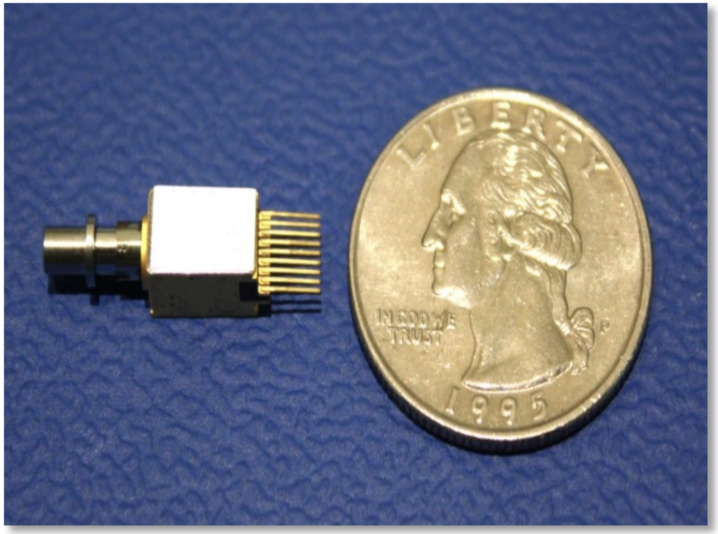
PPM-16 waveform (electrical)



Laser Selection & Characterization



- Telecom DFB Lasers: **TOSA**
  - Transmitter Optical Sub-Assembly
  - Compact packaging
  - **Low TEC power**
    (Measured <0.4 W across expected range)

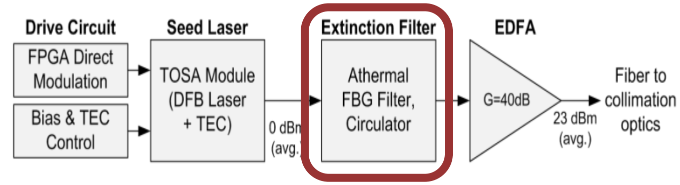


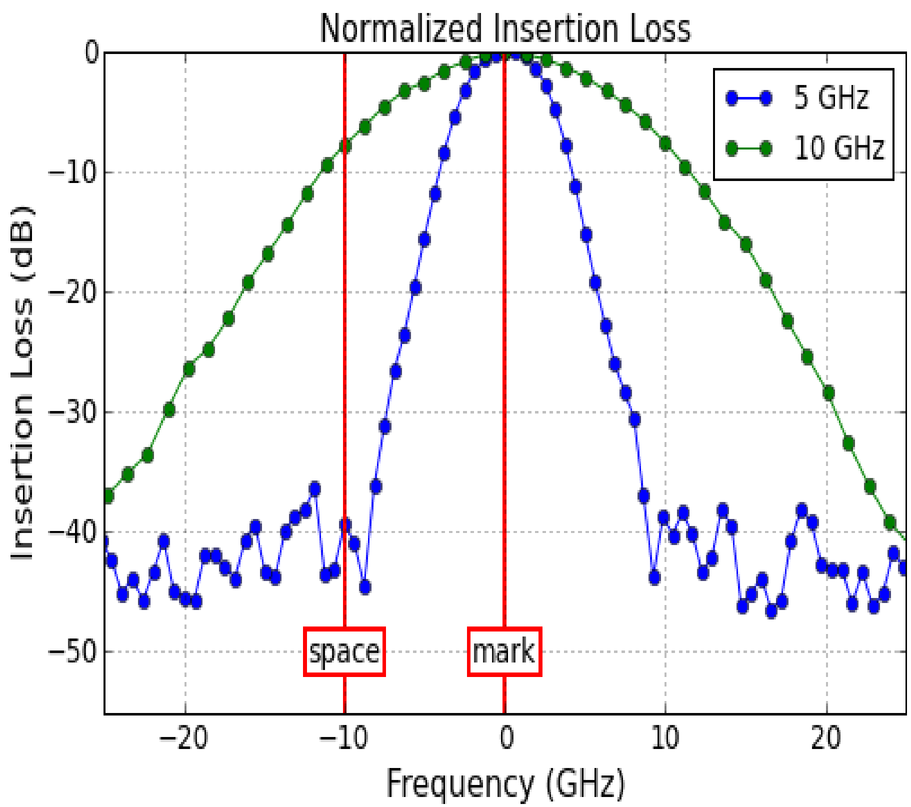
- Custom mounting jig for characterization
- Measured laser tuning parameters:

FPGA 50mA drive provides ~10 GHz of frequency shift

Extinction Filter Characterization

- Waveform ER is enhanced through FM-to-AM conversion
- Athermal Fiber Bragg grating filter
  - Bandwidths: 10 GHz and 5 GHz
  - >40 dB stop band
- Temperature/DC bias wavelength tuning aligns seed laser with filter

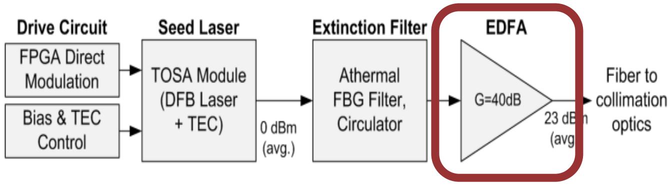


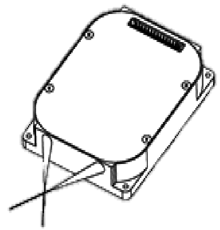


5 GHz filter provides **ER > 33 dB** → permits PPM-64 w/o power robbing

EDFA Selection

- Modified COTS Fiber Amplifier (NuPhoton)
  - Customized fiber egress, increased gain
  - Vendor has similar units with flight heritage





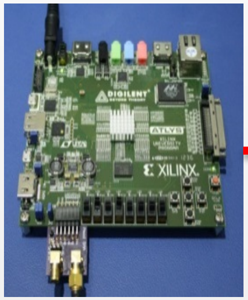
MSA chassis
9 x 7 x 1.5 cm

- Key Parameters
  - Optical output: 200 mW average
  - Electrical input: 5.7 W at 5 V
  - Gain: 40 dB
  - “Wall plug” efficiency: 3.5%

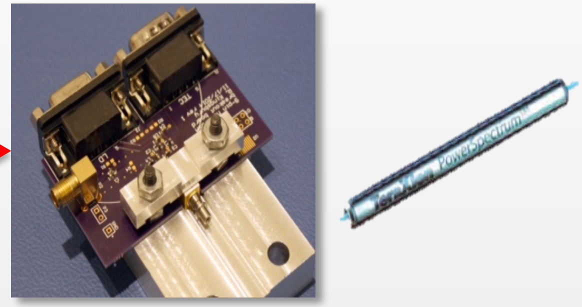
Industry-standard “MSA” form factor is a good match for CubeSat volume constraints

