Future Planetary Optical Access Links

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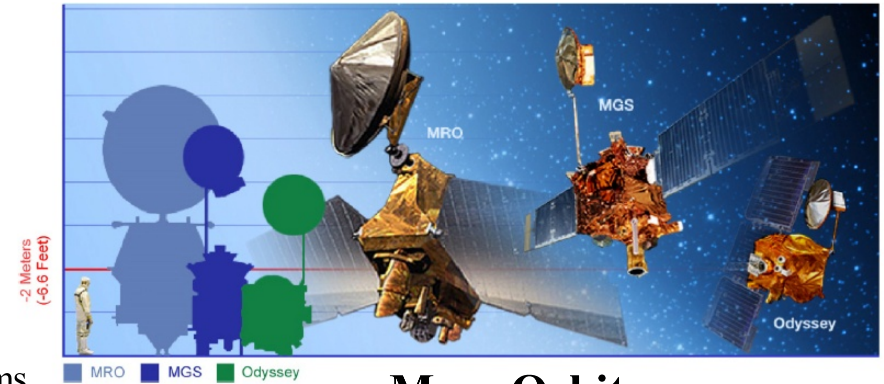
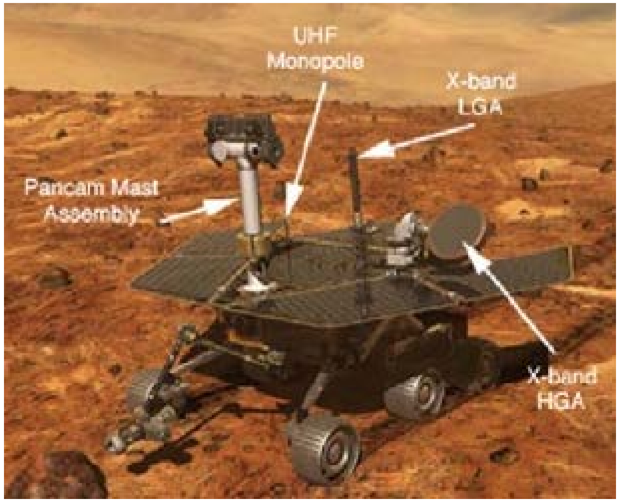
Introduction Mars Access Link

- **The bulk of data returned from the surface of Mars has been via UHF access links**
  - Rovers (*Path finder and Mars Exploration Rovers, Phoenix*) equipped with UHF monopole antennas
  - Orbiters receive data as they fly over the landed assets
    - 2-3 short contacts per sol
    - Typical data rates up to 256 kb/s today
    - 150 – 600 Mb per pass
  - Supports EDL and surface comm, robust through dust storms
  - Typical 5-10 kg mass and 40-70 W power



Mars Orbiters

- **Limited data return capacity**
  - For example, could support a maximum of 40-50 seconds of HD video per pass
  - Could deploy steerable X- or Ka- band antennae
    - Mass and power penalty
  - Low complexity, mass and power optical transceivers deployable on surface that can operate autonomously for high-rate data return



Mars Exploration Rover (MER)

C. D. Edwards and R. DePaula, "Key communication technologies for increasing data return for future Mars Exploration, " Acta Astronautica, 61, 131-138, 2007

