Wavelength Selection for Free space Optical Communications

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JPL

Outline

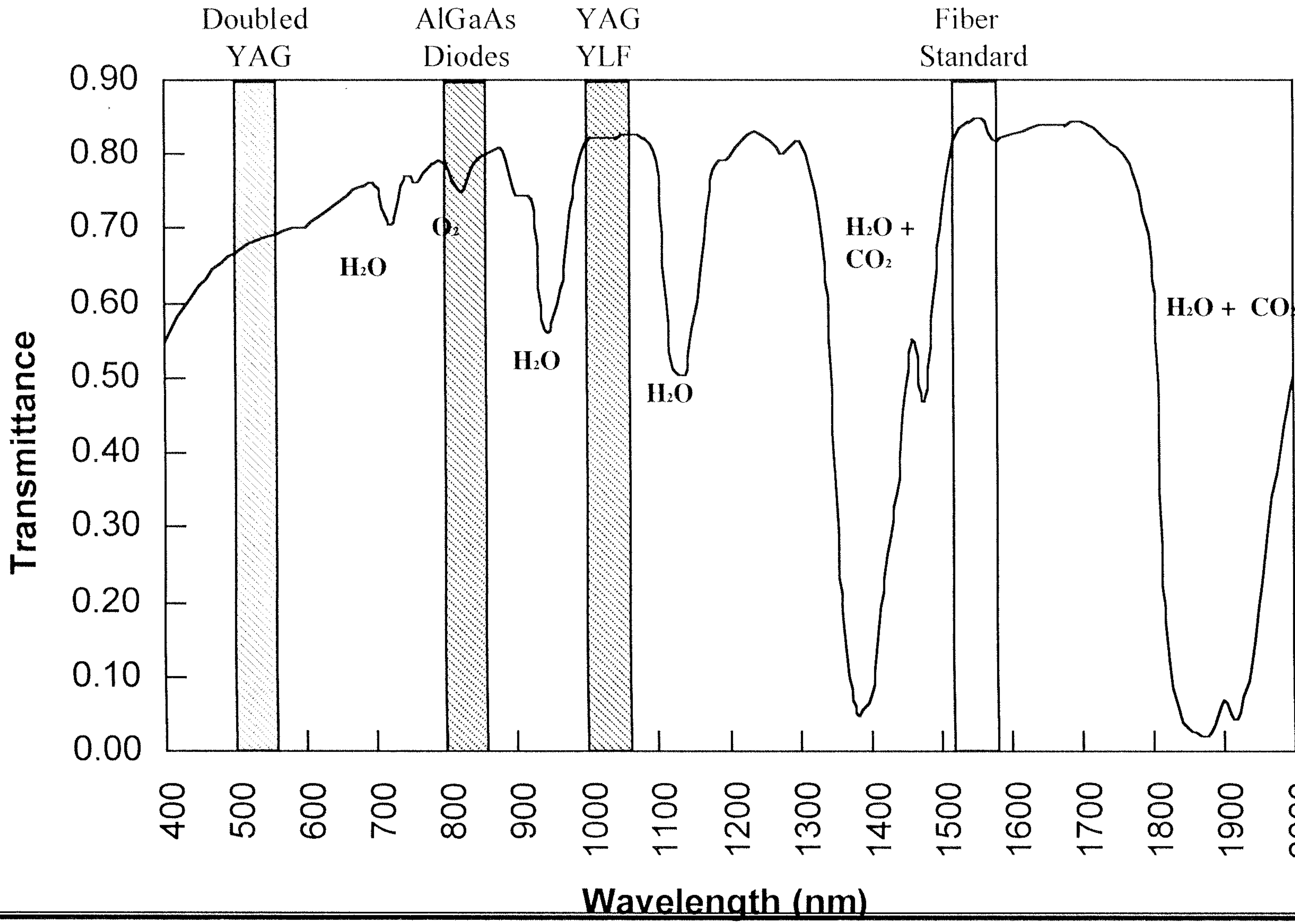
- Free space optical communications
  - Advantages and challenges of free space optical communications
  - Atmospheric effects
- Requirements
  - Deep Space and Near-Earth Missions
  - Optical sources
- Laser development
  - Deep Space Communications
    - Solid state lasers
      - Current status of laser performance
      - High peak power lasers
  - Near-Earth communications
    - Diode and fiber based MOPA devices for high data rate communications
- Summary

