Strategies for Optimization of Deep Space Links: *Selected Examples for Managing Propagation Path Loss*

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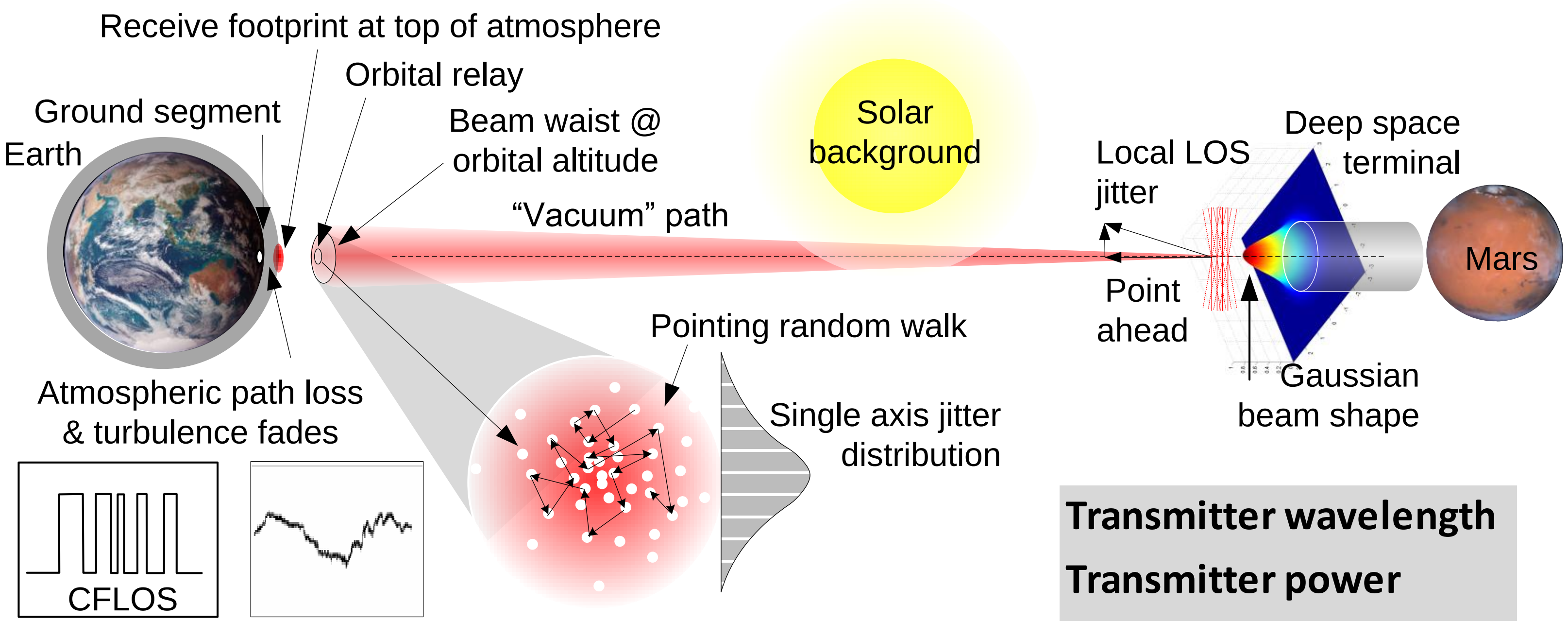
Overview

- Overview
- Notional deep space link attributes
- System application methodology
- Potential design and mitigation strategies
- Optical turbulence modeling methodology
- Key metrics and turbulence path modeling results
- Simulation versus preliminary field test results
- Dual-band technology design concept highlights
- Summary
- Citations

