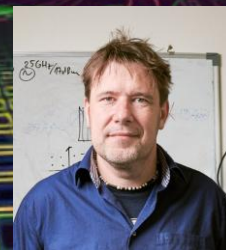


# Free Space Optical Communications – Part II – FOG

**Prof. Zabih (Fary) Ghassemlooy**  
*Optical Communications Research Group*  
*Faculty of Engineering and Environment*  
*Northumbria University, Newcastle upon*  
*Tyne, UK*  
[z.ghassemlooy@northumbria.ac.uk](mailto:z.ghassemlooy@northumbria.ac.uk)



**Prof. Stanislav Zvanovec**  
*Wireless and Fiber Optics Team*  
*Czech Technical University in Prague*  
*Czech republic*  
[xzvanove@fel.cvut.cz](mailto:xzvanove@fel.cvut.cz)



**Dr. Ali Khalighi**  
*Ecole Centrale*  
*Méditerranée, Fresnel*  
*Institute research lab,*  
*Marseille, France*  
[Ali.Khalighi@fresnel.fr](mailto:Ali.Khalighi@fresnel.fr)



# FSO - Challenges

- Terrestrial
  - Introduction
  - Channel effects
  - Atmospheric conditions
    - Rain
    - Sandstorm
    - Smoke
    - Fog

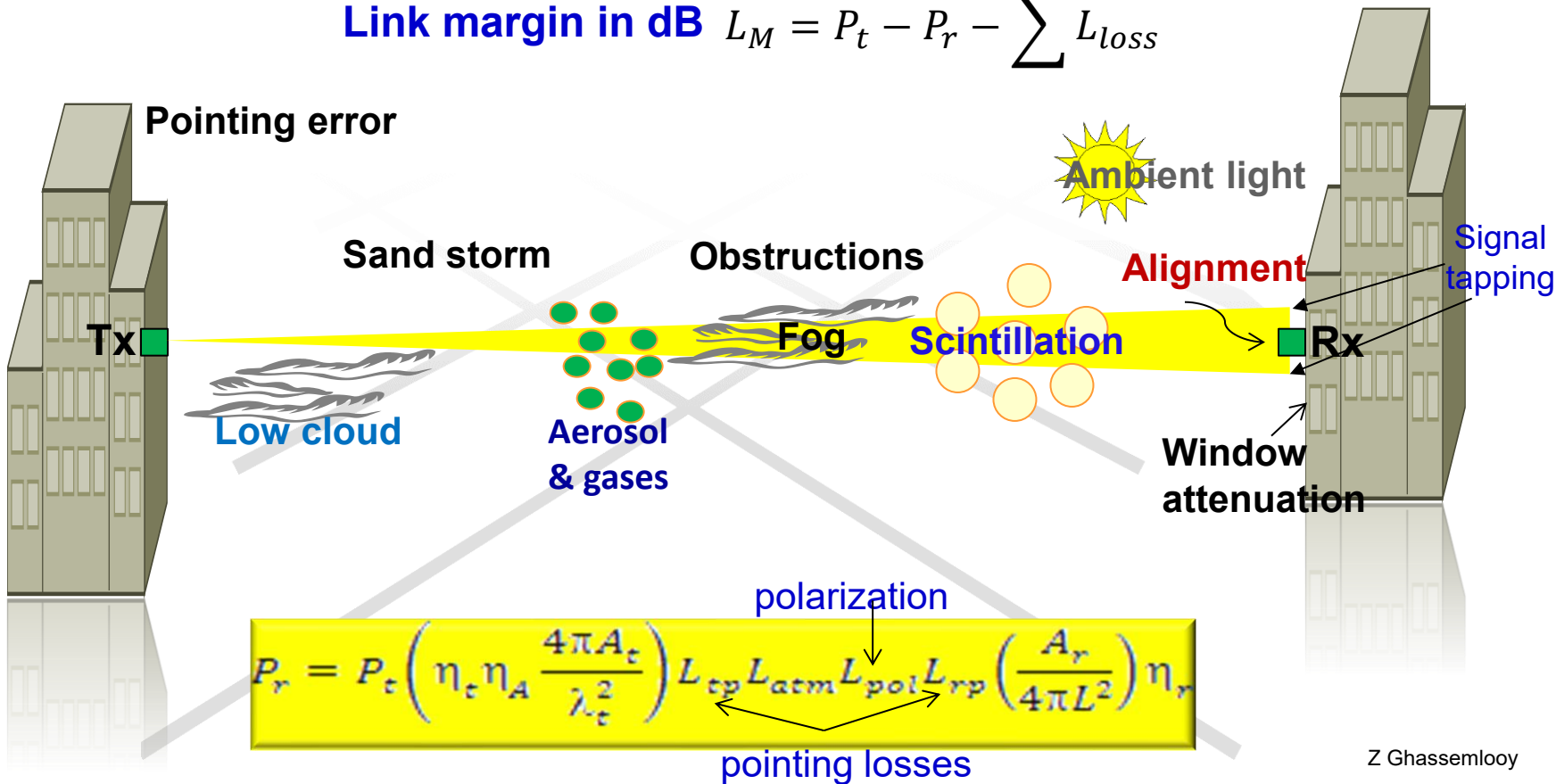
<https://www.mathworks.com/help/radar/ug/modeling-the-propagation-of-rf-signals.html>

# FSO - Challenges

Channel behaves like a time varying attenuator:

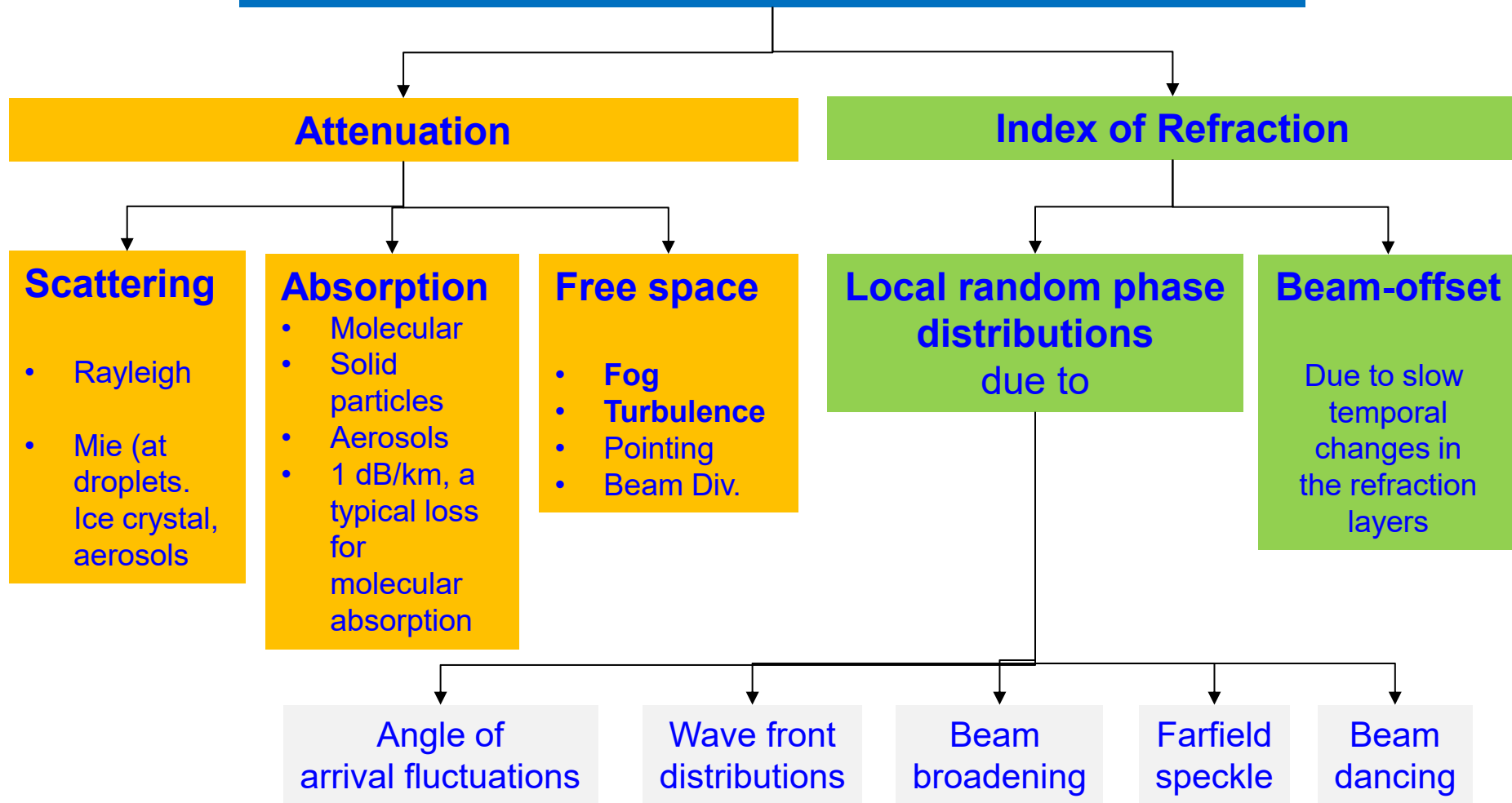
- Attenuation: Fixed geometric spreading + Atmospheric attenuation
- Noise

Link margin in dB  $L_M = P_t - P_r - \sum L_{loss}$



# FSO – Channel Effects

## Effect of Atmosphere on the Propagating Optical Beam



# FSO – Atmospheric Attenuation

$$\frac{P_r}{P_t} = \exp[-\gamma_t(\lambda)L]$$

$\alpha$  : absorption coefficient  $\beta$  : scattering coefficient

$$\gamma_t(\lambda) = \alpha_{ml}(\lambda) + \alpha_{al}(\lambda) + \beta_{ml}(\lambda) + \beta_{al}(\lambda)$$

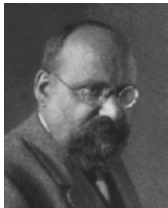
*ml: molecular*  
*al: aerosol*

Absorption: can be minimized by selecting suitable wavelength windows

Due to fog, haze and pollution

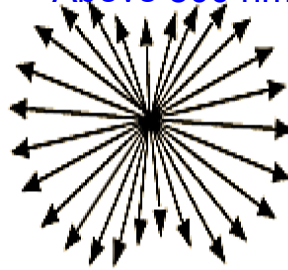


Lord Rayleigh  
(John W. Strutt)  
(1842-1919)

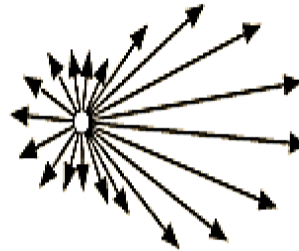


Gustav Adolf Feodor Wilhelm Ludwig Mie  
(1869-1957)

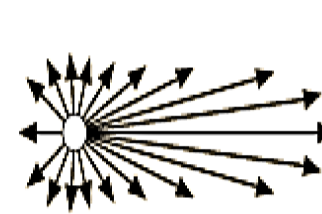
Rayleigh scattering  
 $r < \lambda$   
Above 800 nm



Mie scattering  
 $r = \lambda$



Geometric scattering  
 $r > \lambda$



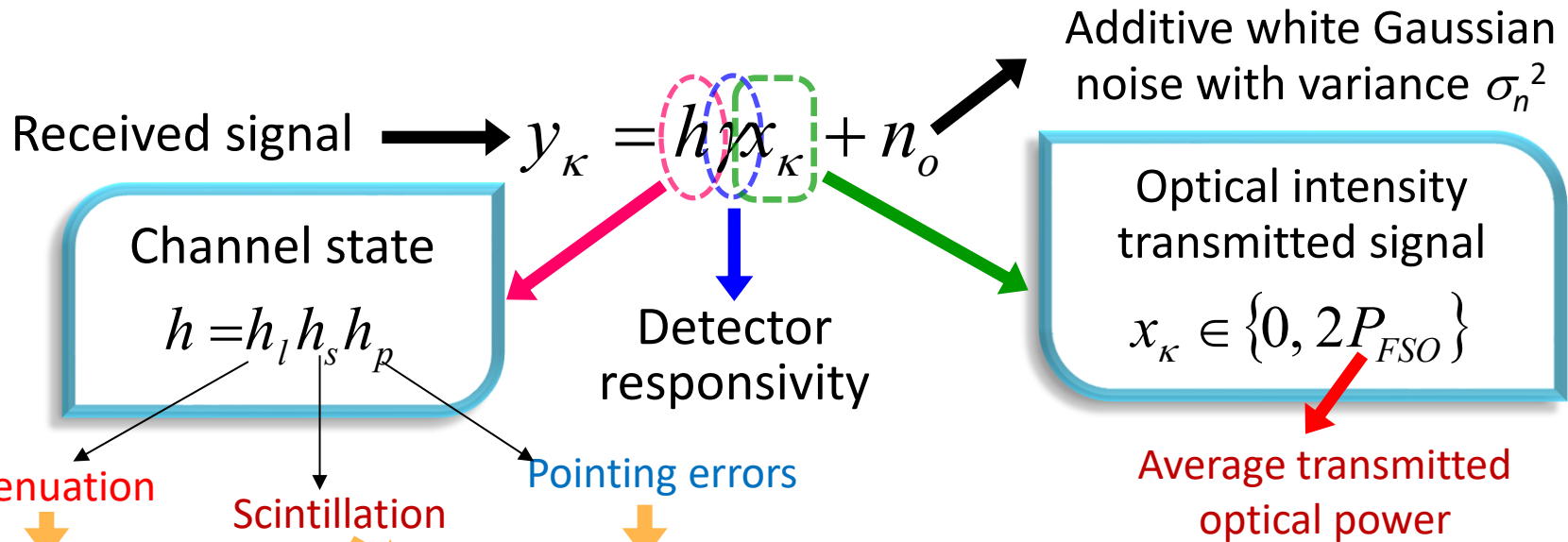
Incident light

$$\sigma_{Ray} = \frac{8\pi}{3} \left( \frac{2\pi m_{med}}{\lambda_0} \right)^4 a^6 \left( \frac{m^2 - 1}{m^2 + 2} \right)^2$$

$$\sigma_{Mie} = \left( \frac{\lambda_0^2}{2\lambda n_{med}^2} \right) \sum_{n=1}^{\infty} (2n+1) (|a_n|^2 + |b_n|^2)$$

# FSO – System Model

## Conventional channel model



Deterministic

Time-variant

Received electrical SNR

$$SNR(h) = \frac{2P_{FSO}^2 \gamma^2 h^2}{\sigma_n^2}$$

- A **fluctuating** term due to the influence of  $h$
- Chosen from the **random ensemble** according to the **distribution**  $f_h(h)$