Mars Optical Access Link

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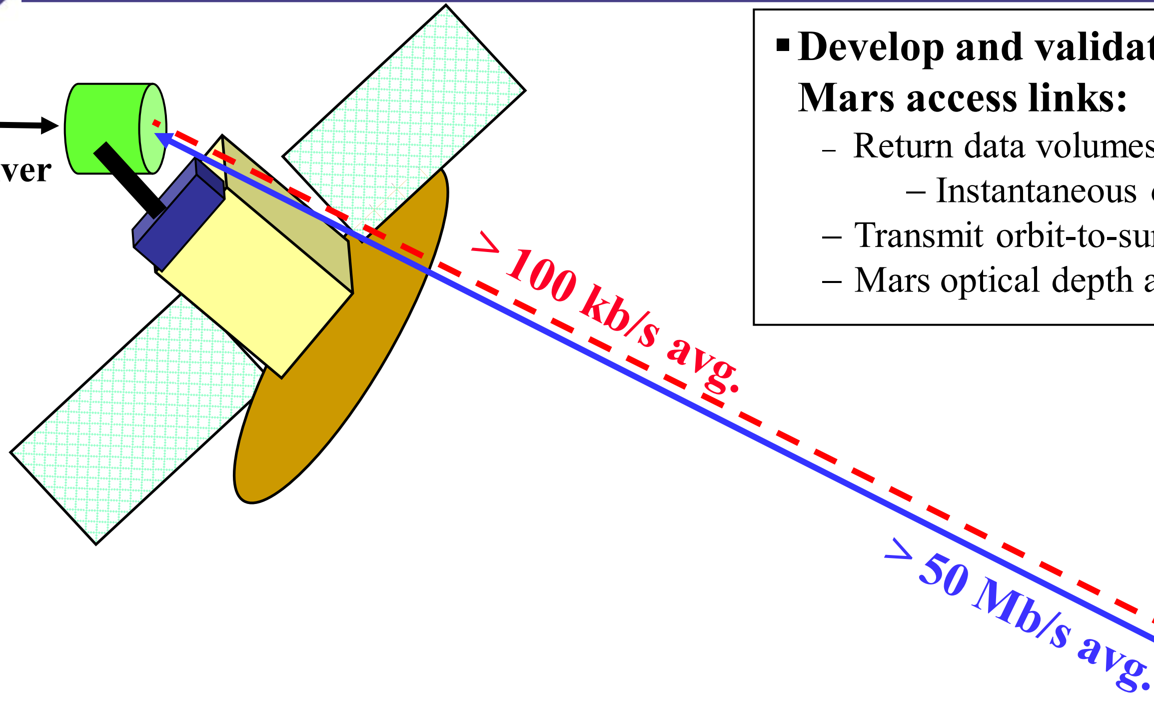
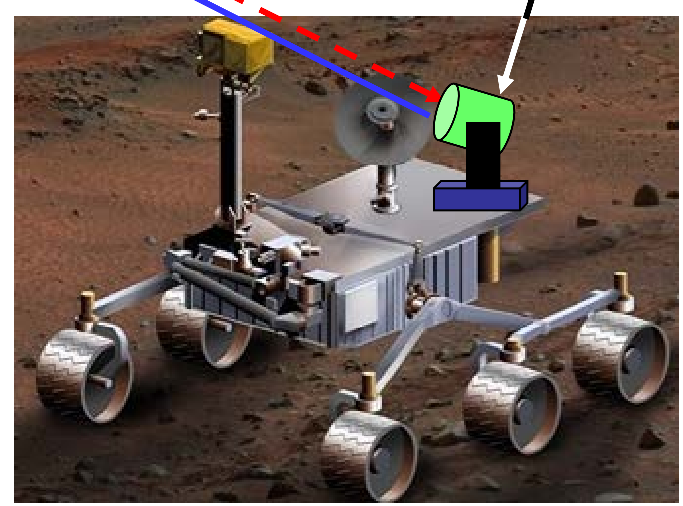


- **Develop and validate flight transceiver designs for Mars access links:**
  - Return data volumes of **10-100 Gbits/sol**
    - Instantaneous data-rates of **50-200 Mbits/sec**
  - Transmit orbit-to-surface data rates of **10-100 Kbits/sec**
  - Mars optical depth and dust accumulation on optics



Key Characteristics

- Emphasized low mass/power burden on host spacecraft
- Low-complexity acquisition tracking pointing (ATP)
  - Orbiter "knows" Lander position
  - Lander does not need orbiter position knowledge

Mars Optical Access Links

- **Future optical transceivers for supporting Mars relay must satisfy aggressively low**
  - **Complexity**
  - **Mass**
    - Target < 10 kg
  - **Power**
    - Target < 50 W

- **Reasonable link availability under dust-laden Mars atmospheric conditions**
  - Assume outages or lower performance during severe dust storms
  - Optical will augment the UHF probably not replace it

- **CONOPS should rely on robust autonomous acquisition and tracking**
  - Unlike omni-directional UHF beams, narrow laser beam pointing and tracking

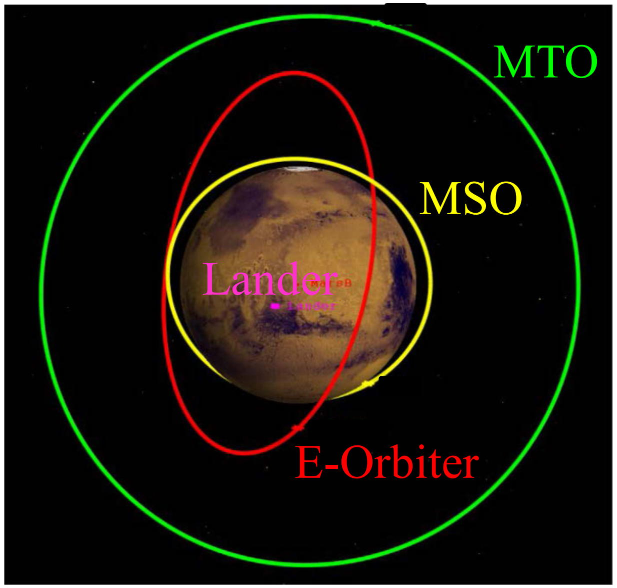
- **Targeted link performance for first generation transceivers**
  - Support streaming of compressed HD Video i.e. instantaneous rates > 30 Mb/s
  - Supports data volume of 45 Gb/sol assuming average 1500 secs of contact time per
  - In MSL era the UHF will be operating at nominally 0.7 Gb/sol

