# Beaming Bandwidth via Laser Communications

**M. Kavehrad, B. Hamzeh**

The Pennsylvania State University,
Department of Electrical Engineering,
Center for Information & Communications Technology Research (CICTR)
University Park, PA 16802
Phone: (814) 865-7179
E-mail: mkavehrad@psu.edu

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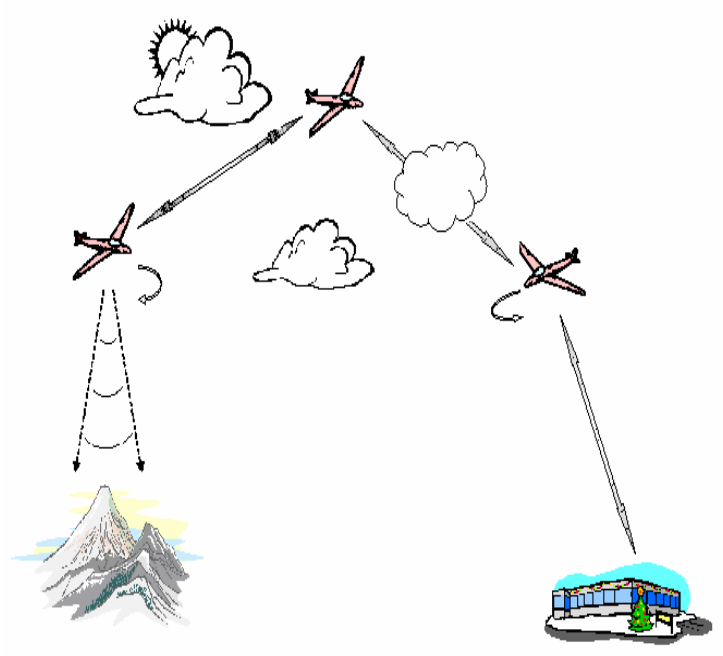
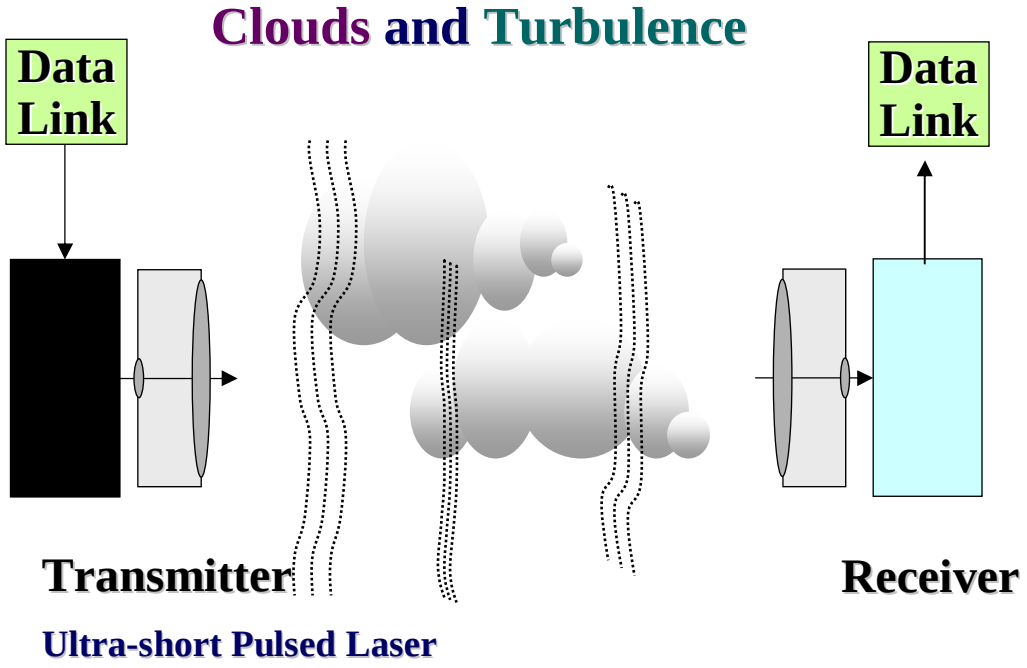
# Objectives

Investigate and demonstrate an Air-to-Air-to-Ground hybrid RF/FSO System, promising a broadband *"See Thru Clouds"*, using ultra-short-pulsed laser link with time/frequency diversity provided by "Fractal Wavelet Modulation" to increase the hybrid link availability and average data rate.





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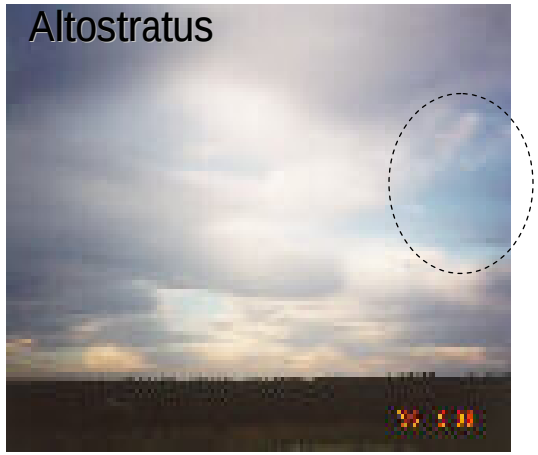
# Typical Clouds

ORCLE

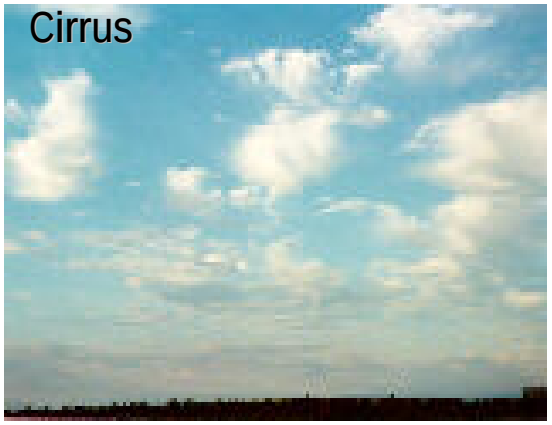
**Clouds → Dispersion (Multi-scattering)**

**Turbulence → Scintillation Fade (Single-scattering)**

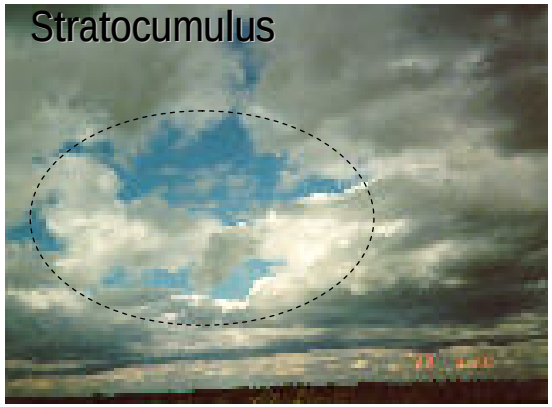
**Middle (2-7 km):**




**High (> 7 km):**




**Low (< 2 km):**



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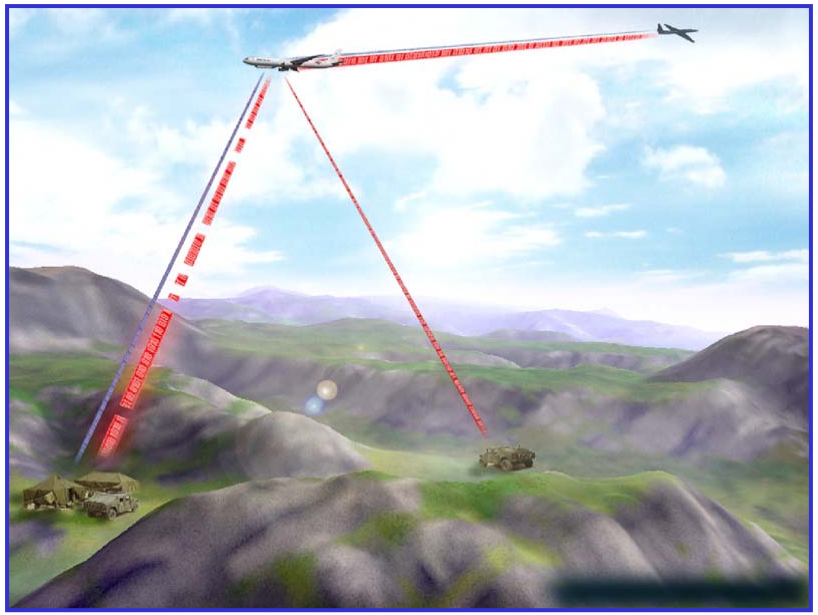
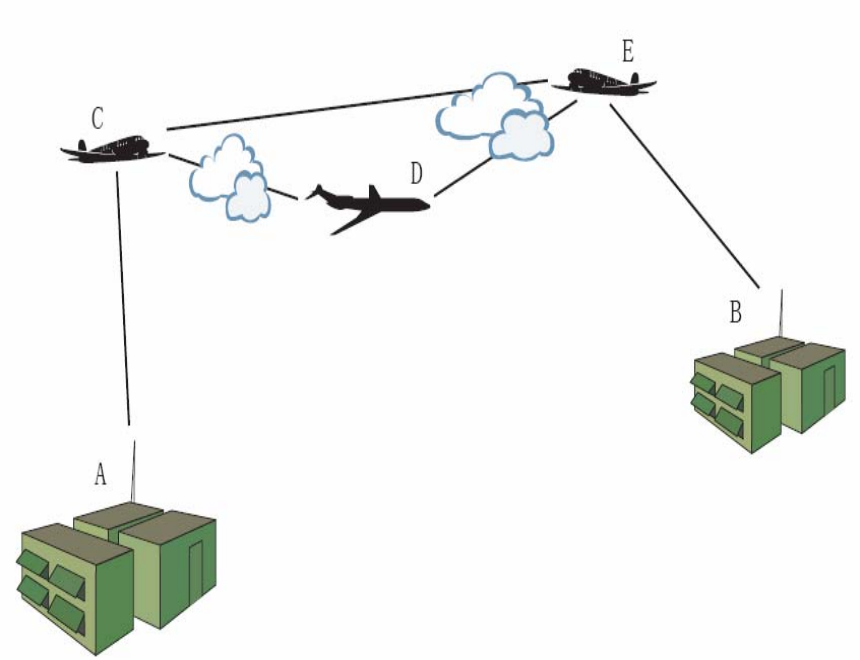
# Anti-correlation under Adverse Weather






| | Cloud/Fog | Rain |
|---|---|---|
| **FSO** | **Severe Attenuation** | **Slight Attenuation** |
| **RF** | **Slight Attenuation** | **High Attenuation** |


• **M. Kavehrad, " A New Diversity Technique for Interference-Limited Microwave Digital Radios," Canadian Conf. on Elect. and Computer Engineering, Ottawa, Ontario, September 1990.**