# FSO Challenges – Rain & Snow

Typical size of raindrops is 0.4 to 4 mm

$> \lambda_{\text{light}} = 800 - 1550 \text{ nm}$

In general, snow is larger than rain

Effects	Options	Remarks
Photon absorption	<ul style="list-style-type: none"> <li>Increase transmit optical power</li> </ul>	Effect not significant

- A heavy rainfall of 15 cm/hour causes 20 - 30 dB/km loss in optical power
  - Light snow about 3 dB/km power loss, Heavy snow: 30 dB/km
    - Blizzard could cause over 60 dB/km power loss
    - Heavy snow → ice build-upon windows

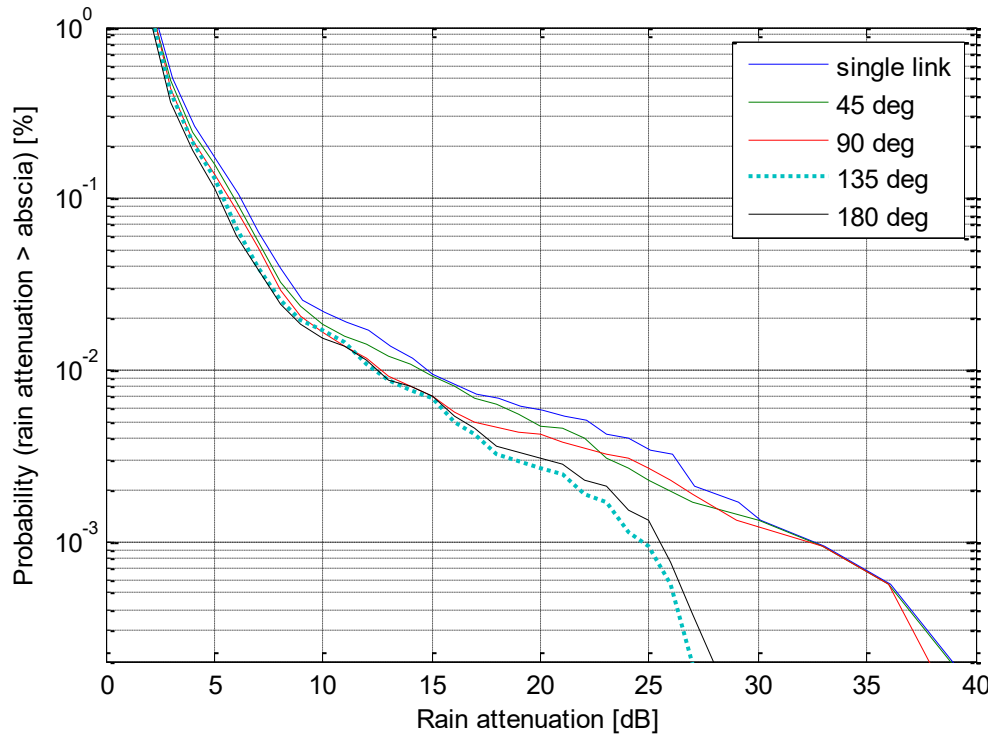
- "Specific Attenuation Model for Rain for Use in Prediction Methods," Recommendation ITU-R Rec P. 838, 2005.

- T. H. Carbonneau and D. R. Wisely, "Opportunities and challenges for optical wireless; the competitive advantage of free space telecommunications links in today's crowded marketplace.," *Wireless Technologies and Systems: Millimeter-Wave and Optical*, vol. 3232, pp. 119-128, 1998.

- "Prediction methods required for the design of terrestrial free-space optical links," Reco. ITU-R Rec P. 1884, 2007.

# Rain attenuation statistics – For a single link and two-branch diversity links

Equal lengths 2 km for different angular separations.



Rain attenuation mainly depends on rainfall rate  $R$  and PSD.

The specific attenuation  $\gamma_{rain} = aR^b$  dB/Km

The constants  $a$  and  $b$  depend on the frequency, temperature, and polarization of the wave, see as the Recommendation ITU-R P.838.

Total rain attenuation inside a precipitation (dB)

$$A_{rain} = \int_0^L \gamma_{rain}(x) dx$$

Distance

# Snow Attenuation statistics

The model proposed in [1] based on the Rayleigh approximation define the snow attenuation as:

$$\gamma_{snow} = 0.00349 \frac{S^{1.6}}{\lambda^4} + 0.00224 \frac{S}{\lambda} \quad \text{dB/Km}$$

Snow fall rate mm/h
↑
↓
In cm

Note,

- (i) water presents larger dissipative properties compared to dry snow.
- (ii) snowflake attenuation increases with its wetness.

Alessandro Rosiello, Characterisation and modelling of snow effects on EM waves propagation for EHF satcom systems, Politecnico, Milano, 1863, 2018-19

1- Gunn, K. L. S. and East, T. W. R. (1954). The microwave properties of precipitation particles. Quarterly Journal of the Royal Meteorological Society, 80(346):522?545.

# FSO Challenges – Low Clouds & Sandstorm

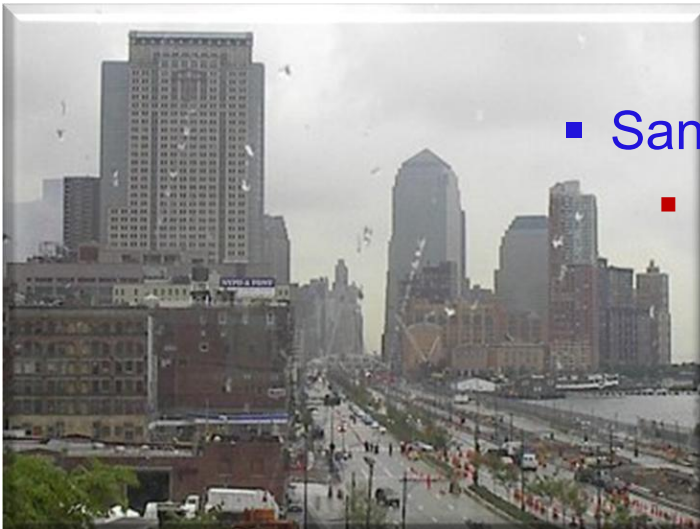


- Low Clouds
  - Very similar to fog
  - May accompany rain and snow



<https://www.breeze-technologies.de/blog/main-sources-of-air-pollution/>

## Pollution



- Sandstorms
  - Likely only in desert areas; rare in the urban core

# FSO Challenges – Aerosols Gases & Smoke



Effects	Solutions	Remarks
<ul style="list-style-type: none"> <li>▪ Mie scattering - particle size <math>\geq \lambda</math></li> <li>▪ Photon absorption</li> <li>▪ Rayleigh scattering – particle size <math>&lt; \lambda/10</math></li> </ul> <p>These contribute to signal loss:</p> $\gamma(\lambda) = \underbrace{\alpha_m(\lambda) + \alpha_a(\lambda)}_{\text{Absorption coefficient}} + \underbrace{\beta_m(\lambda) + \beta_a(\lambda)}_{\text{Scattering coefficient}}$	<ul style="list-style-type: none"> <li>▪ Increase transmit power</li> <li>▪ Diversity techniques</li> </ul>	<ul style="list-style-type: none"> <li>▪ Effect not severe</li> <li>▪ Smog is difficult to characterize as it contains both particulate matter and water droplets</li> </ul>

# FSO Challenges - Smoke

The intensity of monochromatic light passing a distance through smoke:

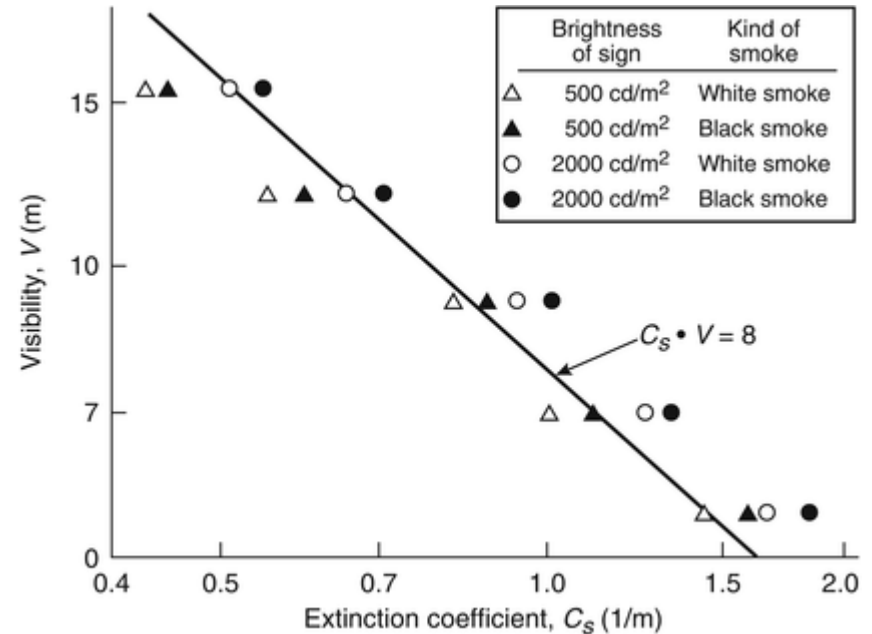
$$I = I_0 e^{-KL}$$

↑ Light extinction coefficient  
 ↓ Incident light  
 ↘ Distance

Visibility  $V = C/K$

↓  
Weber contrast

[https://www.thunderheadeng.com/docs/2026-1/pyrosim/examples/how-to/smoke-visibility-obscuration/#bibliography\\_entry\\_JinHumanBehavior](https://www.thunderheadeng.com/docs/2026-1/pyrosim/examples/how-to/smoke-visibility-obscuration/#bibliography_entry_JinHumanBehavior)



Yamada, T., Akizuki, Y. (2016). Visibility and Human Behavior in Fire Smoke. In: Hurley, M.J., et al. SFPE Handbook of Fire Protection Engineering. Springer, New York, NY. [https://doi.org/10.1007/978-1-4939-2565-0\\_61](https://doi.org/10.1007/978-1-4939-2565-0_61)

# FSO Challenges - Fog

Mie scattering to predict fog attenuations

$$\gamma_{Fog} = \int_{r_1}^{r_2} \pi r^2 Q_{ext}(m, r/\lambda) n(r) dr \quad [1/km]$$

*m and r are the refractive index and radius of the fog droplets, respectively. Q<sub>ext</sub> is the extinction efficiency and n(r) is the modified gamma size distribution of the fog droplets.*

6.5 dB/km      150 dB/km      225 dB/km



Fog particles size:  
0.01 to 0.05 mm

Effects	Options	Remarks
<ul style="list-style-type: none"> <li>Mie scattering</li> <li>particle size <math>\geq \lambda</math></li> <li>Photon absorption</li> </ul>	<ul style="list-style-type: none"> <li>Increase transmit optical power</li> <li>Hybrid FSO/RF</li> </ul>	<ul style="list-style-type: none"> <li>Thick fog limits link range to ~500m</li> <li>Safety requirements limit maximum optical power</li> </ul>

1. Iniguez, R.R., Idrus, S.M., and Sun, Z.: 'Atmospheric transmission limitations, in Optical Wireless Communications - IR for Wireless Connectivity', 2008, Taylor & Francis Group, LLC, London, pp. 25 – 42

2. Pratt, W.K.: 'Atmospheric propagation', in Ballard, S.S. (Ed.): 'Laser communication systems' (John Wiley & Sons, Inc., 1969), pp. 128 - 144

3. Saleh, A.A.M.: 'An investigation of laser wave depolarization due to atmospheric transmission', IEEE Journal of Quantum Electronics, June 1967. 3, (6), pp. 256

# FSO Challenges - Fog

The attenuation due to the fog depends on the location, refractive index, relative humidity particle size distribution and on liquid water content in spatial domain from one position to another.

## Theoretical model

- Since the particle concentration and size distribution vary in spatial domain from one position to another it is challenging to predict the fog-induced attenuation by theoretical approach.
- Therefore, the distribution is not readily available and reported in standard meteorological data.

## Empirical model

- Simpler
- Uses measured visibility data to estimate the fog induced attenuation

# FSO Challenges - Fog

FSO link availability is limited by the visibility  $V$  reduction due to fog:

- Site characterization through long term statistics & signal behaviour description
- Visibility measurements are simple and inexpensive

**Koschmieder Law** - A fundamental law to measure attenuation of optical signal based on  $V$  (in km) **BUT not  $\lambda$** :

Defines  $V$  as the distance to an object at which the visual contrast/ transmittance of an object drops to certain value of the visual/ transmittance threshold  $T_{th}$  of the original visual contrast (100%) along the propagation path.

$$V = -\frac{10 \log_{10}(T_{th})}{\beta_{\lambda}} \quad (\text{km}) \quad \text{The most adopted values of } T_{th} \text{ are 2\% and 5\% [1].}$$

**Beer- Lambert law**  $\rightarrow$  
$$\beta_{\lambda} = -\frac{\text{Loss}}{4.343L} \quad (\text{dB/km})$$

# FSO Challenges - Fog

**International visibility code**

Atmospheric conditions	Weather Constituents <small>mm/hr</small>		Visibility (m)	Attenuation (dB/Km)	
Dense fog			50	315	
Thick fog			200	75	
Moderate fog			500	28.9	
Light fog	<b>Snow</b>	Storm	100	770	18.3
very light fog				1000	13.8
		Strong rain	25	1900	6.9
Light mist				2000	6.6
		Average rain	12.5	2800	4.6
Very light mist				4000	3.1
		Light Rain	2.5	5900	2
			10 000	1.1	
Clear air	Drizzle	0.25	18 100	0.6	
			20 000	0.54	
Very clear air			23 000	0.47	
			50 000	0.19	



