Characterization of Hydrometeor Scattering Effects and Experimental Measurements Using Near-Infrared Free-Space Urban Links

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ISTITUTO SUPERIORE DELLE COMUNICAZIONI E DELLE TECNOLOGIE DELL'INFORMAZIONE
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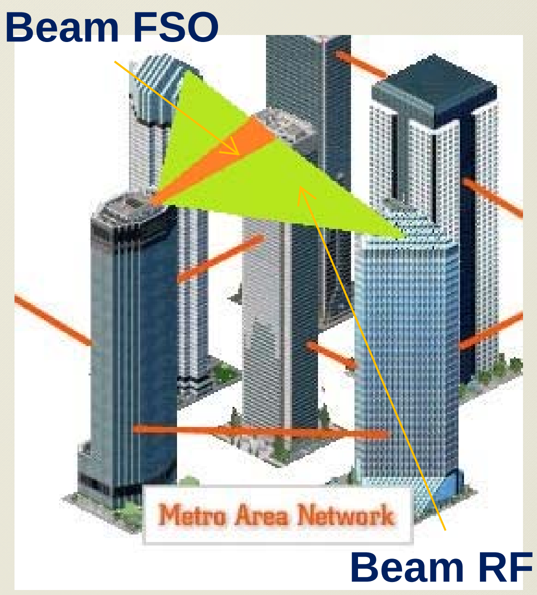
FREE SPACE OPTICS
Advantages and disadvantages

Advantages:

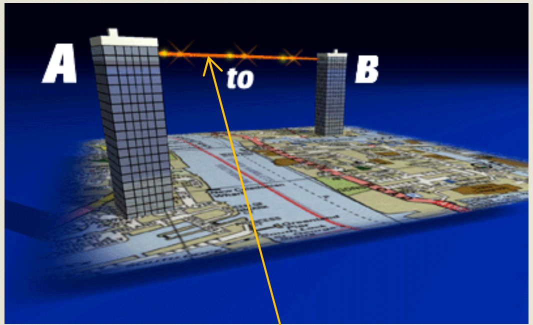
- **High link capacity** (bit rate> 1 Gbs) with respect to RF/MW technologies
- Reduced costs for **installation and maintenance** with respect to optical fiber technologies
- Highly directional beams and larger robustness with respect to the risk of **interception and intereference**
- Optical frequencies not subject to **spectrum regulation** with less bureaucratic costs
- Effective low cost **modulation schemes** such as BASK (i.e., On-Off Keying, OOK)



Disadvantages:

- High attenuation along the line-of-sight between TX and RX due to particulates, such as **aerosols, fog, rain and/or snow**
- Significant fading due to atmospheric **turbulence** causing strong scintillation and possibly to accidental **obstacles and volatiles**
- Need of **hybrid (FSO + RF/MW) links** to guarantee high availability larger than 95% (up to 99.9%)

FREE SPACE OPTICS
Applications and objectives



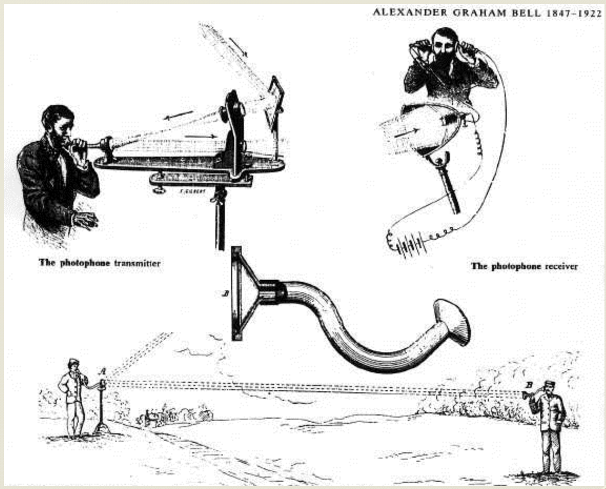
Larger than 2.5 Gbit/s

Applications:

- **Point-to-point** link between buildings in urban environment
- Optical communications between **space and Earth** and inter-satellite
- Penetration to **inaccessible areas** where RF cable and optical fibers are useless
- Distribution of digital connectivity in **LAN areas** where cable/fiber installation are costly

Objectives

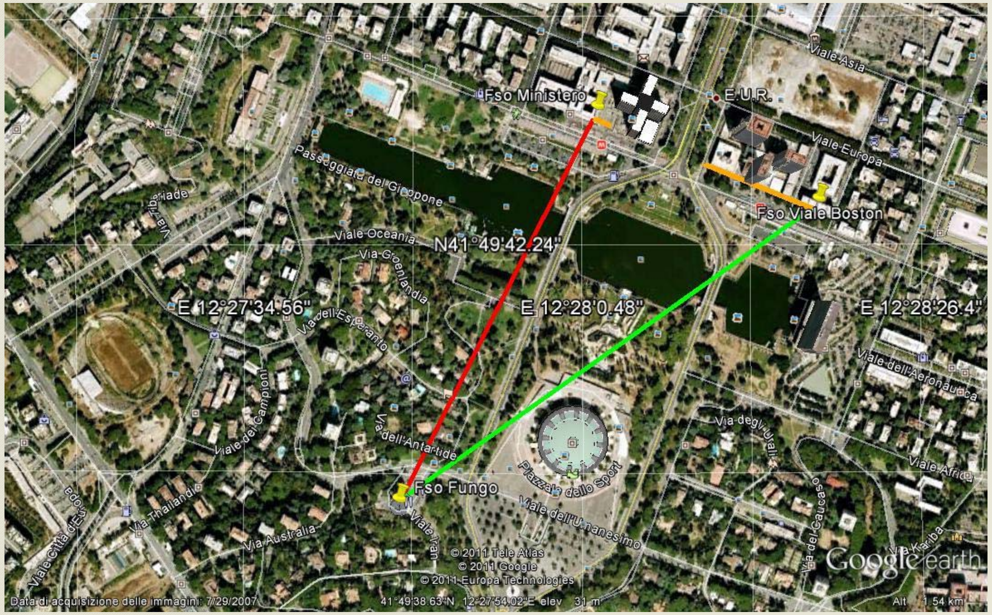
- **Description** of an urban FSO high-capacity link at 1550 nm
- **Channel modeling** of FSO link at 1550 nm due to weather effects
- **Preliminary results** by comparing measurements/predictions



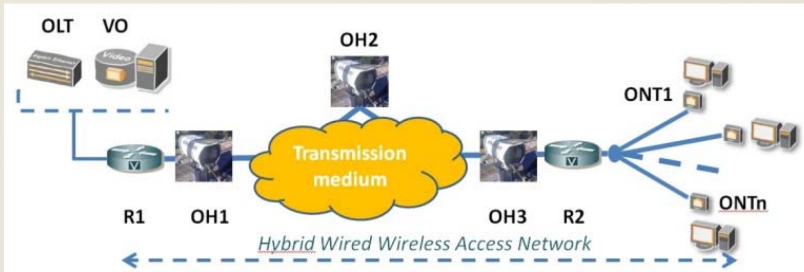
OUTLINE

- Introduction
- FSO high-capacity urban link at 1550 nm
  - Location and geometry
  - FSO trans-receivers
  - Meteorological instrumentation
- Weather effects on FSO links
  - Fog and precipitation (rain and snow)
  - FSO link budget
- FSO urban link data examples
  - Measurements
  - Case studies
- Conclusions

URBAN FSO LINK
Rome test bed



Simulation and experimentation activity in joint collaboration with ISCOM and both University of Rome "La Sapienza" on optical propagation and University of Rome "Tre" on QoS and Broadband Access.



Roman Test Bed site made by:

1) 4 Sona beam 1250-E heads
2) 1 Meteo station and Rain gauge
3) 1 Disdrometer (drop size distribution)
4) 1 Visibilimeter
5) 1 Videocamera
6) 1 MMW radiometer

Towards a full operative Wireless Wired test bed. OLT: Optical Line Termination, VO: Video Overlay, OH: Optical Head, ONT: Optical Network Termination, R: Router.

