Signal Control in Optical Ground-to-Space Links

Optical Uplinks from Ground Stations to Receivers in Space suffer from atmospherically induced intensity scintillations and beam pointing jitter.

These channel impairments limit the effective transmit aperture size and thus set a restriction to the link budget. Transmitter diversity helps to reduce fading but at the expense of spectral efficiency and additional power. An artificial Laser Guide Star allows better knowledge of the atmospheric index-of-refraction structure and thus - together with Adaptive Optics - complete uplink beam control seems possible in future. Another fading-reduction is withal offered from the sensitivity run of coherent- or APD-receivers in contrast to thermal-limited power detectors.

This talk introduces the different techniques which have been investigated in theory and practice by the Optical Communication Groups of DLR-IKN.

“Signal Control in Optical Ground-to-Space Links“

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Seminar, 20170911

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Content

- Conventional Limitation in Optical Uplink Budget
- Transmitter Diversity Solutions
- Pointing-Control through Artificial Reference Sources
- Receiver Sensitivity Characteristic
- Combination: Amplitude-linear Receiver and Diversity

Angles in the Optical Uplink Channel

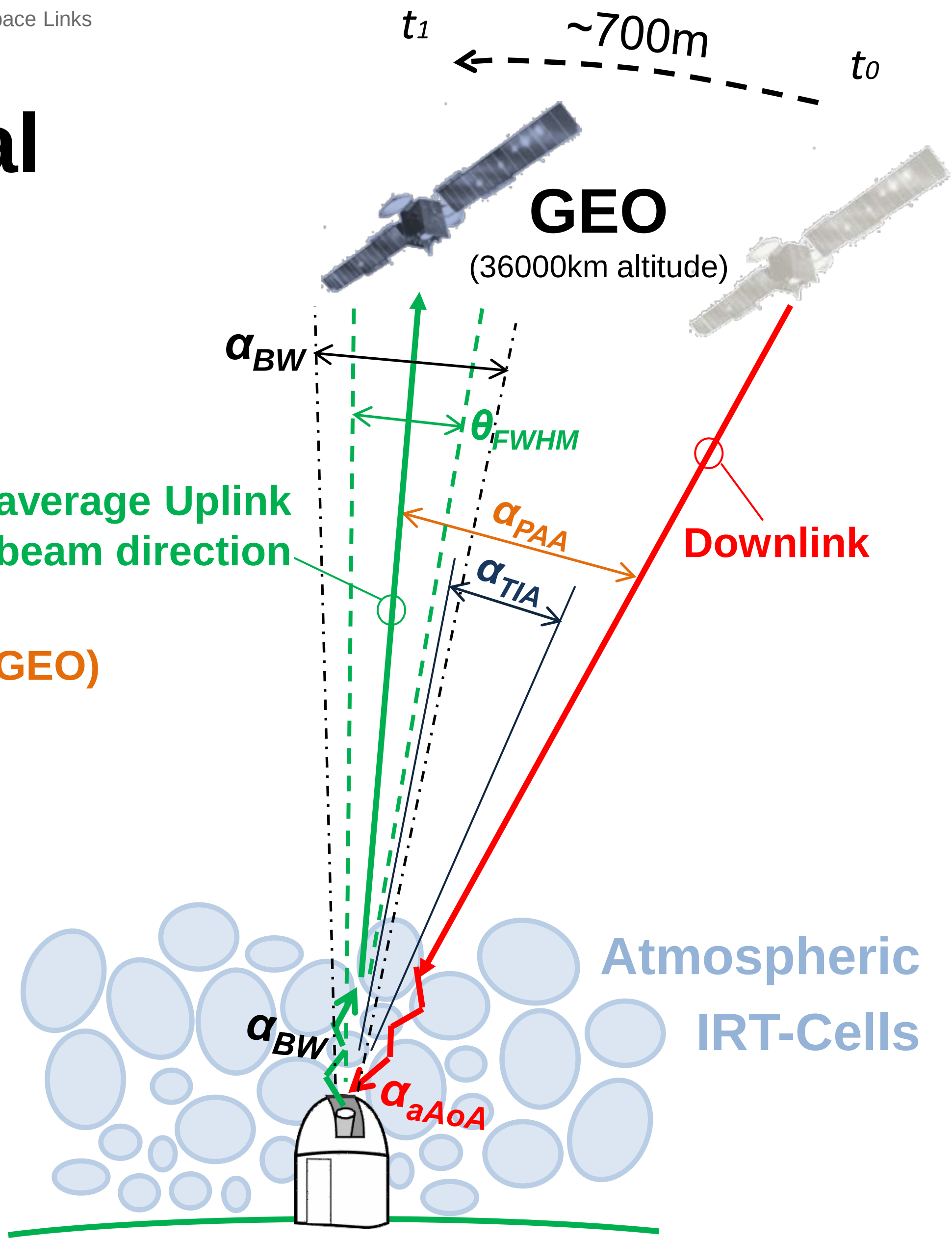
α_{aAoA}: Downlink atmos. Angle-of-Arrival (~10µrad)