Notional Deep Space Link Attributes



Background

P_{CFLOS}

Data volume

Schedule

PATS LOS jitter

Turbulence jitter

Terminal mass

Antenna aperture

Wall plug efficiency

Transmitter wavelength

Transmitter power

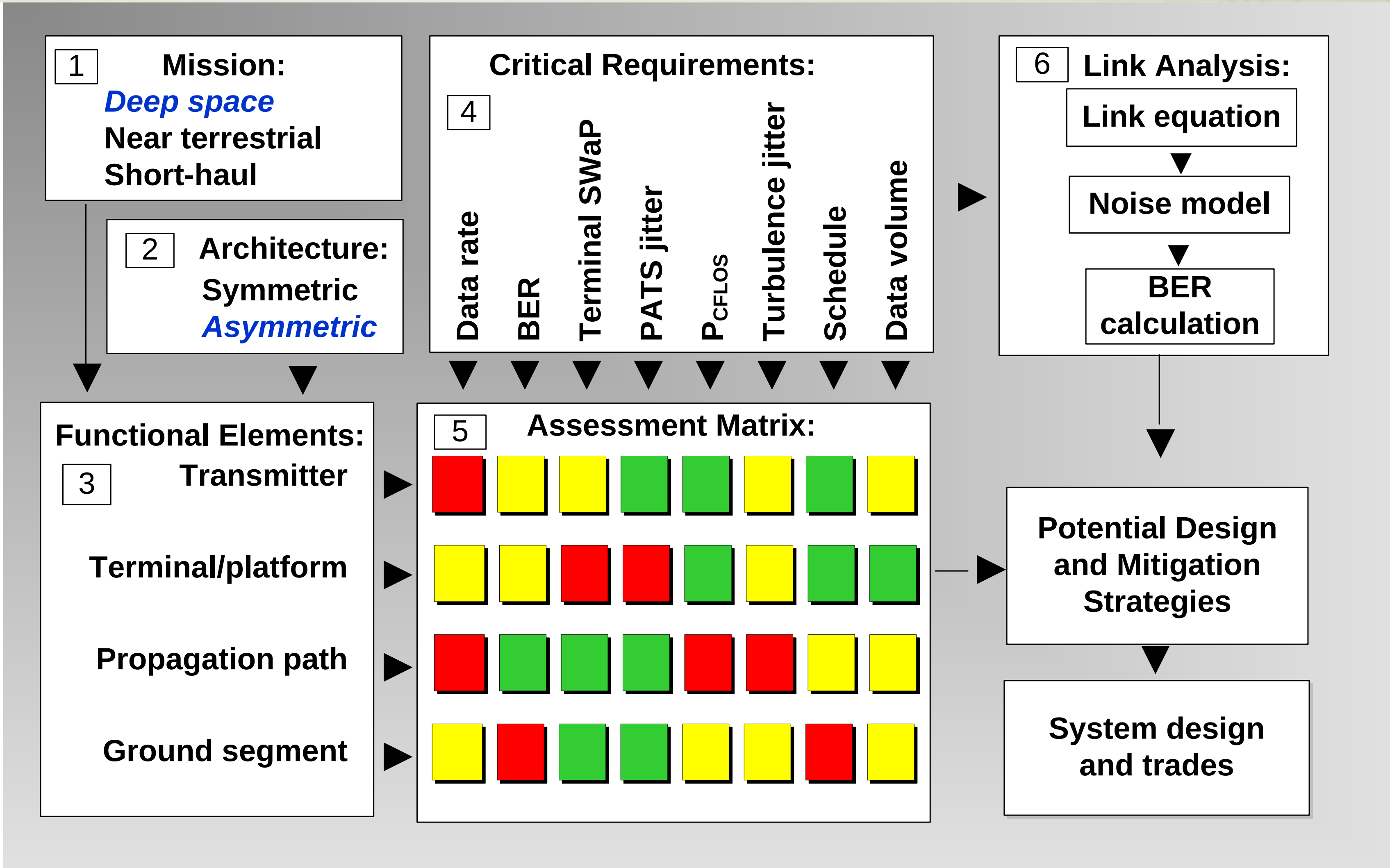
Data rate

BER

Modulation (PPM)

Noise model

System Application Methodology



1 **Mission:**
Deep space
Near terrestrial
Short-haul

2 **Architecture:**
Symmetric
Asymmetric

Critical Requirements:
4 Data rate, BER, Terminal SWaP, PATS jitter, P_{CFLOS}, Turbulence jitter, Schedule, Data volume

3 **Functional Elements:**
Transmitter
Terminal/platform
Propagation path
Ground segment

5 **Assessment Matrix:**

	Data rate	BER	Terminal SWaP	PATS jitter	P_{CFLOS}	Turbulence jitter	Schedule	Data volume
Transmitter	🟥	🟨	🟨	🟩	🟩	🟨	🟩	🟨
Terminal/platform	🟨	🟨	🟥	🟥	🟩	🟨	🟩	🟩
Propagation path	🟥	🟩	🟩	🟩	🟥	🟥	🟨	🟨
Ground segment	🟨	🟥	🟩	🟩	🟨	🟨	🟥	🟨

