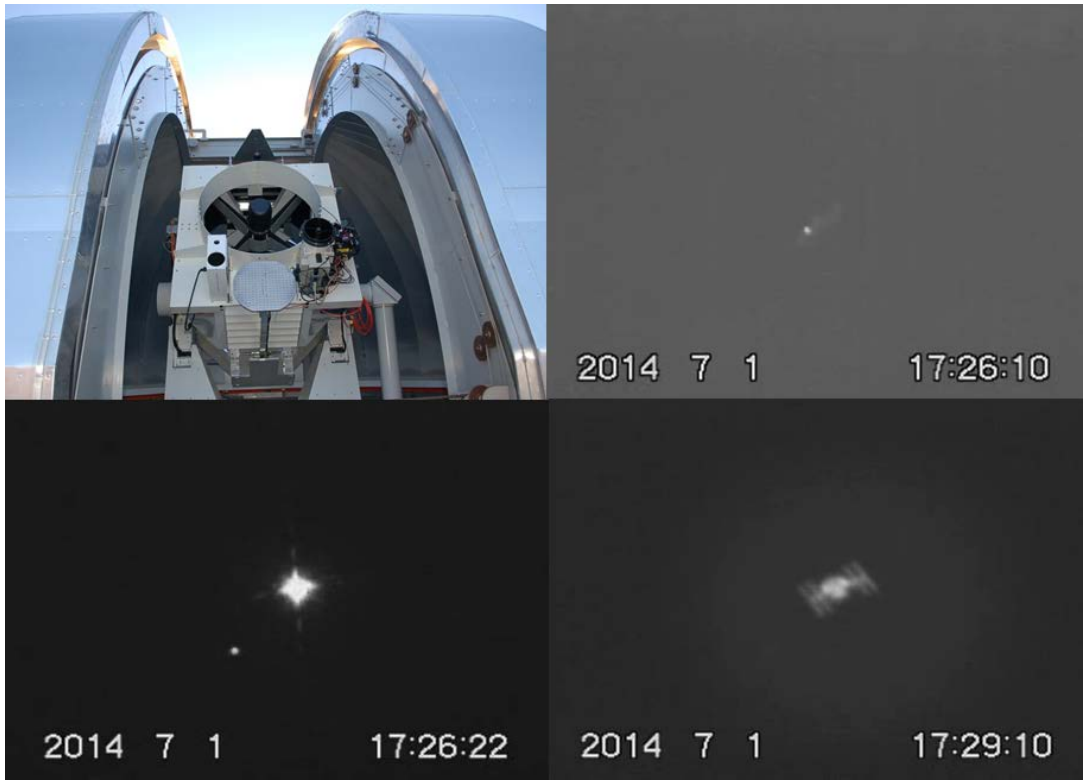

Free Space Optical Communications

Joe Kovalik, Optical Communications Group
Jet Propulsion Laboratory
California Institute of Technology

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Government sponsorship acknowledged.

Overview

- Free Space Optical Communications
  - Spectrum
  - Antenna Gain
  - Noise Sources
  - Link Parameters
  - Simplified Link Calculation
- Optical Communications Telescope Laboratory (**OCTL)**
- Demonstrations
  - Satellite Retro Reflector Experiments
  - OICETS Optical Communications Experiment
  - Lunar Laser Communications Demonstration (LLCD)
    - Description
    - Telescope Pointing
    - Link performance
  - Optical PAyload for Lasercomm Science (OPALS)
    - Flight System
    - Downlink Performance
    - Data Transfer
- Summary

Microwave and Optical Bands

- Microwave frequency limits data rate
- Infrared laser data rate limited by capability of electronics
- Infrared lasers can be multi-plexed to provide multiple data channels
  - Dense Wavelength Division Multiplexing (**DWDM**) can provide hundreds of channels spaced 25 GHz apart
  - Huge infrastructure for fiber optic communication links
    - 1550 nm has low absorption in optical fibers
    - 1064 nm has higher efficiency (electrical to light conversion)

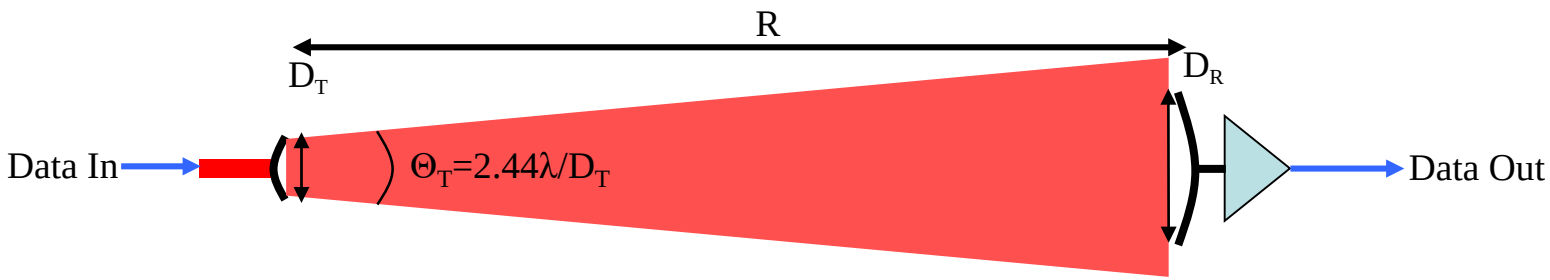
Band	Frequency	Wavelength
Microwave X	5.2-10.9 GHz	2.8-5.8 cm
Microwave K_u	15.35-17.26 GHz	1.7-2.0 cm
Microwave K_a	33-36 GHz	8.3-9 mm
Infrared L band	187-191 THz	1.570-1.607 µm
Infrared C band	192-196 THz	1.530-1.560 µm
Infrared Nd:YAG	282 THz	1.064 µm

Antenna Gain

- Shorter optical wavelength allows trade between power, transmitter and receiver antenna size
- Smaller beam divergence requires more stringent acquisition, tracking and pointing

$$P_R \approx P_T \frac{1}{4}\left(\frac{\pi D_T D_R}{2\lambda R}\right)^2 = P_T \frac{A_T A_R}{\lambda^2 R^2}$$

P_T -Transmitter Power
D_T -Transmitter Diameter
D_R -Receiver Diameter
R -Range
λ -Wavelength



TRANSMITTER
- Laser Power
- Laser wavelength
- Aperture
- Optical Losses
- Pointing

LINK
- Range
- Atmosphere
  - attenuation
  - turbulence

PERFORMANCE
- Data rate
- Bit Error Rate

RECEIVER
- Telescope aperture
- Optical Losses
- Pointing
- Detector noise

Noise Sources

- Shot Noise
  - Laser power limited by that available from transmitter platform
  - Motivates the use of high wall plug efficiency lasers
  - Modulation extinction must be high
  - Background light must be removed by narrow band filtering
- Photodetector noise
  - Use high quantum efficiency for particular wavelength
  - Thermal noise
    - Trade between detector bandwidth and noise
    - Requires small area detectors which increases pointing requirements
  - Dark noise
    - PIN (positive Intrinsic Negative) has fixed noise
    - APD (Avalanche PhotoDetector) has gain dependent noise which must be optimized
- Amplifier noise
- Pointing error causes mean power level to vary
  - Bias error from static pointing offset
  - Jitter from transmitter vibration
- Atmospheric effects can lead to signal “fades”
  - Beam spreading from
  - Jitter from turbulence
  - Attenuation from clouds