Measured Electrical/Optical Waveforms

FPGA



Seed Laser + ER Filter

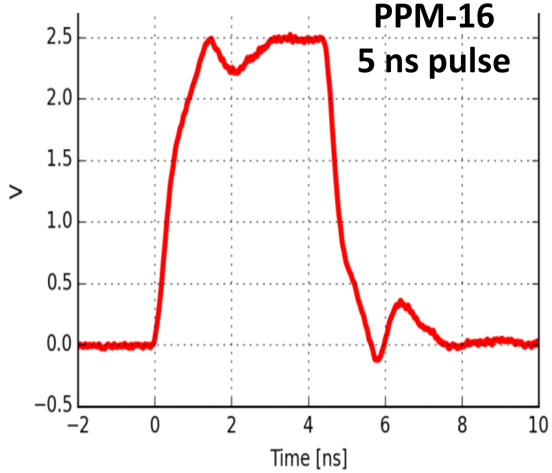


-7 dBm

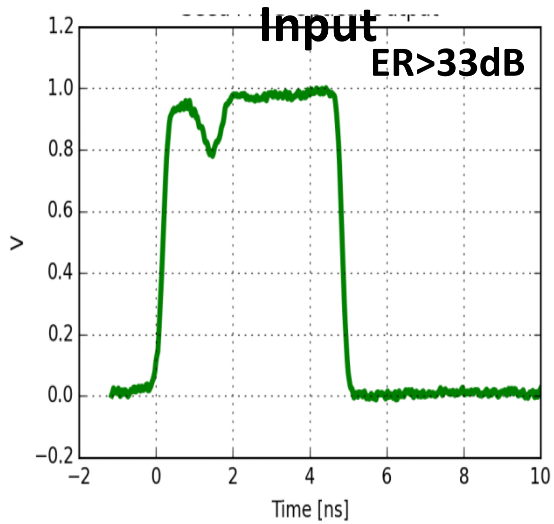
EDFA

+23 dBm

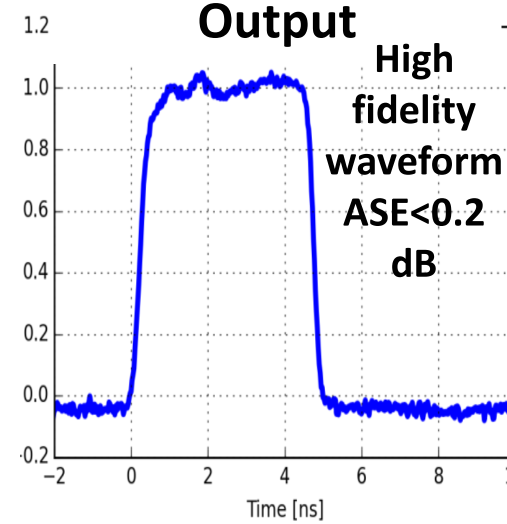
FPGA Electrical Output



EDFA Filtered Optical Input



EDFA Optical Output



Transmitter Power Budget

	Value	Notes
EDFA	5.7 W	Manuf. worst case, **(we measured: 4.1 W)**
Seed laser TEC	0.4 W	Peak power, over temp
Seed laser DC bias	0.2 W	Worst case
Seed laser AC drive	0.01 W	50 mA, 1/16 duty
FPGA logic	0.2 W	Only TXer related portion of FPGA
Total:	**6.51 W**	
Margin:	**1.49 W**	**8 W budgeted**

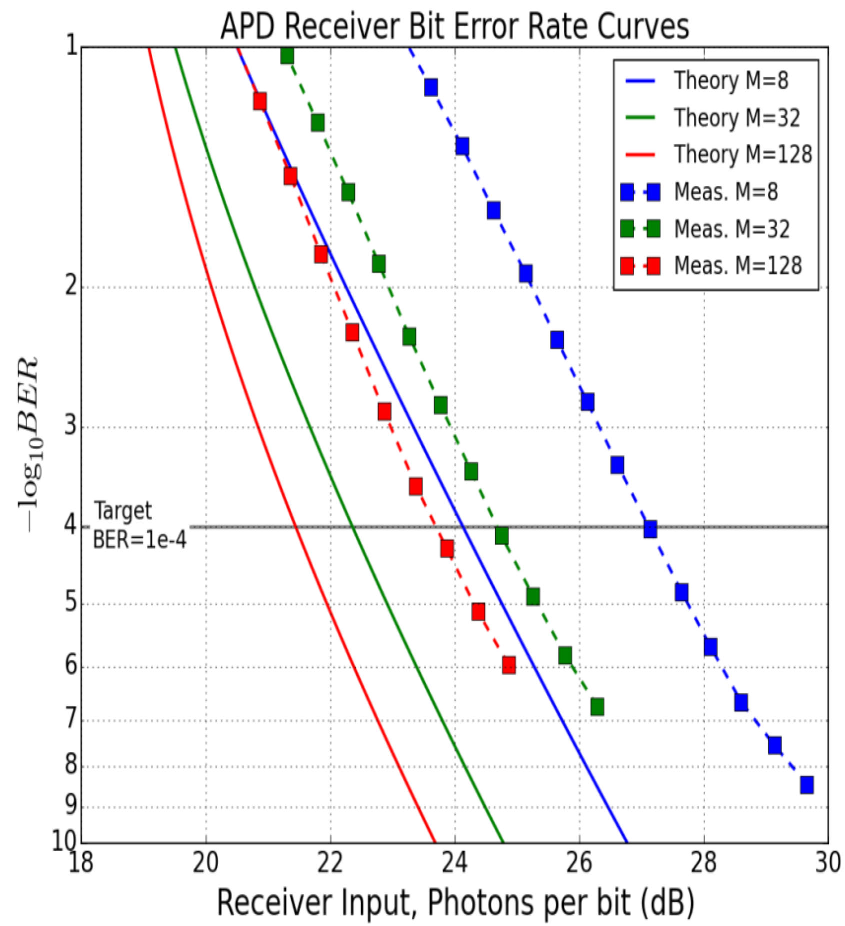
Transmitter meets power budget with 18% margin

Flight Receiver BER Curves

- Theoretical sensitivity from link budget

Sensitivity vs. Theory at BER=1e-4					
M	8	16	32	64	128
dB	2.98	2.57	2.32	2.24	2.24

d



System is currently 2.2– 3.0 dB from theory (mode dependent).

