Laser Frequency Combs for Atmospheric Characterization

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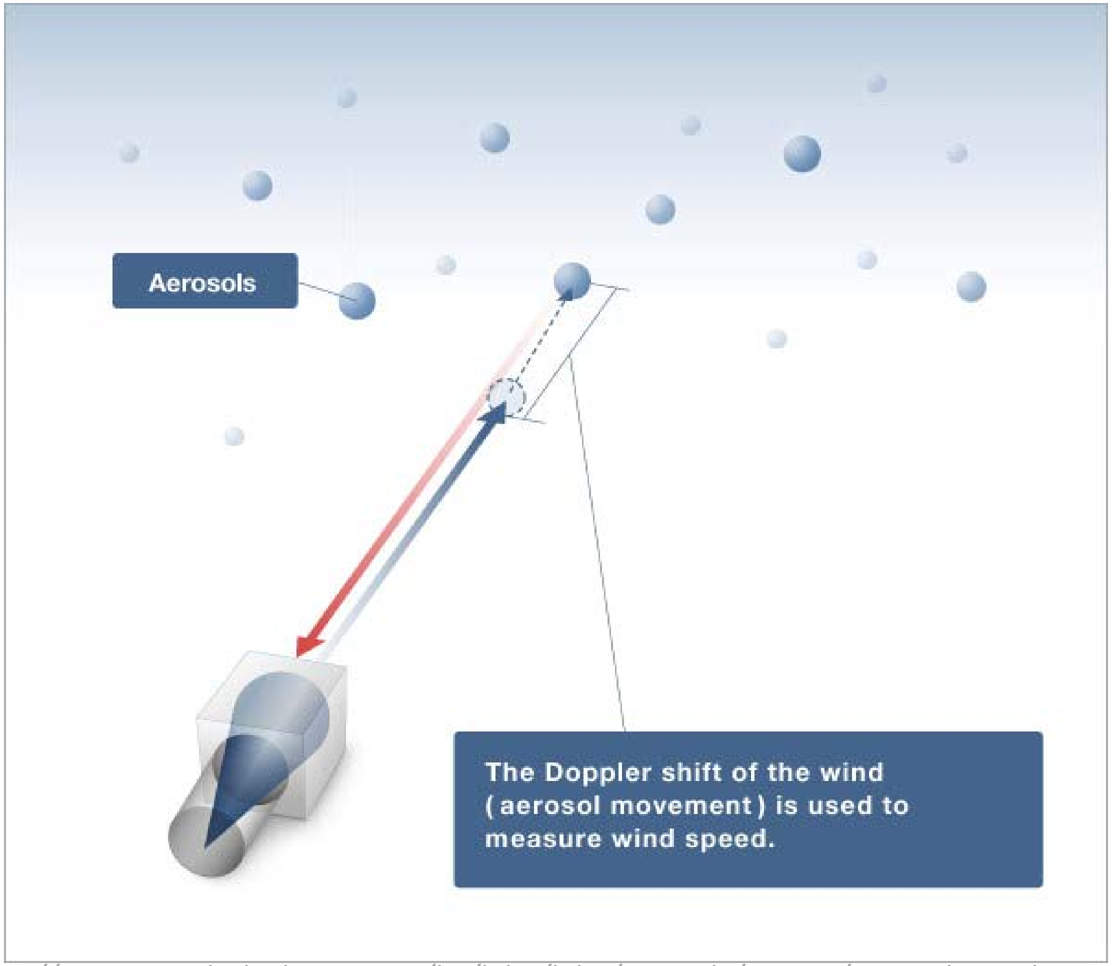
Overview

- LFCs to characterize planet atmospheres
- ***Near***
  - Solar system, including Earth (<50 AU)
  - *LIDAR*
  - *Radio occultation*
  - *Laser occultation*
- ***Far – talk for another time…***
  - Exoplanets
  - Out to about 50 *parsecs* (50 x 2 x 10^5 AU)
  - Direct imaging in the optical
    - Space telescope + coronagraph
  - Radial velocity measurements
    - Space telescope + spectrograph

Atmospheric measurements

- Laser sounding
  - LIDAR
    - Coherent vs. direct
      - Coherent via optical heterodyne detection
    - Doppler LIDAR
- Occultation sounding
  - High vertical resolution
  - Radio occultation
    - LFC as frequency reference for custom RO
  - Laser occultation
- Passive microwave sounding, multispectral, mm-wave
- Imaging, visible, NIR, multispectral, spectrometry

LIDAR - Wind



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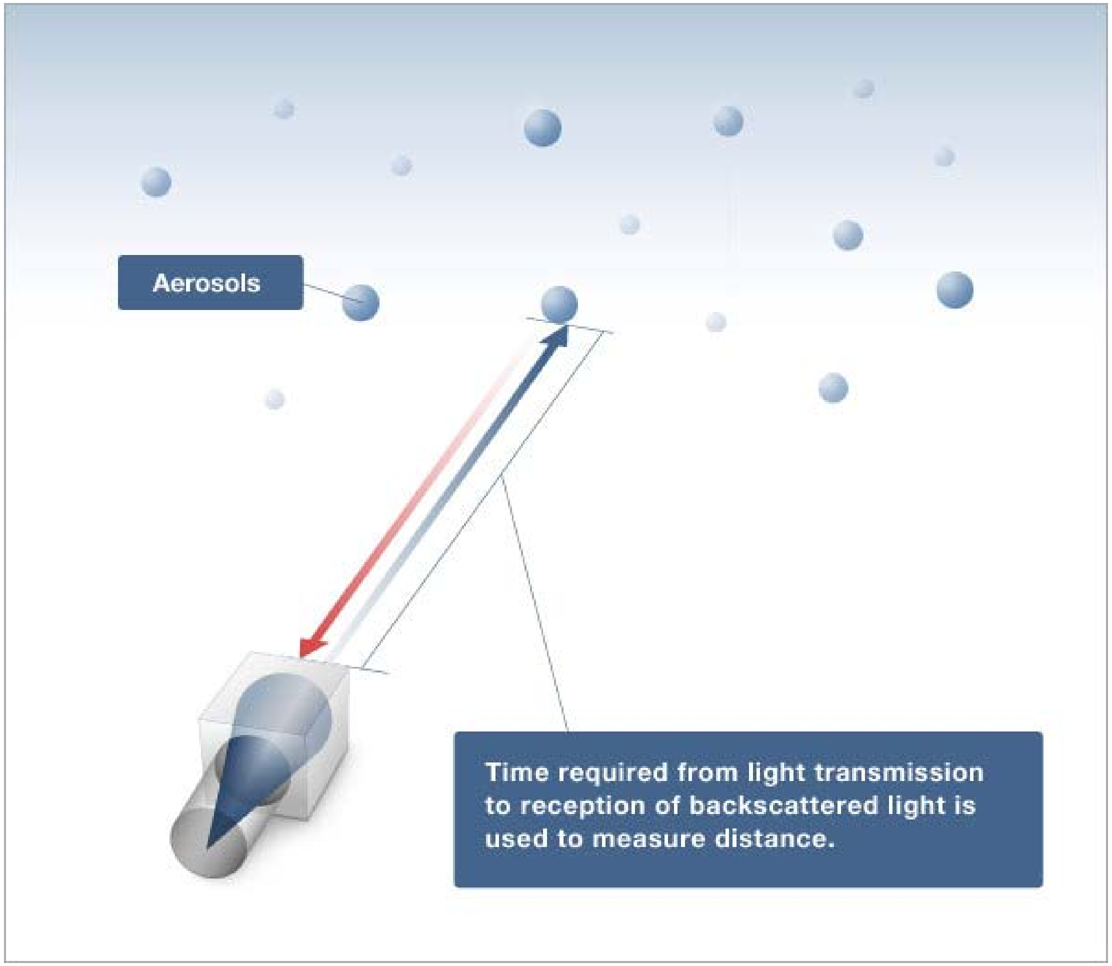
LIDAR - Range



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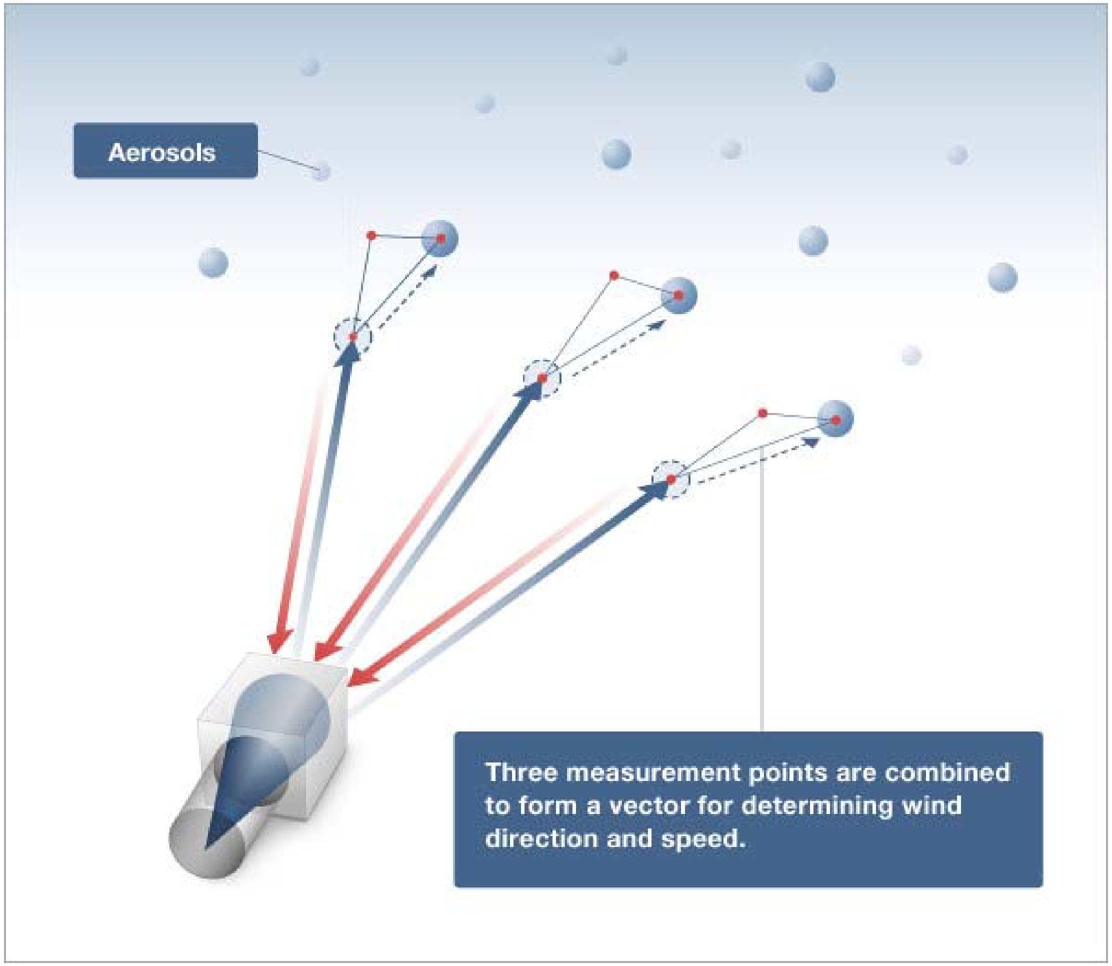
LIDAR – Wind direction and speed



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- LIDAR, substantial loss of signal, since measuring reflection

oc·cul·ta·tion [ok-uhl-tey-shuhn]–noun

1. Astronomy. The passage of one celestial body in front of another, thus hiding the other from view: applied esp. to the moon's coming between an observer and a star or planet.

2. Disappearance from view or notice.

3. The act of blocking or hiding from view.

4. The resulting hidden or concealed state.

[Origin: 1375–1425; late ME < L occultātiōn- (s. of occultātiō) a hiding, equiv. to occultāt(us) (ptp. of occultāre to conceal, keep something hidden, freq. of occulere; see occult) + -iōn- -ion]

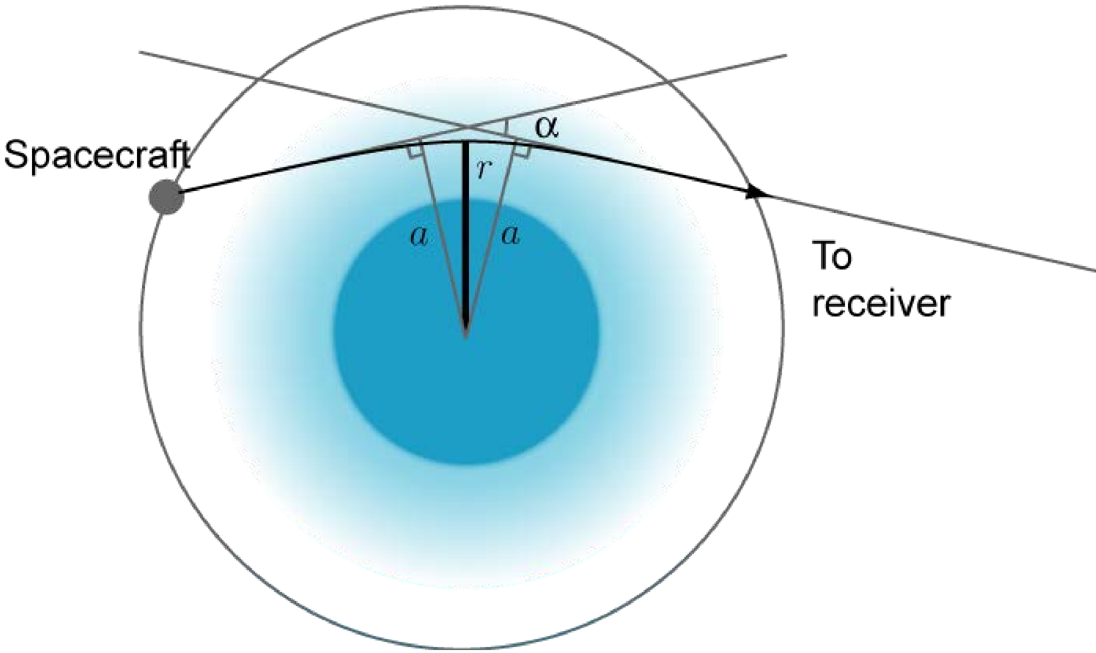
Dictionary.com Unabridged (v 1.1)
Based on the Random House Unabridged Dictionary, © Random House, Inc. 2006.