Link Parameters

TRANSMITTER		
optics:		
wavelength*	nm	1550
modulation extinction ratio*	none	0.1
aperture diameter (GEO) *	cm	30
aperture diameter (LEO) *	cm	10
optical efficiency*	%	60
pointing:		
pointing bias	% of beamwidth	10
rms beam pointing jitter	% of beamwidth	10
Pointing loss (GEO)	dB	-0.4
Pointing loss (GEO)	dB	-0.6
LINK		
Ranges:		
Earth to GEO orbit	km	36000
Earth to LEO orbit	km	300
atmosphere:		
elevation angle	degrees	20
Nominal transmission	%	79
Loss due to turbulence effects (GEO)	dB	-7.2
Loss due to turbulence effects (LEO)	dB	-12.5
sky radiance*	W/(m^2×ster× nm)	2.0

RECEIVER		
optics:		
aperture diameter*	cm	40
optical efficiency*	%	60
bandpass filter width*	nm	10
APD detector:		
receiver temperature*	Kelvin	300
photodiode efficiency*	%	70
capacitance of detector	pF	0.25
diameter of detector	µm	30
gain independent dark current*	Amps	2.0×10^{-11}
gain dependent detector dark current*	Amps	4.0×10^{-14}
gain	none	15
carrier ionization ratio*	none	0.45
CALCULATED OUTPUT		
beam divergence:		
minimum beam divergence (GEO)	µrad	12.6
minimum beam divergence (LEO)	µrad	37.8
detector sensitivity:		
10 Gbps data rate	dBm	-24.2
2.5 Gbps data rate	dBm	-30.2

$$dB = 10\mathrm{Log}_{10}\left(\frac{P_2}{P_1}\right)$$

Simplified Link Table

- Determine sensitivity (in power) required for a given detector to achieve a Bit Error Rate for a specific data rate
- Calculate antenna gain, range, optical efficiencies and atmospheric effects
- Add numbers up and require at least 3 dB margin
- Communications drivers:
  - High Definition Television (**HDTV**) standards from the Society of Motion Pictures and Television Engineers (**SMPTE**) require a data rate of 1.485 Gbps
  - Hyperspectral Imaging >100 Mb/s
  - Ethernet standard 10 Gbps at BER<10^{-12}

Link to GEO requires 8 to 63 W

Pointing Losses (dB)	-0.4
G_T (dB)	115.7
η_T (dB)	-2.2
L_S (dB)	-290.2
T_A (dB)	-1.0
Turbulence Losses (dB)	-7.2
G_R (dB)	118.2
η_R (dB)	-2.2
Link Loss (dB)	-69.3

data rate (Gbps)	10	2.5
Laser Power (dBm)	48.0	39.0
Link Loss (dB)	-69.3	-69.3
Detector Sensitivity (dBm)	(-24.0)	(-33.0)
Link Margin (dB)	2.7	2.7

Link to LEO requires 100 to 800 mW

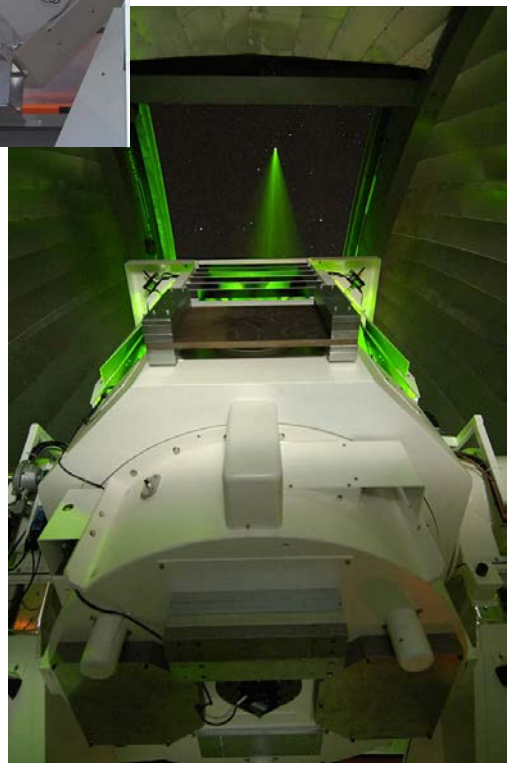
Pointing Losses (dB)	-0.6
G_T (dB)	106.1
η_T (dB)	-2.2
L_S (dB)	-255.8
T_A (dB)	-1.0
Turbulence Losses (dB)	-12.5
G_R (dB)	118.2
η_R (dB)	-2.2
Link Loss (dB)	-50.0

data rate (Gbps)	10	2.5
Laser Power (dBm)	29.0	20.0
Link Loss (dB)	-50.0	-50.0
Detector Sensitivity (dBm)	(-24.0)	(-33.0)
Link Margin (dB)	3.0	3.0

Optical Communications Telescope Laboratory (**OCTL**)

Jet Propulsion Laboratory
California Institute of Technology

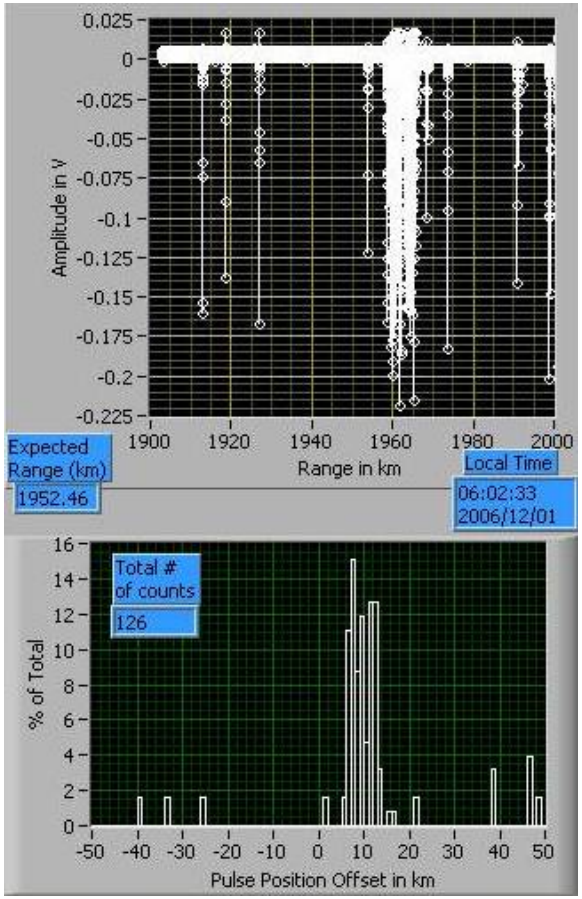
- Location:
  - San Gabriel Mountains Wrightwood ,California
    - 34°22.9’ North Latitude, 117° 40.9’ West Longitude
    - 2.2km (7400 ft) altitude MSL
  - Convenient access from JPL
    - 1.5 hours drive
    - lodging accommodations
- Optical configuration:
  - 1-m Az/El telescope
  - F/75.8 seven-mirror coudé optical path
    - 4 separate transmission/receive ports
  - <17 µrad blind pointing and tracking error
  - Track rates: 20 deg/sec azimuth, 10 deg/sec elevation
  - Full daytime operation
    - Points and tracks to within 5 degrees of sun
    - Filter supports 3-degree sun angle operation
  - 20 cm Acquisition telescope
    - F/7.5 Newtonian
    - Instrumentation support and cabling
- Supports other testing
  - Small gimbals for other experiments
  - 1-4 km range testing to opposing mountainside