Beacon Camera

- CMOS focal plane array (5 Mpixels)
- COTS camera lens system (1”, f = 35 mm)
- Bandpass filter – reject background light
- UV/VIS-cut filter – reduce system heating

Beacon camera prototype

CMOS array - Aptina MT9P031	
Optical format	1/2.5”
Resolution	2592H x 1944V
Pixel's pitch	2.2 µm
QE at 850 nm	15%

Lens + filters	
Focal length	35 mm
Aperture	1”
Band-pass filter	(850 5) nm
Long-pass filter	> 700 nm

COTS = Commercial Off the Shelf

Beacon Simulation

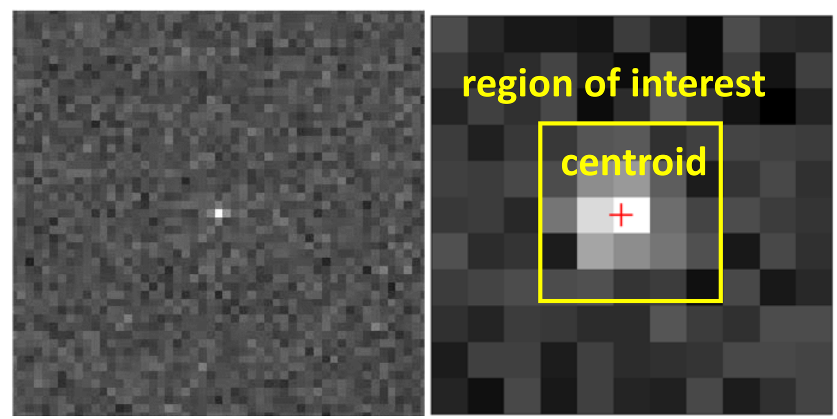
Link analysis

Transmit power	10	W
Wavelength	850	nm
Beamwidth	5	mrad
Range (20° elevation)	984	km
Atmospheric absorption/scattering	-6	dB
Sky radiance[5]	180	$W/m^2/sr/um$
Receiver bandwidth	10	nm
Optics loss (Tx + Rx)	-8	dB

Received power	0.013	nW
Margin	10	dB

Scintillation statistics

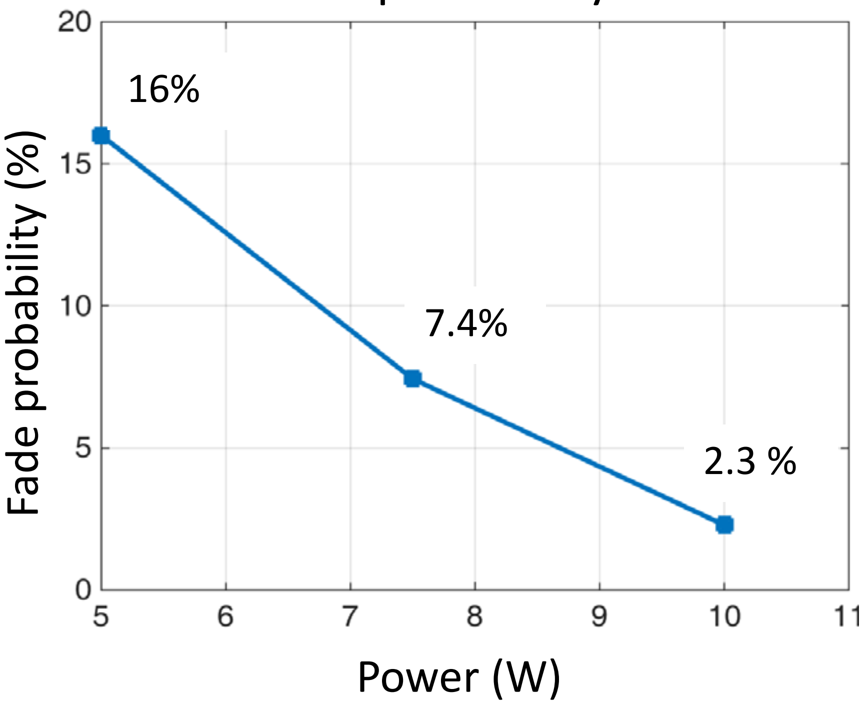
profile	Huffnagel-Valley model[3] 1°/s slew speed
Scintillation index	Strong-turbulence model[3] Spatial diversity (4 beams)
Distribution	Log-normal