α_{PAA}: Point-Ahead Angle (~18µrad for GEO)

θ_{FWHM}: Uplink Divergence Angle (~10µrad)

α_{BW}: Uplink atmos. Beam-Wander (~10µrad)

α_{TIA}: Tilt-Isoplanatic Angle (dep. on elevation, altitude, …)



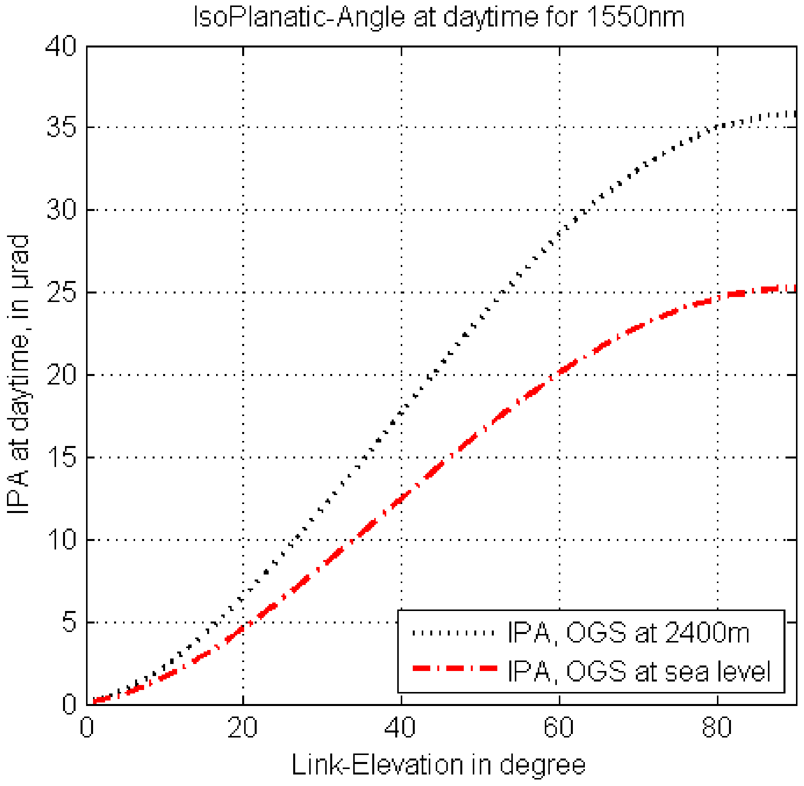
Problem when Downlink Path $\neq$ Uplink Path:

IPA < PAA prevents optimal Uplink Beam Control

- **No optimal Pointing-by-Tracking possible**
- **Uncontrollable Wavefront Distortion prevents large *effective* Uplink Tx-Apertures**

Examples of PAA Values in Zenith:

Scenario: GND to…	PAA /µrad
LEO (600 km)	~ 50
GEO (36000 km)	17 .. 20
Moon (378 Tkm)	~ -3.7
Mars at min. distance	~ -38
Mars at max. distance	~ 159
Proxima Centauri	~ 166



