Free Space Laser Communications

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Outline of Presentation

- Fundamentals
- Spacecraft Technology
- Ground Reception Systems
- Simplified Link Calculation
- Recent Demonstrations
- Future Demonstrations

Fundamentals

Free Space Propagation

- Electromagnetic beams diverge at rates at least as fast as λ/d (Diffraction-limit)
  - λ is the wavelength of the radiation
  - d is the diameter of the transmitting aperture
- RF wavelengths usually in the cm-m range
- Optical wavelengths are in the μm range
- The more wavelengths across the aperture, the more narrow the beam divergence

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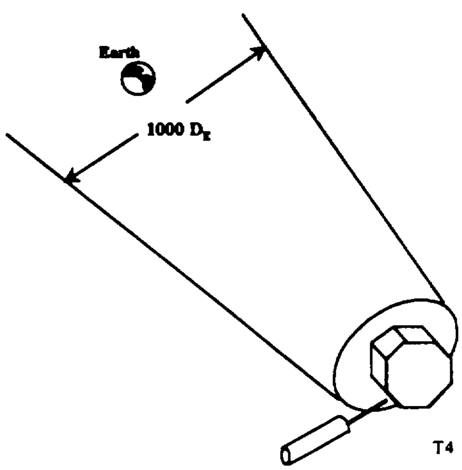
Deep Space Communications

Beam Spread

Voyager (X-Band) at Saturn

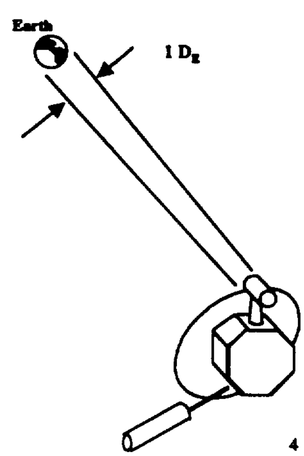
(3.8m S/C Antenna)



T4

Optical at Saturn

(10 cm Telescope)



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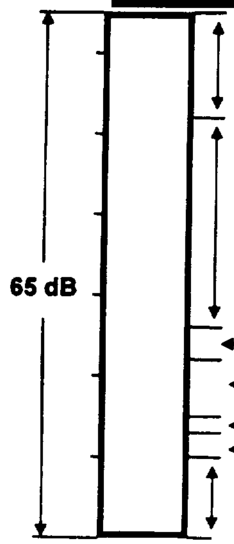
Optical Advantage Relative to Ka-Band

(Based on a Pluto FB Example)*



13 dB -Data Rate Increase (4.9 kbps vs 270 bps)

26 dB -Smaller S/C Aperture (10 cm vs 2.0 m)

4 dB -Less Transmitted Power Required (1.0 W vs 2.7 W)

7 dB -Lower Transmitter Efficiency (5 % vs 28 %)

2 dB -Lower System Efficiencies (24 % vs 40 %)

3 dB Atmospheric Loss

10 dB - Smaller Ground Station (10 m vs 34 m)

* Same Input Electrical Power

T4

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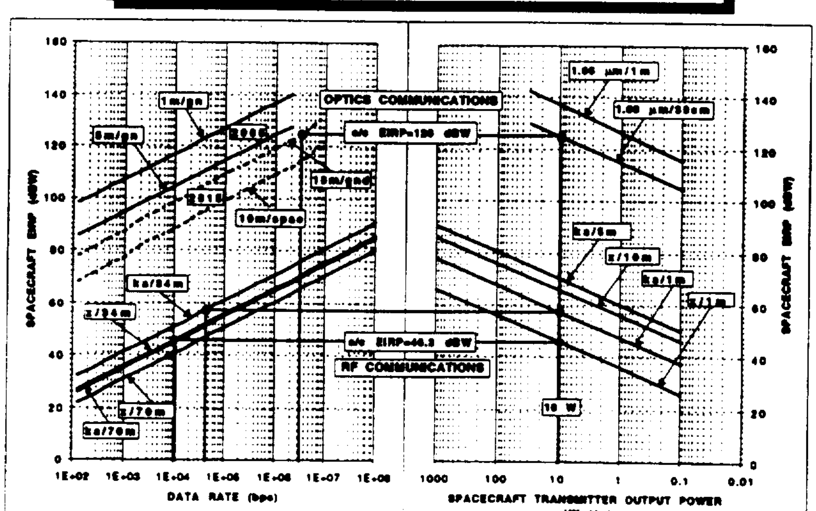
Comm Link Nomograph