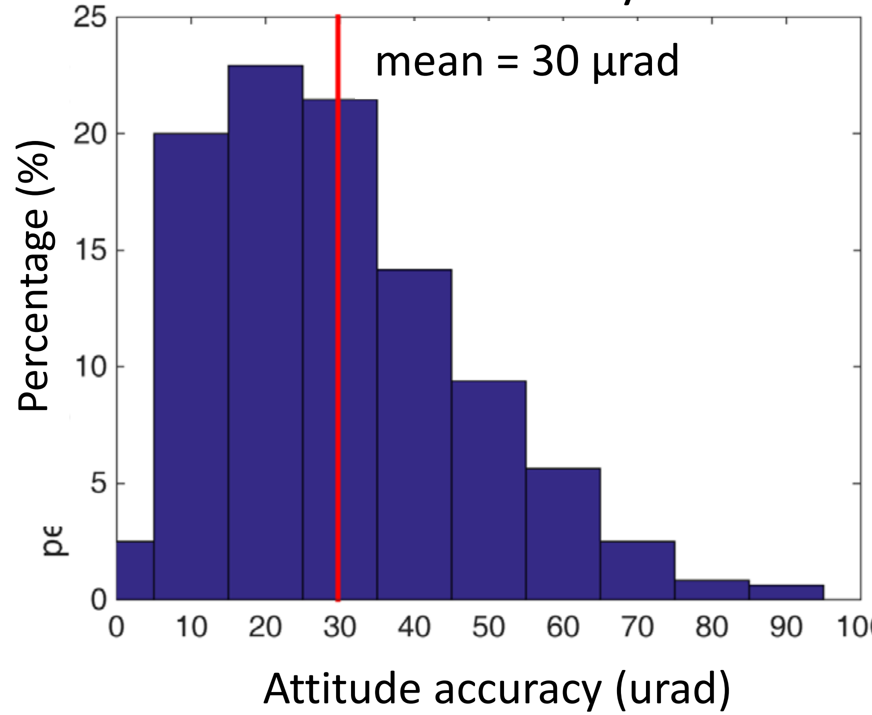
Simulated beacon image and centroid

Beacon Simulation Results

Fade probability

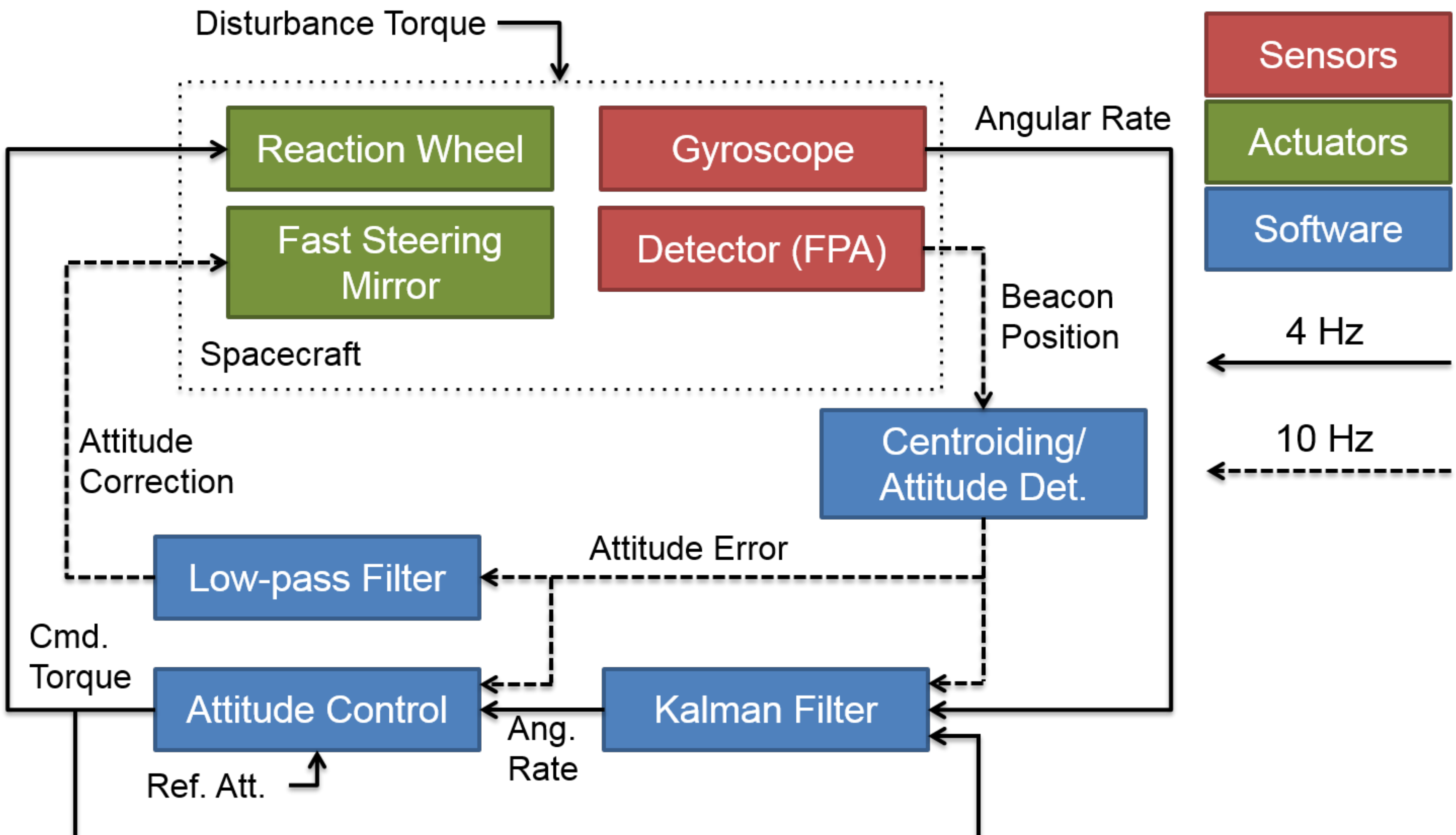


Centroid accuracy

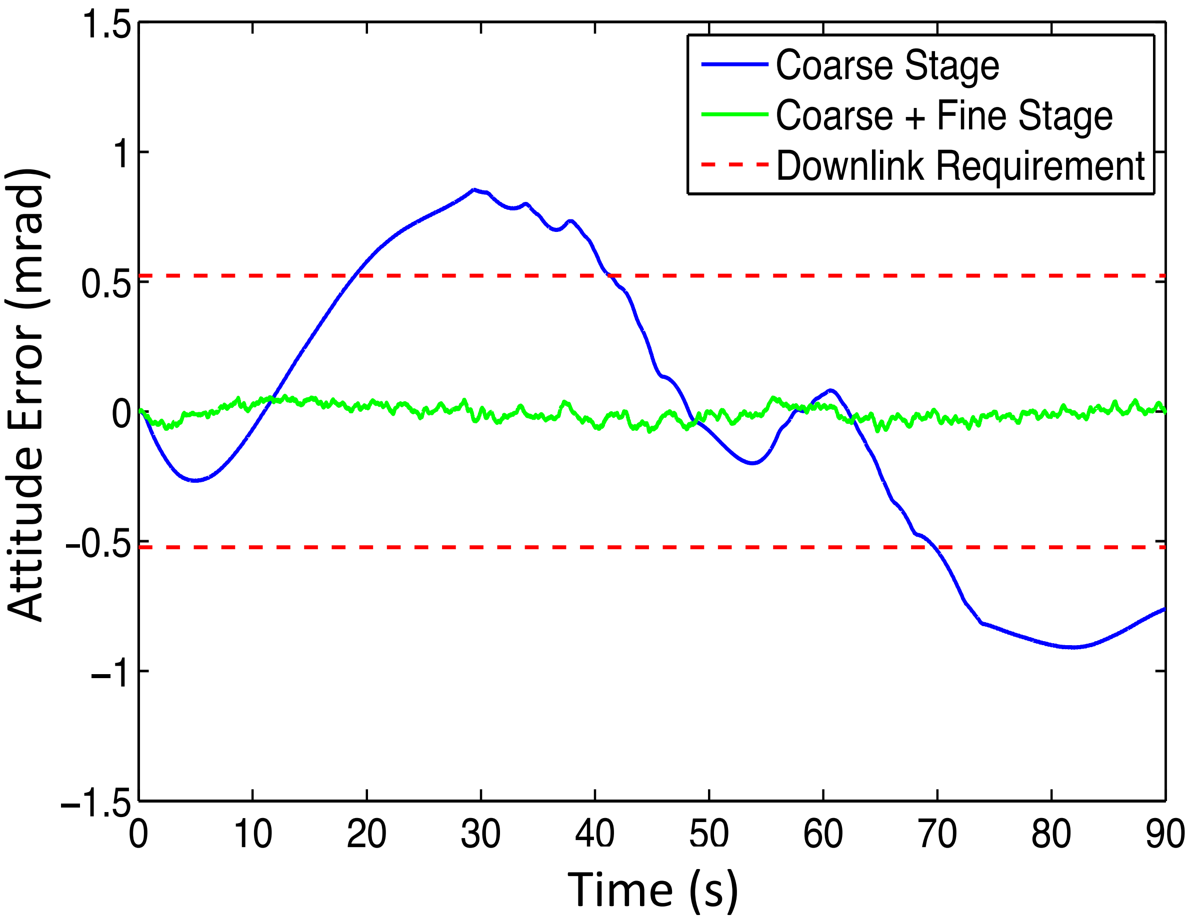


Fade probability per frame (10 W)	2.3 %
Attitude knowledge accuracy	**30 μrad** (< 1/10 required accuracy)

Control Simulation



Control Simulation Results



Tracking simulation results

Pointing Results (3-σ)	
Coarse stage only	±0.09° (1.6 mrad)
Coarse + fine stage	**±0.005° (80 µrad)**
Requirement	±0.03° (525 µrad)

Limitation: Result does not consider pointing bias.

NODE Future work

Nanosatellite Optical Downlink Experiment (NODE)

- CubeSat-sized laser communication module
- Pointing performance
  - Attitude knowledge: 30 µrad (2.3% fading)
  - Tracking accuracy: 80 µrad

<u>Future work</u>

- Hardware checkout and model validation
- Camera readout and image processing implementation