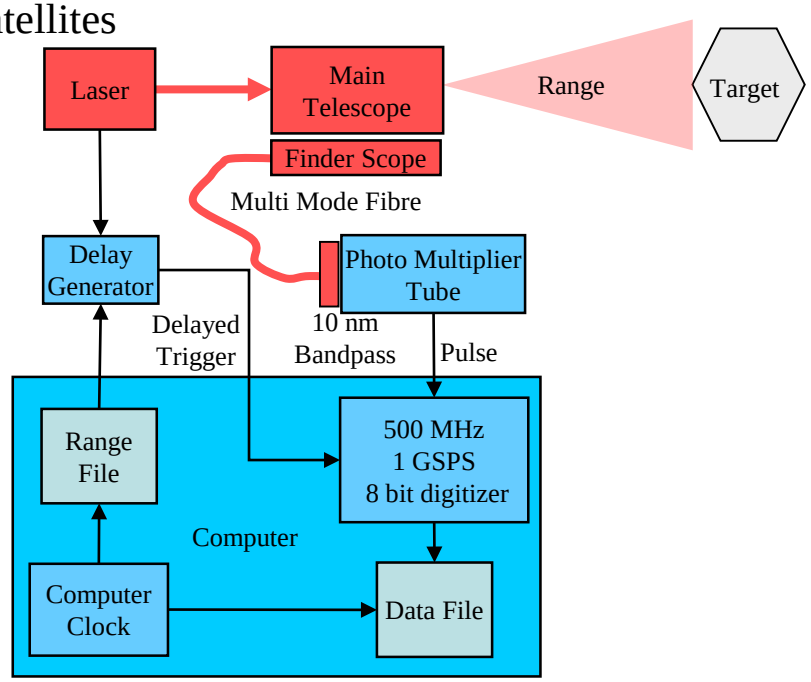


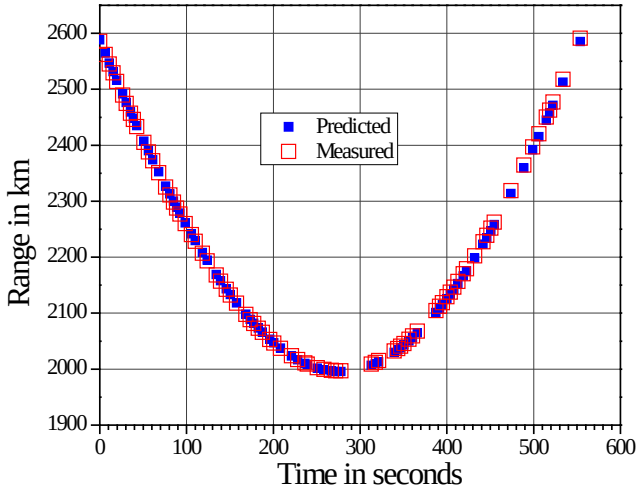
Satellite Retro Reflector Experiments

Jet Propulsion Laboratory
California Institute of Technology

- Test telescope blind pointing by targeting geodetic satellites
  - Narrow beams 30-60 µrads
  - Both monostatic and bistatic configurations



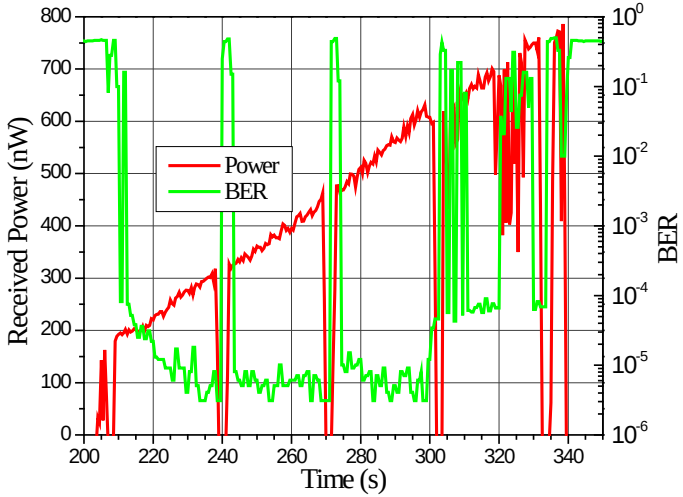


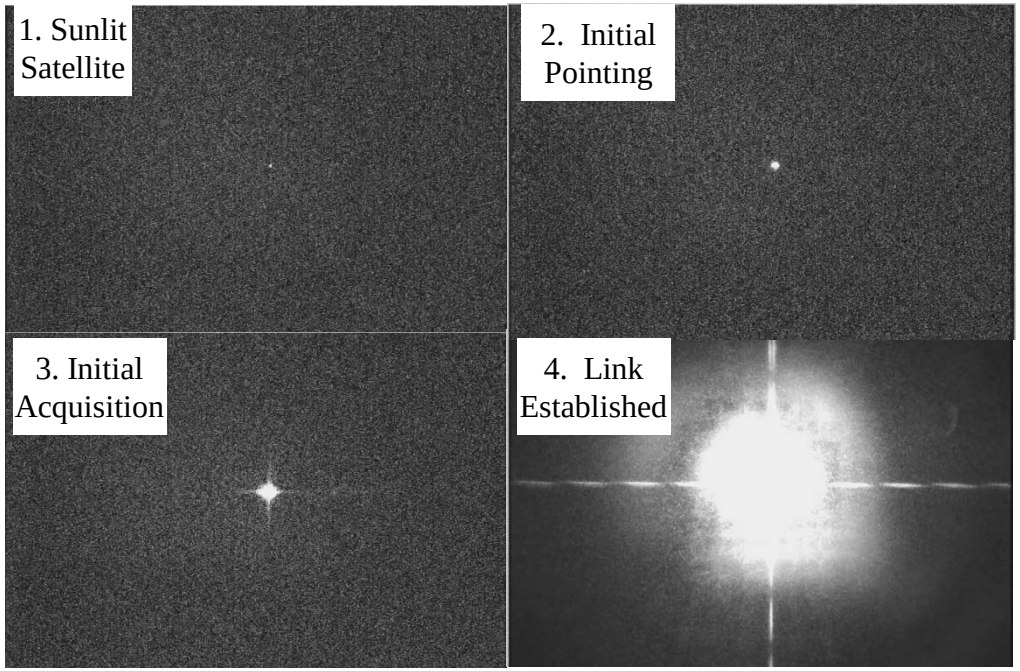


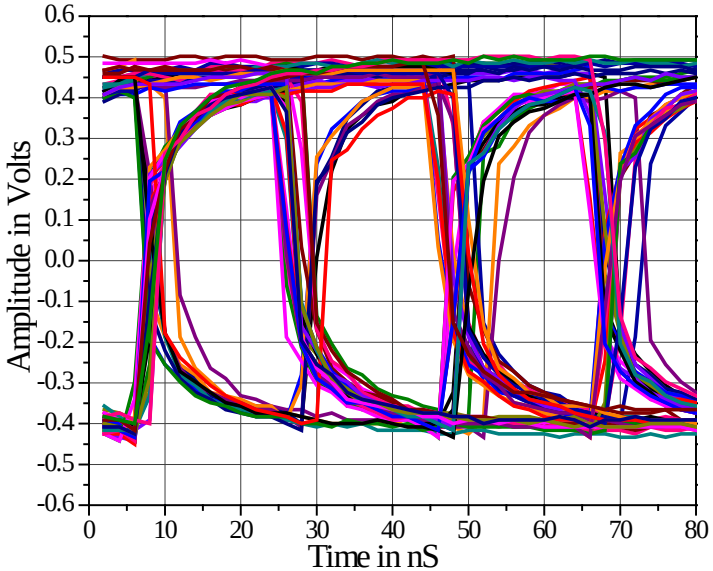
OICETS Optical Communications Experiment