6 **Link Analysis:**
Link equation
Noise model
BER calculation

Potential Design and Mitigation Strategies

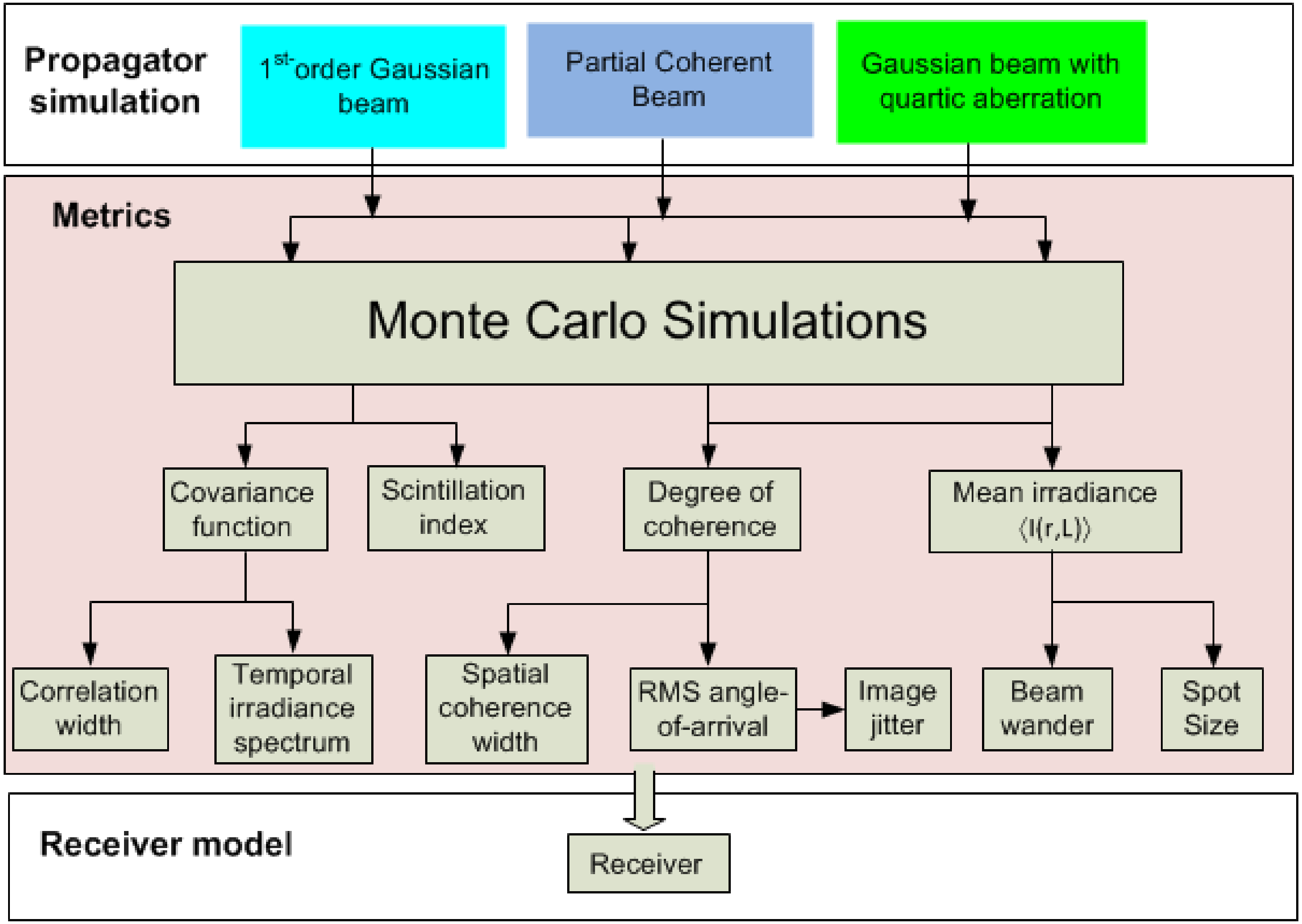
System design and trades

🟥 Strong or adverse constraint 🟨 Moderate constraint 🟩 Little or no constraint

Potential Design Strategies and Trades

Strategy	Definition	Benefit	Cost
Dual-band operation	RF/optical	CFLOS mitigation	Integrated design constrained
Multichannel operation	Fully parallel channels	CFLOS mitigation Site diversity	Ground segment redundancy Multi-aperture gnd terminals
Optical wavelength diversity	Spatially multiplexed channels	Fade reduction	Terminal complexity New technology investment
Very fine PATS	Sub-microradian (300-400 nrad @ Mars)	Optimized to larger common aperture	Very fine steering, high isolation & inertial updates
Lightweight common aperture	Low areal density materials	≥ 50% mass reduction vs separate apertures	Technology leveraging
Adaptive optics	Dynamic curvature	Fade reduction	Complexity, miniaturization
Homogenization	Beam scrambling	Fade reduction	Minimal non-adaptive means
Orbital relay	Very large ultralightweight orbital diffractive w/PATS	≥ 40 dB gain for very large apertures	New tchnology invesment
Site diversity	Multiple ground terminals separated by weather cells	Asymptotic avaialbility → 0.98 or greater	Ground segment redundancy up to 9 (min) sites worldwide
Enhanced receiver detectors w/adaptive FOV	High gain very low noise cryo-detectors	Data rates → 1 Gbps from Mars	New technology invesment