URBAN FSO LINK
Experimental set up at 1550 nm

- **Site:** Rome, EUR area across an **artificial lake**
  - Vegetation and close to **high traffic road**
  - **Triangle geometry**:

A: Viale America, ISCOM building (25 m high)

B: EUR Fungo Tower (50 m high)

C: Viale Boston, Dept Commerce Building (25 m high)

  - **Link A-B**: about 800 m;
  - **Link C-A**: closed loop by optical fiber and 850 FSO
  - **FSO heads**: 2 SONAbeam® at 1550 nm in A and B

URBAN FSO LINK
The EUR Fungo tower site

- **Site**: EUR Fungo tower at 50 m
  - Agreement with EUR SpA
  - SONAbeam® 1250-E head for A-B
  - Radio link to ISCOM building in A
  - Power load: 50 W FSO
  - Undergoing characterization: FSO link B-C (Tower-Roof2)


URBAN FSO LINK

Optical transceiver at 1550 nm

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SONAbeam 1250-E

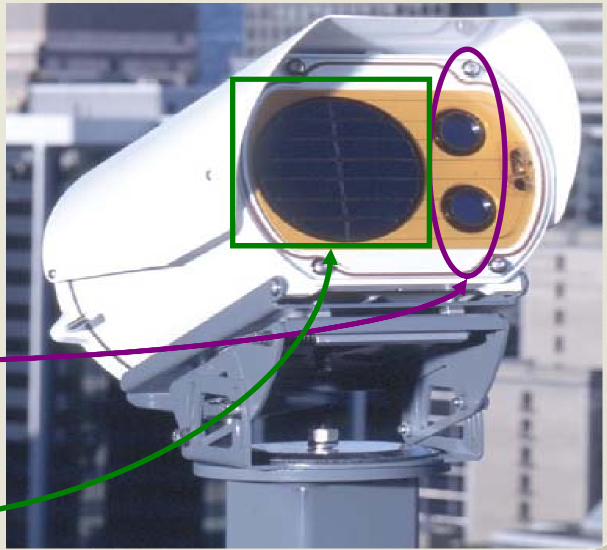
- Supporting OC-3/STM-1, OC-12/STM-4, Fast Ethernet, Gigabit Ethernet (1.25 Gbps) or datarate transparent transmission and offers the added reliability of clock data-rate recovery (CDR)
- Managed over Ethernet and it is IP addressable

Mechanical / Electrical / Environmental

Operating temperature	-40 to 60°C (-40 to 140°F)
Solar filters	2 spatial, 2 spectral
Pointing stability	120 km/h (75 mp/h) operating, >160 km/h (100 mp/h) survivability
Environmental seal	Water-tight, IP66 and NEMA-4 certified
Dimensions (W*H*D)	cm: 25 x 33 x 46 (in: 10 x 13 x 18)
Weight	Optical Head: 10 kg (22 lbs);
Input voltage	22-57 VDC or 85-260 VAC
Power consumption (electronics & heater)	50 watts, max

Free-Space Optical

Transmission rates	100 - 1602 Mbps (datarate transparent or reclocked) Clocked datarates: Fast Ethernet, Gigabit Ethernet, OC-3/STM-1, OC-12/STM-4
Operational range	3 dB/km clear air: 50 m to 3600 m (160 ft to 2.0 mi) 10 dB/km extreme rain: 50 m to 1710 m (160 ft to 1.1 mi)
Laser output power	320 mW (2 transmitters at 160 mW)
Free-space wavelength	1550 nm
Transmitter type	Directly modulated laser diode
Receive aperture	10cm (4 in) diam. (effective clear aperture)



URBAN FSO LINK
Meteorological instrumentation

- **Meteo station at site A**
  - 1 station pTq (pressure, temp., humidity)
  - 1 raingauge and 1 anemometer

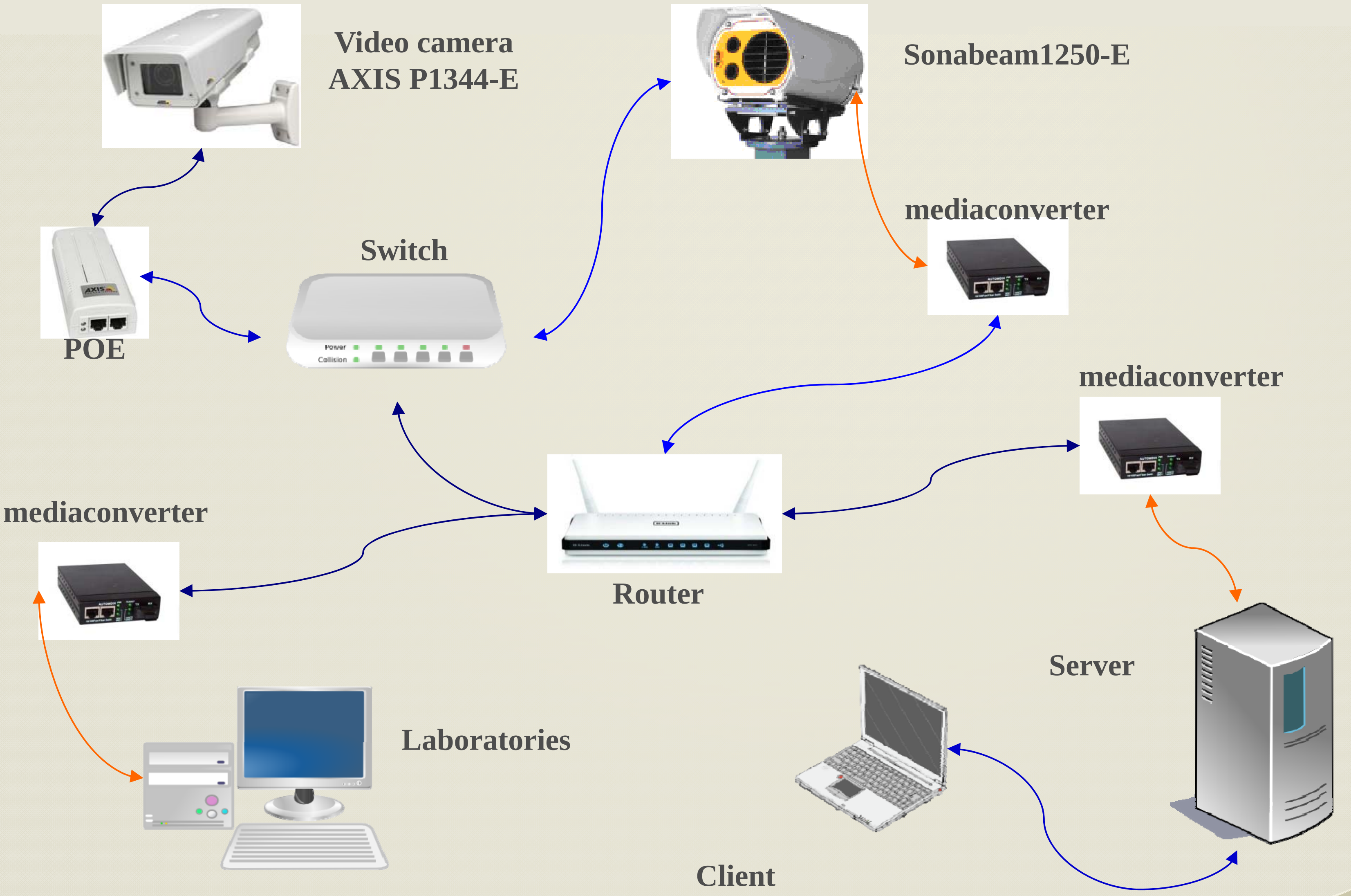
- **Disdrometer & Visibilimeter**
  - Particle size spectrum using a laser at 830 nm
  - Fog density and visibility
  - Installed on spring 2012

- **Radiometer at mm-wave (90 GHz)**
  - Integrated water vapor and cloud liquid
  - Lab. development to be completed within 2012