# Hybrid Radio Experimental Setup

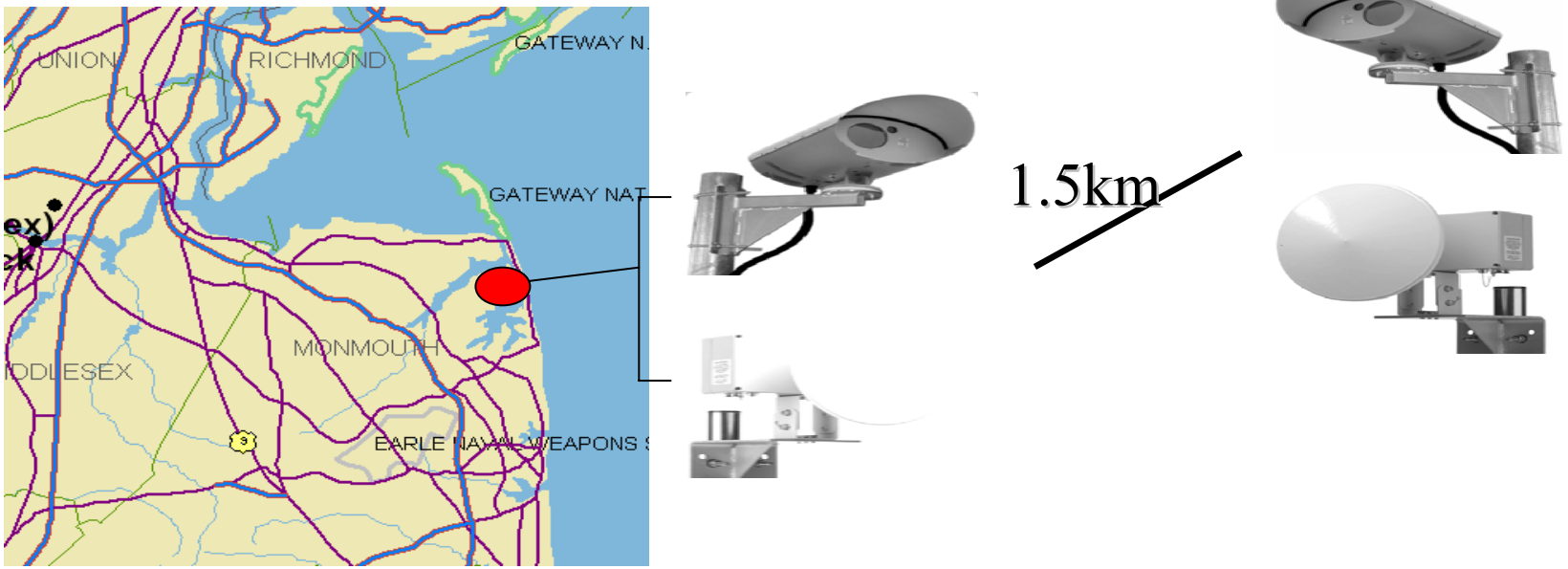
– **Full-Duplex Radios:**

**38 GHz: 16QAM OC-3 (155Mbps)**

**60 GHz: ASK Fast Ethernet (~100Mbps)**

**TeraBeam FSO: ASK Fast Ethernet (~100Mbps) or OC-3 (155Mbps)**

- **Only Received Signal Strength Levels were measured, hence, only "SNR Outage Probability" could be evaluated.**





- **H. Wu, B. Hamzeh, M. Kavehrad, "Achieving Carrier Class Availability of FSO Links via Complementary RF Links," Proceedings of the 38th Asilomar Conference on Signals, Systems & Computers, Monterey-California, November 2004.**

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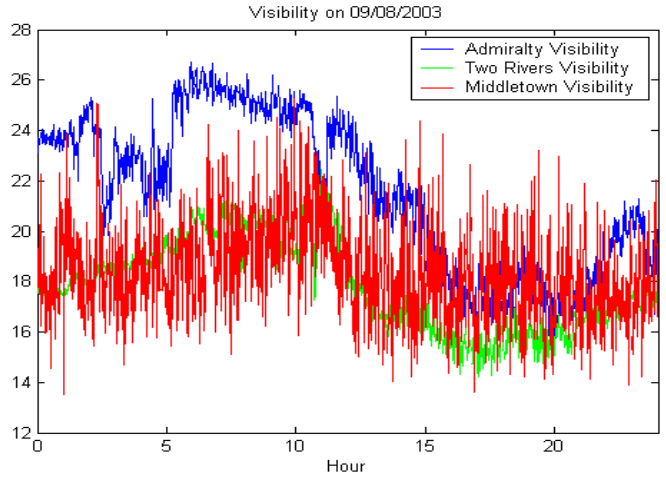
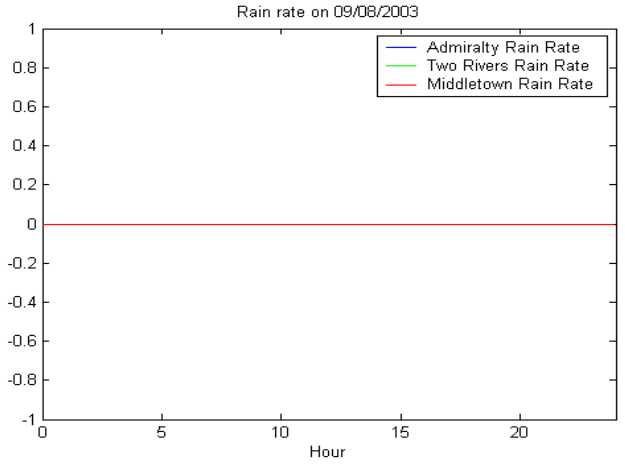
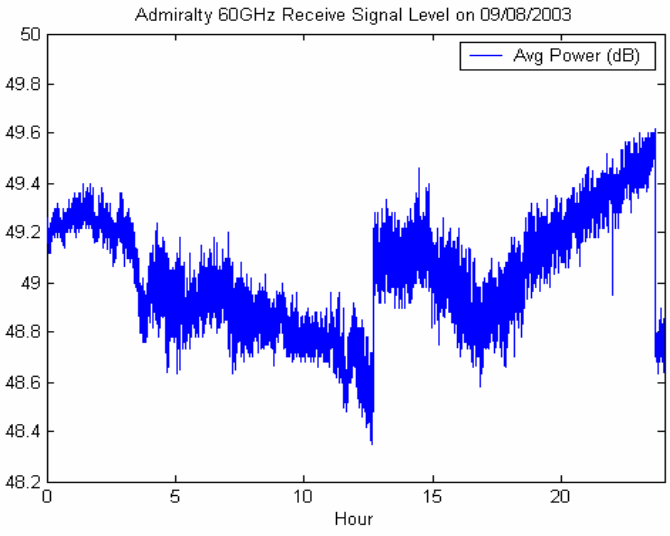
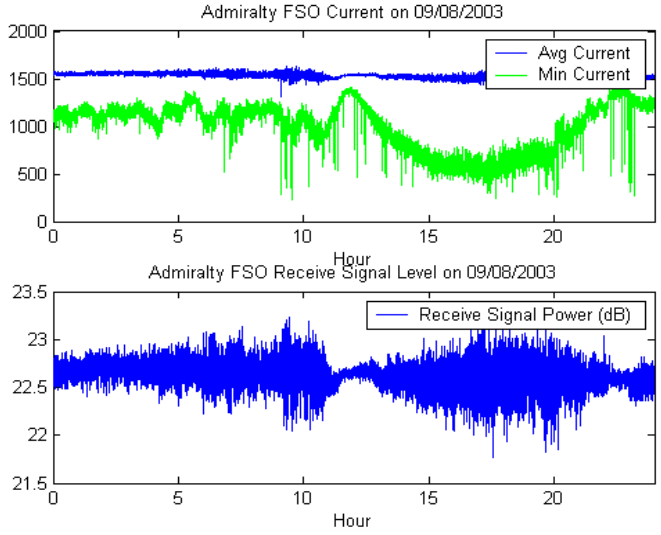
# Hybrid FSO/RF (Clear Weather)

