Adaptive optics for GEO-Feeder links: analysis of point-ahead anisoplanatism impact via reciprocity based models

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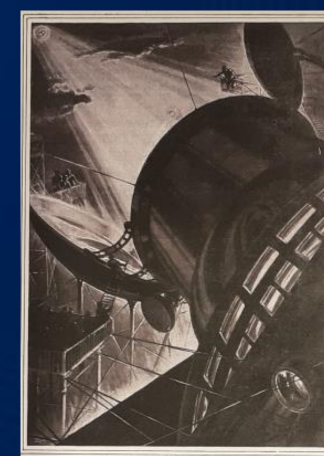

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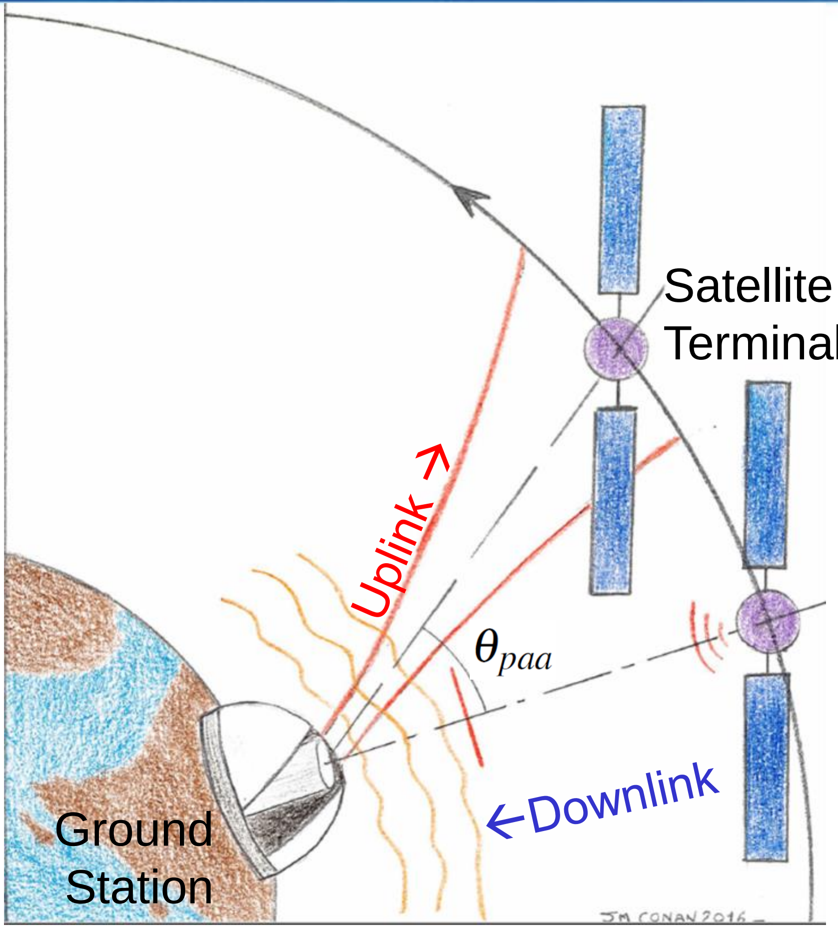
Ground - GEO Scenario : key numbers & notion of point ahead



Dist(OGS-SAT) = L_{sat} ~ 38000 km

- **LINK BUDGET** (Pupil size D_{ogs} = 50 cm & D_{sat} = 20 cm)
  - Beam size @ SAT ~ 80 m ; @ OGS ~ 200 m
  - **Geometrical Loss ~ 10^{-5} (50 dB) !**
- **POINT-AHEAD ANGLE (PAA)**
  - Round-trip light travel time τ ~ 250 ms
  - Satellite has moved of ~ 800 m during τ
  - **Point ahead angle : θ_{paa} ~ 20 µrad**
- **BEAM GEOMETRY DOWN vs UP**
  - Elevation ~ 30°
  - DOWNLINK : nearly Plane-Wave
  - UPLINK : diverging Gaussian beam @ θ_{paa}

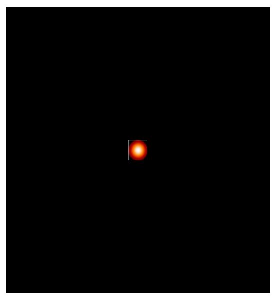
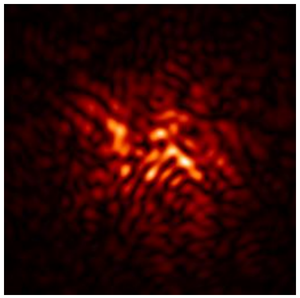
Huge geometrical losses + turbulence penalty: link budget is a critical issue!

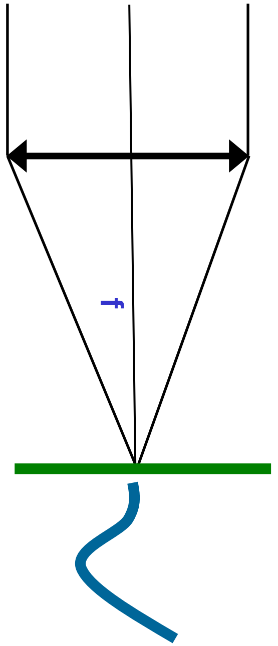
Adaptive Optics correction for this bidirectional link? effect of Point-Ahead?

*Reminder : **dB** = log scale ; factor 2 = 3 dB ; factor 10 = 10 dB*

Single Mode Fiber coupling : pupil or focal plane

Key metric: coupling efficiency

- Coupling efficiency $\rho = |\mathscr{C}|^2$
- Overlap Integral $\mathscr{C} = \int \mathscr{E}_{SMF}^*(\mathbf{r}) \times \mathscr{E}_{received}(\mathbf{r})\ dr$
- in focal plane: $\int$  x 



Adaptive optics required to maximize the coupling efficiency

Choice of ground aperture?

- **Larger D reduces aperture averaged scintillation**
- **However more demanding on AO since D/r_0 is larger**