Earth-Mars range: 2.5 AU



T4

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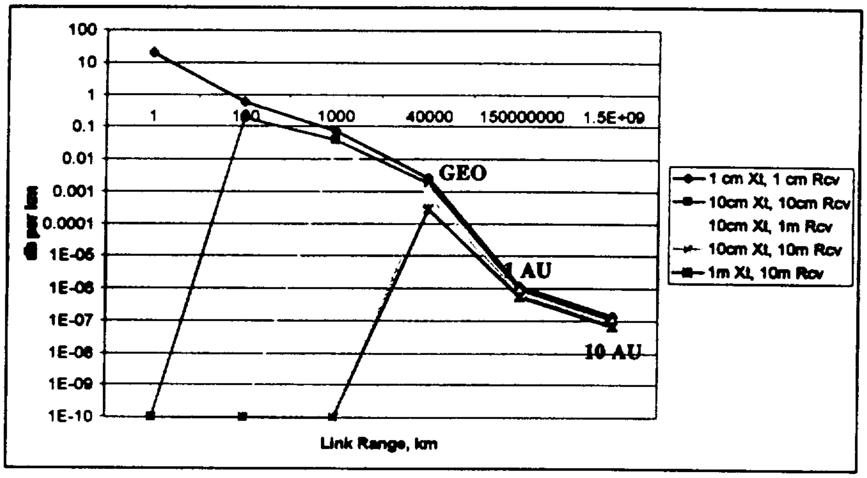
Fundamentals

Equivalent dB/km Loss for Free Space



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Fundamentals

Good News/Bad News

- Good News:
  - Optical beams are more narrow
  - Concentrate transmitted energy on target RCVR
- Bad News:
  - Optical beams are more narrow
  - Narrow beams must be more precisely pointed
  - Must track beacon signal from intended receiver

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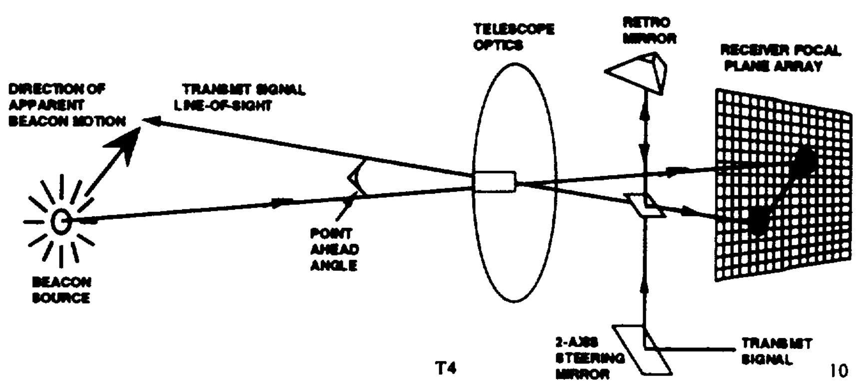
Spacecraft Technology

T4 9

Optical Communications Demonstrator (OCD)
Simplified Optical Design

- Uses only one steering mirror and one detector array for all beam control functions
- Eliminates many beam relay optics and need for large optical bench
- All optics are located on telescope body
- Fiber-coupled laser transmitter signal removes laser heat from optics



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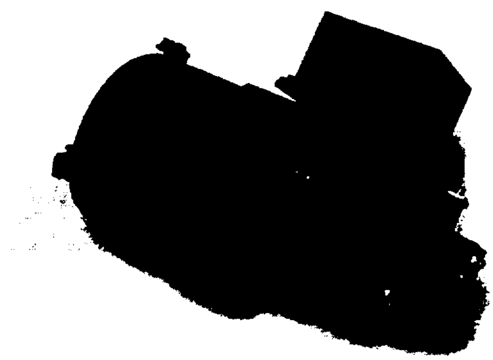
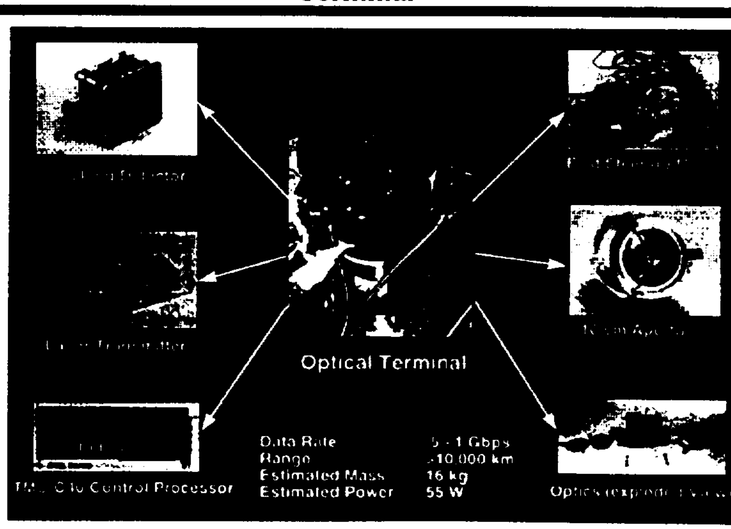
Optical Communications Demonstrator

Telescope Optical Assy (TOA)