Occultation Concept

- Titan occults a double star
  - Movie courtesy A. Bouchez
- Palomar 241-actuator adaptive optics system on the 5-m Hale telescope
- PHARO near-IR camera, K’ filter (1.95 – 2.30 μm)

What is Radio Occultation?

- Spacecraft transmitter + receiver
- Atmospheric gas + plasma – refractive index
- Refractive index – frequency shifts
- Invert to get thermophysical data
- Ways to do it:
  - Downlink
  - Uplink
  - Intersatellite link
- Design drivers:
  - Frequency stability
  - Signal to Noise
  - Attitude stability
  - Orbit tracking and geolocation



What is Radio Occultation?

- "Bending" α is received as a frequency shift *(Fjeldbo, 1971)*

$$\cos\left[2\pi\left(f(t)+\Delta f(t)+\theta(t)\right)\right]$$

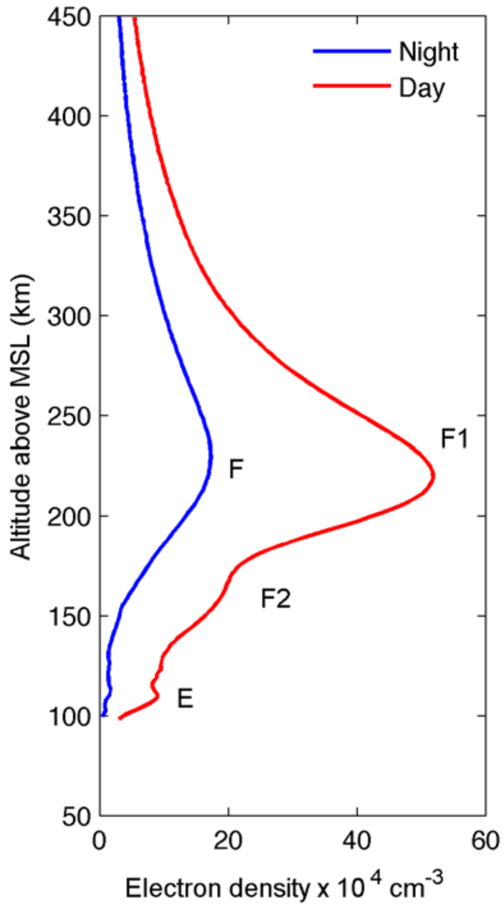
- Abel transform relates the amount of "bending" $\alpha(a)$, to refractivity as a function of altitude, *v(r)*

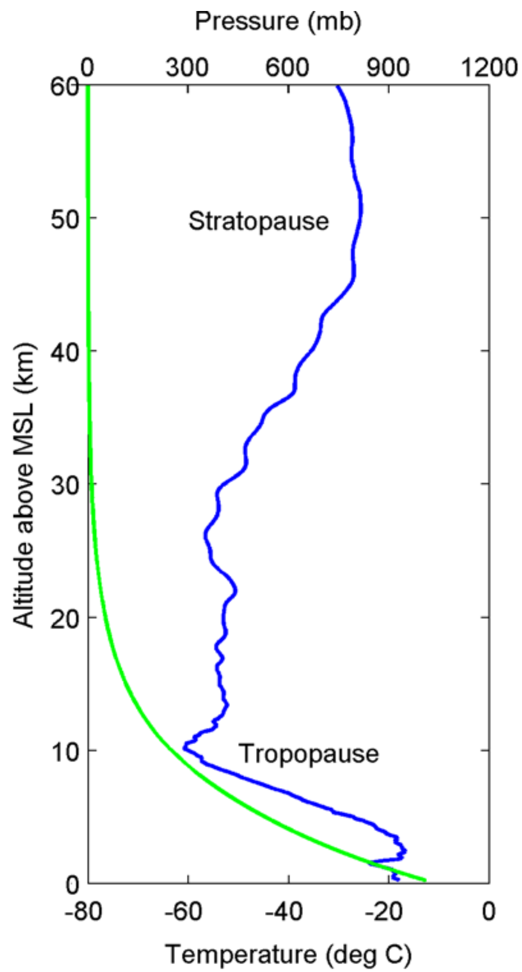
$$\nu(r_0)=\exp\left[\frac{1}{\pi}\int_{a=a_1}^{a\to\infty}\ln\left(\frac{a}{a_1}+\sqrt{\left(\frac{a}{a_1}\right)^2-1}\right)\frac{d\alpha}{da}\,da\right]$$

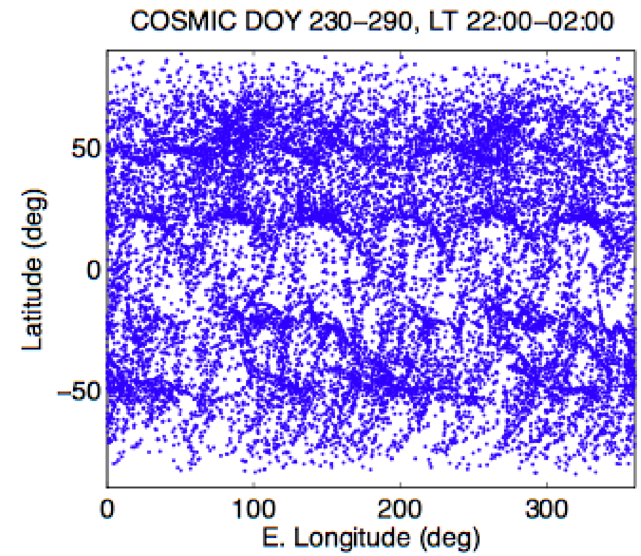
- Yields atmospheric refractivity *profiles*
  - Gas density, plasma density
  - Temperature, Pressure

Niels Henrik Abel, 1802-1829

Example data from GPS—LEO RO on Earth







COSMIC/FORMOSAT-3:
17,544 profiles

- Temperature (blue) and pressure (green) profiles at 03:22:06 UT, 52.5º N latitude and 147.7º E longitude. Daytime electron density profile (red curve) at 19:53:1 UT, 36.8º N latitude and 71.5º W longitude. Nighttime electron density profile (blue curve) at 19:06:01 UT, 35.9º S latitude and 155.7º E longitude.

Solar system atmospheres

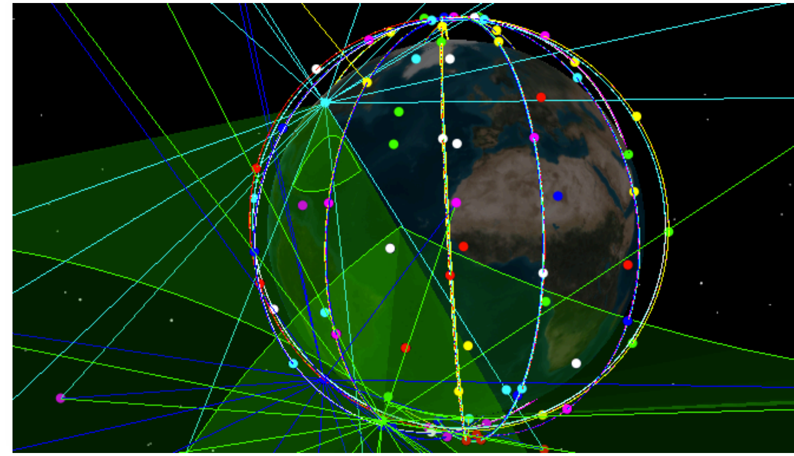
- Atmosphere + ionosphere
  - Mercury
  - Venus (CO_2, N_2)
  - Earth (N_2, O_2)
    - Moon
  - Mars (CO_2, Ar)
  - Jupiter (H_2, He, CH_4, NH_3)
    - Io, Callista, Europa, Ganymede
  - Saturn (H_2, He, CH_4, NH_3)
    - Titan (N_2, CH_4)
    - Enceladus (H_2O geysers)
  - Uranus (H_2, He, H_2O, CH_4, NH_3)
    - Titania (CO_2?)
  - Neptune (H_2, He, CH_4)
    - Triton (N_2, CH_4, CO)
  - Pluto (N_2)

Radio Occultation Planetary Heritage
(input from Withers et al. 2010)

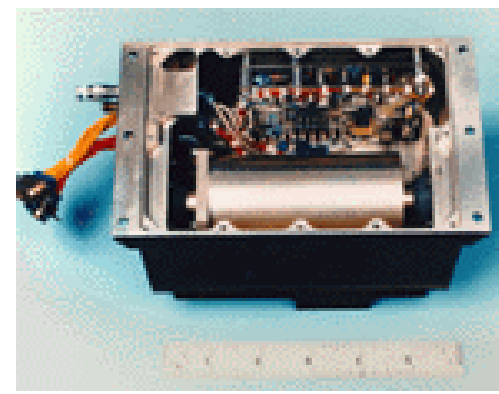
- Mercury
  - Mariner 10 (1973)
- Venus
  - Mariner 5 (1967), 10; Venera 9, 10, 15, 16; Pioneer Venus Orbiter (1978); Magellan (1989); Venus Express (2005)
- Moon
  - Pioneer 7; Luna 19, 22; SMART-1, SELENE
- Mars
  - Mariner 4, 6, 7, 9 (1964, 1969, 1971; Mars 2, 4, 5, 6; Viking 1, 2 (1975); Mars Global Surveyor (1996*);* Mars Express (2003); Mars Reconnaissance Orbiter (current)
- Jupiter, Io, Europa, Ganymede, Callisto
  - Pioneer 10, 11, Voyager 1, 2 (1977); Galileo (1989)
- Saturn, rings, Titan
  - Pioneer 11; Voyager 1, 2 (1977); Cassini (1997)
- Uranus, Neptune, Triton
  - Voyager 2 (1977)
- Pluto
  - New Horizons (2015 uplink)
- IP/Halley
  - Vega 1, Vega 2, Giotto

What are the technologies that we need?