Adaptive optics for GEO-Feeder links: Outline

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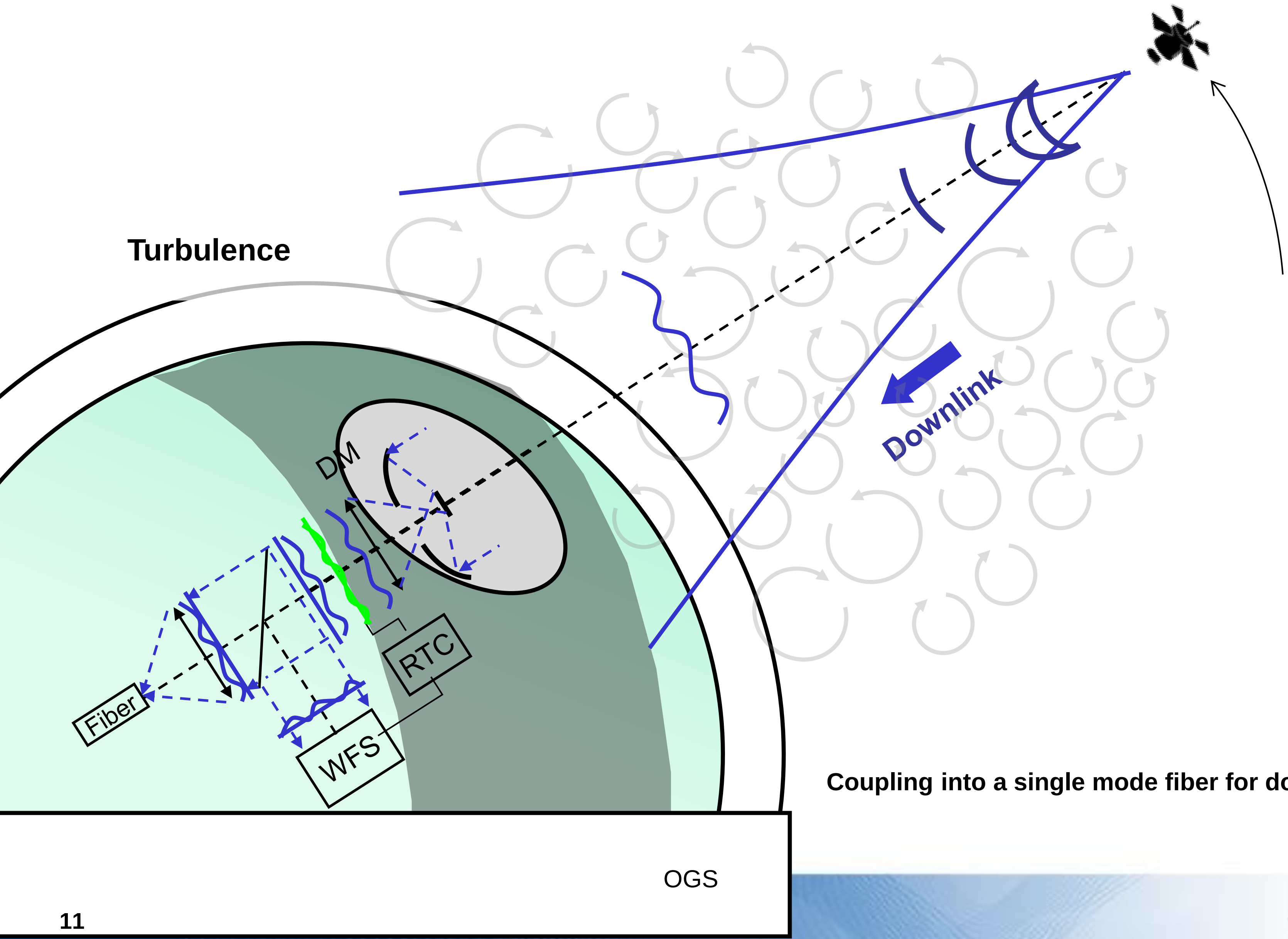
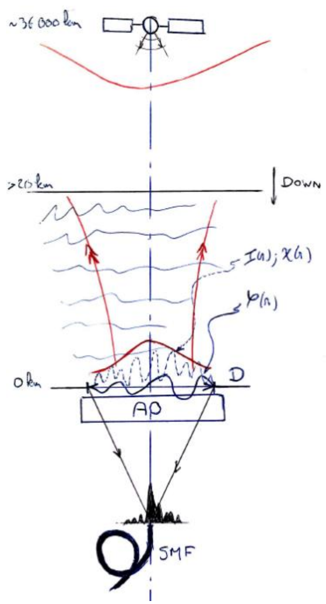
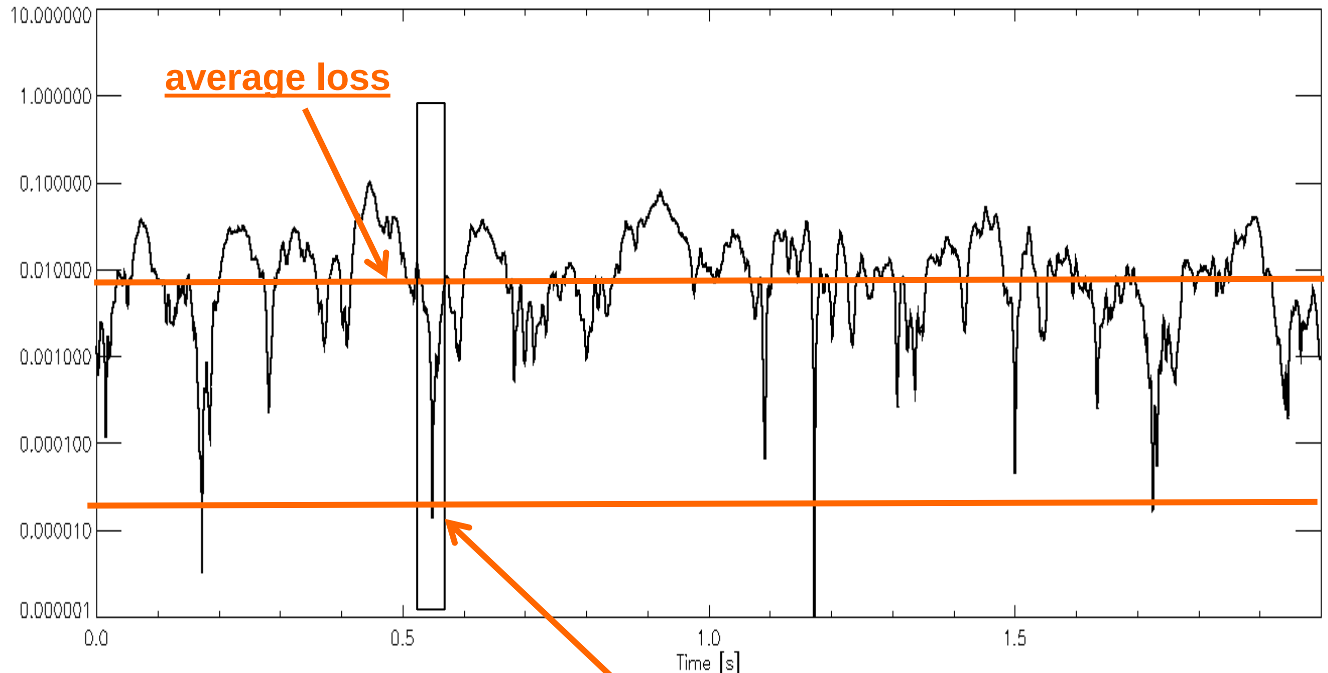
Turbulence mitigation : AO correction on downlink