Optical Turbulence Modeling Methodology



Propagator simulation

1st-order Gaussian beam

Partial Coherent Beam

Gaussian beam with quartic aberration

Metrics

Monte Carlo Simulations

Covariance function

Scintillation index

Degree of coherence

Mean irradiance $\langle I(r,L)\rangle$

Correlation width

Temporal irradiance spectrum

Spatial coherence width

RMS angle-of-arrival

Image jitter

Beam wander

Spot Size

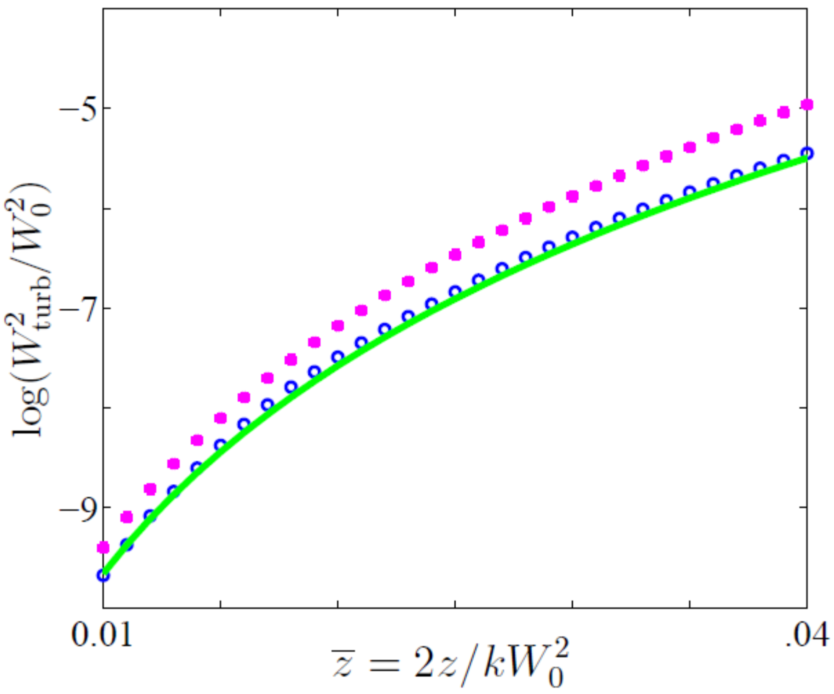
Receiver model

Receiver

Key Evaluation Metrics

- **Beam radius**
- **Structure function**
- **Intensity**
- **Spatial intensity pattern**
- **Probability density function**
- **Simulation vs. field test**

Beam Radius in the Presence of Turbulence



$$\Gamma_2(\mathbf{r},\mathbf{r},z) = \left(\frac{k}{2\pi z}\right)^2 \int\int_{-\infty}^{\infty} d^2\mathbf{Q} \int\int_{-\infty}^{\infty} d^2\mathbf{S}$$

$$\times U_0\left(S+\frac{Q}{2}\right) U_0^*\left(S+\frac{Q}{2}\right) \exp\left(\frac{ik}{L}(S-r).Q\right) \times \exp\left(\frac{ik}{z}(S-r).Q\right)$$

$$\times\left(-\frac{1}{2}D_{\mathrm{sp}}(Q)\right)$$

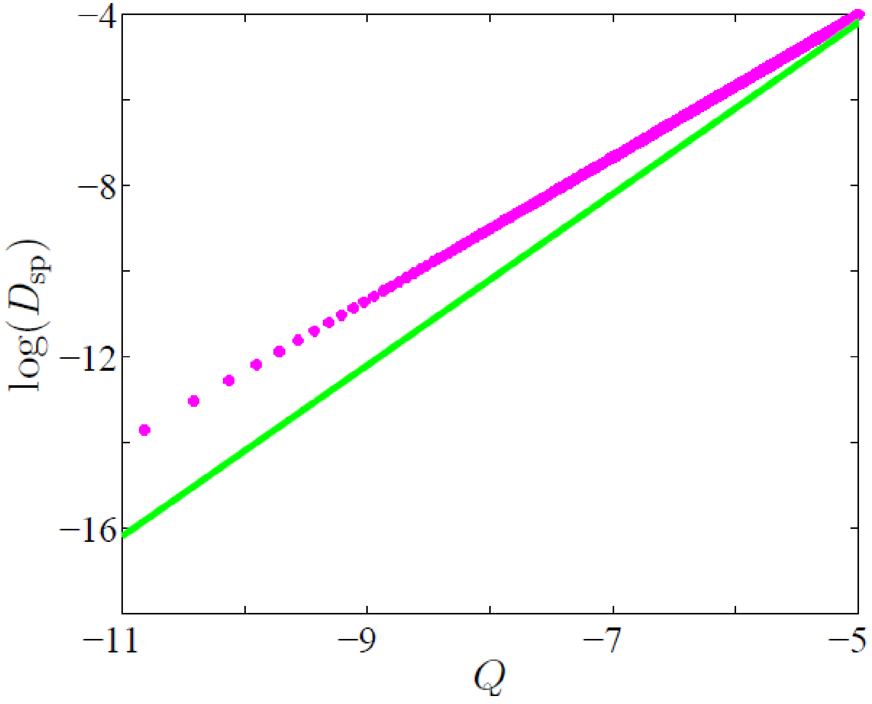
⇩

$$\langle W^2(z)\rangle = 2\langle\overline{r^2}\rangle = 2\frac{\int\int_{-\infty}^{\infty} d^2\mathbf{r}\ r^2\Gamma_2(\mathbf{r},\mathbf{r},z)}{\int\int_{-\infty}^{\infty} d^2\mathbf{r}\ \Gamma_2(\mathbf{r},\mathbf{r},z)}$$

⇩

$$\langle W^2(z)\rangle = 2\langle\overline{r^2}\rangle = W_0^2 + W_{\mathrm{diff}}^2 + \langle W_{\mathrm{turb}}^2\rangle$$