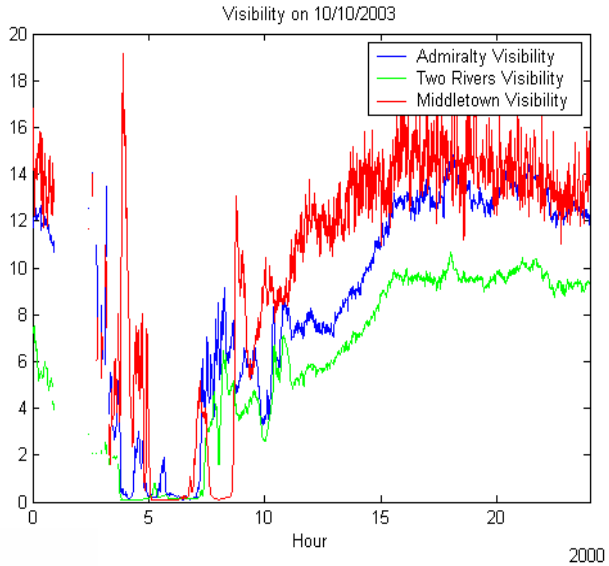


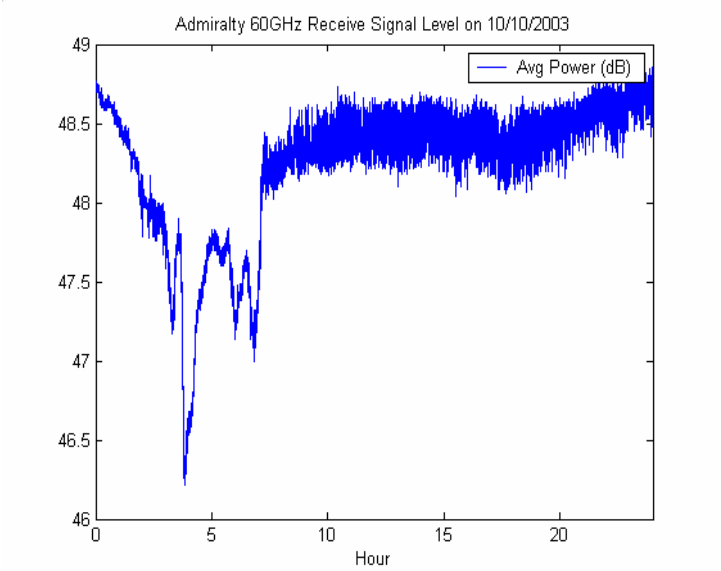



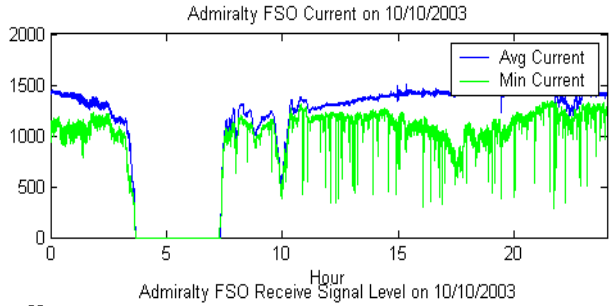



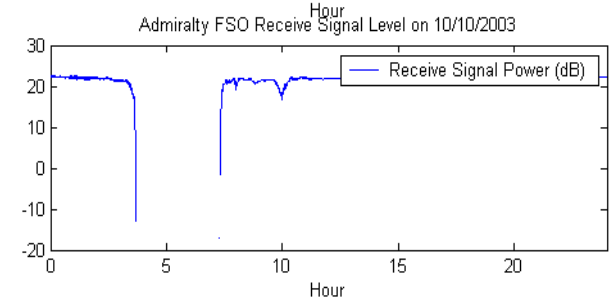



# Hybrid FSO/RF (Foggy Weather)

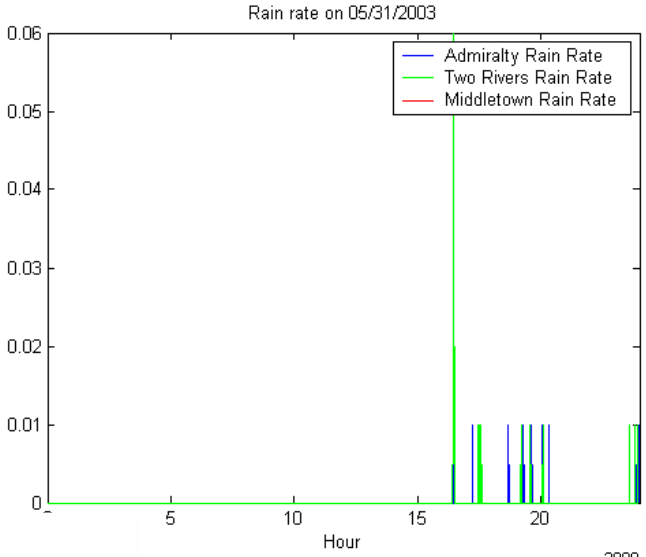


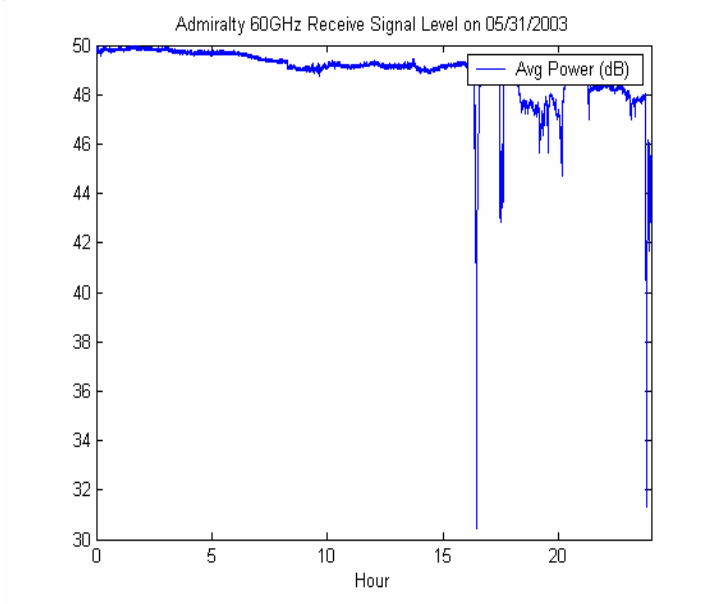



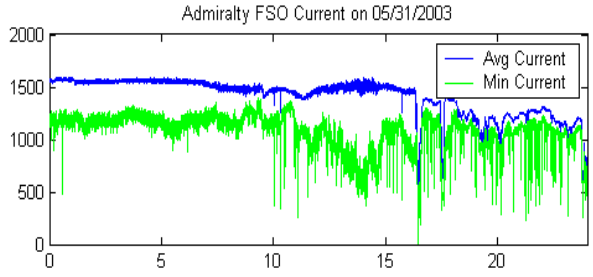



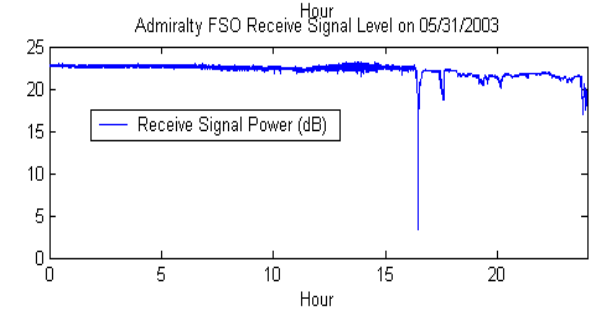



# Hybrid FSO/RF (Rainy Weather)



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# Availability of ORCLE Airborne Hybrid Link


- Tools developed, to define availability of ORCLE hybrid links. In doing this, NASA ISCCP cloud models were incorporated.

- "Capacity availability probability" was used in order to incorporate thru clouds temporal and spatial dispersion effects.

- RF frequency in the KU Band and FSO wavelength at 1550 nm.

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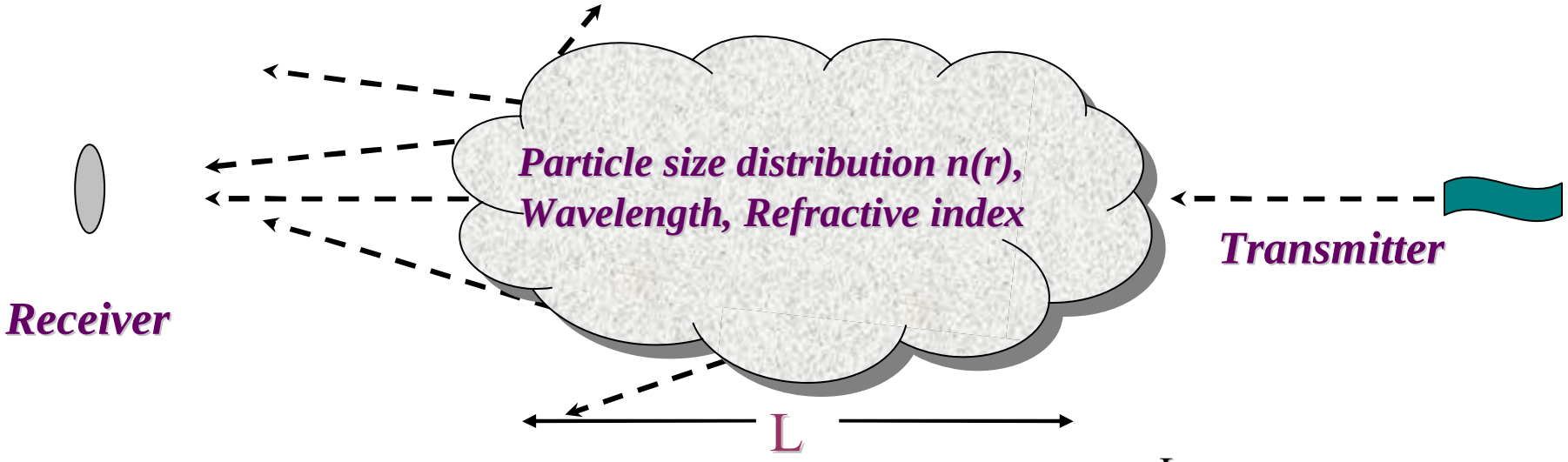
# Clouds Multi-scattering Modeling

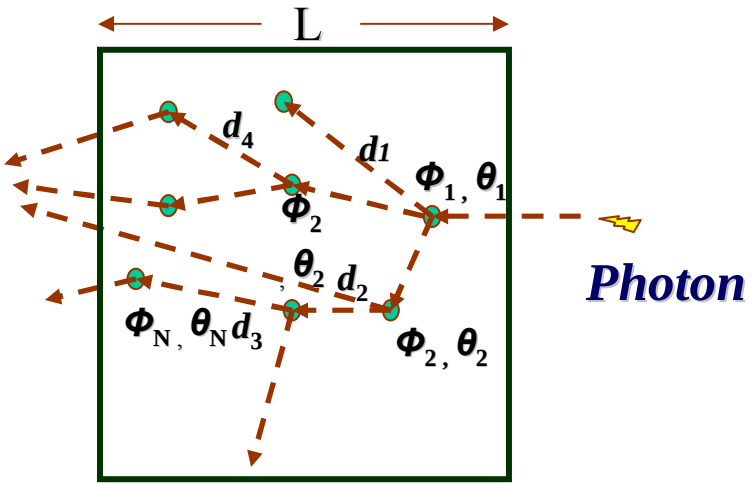

***Model uses Mie Theory***




- Thru Cloud Channel is characterized by:

**Optical Thickness; $\tau = L / d_{AVG}$**

- Φ defines the rotation angle of the scattering plane about the incident plane and θ is the angle between the incident ray and the scattered ray.




***Dispersive Clouds***

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# Experimental Observations


- **Obtained data from the International Satellite Cloud Climatology Project (ISCCP), which focuses on the distribution and variation of cloud radiative properties.**

- We chose part of the investigation that covered the State of Pennsylvania over a 2 year span, starting Jan. 1999, ending Jan. 2001.