- **Eventual target could be the capability to stream uncompressed imagery @ multi-Gb/s**
  - Will require higher complexity receivers and transmitters but could return 2-25 Tb/sol

Orbital Characteristics

- **Considered characteristics of Mars orbiters flown or planned**
  - Assumed a minimum elevation angle of 10°
  - Solar exclusion angle of 25°
  - Used Satellite Orbital Analysis Program (SOAP)
  - Summary of some critical parameters provided below

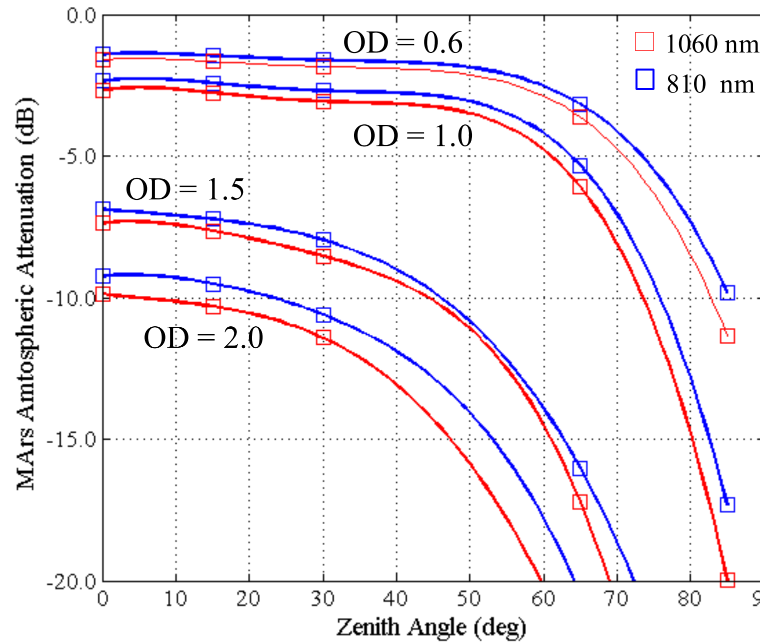
	Science Orbiter	**Telecom Orbiter**	**Elliptical Orbiter**
Orbit	Cicular	Circular	Elliptical
Eccentricity	0	0	0.46
Inclination (deg)	75	75	75
Semi Major Axis (km)	3797	7876	6572
Maximum Link Range (km)	1206	6540	8426
Mean Link Range (km)	862	5609	6035
Mean Contact Time per sol (sec)	690	5650	5654
Lander Location	0 deg LAT; 0 deg LONG; 0 Km ALT	0 deg LAT; 0 deg LONG; 0 Km ALT	19 deg LAT; 33 deg LONG; 0 km ALT