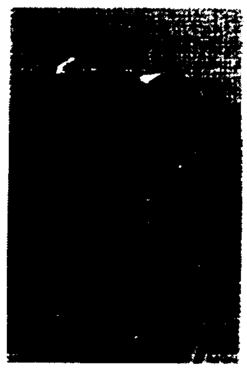


Optical Communications Demonstrator

Terminal

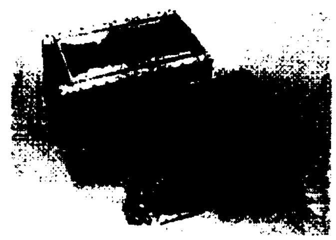


OCD with Electronic Assy



Telescope Optics Assembly (TOA) on gimbal

Control Electronics and Enclosure



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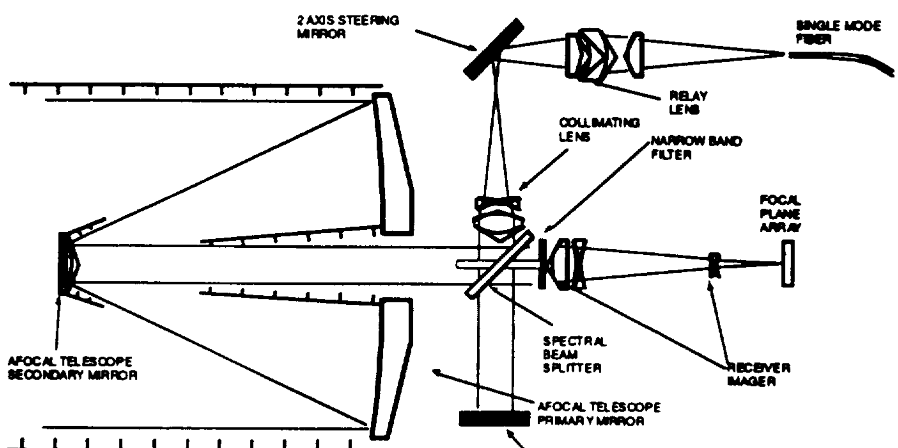
Optical Communications Demonstrator

Optics Layout



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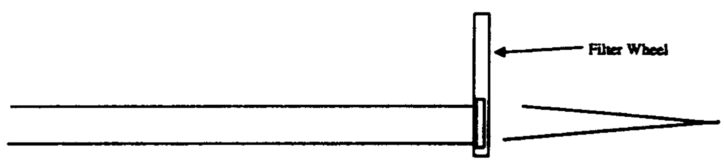
(With Imager)



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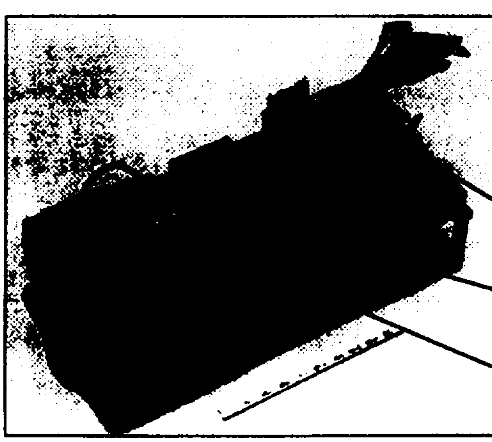
ACLAIM Breadboard Terminal



ACLAIM
- Laboratory breadboard terminal
- Overall dimensions:
  (4" x 4" x 8")
- Built from COTS parts
- Demonstrates camera/opt comm
- Part of microspacecraft breadboard

2-axis Steering Mirror

APS Detector Array
(256 x 256)

Fiber Coupled Laser
(Laser transmitter hidden from view)

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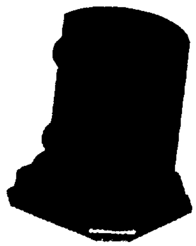
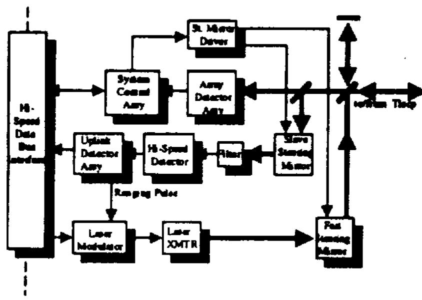
X2000 Program

Optical Comm Subsystem



Multi-Function Uses:

- Optical Comm (uplink and downlink)
- High-Resolution Imaging
  - Science Images
  - Optical (Image-based) Navigation
- Laser Altimeter Reception
- Uplink Ranging Reception
- Downlink Ranging Transmission



Communications Characteristics:

- Beacon Laser Tracking out to 1 AU
- Earth-Image Tracking Beyond 1 AU
- Redundant Critical Components
  - Lasers, Detectors, Steering Mirrors, Electronics
- >100 kbps (daytime reception)*
- >300 kbps (nighttime reception)*
- Mass < 13kg • Power < 38W

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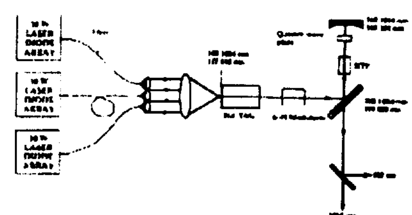
* From Europa to a 10-m Photon-bucket Receiver