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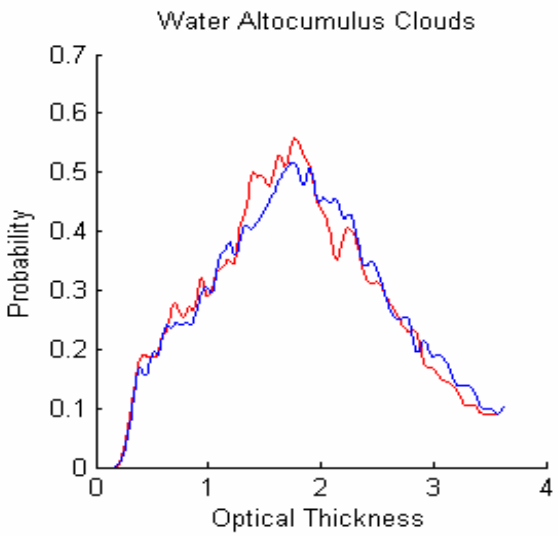
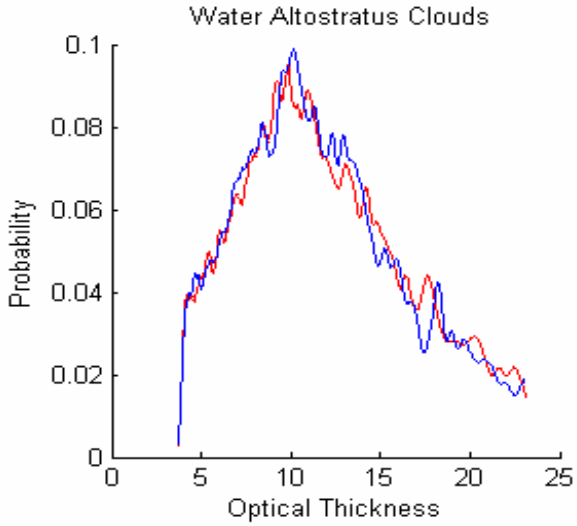
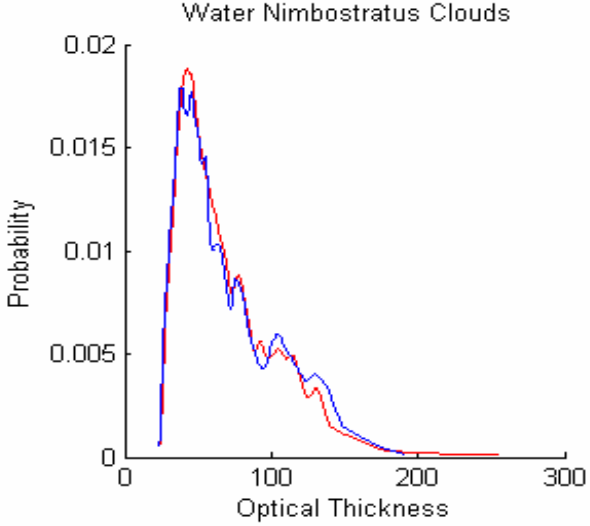
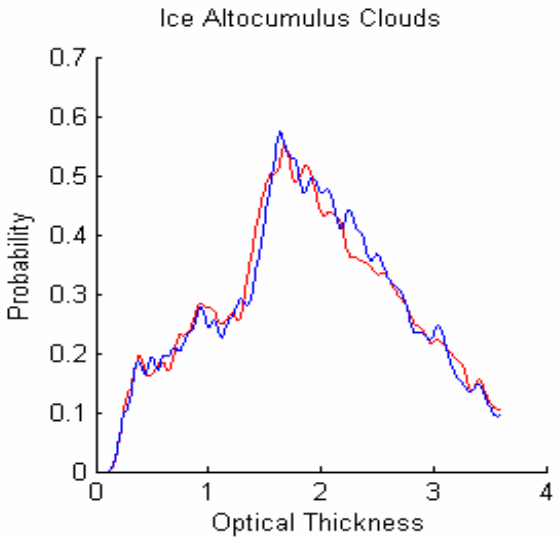
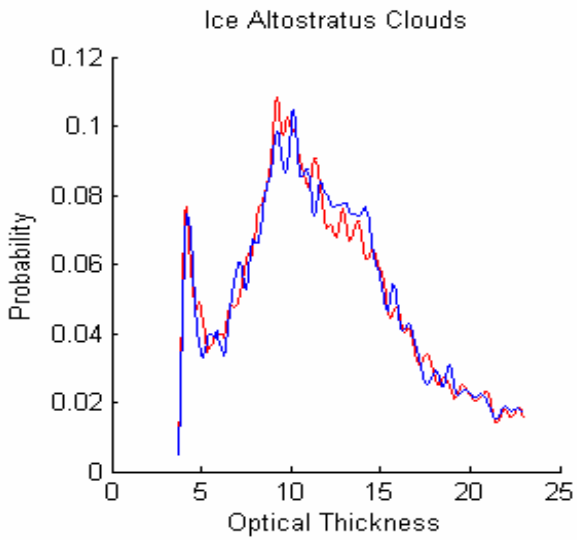
# Mid Altitude Clouds - - Vertical Communications

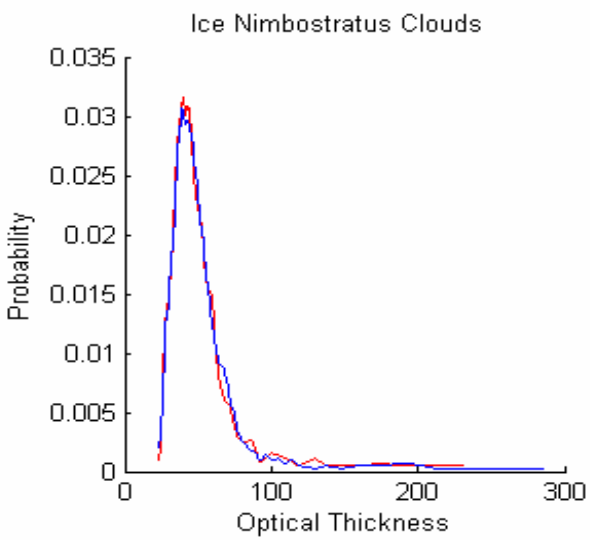


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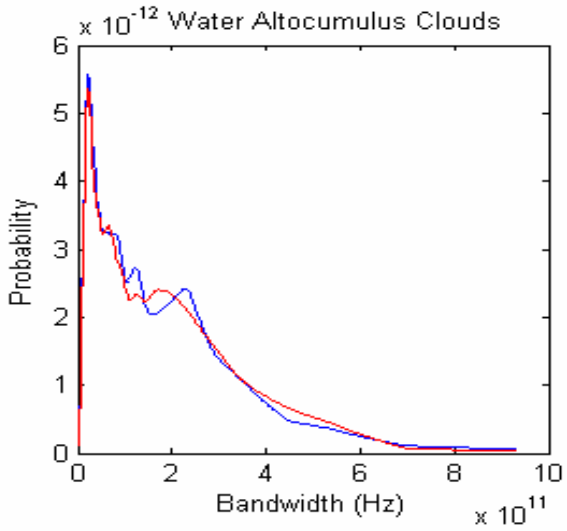
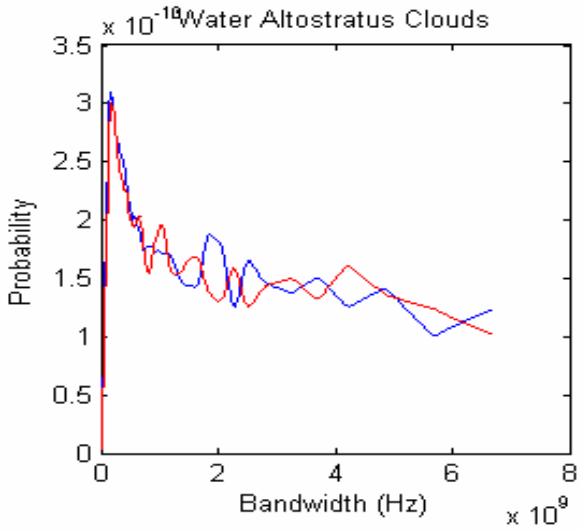
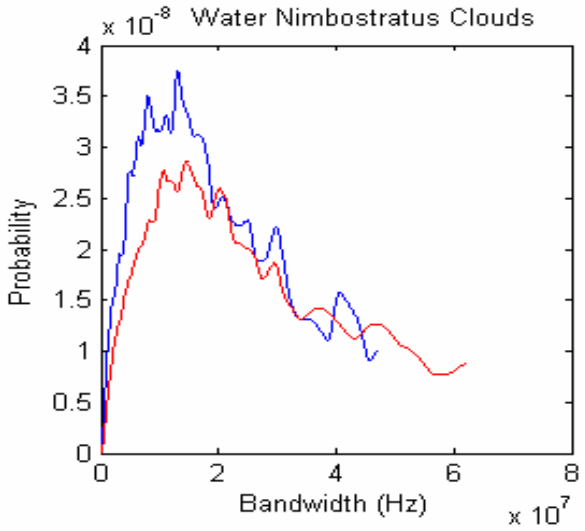
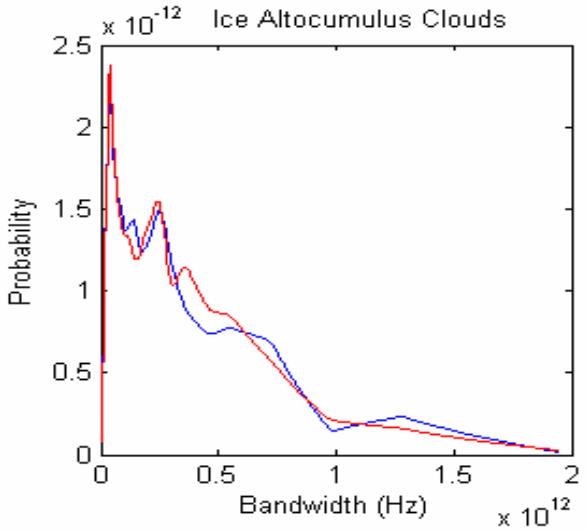
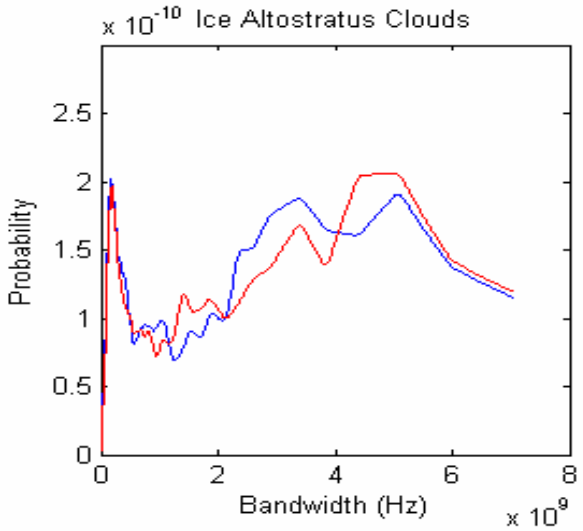
# Mid Altitude Clouds - - Vertical Communications