- Radio science instrument
  - Software defined radio rx/tx
    - Multi-channel
    - Multi-frequency
    - Open or closed loop (trade)
  - Stable oscillator/clock
    - Across multiple frequencies
  - Onboard processing
  - Navigation and ranging
- Antennas
  - Larger aperture
  - Radiating efficiency
    - Broadband multi-frequency intersatellite
  - Beamwidth
  - Or maybe we can do this with **lasers**…



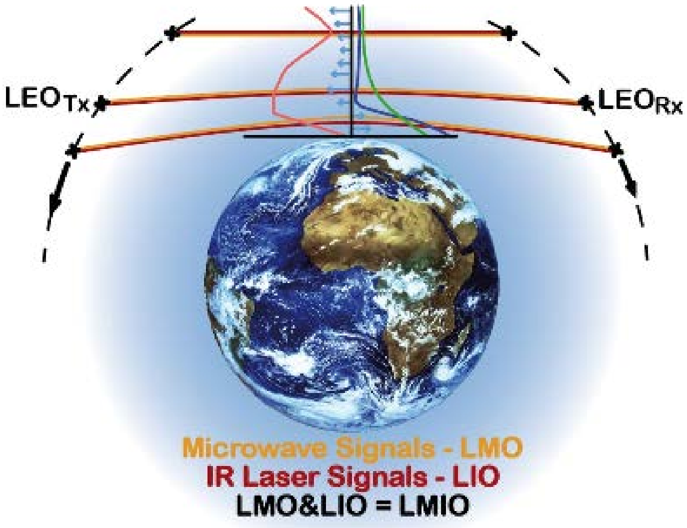
GNSS RO simulation, I. Beerer



Mars Global Surveyor's Ultra-stable Oscillator

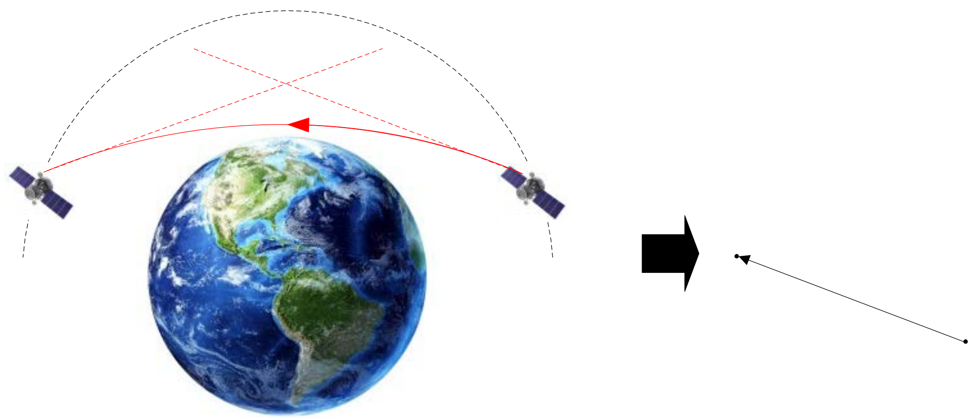
Laser Occultation

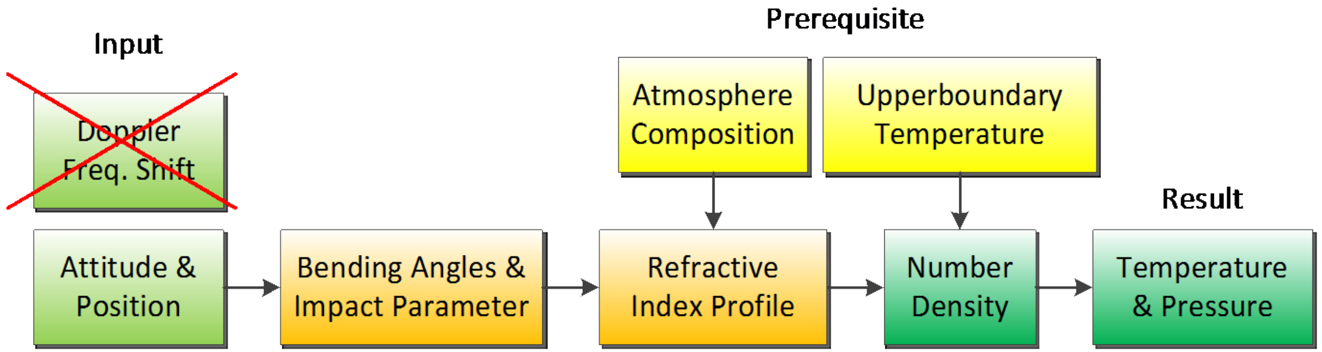
- Intersatellite LEO IR laser link
  - Range of wavelengths from 2 – 2.5 um (best)
- Transmitted signal is attenuated by atmosphere
  - Attenuation at different bands → differential transmission → thermodynamic variables composition information
  - Based on ACCURATE mission (Kirchengast, *et al.*): IR lasers at a range of frequencies
- Transmitted signal also bent by atmosphere
  - Measure bending angle based on position of beam on detector
- Use wavefront control to improve signal measurements?
  - May need improvements with adaptive optics



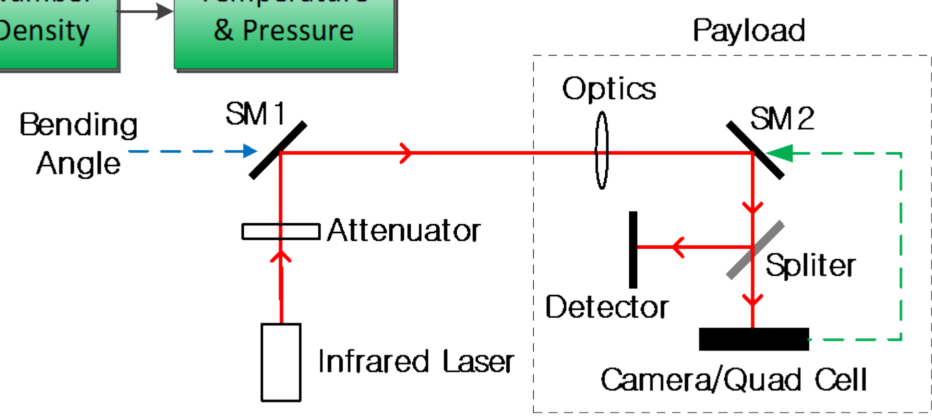
Schweitzer, et al

Laser Occultation





- Use multiple frequencies to measure greenhouse gases like CO2, CH4



Global XCO2 map

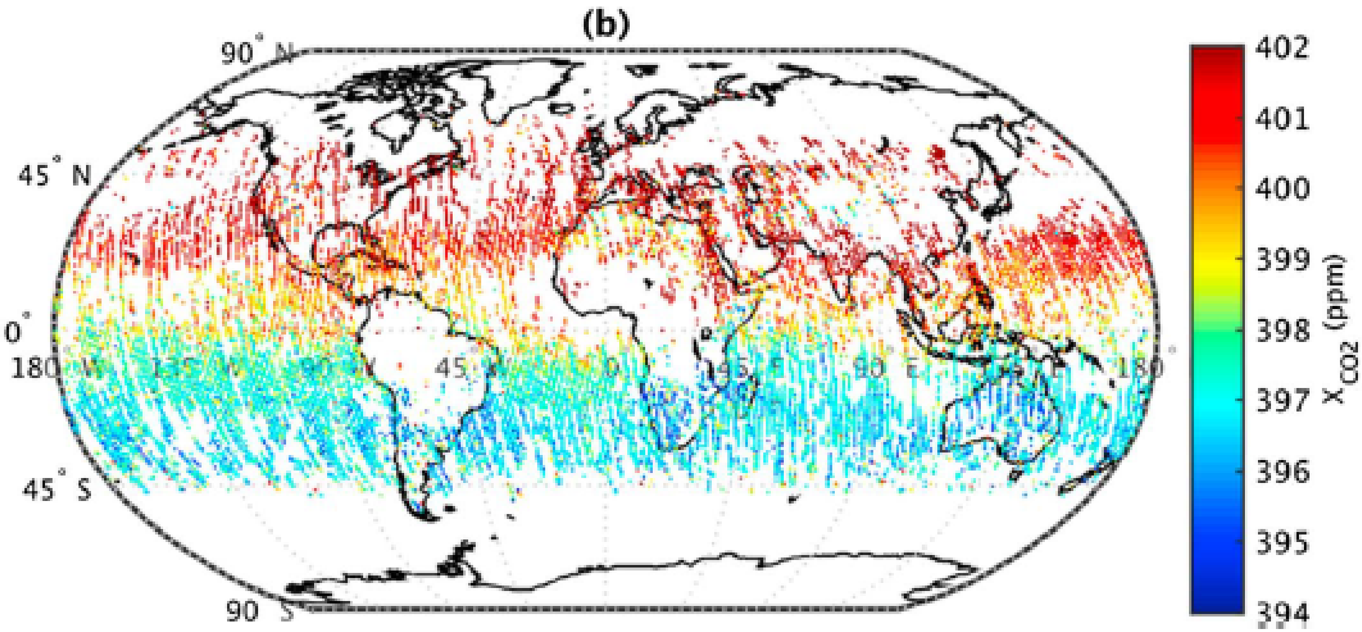


Figure 1. Global map of OCO 2 X_{CO2} retrieval in April 2015. (a) All the data points are displayed. In OCO 2 retrievals, data qualities are labeled with flags 0 and 1: 0, passed internal quality check; 1, failed internal quality check. (b) Only the data points labeled with "flag 0" are displayed.

http://onlinelibrary.wiley.com.libproxy.mit.edu/doi/10.1002/2015EA000143/epdf

- Need 1 ppm accuracy
- Go from column to vertically resolved
- Help manage issues with aerosols (layers)

CO2 lines

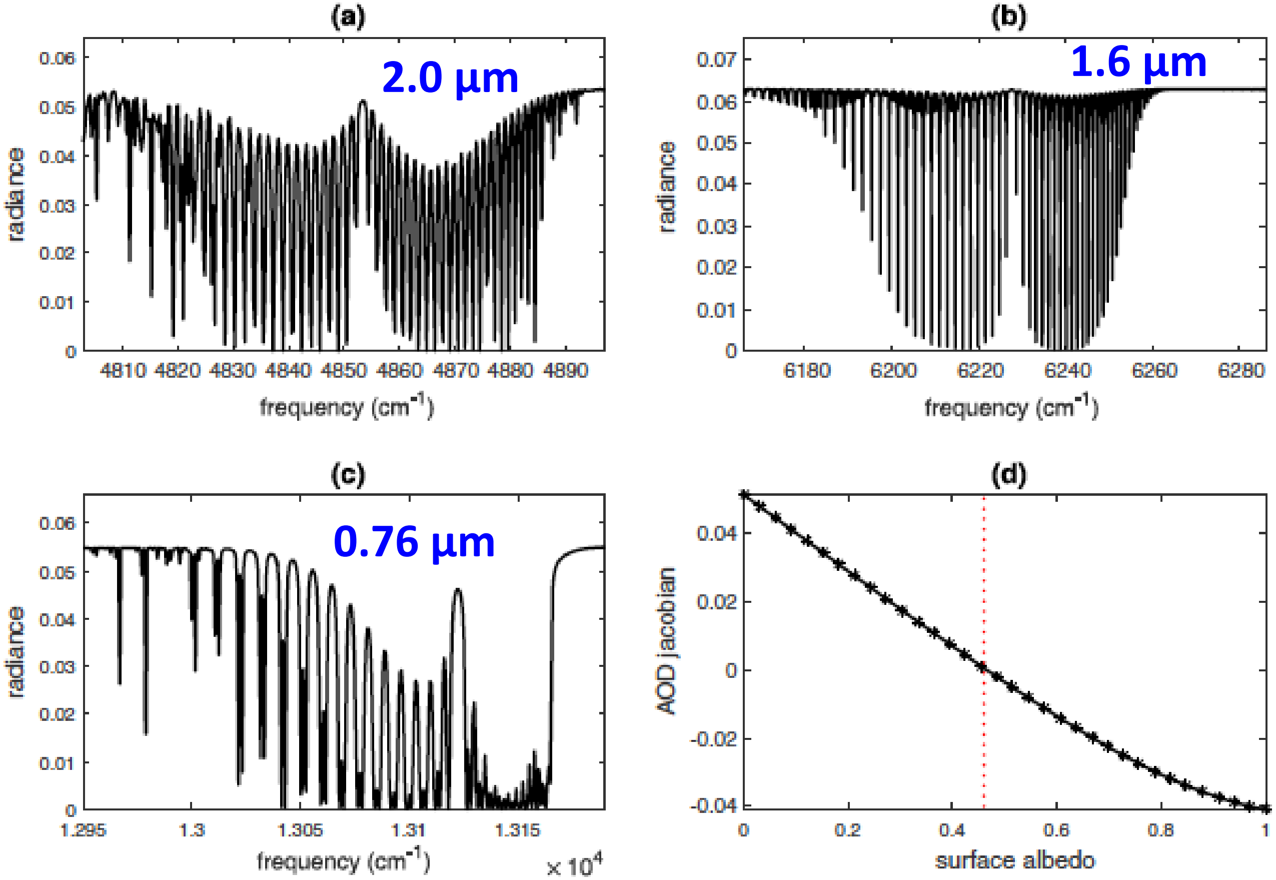


Figure 5. (a) Spectrum of 2.0 µm strong CO_2 band. (b) Spectrum of 1.6 µm weak CO_2 band. (c) Spectrum of 0.76 µm weak O_2-A band. (d) AOD Jacobian in the continuum as a function of surface albedo. The critical surface albedo (0.46) is marked by the red dotted line.

http://onlinelibrary.wiley.com.libproxy.mit.edu/doi/10.1002/2015EA000143/epdf

Species of interest

Gas	Center ν (cm^{-1}) (λ(μm))	Transition	Band interval (cm^{-1})
H_2O	- 1594.8 (6.3) continuum*	pure rotational ν_2; P, R far wings of the strong lines; water vapor dimmers $(H_2O)_2$	0-1000 640-2800 200-1200
CO_2	667 (15) 961 (10.4) 1063.8 (9.4) 2349 (4.3)	ν_2: P, R, Q overtone and combination ν_3: P, R overtone and combination	540-800 850-1250 2100-2400
O_3	1110 (9.01) 1043 (9.59) 705 (14.2)	ν_1: P, R ν_3: P, R ν_2; P, R	950-1200 600-800 600-800
CH_4	1306.2 (7.6)	ν_4	950-1650
N_2O	1285.6 (7.9) 588.8 (17.0) 2223.5 (4.5)	ν_1 ν_2 ν_3	1200-1350 520-660 2120-2270
CFCs			700-1300