Advantages & Challenges of Lasercom

- Higher data rates
    - Modulation limited to few percent of carrier frequency, optical: THz
    - For example, near Earth RF typically limited to 10 - 100s Mbps
        - Can be increased to Gbps by with advanced BEM schemes

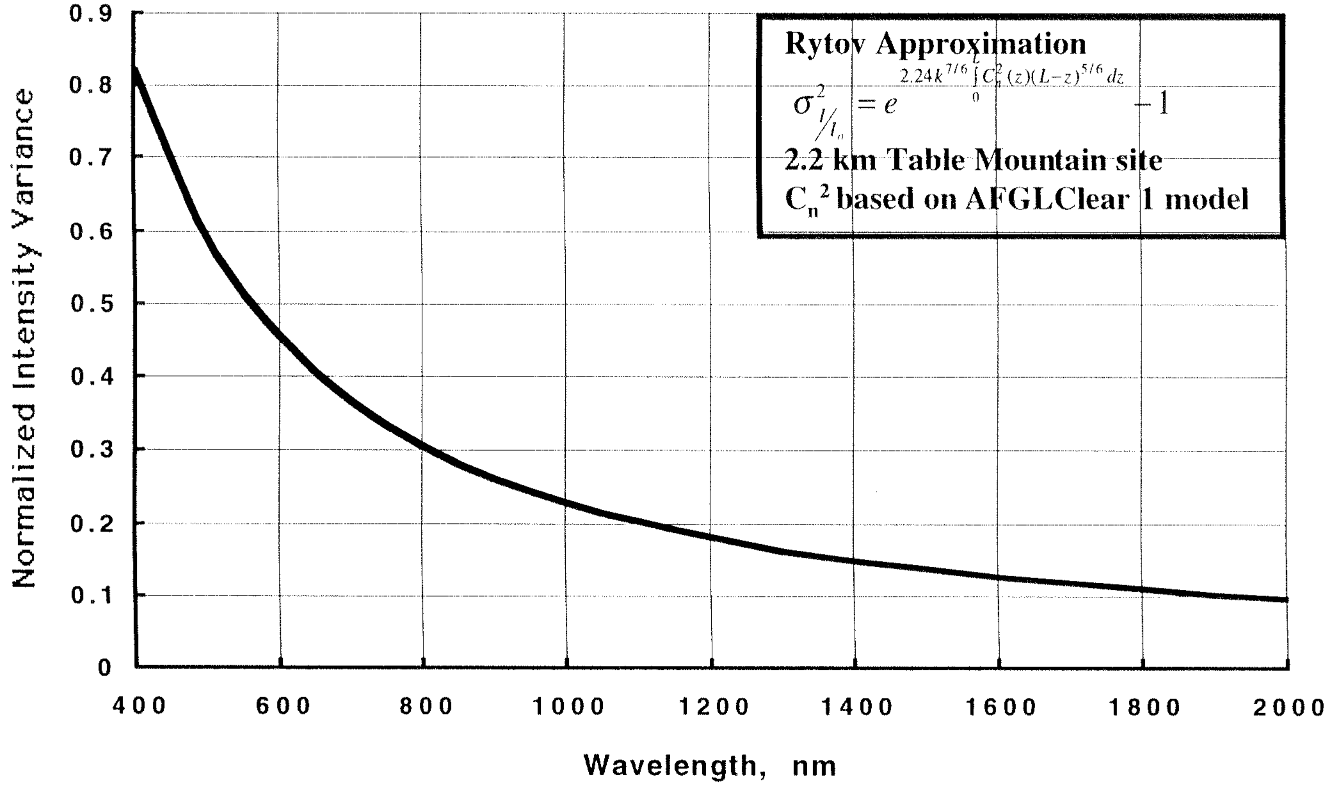
- Lower beam divergence $\Rightarrow$ smaller transmit aperture
  $\Rightarrow$ lower mass
- Optical has no bandwidth allocation restrictions
    - RF bandwidth for earth science support limited to
        - 50 MHz at X- and
        - 1.5 GHZ at Ka-band
- Challenges
    - clouds - availability of coverage
      $\Rightarrow$ *site diversity*
    - atmospheric induced scintillation effects - beam breakup and wander
      $\Rightarrow$ *adaptive optics, aperture averaging, multi-beam strategies*
    - Availability of optical sources and large area high speed detectors