Structure Function



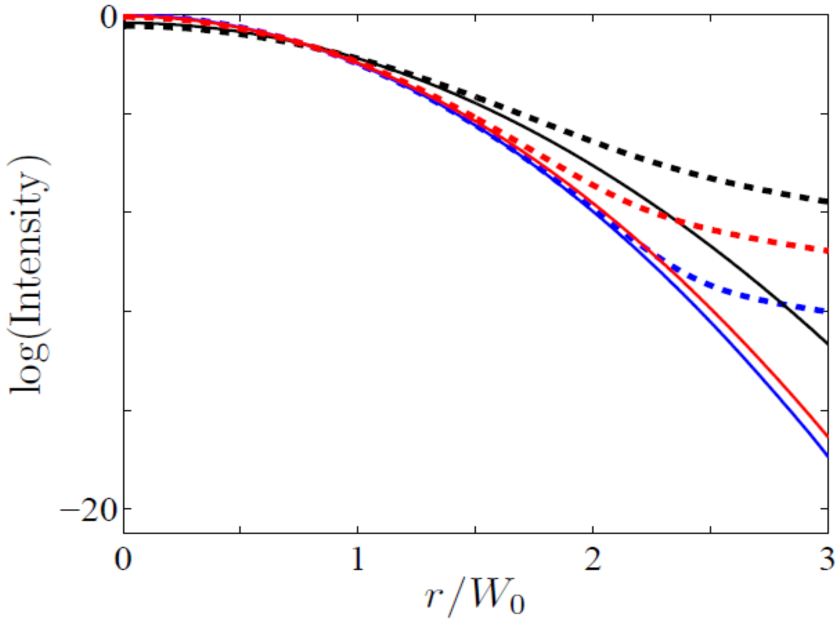
$$Q \ll l_0 \implies D_{\mathrm{sp}}(Q) \simeq 1.09 C_n^2 k^2 z l_0^{1/3} Q^2$$

$$Q \gg l_0 \implies D_{\mathrm{sp}}(Q) \simeq 1.09 C_n^2 k^2 z Q^{5/3}$$

Stars ($*$) indicate $D_{\mathrm{sp}}(Q) = 1.09 C_n^2 k^2 z Q^{5/3}$.

The solid line (—) indicates $D_{\mathrm{sp}}(Q) = 1.09 C_n^2 k^2 z l_0^{-1/3} Q^2$

Intensity



$$\langle I(\mathbf{r},z)\rangle = \Gamma_2(\mathbf{r},\mathbf{r},z) = \left(\frac{k}{2\pi z}\right)^2 \int\int_{-\infty}^{\infty} d^2\mathbf{Q} \int\int_{-\infty}^{\infty} d^2\mathbf{S}$$

$$\times U_0\left(S+\frac{Q}{2}\right) U_0^*\left(S+\frac{Q}{2}\right) \exp\left(\frac{ik}{L}(S-r).Q\right) \times \exp\left(\frac{ik}{z}(S-r).Q\right)$$

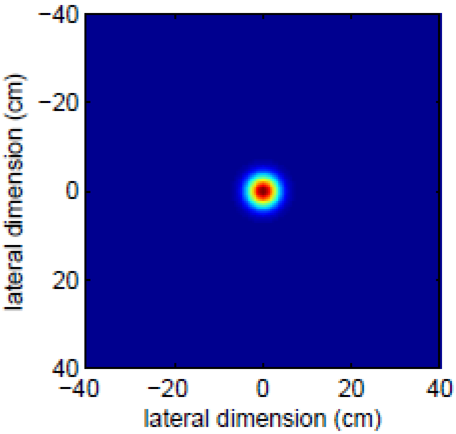
$$\times\left(-\frac{1}{2}D_{\mathrm{sp}}(Q)\right)$$

Solid lines are $D_{\mathrm{sp}}(Q) \simeq 1.09 C_n^2 k^2 z l_0^{1/3} Q^2$

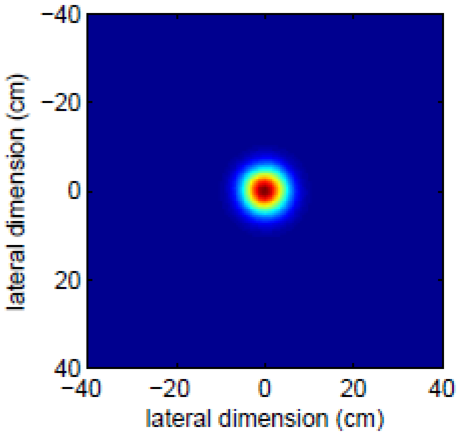
Dashed lines are $D_{\mathrm{sp}}\,(Q) \simeq 1.09 C_n^2 k^2 z Q^{5/3}$

Blue, red, and black indicate respectively $\overline{z} = 2z/kW_0^2 = .01, .03, .06$