Species of interest

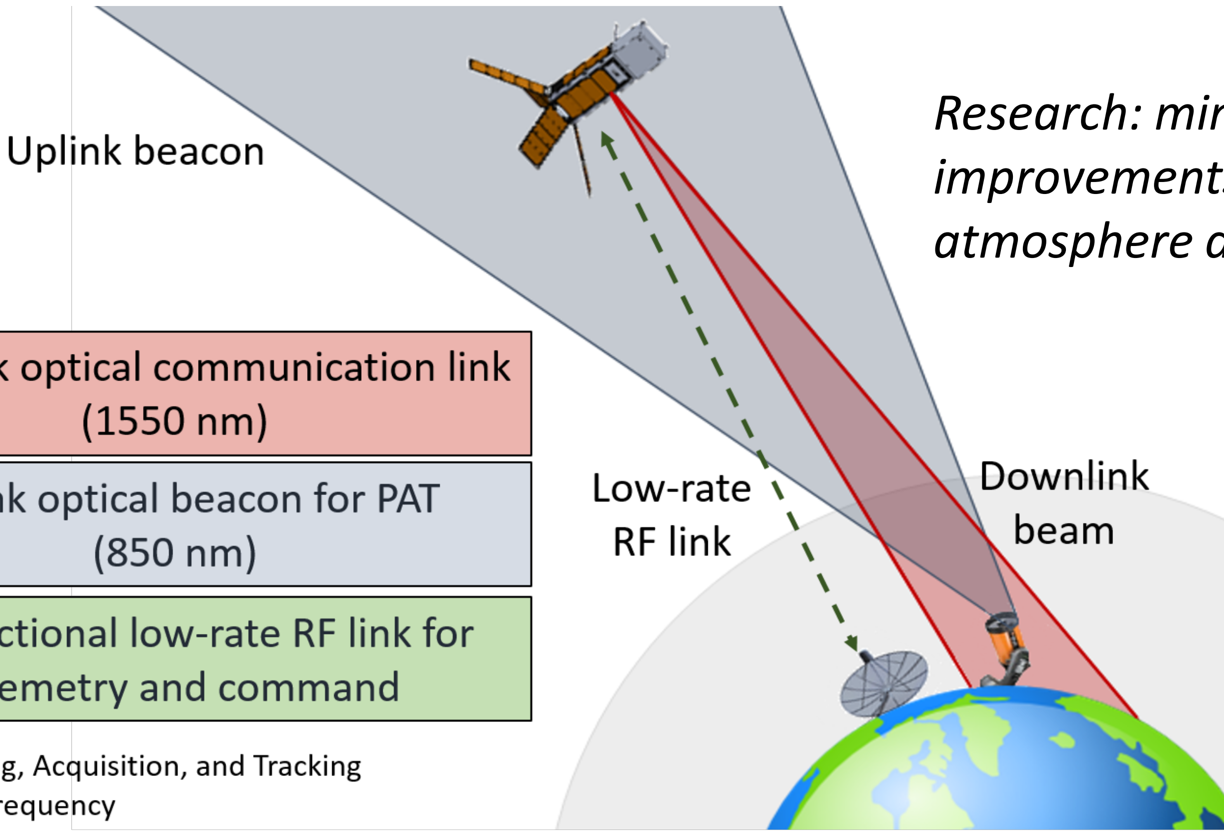
Species	Wavenumber (cm^-1)	Wavelength (nm)	
Abs H2O-1	4204.8403	2378.211605	
Ref H2O-1	4226.07	2366.264638	
Abs H2O-2	4475.803	2234.235957	
Ref H2O-2	4770.15	2096.370135	
Abs H2O-3	4747.0548	2106.56932	shortest wavelength pair
Ref H2O-3	4731.03	2113.704627	shortest wavelength pair
Abs 12CO2	4771.6214	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

Platform development: Lasercom

- Need relatively inexpensive small satellites with precise pointing control for laser occultation
- Very similar to demands for laser communication
- MIT developing optical transmitter for CubeSats: NODE
  - Nanosatellite Optical Downlink Experiment
- Also higher-powered bus with propulsion: KitCube
  - Lasercom and green monopropellant, NASA CubeQuest Lunar Derby
- Also applying to crosslinks: FLARE
  - Free-space lasercom and radiation experiment

Laser Communications

1. Ground station sends uplink beacon to satellite
2. Beacon detector on satellite provides fine attitude knowledge
3. Fine-steering mirror corrects downlink pointing



Research: miniaturization and improvements in ADCS; atmosphere also a challenge.

Downlink optical communication link (1550 nm)

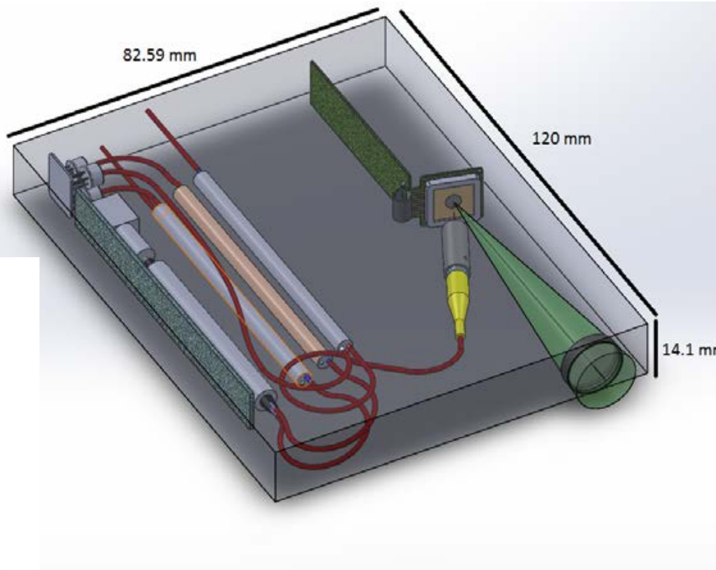
Uplink optical beacon for PAT (850 nm)

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

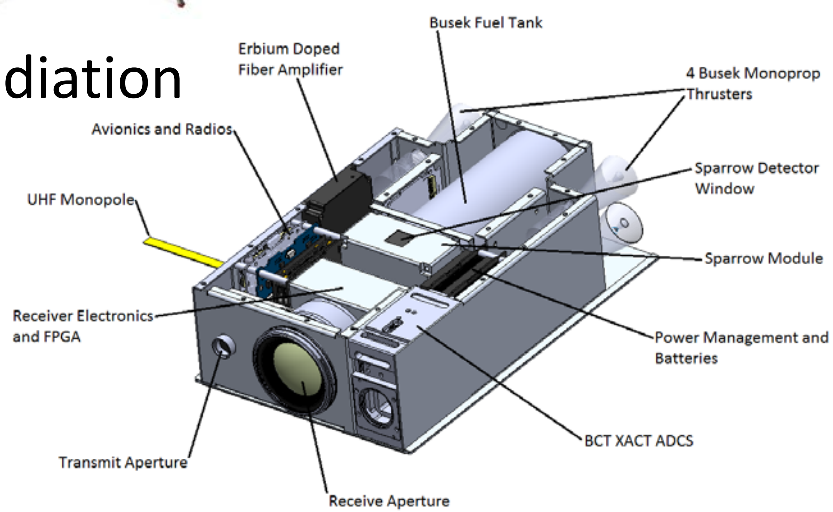
PAT = Pointing, Acquisition, and Tracking
RF = Radio Frequency

NODE and FLARE

- NODE:
  - Nanosatellite optical downlink experiment
  - Transmitter module in commercial CubeSat
  - Flight planned late 2016



- FLARE:
  - Free-space Lasercom And Radiation Experiment
  - UNP-9
  - Intersatellite crosslinks
  - Radiation spectrometer



Link Budget

- RF vs. FSO – the same principles apply
  - Determine signal power at receiver which is then compared to noise → SNR
  - Receiver, modulation and coding design demand a certain SNR to achieve desired bit error rate

- Common metric for RF sensitivity: E_b/N_0

- Common metric for FSO RX sensitivity: *photons per bit*

Link Budget

$$P_{rx} = P_{tx} \cdot G_{tx} \cdot S \cdot \tau_{tx} \cdot \tau_{atm} \cdot G_{rx} \cdot \tau_{rx}$$

$P_{rx} =$ received optical power [W]

$P_{tx} =$ transmitted optical power [W]

$G_{tx} =$ transmitter gain $= \left(\dfrac{8}{\theta_{tx}^2}\right)$ where θ_{tx} is divergent tx angle

$S =$ free space loss $= \left(\dfrac{\lambda}{4\pi L}\right)^2$ where L [m] is path length

$G_{rx} =$ receiver gain $= \left(\dfrac{\pi D_{rx}}{\lambda}\right)^2$ where D_{rx} [m] is receive aperture

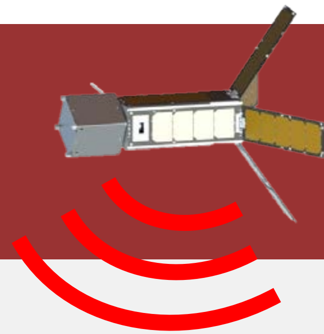
$\tau_{tx} =$ transmitter optical efficiency

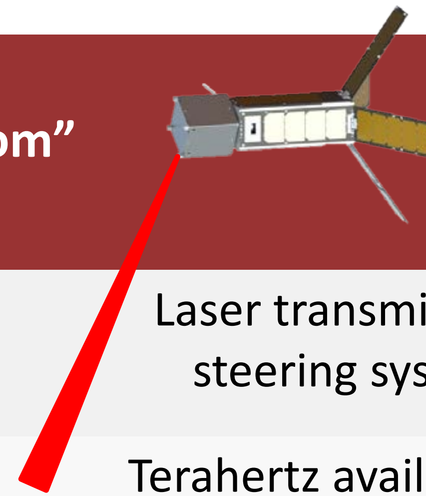
$\tau_{atm} =$ atmospheric transmission factor

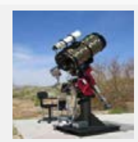
$\tau_{rx} =$ receiver optical efficiency

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, facility (several meters) $1M and up	30 cm amateur astronomy telescope $100k

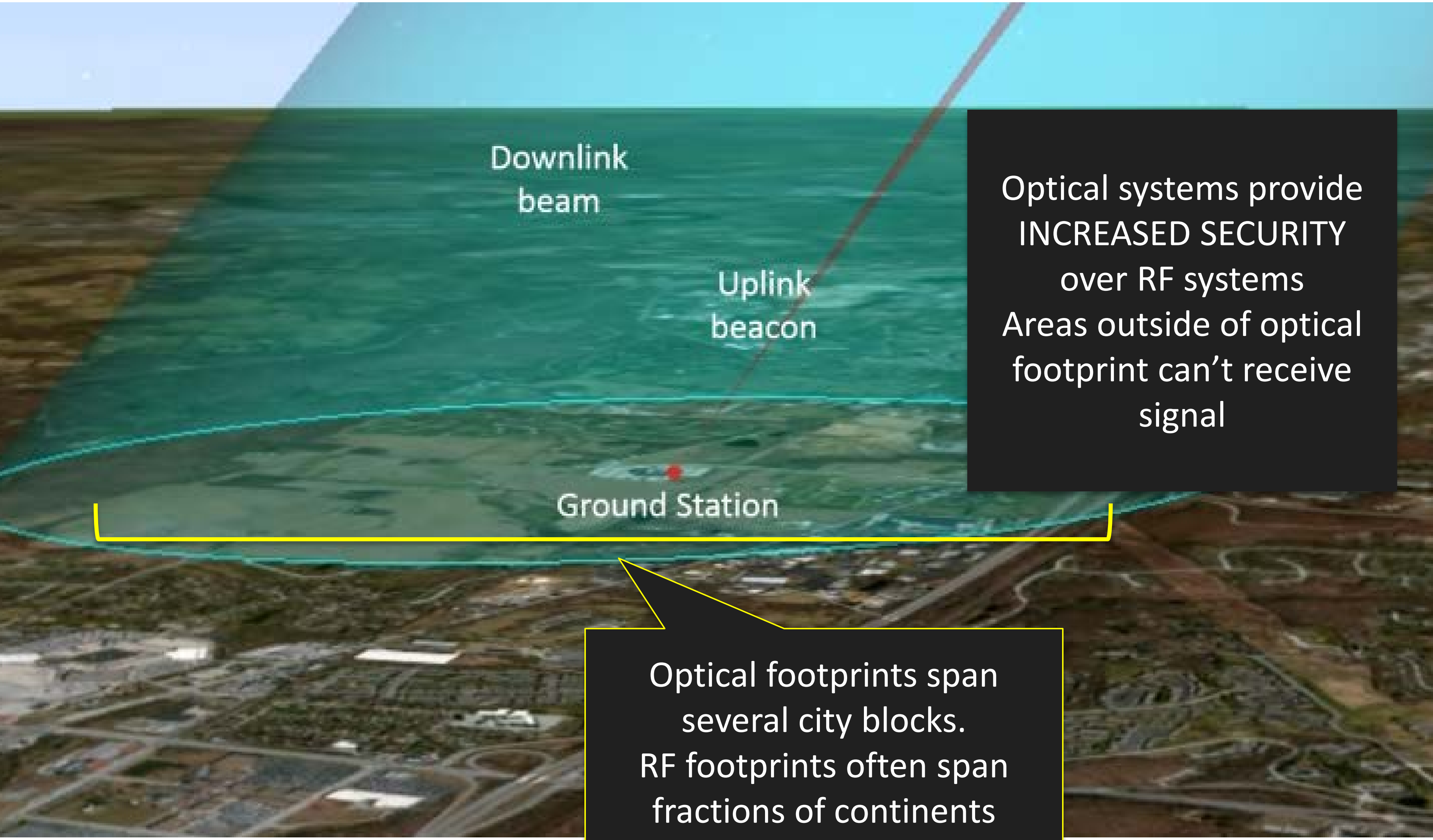






Lasercom offers **superior link efficiency** (less power per bit) due to its ability to better direct signal to receiver.