Atmospheric Transmission

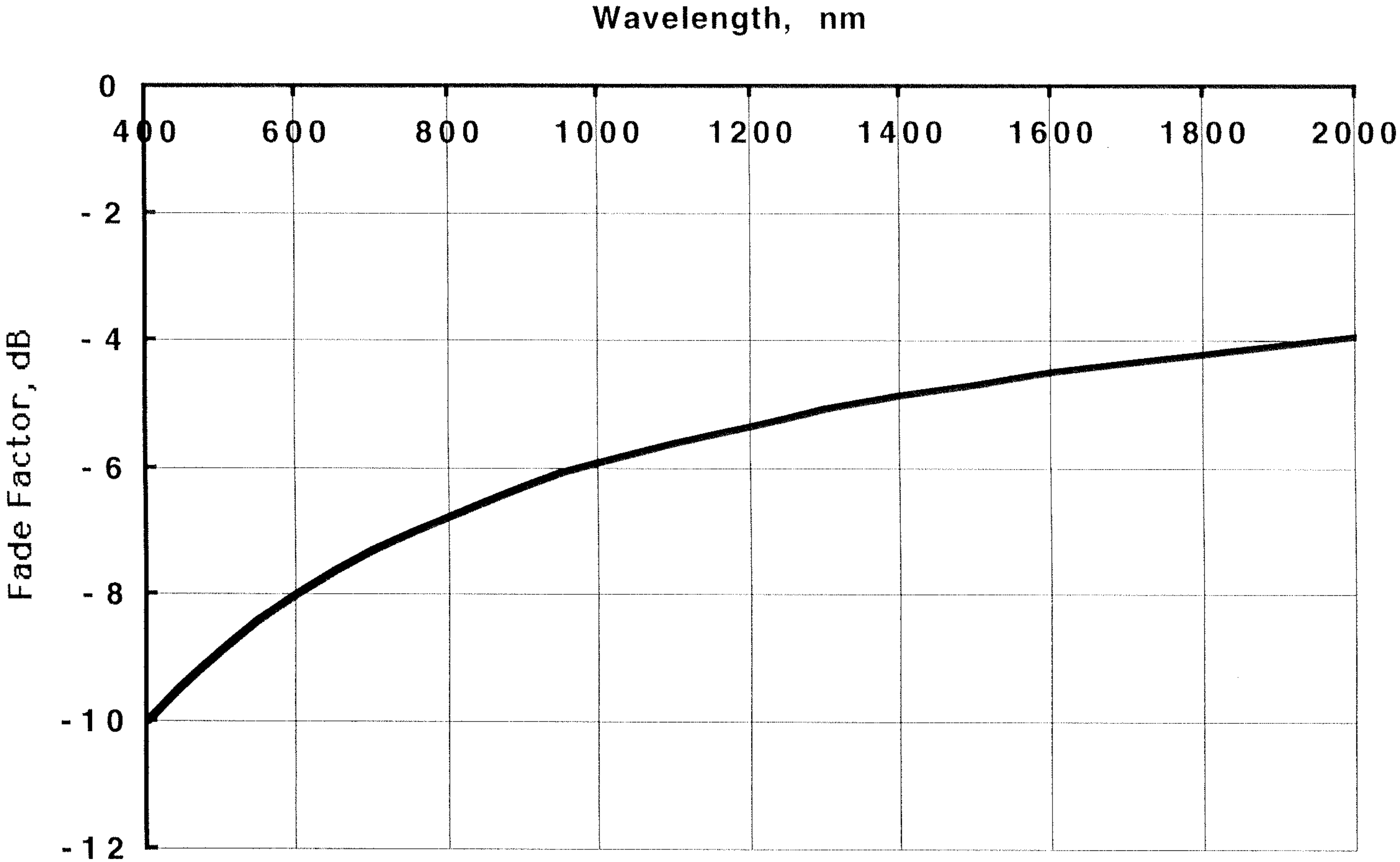


Atmospheric Scintillation

Normalized Intensity Variance $\sigma^2_{I/Io}$ vs. Wavelength



Scintillation fades



JPL/NASA Mission Requirements

- Mission definition determines data rate and or data volume

  ⇒ drives size, aperture, transmit power required

- Near Earth:
  - LEO / GEO - ground
  - Example: ISS demonstration: LEO - ground, unidirectional link with ground beacon acquisition, 10cm → 1m
    - λ = 1550 nm
    - 2.5 Gbps
    - 200 mW average laser power