Coupling into a single mode fiber for downlink

Turbulence impact : D = 50 cm ; D/r_0 = 10
i. downlink - no correction



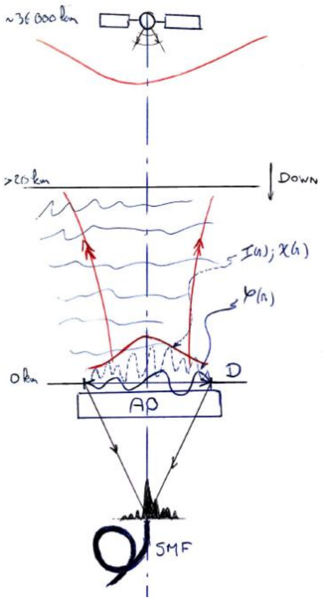


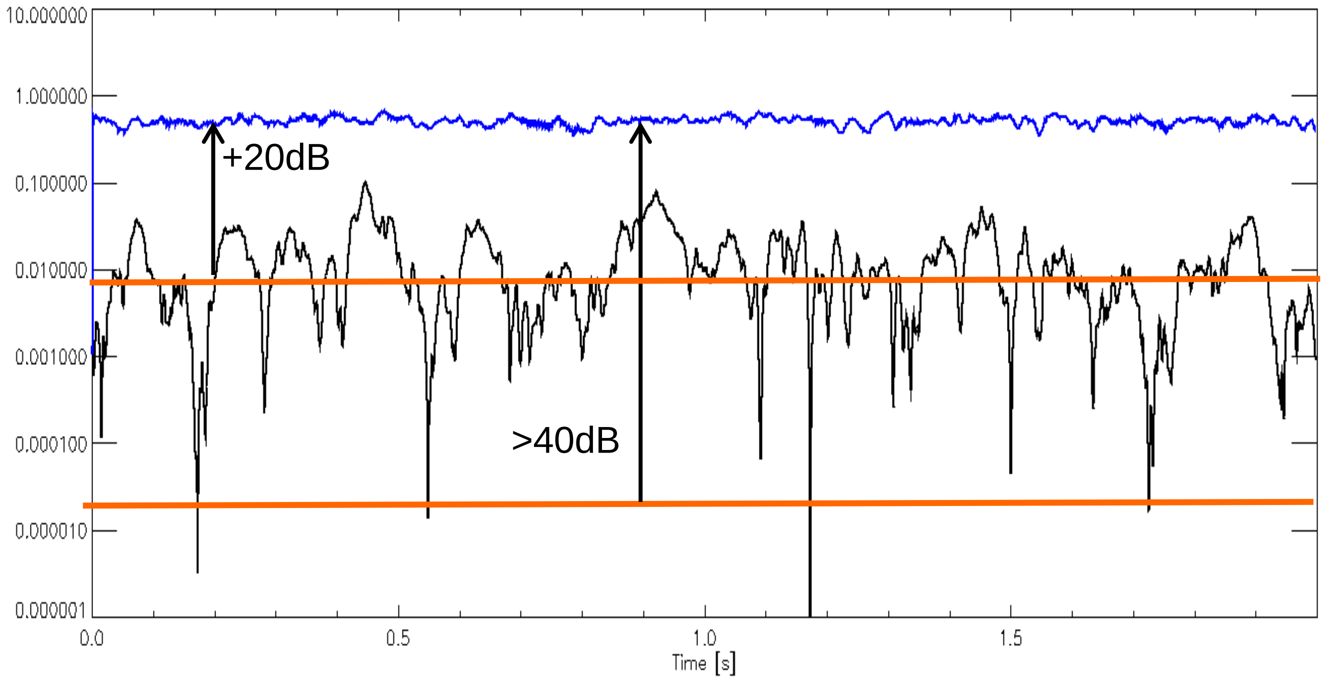
Simulation conditions :
- 1.55 µm link @ 30° elevation , distance to satellite = 38614 km
- Turbulence integrated parameters:
  - r_0 = 2 cm @ 0.55 µm at zenith
  - **r_0 = 5 cm @ 1.55 µm on line of sight**
  - **σ_χ^2 = 0.09**
  - τ_0 = 2.8 ms
  - θ_0 = 9 µrad

Deep fadings about 50 dB!
(in addition to 50 dB geometrical losses...)

*Reminder : **dB** = log scale ; factor 2 = 3 dB ; factor 10 = 10 dB*

Turbulence impact : D = 50 cm ; $D/r_0 = 10$
ii. downlink – AO correction





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AO correction brings huge reduction:
- **of the average power loss**
- **and, even more, of the fading depth**

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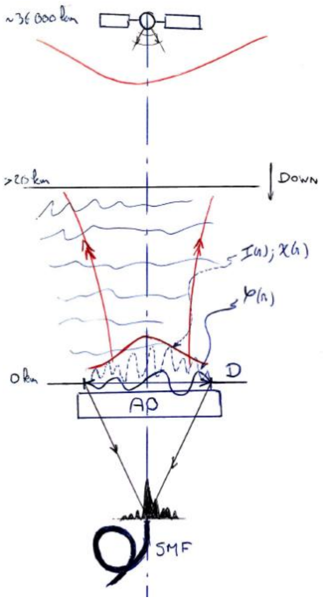

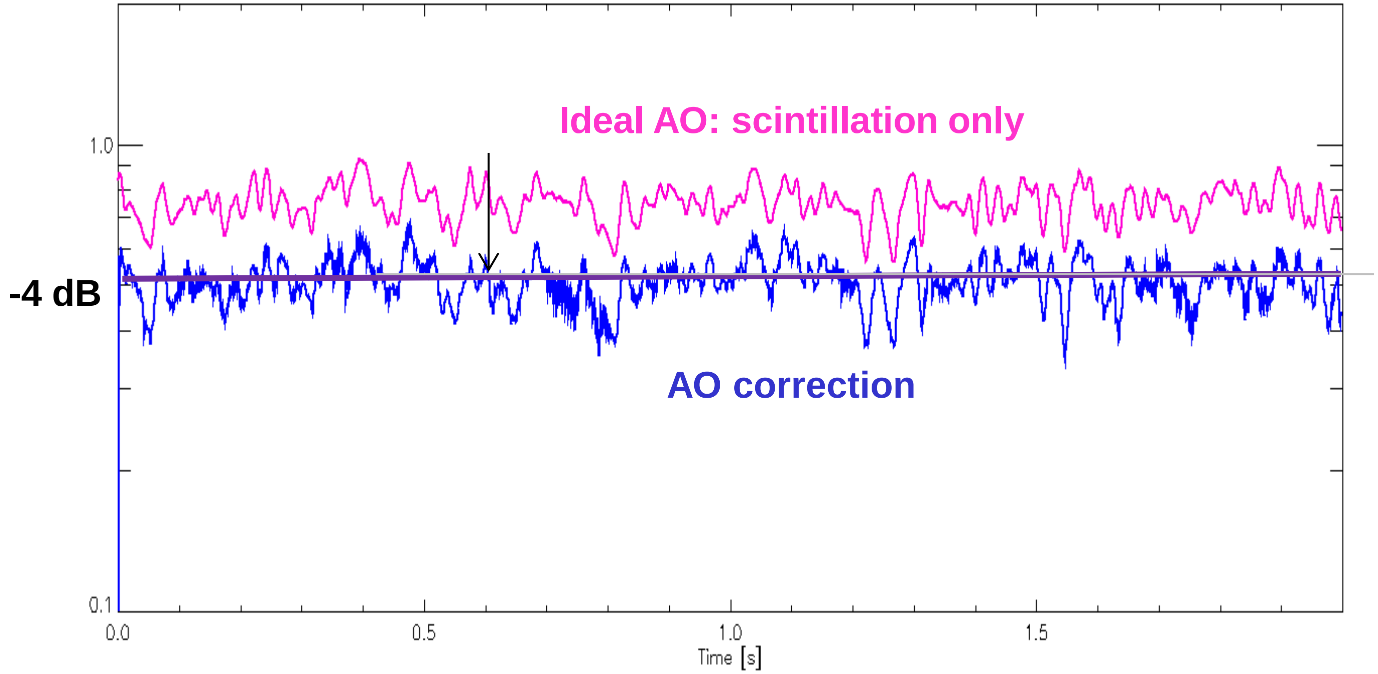

AO correction brings huge reduction:
- **of the average power loss**
- **and, even more, of the fading depth**

AO does not correct for scintillation
AO design allows to reach required perf
(here 12 Zernike radial orders, 1.5 kHz)