**Prague, Czech Rep.**

# FSO – Fog – Empirical Model

**Kruse model** - Considers the effect of  $\lambda$  on the fog induced attenuation.

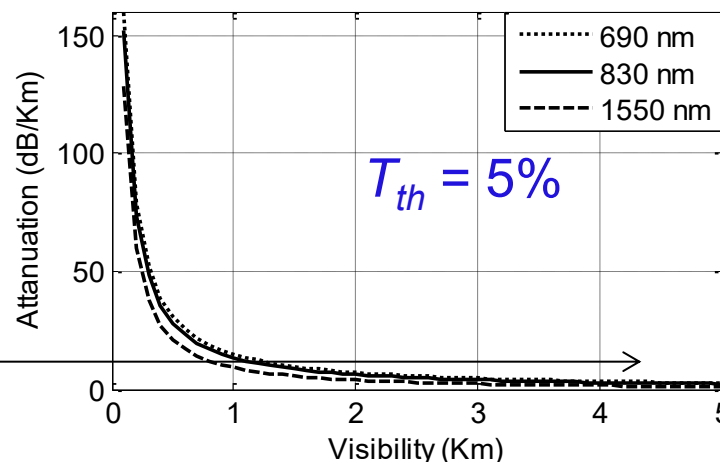
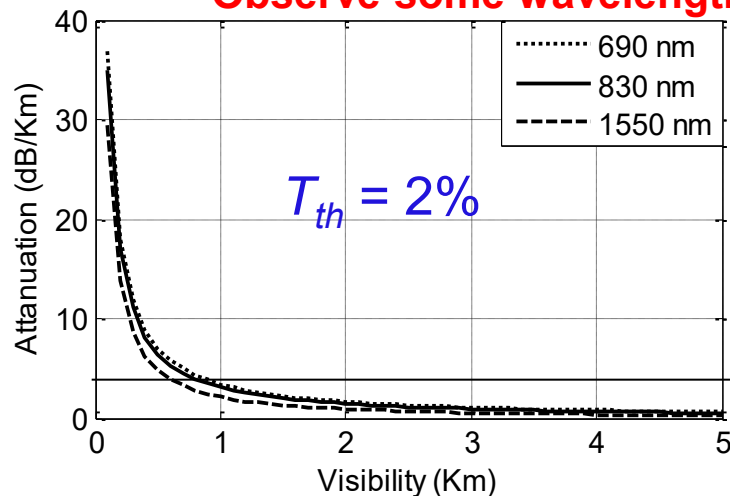
$$\beta_{\lambda} = \frac{10 \log_{10} T_{th}}{V(km)} \left( \frac{\lambda}{\lambda_o} \right)^{-q}$$

Fog particle size distribution

$$q = \begin{cases} 1.6 & \text{for } V > 50 \text{ km} \\ 1.3 & \text{for } 6 < V < 50 \text{ km.} \\ 0.585V^{1/3} & \text{for } 0 < V < 6 \text{ km} \end{cases}$$

$\lambda_o$  - the maximum spectrum of the solar band

Observe some wavelength dependency at lower  $V$



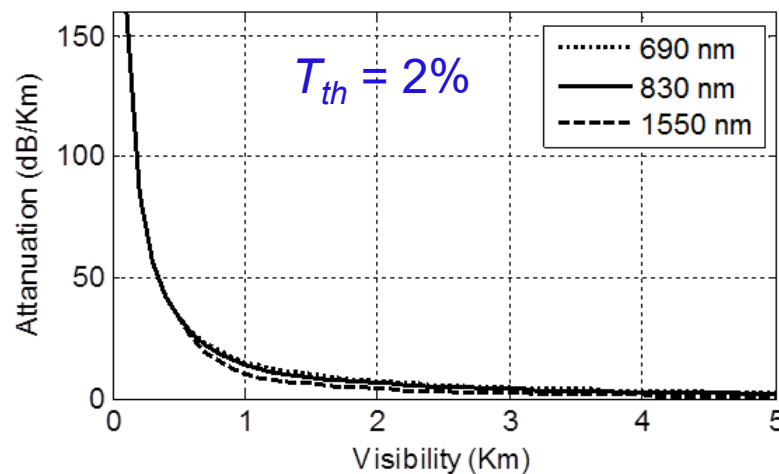
# FSO – Fog – Empirical Model

**Kim model** - Estimates  $\beta_\lambda$  which is wavelength independent for  $V < 0.5$  km, by modifying Kruse model using theoretical assumptions:

$$\beta_\lambda = \frac{10 \log_{10} T_{th}}{V(km)} \left( \frac{\lambda}{\lambda_o} \right)^{-q}$$

$$q = \begin{cases} 1.6 & \text{for } V > 50 \text{ km} \\ 1.3 & \text{for } 6 < V < 50 \text{ km} \\ 0.16V + 0.34 & \text{for } 1 < V < 6 \text{ km} \\ V - 0.5 & \text{for } 0.5 < V < 1 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases}$$

Weather condition	Visibility range (m)
Thick fog	200
Moderate fog	500
Light fog	770 – 1000
Thin fog/heavy rain (25mm/hr)	1900 – 2000
Haze/medium rain (12.5mm/hr)	2800 – 40000
Clear/drizzle (0.25mm/hr)	18000 – 20000
Very clear	23000 – 50000



# FSO – Fog – Empirical Model

For  $\lambda = 0.69$  to  $1.55 \mu\text{m}$  and for  $V = 0.050$  to  $1 \text{ km}$

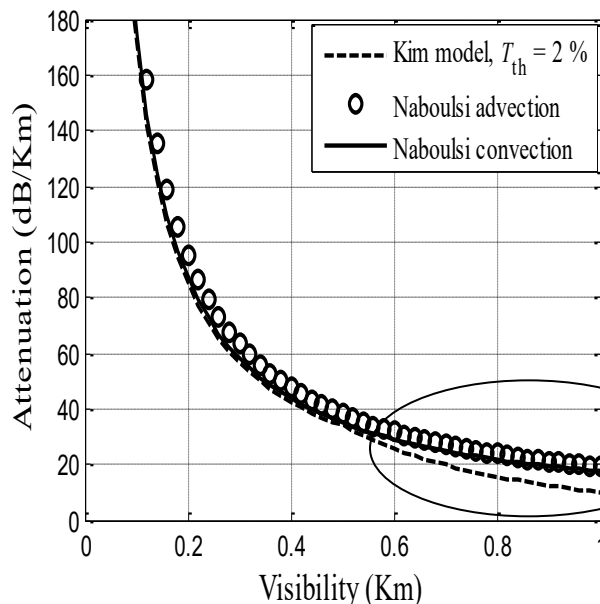
**Naboulsi Convection Model**

$$\beta_{Con}(\lambda) = 4.343 \left( \frac{0.11478\lambda + 3.8367}{V} \right)$$

**Naboulsi Advection Model**

$$\beta_{adv}(\lambda) = 4.343 \left( \frac{0.18126\lambda^2 + 0.137\lambda + 3.72}{V} \right)$$

These models need to be explicitly verified experimentally, not for a selective or specific wavelength but for the entire spectrum from the visible – NIR range for dense to light fog.



Note the deviation from Kim's model at  $\lambda \approx 900 \text{ nm}$

\* M. A. Naboulsi, F. d. Forne, H. Sizun, M. Gebhart, E. Leitgeb, S. S. Muhammad, B. Flecker, and Christoph Chlestil, "Measured and predicted light attenuation in dense coastal upslope Fog at 650, 850 and 950 nm for free space optics applications.," *Journal of Optical Engineering*, vol. 47, pp. 036001-1-036001-14, 2008.

# FSO – Fog – Empirical Model

**Ferdinandov** - Model is based on **published experimental data** →  $V = 0.1$  to  $1$  km →  $\lambda = 0.3$  to  $1.1$   $\mu\text{m}$

**Grabner 2012, Model** - Wavelength dependent model for fog and haze based on *single scattering Mie theory*

$$\beta_{\lambda} = \frac{10 \log_{10} T_{th}}{V(km)} \left( \frac{\lambda}{\lambda_o} \right)^{s(r_e)}$$

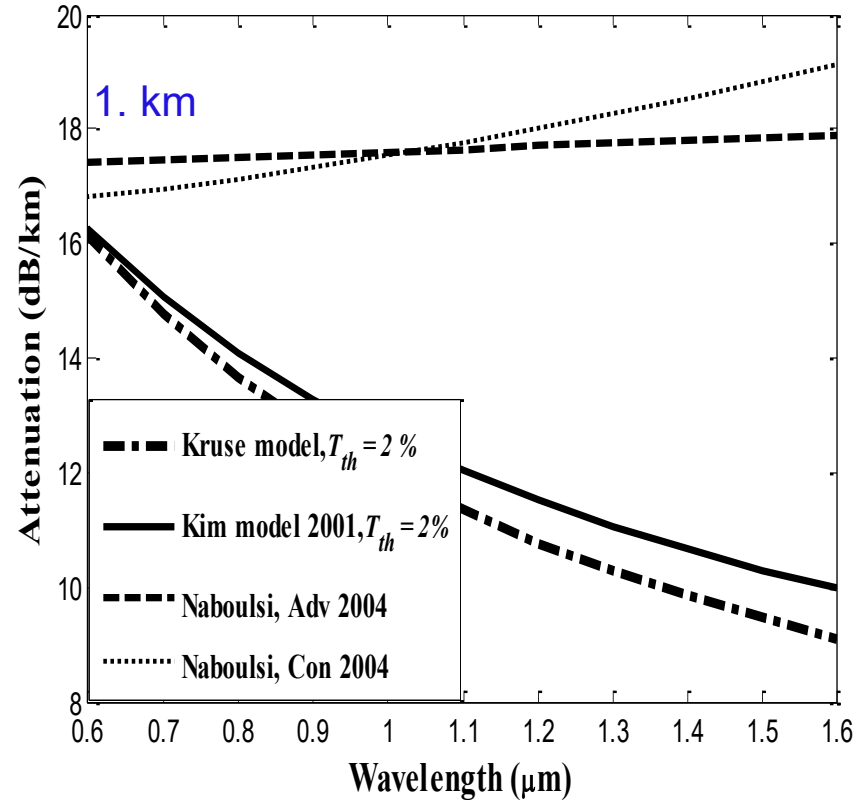
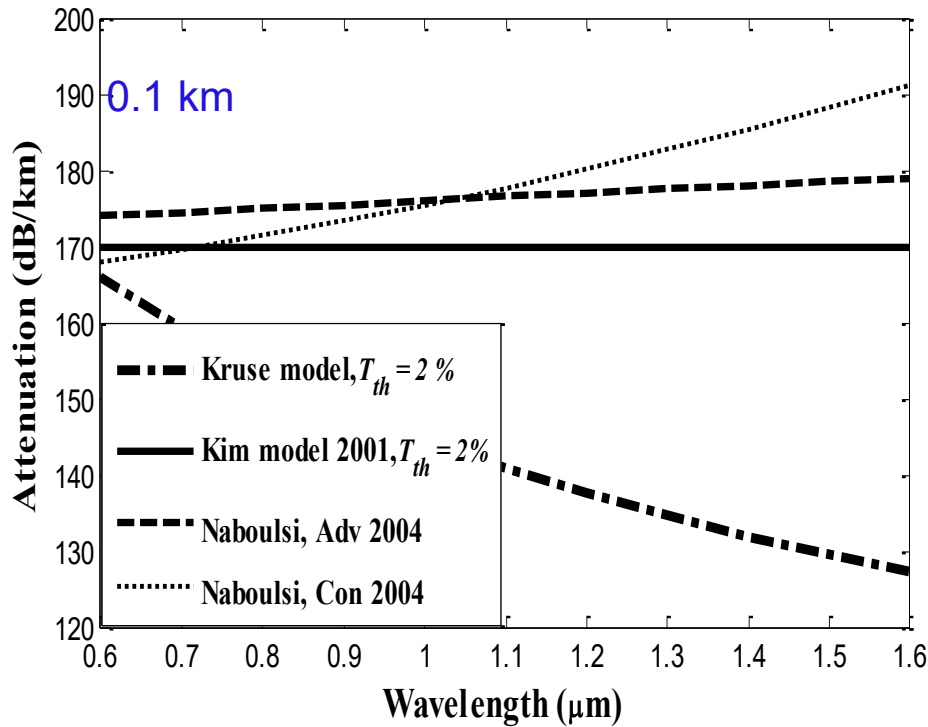
Where  $s(r_e)$  is a function of effective radius  $r_e$  of the fog particle distribution [1].

$$r_e = r_{e0} (0.05 / V)^{1/2} \quad s = 2(\tanh(p_1(w + p_4)) - 1) + \exp(p_3(w + p_5))$$

$w = \log(r_e)$   $p_i$  is the parameter dependent on the selected wavelength interval

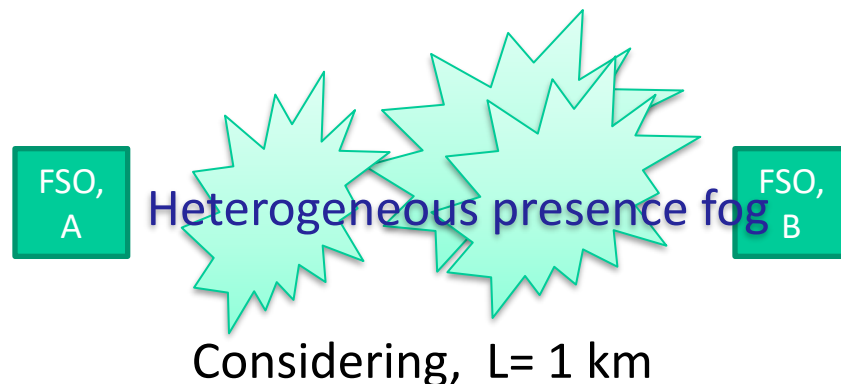
This model is applicable for the wavelength range of  $0.2 \mu\text{m} < \lambda < 2 \mu\text{m}$  for visibility range of 10 km.