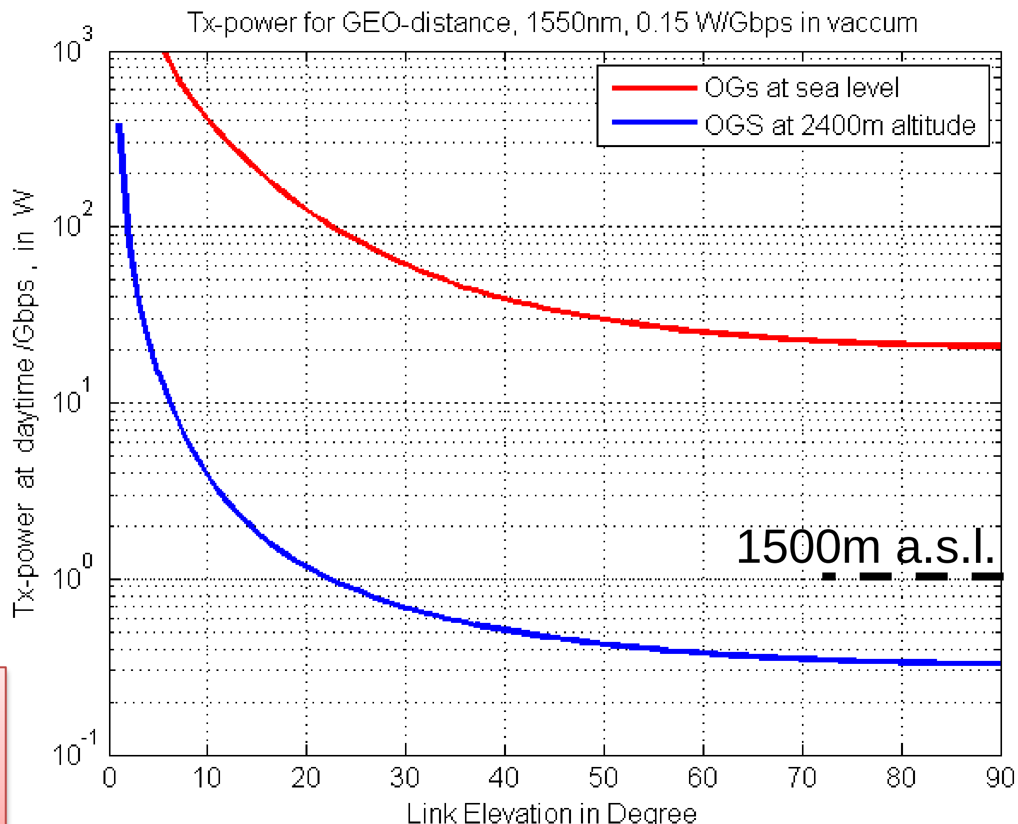
Limit of *Conventional* Linkbudget to GEO

Uplink by optimum aperture and static pointing-angle only
→ no „Pointing-by-Tracking“

- Conditions:
  „GEO-distance without Atmosphere“:
  20cm Rx, 150mW/Gbps in space
  (sensitivity from coherent LCT)

- Additional Atmospheric Losses:
  Pointing, Scintillation, enlarged Divergence, Atmos. Attenuation
  → optimum $D_{Tx} \sim r_0$

- 1% fading outages allowed
  (→ Erasure-FEC)

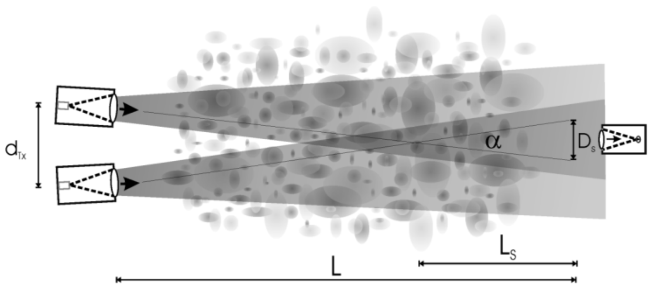


Typical Value: **1W/Gbps**
→ for ***Tbps*** we need ***>kW*** of Tx-Power!