Jet Propulsion Laboratory
California Institute of Technology

- Ground Station for LUCE terminal of OICETS satellite
  - 50 Mbps OOK PN15 downlink
  - 2 Mbps PN15 PRBS in binary PPM format uplink
- Blind pointing to ephemeris file
  - No feedback or fine pointing
- 4 separate links took place on May 21, June 2, June 4 and June 11, 2009
  - Each one successful
- BER measured in real time
  - Data snapshots using PCI based digitizer at 500 MHz with 4000 samples taken every 0.5 s

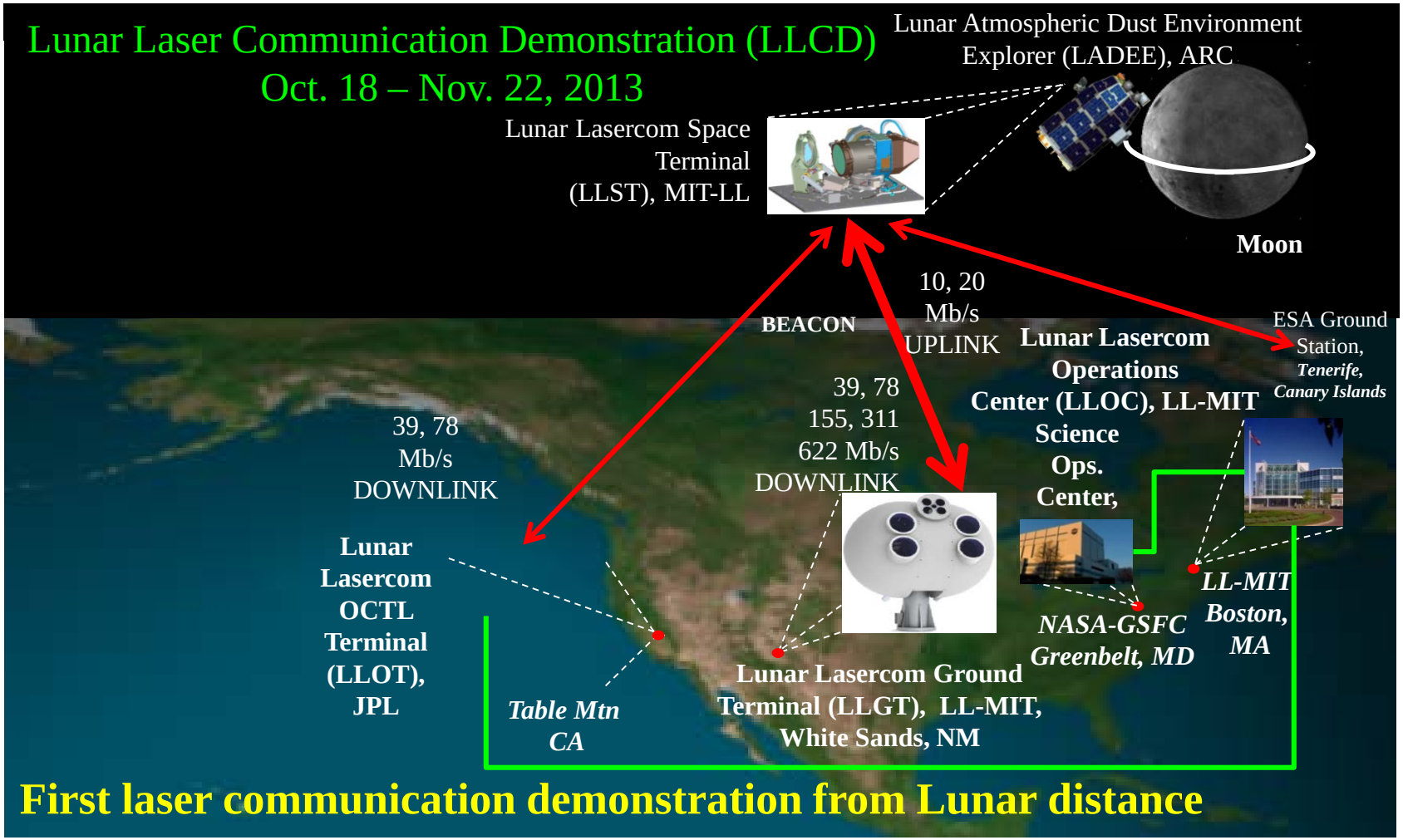






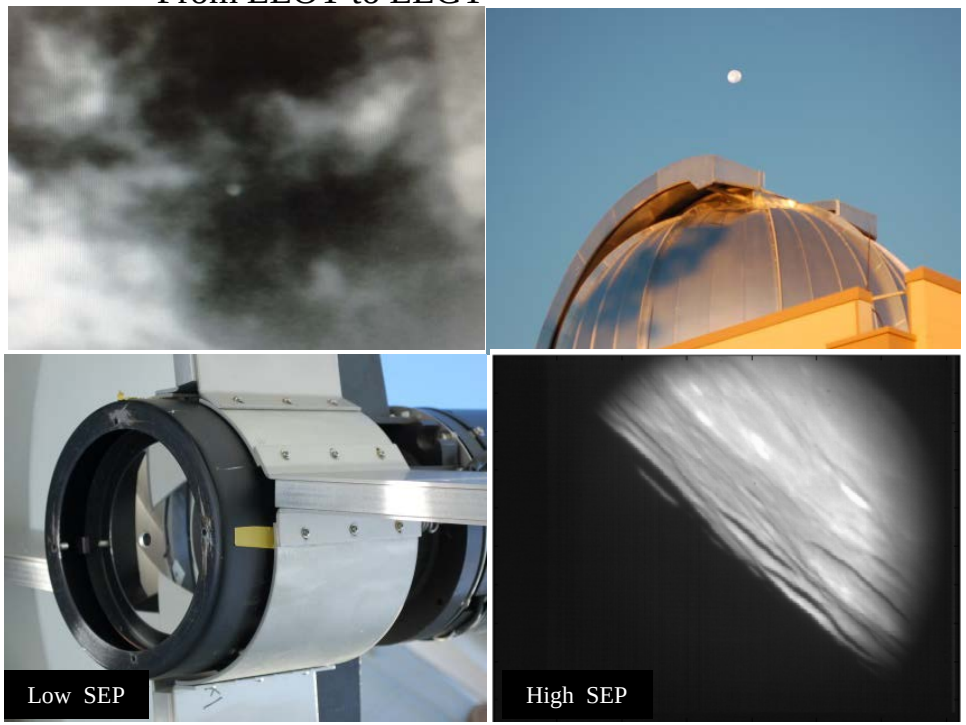
Lunar Laser OCTL Terminal (LLOT)

- LLOT was an alternate ground station for the Lunar Laser Communication Demonstration (LLCD)
- Transmitted a 60 W 1568 nm beam and received 100's of pW through a common aperture
- Demonstrated a 12-pixel tungsten-silicide superconducting nanowire single photon-counting detector (SNSPD) array operating at 780 mK