# FSO – Fog – Empirical Models Comparison



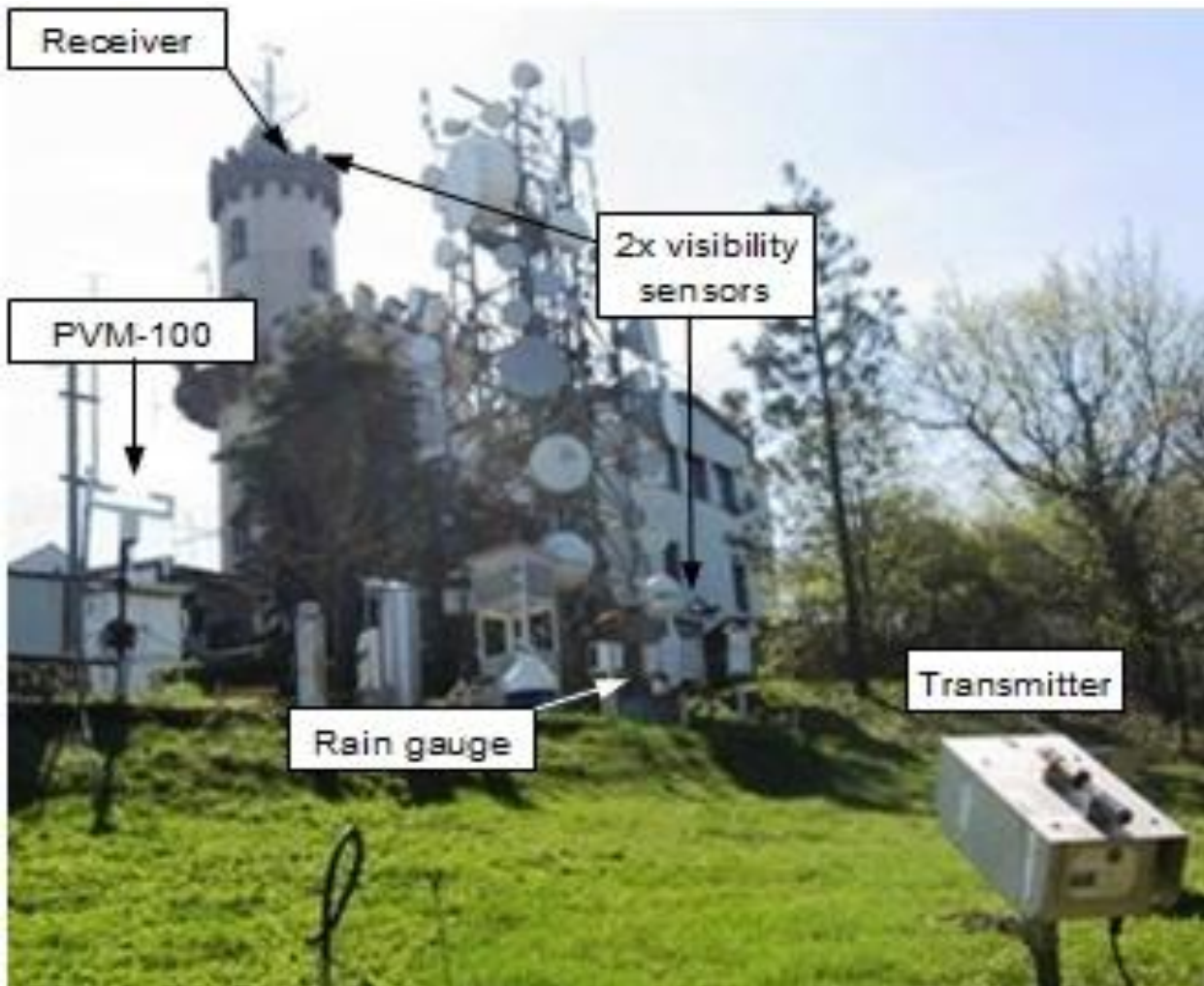
# Fog Model – Measurement Issues

- 1 Long waiting time for fog to occur
- 2 Low probability of dense fog for  $V < 500$  m
- 3 Heterogeneity of fog present along the FSO link



1. M. S. Awan, et al., "Characterization of fog and snow attenuations for free-space optical propagation," *Journal of Communications*, vol. 4, pp. 533-545, 2009.
2. I. I. Kim, et al., "Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications," in *Proc. SPIE 4214*, Boston, MA, USA 2001.

# Fog and Cloud – Outdoor Measurement Setup



LWC (Liquid Water Content)



Particle Volume Monitor

Z Ghassemlooy

# Fog and Cloud – Outdoor Measurement Setup

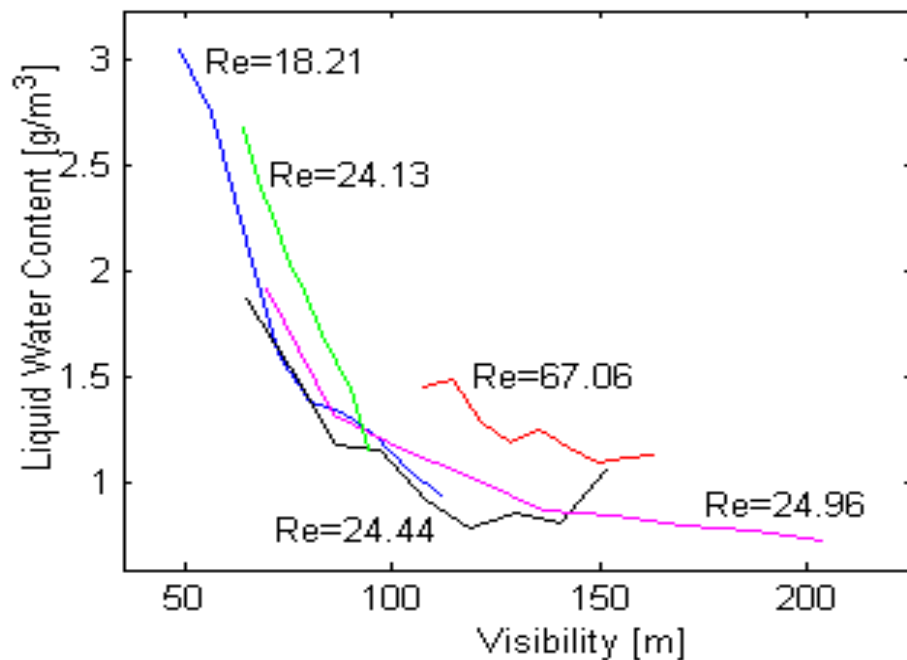
## Cloud microphysics - Particle volume monitor - 100 outputs

- LWC (Liquid Water Content)

$$LWC = \frac{4\pi\rho}{3} \int r^3 N(r) dr \quad [\text{g/m}^3]$$

- PSA (Particle Surface Area)

$$PSA = 4\pi \int r^2 N(r) dr \quad [\text{cm}^2/\text{m}^3]$$



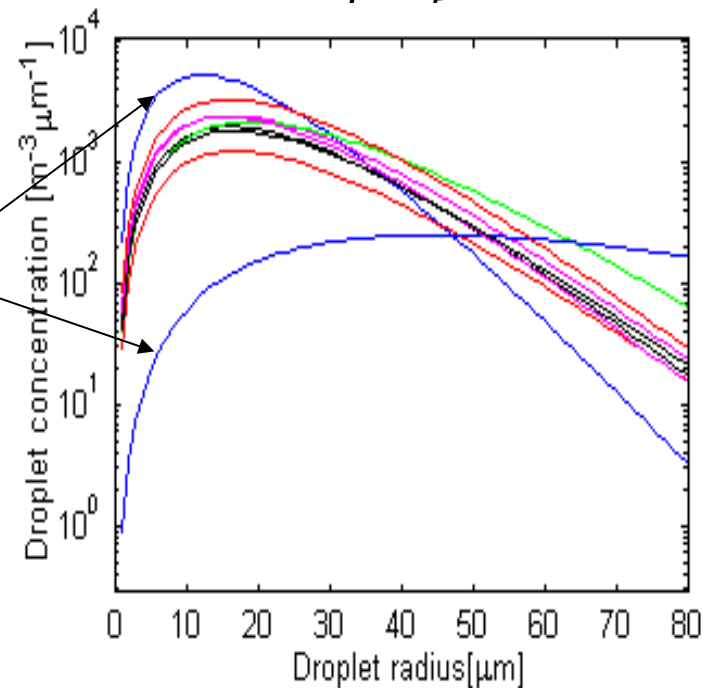
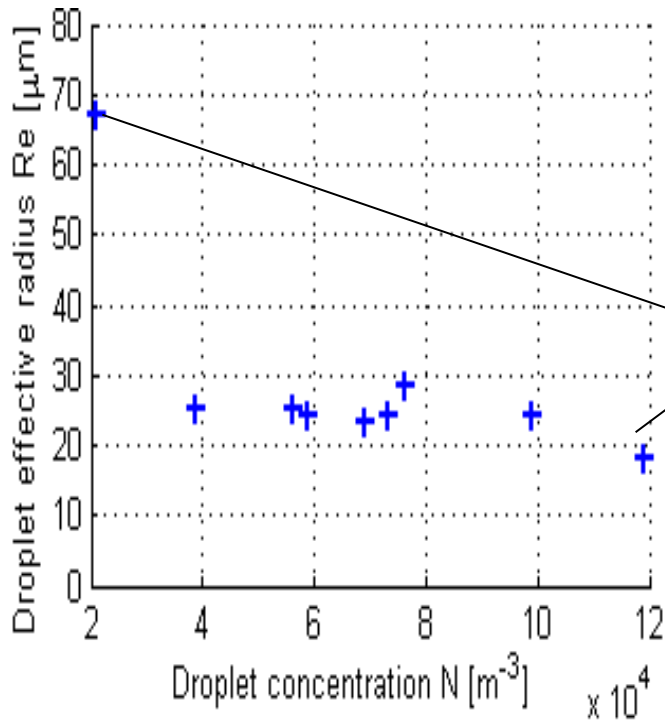
# Fog and Cloud – Outdoor Measurement Setup

## Cloud microphysics - Droplet effective radius $R_e$

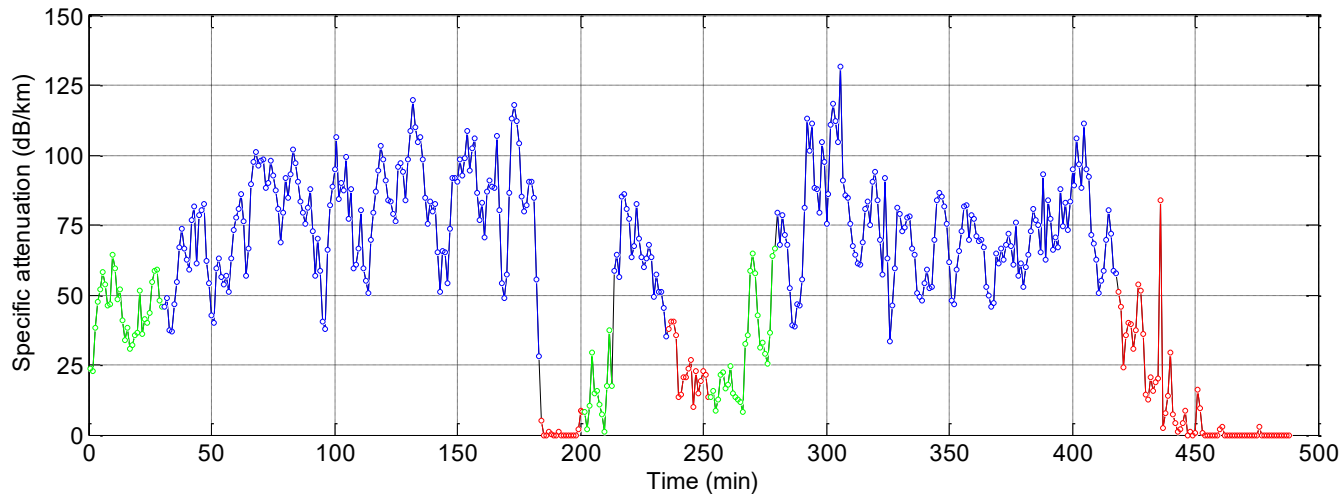
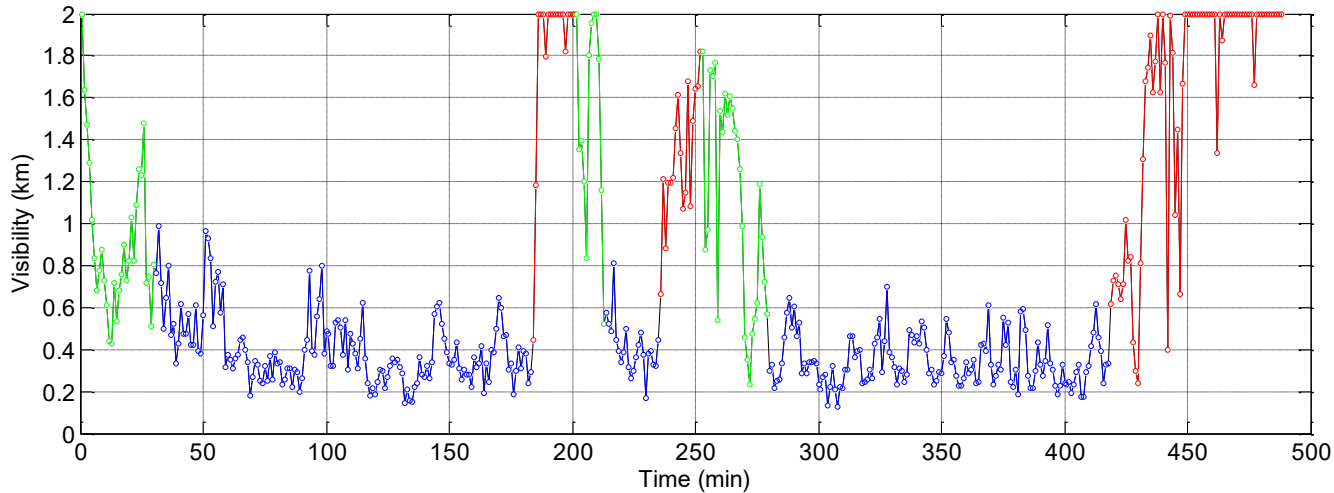
$$R_e = 3.10^4 \frac{LWC[g/m^3]}{PSA[cm^2/m^3]} \quad [\mu m]$$

Total concentration of particles per cubic meter:

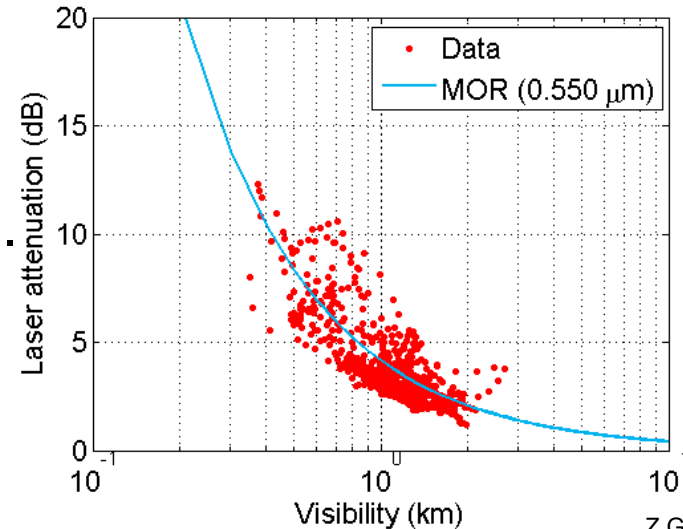
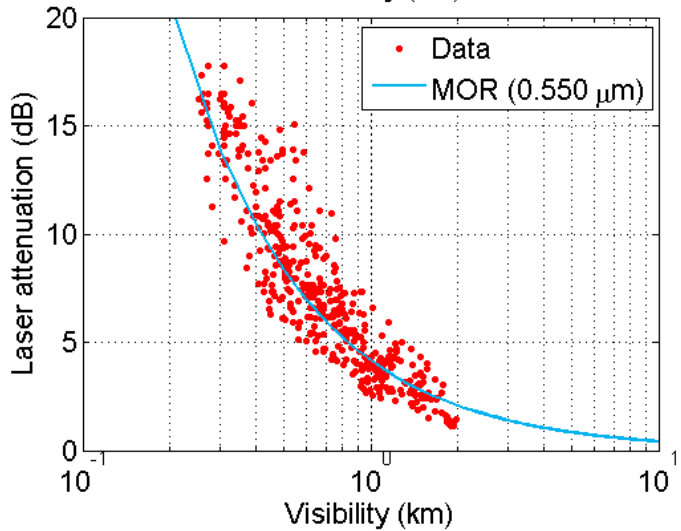
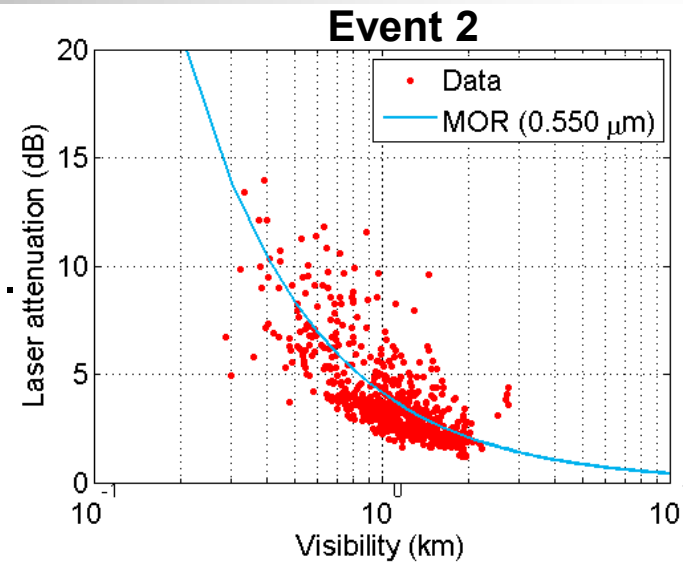
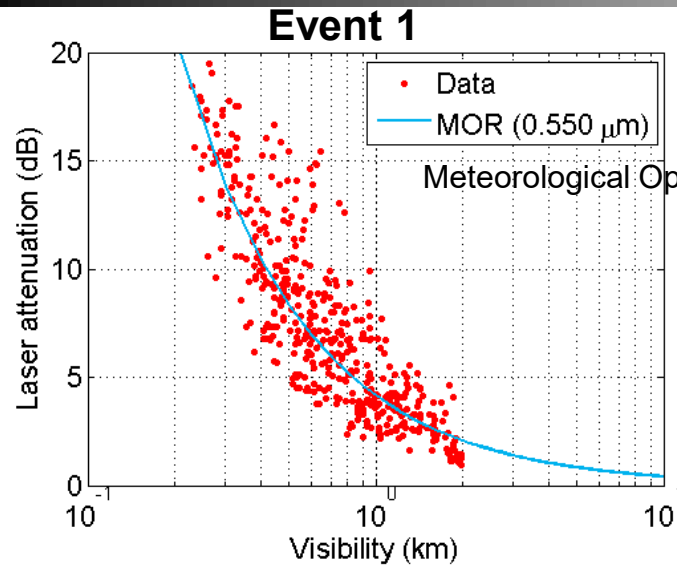
$$N = 1.07 \cdot \frac{LWC}{\rho \cdot R_\rho^3} \quad [m^{-3}]$$



# Fog – Measurement – Visibility and Attenuation Time Series



# Fog – Measurement – Data processing: Scatterplots

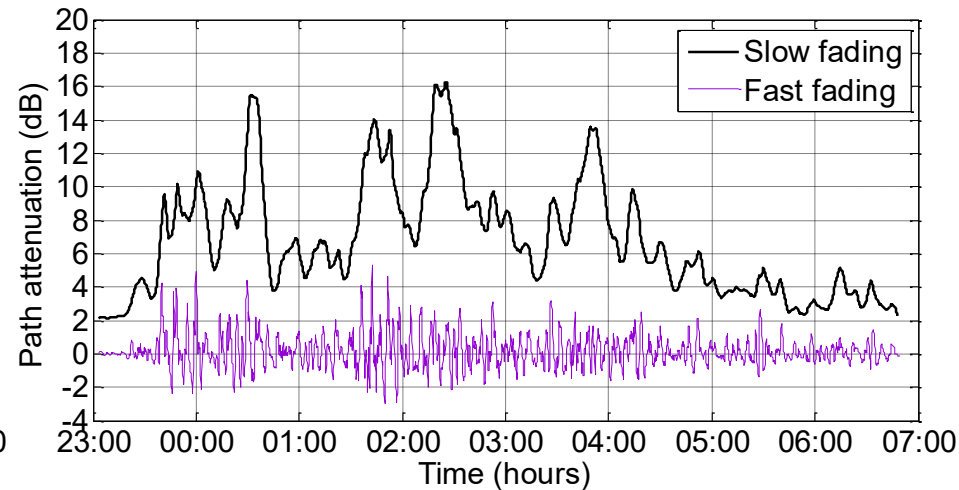
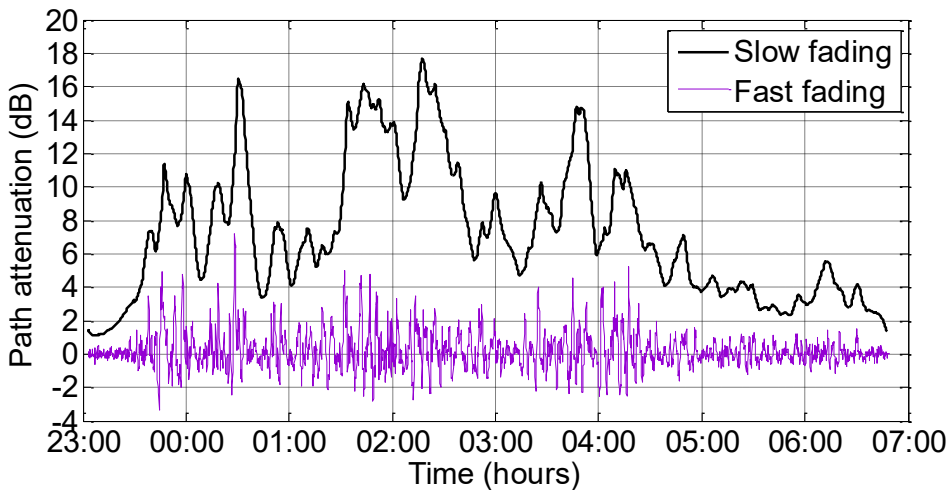


# Fog – Measurement – Signal Characteristics: Slow and Fast Fading

A 5-min. moving average over 10 s data - filter separating signal components

$$\text{Attenuation: } A_v = \frac{L}{V} \log(1/0.015)$$

Visibility



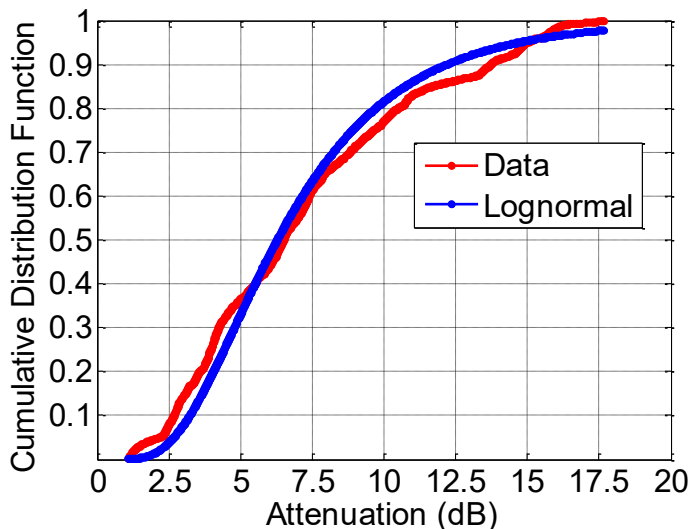
Attenuation measured by the laser link

Attenuation measured by the visibility sensor

- Slow and fast fading components with different statistical properties.

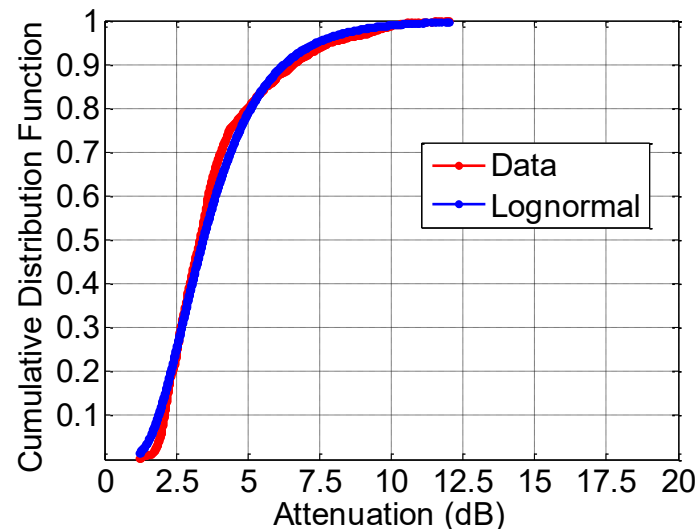
# Fog – Measurement – Signal Characteristics: CDF of Slow Fading

Sets of measurement 1

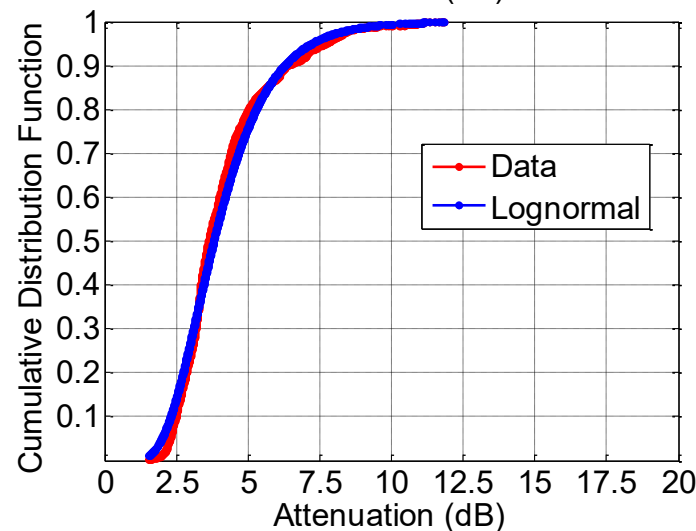
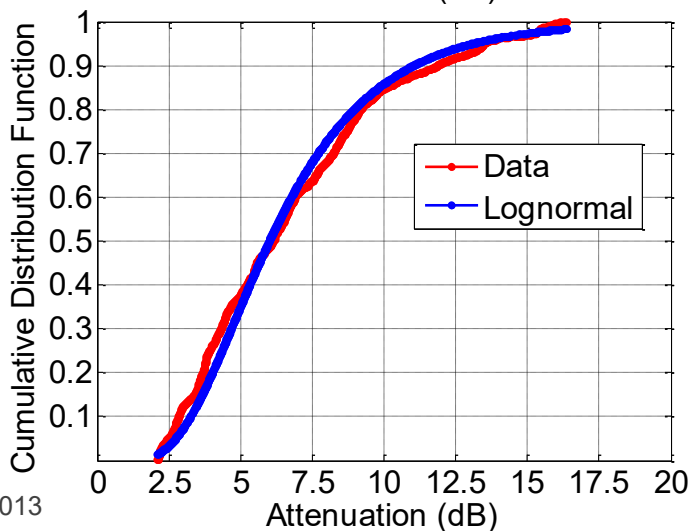


Attenuation by the  
laser link  
5-min avg.

Sets of measurement 2



Attenuation  
By the visibility  
5-min avg.

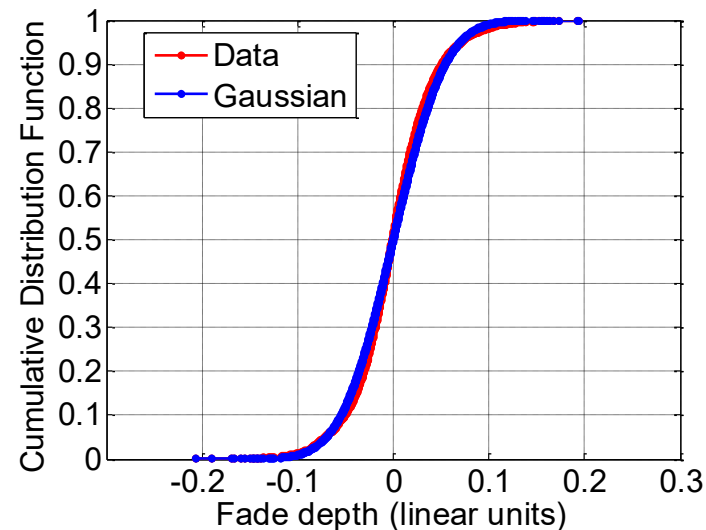
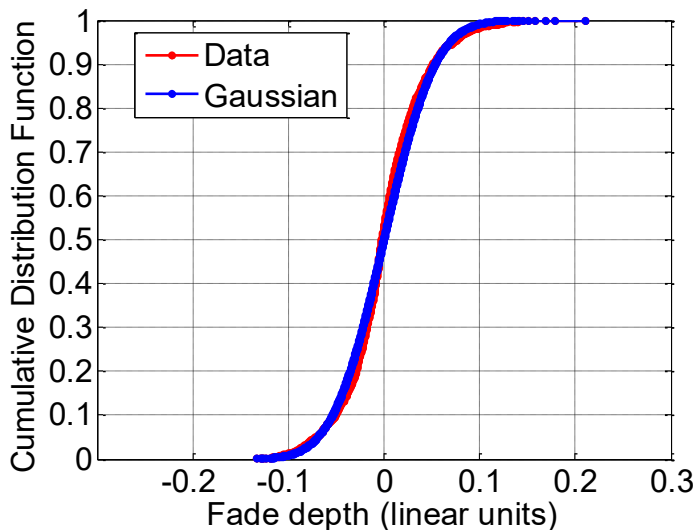