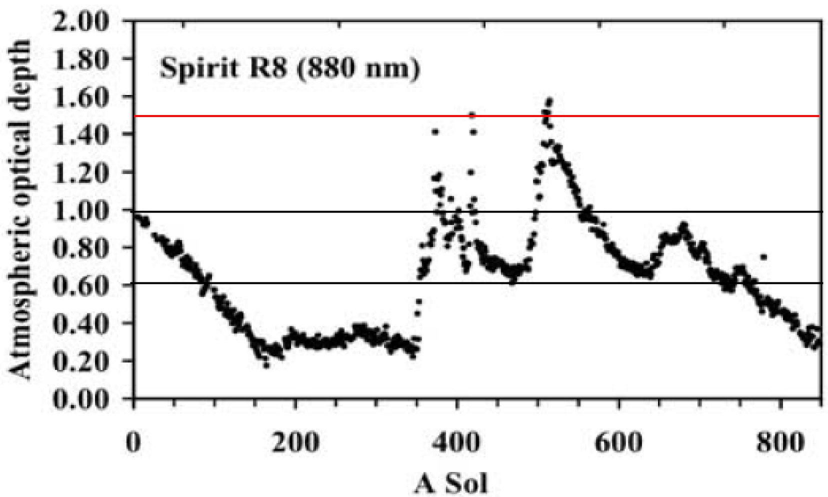


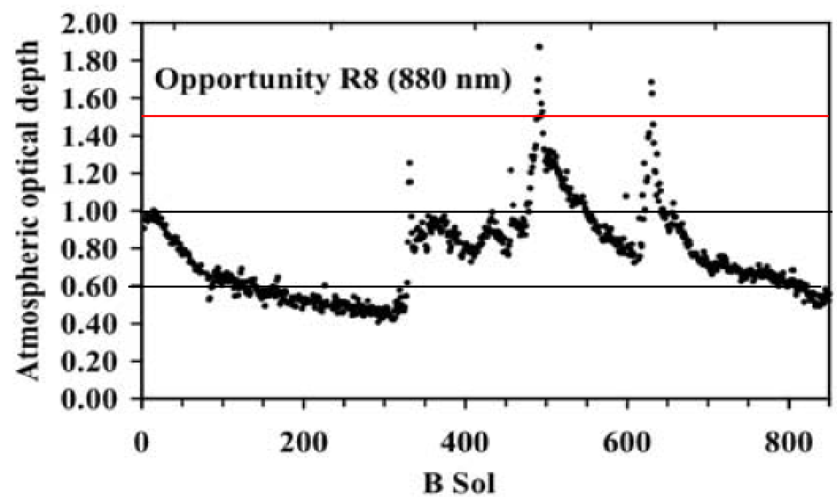
Representative Mars orbiters

Mars Atmosphere

- **Computed Mars atmospheric attenuation**
  - Spectral Mars Radiative Transfer (SMART) Model
  - Mie scattering transmittance using Mariner 9 dust data
- **90% of time the attenuation is OD 1.0**
  - Based on recent MER rover data
- **Recommend system design to target operations**
  - Zenith angles of 80°
  - OD of 1.0