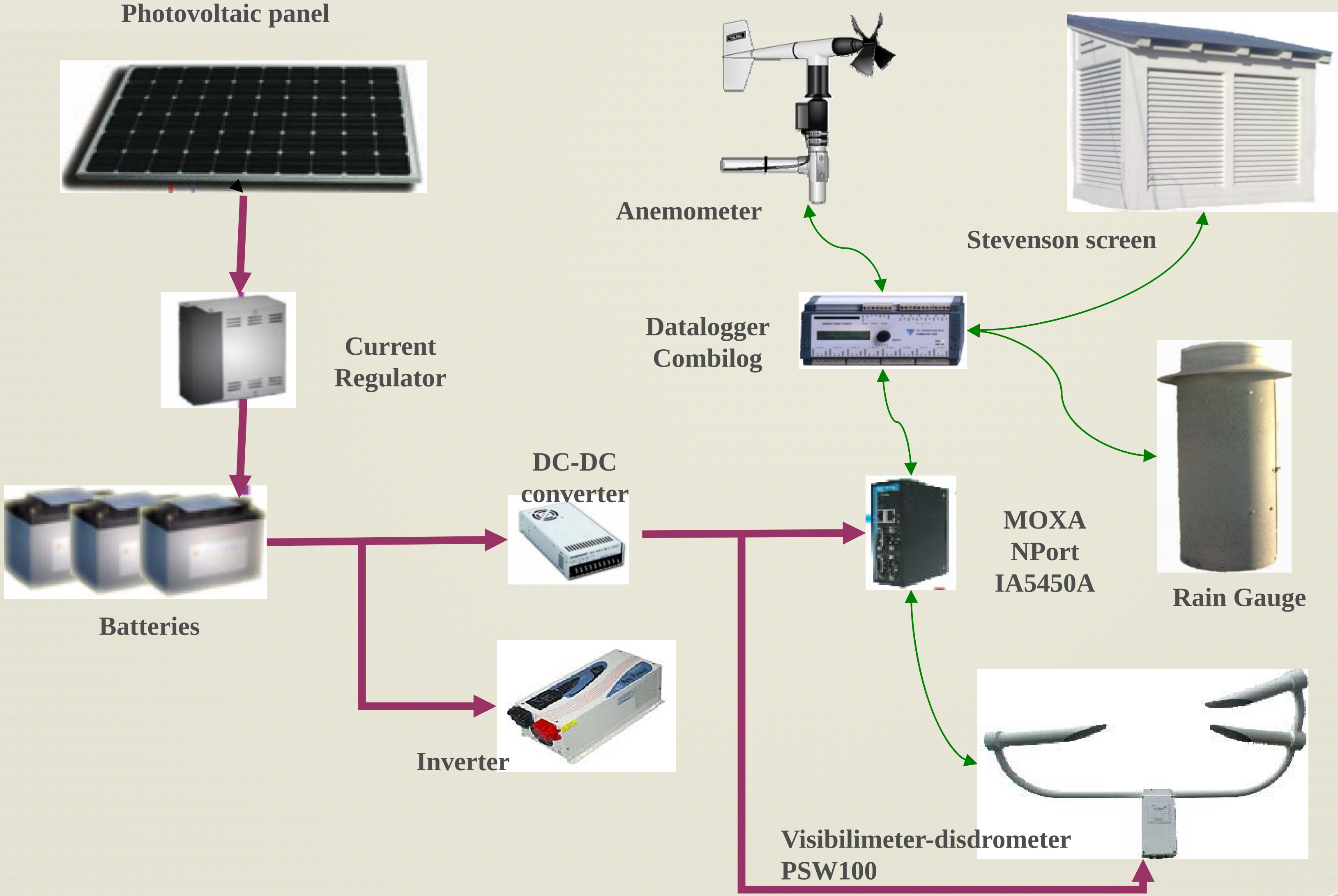
- **Video camera**
  - FSO link video-monitoring (VIS+NIR channel)
  - Visibility estimation through image processing

URBAN FSO LINK

FSO+video experimental set up



URBAN FSO LINK
Meteorological network



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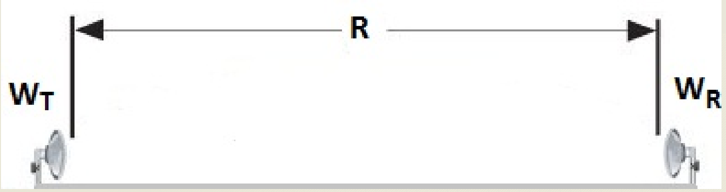
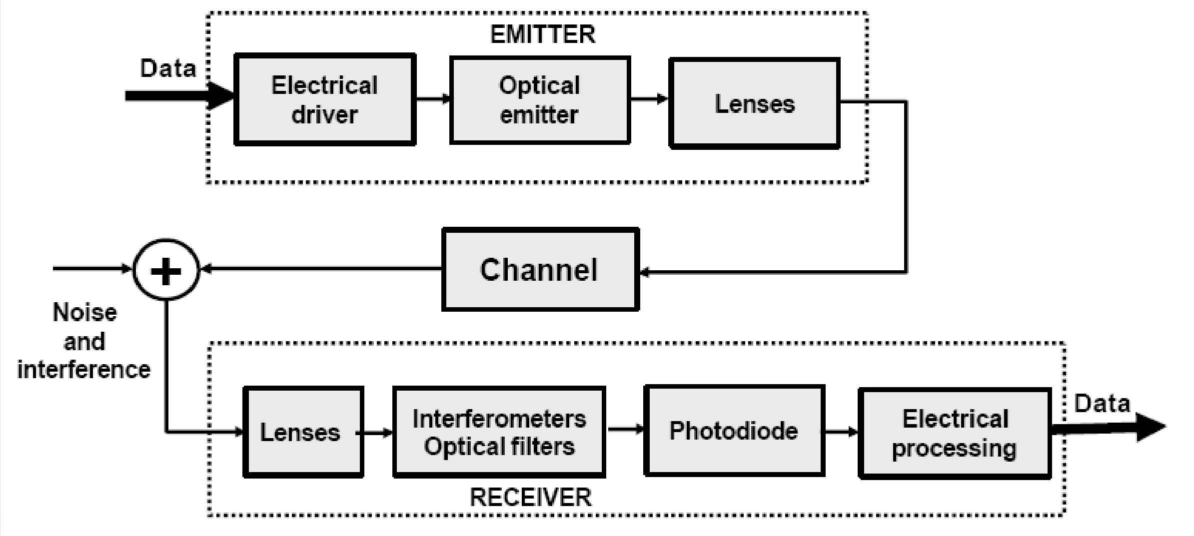
FSO CHANNEL MODELING
Optical systems

Optical link:



- **Free space (vacuum):** $W_R = W_T D_T D_R \left(\frac{\lambda}{4\pi R}\right)^2$ → $L_{FS} = \left(\frac{\lambda}{4\pi R}\right)^2$
- **Channel extinction:** $W_R = W_T D_T D_R L_{FS} L_{PA}$ → $L_{PA} = e^{-\alpha_{SP} R}$



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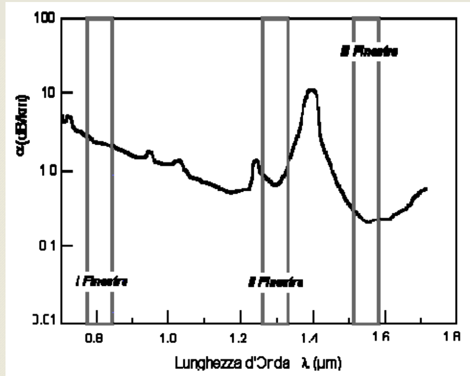
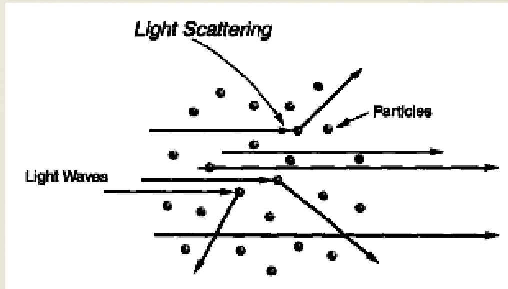
FSO CHANNEL MODELING
Weather effects

Absorption: part of the optical beam energy is captured by **gas molecules** (water vapor, carbon dioxide, ozone) and **medium particulates** (aerosols, hydrometeors), if present.
Optical windows: 850 nm and 1550 nm



Scattering: interaction between beam photons and **medium particles** causing the deviation of the optical beam:

- Aerosols (1-20 μm size, solid)
- **Fog (1-20 μm size, liquid)**
- **Rain (0.1-8 mm, liquid)**
- **Snow (0.1-10 mm size, ice-air)**



Turbulence: random variability of temperature and humidity, inducing **refractivity fluctuation** and eddy cascade in the inertial energy range, causes signal **scintillation** in amplitude and phase.
Beam wander can be also associated to refractivity variability.