Pass Summary

- Operated 20 downlink passes to LLOT during the LLCD
- Diverse conditions
  - Time of Day - atmospheric turbulence
  - Air-mass - atmospheric turbulence and attenuation
  - Sun-Earth-Probe (SEP) angle – additive background noise
- Closed links through thin clouds
- Exercised link handover
  - From LLGT to LLOT
  - From LLOT to LLGT



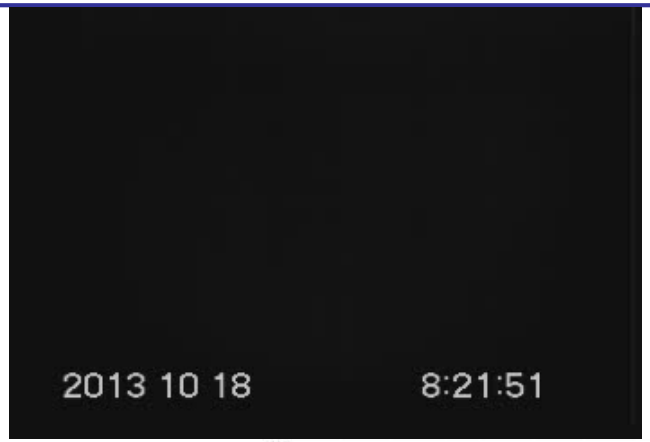
	Date	Start Local Time	Duration	Start El (deg)	Stop El (deg)	Mean Range (km*1E3)	Mean SEP (deg)	Air-Mass Range	Data-rate (Mb/s)
1	10/18/2013	1:12:23	0:22:40	58.1	56.5	376.4	171.1	1.17-1.19	39, 78
2	10/18/2013	5:45:47	0:12:49	9.79	7.45	381.5	173.5	5.7-7.3	39, 78
3	10/18/2013	23:23:52	0:19:05	60	62.7	379.7	176.4	1.12-1.15	39, 78
4	10/19/2013	5:54:18	0:19:08	20	16.4	384.3	174.1	2.9-3.5	39
5	10/20/2013	3:46:11	0:14:31	56.3	53.8	394.9	163.0	1.20-1.24	39, 78
6	10/20/2013	5:59:56	0:12:16	30.4	28.1	387.2	162.2	1.97-2.11	39
7	10/21/2013	5:58:18	0:15:26	41.7	38.8	390.0	150.5	1.50-1.59	78
8	10/21/2013	8:17:42	0:15:20	14	11.2	393.1	149.6	4.1-5.0	39, 78
9	10/27/2013	9:48:46	0:22:26	48.7	44.4	395.4	82.5	1.33-1.42	39, 78
10*	10/27/2013	12:20:37	0:11:10	18.5	16.3	397.8	81.6	3.12-3.52	39
11**	10/29/2013	7:53:10	0:14:24	58.3	59.2	387.5	60.4	1.16-1.17	39
12**	10/29/2013	9:54:16	0:24:15	55.9	52.8	387.3	59.7	1.20-1.25	39,78
13	11/2/2013	12:48:35	0:13:08	40.9	40	367.6	9.2	1.52-1.55	39
14	11/4/2013	13:48:35	0:22:27	35	33.5	361.6	18.4	1.74-1.80	39
15	11/4/2013	15:48:35	0:21:07	22.9	20.00	362.6	19.0	2.55-2.9	39, 78
16	11/5/2013	10:13:05	0:02:08	16.1	16.40	362.3	30.6	3.49-3.56	39
17	11/17/2013	21:59:21	0:27:12	57.3	62.1	391.1	172.2	1.13-1.17	39,78
18	11/18/2013	0:01:20	0:21:13	73.9	73.7	390.7	171.6	1.04	39,78
19	11/18/2013	2:04:26	0:23:57	60.4	56	391.7	171.1	1.14-1.20	39,78
20	11/18/2013	4:06:39	0:19:16	36.5	32.6	393.9	170.4	1.75-1.85	39,78

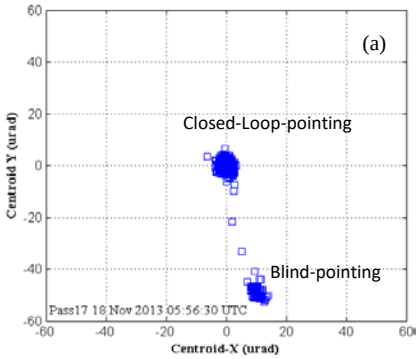
* Hand over from LLGT

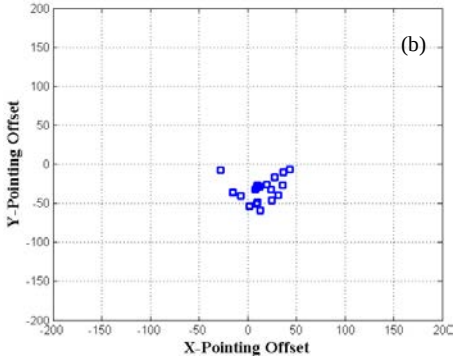
**Through thin clouds and/or cloud interruption

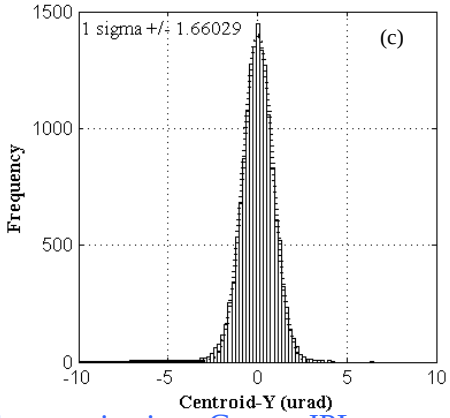
Telescope Pointing Performance

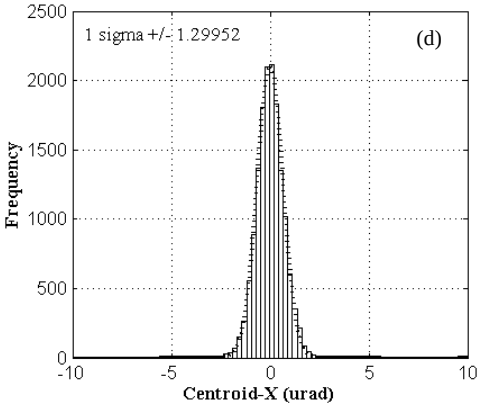
- LLOT link acquisition established on every pass used
  - First test of downlink at OCTL due to clouds at White Sands
- Blind pointing telescope based on ephemeris predicts and transmitting 110 µrad beacon
  - After downlink signal detected on acquisition camera
  - Telescope focus adjusted
  - Transition to closed-loop pointing
    - Telescope pointing ahead
    - FSM adjusting "point-behind" on downlink spot
- Typical pass results
  - Centroid on acquisition camera as soon as signal exceeding asset threshold is detected
  - Initially spot is offset from camera center
  - After closed-loop spot moves to camera center
- Composite blind-pointing error for all passes shown
  - < 60 µrad
- Closed-loop pointing performance
  - Typical 1-sigma error < 2 µrad