Narrow laser beam: speed and security



Optical systems provide INCREASED SECURITY over RF systems
Areas outside of optical footprint can't receive signal

Optical footprints span several city blocks.
RF footprints often span fractions of continents

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**

All system parameters are matched, except wavelength

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

Optical system has a **70 dB advantage**

Link Budget – Laser Occultation

Source: ACCURATE LEO-LEO Infrared Laser Occultation Initial Assessment: Requirements, Payload Characteristics, Scientific Performance Analysis, and Breadboarding Specifications

Author: Hyosang Yoon   Date: 2015. 2. 11.

Constants	Value	Notes
Tx Power (W)	1.0000	
Tx Beamwidth (mrad)	3.0000	At e^-2, Full Angle
Tx Pulse Duration (ms)	1.5000	2000 nm
Rx Mirror Diameter (m)	0.3600	
Rx Integration Time (ms)	2.0000	
Rx Detector NEP (W)	8.00E-13	Noise-Equivalent Power
Rx Optical Loss (%)	35	Assumption
Distance between Tx and Rx (km)	6,200.00	Assume 6000 km for 600km sun sync. orbit
Sampling Frequency (Hz)	50	Raw sampling frequency
Filtered Sampling Frequency (Hz)	2	Filtered sampling frequency
Typical set/rise vel, Vscan (km/s)	0.3	Empirically modeled, Vscan[km/s] = {0.3, 2.8, 3, 3.15, 3.2, 3.2} at z[km] = {0, 25, 30, 35, 40
Required Vertical Resolution (km)	2	dz_target

- Assumptions from ACCURATE SSO counter-rotating orbits

Link Budget – Laser Occultation

Type	Best Case Pointing (25 µrad)	Notes and Equations
Tx Power (dBW)	0.0000	
Rx Mirror Area (m^2	0.1018	pi * d^2 / 4
Beam Area (m^2)	271716349	(beamwidth * dist)^2 * pi / 4
Propagation Loss (W/W)	7.49E-10	2 * Ar / Abeam, 2 is from the ratio of the intensity of the Gaussian beam near the optical axis (Wm-
Propagation Loss (dB)	-91.2539	
Reception loss (dB)	-1.2494	t_pulse / t_integration
Rx Optical Loss (dB)	-1.8709	
Pulse power at detector (dBW)	-94.37416271	
Rx Detector NEP (dBW)	-120.9691001	
SNR Detector (dB)	26.59	Basic SNR at detector
Down Sampling Gain (dB)	6.989700043	G_ds = 10*log(sqrt(f_s,raw / f_s, filt))
dz_filt (km)	0.3	dz_filt = V_scan / (0.5 * f_s,filt)
Resolution Gain (dB)	4.119543705	
SNR Basic (dB)	**37.70418117**	**SNR basic = SNR**
Background Loss for Abs ch. (dB)	7.97	Vary from 0.21 to 7.97 dB according to Altitude. To be simulated numerically with accurate atmosphere model
SNR Ref. Ch. (dB)	**29.73418117**	
Target Species Absorption Loss (dB)	13	Designed maximum of 13 dB for detection
SNR Abs. Ch. (dB)	**16.73418117**	
Error in Ref. Ch. (%)	0.1063119009	100 * 10^ (-SNR / 10)
Error in Abs. Ch. (%)	2.121201294	100 * 10^ (-SNR / 10)
Error residual (%)	2	[%] = {2, 1, 0.5, 0.3, 0.2, 0} at z[km] = {0, 5, 10, 20, 30, 120}

- Assumptions from ACCURATE SSO counter-rotating orbits

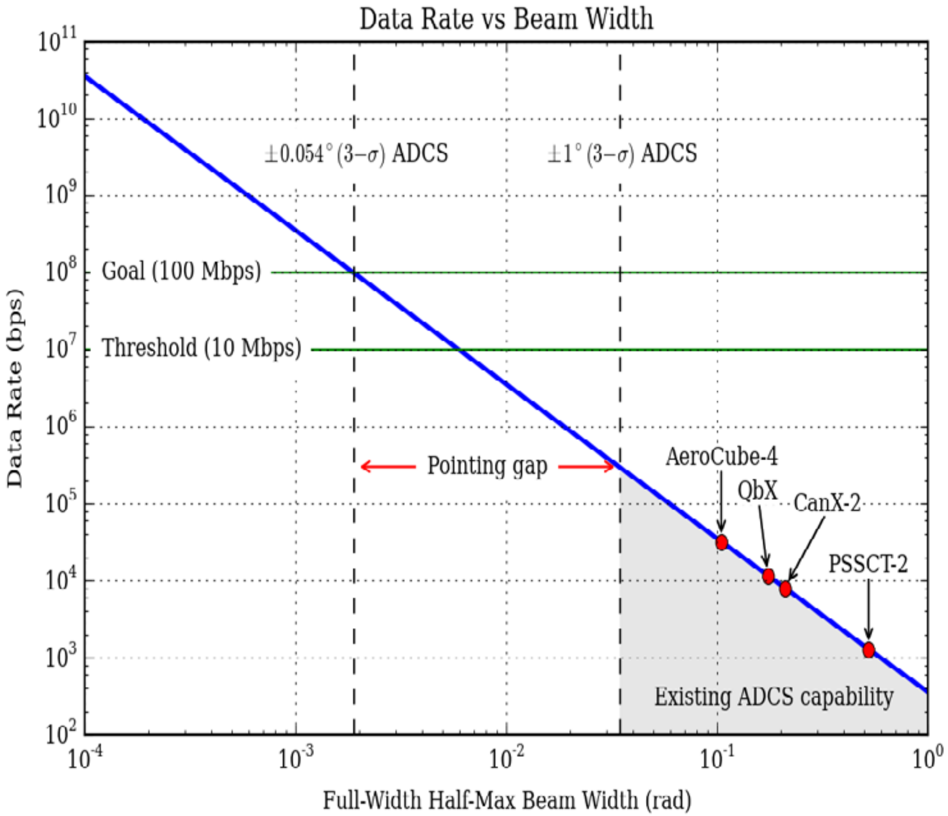
Link Budget – Laser Occultation

Differential log-transmission error (%)	**2.917327056**	**E = sqrt(E^2 + ...)**
E_delT_abs (dB)	0.1266965967	Differential log-transmission error in unit dB
SNR Difference (dB)	13	Differential log-transmission between the absorption and reference channel
Diff. log-trans. relative error (%)	**0.9745892054**	**100*E_delT_abs / (SNR diff)**
Species absorption coefficient error (%)	2.436473014	E_absC = g_AbelTr * E_delT_rel, g_AbelTr: error gain factor from Abelian transformation
Absorption cross section error (%)	0.8	Empirically modeled to be <0.4-0.8% within 5-10 km and 0.4%< within 10-40km (with increasing error upwards) E_sigmaAbs[%] = {0.8, 0.8, 0.4, 0.4, 1.6, 8} at [km] = {0, 5, 10, 40, 60, 120}
Species profile retrieval error (%)	**2.564449404**	**E_Sp = sqrt(E_absC^2 + E_sigmaAbs^2)**

- Assumptions from ACCURATE SSO counter-rotating orbits

Identification of Pointing Gap

- Consider end-to-end laser link:
  - Realistic laser transmitter (1 W)
  - Inexpensive RX aperture (30 cm)
  - COTS detector (APD)
- CubeSat ADCS today:
  - Flight demos +/- 1 deg (3-σ)
  - Typically sensing-limited
  - Although, slew can be actuator-limited…
  - Insufficient for lasercom goals
- Add ***fine-stage*** to bridge gap
  - Beacon: improves sensing
  - FSM: improves actuation



Curve above assumes: 0.5*FWHM = 3-σ pointing

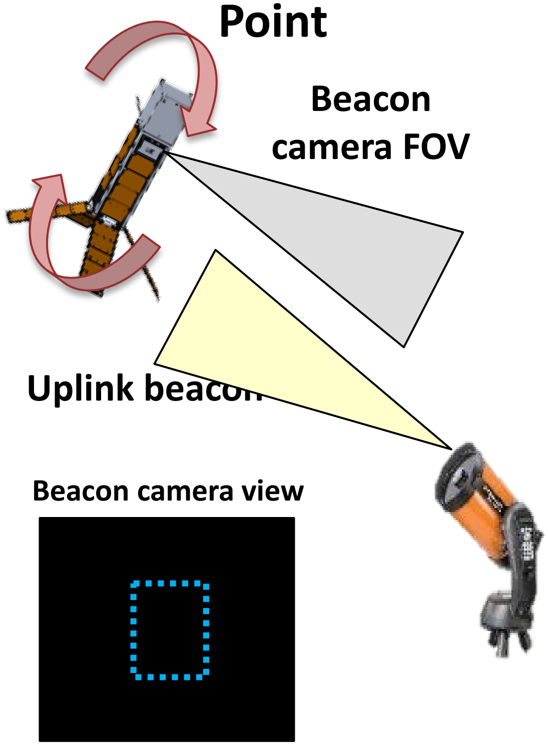
A >10X improvement in pointing is needed to make lasercom competitive with RF.

NODE Key Parameters

Link Parameters		
Data rate	**10-100 Mbps (stretch)**	
Bit error rate	10^-4 without coding	Conservative baseline for FEC (7% RS planned)
Path length	**<1000 km**	~20 deg elev @ 400 km LEO
Space Segment Parameters		
Size, Weight	**10 x 10 x 5 cm, 600 g**	CubeSat mid-stack payload: 0.5 U
Power	**10 W (transmit mode)**, 1 W (idle)	Entire lasercom payload
Downlink Beam	1550 nm, **0.12° (2.1 mrad) FWHM**	Radiometric constraint for 10 Mbps
Beacon Detector	CMOS camera (silicon)	Ground-station-relative pointing knowledge
Ground Segment Parameters		
Apertures	**RX: 30 cm**, beacon: four at 2 cm each	Mount capable of tracking LEO object
Comm. Detector	Commodity APD/TIA Module	**Operating at 300 photons/bit (no exotic detectors)**
Pointing	Coarse: TLE, Fine: tip/tilt FSM	Detector size demands fine stage

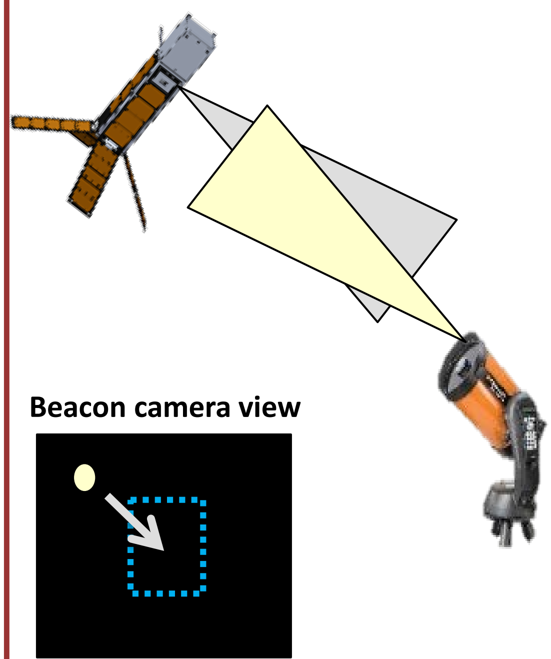
Pointing, Acquisition and Tracking

Point



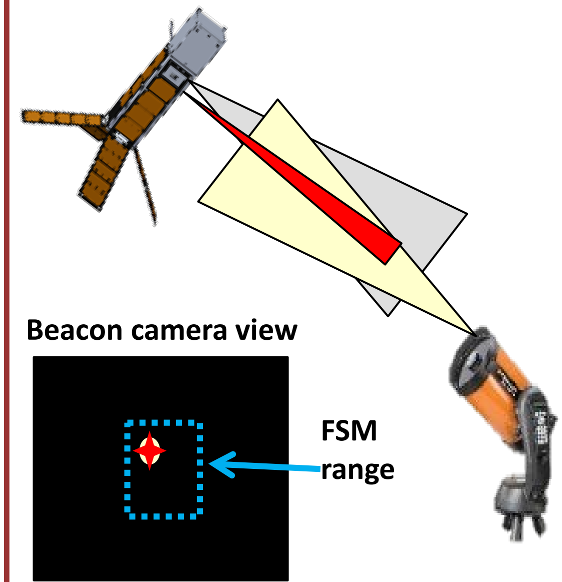
- Satellite slews to point camera at estimated ground station location.
- Ground station points beacon at estimated satellite position.