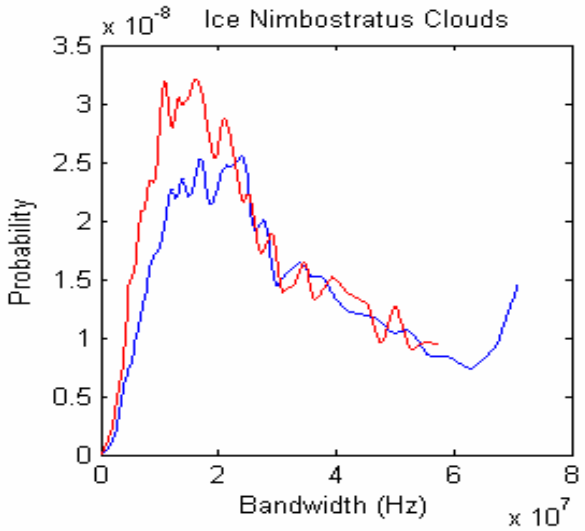


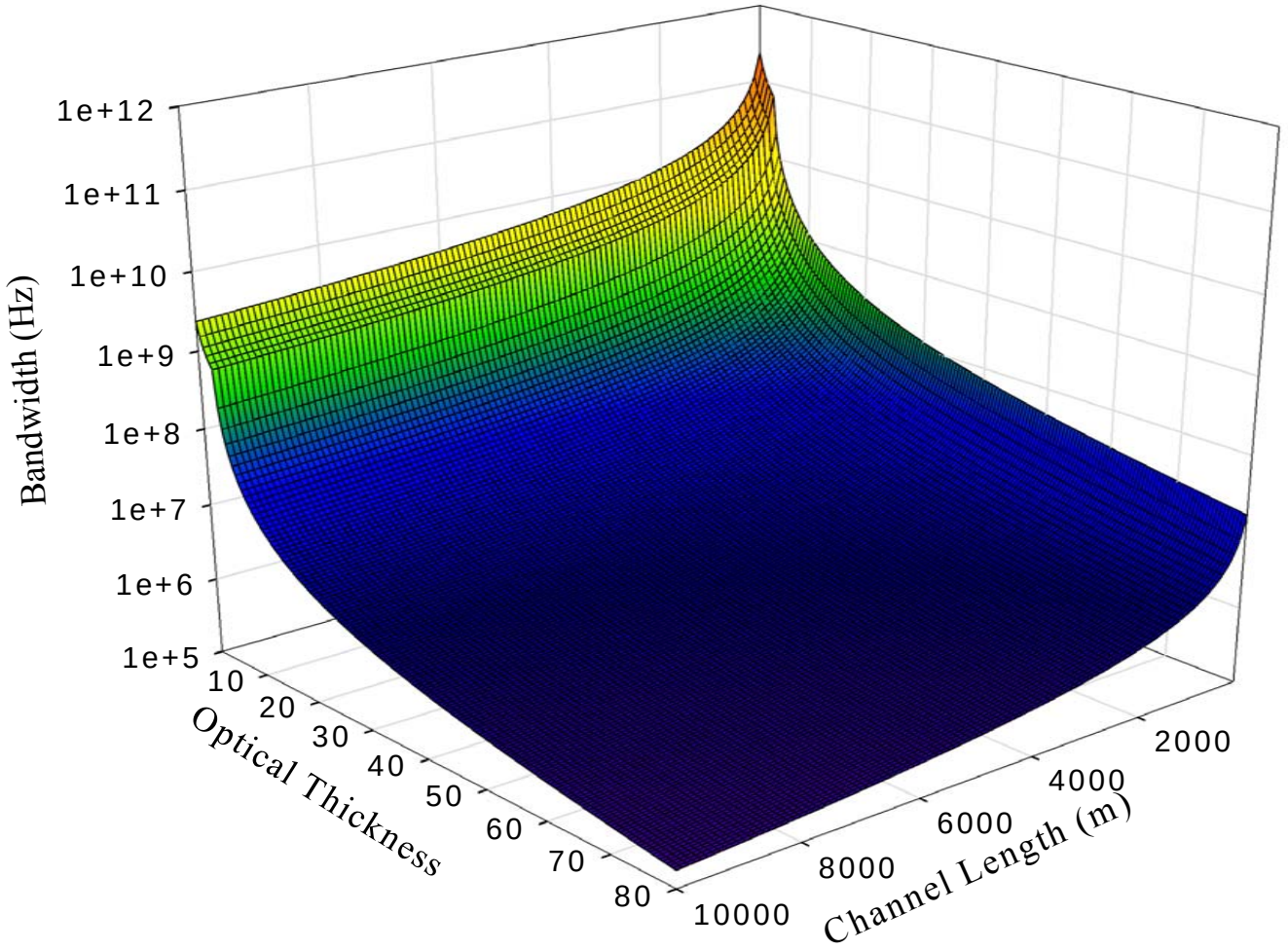



# Available Bandwidth




**B. Hamzeh and M. Kavehrad, "Characterization of Cloud Obscured Free Space Optical Channels," The 9th World Multi-Conference on Systemics, Cybernetics and Informatics , Orlando, Florida, July 2005.**

# Scintillation by Turbulence (Fading) Model


- Most popular model for scintillation effects is Hufnagel-Valley model, due to its simplicity. Refractive index structure coefficient:

$$C_n^2(h) = 8.2\times10^{-26} W^2 h^{10} e^{-h} + 2.7\times10^{-16} e^{-h/1.5} + A e^{-10h}$$

h: Altitude in km

W: Wind speed in m/s

A: $C_n^2(0)$ at earth surface

– Multiplicative lognormal flat fading effect is given by:

$$\alpha = exp(\, 2\sigma_x x \,)$$

where x is a Gaussian random variable with zero-mean and unit variance:

$$\sigma_x^2 = .56\, k^{7/6} \int_o^L C_n^2(\, z \,).z^{\frac{5}{6}} .dz$$

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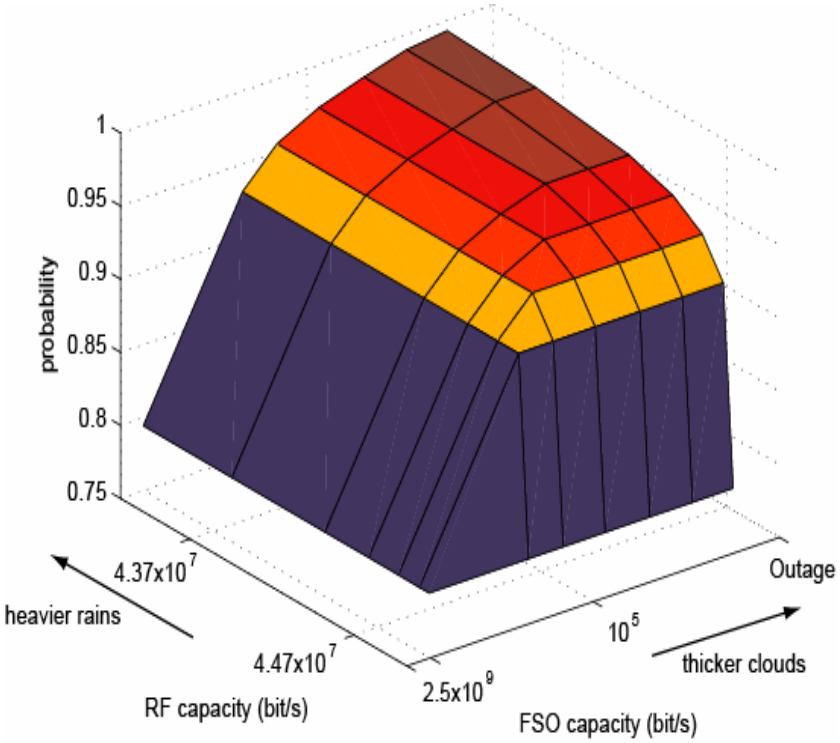
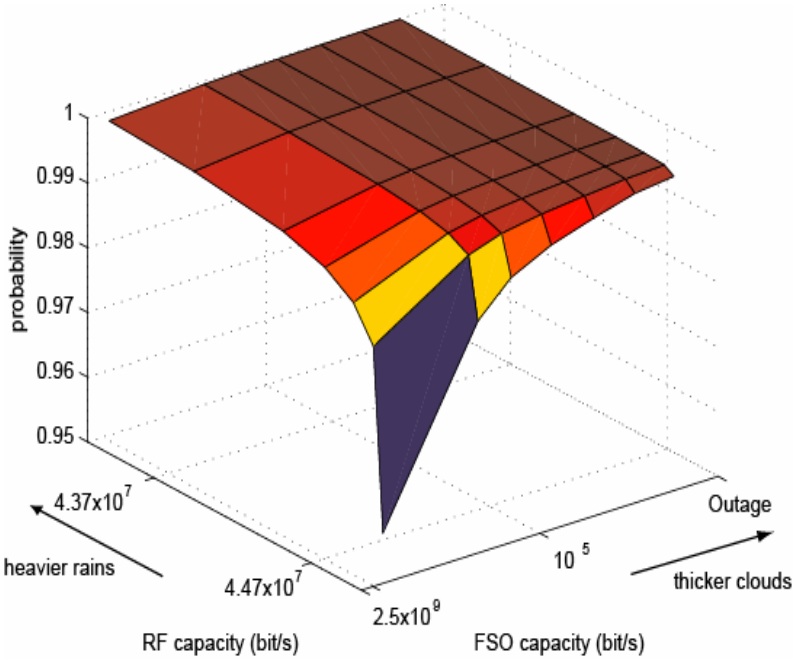
# ORCLE Airborne Hybrid Link Capacity Availability Model

**The assumption of perfect dependence implies thick clouds generally accompany heavy rains.**




***Perfect dependence***

**The perfect independence assumption assumes that when it rains heavily, the chance of having any form of cloud is the same as when it does not rain.**
**It does provide us with another bound that defines outage probability.**




***Perfect independence***

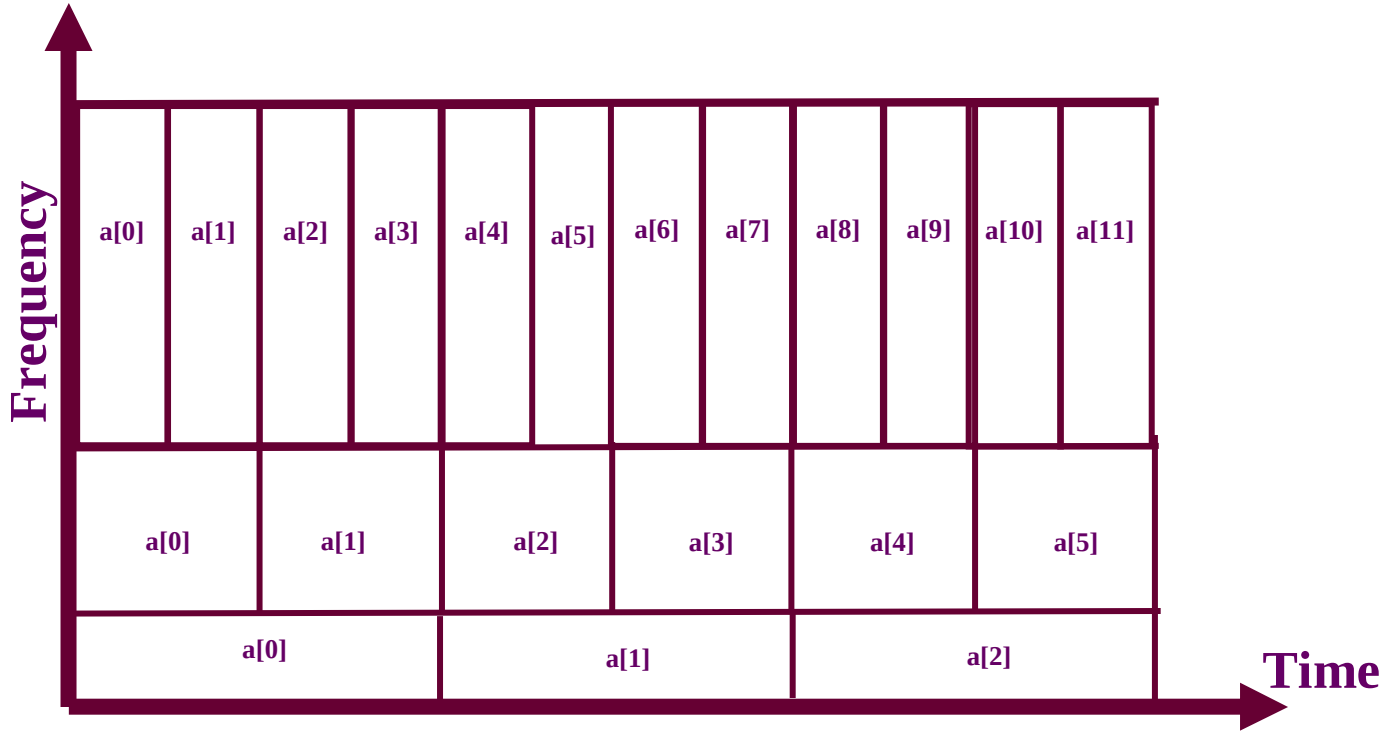
**A Hybrid RF/FSO Link has a Higher Availability than an FSO Link, stand-alone.**

**H. Wu, B. Hamzeh and M. Kavehrad, "Availability of Airborne Hybrid FSO/RF Links," SPIE Defense and Security Symposium, Orlando, Florida, March 28-April 1, 2005.**

# Increased FSO Link Availability using Fractal Wavelet Modulation on Ultra-short Laser Pulses



- Redundant copies of transmitted data are provided across the time-frequency plane.
- Multi-rate diversity gain is achieved.