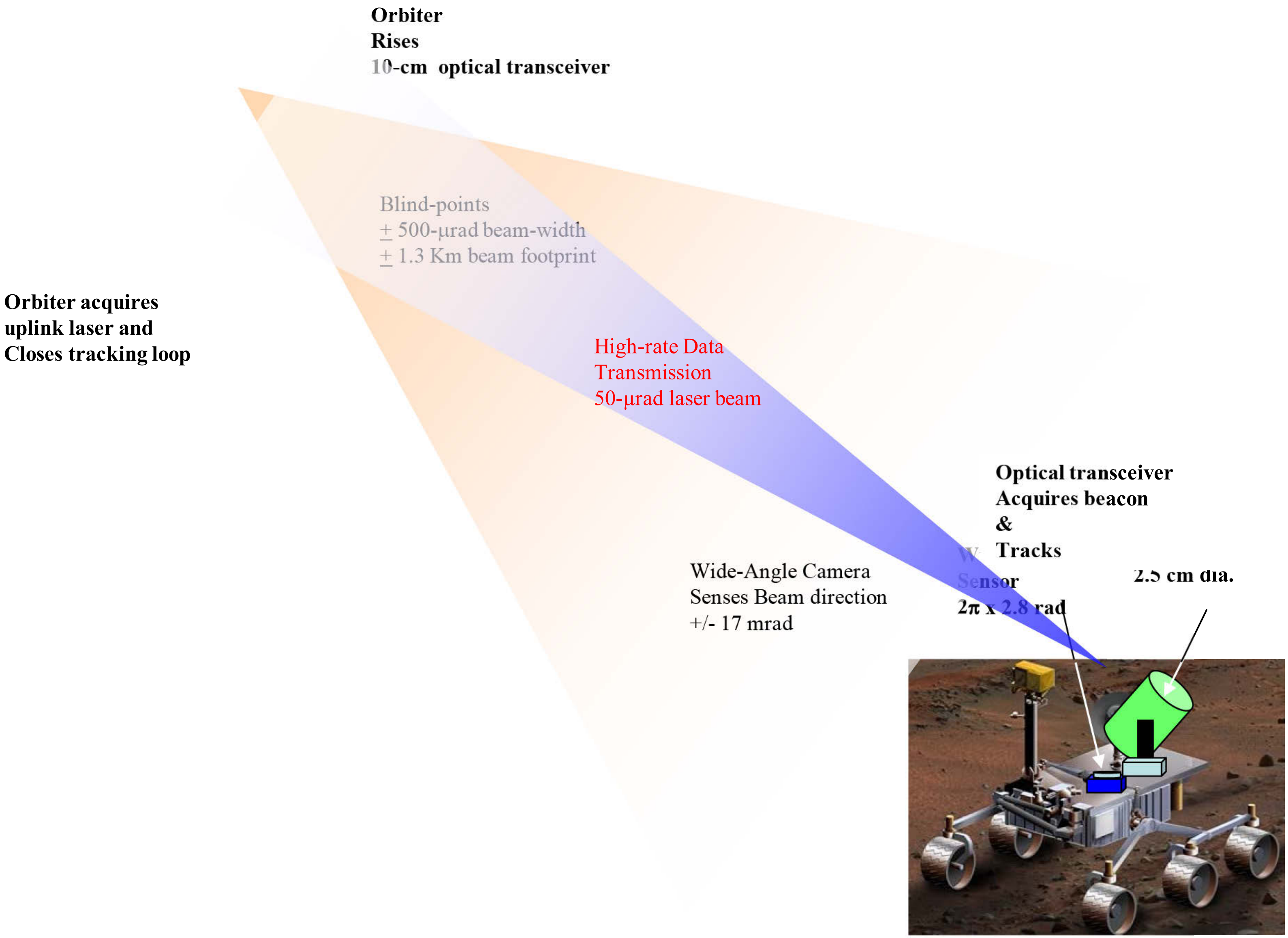






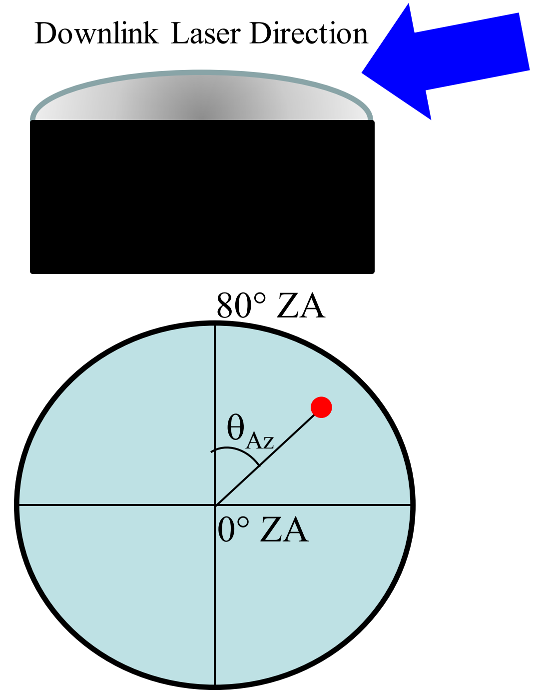
Kjartan M. Kinch et al., "Dust deposition on the Mars Exploration Rover Panoramic Camera (Pancam) calibration targets, " J. Geophys. Res. 112, E06S03, 2007

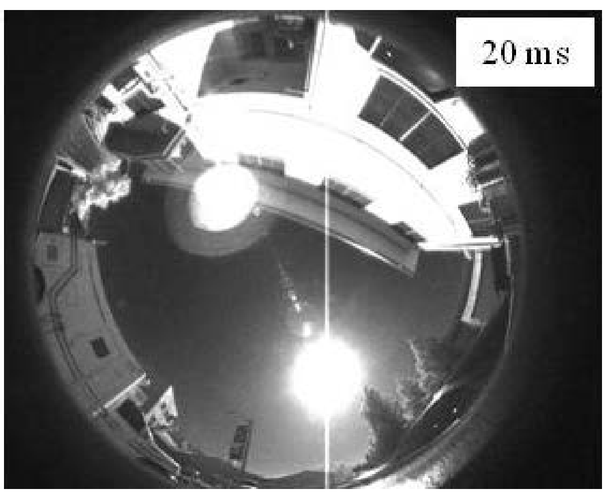
Concept of Operations



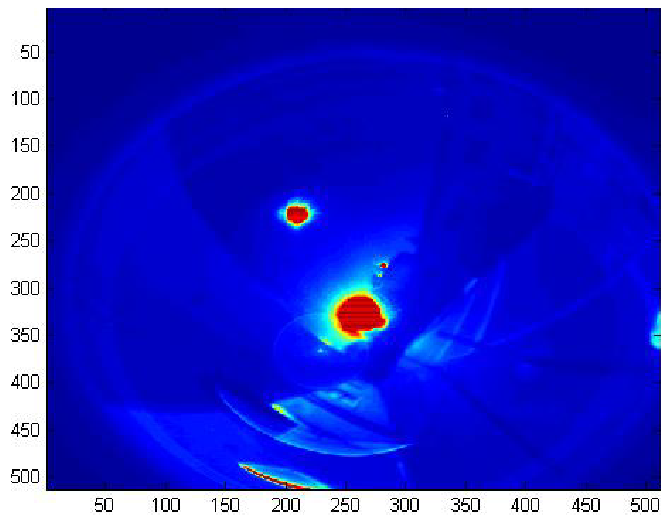
Mars Optical Access Downlink

- **Link acquisition is challenging for downlink laser**
  - Wide angle lens has small entrance aperture diameter
  - Not readily amenable to narrow spectral filtering
    - JPL optical design (next slide)
      - 4.62 mm aperture diameter
      - 50% efficiency
  - For day time links Sun will be present in FOV
    - Stray light or "bleeding" of camera can compromise acquisition
    - Frame differencing in presence of Sun works as long as excessive "bleeding" can be avoided
    - Use of Sun masking techniques need to be explored