- Deep Space:
  - Planetary to Interstellar missions, distances AU - > 100 AU
  - Example: Mars downlink, 30cm → 1m aperture
    - 20 kHz, 160 kbps
    - λ = 1000 -1100 nm
    - P_{peak} ~ 30 kW, P_{avg} ~ 1 W,

Optical Sources

- High rate optical channel using direct detection determined by application:

- Near Earth links:
  - high data rates desired, 100's Mbps - 10's Gbps
  - high average power sufficient, 1-5 W

  $\Rightarrow$ Semiconductor diode or fiber based lasers with OOK modulation

- Deep space links:
  - maximize photon efficiency $\Rightarrow$ high average and peak powers, kW - MW/pulse
  - data rates, 10 kbps - 10 Mbps

  $\Rightarrow$ Diode pumped solid state lasers and PPM

Both mission scenarios require compact, efficient, reliable, rad. hard lasers with good beam quality

Deep Space Com Laser Requirements

	Mars 1.5 AU	Jupiter 6 AU	Interstellar Probe 200 AU
Downlink Laser			
Data rate, Mbps	10	0.05	0.001
Average Power, W	6	3	15
Peak Power, MW	0.001	0.022	11.3
Repetition Rate, Hz	1.42 E6	6650	135
Energy per pulse, mJ	0.002	0.44	110
Pulse width, nsec	2	20	10
*** Uplink Laser**			
Average Power, W	1	7.3	135
Peak Power, MW	0.35	1.46	12000
Repetition Rate, Hz	142	250	1.1
Energy per pulse, J	0.007	0.04	120
Pulse width, nsec	20	25	10

Requirements met by solid state lasers operating 1000 nm - 1100 m spectral range

Assumption: 30 cm aperture on spacecraft, 10 m on ground
* No adaptive optics atmospheric compensation

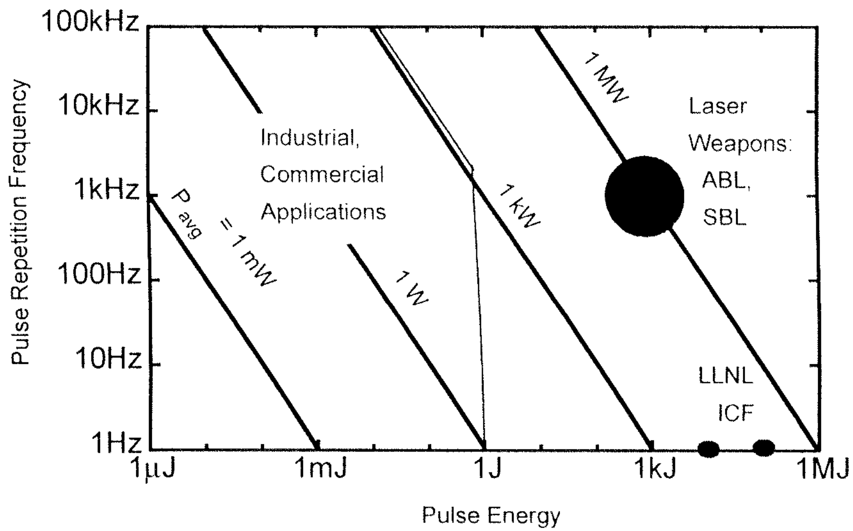
Current Solid State Laser Technology

Laser Transmitter:

- Good beam quality, ~ diffraction limited, $M^2 < 1.3$
- Reasonable overall efficiencies, ~ 6 - 10%
- Good modulation extinction ratio, 50 dB

Operational modes of Candidate Solid State Lasers:

- Q-Switched ⇒ direct detection, limited to < 1 Mbps (100 kHz)
- Cavity dumping ⇒ direct detection, will support 1- 10 Mbps
- Continuous wave ⇒ coherent detection



High Peak Power Q-switched Lasers

	Nd:YAG 1064 nm		Nd:YLF 1050 nm	Yb:YAG 1030 nm	Doubled 532 nm		YALO 1084 nm
Pav W	10	690	29	280	120	175	140
PRF kHz	0.1	2.5	5	10	5	2.5	0.1
Pulsewidth ns	20	~100	20	30	-	~100	-
Efficiency %	6	?	6	6	2	?	1.8
BQ / D.L.	1.05	1.1	1.1	5	5	1.5	1.1
P_{pk} MW	5	2.76	0.29	0.93	-	0.7	-
Developer	ESA	TRW	SEO	LLNL	DOS	TRW	German