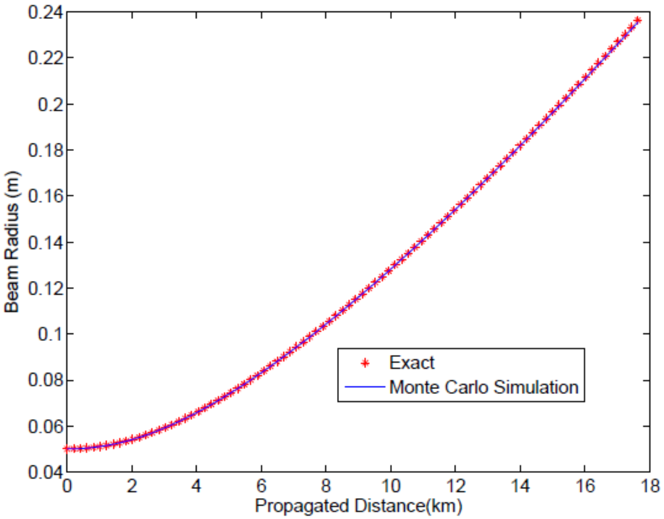
Spatial Intensity

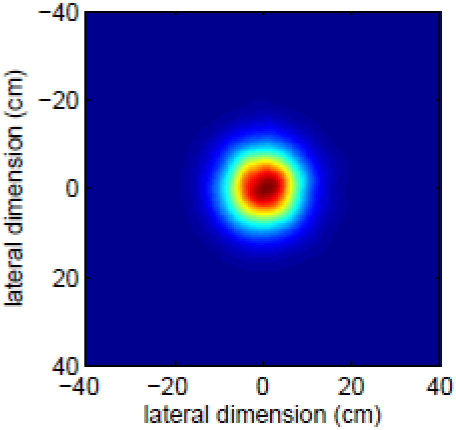


(a) Inital beam profile

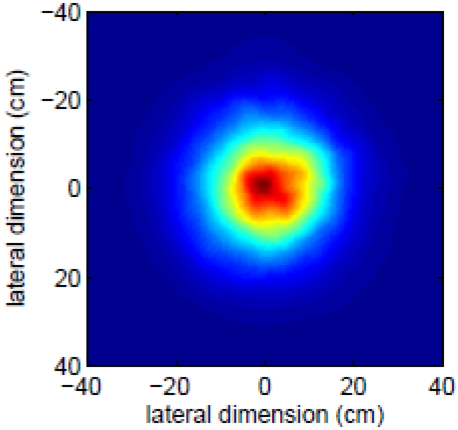


(b) beam profile at 5.1 km



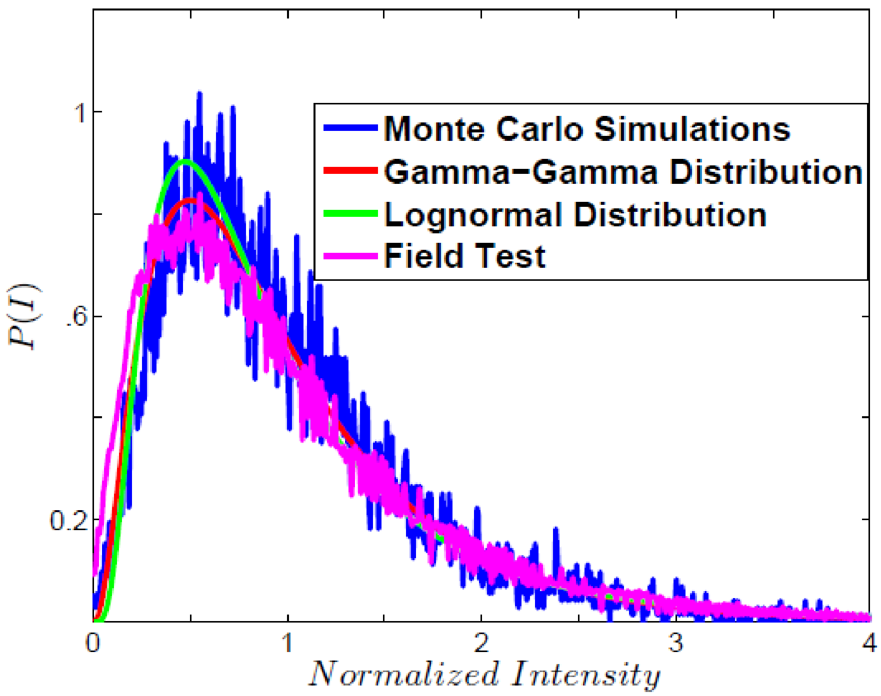


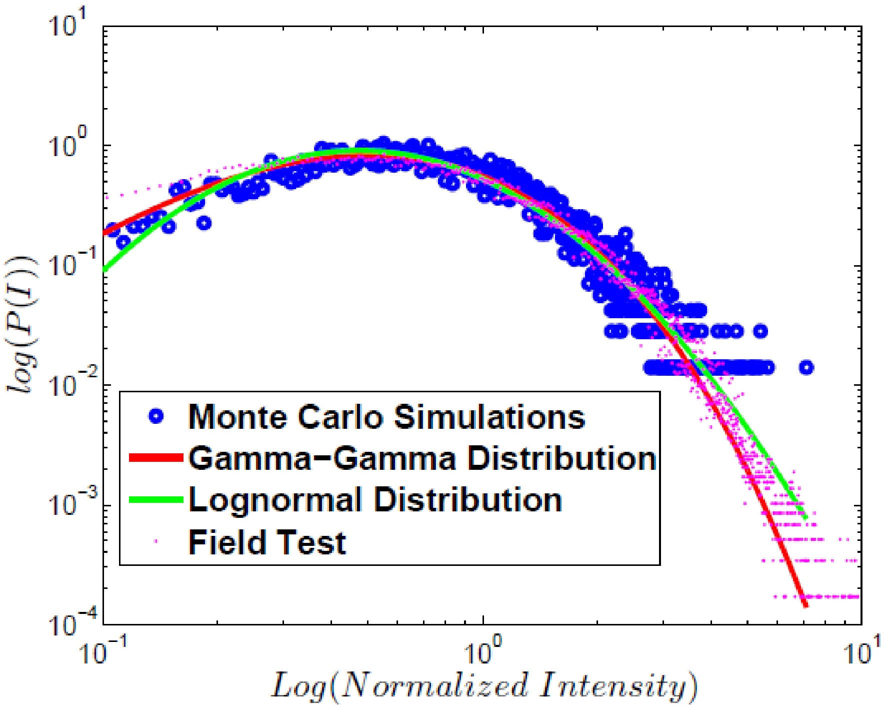
(c) beam profile at 10.7 km



(d) beam profile at 17.8 km

Probability Density Function





Simulation vs. Field Test Results

case	Scintillation Index		Number of points below threshold		Channel Availability	
	Simulation	Experimental	Simulation 10k iterations	Experimental 600k iterations	Simulation	Experimental
5.1 km	0.048	0.066	17	3357	99.8%	99.4%
10.7 km	0.165	0.123	568	19658	94.3%	96.7%
17.8 km	0.467	0.635	1546	112899	84.5%	81.1%