- Hardware-in-the-loop testing and integration
- On-orbit calibration algorithm development

NODE References

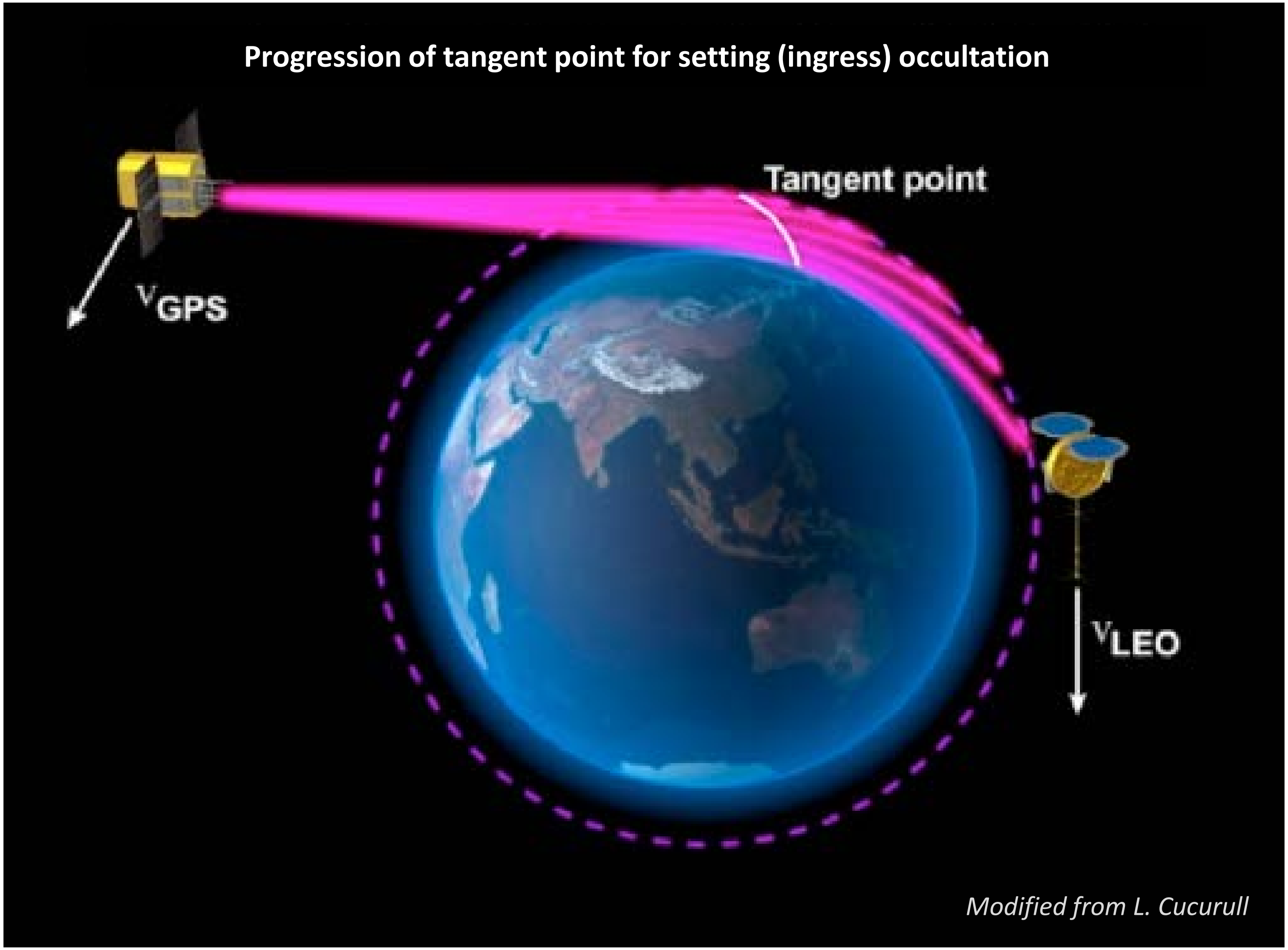
1. E. Buchen and D. DePasquale, *"2014 Nano / Microsatellite Market Assessment,"* Spaceworks Enterprises, Inc. (SEI), Atlanta, GA. 2014.
2. B. Klofas and K. Leveque, *"A survey of cubesat communications systems: 2009-2012,"* in Proc. of CalPoly CubeSat Developers Workshop, 2013.
3. L. Andrews and R. Phillips *"Laser Beam Propagation through Random Media, Second Edition" (SPIE Press Monograph Vol. PM152). SPIE – The International Society for Optical Engineering*. ISBN-13: 978-0819459480
4. A. Schwarzenberg-Czerny, W. Weiss, A. Moat, R. Zee, and S. Rucinski, \The BRITE nano-satellite constellation mission," in Proc. of 38th COSPAR Scientic Assembly, 2010.
5. S. Lambert and W. Casey, Laser Communications in Space, Artech House Publishers, Boston, MA, 1995.