# Fog – Measurement – Signal Characteristics: CDF of Fast Fading

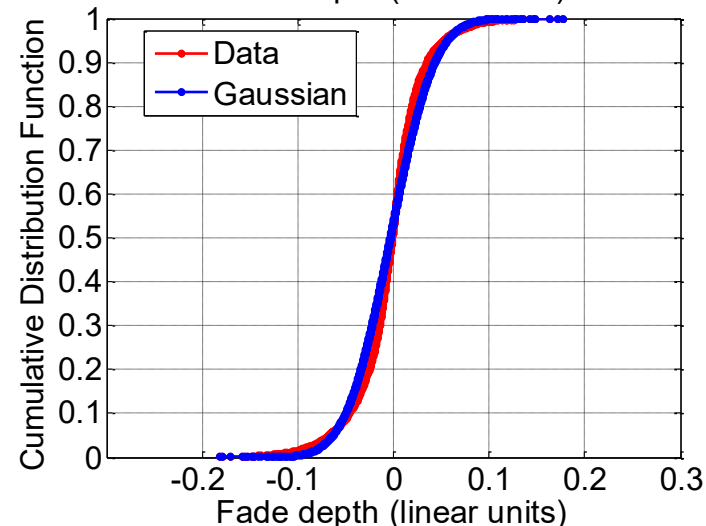
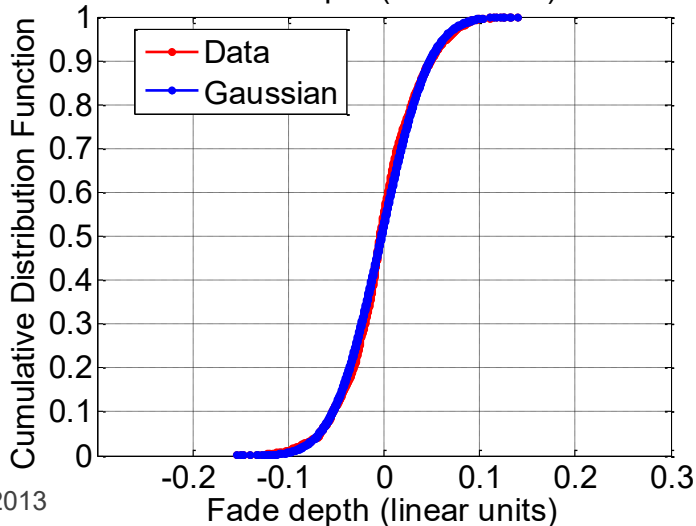
Event 1

Event 2

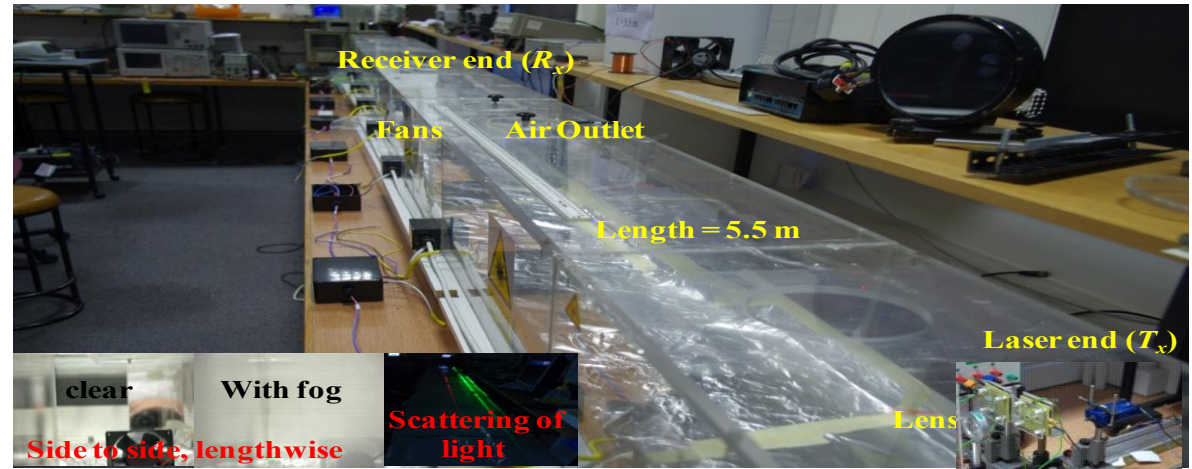
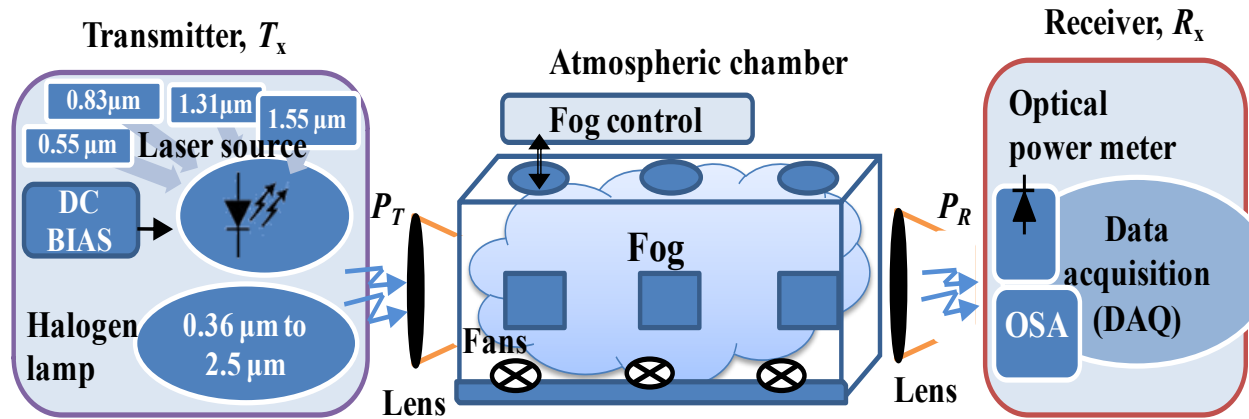
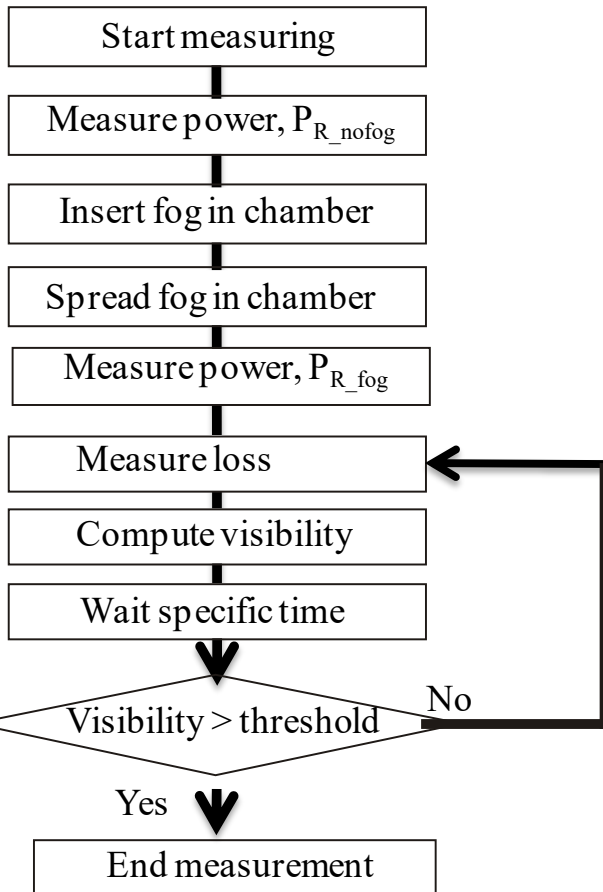
Laser  
attenuation  
5-min avg.



Attenuation  
from visibility  
5-min avg.



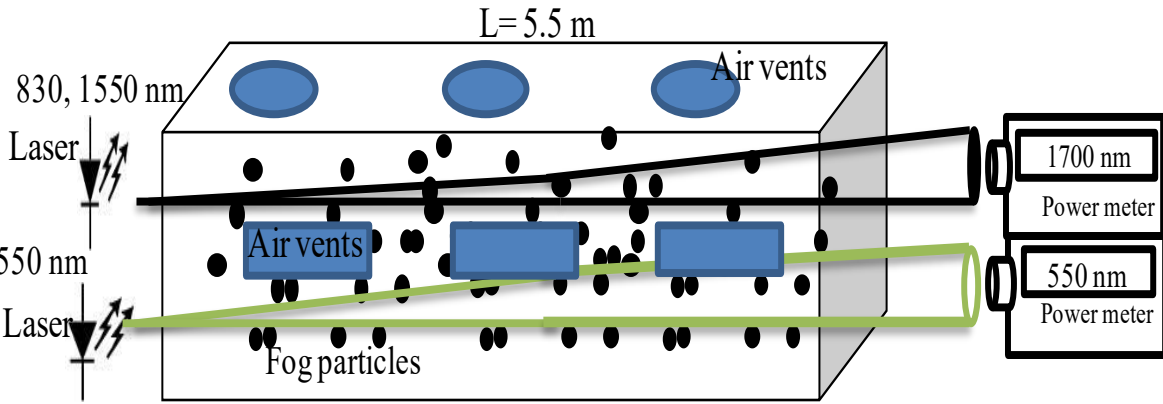
# FSO – Fog – Measurement



Indoor atmospheric chamber at OCRG

- Could use:
- (i)- A range of light source
  - (ii)- A halogen lamp

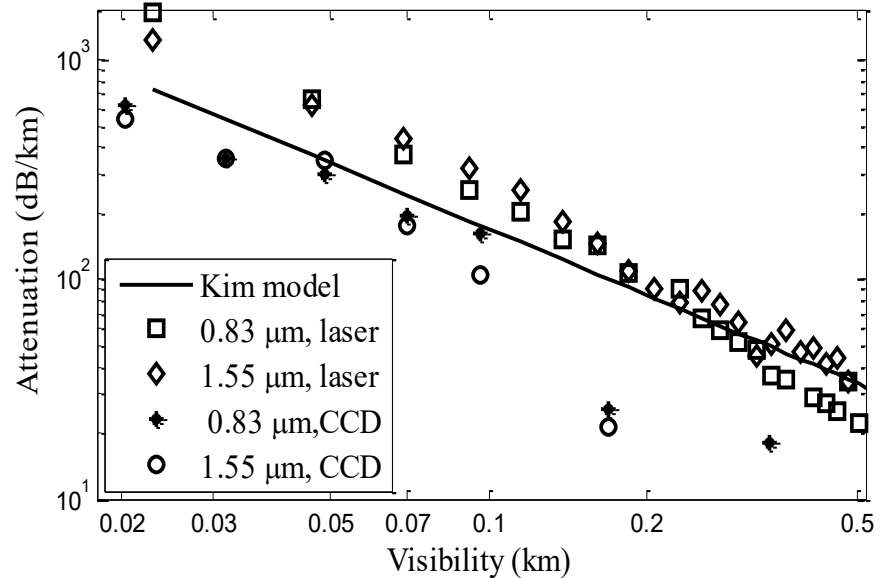
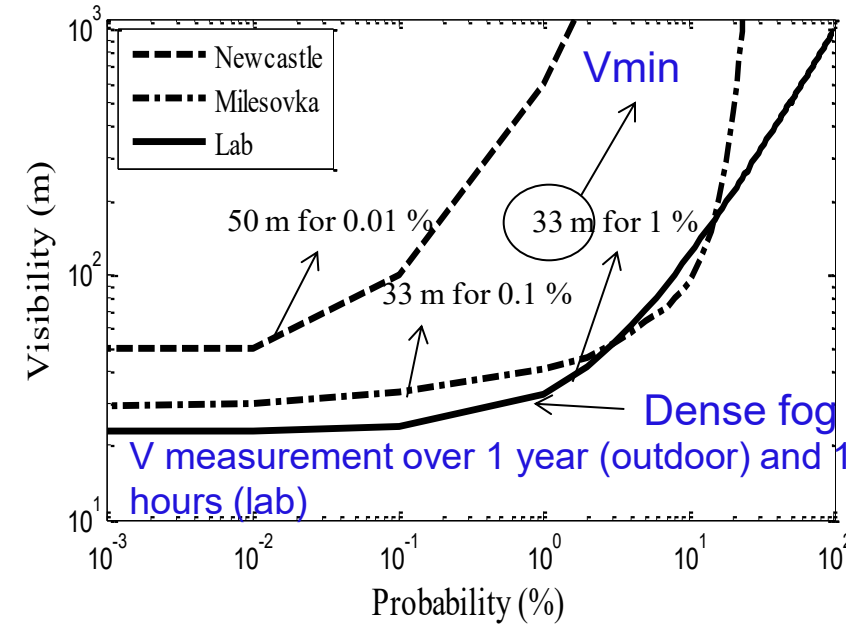
# FSO – Fog – Measurement using Laser Diodes



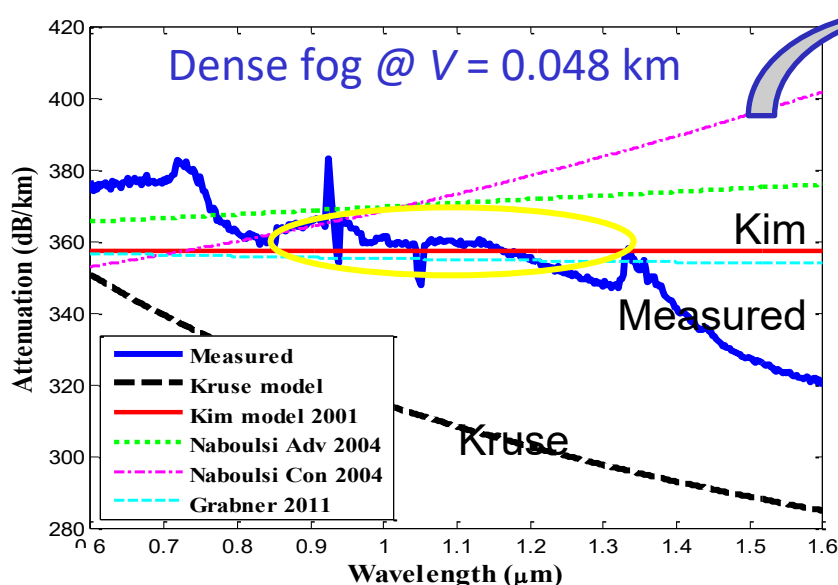
Link visibility is measured using a laser at 0.55 μm to characterise the fog.