Acquire



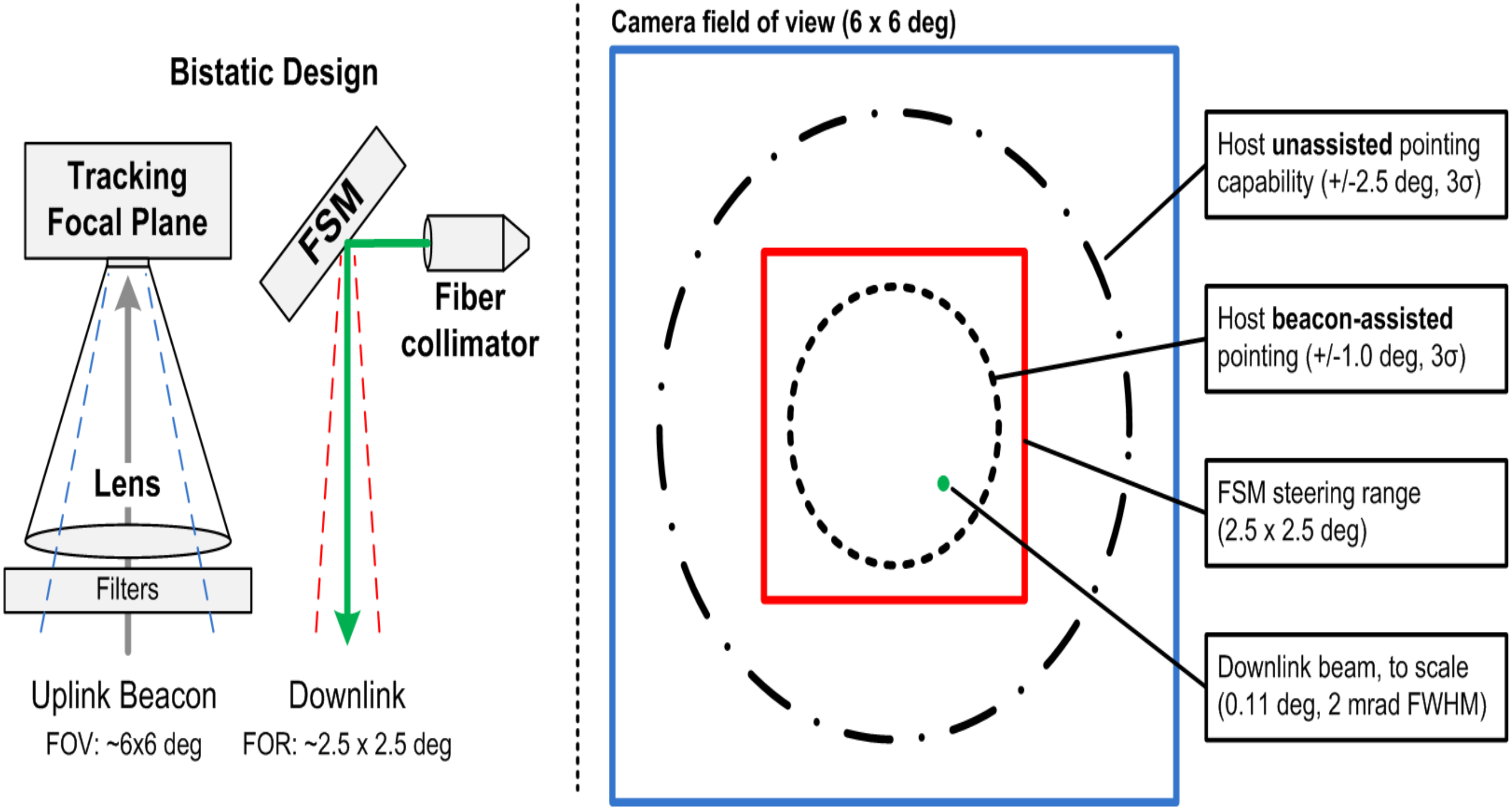
- Beacon camera provides absolute measurement of pointing error.
- Satellite body pointing is further improved with this knowledge.

Track



- Fine-steering mechanism corrects for residual body pointing error.

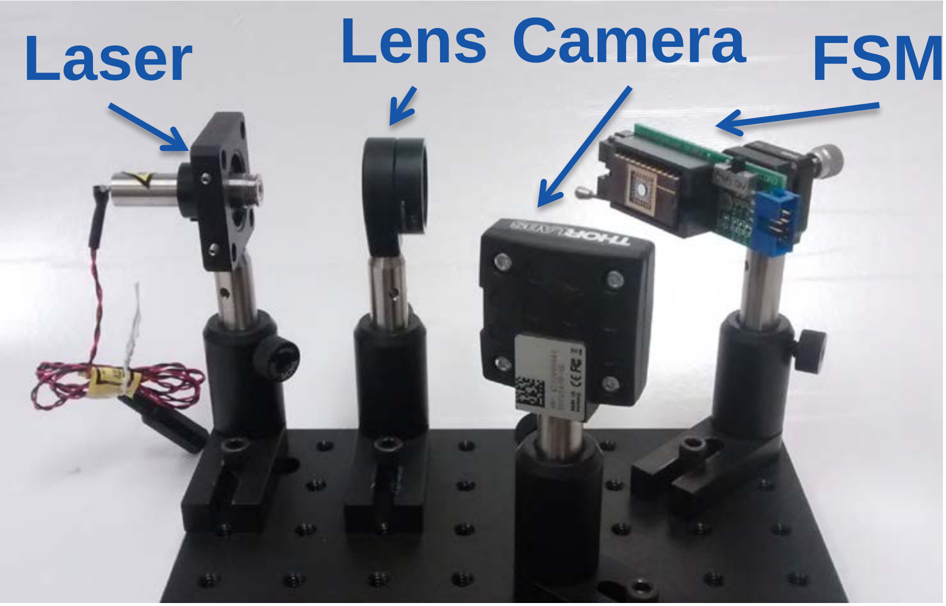
PAT / Stage Handoff



Camera FOV oversized to avoid time-wasting search. Fine stage oversized to avoid saturation.

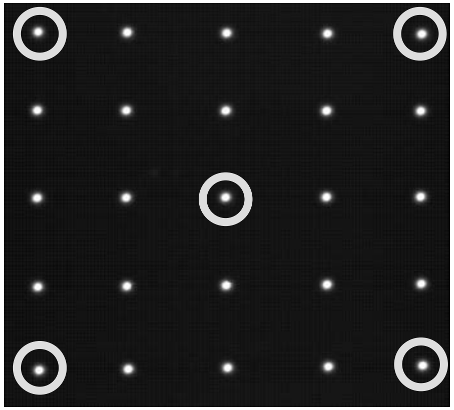
Two-stage CubeSat ADCS

- Characterization of MEMS fast steering mirror
- Thermal properties, hysteresis, linearity
- Hardware tests in progress…
- 6 DOF simulation in progress
- On-orbit calibration scheme in progress…



Pointing Req.: ±0.03°

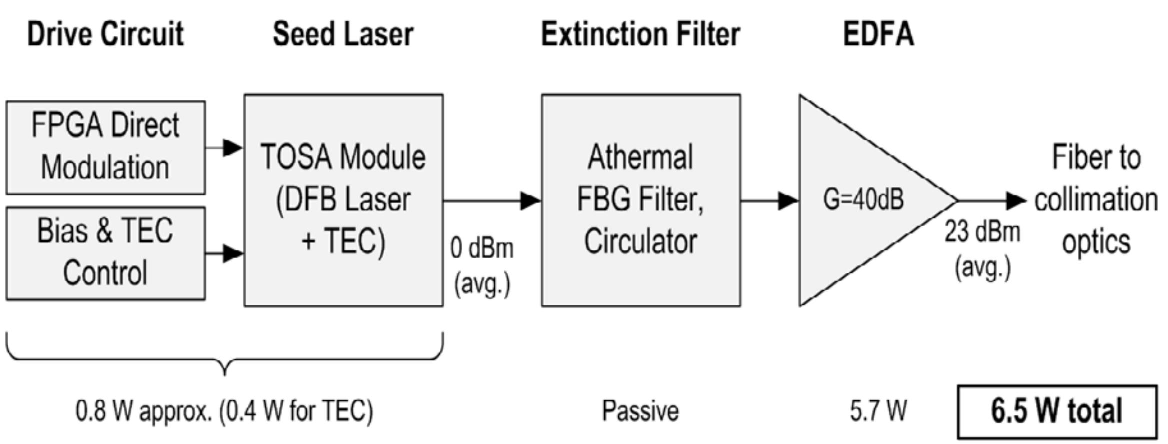
Repeatability Test	RMS Error
Best device	0.0007° (12 μrad)
Worst device	0.0039° (67 μrad)



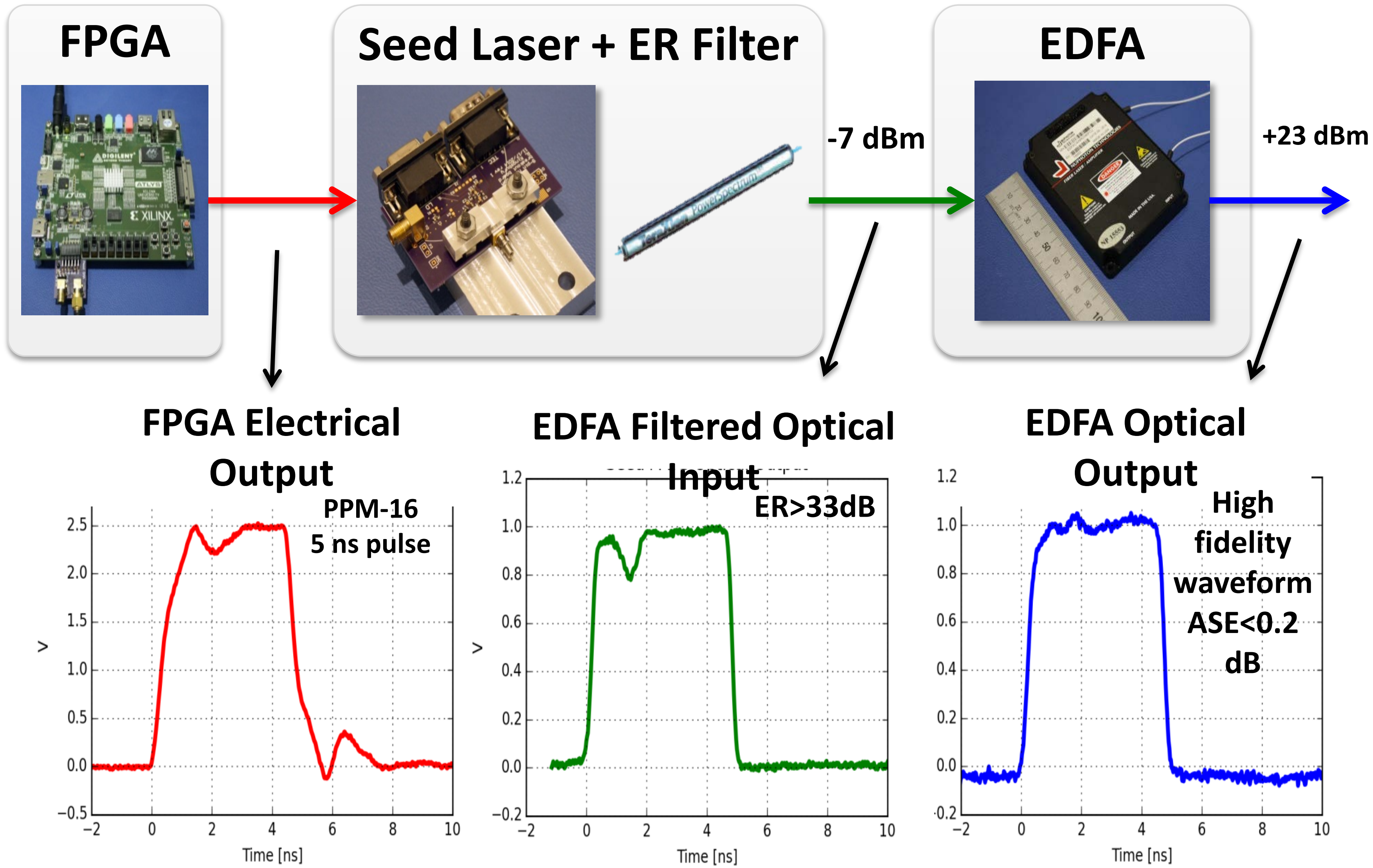
MOPA Approach

- MOPA: Master Oscillator Power Amplifier
  - **Ample modulation bandwidth (>GHz)**
- Two wavelength options:
  - Best Efficiency: YDFA (2X efficiency)
  - **Best Availability: EDFA (telecom)**
- External modulators are power hungry → **direct modulation of seed is desirable**