*Reminder : **dB** = log scale ; factor 2 = 3 dB ; factor 10 = 10 dB*

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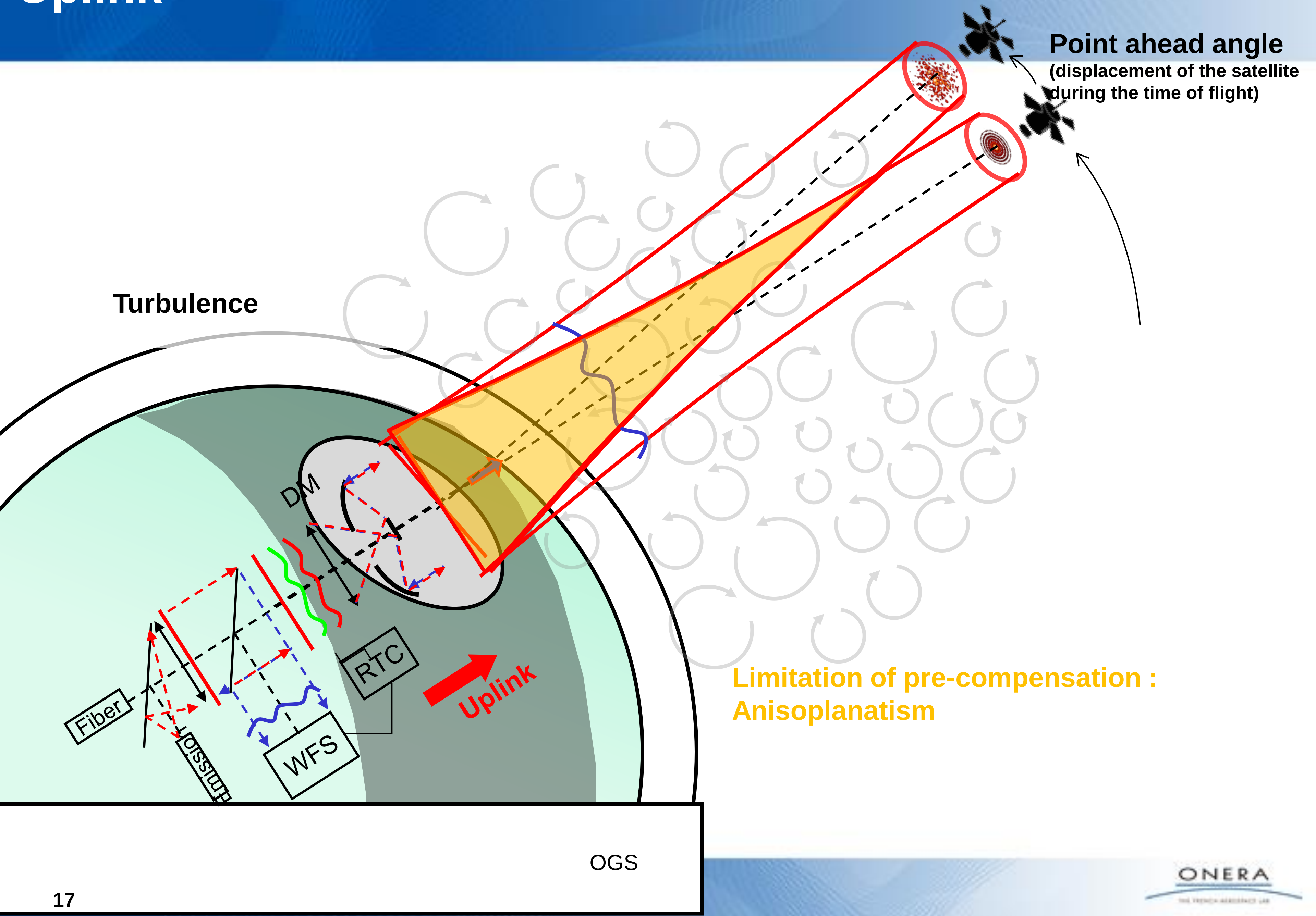
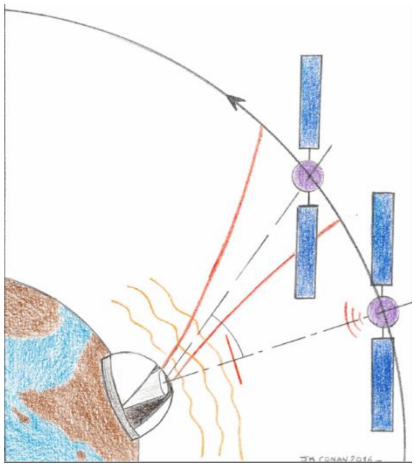
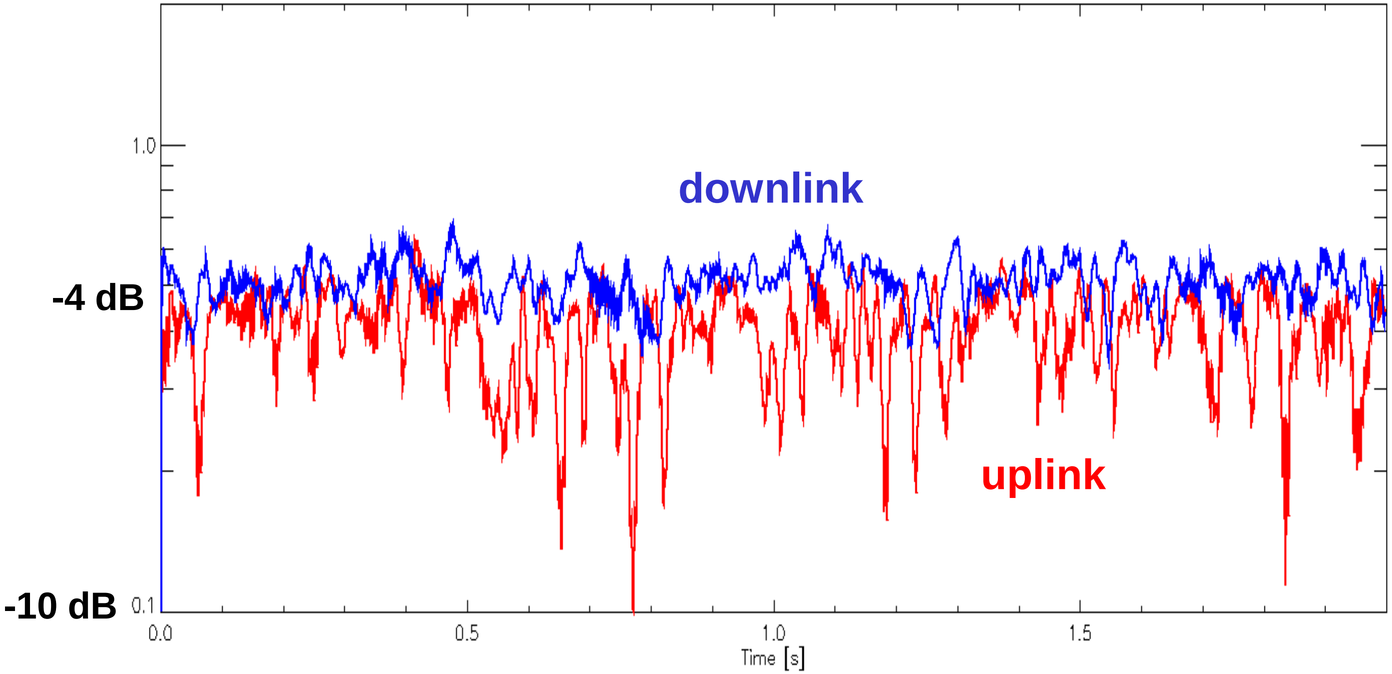
Uplink



Limitation of pre-compensation : Anisoplanatism

Turbulence impact : D = 50 cm ; D/r_0 = 10
iii. uplink : effect of point ahead anisoplanatism