JPL

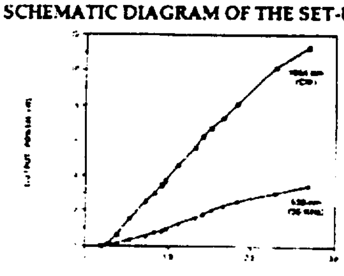
2-WATT LASER DEVELOPMENT

- DESIGNED & DEMONSTRATED A MODULATED, SOLID-STATE GREEN LASER SOURCE.
  - GOAL: 2 W OF GREEN AT 50 KHz PULSE RATE
  - ACHIEVED: 3.5 WATTS (11.7 WATTS CW AT INFRARED WAVELENGTH)
- USES THREE 10-WATT FIBER-COUPLED DIODE-LASER-BARS AS PUMP
- SEVERAL COMMERCIAL COMPANIES INTERESTED IN DESIGN



SCHEMATIC DIAGRAM OF THE SET-UP

PICTURE OF THE SET-UP



OUTPUT POWER VS. INPUT POWER

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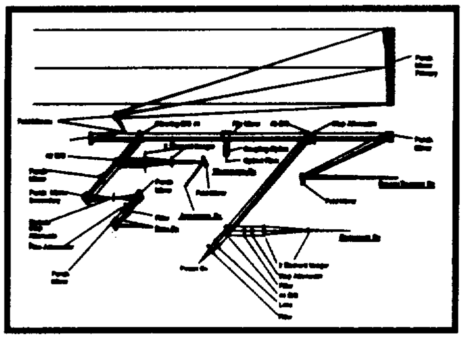
Lasercom Test and Eval Station

- **LTES is a high optical quality instrument that characterizes the performance of laser communications terminals (LCT's)**
  - **Measures beam divergence, acquisition and tracking performance, optical output power, and BERs of LCTs up to 1.4 Gbps data rates**
  - **Appropriate exchange of beamsplitters and detectors allows spectral operating range to extend from 0.5 μm to 2 μm**



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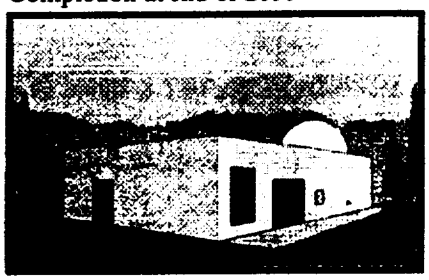
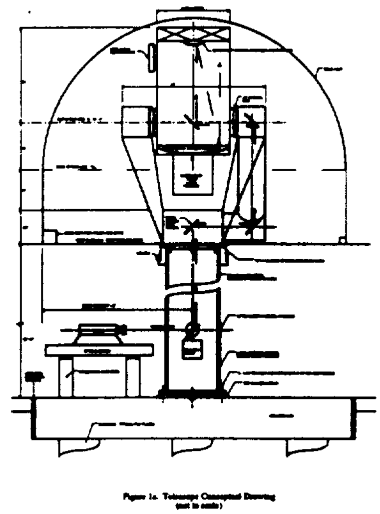
Ground Reception Systems

T4 20

1-m Optical Comm R+D Facility

- Optical Comm Telescope Laboratory (OCTL)
- Located at JPL's Table Mountain Facility
  - 2.4 km (7400 ft) elevation
- 1-m diameter aperture
- Fast (Earth-orbit) tracking mount
- Completion at end of 2000





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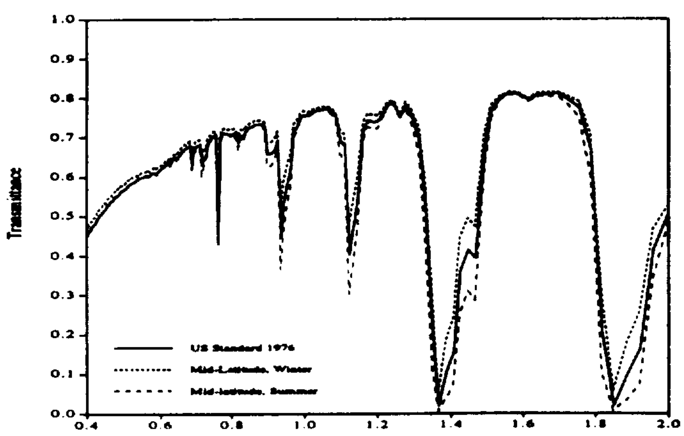
Atmospheric Transmission