FSO CHANNEL MODELING
Extinction due to fog (1/2)

***$N_p(r)$*: particle size distribution (PSD), i.e. # particles per unit volume and radius *r* size.**

$$N_p(r) = N_e \left(\frac{r}{r_e}\right)^{\mu_e} e^{-\Lambda_e \left(\frac{r}{r_e}\right)}$$

Units: [m^{-3} mm^{-1}]

$$\begin{cases} N_e = 10^3 W_p \dfrac{3\Lambda^{4+\mu_e}}{4\pi\rho_p} \dfrac{1}{r_e^4} \dfrac{1}{\Gamma(\mu_e+4)} \\ \Lambda_e = \dfrac{\Gamma(\mu_e+4)}{\Gamma(\mu_e+3)} \end{cases}$$

***W_p*: liquid water content due to sphere-equivalent particles.**

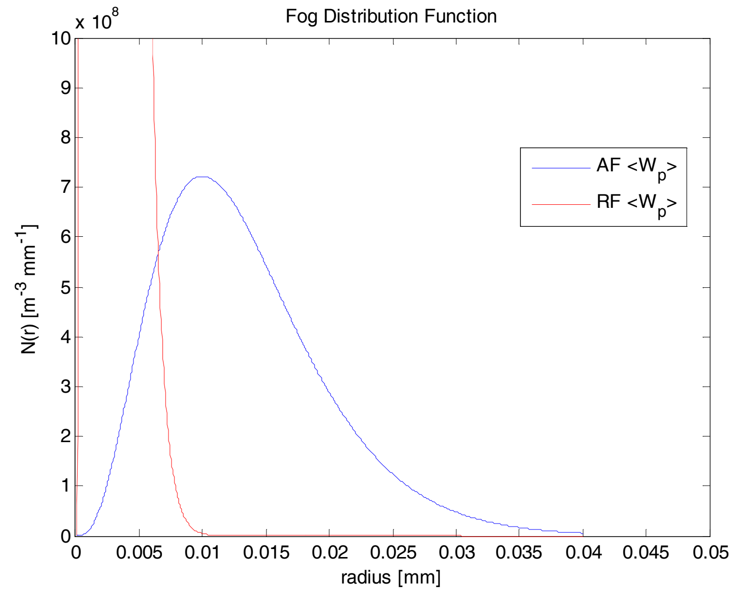
$$W_p \equiv \int_0^\infty \left(\frac{4}{3}\pi r^3\right) \rho_p N_p(r)\, dr$$

Units: [g cm^{-3}]

Radiation fog: related to the ground cooling by radiation, it appears when the air is sufficiently cool and becomes saturated.

Advection fog: is formed by the movements of wet and warm air masses above colder maritime or terrestrial surfaces [Gebhart et al., 2005].

Class	W_p [g m^{-3}]	r_e [mm]	μ [adim]	N_e [adim]	Λ_e [mm^{-1}]
Advection Fog	$0.0 \le W_p \le 0.4$	$0.019 \le r_e \le 0.021$	$2.9 \le \mu \le 3.1$	$5.2 \cdot 10^7 \le N_e \le 3.0 \cdot 10^{11}$	$5.9 \le \Lambda_e \le 6.1$
Radiation Fog	$0.0 \le W_p \le 0.02$	$0.001 \le r_e \le 0.006$	$1.0 \le \mu \le 5.0$	$1.4 \cdot 10^{10} \le N_e \le 3.5 \cdot 10^{15}$	$4.0 \le \Lambda_e \le 8.0$



FSO CHANNEL MODELING
Extinction due to fog (2/2)

Extinction coefficient

$$\alpha_e = 10\log_{10}\left(\int_{r_m}^{r_M} \sigma_e(r) N_p(r) dr\right) \quad \text{dB/km}$$

σ_e extinction cross section

Parametric models :

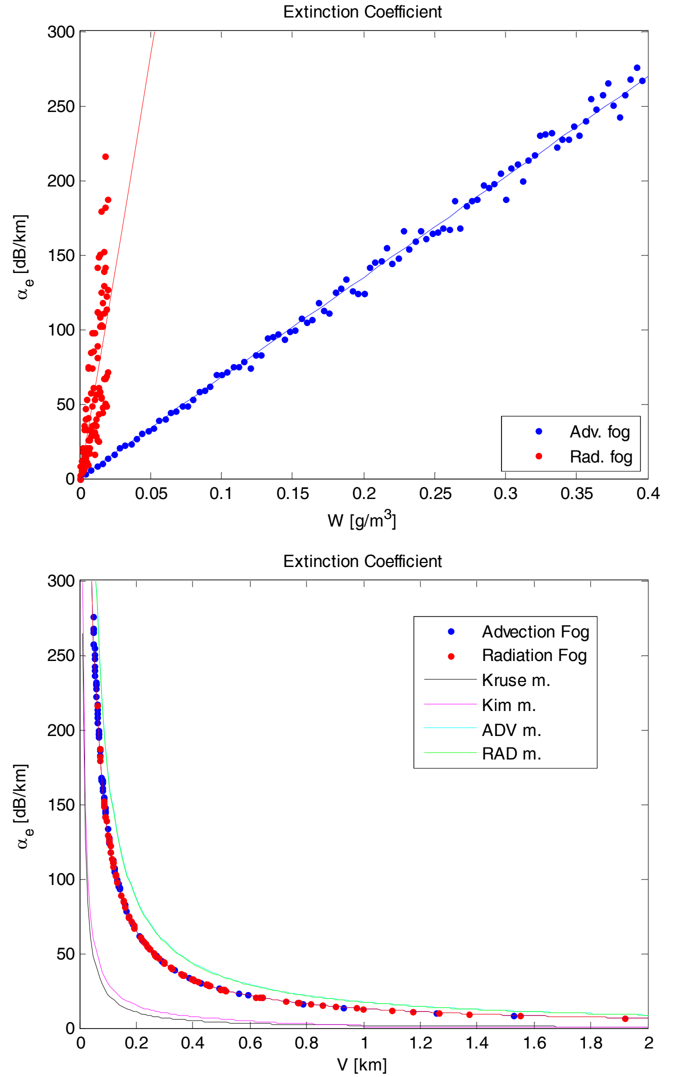
$$\alpha_{e\_fog} = \frac{10\log(V_{\%})}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q}$$

V = visibility [km], λ = wavelength [nm]
V% transmission of air drops to percentage of clear sky
λ_0 = reference wavelength (550 nm)
q = scattering spatial distribution coefficient

Formulas from [Kim et al., 2001]:

$$q = \begin{cases} 1.6 & V > 50\ km \\ 1.3 & 6\ km < V \le 50\ km \\ 0.16V + 1.34 & 6\ km < V \le 50\ km \\ V - 0.5 & 0.5\ km < V \le 1\ km \\ 0 & V \le 0.5\ km \end{cases}$$