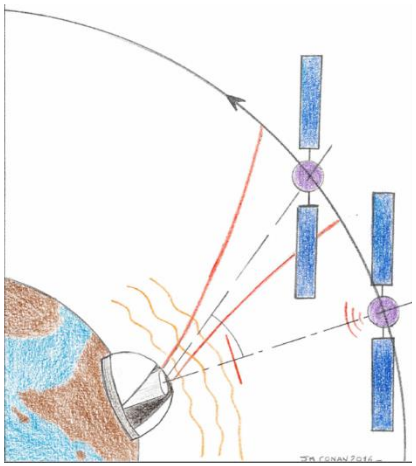


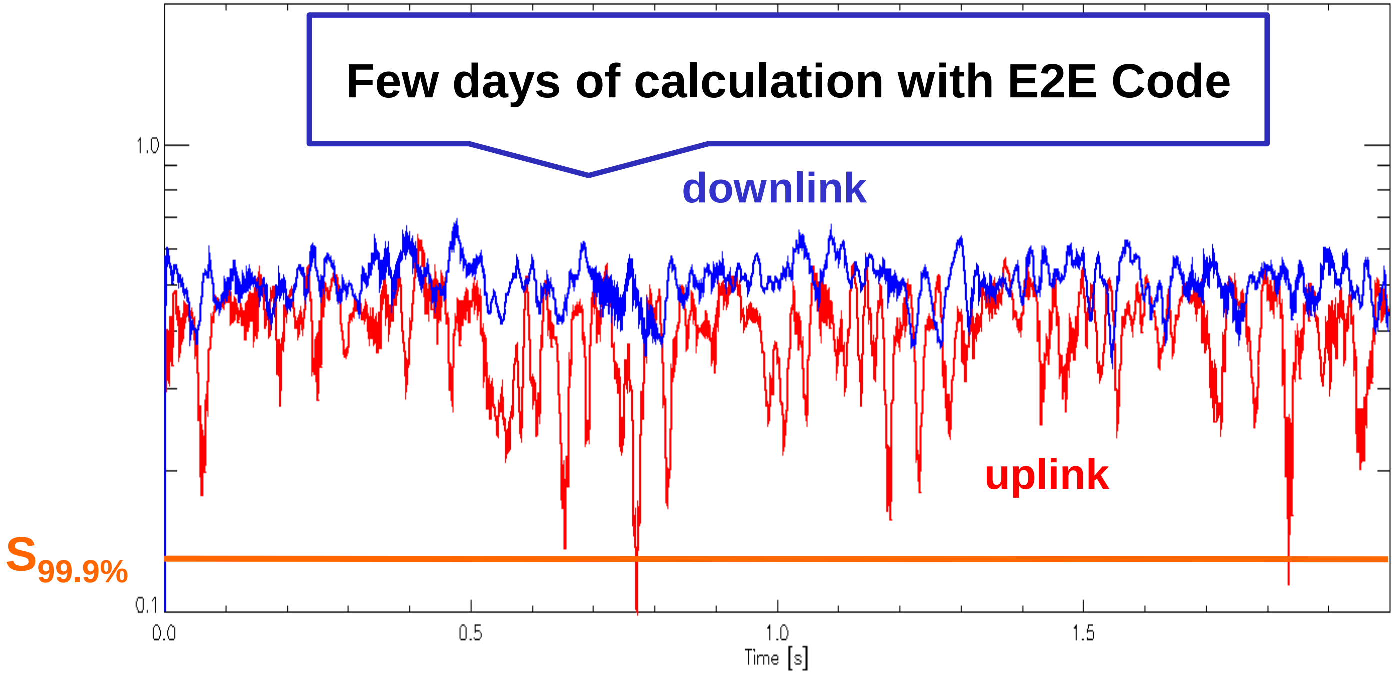


Severe loss in performance compared to down-link

*Reminder : **dB** = log scale ; factor 2 = 3 dB ; factor 10 = 10 dB*

Telecom Performance metric capturing coupling statistics: Link availability threshold @ XX%





99.9% of occurences are above $S_{99.9\%}$

$P(I > S_{99.9\%}) = 0.999$

Scalar metric to account for average loss + fluctuations

Uplink & downlink performance vs aperture diameter ?

Implies considering link availability threshold + geometrical losses

*Reminder : **dB** = log scale ; factor 2 = 3 dB ; factor 10 = 10 dB*

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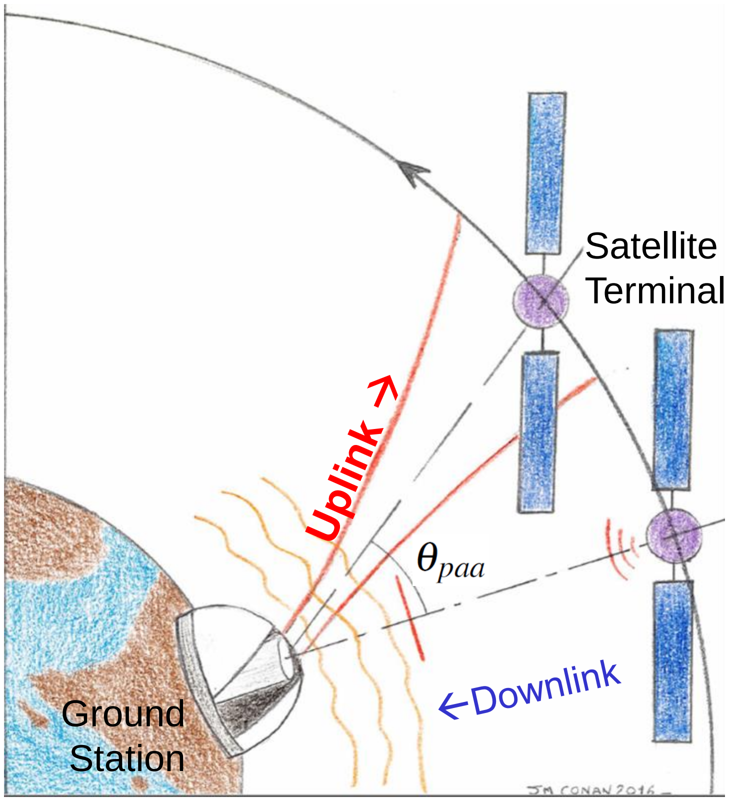
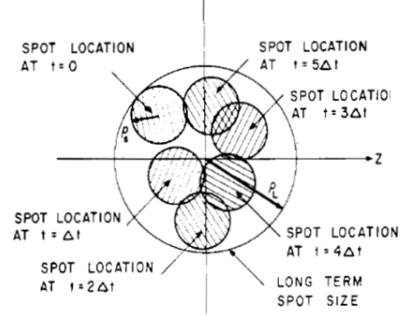
Uplink modeling: descriptive models dedicated to uplink?



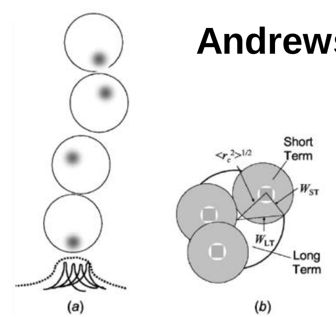
Fante IEEE 1975



$$\langle \rho_c^2 \rangle = \frac{\iint_{-\infty}^{\infty} d^2\rho_1 \iint_{-\infty}^{\infty} d^2\rho_2 (\rho_1 \cdot \rho_2)\Gamma_4(x, \rho_1, \rho_1, \rho_2, \rho_2)}{\left[\iint_{-\infty}^{\infty} d^2\rho_1 \Gamma_2(x, \rho_1, \rho_1)\right]^2}$$

$$\langle \rho_L^2 \rangle = \frac{\iint_{-\infty}^{\infty} d^2\rho\, \rho^2\, \Gamma_2(x, \rho, \rho)}{\iint_{-\infty}^{\infty} d^2\rho\, \Gamma_2(x, \rho, \rho)}.$$