- Design challenges:
  - **Achieving sufficient extinction ratio (ER)**
  - Need ER > 27 dB for PPM-16
  - **Thermal stabilization of seed laser**



Measured Electrical/Optical Waveforms



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**

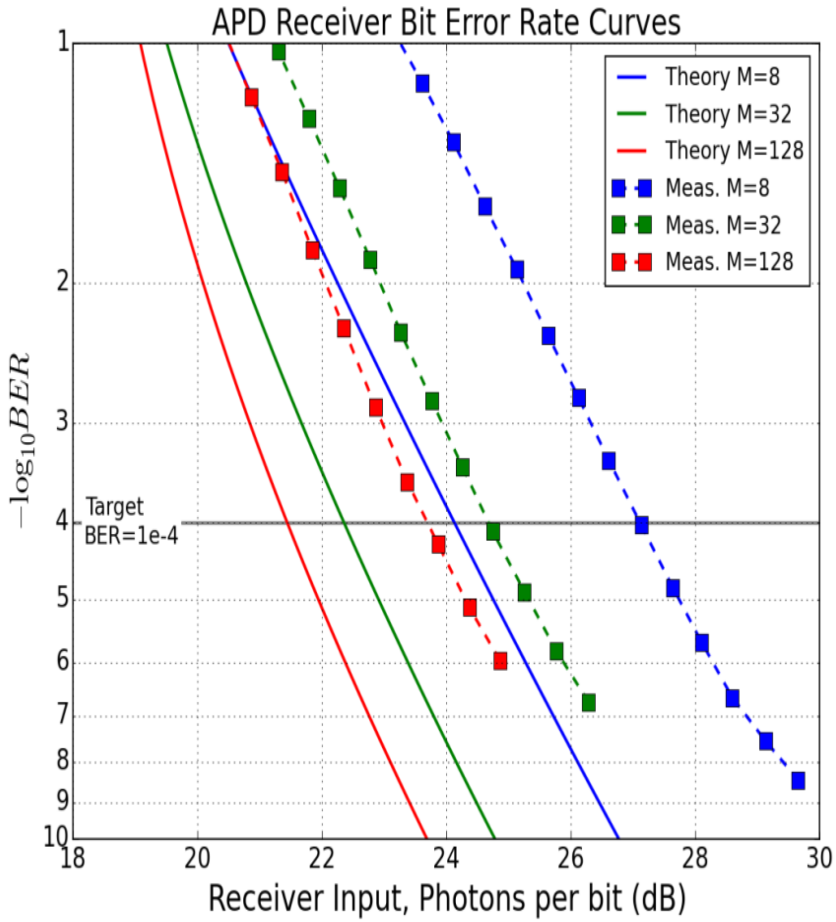
Transmitter meets power budget with 18% margin

Flight Receiver BER Curves

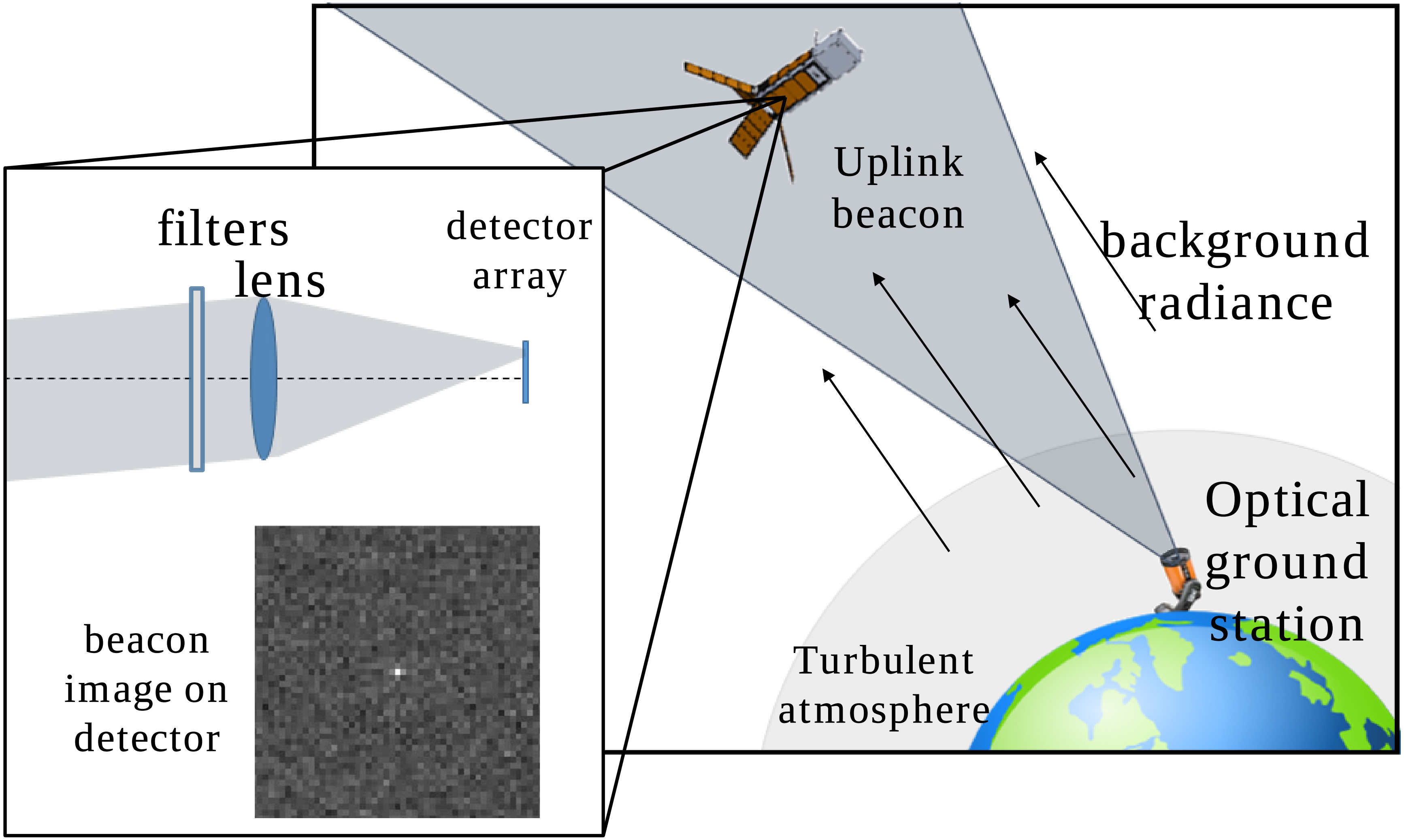
- Theoretical sensitivity from link budget

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

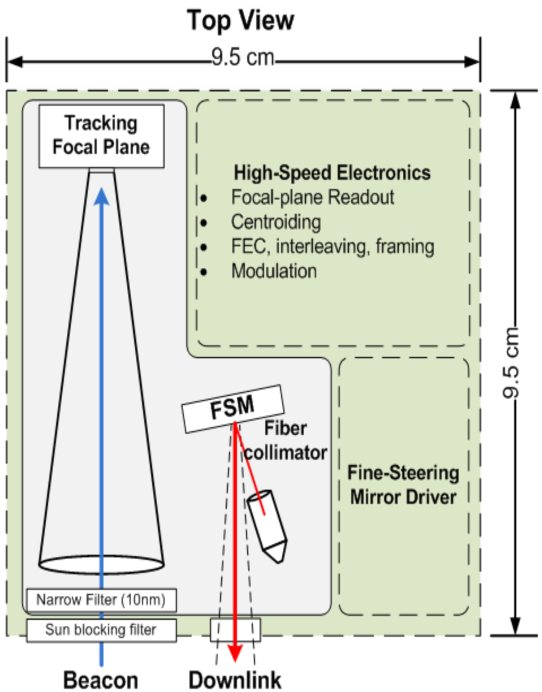
System is currently 2.2– 3.0 dB from theory (mode dependent).

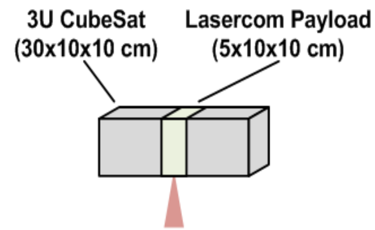


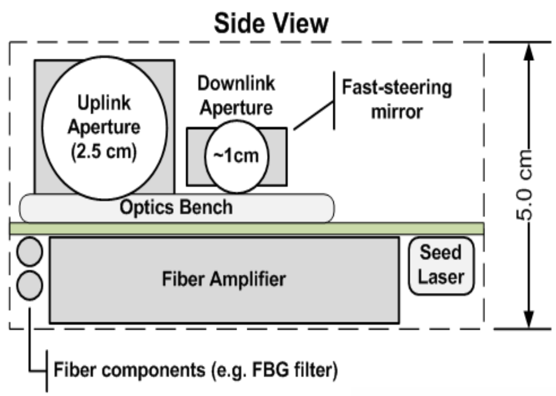
Beacon system

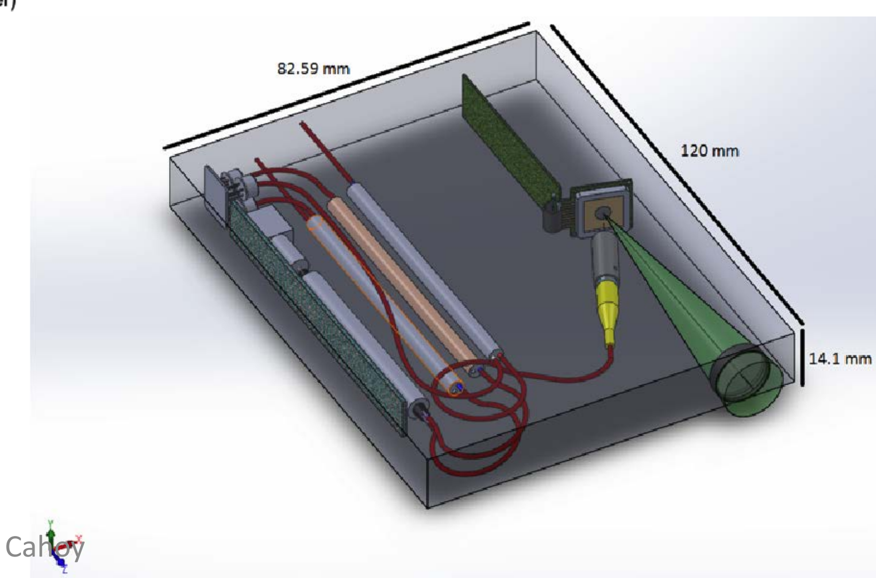


“0.5U” Physical Layout

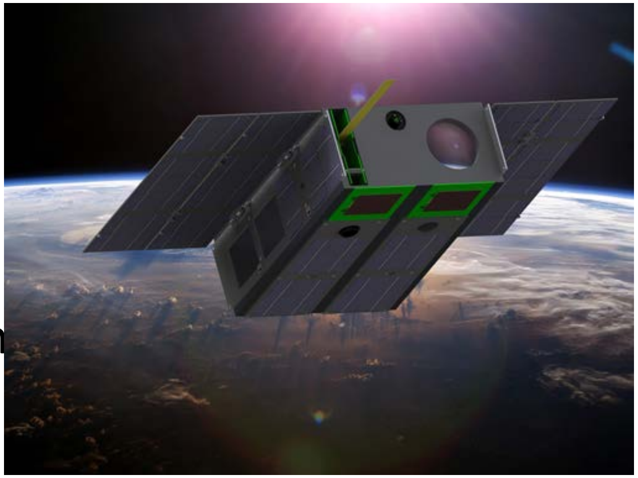








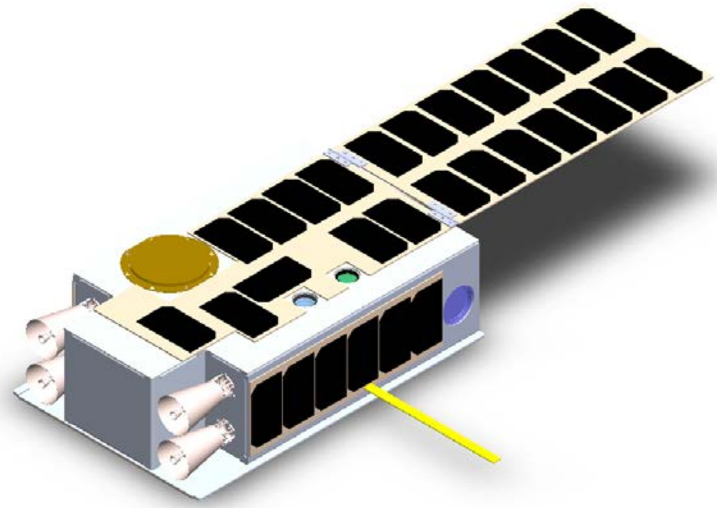
Deformable Mirror Demonstration (DeMi)



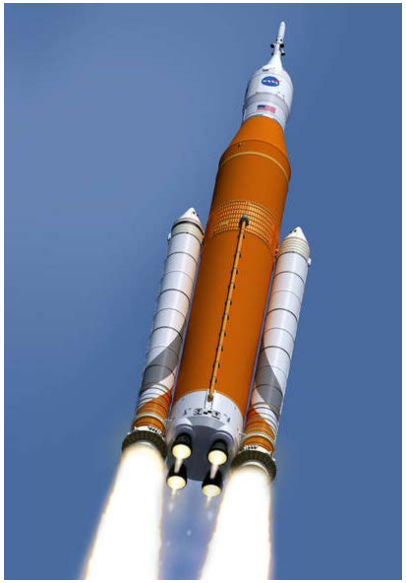
- (1) open-loop mirror characterization
  - Illuminate mirror with internal laser
  - Measure mirror deflections to a precision of 10 nm with wavefront sensor
  - Repeat experiment frequently over mission
- (2) Image correction on an external object.
  - Requires that a star or extended object (Earth, moon, etc.) stay within the field of view of the external aperture for at least 5 consecutive minutes.
  - During this time, a closed-loop algorithm will run to improve the image quality of that external object within the control authority of the mirror.