Clear Weather



T4

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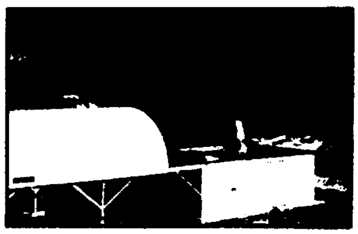
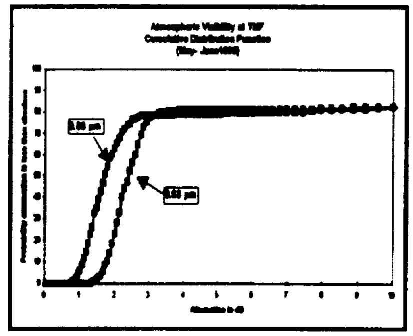
Atmospheric Visibility Data

- AVM Observatory at Goldstone, CA



- AVM Observatory at Table Mtn, CA

- Visibility Cumulative Distribution



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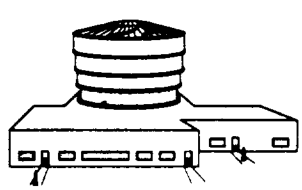
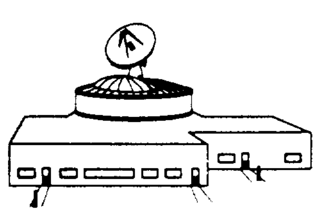
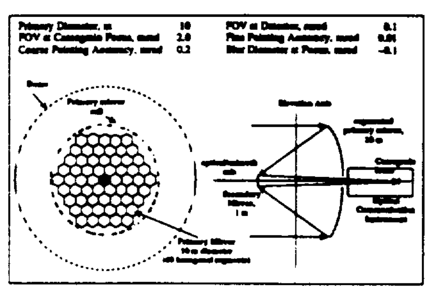
Deep Space Reception Station





- 10-m collection aperture
- Photon bucket (non-diffraction-limited)
- Segmented primary mirror



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Simplified Link Calculation

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Simplified Link Calculation
(Signal Level at Receiver)

- Calculate transmit beam divergence, $\theta = \lambda/d$
- Calculate spot diameter, Z, at target R meters away using $Z = R * \theta$
- Calculate area of illuminated spot ($\pi Z^2/4$)
- Area of receiver = $\pi D^2/4$ (D=receiver diameter)
- Propagation loss (L_s) is fraction of signal intercepted (receiver area) relative to total spot area = D^2/Z^2
- Received power P_r (Watts) = $P_t * L_s * T_a * T_{to} * T_{ro}$
  - P_t = Transmitted power - T_a = Atmospheric Transmission
  - T_{to} = Transmit Optics Thruput - T_{ro} = Receive Optics Thruput
- Received signal rate = Pr/(hv) (photons/sec) $hv = \frac{2e\text{-}19}{\lambda \text{ (in microns)}}$

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Simplified Link Calculation
(Background Level at Receiver)

- Background Effects
  - Point source interference signals produce a background flux rate over the receive aperture and over a spectral bandwidth (Watts/ m^2*nm) if in the detector field-of-view
  - Distributed sources (e.g. daylight) provide a background flux rate over the receive aperture over the entire field-of-view of the receiver (Watts/ m^2*nm*Sr)
  - Background signals are limited by narrow band filters of BW (in nm) and by detector FPV (in Sr)
  - Received background power (P_b) = background flux level*Receiver area*filter BW (*FOV if extended source)
  - Background Noise rate = P_b /(hv) (in photons/sec)

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Simplified Link Calculation
(Detection Performance)

- Signal Detection (performance depends on type of detector, coding, and background levels)

Receiver Type	Sensitivity
Inexpensive Receiver	> 100 photons/bit
State-of-the-Art Receiver	~ 10-20 photons/bit
Low Background/Low Rate Rcvr	< 1 photons/bit

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Comparison of Optical and RF Links

- Optical links are often compared to RF links
  - Need to use a common comparison basis
  - But, optical and RF have some fundamental differences
- Weather affects RF and optical systems differently
  - RF links experience weather fades infrequently
  - Optical must consider spatial diversity reception from the start.
- Need to develop an optical link design methodology that enables comparison with RF but allows for uniqueness of the two technologies

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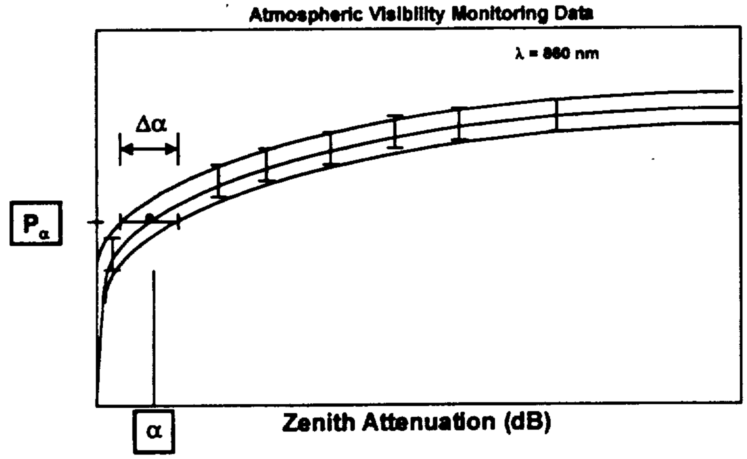
Optical Weather Statistics