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# Ultra-short Pulse Laser Technology


- Ultra-fast switching times and ultra-high transmit powers enable communication capabilities that far exceed anything available today.

- A 30 micron long 100 fs pulse at 100 mJ would produce an average power of 1 Terawatt.

- Research into high speed ultra-short pulsed lasers and their interaction with matter indicate there may be opportunities using extremely short pulse-shaped techniques to condition the molecular interactions in order to reduce absorption. Reduced loss of laser energy due to atmospheric attenuators would be a vital element in the expansion of FSO based communications.

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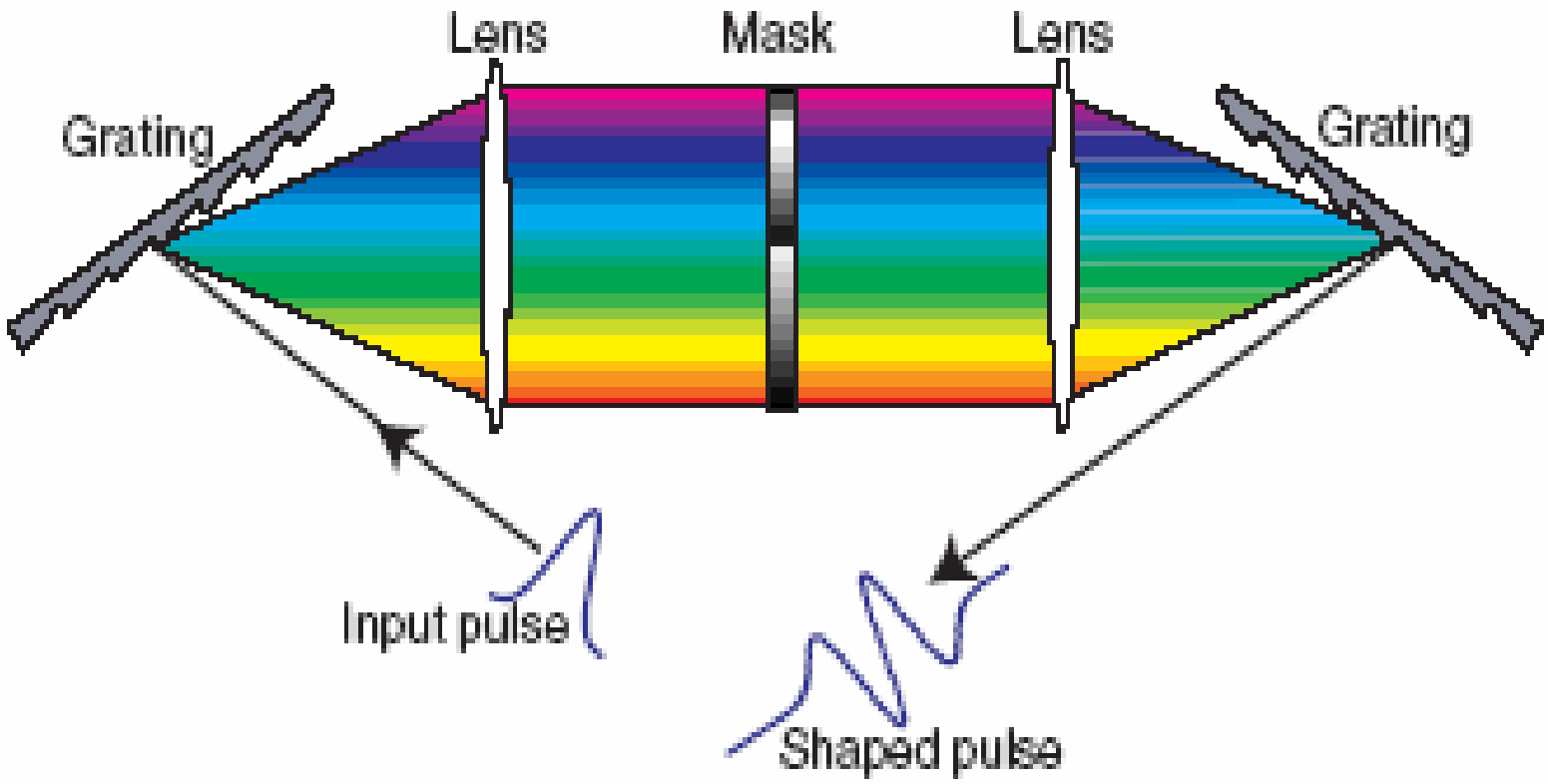
# Spectral Encoding Wavelet Generator



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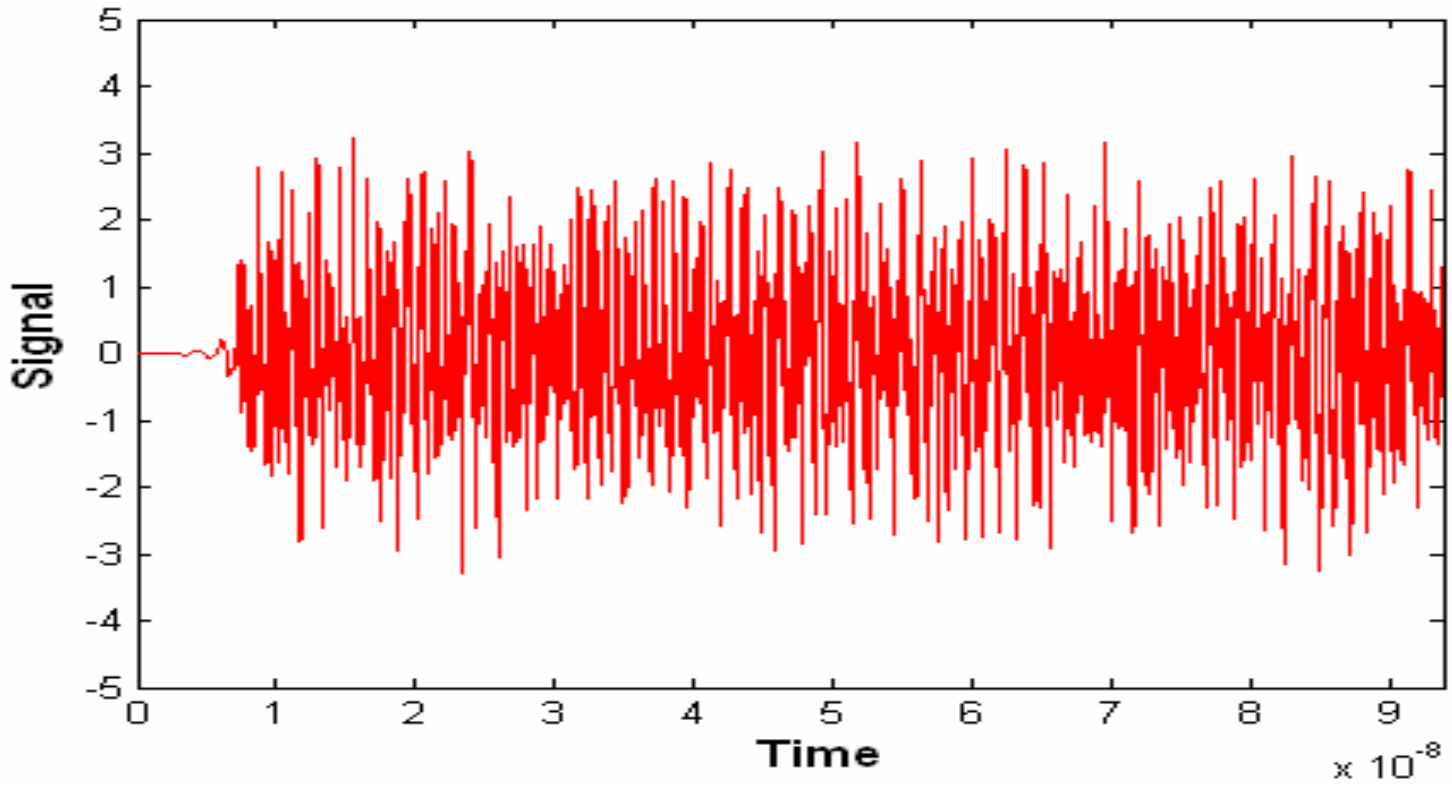
# Wavelet Modulation

- Signal starts to look like a random noise (enhanced security).
- Can get closer to Shannon Limit.