Andrews Opt. Eng. 2006



Camboulives Appl. Opt. 2018

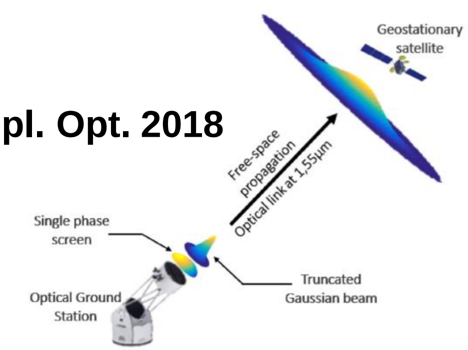


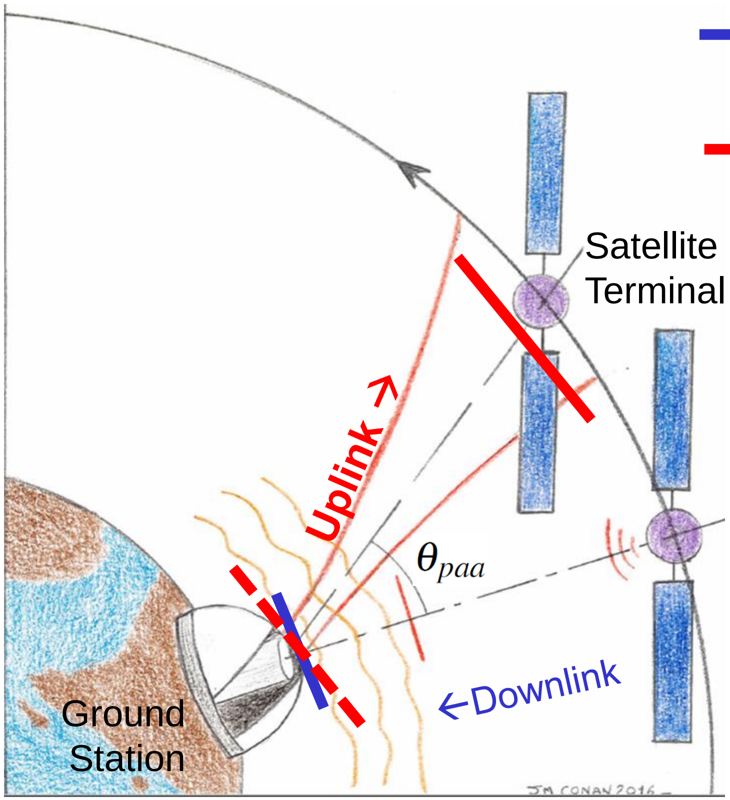
Fig. 1. Presentation of the LOT model. This model is equivalent to a single phase screen resulting from tilt, defocus, and astigmatism placed in the emission plane of the beam.

However :

- **Limited validity domains**
- **Account of AO pre-compensation is difficult...**

Is uplink so different?

Downlink & Uplink: not identical but reciprocal



Overlap Integral $\mathscr{C} = \int \mathscr{E}_{SMF}^*(\mathbf{r})\ .\ \mathscr{E}_{turb\text{-}on\text{-}axis}(\mathbf{r})\ dr$

Overlap Integral $\mathscr{C}_1 = \int \mathscr{E}_{LASER}^*(\mathbf{r})\ .\ \mathscr{E}_{turb@paa}(\mathbf{r})\ dr$

Don't worry about uplink modeling

Think reciprocal !

Shapiro & Puryear, Opt. Commun. Netw. 4, 947 (2012).

Robert, Conan & Wolf, Phys. Rev. A, 93(3), 033860 (2016).

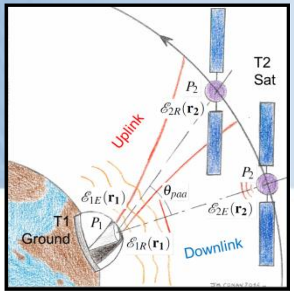
Down & Uplink simplified models exploit coupling efficiency @ ground aperture

Simply add anisoplanatism error for uplink!

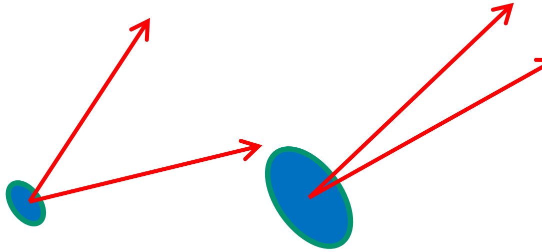
Védrenne et al., SPIE (2016).

Canuet et al., JOSA A, 35(1), 148-162 (2018).

Downlink & Uplink: not identical but reciprocal

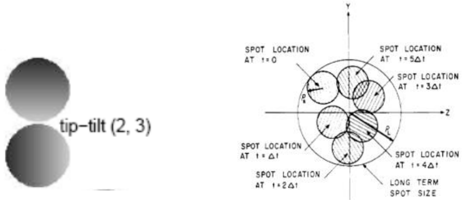


- Uplink beam @ SAT can not be deduced from downlink beam @ GRND
- **HOWEVER RECIPROCAL EFFECTS ARE OBSERVED:**



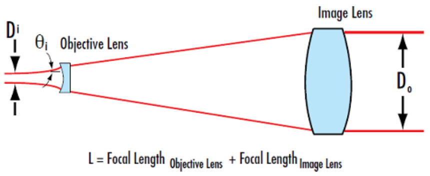
- @ Order 0 : ground aperture

Increased collecting area reciprocal of reduced beam divergence



- @ Order 1 : tip-tilt

  Tilp-tilt @ GND reciprocal of beam wander @ SAT



- @ Order 2: focus in altitude

  Aperture averaged scintillation reciprocal of

  beam expander/reducer effect

  (= apparent change of ground aperture)

- etc...