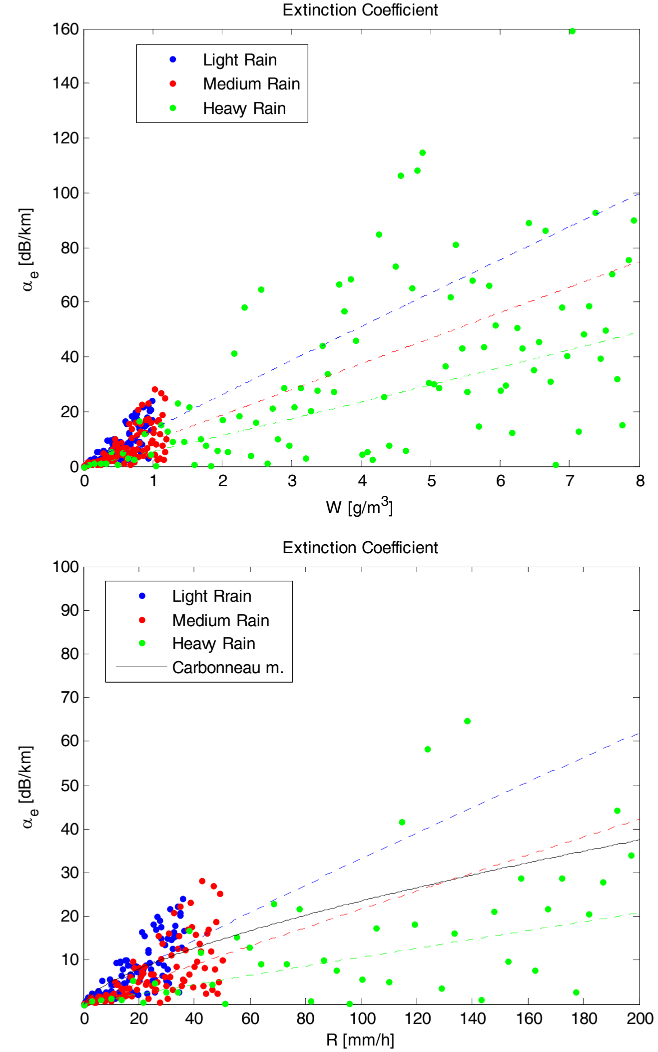
Other parameteric models:
- [Kruse et al., 1962]
- [Al Naboulsi et al., 2004]: ADVection and RADiation fog



FSO CHANNEL MODELING
Extinction due to rain

Rain can be categorized according to raindrops mean diameter D_0 in light (D_0<1mm), medium (1mm<D_0<2mm) and heavy (D_0>5mm) [Straka et al., 2000].

Raindrops can have radii up to 8 mm (breakdown with oblate shapes).



Empirical model:

$$\alpha_{e\_rain} = aR^b$$

R = Rain Rate [mm/h]

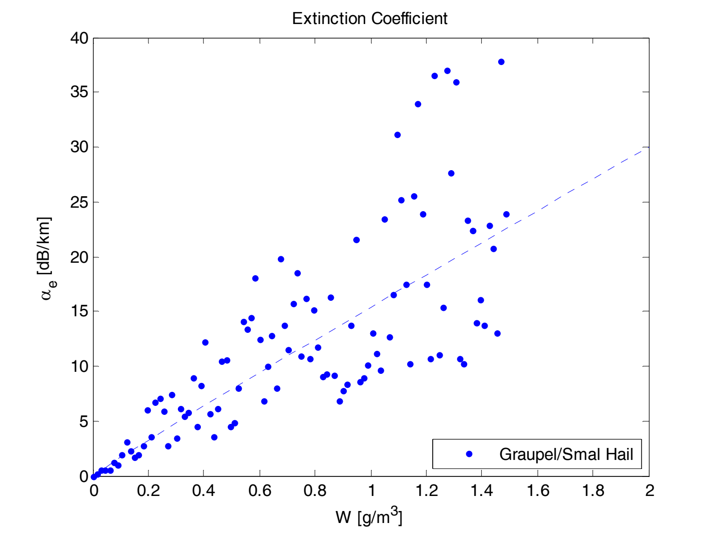
a=1.076, b=0.67 [Carbonneau et al., 1998]

Physical model:

Class	W_p [g m^{-3}]	r_e [mm]	μ [adim]	N_e [adim]	Λ_e [mm^{-1}]
Light Rain	$0.0 \le W_p \le 1.0$	$0.3 \le r_e \le 1.5$	$-1.0 \le \mu \le 4.0$	$3.5 \le N_e \le 1.3 \cdot 10^7$	$2.0 \le \Lambda_e \le 7.0$
Medium Rain	$0.0 \le W_p \le 1.2$	$0.5 \le r_e \le 2.0$	$-1.0 \le \mu \le 4.0$	$3.7 \le N_e \le 2.5 \cdot 10^6$	$2.0 \le \Lambda_e \le 7.0$
Heavy Rain	$0.0 \le W_p \le 8.0$	$0.7 \le r_e \le 3.0$	$-1.0 \le \mu \le 4.0$	$2.3 \le N_e \le 5.4 \cdot 10^6$	$2.0 \le \Lambda_e \le 7.0$

FSO CHANNEL MODELING
Extinction due to Snow

Snow can be considered an aggregate of air and ice (Dry Snow) or air, water and ice (Wet Snow). Large aggregates can reach D≅20-50mm, while density rages from 50 to 900 kg m^{-3} [Straka et al., 2000].

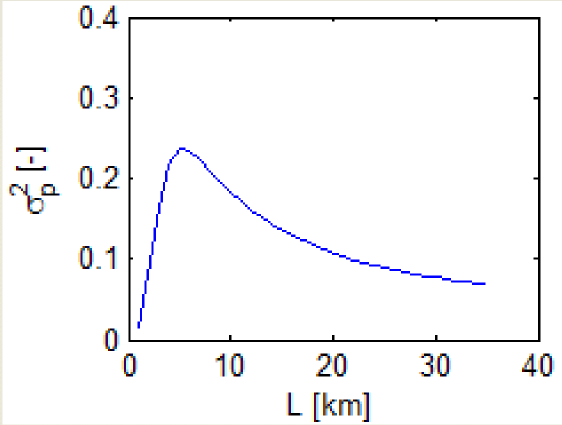


Graupel (0.5mm<D<5mm) coexist often with Small Hail (5mm<D<20mm) and are indistinguishable. The density of Graupel/Small Hail can range from 100 to 900 kg m^{-3} [Straka et al., 2000].

Physical model:

Class	W_p [g m^{-3}]	r_e [mm]	μ [adim]	N_e [adim]	Λ_e [mm^{-1}]
Graupel Small Hail	$0.0 \le W_p \le 1.5$	$0.8 \le r_e \le 2.5$	$0.0 \le \mu \le 0.0$	$4.0 \cdot 10^2 \le N_e \le 1.0 \cdot 10^4$	$3.0 \le \Lambda_e \le 3.0$
Dry Snow	$0.0 \le W_p \le 1.0$	$0.7 \le r_e \le 1.0$	$0.0 \le \mu \le 0.0$	$1.5 \cdot 10^1 \le N_e \le 6.5 \cdot 10^4$	$3.0 \le \Lambda_e \le 3.0$
Wet Snow	$0.0 \le W_p \le 1.0$	$0.7 \le r_e \le 1.0$	$0.0 \le \mu \le 0.0$	$2.0 \cdot 10^1 \le N_e \le 1.6 \cdot 10^4$	$3.0 \le \Lambda_e \le 3.0$

FSO CHANNEL MODELING
Scintillation due to turbulence



Power scintillation index σ_P

Under strong scintillation, PSI is non linearly dependent on the range (aperture averaging, saturation)