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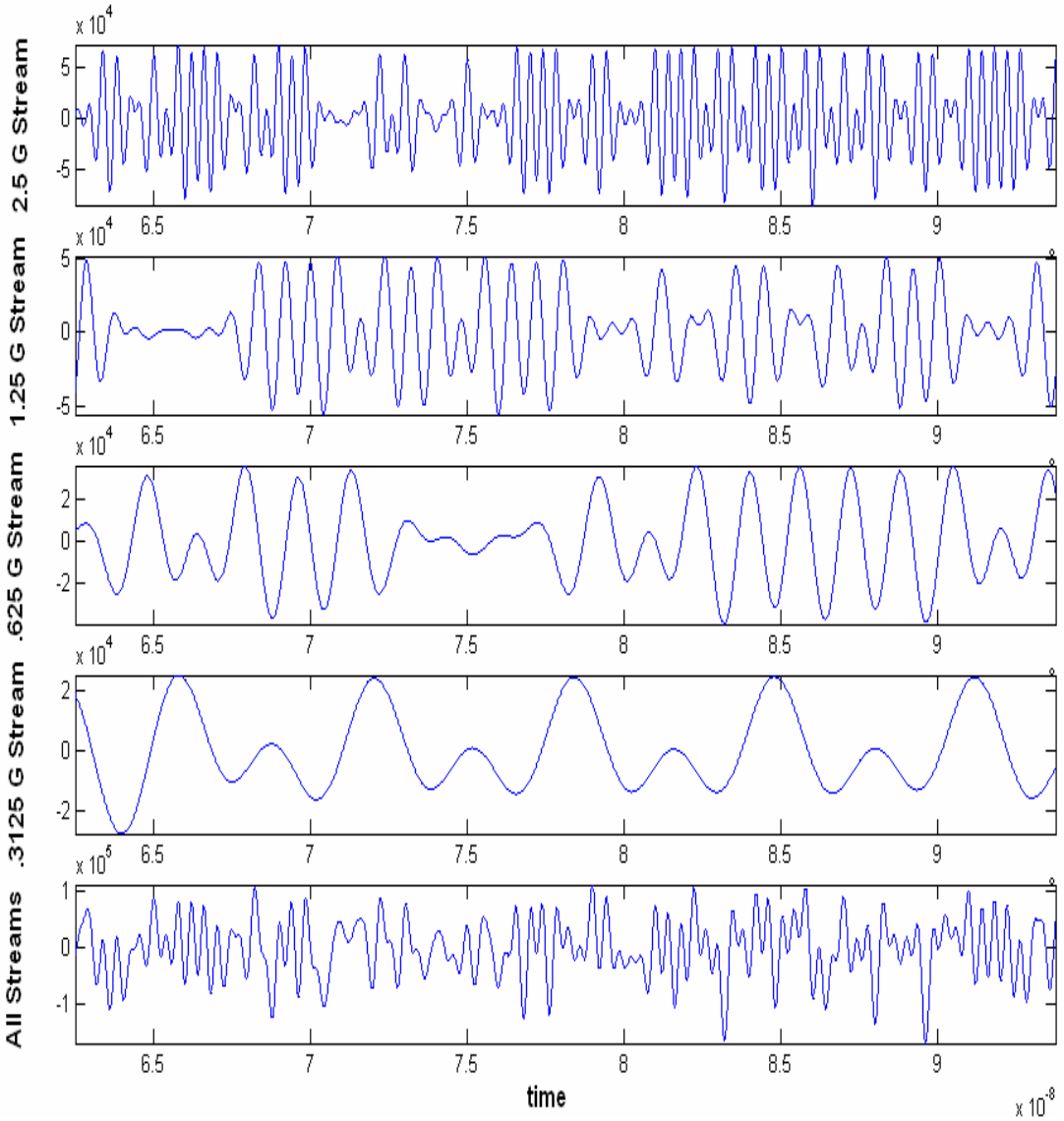
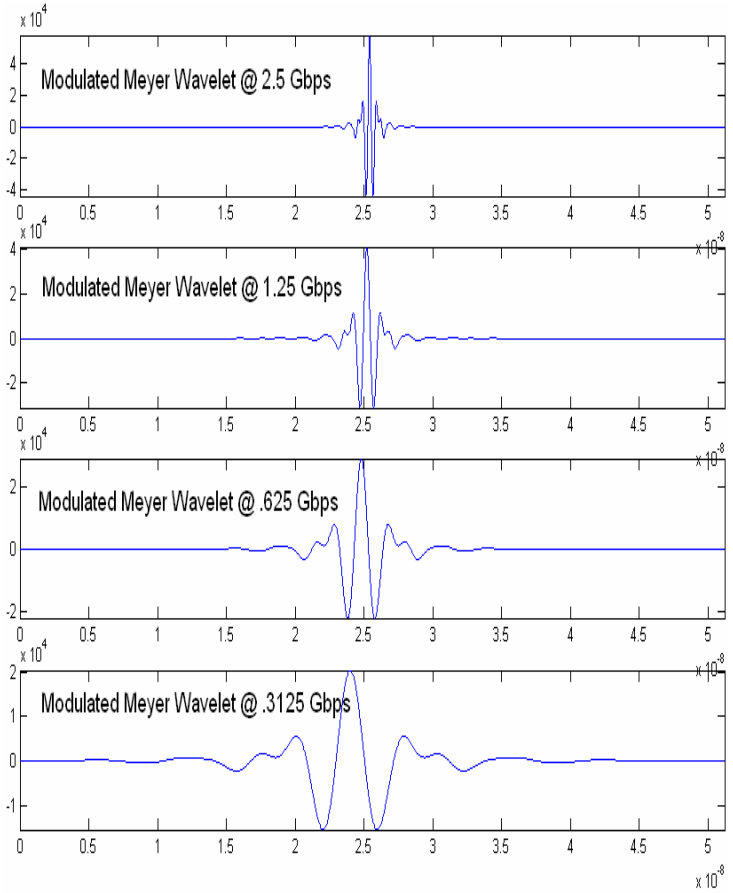
# Modulated Meyer's Wavelets



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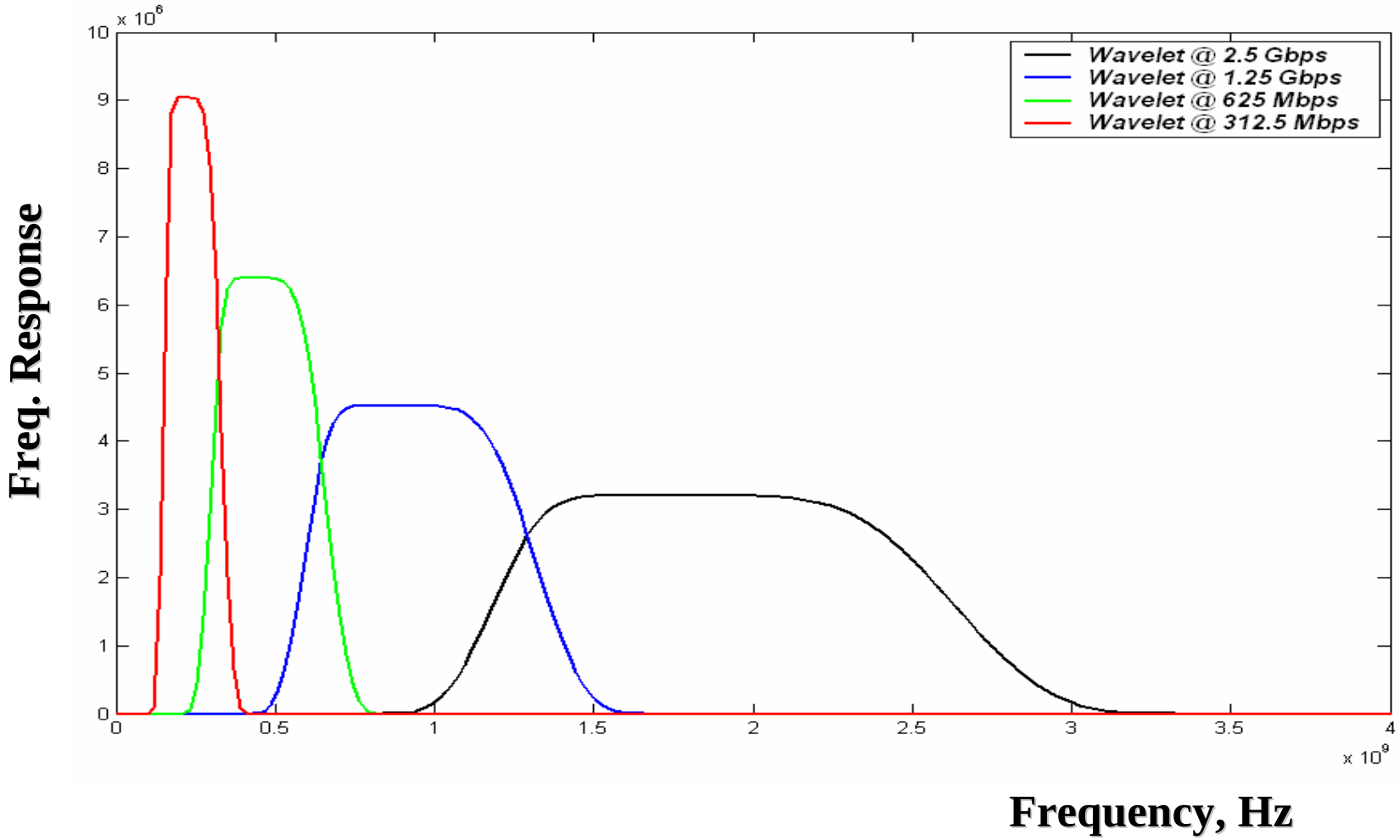
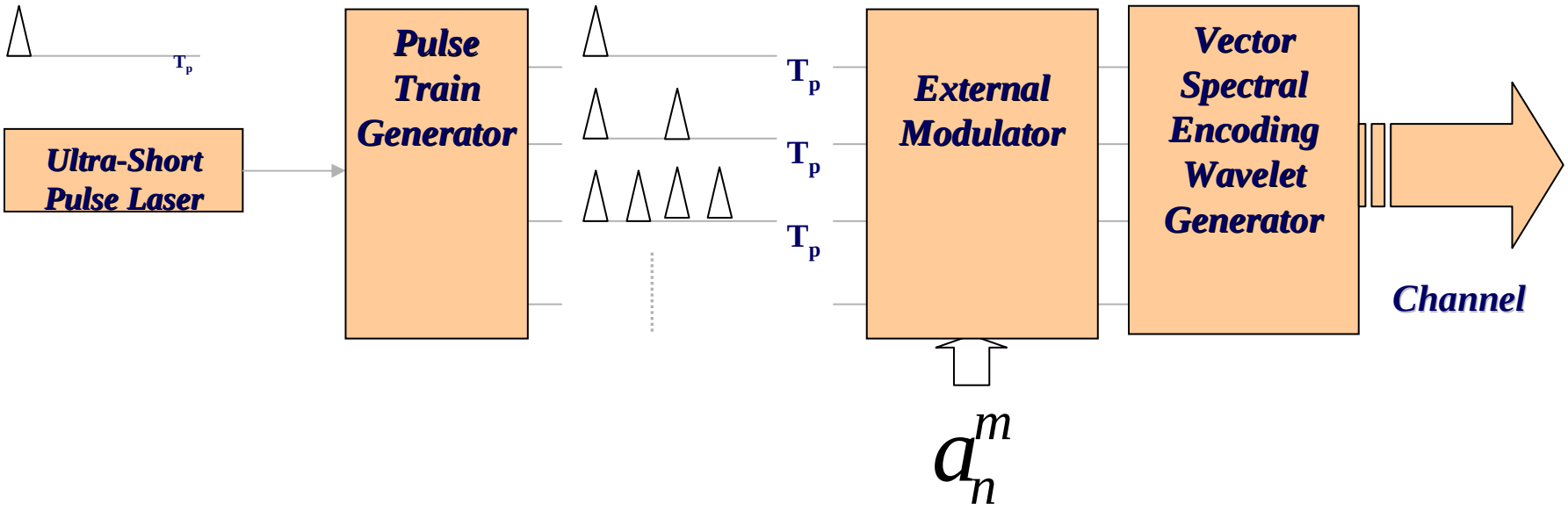
# Meyer's Wavelets