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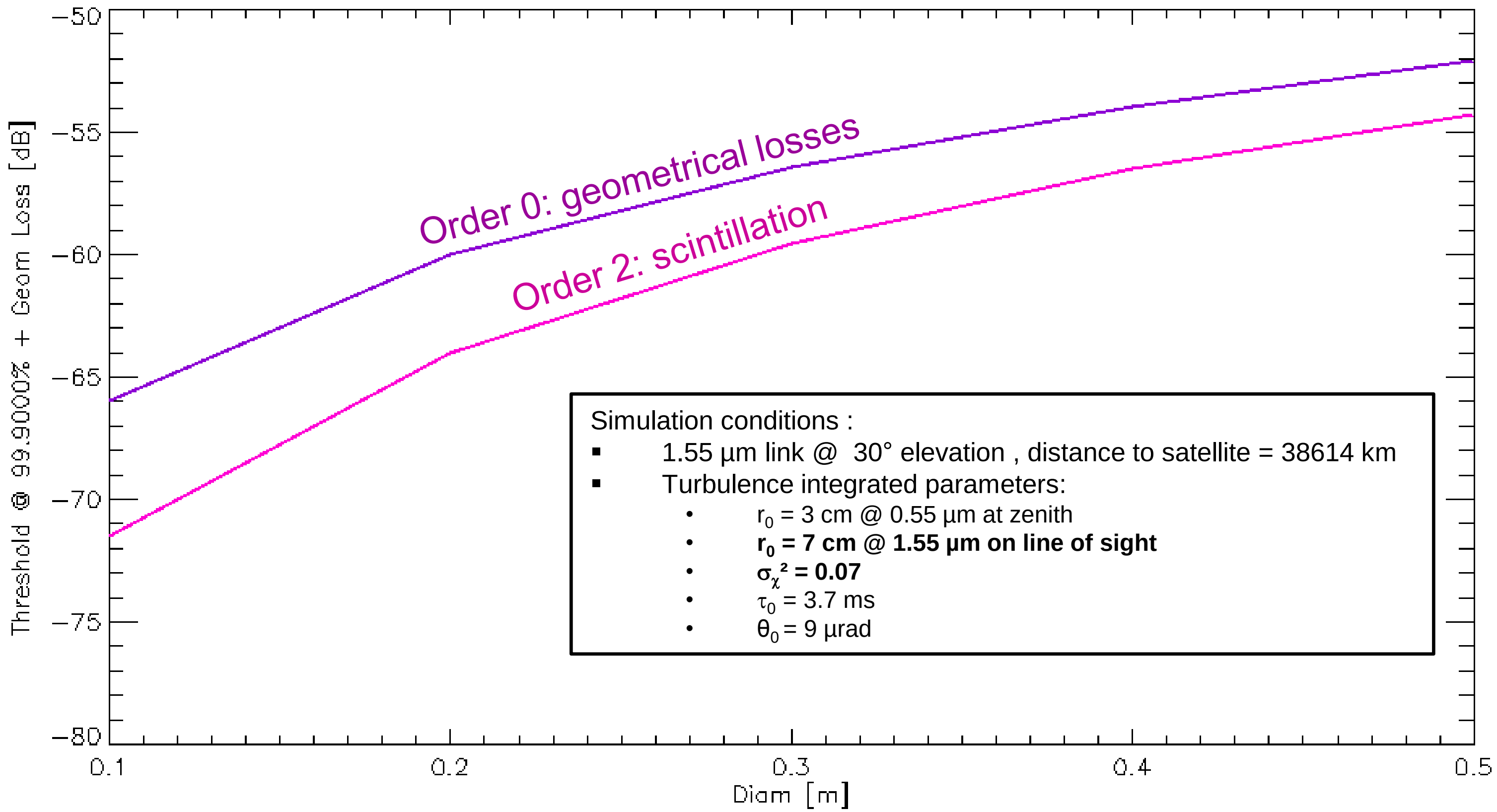
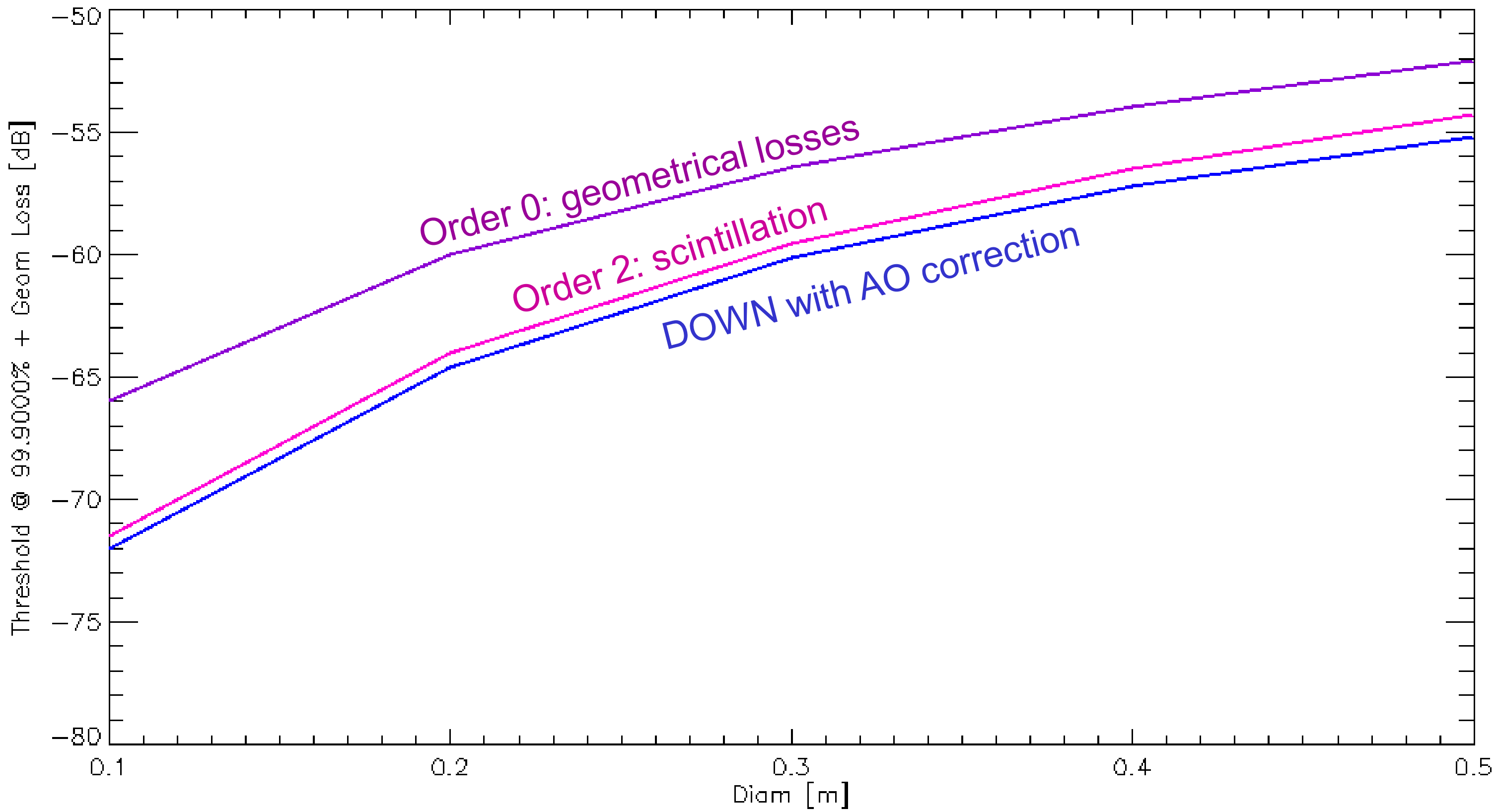
Performance versus aperture diameter D
2 limiting cases