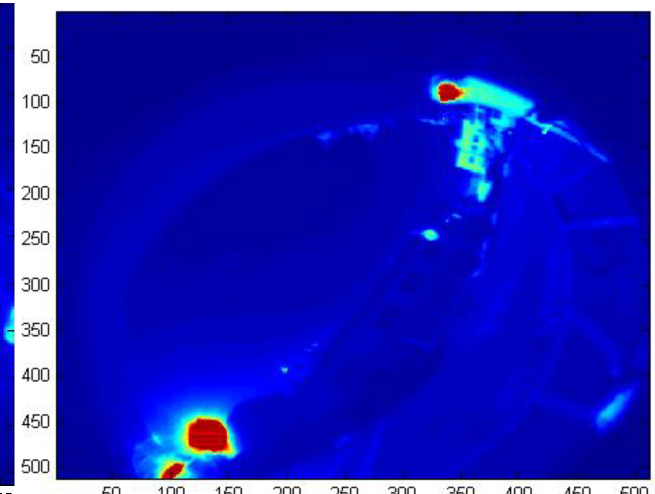




CCD Camera



CMOS Camera



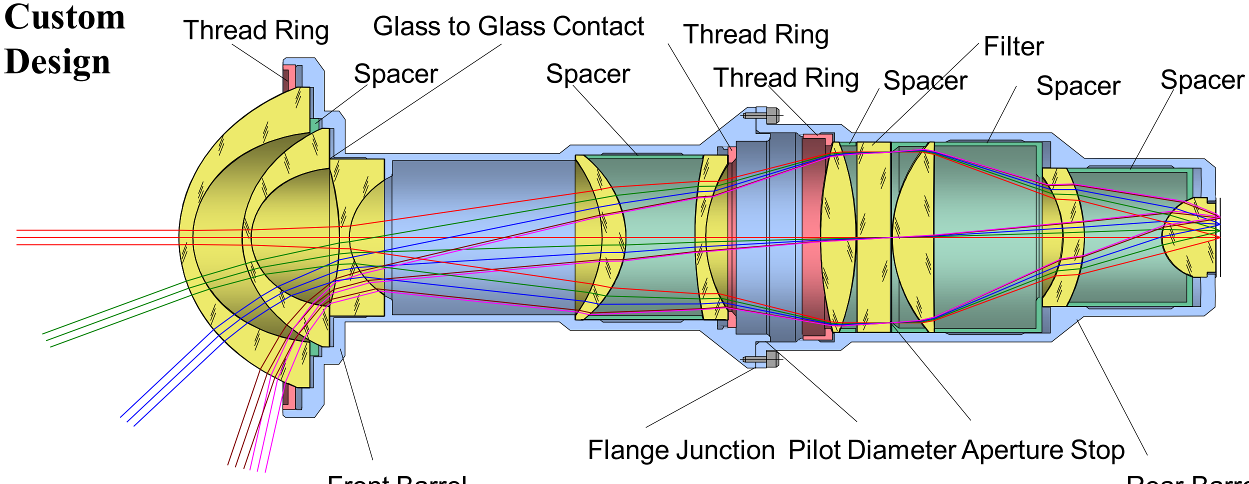
CMOS Camera

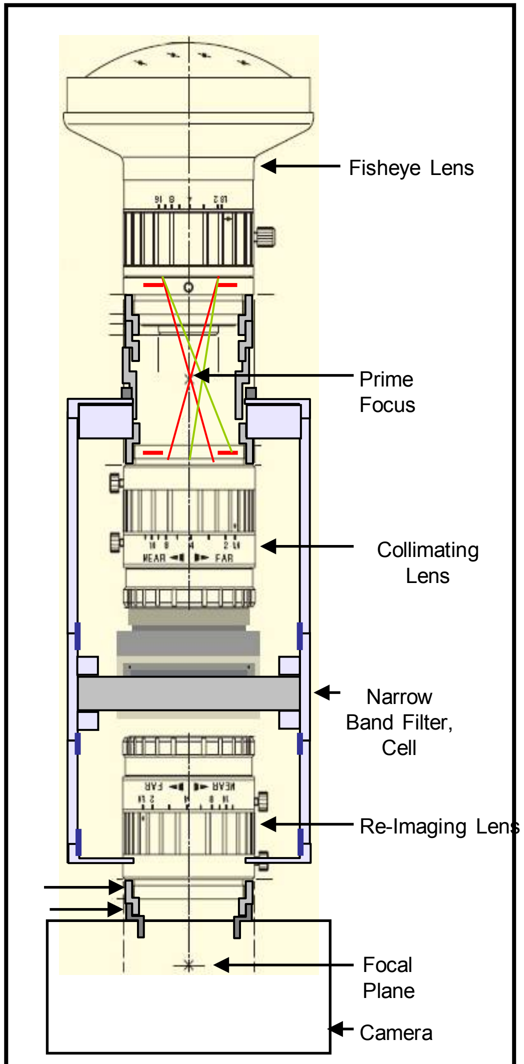
Ground Transceiver Development

- **Autonomous acquisition by ground transceiver uses spectrally filtered wide-angle camera**
  - Area × Solid angle invariant restricts entrance aperture diameter
  - Wide range of angles complicates spectral filter placement