Overview

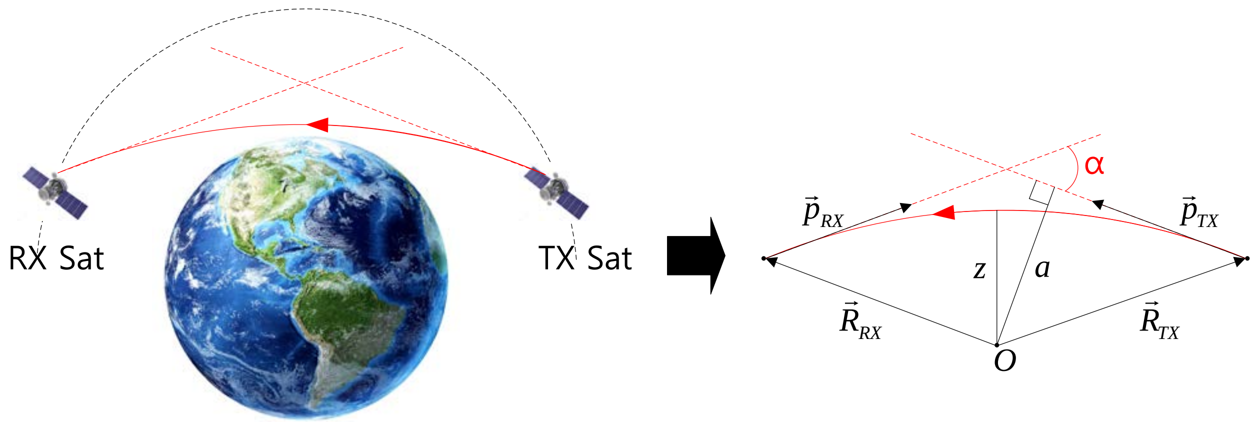
- Introduction
  - CubeSats 101
- Communications
  - NODE
    - Laser communication downlink
- **Laser Occultation**
  - Bending angle and T,P profile recovery
    - GPS Radio Occutlation for validation

NanoRacks deployment of MicroMAS from the ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). Photo courtesy NASA/NanoRacks

Radio Occultation Illustration



Laser Occultation for Greenhouse Gas Sensing



- Laser occultation
  - Measure bending angles of laser beams *directly* from the attitude and position of two LEO satellites

- The bending angle (α) and impact parameter (a) can be calculated if the pointing vectors P_{RX} and P_{TX} and the positions R_{RX} and R_{TX} are known.

Laser Occultation Angle Recovery

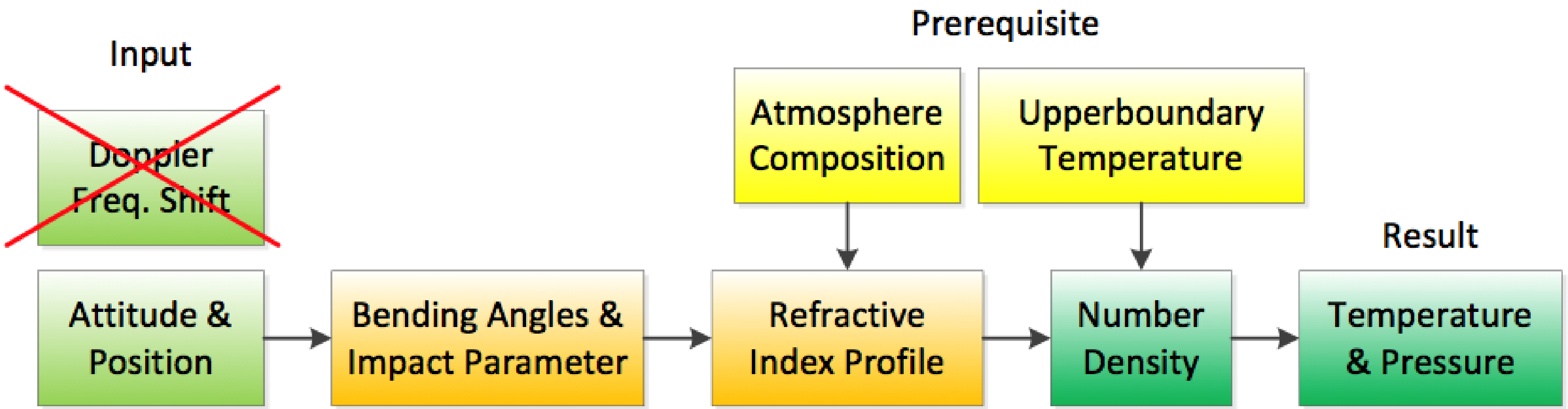


Figure 2. New approach to obtaining both thermophysical profiles and composition with Laser Occultation measurements. The need for Radio Occultation measurements of spacecraft Doppler frequency shifts and atmospheric frequency shift predictions is eliminated. The bending angles can be measured directly with the LO payload (free space optical transmitter and receiver).