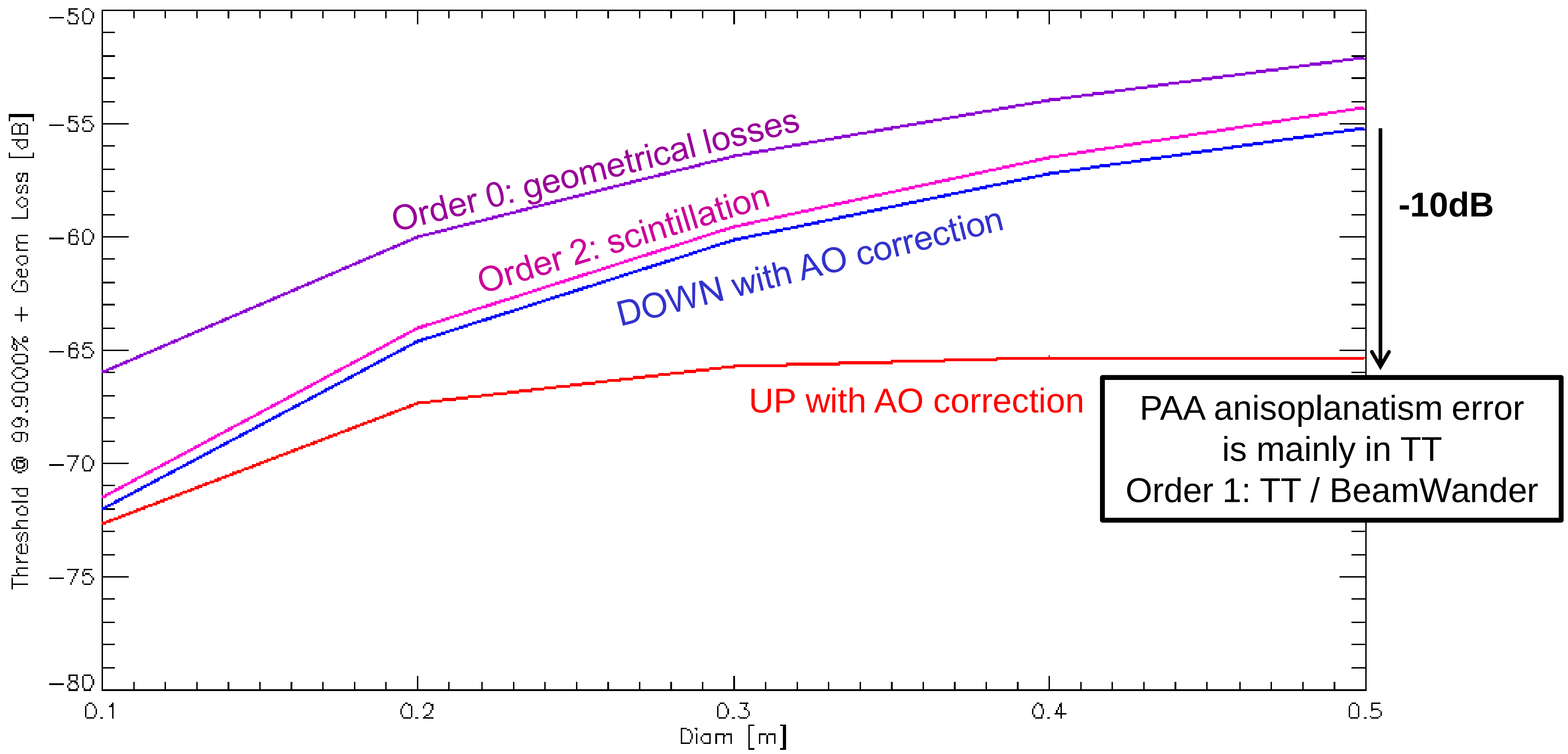
- **Geometrical losses benefit from aperture increase**
- **Scintillation (perfect AO) adds a penalty**

Performance versus aperture diameter D
Downlink with AO



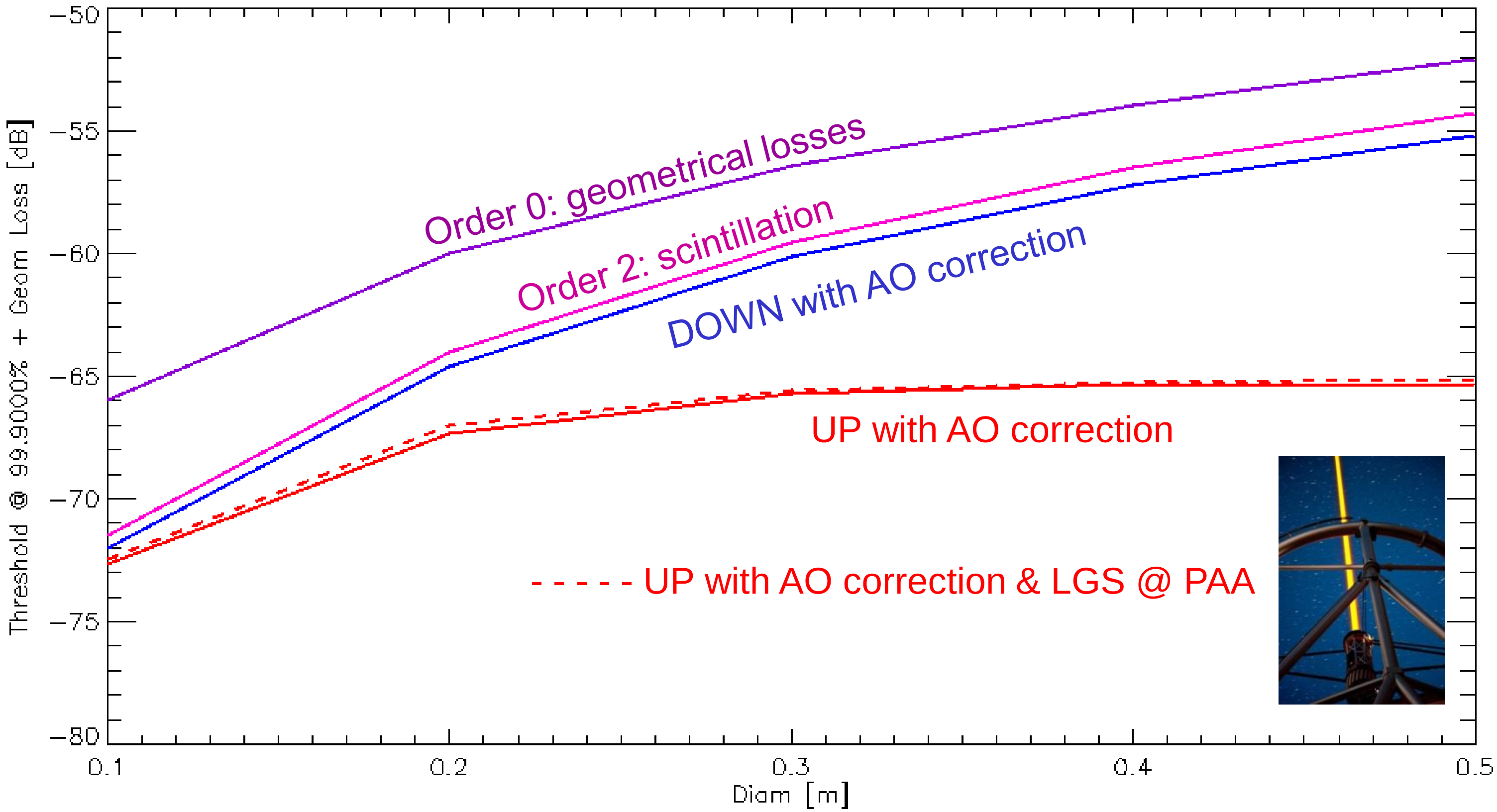
- Aperture increase gives huge gains for downlink
- Ex : Gain ~ 20 dB between D=10cm and D=50cm !

Performance versus aperture diameter D
Uplink (impact of PAA anisoplanatism)



- **Point ahead anisoplanatism levels performance beyond D~20cm**

Performance versus aperture diameter D
Uplink with LGS (PAA anisoplanatism only on TT)



- **Nearly no performance gain...**
- **Unless one solves the Tip-Tilt indetermination issue...**
  (slave satellite, polychromatic LGS, other solutions?)

Conclusion & Perspectives

- Adaptive Optics is therefore mandatory for downlink & uplink
- Reciprocity is a key principle for the understanding & modeling of such bi-derectional links
- Choice of ground aperture diameter implies considering: geometrical losses, AO performance, impact of point-ahead angle, telecom metrics...
  - 50 to 60 cm reception aperture @ Ground is considered for downlink
  - diameters > 20 cm is more questionable for uplink (due to point-ahead anisoplanatism liimitation)
  - use of a standard LaserGuideStar does not solve point-ahead anisoplanatism

    [solution in talk of Matthew J. Townson @ COAT?]
- NEXT:
  - Explore joint optimization of digital communication algorithms & adaptive optics design
  - Move to coherent detection telecom links (coding in phase...) [see poster by Laurie Paillier @ COAT]
  - Study alternatives to standard adaptive optics (sensorless, integrated optics components...)

    [see poster by Luca Rinaldi @ COAT]
  - Need for experimental demonstrations:
    - FEEDELIO [see talk of Aurélie Bonnefois @ COAT]
    - H2020 VERTIGO [see talk of Arnaud Le Kernec @ COAT]
  - Development of a ground station with adaptive optics [FEELINGS in progress @ ONERA]