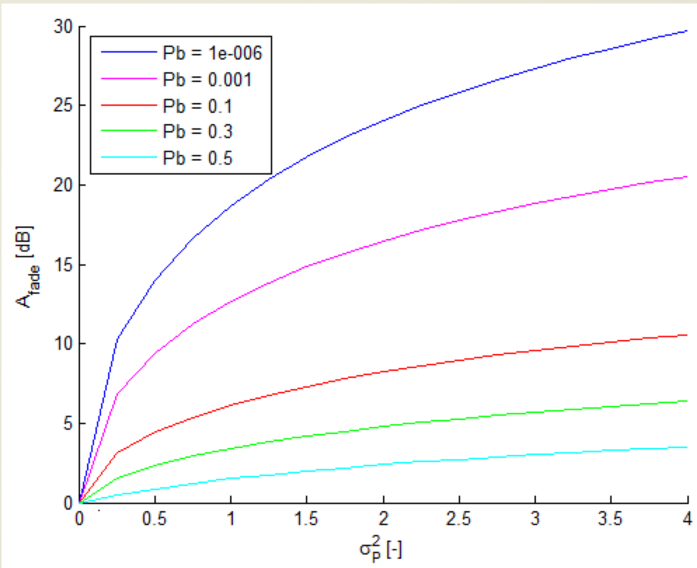
Rytov parameter β_0

Proportional to structure constant C_n^2 (average 10^{-14} $m^{-2/3}$) and $L^{11/6}$ (weak scintillation)

Scintillation fade A_{fade}

Outage probability p_B under log-normal PDF of received power (Henninger and Wilfert, 2010)

$$A_{fade}(\sigma_P^2, p_B)[\text{dB}] = -4.343\left(\sqrt{2\ln(\sigma_P^2+1)}\cdot \operatorname{erf}^{-1}(2p_B-1) - \frac{1}{2}\ln(\sigma_P^2+1)\right)$$



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FSO CHANNEL MODELING
Link budget

- FSO link margin

$$M_{link}[\text{dB}] = P_{Rx,dBm} - S_r - L[\text{km}] \cdot A_e - A_{fade}$$

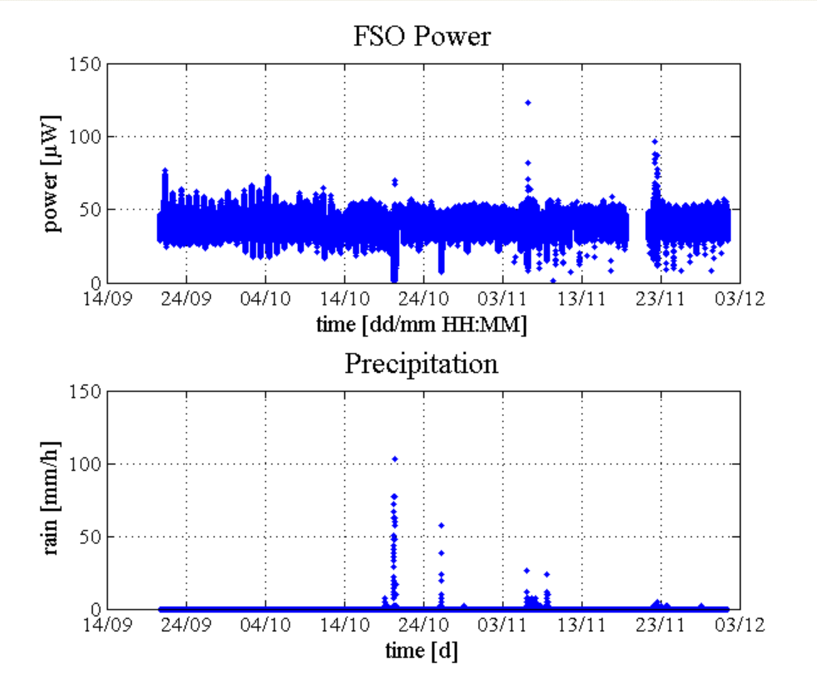
  - P_{Rx}: received power in vacuum
  - S_r: minimum power for requested BER

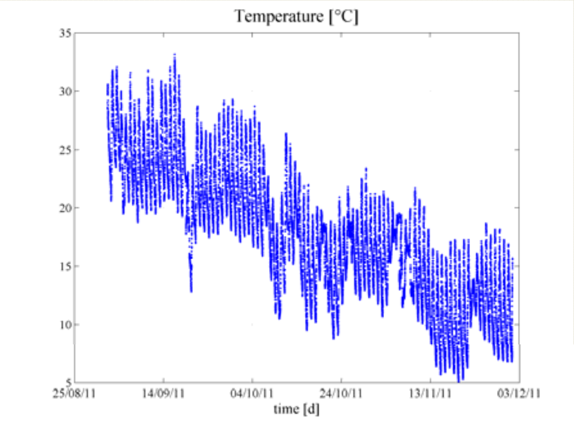
- Urban link in Rome at 1550 nm
  - $C_n^2 = 10^{-14}\ m^{-2/3} \Rightarrow$ Scintillation fade A_{fade}=1.25 dB
  - R=0.1 mm/h $\Rightarrow$ Rain extinction A_{rain}=0.2 dB
  - Outage prob.: 10^{-2}; L = 1 km;
  - Assumptions: S_r=-34 dBm; W_T=320 mW;
    D_{lens}=10 cm; BW=1 mrad; A_{sys}=0.5 dB

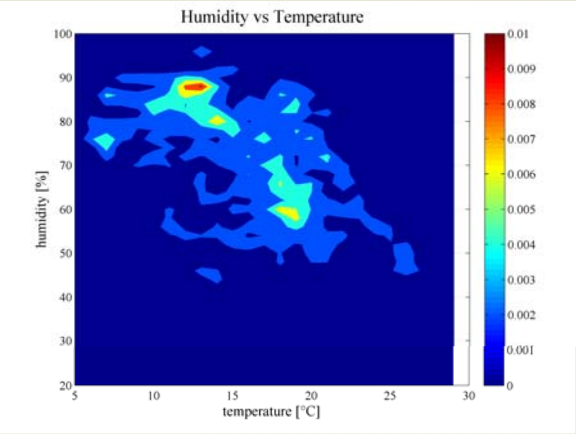
Vacuum Link Margin M_{link} = 39.1 dB
Expected Link Margin M_{link} = 37.6 dB

FSO MEASUREMENTS IN ROME
Examples of data

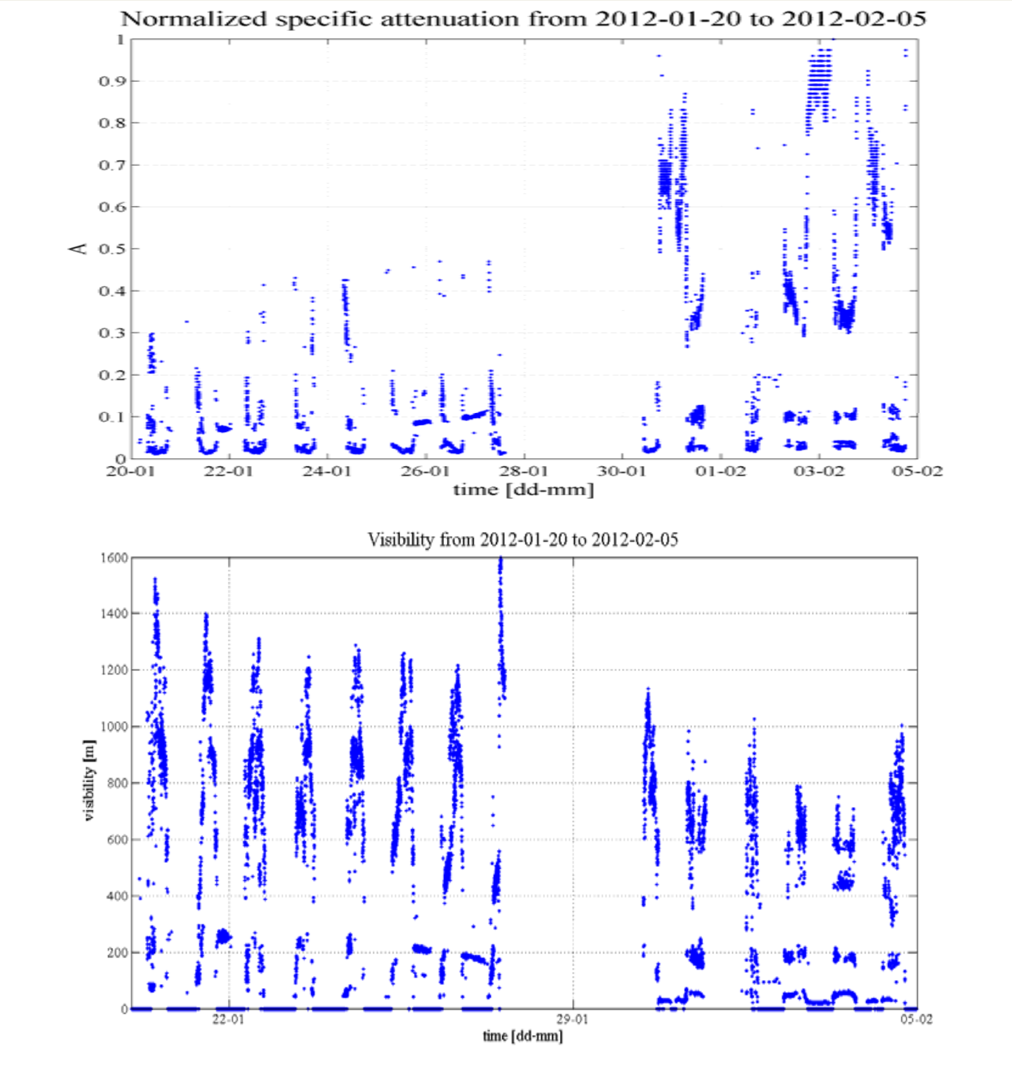
- Measured data
  - FSO link between A and B sites
  - Range=800 m
  - Meteo and raingauge data available