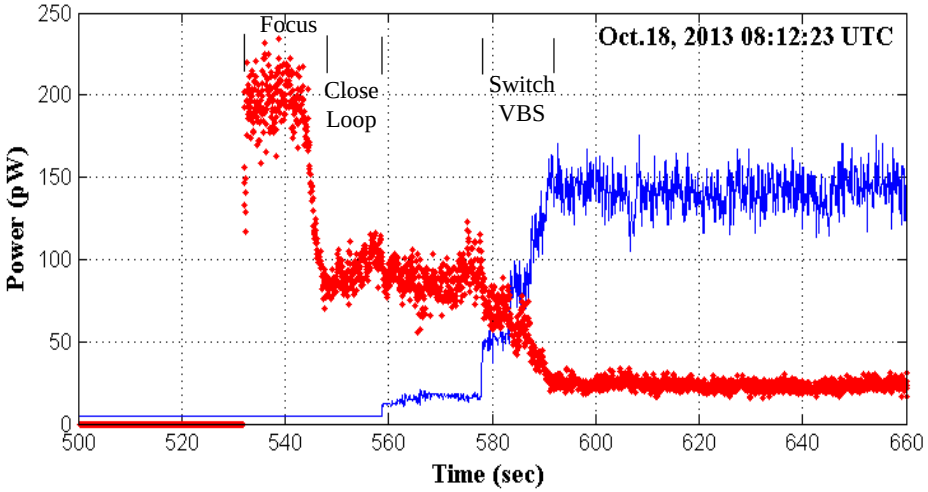


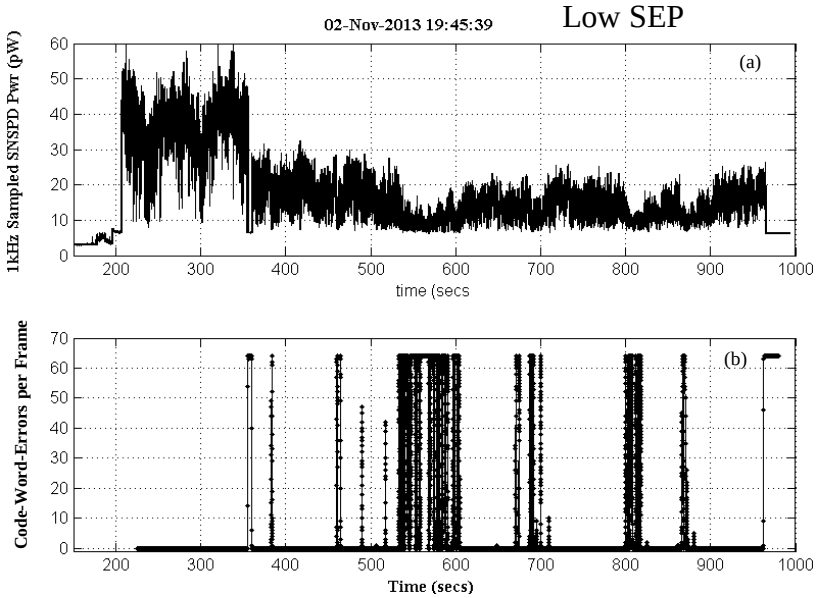


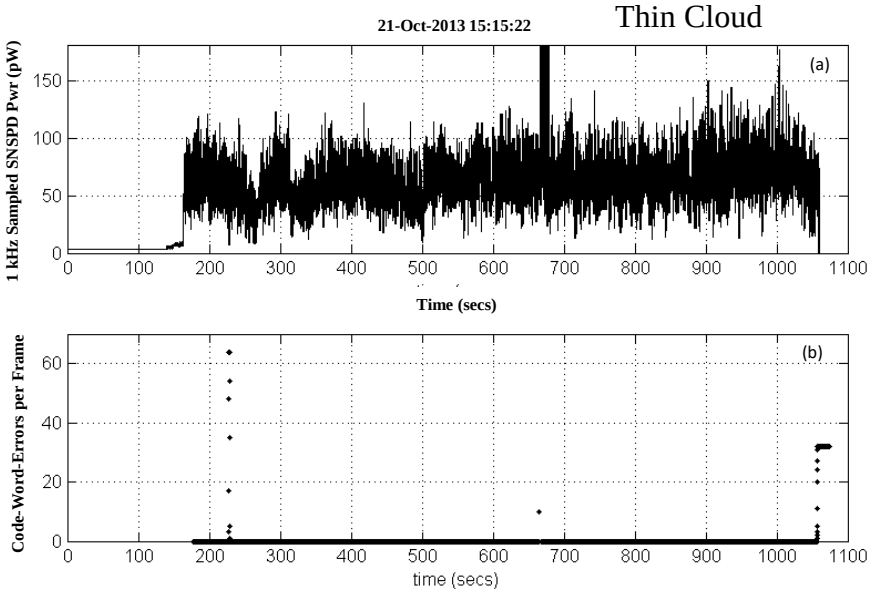


Link Performance

- Downlink average power falls within the predicted bounds
- Typically link performance was very good with 0 code-word error rate (CWER)
  - Low SEP angle (high background)
    - At full 0.5 W power from LLST 0 CWER
    - When power is halved the performance becomes marginal
  - Link through thin clouds shows zero CWER except for when data-rate switched