High Power cw Solid State Lasers

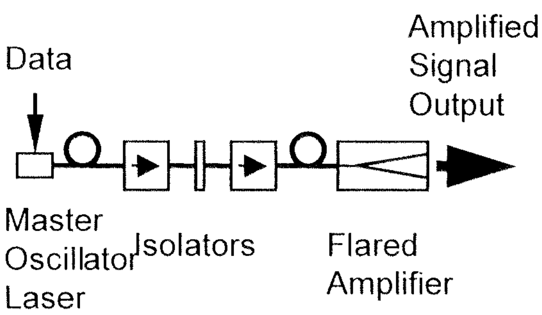
	Nd:YAG				Nd:YLF	Yb:YAG		Doubled	
Wavelength nm	1060				1050	1030		532	
Pcw W	1	10	45	107	50	430	40	5	.2
Efficiency %	6.3	<8	6	11	8	6.3	2.5	0.4	~ 0.5
BQ / D.L.	~1	1.05	<1.3	5	~ 1.1	5	1.02	-	1.1
Linewidth kHz Timescale	10 10ms	Q.L.*	?	-	?	?	?	5000 50 ms	<10 1 ms
Comments		Freq. Stable	300 W poor BQ	147 W BQ=45 η~14			T=100K	commercial	commercial NPRO†
Developer	JPL	Japan	German	Japan	SEO	LL NL	DOS	Coh.	Light-wave

* Injection locked to a single frequency NPRO laser.
Frequency noise $2\text{x}10^{-5}$ / Hz at 300 Hz. Shot noise limited above 1 MHz.

† Two 40 mW Nd:YAG devices frequency locked to high finesse Fabry-Perot cavity: $\Delta\nu$ = 330 mHz.

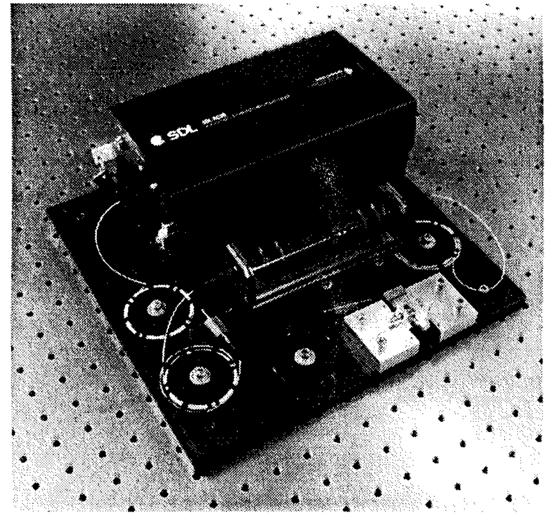
Sources for near-Earth Com

Flared Amp MOPA



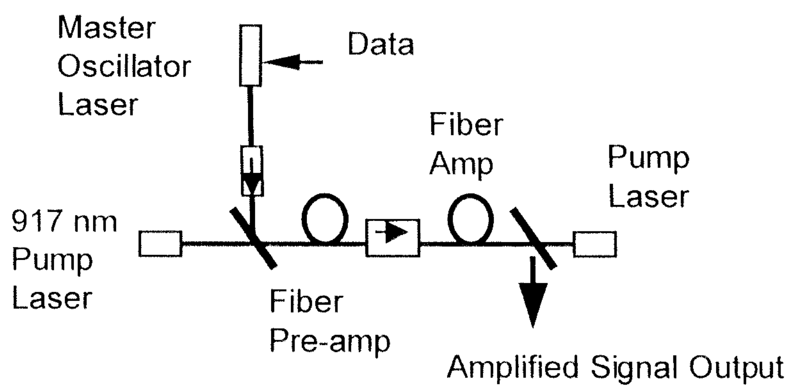
Laboratory Prototype

MO: InGaAs FP oscillator capable of 10 Gbps
λ = 960 nm
InGaAs flared amplifier
Packaged: 1 Watt InGaAs flared amplifier,
2.5 Gbps, OOK
Efficiency ~ 24%
Table-top: 3.6 W at 2.5 Gbps
Poor modulation extinction ratio due to ASE