$V$  (km) is calculated

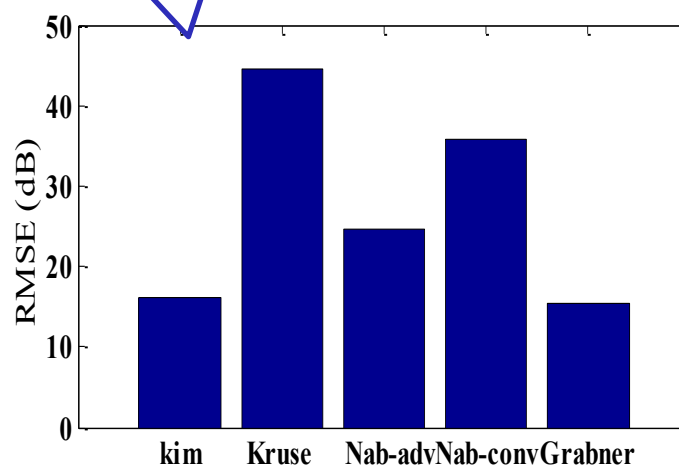
$$V = -\frac{10 \log_{10}(T_{th})}{\beta_{\lambda}} \quad \beta_{\lambda} = -\frac{10 \log_{10}(T)}{4.343L}$$



# FSO – Fog – Measurement



Comparison of the selected empirical models with measured spectrum fog attenuation (dB/km)



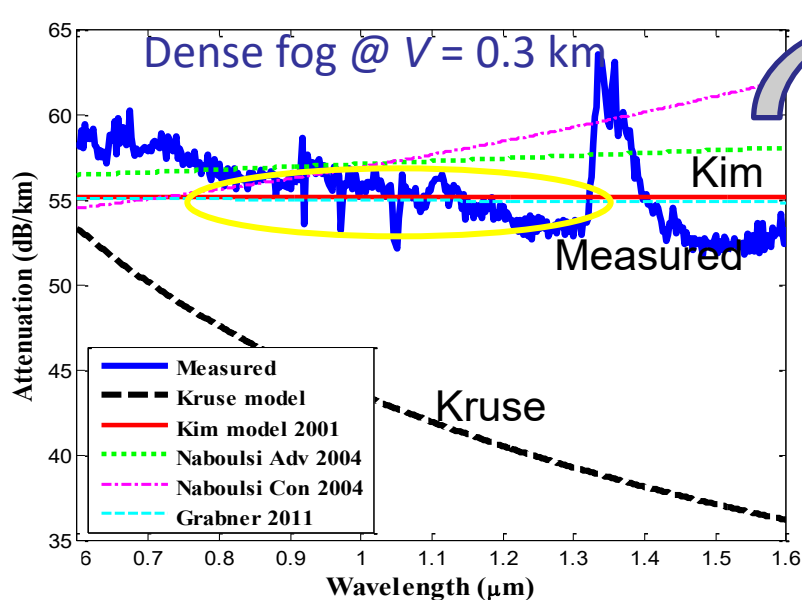
Root Mean Square Error (RMSE) of selected empirical fog models from measured spectrum attenuation data

**Measured attenuation** for very dense fog ( $V = 0.048$  km) notably higher at the visible range than at the NIR range for  $V < 0.5$  km

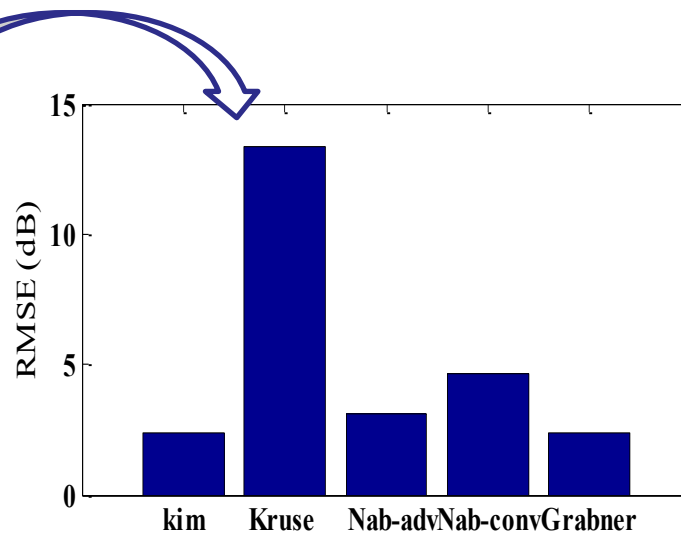
**Kim model** - Contradicts the measured data, suggesting wavelength independency at  $V < 0.5$  km.

**Grabner model** - a close agreement with measured data.

# FSO – Fog – Measurement



Comparison of the selected empirical models with measured spectrum fog attenuation (dB/km)

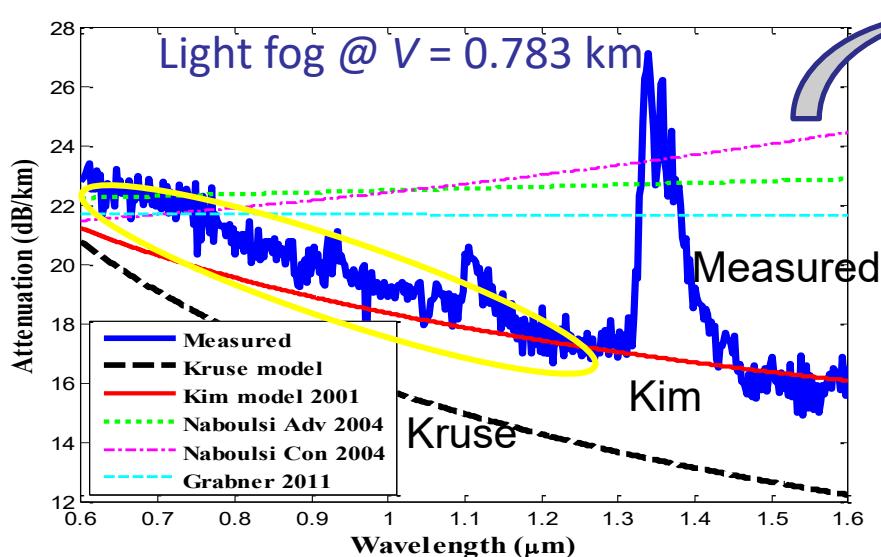


RMSE of selected empirical fog models from measured spectrum attenuation data

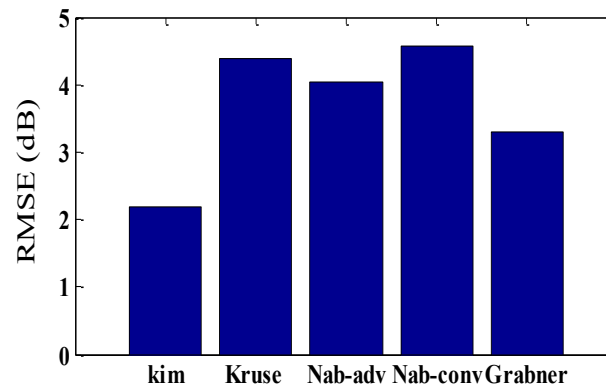
The measured peak attenuation at  $\lambda = 1.35-1.45 \mu\text{m}$  is due to strong water absorption, which is consistent to the published results in [1].

This has to be underestimated for fair comparison with previous mentioned models.

# FSO – Fog – Measurement



Comparison of the selected empirical models with measured spectrum fog attenuation (dB/km)



RMSE of selected empirical fog models from measured spectrum attenuation data

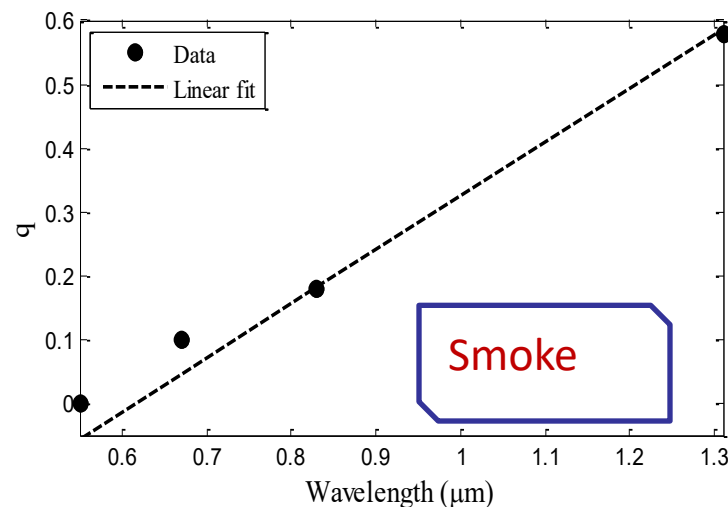
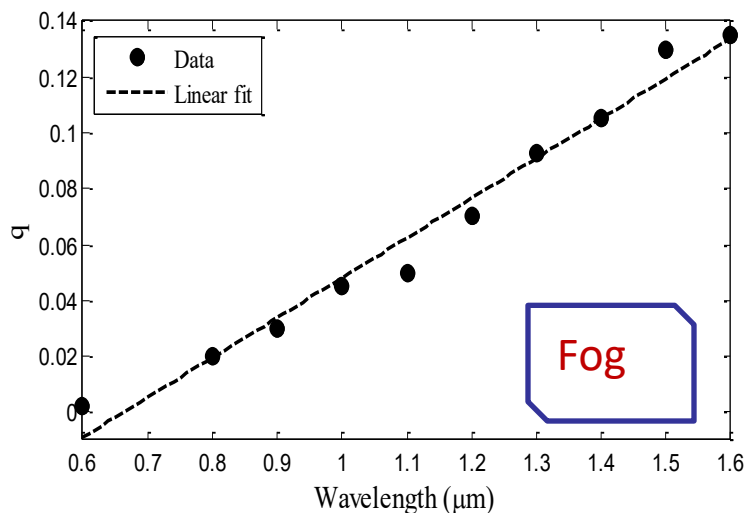
RMSE value is ~2 dB for Kim model, which is better than Grabner model (3.5 dB) and other models (> 4 dB).

This validates that Kim model

- is more realistic to use when  $V > 0.5$  km.
- need to be revised for  $V < 0.5$  km to predict the wavelength dependent fog attenuation for dense fog conditions, *i-e.*,  $V < 0.5 \text{ km}^1$ .

# FSO – Fog – New Model

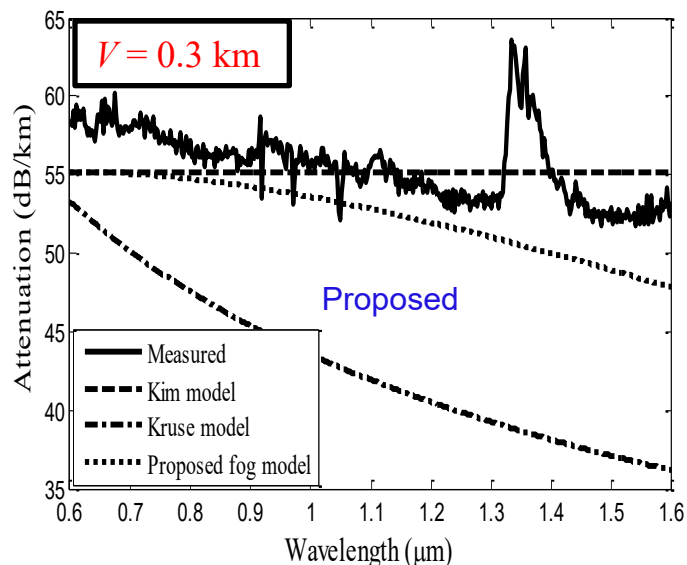
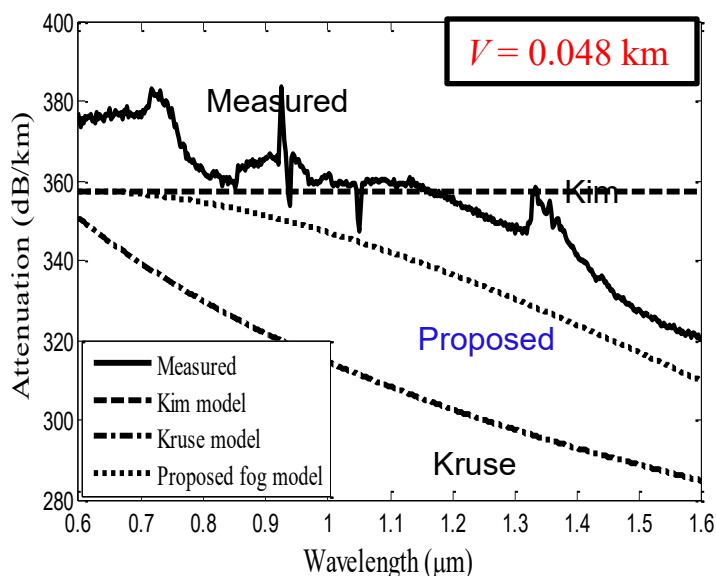
The model is wavelength dependent and is valid for the link span < 1 km



$$\beta_{\lambda} (dB / km) = \frac{17}{V(km)} \left( \frac{\lambda}{\lambda_o} \right)^{-q(\lambda)} \Rightarrow q(\lambda) = \begin{cases} 0.1428\lambda - 0.0947 & \text{Fog} \\ 0.8467\lambda - 0.5212 & \text{Smoke} \end{cases}$$

0.55 μm < λ < 1.6 μm is valid for the visibility range of 0.015 km < V < 1 km.

# FSO – Fog – New and Old Models

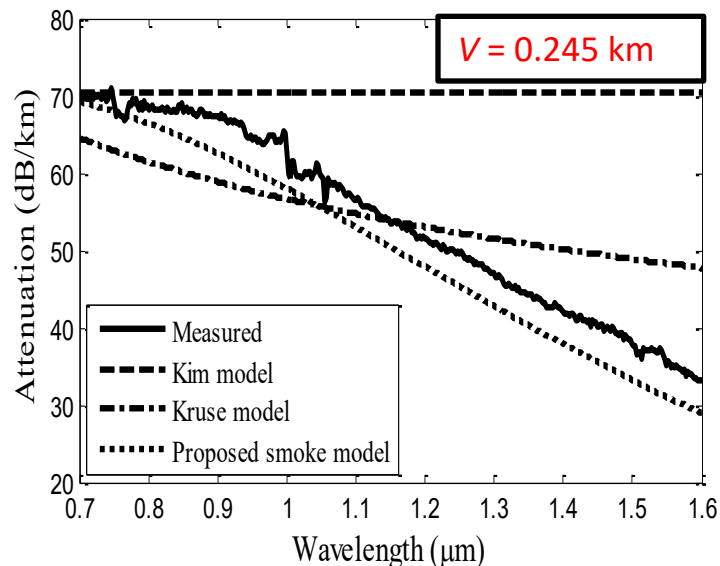
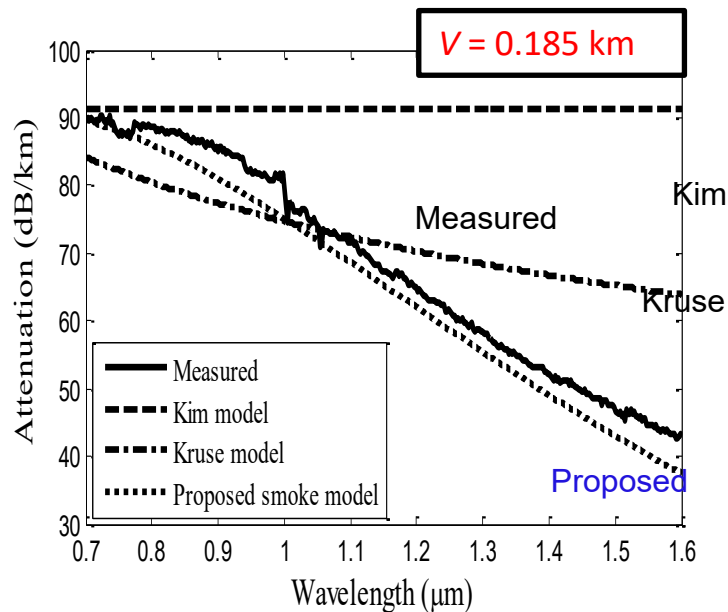


The measured fog attenuation (dB/km) from the visible – NIR spectrum

$$\beta_{\lambda} (dB/km) = \frac{17}{V(km)} \left( \frac{\lambda}{\lambda_o} \right)^{-q(\lambda)} \Rightarrow q(\lambda) = \begin{cases} 0.1428\lambda - 0.0947 & \text{Fog} \\ 0.8467\lambda - 0.5212 & \text{Smoke} \end{cases}$$

0.55 μm < λ < 1.6 μm is valid for the visibility range of 0.015 km < V < 1 km.