Atmospheric Visibility Monitoring Data



α = atmospheric attenuation; Δα = attenuation uncertainty; Pα = prob(attenuation < α)

Note: α must be adjusted for operational wavelength based on known (LOWTRAN) models (if different from measured wavelengths), and for elevation angle

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Optical Weather Model

- Atmospheric attenuation (α) is a continuous distribution ranging from low values (clear conditions) to very high values (due to clouds)
- Cloud outages impact "Station Availability"
  - Mitigated by station diversity
- Need to define what "outage" means
- Recommendation
  - Use AVM data to define atmospheric model
  - Select a value of α and the corresponding value of (P_α)
    - P_α = Probability that attenuation < α
    - Must be corrected for wavelength and elevation angle
  - Approximate the AVM distribution by two states
    - < α means clear (but with some attenuation)
    - > α means (totally) obscured by clouds
  - P_α determines station availability; α is nominal link attenuation and $\Delta\alpha$ is weather attenuation uncertainty (when available)

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Link Analysis Using Weather Model

- Analyze link using -α (dB) for atmospheric transmission and +/- $\Delta\alpha/2$ as the favorable and adverse tolerances
- Design link Initially for a "Link Summary" of 0 dB margin using nominal parameter values and calculate the favorable ($+\sigma_1$) and adverse ($-\sigma_2$) uncertainties
- Calculate "Recommended Link Margin" based on the adverse link uncertainty (i.e. margin = $2\sigma_2$)
- Redo link design with a nominal link margin equal to the "Recommended Link Margin"
  - Uses visibility data as a basis for link loss and link loss uncertainty
  - Provides a formal basis for establishing value of link margin

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Link Analysis Example

Link Design Control Table

Parameter	Nominal	Fav	Adv
Transmit laser power	XXX	FFF	AAA
Transmit aperture dia	...	...	...
•	•	•	•
•	•	•	•
•	•	•	•
Atmospheric Trans. (dB)	$-\alpha$	$\Delta\alpha/2$	$-\Delta\alpha/2$
•	•	•	•
Link Summary (0 dB Margin)	0	σ_1	$-\sigma_2$
Recommended Margin (dB)	$2\sigma_2$		

Note: 2.2σ corresponds to 97% confidence

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Link Availability Analysis

- Optical systems assume spatially-diverse reception
- Assume all ground stations are in independent weather cells (separated by few hundred km)
- Define a station as a "Candidate Station" if it can see spacecraft when atmosphere removed and above some minimum elevation angle (say 20 degrees)
- Define a station as "Available" if it is a candidate station and it has clear weather (i.e. atmospheric attenuation $< \alpha$)

T4 34

Link Availability Analysis (Cont)

If N stations are "Candidate Stations", then the probability that m of them are "Available" is

$$P_N(m) = \binom{N}{m} (P\alpha)^m \, (1-P\alpha)^{N-m}$$

and the probability that <u>at least one</u> of the N stations is able to receive the link is

$$P_N = \sum_{m=1}^{N} P_N(m) = 1 - (1-P_\alpha)^N$$

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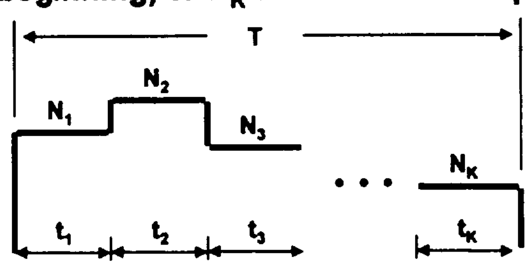
Link Availability Analysis (Cont)

Next, consider total time (T) of spacecraft support "pass". Let N_1 be the number of candidate stations at the beginning of this time, and let the number of candidate stations change with time over the pass duration from N_1 (at the beginning) to N_K at the end of the pass.



Let the corresponding times of N_i candidate stations be t_i

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Link Availability Analysis (Cont)

Then, the daily "Expected Data Volume" (EDV) returned for the link considered above, with the weather and station configuration being considered is