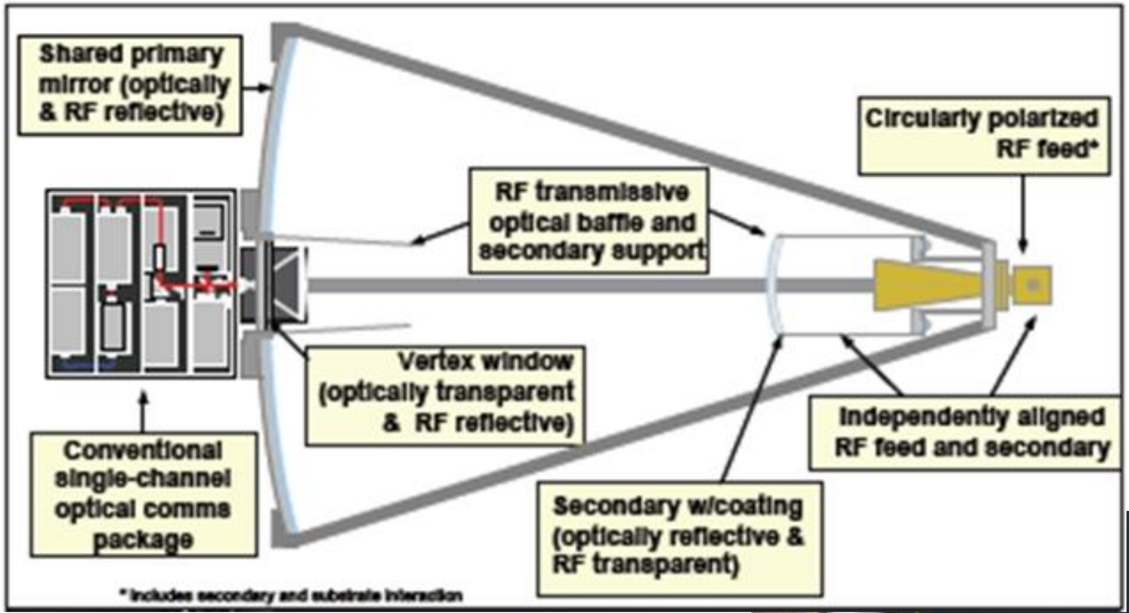
$$C_n^2 = 2.7e^{-15}\ \mathrm{m}^{-2/3}$$

Channel Availability=(Total number of iterations-number of points below threshold)/ total number of iterations

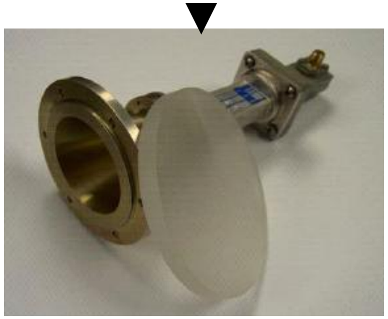
Summary of Turbulence Simulation Results

- Obtained an exact beam radius expression for all distances and verified theory by using Monte Carlo simulations
- Results were applied to correct the classic Fante expression for a Gaussian beam over short propagation distances
- This result applies to both aberrated and unaberrated beams
- It demonstrates the power of the moment method and opens the door to calculation of higher-order moments
- Simulation validation with field tests is planned for this FY