Fiber MOPA

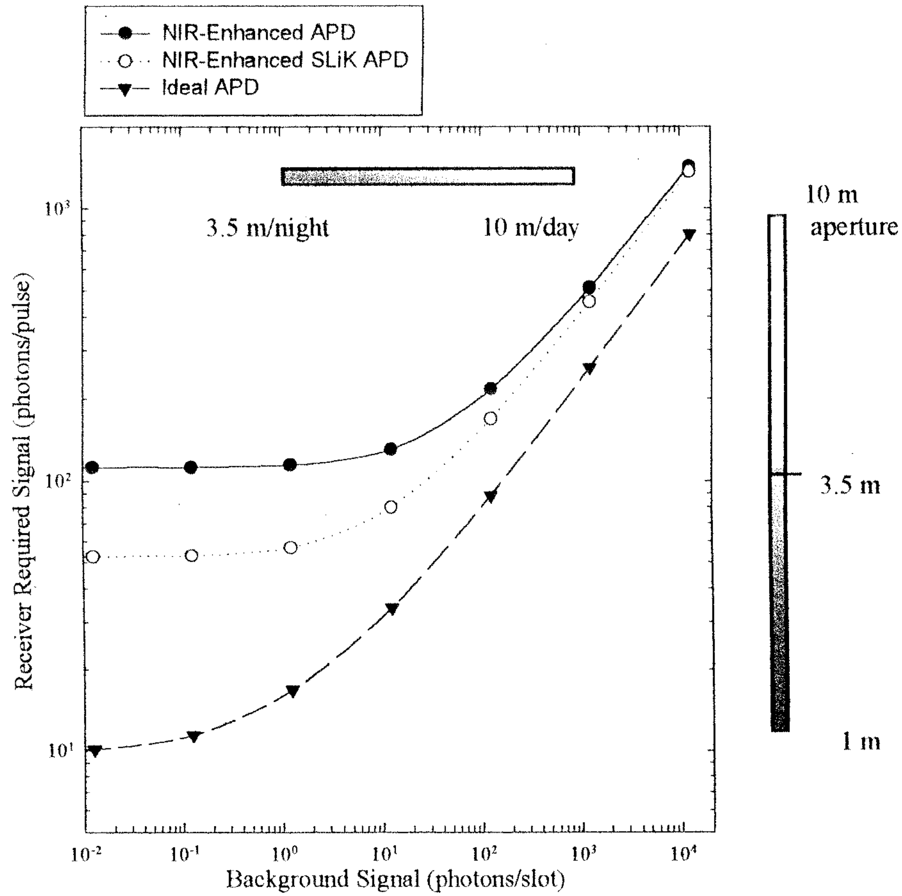
MO: InGaAs diode oscillator
λ = 1070 nm
5 W 2-stage YDFA
2.5 Gbps, OOK
Good beam quality



Detector/Link Requirements

Laser requirement also driven by detector capabilities:

- Transmitter:
  1 Watt Q-switched Nd:YAG laser
  1064 nm
  25 ns pulse width
  10^{-5} modulation extinction ratio
  10 cm telescope
  27.8 % transmitter optics losses
  16 kbps
  10^{-5} BER
  PPM (M=256)
  Reed-Solomon coding
- Channel:
  Mars at 2 AU link range
  32.8 % atmospheric loss
- Receiver:
  Telescope diameter -various
  55.1 % receiver optics losses
  Silicon APD Detector - various
  High-Impedance Pre-amplifier
  31.25 ns slot width



Depending on background level,
link is viable with 3.5 or 10 m aperture

Summary

- Considered free space optical communications in 400 nm - 2000 nm spectral range
  - Sky background (Rayleigh scattering) and scintillation effects drive operational wavelengths for free space optical communications toward red end of spectrum
  - Molecular absorption, availability of small, efficient high power optical sources and high quantum efficiency detectors drive operational wavelengths to blue end of spectrum
  - Deep space communications PPM format requires high peak power sources
    - Small efficient high peak power sources are available in 1000 nm -1100 nm range
  - Near-Earth communications OOK modulation format supports Gbps data rates requires efficient high average power sources
    - Small efficient high average power semiconductor, and fiber lasers and amplifiers are available in 1500 nm to 1550 nm spectral range
      - Broad gain bandwidth of these devices facilitates WDM techniques for increased data rates