$$EDV = R \sum_{i=1}^{K} t_i P_{Ni}$$

where "R" is the data rate in the link design control table

RECOMMENDATION : Use EDV for RF/Optical comparisons

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Recent Demonstrations

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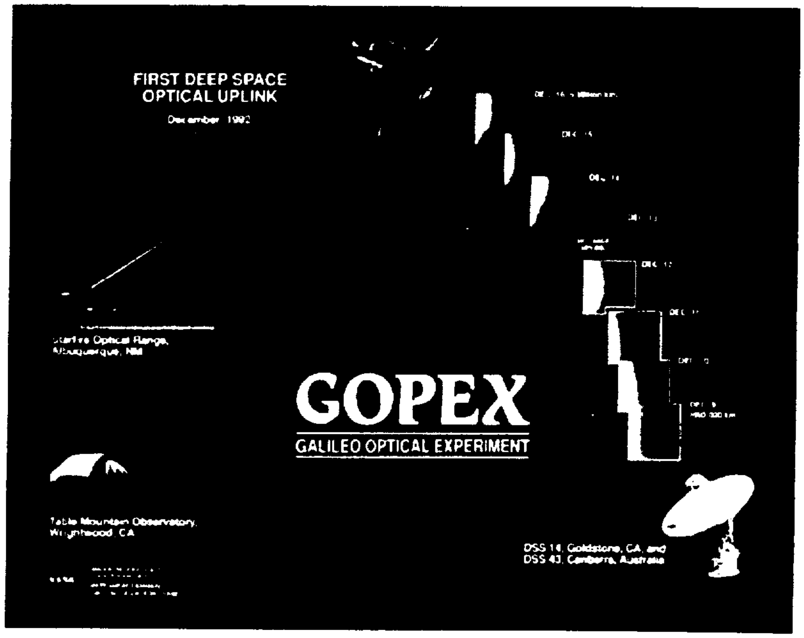
FIRST DEEP SPACE
OPTICAL UPLINK
GOPEX
GALILEO OPTICAL EXPERIMENT
DSS 14, Goldstone, CA, and
DSS 43, Canberra, Australia

T4

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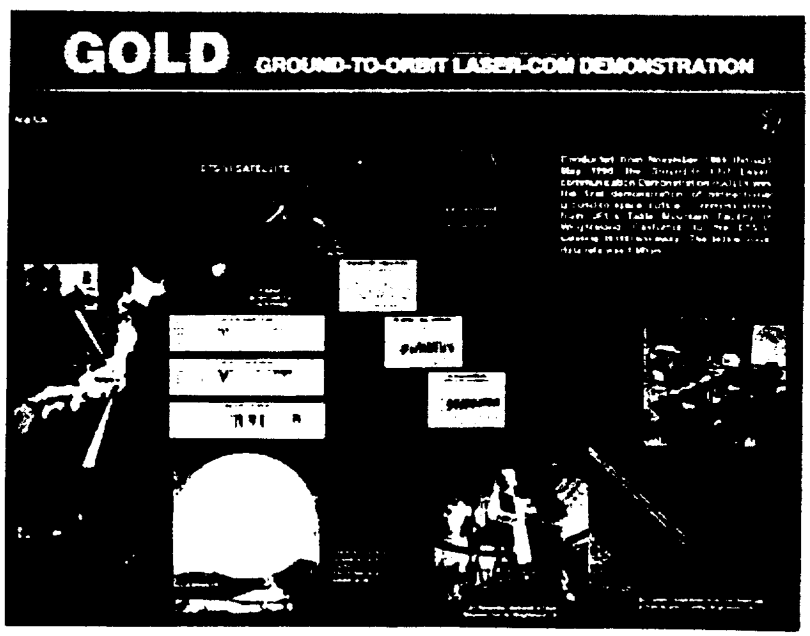
GOLD
GROUND-TO-ORBIT LASER-COM DEMONSTRATION

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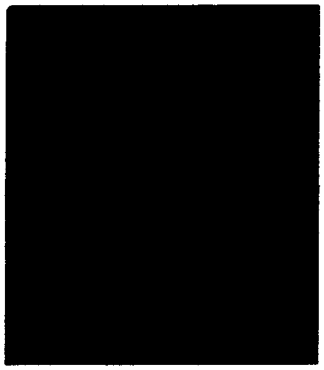
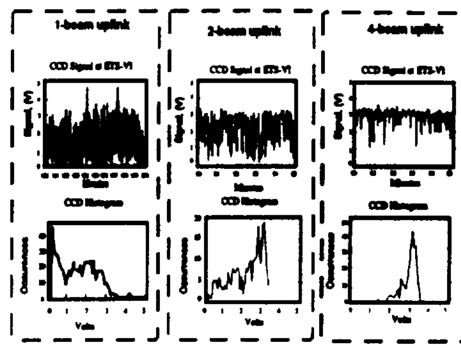
Ground-Orbit Lasercom Demo (GOLD)

GOLD Multiple-beam Transmission

- **Multiple beam uplink mitigates effects of atmospheric scintillation and beam wander**
  - **Beams are propagated through different atmospheric coherent cells**
  - **Each beam is delayed relative to the other by greater than laser's coherence length**