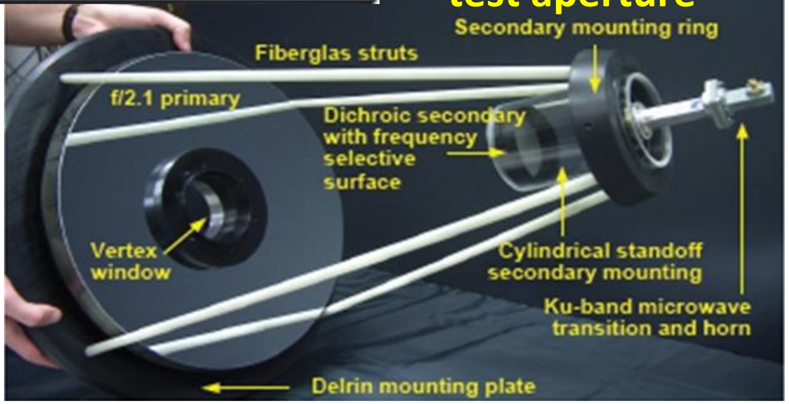
Dual-Band RF/Optical Terminal



Ka-band direct-feed horn with rexolite secondary blank ▼



RF/optical test aperture



Frequency selective convex ► secondary surface

System Optimization for Deep Space Missions

- System performance metric normalized to compare Ka-band and optical comms terminal designs on equal footing:

$$\boxed{FoM[dB] = 10\log\left(\frac{D^2 R_{Max}}{M P_T}\right)}$$

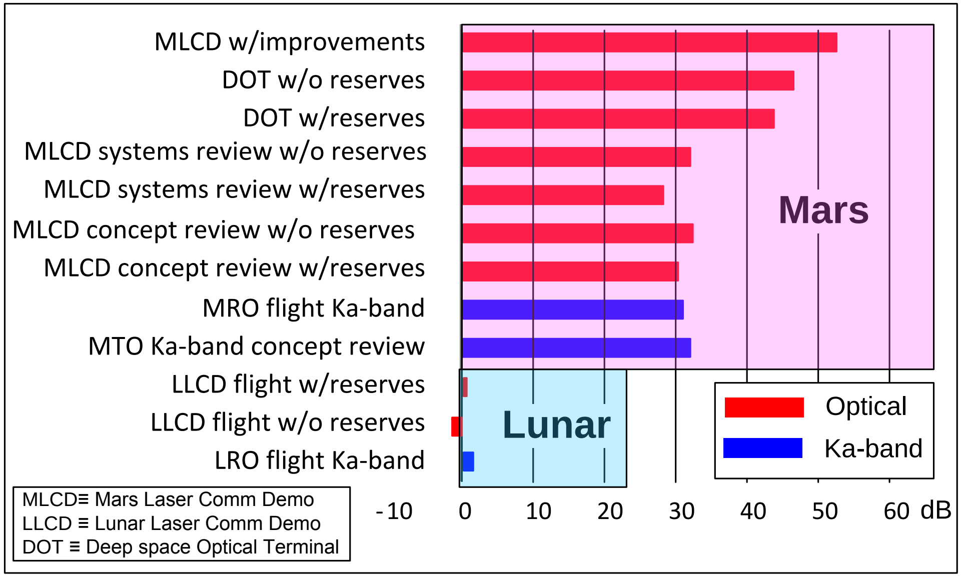
$D \equiv$ aperture [m]

$R_D \equiv$ maximum data rate [bps]

$M \equiv$ terminal mass [kg]

$P_T \equiv$ transmit power [W]

- Out to Mars optical comms can equal or exceed Ka-band performance only with additional improvements beyond SOTA in lasers and detectors
- Beyond Mars, Ka-band remains competitive because of more stringent pointing requirements on optical and need for larger apertures
- Both performance and SWaP must be optimized



MLCD≡ Mars Laser Comm Demo
LLCD ≡ Lunar Laser Comm Demo
DOT ≡ Deep space Optical Terminal

Summary

- **Traceable cost-benefit trades for integrated systems require comprehensive optimization methods**

- **Turbulence mitigation using beam homogenization and spectral diversity may be competitive with adaptive optics to minimize losses, but require integrated photonics**

- **Common aperture optical link gains entail extra cost due to tighter pointing requirements**

- **Lightweight material effects on alignment, solar loading, and vibration compensation are critical**

- **Complex link management is necessary to optimally allocate data rates between bands**

- **Dual-band operation should be synergistic wrt atmospheric losses, but increased laser power, efficiency, and reliability are needed to permit *scalable* designs for a range of missions**

Citations

- **C.L. Edwards, J.R. Bruzzi , and B.G. Boone, "Free-space high data rate communications technologies for near terrestrial space," Proc. SPIE Vol. 7091, Free-Space Laser Communications VIII, 10 - 14 August 2008, San Diego, California**
- **K.B. Fielhauer, B.G. Boone, and D.E. Raible, "Concurrent System Engineering and Risk Reduction for Dual-Band (RF/Optical) Spacecraft Communications," IEEE Aerospace Conference. March 2012**
- **J.R. Bruzzi, and B.G. Boone, "Dual Band Radio Frequency (RF) and Optical Communications Antenna and Terminal Design Methodology and Implementation," U.S. Patent Application JHU/APL File # 2241-SPL, 26 October 2007**
- **B.G. Boone, "Large Aperture Ultralightweight Hybrid Inflatable Telescope," JHU/APL Invention Disclosure, 2 April 2010**