About the Challenge

- NASA's CubeQuest challenge competition inspires development of new small satellite technology
  - Advanced communications and propulsion
  - For exploration and for commercialization

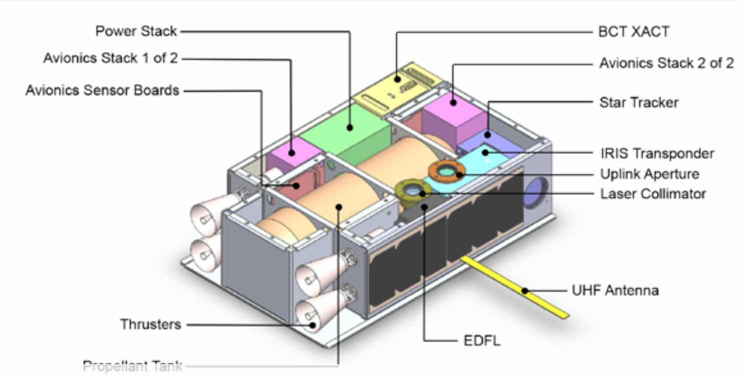


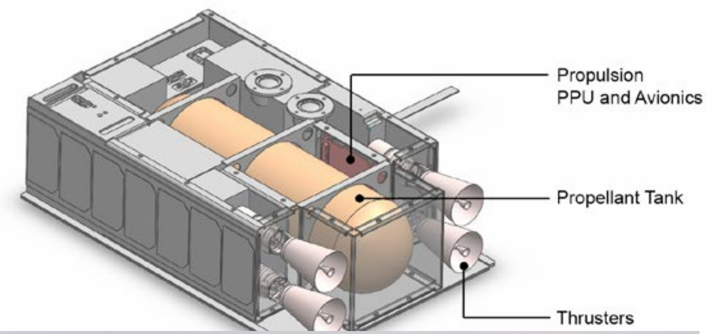
- 3 winners **<u>get a free ride</u>** on Exploration Mission 1, as the Space Launch System rockets the unmanned Orion crew capsule toward the Moon
  - And **$5M cash prizes** for technology demonstrations
    - Achieve lunar orbit (propulsion)
    - Best burst data rate (communications)
    - Most data sent over time

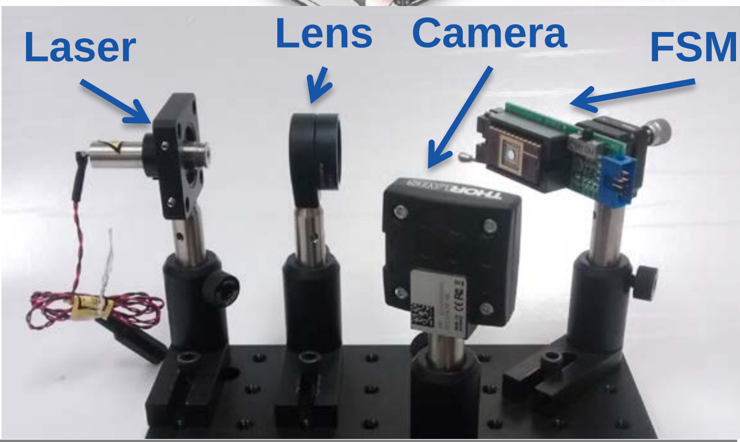


About our Spacecraft Technology

- KitCube has four 0.5N green monopropellant thrusters to get to the Moon
  - Green monopropellant is new, less toxic
  - Trailblazing CubeSat Δv capability of 300 m/s
- Two star trackers and three reaction wheels help us maneuver accurately
  - Goal of 10 arcsec pointing
- A MEMS fine steering mirror provides a new way to achieve precise pointing
  - So we can point our 1W laser beam at the telescope on Earth, with data rates >1 Mbps
- A new CubeSat X-band radio supports two-way ranging
  - So we can talk to KitCube and figure out where we are on the way to the Moon
  - So we can meet the navigation artifact requirement for the competition prizes





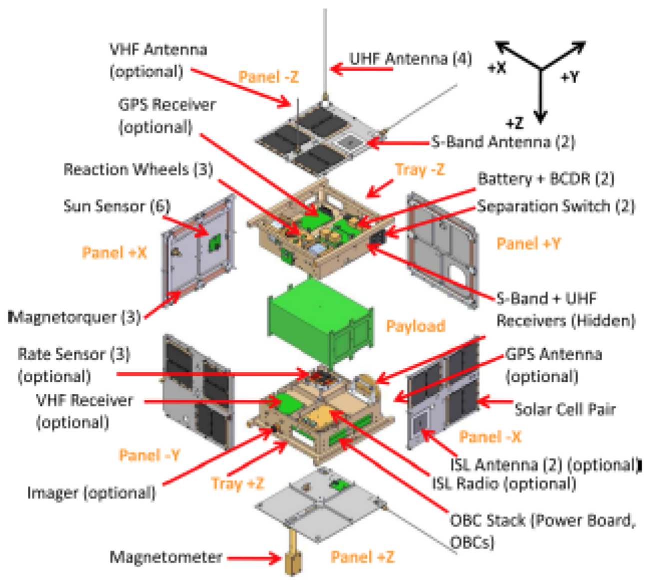


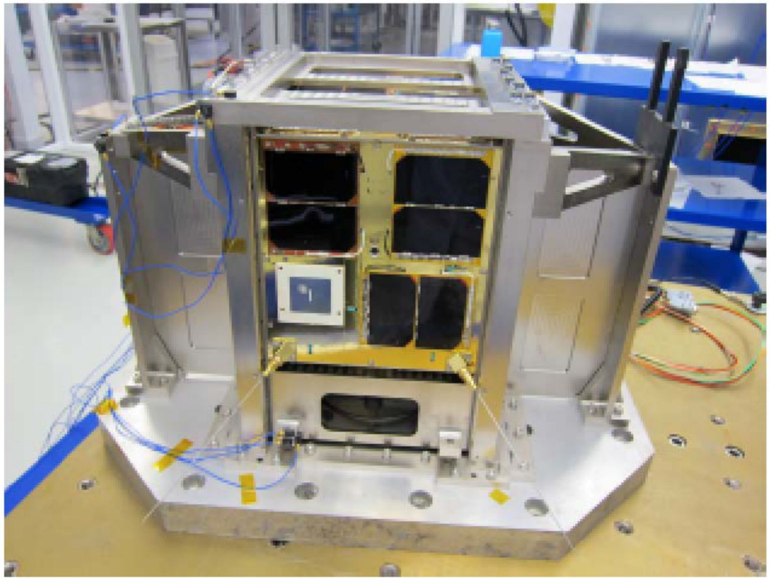
Technology Development: Formation

- CanX-4 and CanX-5 have demonstrated relative navigation using carrier-phase differential
  - *Newman et al., SmallSat 2015*
  - Separations from 1 km to 50 m
  - 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





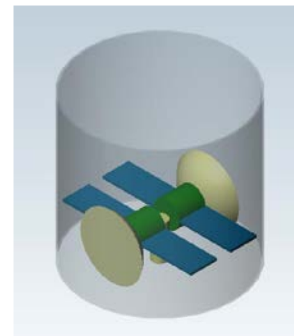
I’ve always wanted to do this…

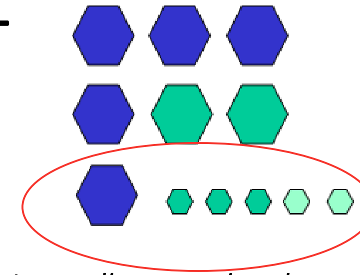
- JPL Planetary Science Summer School 2001
- First-year graduate student

MATR/IX

Mars **A**tmospheric **T**win-Satellite **R**adio / **I**onosphere e**X**periment

August, 2001





I actually wanted to do what would later become “CubeSats” but Team-X shot me down… with their trade studies. They still are working on their “TeamXc”. Sigh.

Mission Ops
- Pre-Launch Cost $7.75M
- Post-Launch Cost $17.1M

} $24.9M

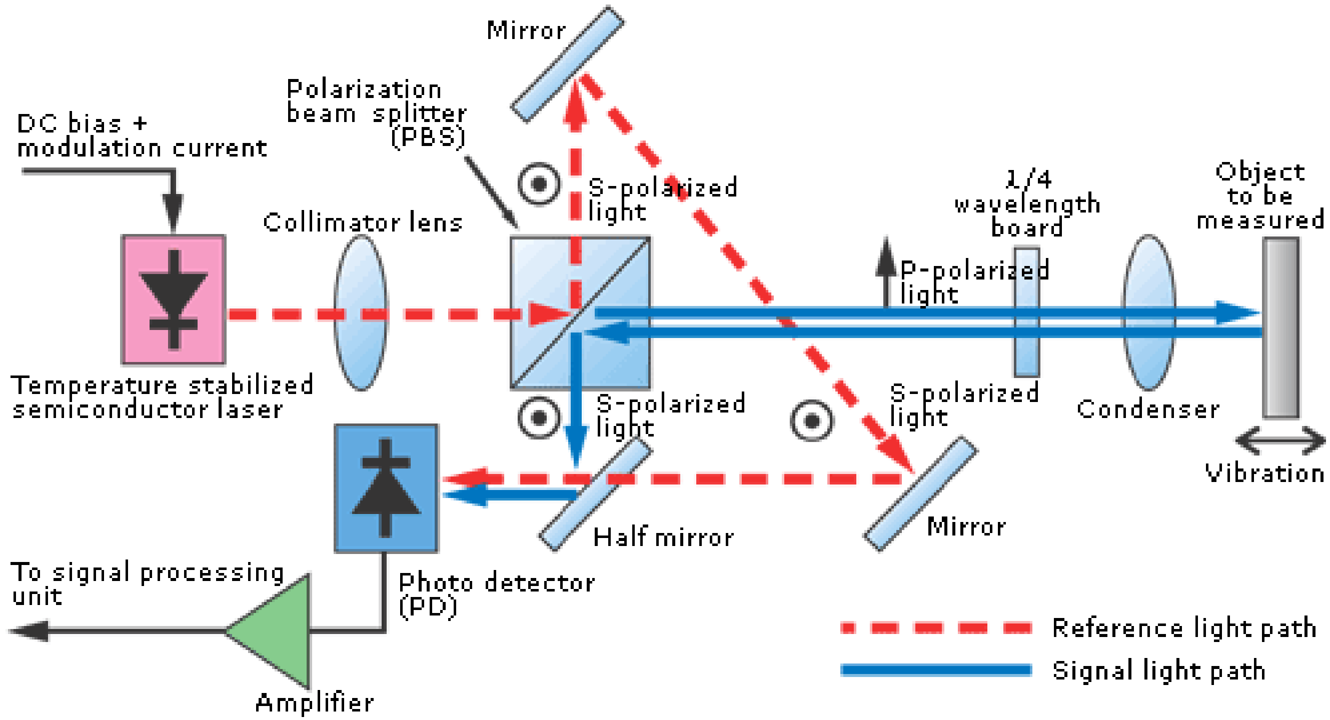
DSN

– Total data volume/week	1428000 kb
– Down-Link data rate	88kbps
– Tracking	6.225 hrs/week
DSN cost share	$4.25M

Summary

- Frequency calibration useful for several atmospheric spectroscopy applications
  - Radio passive, active, laser
- Focus today on laser occultation concept
- Future work needed:
  - Study absorption and instrument performance at different wavelengths
  - Detector sensitivity and noise trade vs. strength of absorption feature
  - Mission design, links, pointing control
  - Opportunities for commercial partnership (e.g., Skybox, Spire)
  - Opportunities for planetary exploration
    - CubeSat sounders

Optical heterodyne detection



http://www.iti.iwatsu.co.jp/en/products/st/st-3761_top_e.html

- Apply a frequency modulation to the injected current of the semiconductor laser
- Divide into reference light and signal light, using polarization beam splitter.
- The signal light reflected from object interferes with reference light
- The difference between the frequencies can be measured as a beat
- If the object moves, beat signal changes