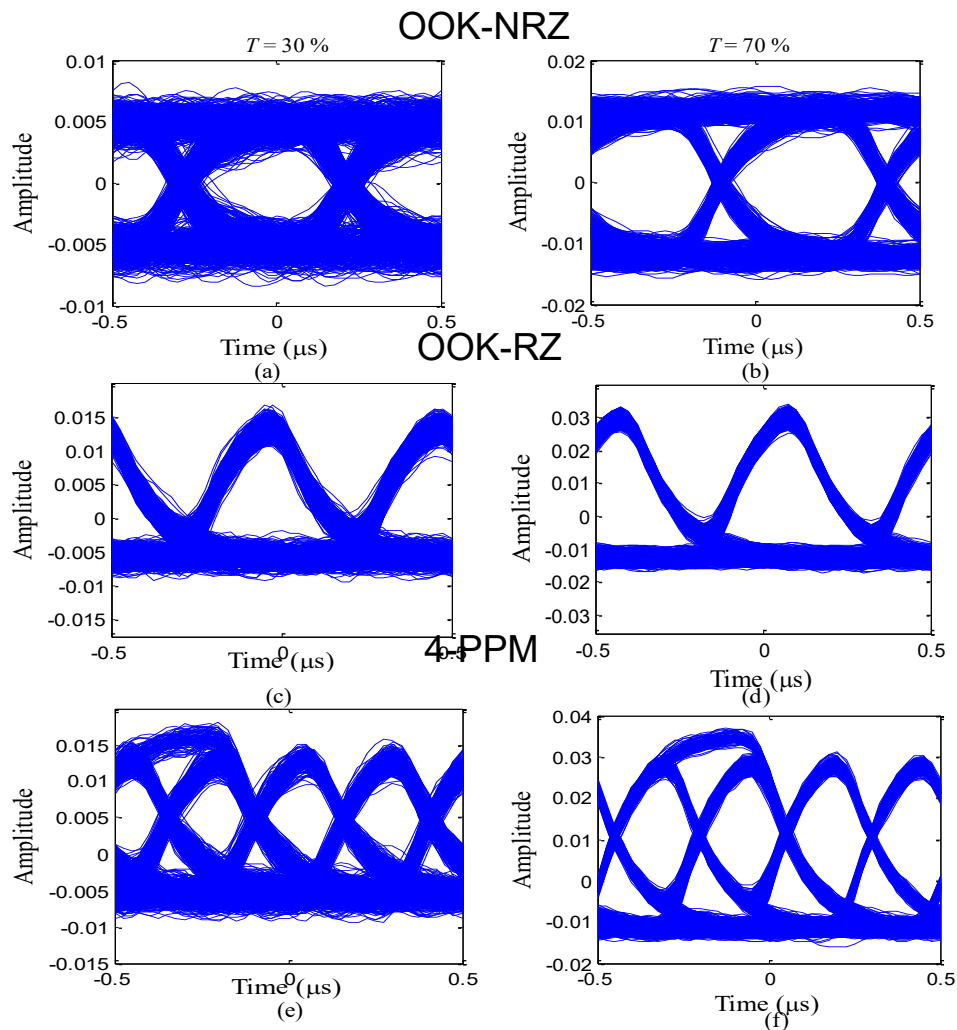
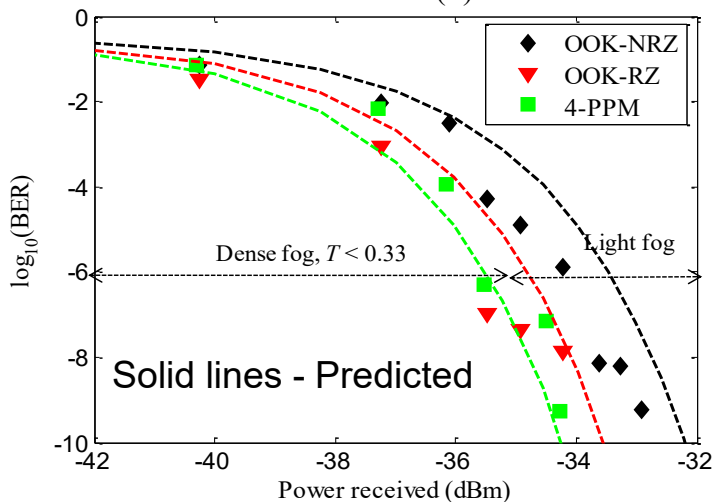
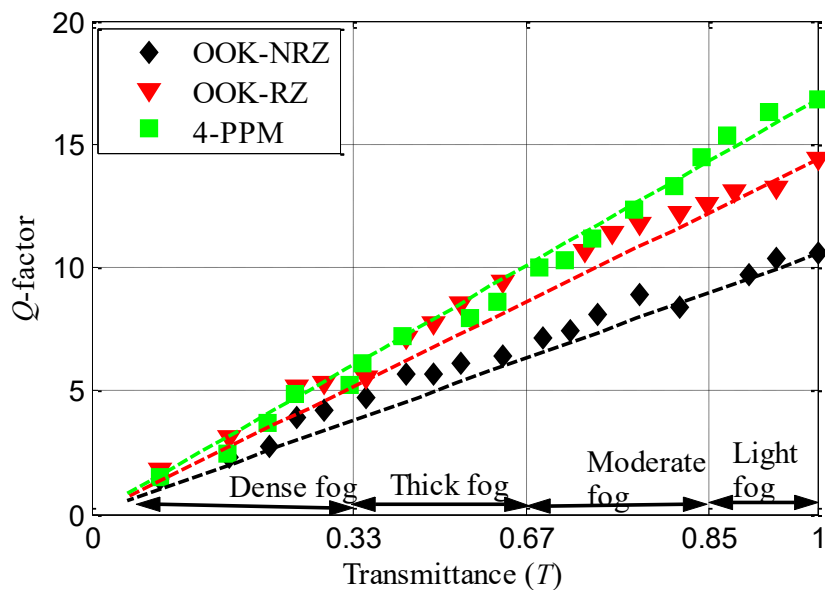
# FSO – Fog – New and Old Models



The measured smoke attenuation (dB/km) from the visible – NIR spectrum

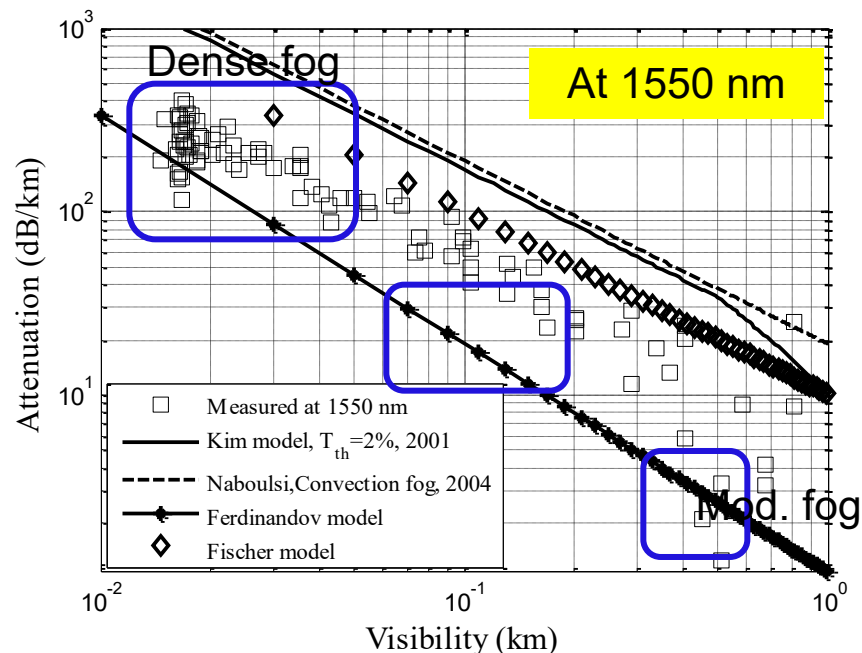
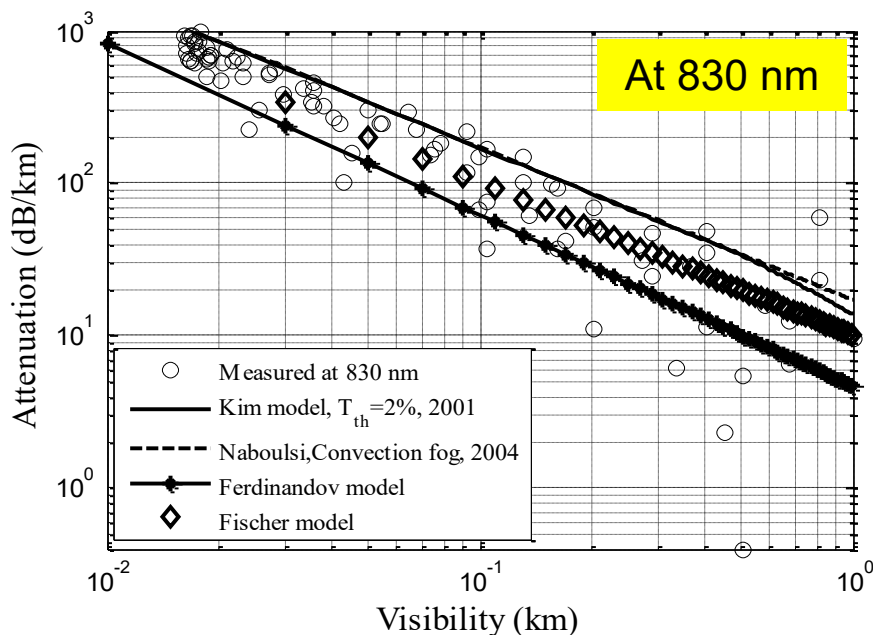
- Resultant smoke attenuation at  $V = 0.185$  km is almost 90 dB/km for the visible range and drops to 43 dB/km at the NIR range
- Propose smoke model is compared with Kim and Kruse model
- The new proposed model fits the experimental data showing a close correlation with the measured smoke attenuation spectrum

# FSO – Fog – Q-Factor Measurement



Dense fog –  $T = 30\%$   
Moderate fog –  $T = 70\%$

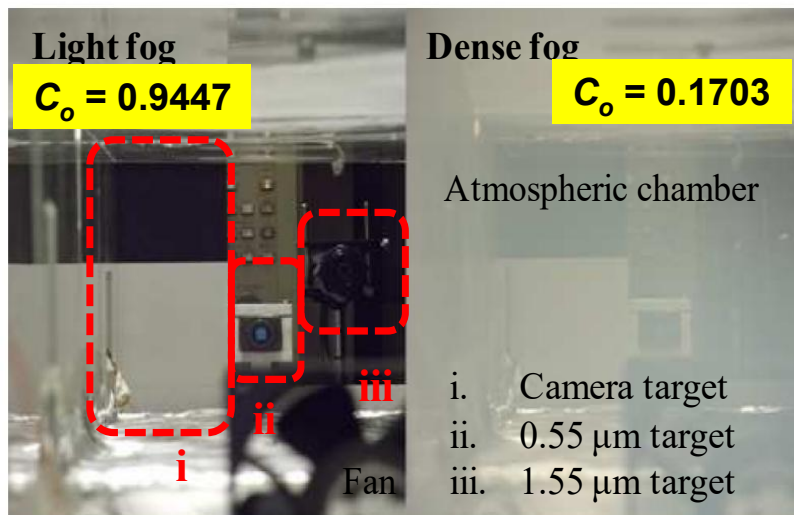
# FSO – Fog – Empirical Model Comparison



- Attenuation - wavelength dependent under dense fog condition for  $V < 500$  m.
- 1550 nm has considerably lower optical loss than 830 nm in dense to moderate fog conditions.
- The average loss difference of 100 dB for dense fog ( $V < 70$  m), 23 dB for thick fog ( $V = 250$  m) and 8 dB for moderate fog ( $V = 500$  m) for a link range of 1 km.

# FSO – Fog – Measurement using CCD Camera

- ❖  $V$  is defined as a range where a contrast ratio  $C_T$  between ideal black and white targets is reduced to value of 2%.
- ❖ Used a CCD camera (model GE X5, 14 megapixels) and two optical links at  $0.83 \mu\text{m}$  and  $1.55 \mu\text{m}$ .



A black and white target is placed at the Rx

The normalized  $C/C_o$  between the black and white areas is computed by measuring the luminance of the white  $L_w$  and black  $L_b$  parts of the target before and after the fog event.

Using Koschmieder relation and Beer-Lambert-Boguer's law,  $V$  is:

$$V = \frac{\ln(0.02)}{\ln(C_T)} \cdot L. \quad C_T = \frac{C}{C_o}$$

The function `imread()` in `matlab` is used to decompose every pixel of a picture to a RGB component in an interval of 0 to 255. The standard conversion from RGB to XYZ component is completed using the following equation:

$$C = 0.212R + 0.7152G + 0.0722B.$$

# FSO – Fog – Mitigation

## Hybrid FSO-RF architectures

- A practical solution
- The FSO link deals with the bulk of traffic under clear conditions
- The RF link is used as a backup during periods of degraded optical transmission
- Hard- and soft-switching mechanisms
  - uses channel-state feedback to transition between links based on signal-quality thresholds.

## AI/Machine Learning Integration

- Enabling dynamic link management in changing atmospheric conditions.
- Algorithms trained on weather datasets (collected for many years) for predicting channel conditions and selecting modulation schemes to maintain BER within acceptable limits without operator input.
- Random-forest classifiers in hybrid FSO-RF with soft-switching strategies assisted by learned atmospheric models improves the reliability of the FSO link in real time [1]

# Final Remarks

- FSO
  - Well established technology and will complement the RF technology
  - Fog is a major issue for terrestrial applications
  - The need for a unified model
  - Adopting new modulation, coding and signal processing schemes to improve the performance of FSO link

**FSO (OWC) is here to stay as part of post RF technology**

# Acknowledgments

- Optical Communications Research Group Members  
*Northumbria University*
- EU Cost Actions IC 802 and IC 1101
- Colleagues and students from several institutions