	COTS Design (Implemented)	Custom Design (Not implemented)
Entrance aperture dia. (mm)	0.7	4.5
Efficiency	23%	50%
Spot size (μm)	~ 100	28
Image Size (mm)	6 x 6	12 x 12
Ghost Imaging	Not quantified	-46 dB

Custom Design





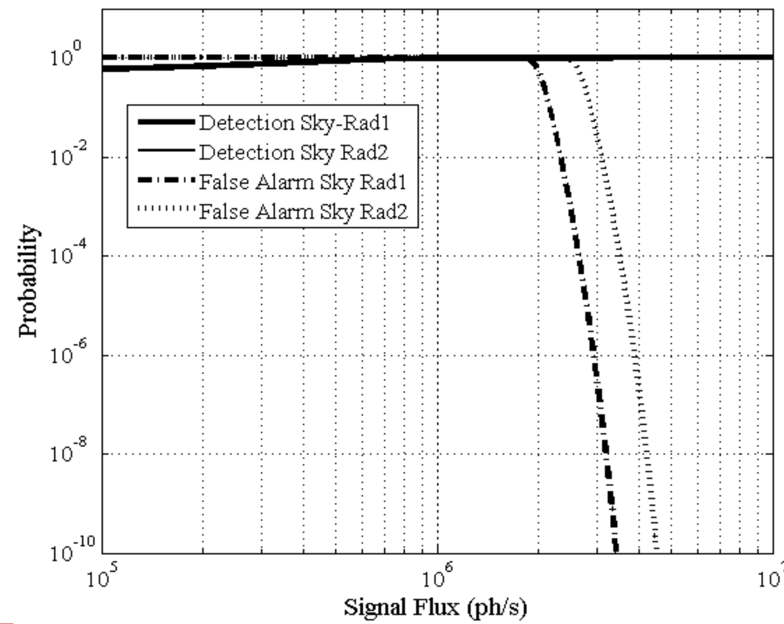
COTS for aircraft experiment

Mars Optical Access Downlink (contd)

- **Analysis supports successful acquisition**
  - Worst link conditions
    - Max science orbiter range of 1206 km
    - Sky radiance 25° from Sun 40 – 70 $W/m^2/sr/\mu m$
  - Fixed exposure time of 10 ms
    - Exposure times greater than 30 ms will cause saturation of pixels
  - For OD 0.6 robust acquisition at max range
  - For OD 1.0 zenith angle of 75° at 1037 km provides equally robust acquisition
  - **Analysis does not account for improvements achievable by implementing acquisition algorithms that take advantage of frame-differencing and spot motion**
  - Option for narrowing beam and using conical scan algorithms likely needed for farther distance orbiters where much longer contact times also afford longer acquisition times

1000 x 1000, 12μm pixels
Downlink laser spot dia. 30μm
MER CCD camera
Full-well capacity 220,000 electrons
Dark Noise 25 e^-/pix/sec
Read Noise 25 e^- rms
2-nm band-pass filter @ 810 nm

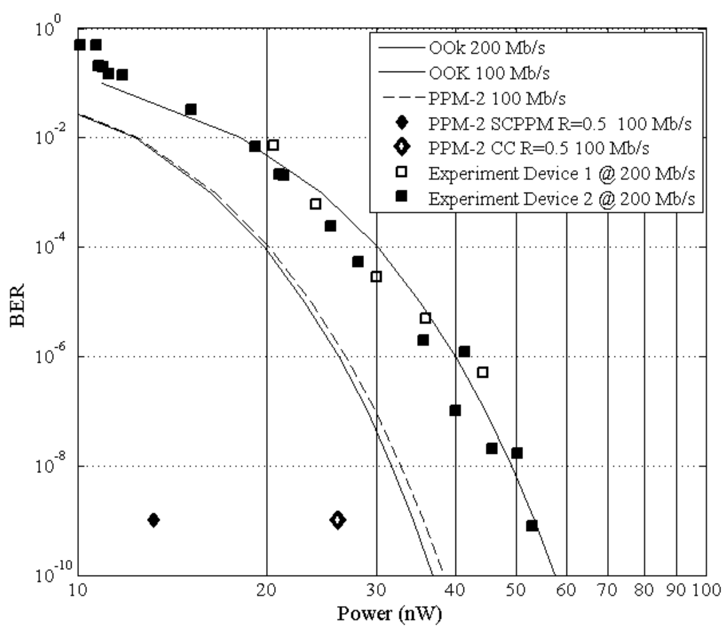
Optical Depth	OD 1.0	OD 0.6
Transmitted laser power @ 810 nm (dBW)	7.0	7.0
Transmission Loss (dB)	-1.4	-1.4
Pointing Loss (dB)	-0.8	-0.8
Transmitter Gain @ 1.08 mrad beam-width	69.3	69.3
Space Loss (dB at 1206 km)	-265.4	-265.4
Atmospheric Attn. (dB)	-12.8	-7.6
Receiver Gain (dB)	85.0	85.0
Receiver Loss (dB)	-3.0	-3.0
Received Signal Power (dBW)	-122.2	-122.2
Received Photon Flux (ph/s)	2.50E+06	8.30E+06