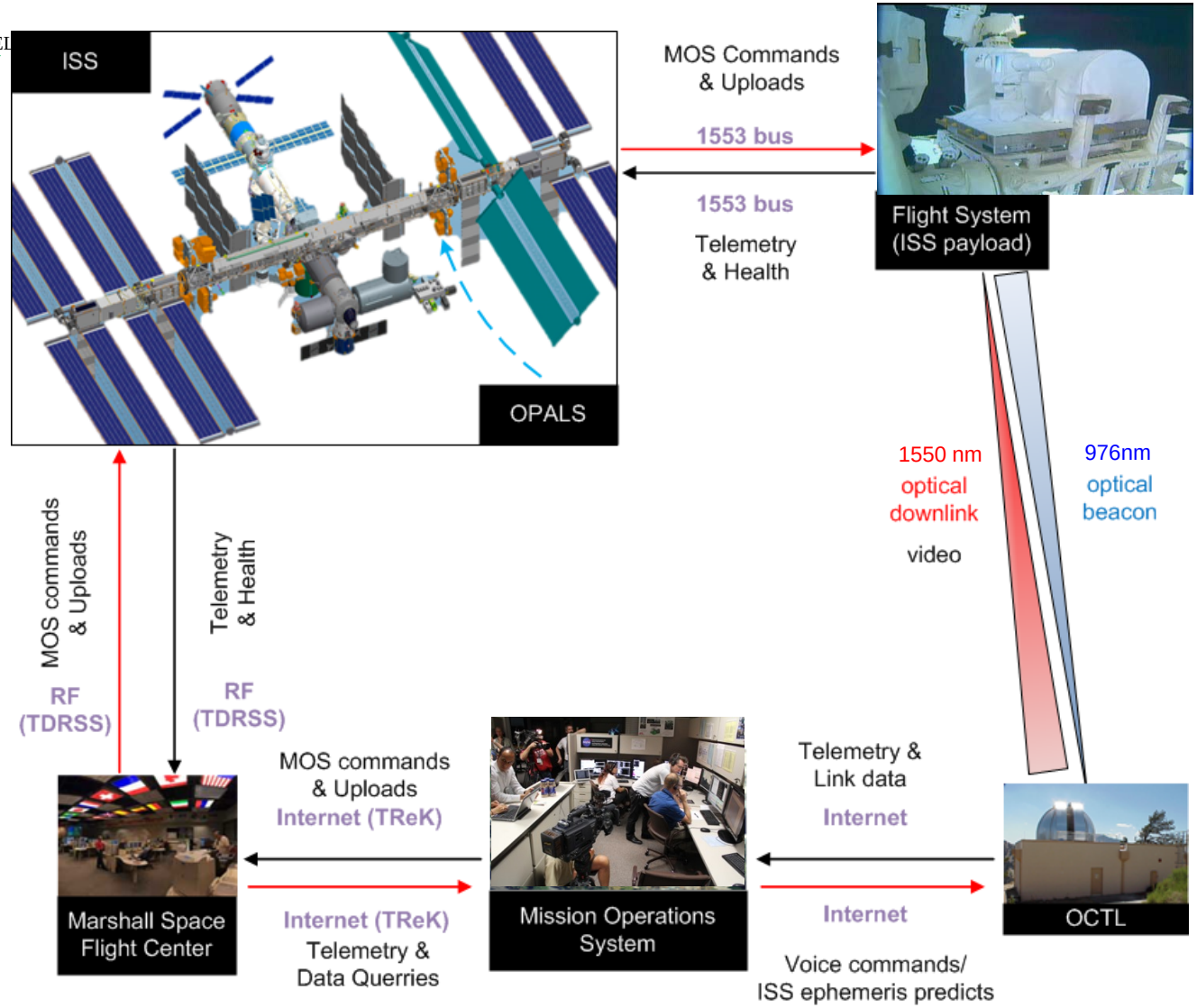






Optical PAyload for Lasercomm Science (OPALS)

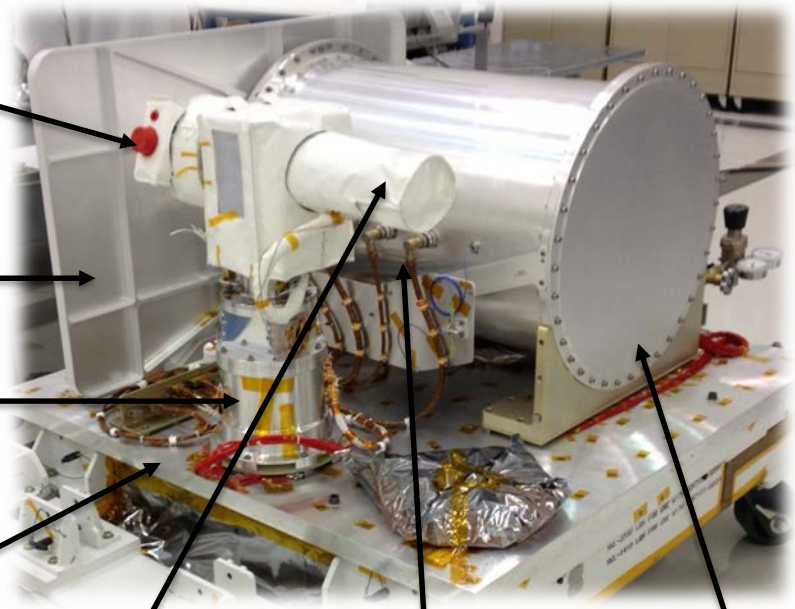
SpaceX CRS-3 Launch April 18, 2014

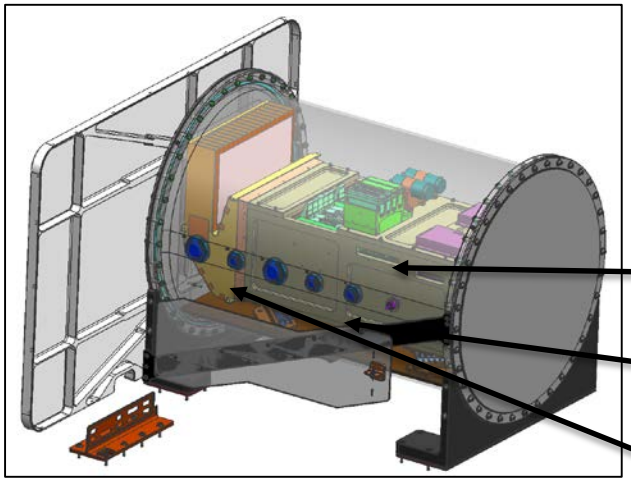


OPALS Flight System

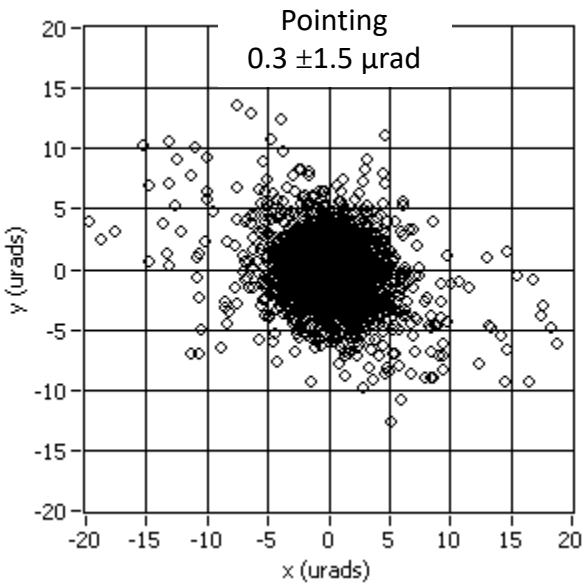
- Cost constrained design
- Class D Payload
- COTS electronics and laser
  - Air cooled sealed container
- Two-axis gimbal
- No independent position/ attitude determination systems on the payload
  - No star trackers/GPS/motor encoders
  - Gimbal is calibrated prior to each operation