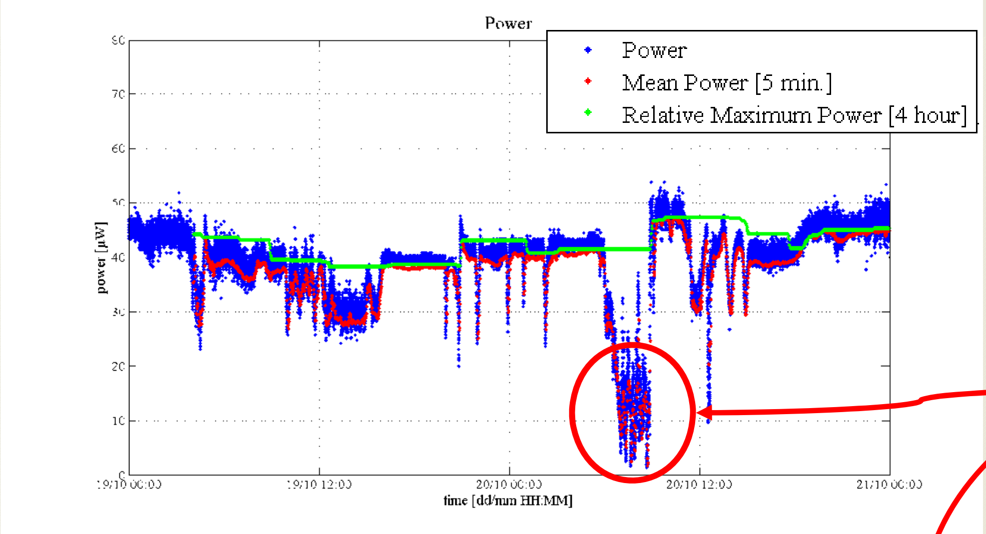
FSO MEASUREMENTS IN ROME
Visibility measurements

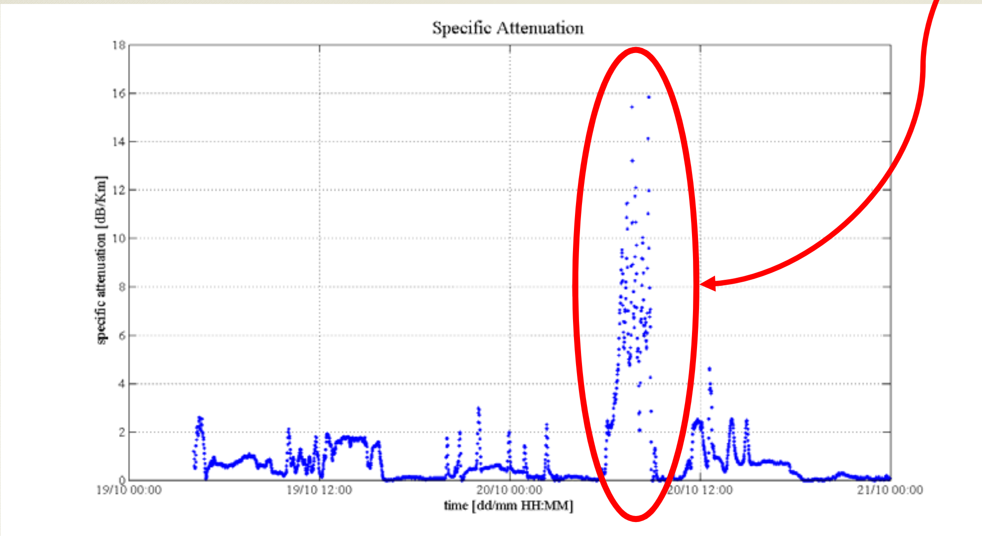


Estimated visibility and specific attenuation from parametric relation converting FSO attenuation into visibility (Kruse model) from 2012-01-20 to 2012-02-05

Note:
- Diurnal cycle
- Normalized atten.