Laser Occultation Schematic

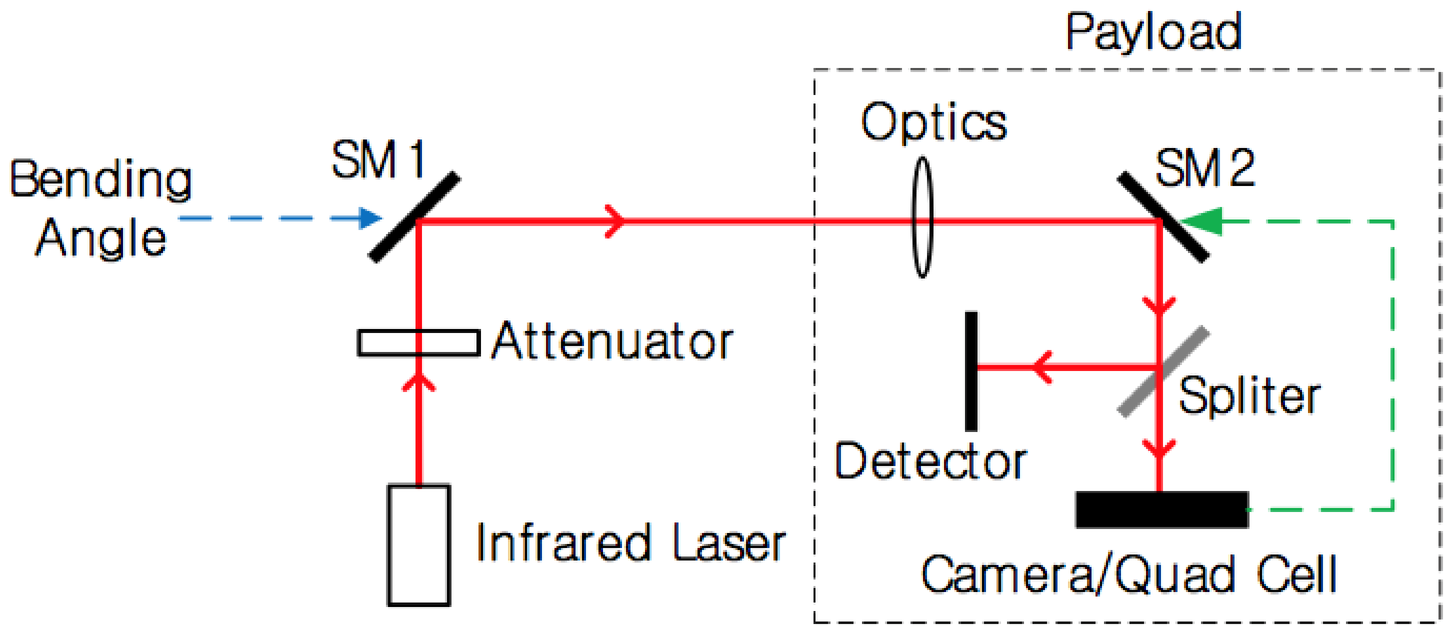


Figure 3. Prototype of Laser Occultation Instrument

Laser Occultation 2um Wavelengths

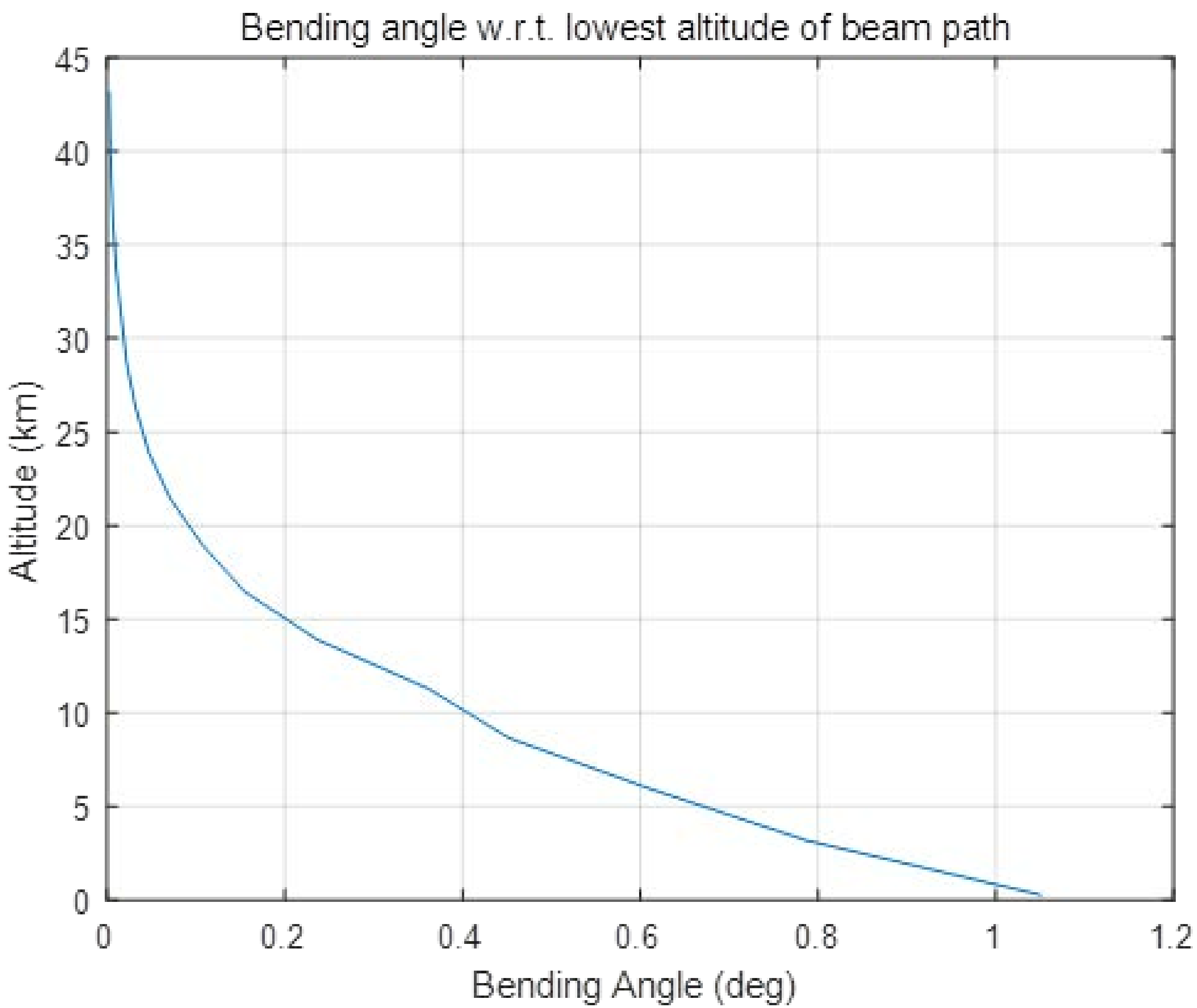
Species	Wavenumber (cm^-1)	Wavelength (nm)	
Abs H2O-1	4204.8403	2378.211605	
Ref H2O-1	4226.07	2366.264638	
Abs H2O-2	4475.803	2234.235957	
Ref H2O-2	4770.15	2096.370135	
Abs H2O-3	4747.0548	2106.56932	shortest wavelength pair
Ref H2O-3	4731.03	2113.704627	shortest wavelength pair
Abs 12CO2	4771.6214	2095.723688	shortest wavelength pair
Ref 12CO2	4770.15	2096.370135	shortest wavelength pair
Abs 13CO2	4723.415	2117.112301	
Ref 13CO2	4731.03	2113.704627	
Abs CH4	4344.1635	2301.939142	
Ref CH4	4322.93	2313.245877	
Abs O3	4029.1096	2481.937945	
Ref O3	4037.21	2476.958097	
Abs N2O	4710.3408	2122.988638	shortest wavelength pair
Ref N2O	4731.03	2113.704627	shortest wavelength pair

From Kirchengast:

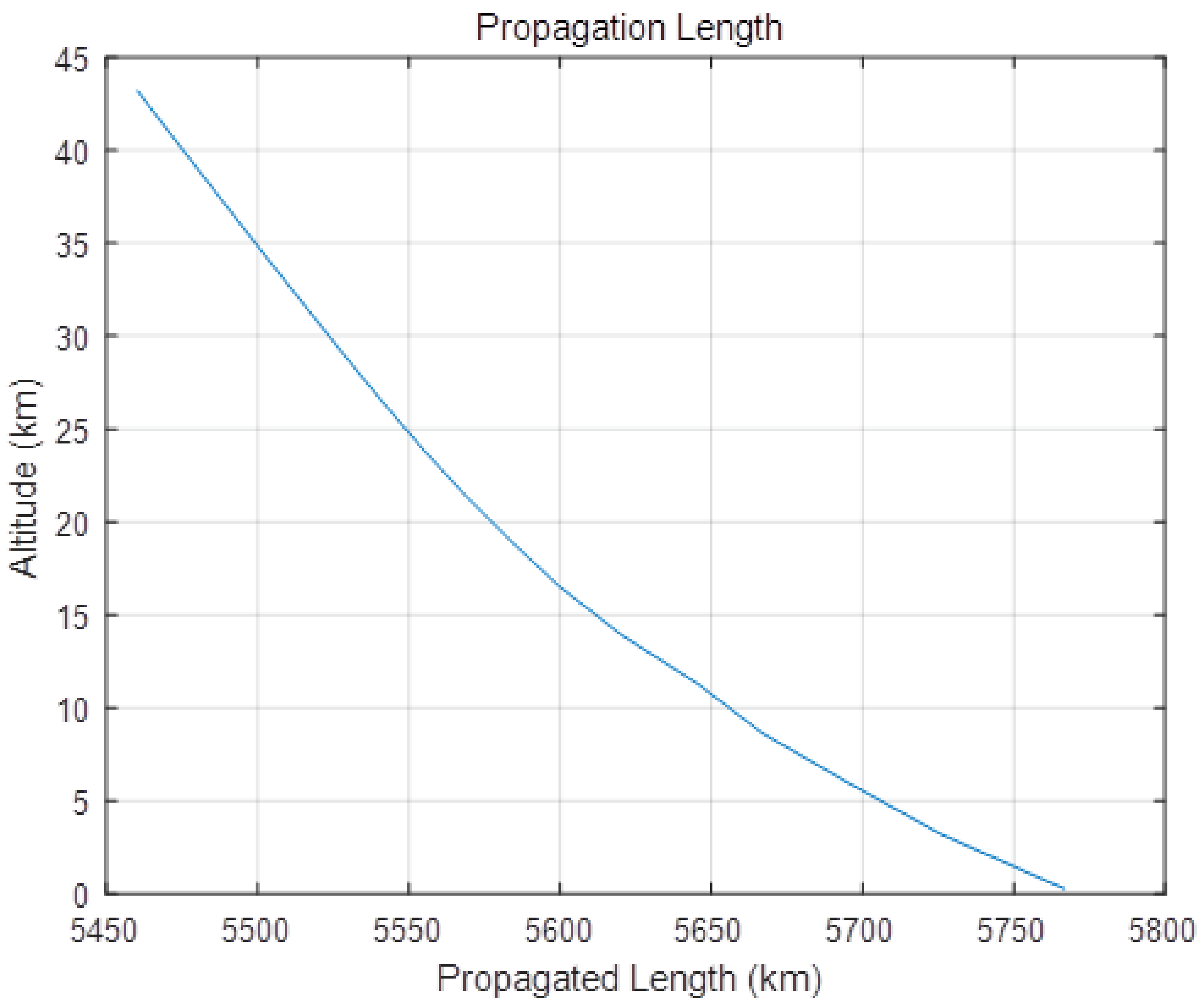
http://wegcwww.uni-graz.at/publ/wegcpubl/arsclisys/2007/wegc_gkirchengastandsschweitzer-wegctechrepfffgalr-no3-2007.pdf

Need to assess 1.5-1.7 um wavelengths

Bending Angle



Separation



Propagation Length
45
40
35
30
25
20
15
10
5
0
Altitude (km)
5450
5500
5550
5600
5650
5700
5750
5800
Propagated Length (km)

"Laser-only" occultation feasibility

- **It is doable**
  - Bending angle for GPS signal
    - Altitudes from 0 km to 20 km: **1 deg to 0.1 deg**.
  - Modern s/c *attitude* knowledge performance
    - Star sensors and filtering gyroscope data
      - **< 10 arcsec ≅ 0.0027 deg**
  - Modern s/c *position* knowledge performance
    - With GPS in LEO, error < 10 m
    - Corresponding pointing error:
      - **0.00024 deg** to **0.00038 deg**
      - Depends on altitude (0 to 20km) and orbit (200 to 400 km)

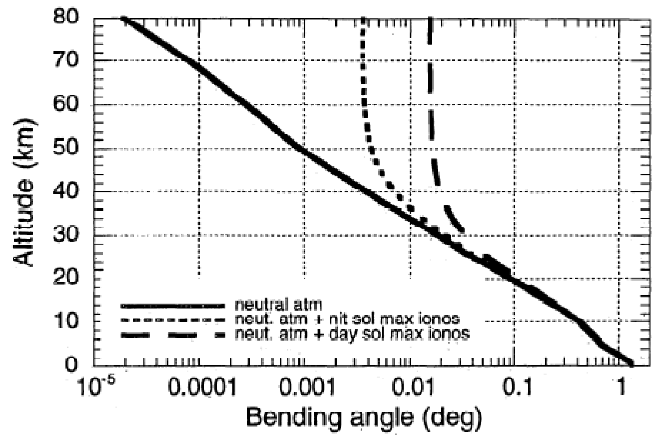


Figure 3. Atmospheric and ionospheric bending for limb ray paths plotted as a function of ray path tangent height. Solid line, bending calculated for U.S. Standard Atmosphere [*Champion et al.*, 1985]. Long-dashed line, bending calculated for U.S. Standard Atmosphere plus typical midlatitude ionosphere during daytime, solar maximum conditions. Short-dashed line, bending calculated for U.S. Standard Atmosphere plus typical midlatitude ionosphere during nighttime, solar maximum conditions.

E. R. Kursinski, et al: "Observing Earth's atmosphere with radio occultation measurement using the Global Positioning System" Journal of Geophysical Research, 102, D19, 23,429-23,465, 1997

Thank you!