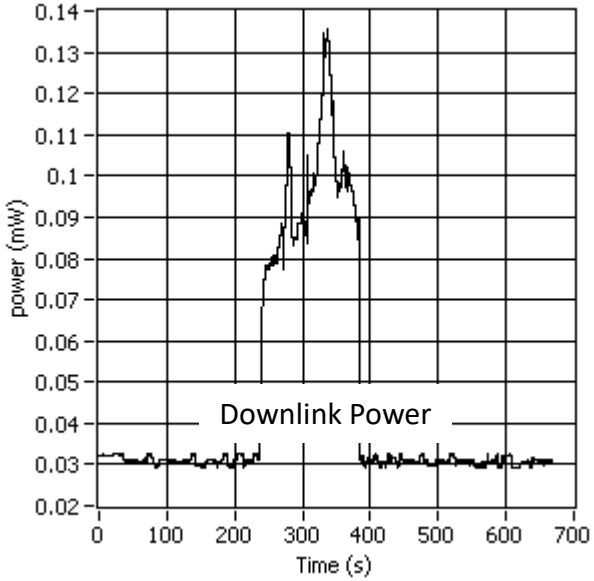
Completed Assembly

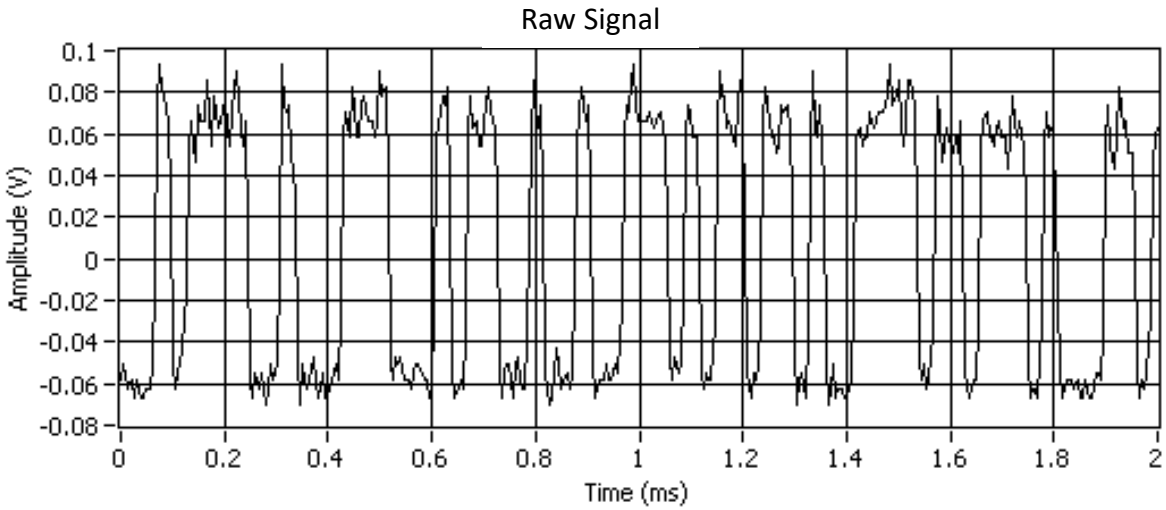


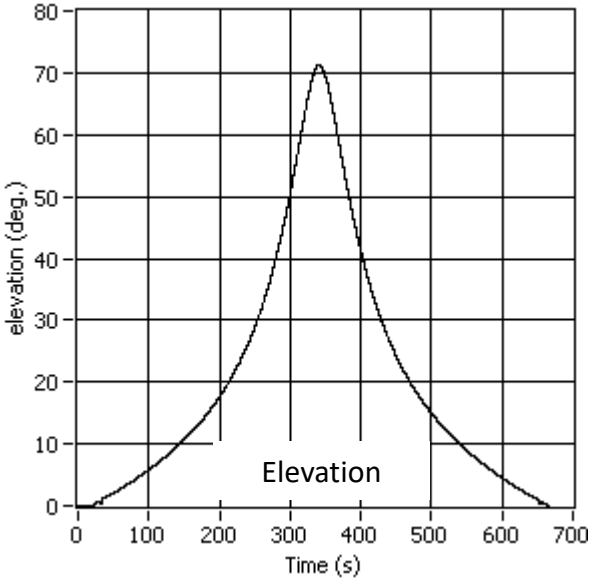


Downlink Performance



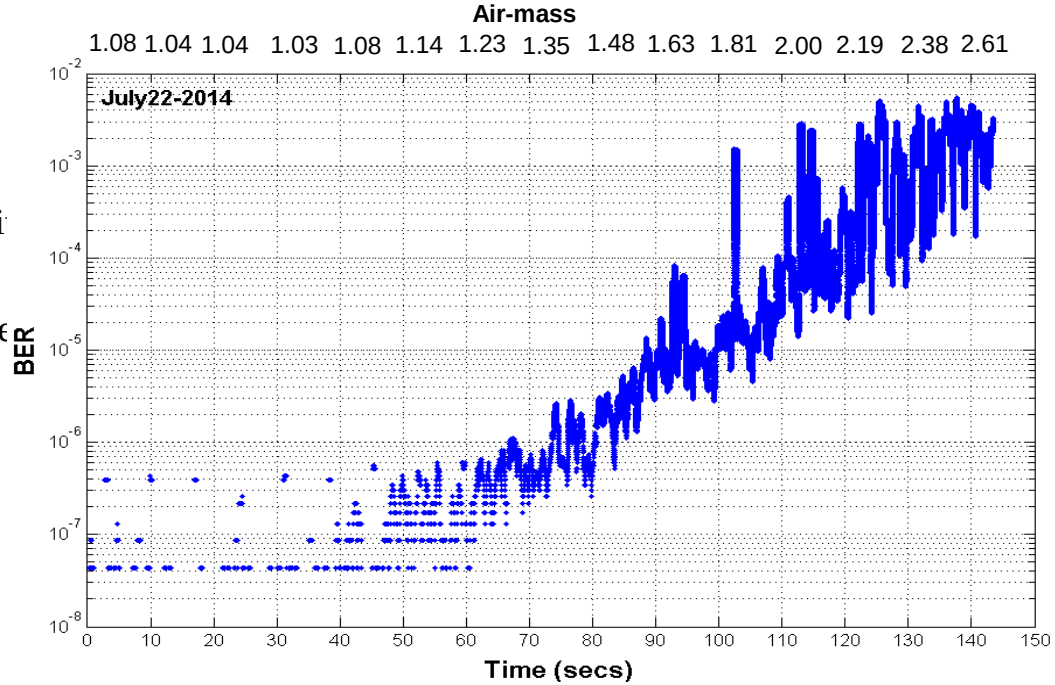






Data Transfer

- Data rates of 50 and 33.3 Mbps
- Video: Hello world! (and others)
  - Reed-Solomon encoded
  - Software decoder used to post-process digi
  - BER < 1E-4 all errors are corrected
  - For worse BER performance of decoder de
- Other data:
  - PN 8 sequence
  - E log ASCII text
- No high speed interface to ISS
  - Shared 15553 with ~kbps rates



```
1411567049.038271934 TLM:TRK EVR: <1411567049.038217737,205362,0,0,0,-0.00120926,-1.1,0,36,0,0,0,-1>
1411567049.048456737 TLM:TRK EVR: <1411567049.048411200,205362,0,0,0,-0.00120926,-1.1,0,36,0,0,0,-1>
1411567049.058642726 TLM:TRK EVR: <1411567049.058596980,205362,0,0,0,-0.00120926,-1.1,0,36,0,0,0,-1>
1411567049.068815027 TLM:TRK EVR: <1411567049.068767465,205362,0,0,0,-0.00120926,-1.1,0,36,0,0,0,-1>
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1411567049.140165146 TLM:TRK EVR: <1411567049.140117514,205362,0,0,0,-0.00120926,-1.1,0,36,0,0,0,-1>
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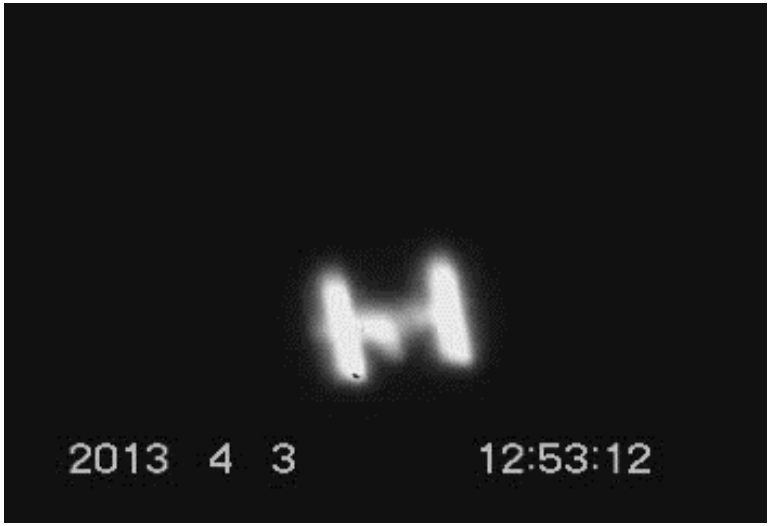
Summary

- Free Space Optical Communications is a technology that can provide high data rates for space flight communications
- Optical communication links from space have been tested and met performance requirements
- To the future:
  - Laser Communications Relay Demonstration (LCRD)
    - Multi-Gbs uplink and downlink to and from GEO
  - Deep Space Optical Communications (DSOC)
    - 200 Mbps from 1 A.U.
    - 5 kW beacon uplink and communications signal
    - Downlink to 5 m Palomar Telescope