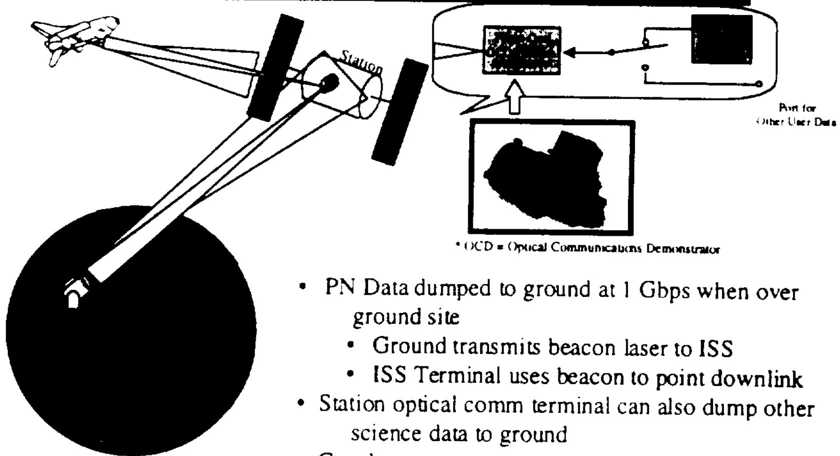


TMF 0.6-m Transmitter Telescope



Future Demonstrations

Demonstration from ISS



* OCD = Optical Communications Demonstrator

- PN Data dumped to ground at 1 Gbps when over ground site
  - Ground transmits beacon laser to ISS
  - ISS Terminal uses beacon to point downlink
- Station optical comm terminal can also dump other science data to ground
- Can demonstrate space-to-space optical comm if second optical terminal on Shuttle

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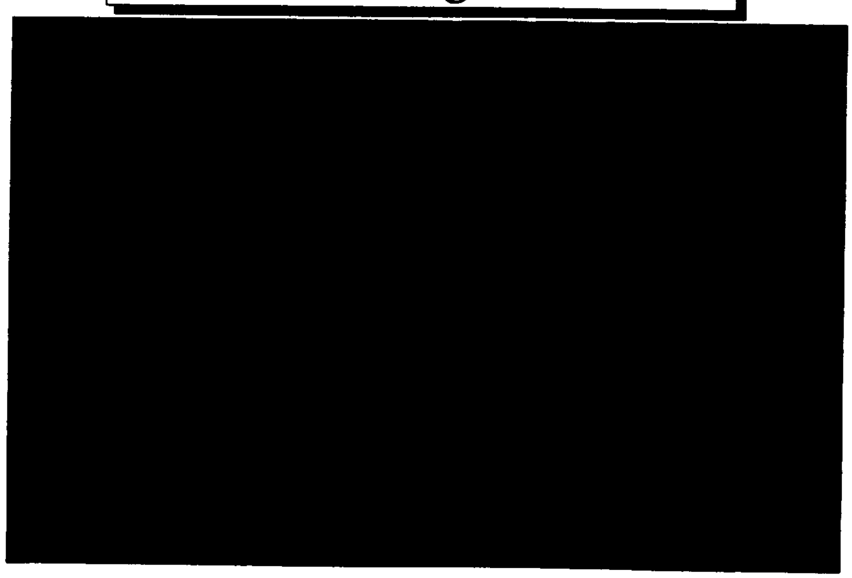
Location of Flight Terminal



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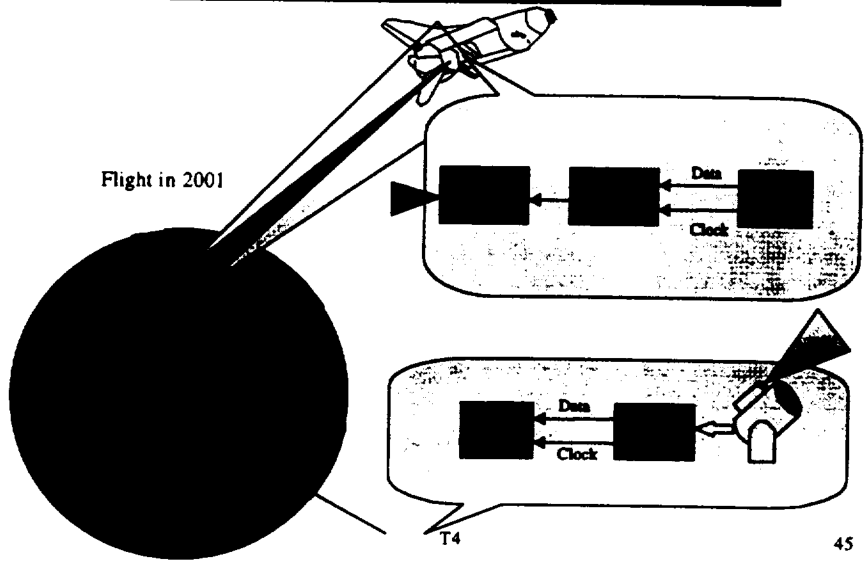
FOCAL Demonstration

FOCAL - A Free-space Optical Communications Assessment Link Demo



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Shuttle Link to Ground

1.6 Gbps

Transmit Laser Power	100	mW
Transmit Telescope Dia. (Space)	10	cm
Link Range (Slant range)	1050	km
Receive Telescope Dia. (Ground)	1	m
Atmospheric Losses (space-ground)	7	dB
System Losses	5.2	dB
Detector Efficiency	60	%
Data Rate	1.6	Gbps
Link Margin	21.3	dB

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