Mars Optical Access Return Link

- **Uplink data-rates supported with a near-infrared Si APD (1060 nm)**
  - **Uncoded OOK with BER of 1E-9**
    - Science Orbiter 100 Mb/s from mean distance 50 µrad beam 1 W
    - Telecom Orbiter 50 Mb/s from mean distance 22 µrad beam 2 W
      - Additional margin achievable with coding
    - High technology readiness level (TRL-9) receiver
  - **20-dB additional gain with photon-counting receiver**
    - Flight qualified photon-counting receiver development required

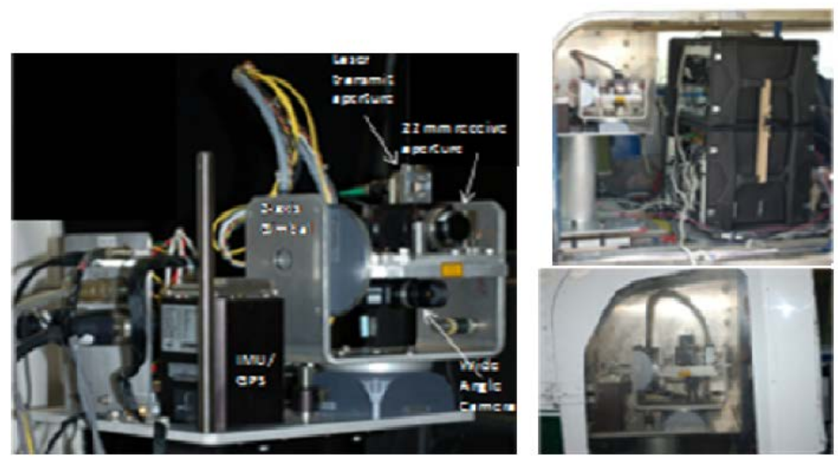
- **Data volumes of 35 Gb/sol and > 100 Gb/sol from Science and Telecom Orbiters**
  - Assuming only 50% realization of available contact time
  - Compares to 1 Gb/sol expected from UHF access links



	Science Orbiter		Telecom Orbiter	
Laser Power @ 1060 nm	30	dBm	33	dBm
Transmitter Efficiency	-2.2	dB	-2.2	dB
Transmitter Gain	95.9	dB	103.4	dB
Pointing Loss	-1	dB	-1.2	dB
Space Loss	-260	dB	-277.1	dB
Atmospheric Loss	-7.5	dB	-7.3	dB
Receiver Gain	109	dB	115.3	dB
Receiver Efficiency	-4.8	dB	-4.75	dB
Other Losses	-1.3		-1.3	
Received Signal Power	-41.7	dBm	-42.2	dBm
Uncoded 100 Mb/s @ BER of 1E-9	-44.7	dBm		
Uncoded 50 Mb/s @ BER of 1E-9			-46.5	dBm
Signal Margin	3	dB	4.35	dB

End-to-end validation of CONOPS

(a) (b)



(c) (d)

End-to-end validation of CONOPS

- Aircraft circled ground transceiver , blind pointed 810 nm laser aided by GPS/IMU
- Wide-field optic on ground located aircraft to within ± 1°, gimballed transceiver acquired link tracked aircraft beacon and transmitted video at 270 Mb/s

Conclusion

- A concept for improving link capacity for Mars relay links has been formulated
- The CONOPS for this concept have been verified with an aircraft-to-ground link
- Not discussed by autonomous acquisition of sun-illuminated ISS and OICETS spacecraft were also accomplished successfully
- The next step for infusing the technology will be to design a flight qualified system
  - low mass and power
  - withstand Mars launch, landing
  - surviving on the surface of Mars
- The pay-off of successfully accomplishing the above could be orders of magnitude communications capacity enhancement in the near term