FSO MEASUREMENTS IN ROME
Rain attenuation



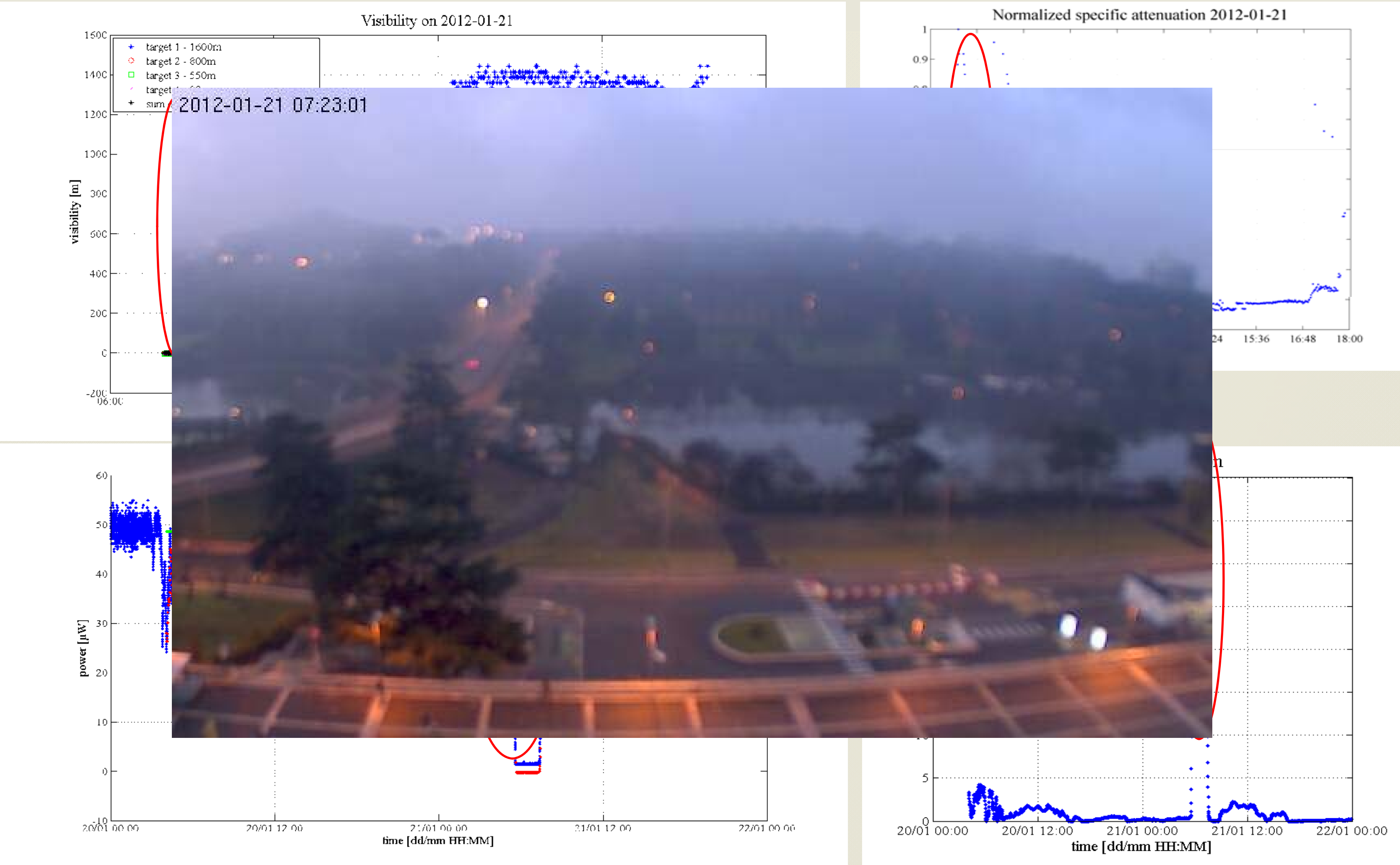


Measured power and specific attenuation on 19-21 October 2011

Heavy rain (day 20)

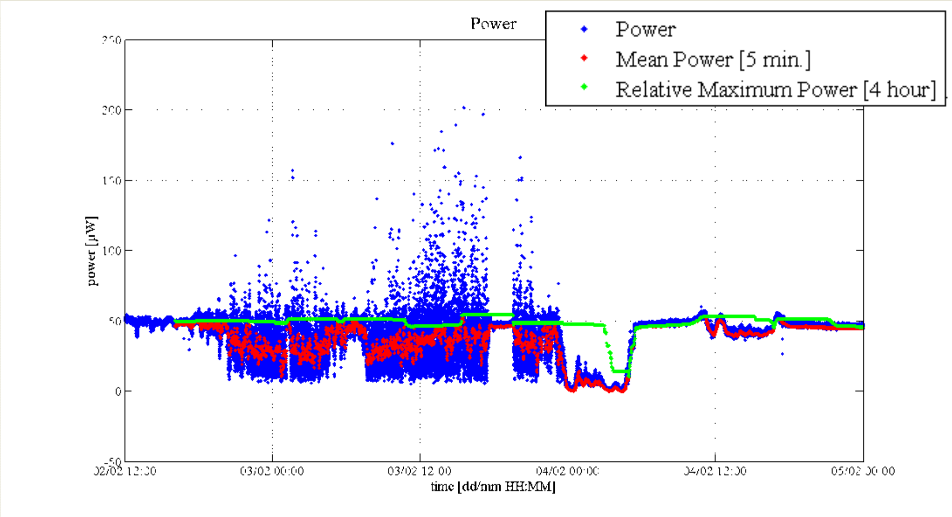
Note:
- Average power in clear air not constant
- Sporadic peaks due to the transit of birds

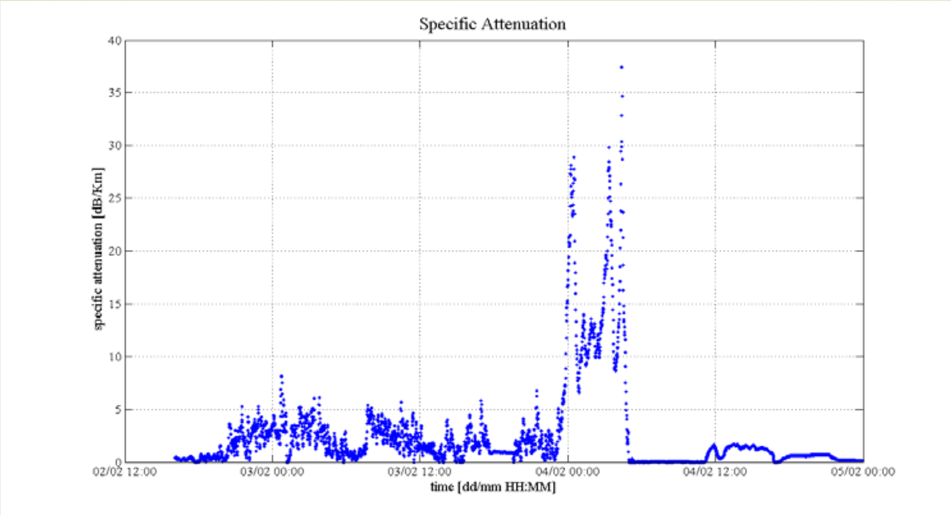
FSO MEASUREMENTS IN ROME
Fog attenuation



FSO MEASUREMENTS IN ROME

Snow attenuation

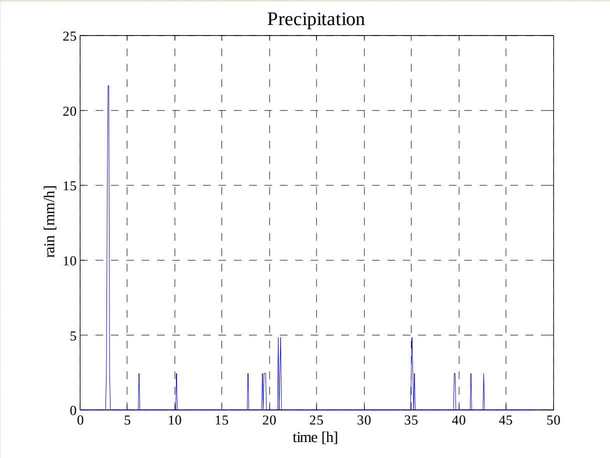




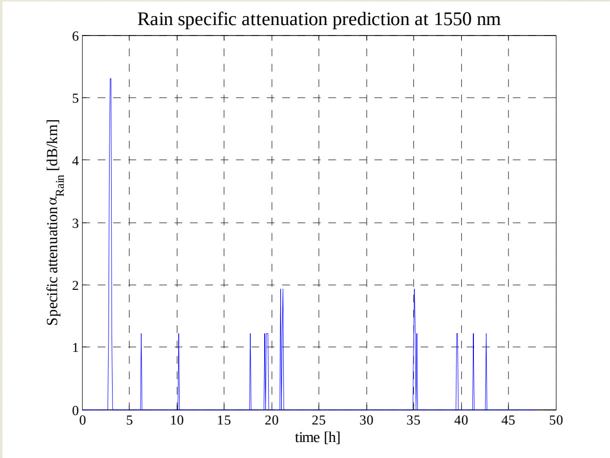
Measured power and specific attenuation on 2-4 Feb 2012

Rain attenuation

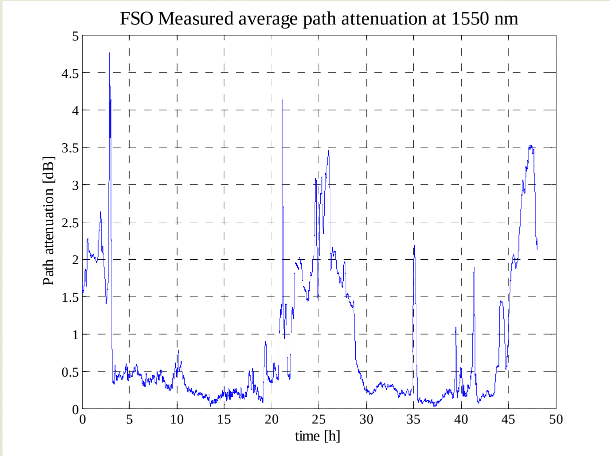
- FSO attenuation prediction using the parametric model



Predicted



Measured



CONCLUSIONS

- A **urban link at 1550 nm** has been set up in the Roman urban area; ancillary meteorological instrumentation is now almost completed.
- **Channel modeling** taking into account rain, for, snow extinction; multiple scattering and and turbulence effects are being taken into account.
- **Systematic measurement campaign** initiated at the beginning of 2012 and still on going. A **diurnal FSO trend** is noted and needs to be carefully filtered removed in order to extract meteorological effects.