# High-Power Transmitter Design

## *Ultra-Short Pulsed FSO Transmitter*




***Required light pulse duration ~ 100 Femtosecond***

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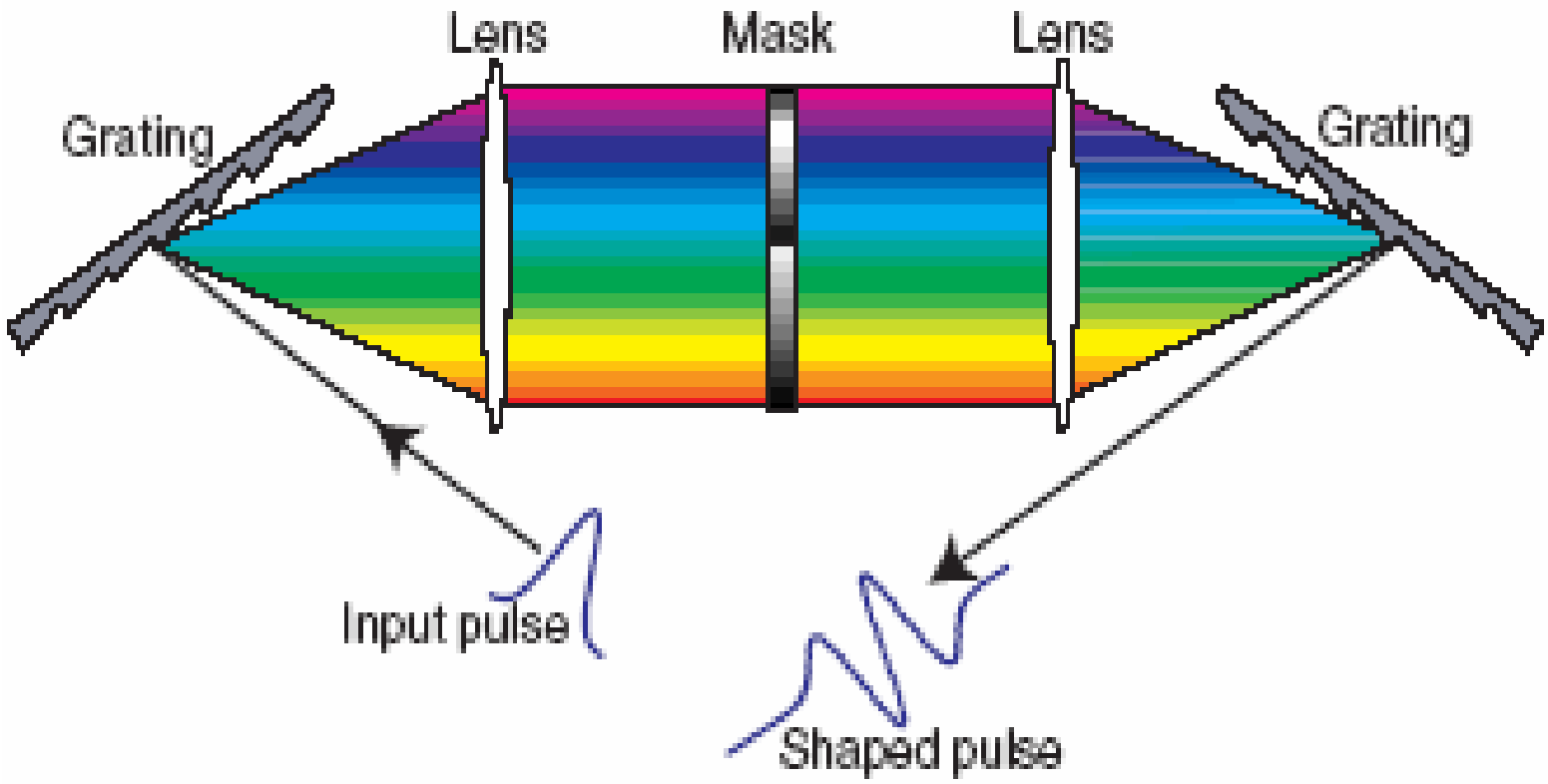
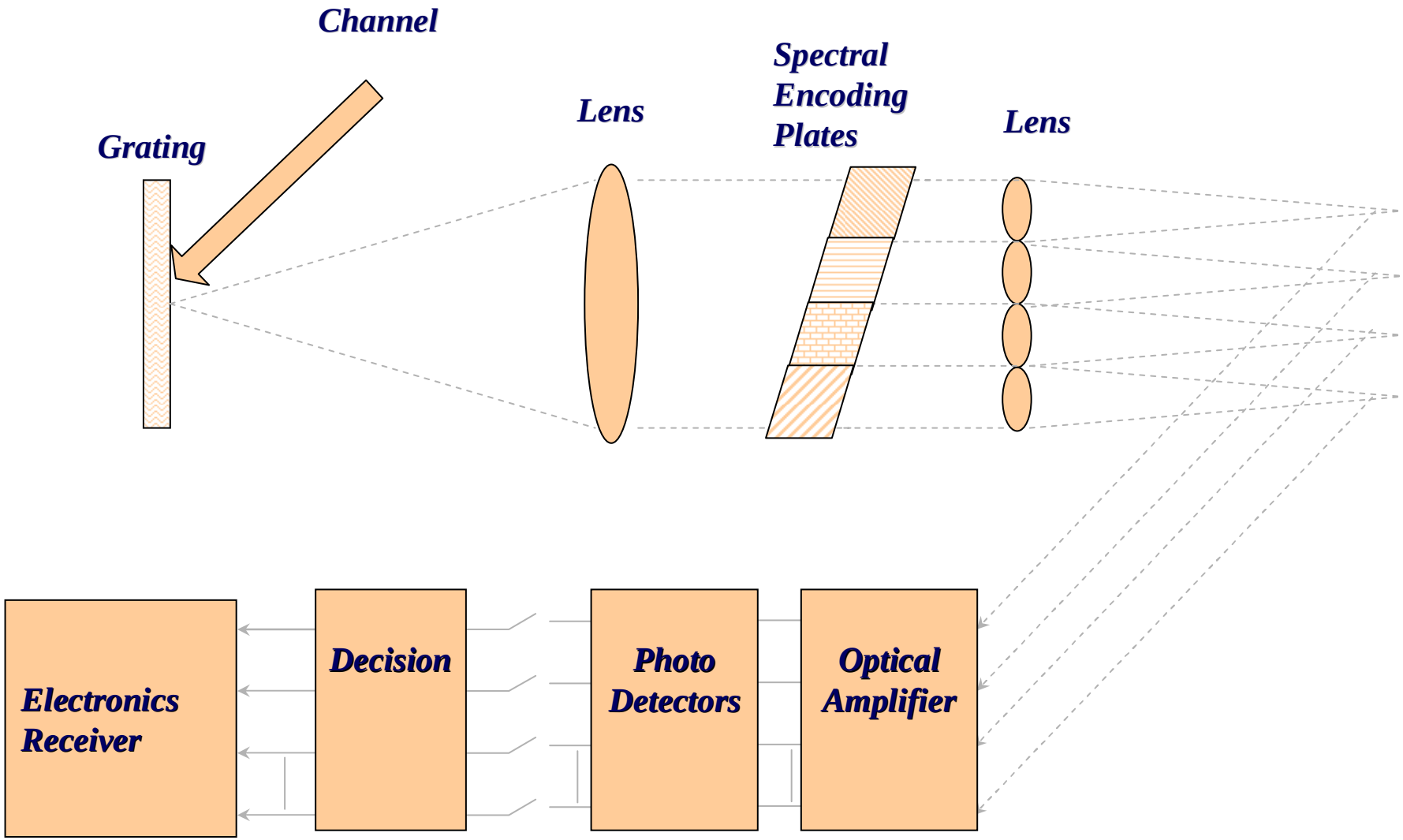
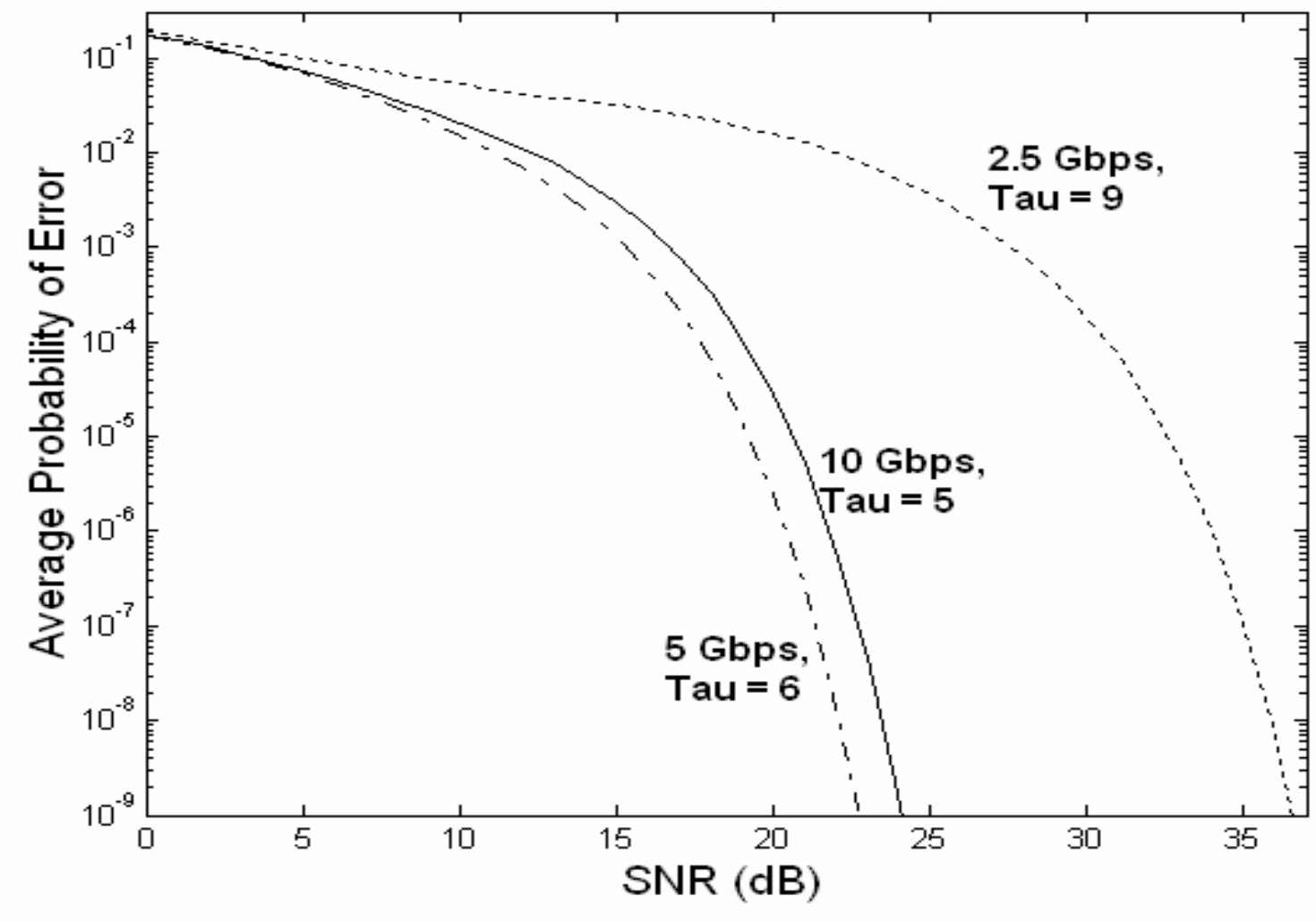
# Spectral Encoding Wavelet Generator



# Opto / Electronic Receiver Design



# FSO Fractal Transmission Link Performance




**M. Kavehrad, B. Hamzeh "Laser Communication System Using Wavelet-Based Multi-Rate Signaling," Proceedings of IEEE MILCOM, Monterey-California, November 2004.**

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# Summary


## ➢ Goal:

**Increased FSO link availability via feed-forward "opportunistic" transmission.**

## ➢ Methodology:

**Multi-rate communication via "Fractal Modulation" using wavelets, and using ultra-short pulsed lasers.**

## ➢ Outcome:

**Overall system design and evaluation, with improved performance.**