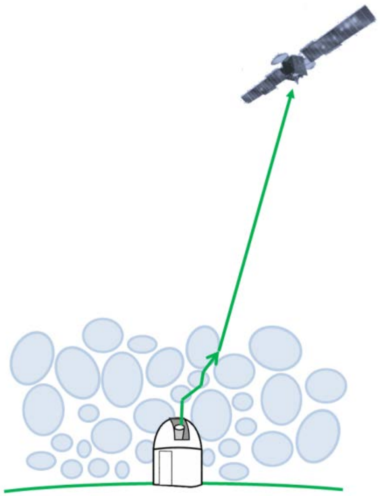
Knopp, Giggenbach, Mata-Calvo, Fuchs, Saucke, Heine, Sellmaier, Huber, “Connectivity Services Based on Optical Ground-to-Space Links", Int. Astronautical Congress, Adelaide, 2017

Advanced Techniques: Enhance Signal Stability by…

Tx-Diversity



Pointing Control



Receiver Technology

$$Q = f(P_{Rx})$$

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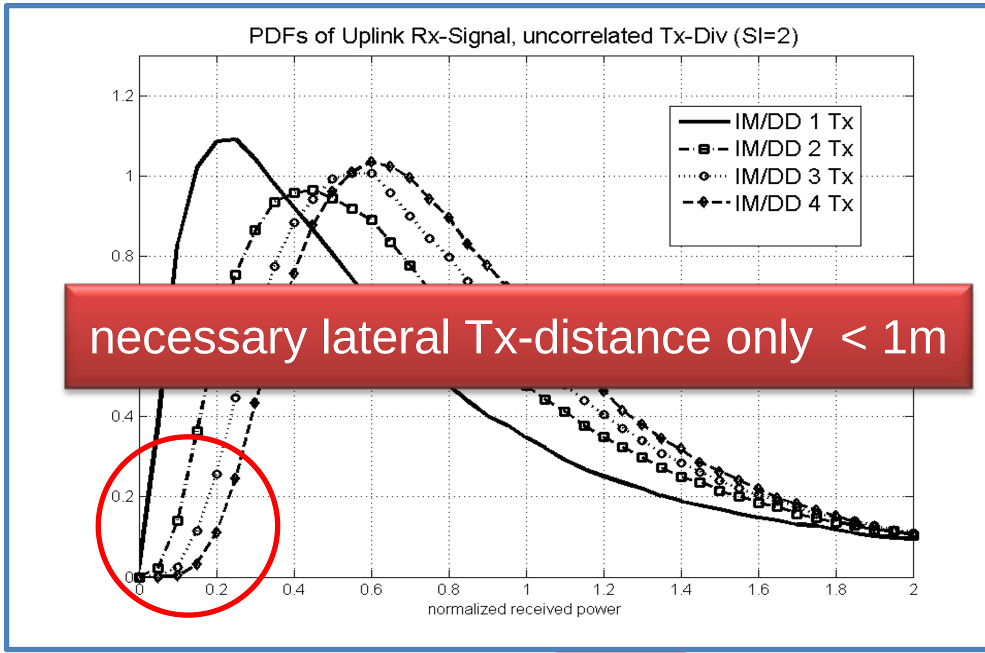
Power Scintillation Index (PSI):

- Intensity Variation at location *P* has constant mean and is defined by ***Intensity Scintillation Index (ISI)***, which is normalized variance over time (… or space → ergodicity) :

$$\sigma_I{}^2(P) = \frac{VAR(I)}{E^2(I)} = \frac{\left\langle I^2(P)\right\rangle_t}{\left\langle I(P)\right\rangle_t^2} - 1$$

- In space-UpLinks the **Intensity**-Variations equals the received **Power** variations (no aperture averaging)



necessary lateral Tx-distance only < 1m

… with Tx-Diversity:

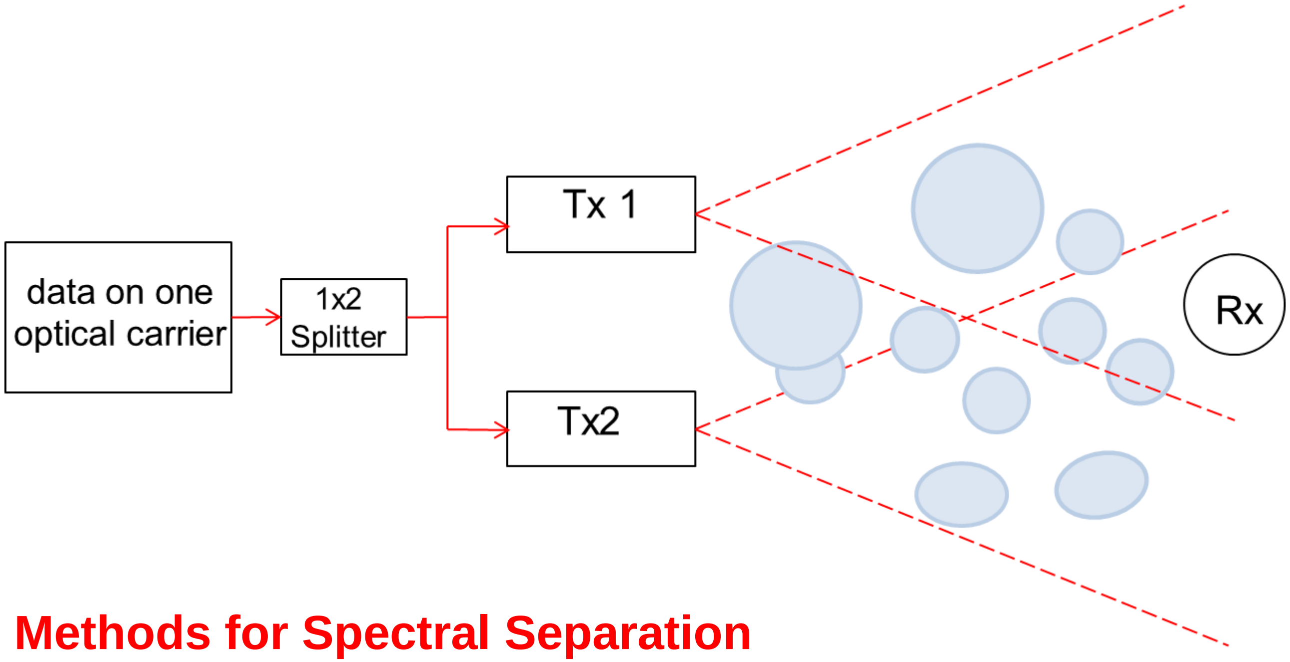
- Scintillation index with
  - ***k*** (spectrally non-overlapping) and
  - ***uncorrelated*** sources
  - when all RVs have ***same density function***

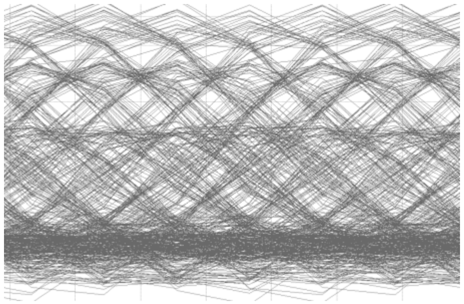
$$\sigma_I^2(X_1 + X_2 + \ldots + X_k) = \frac{VAR(X_1) + VAR(X_2) + \ldots + VAR(X_k)}{\left[E(X_1) + E(X_2) + \ldots + E(X_k)\right]^2} \overset{\text{equal PDFs}}{=} \frac{k \cdot VAR(X)}{\left[k \cdot E(X)\right]^2} = \frac{\sigma_I^2(X)}{k}$$

(not limited to LN-scintillation)

Spatial Tx-*Diversity* needs Channel *Division* to avoid interference

in the case of spectral overlap we experience destructive and constructive interference, leading to unacceptable Rx power-variations



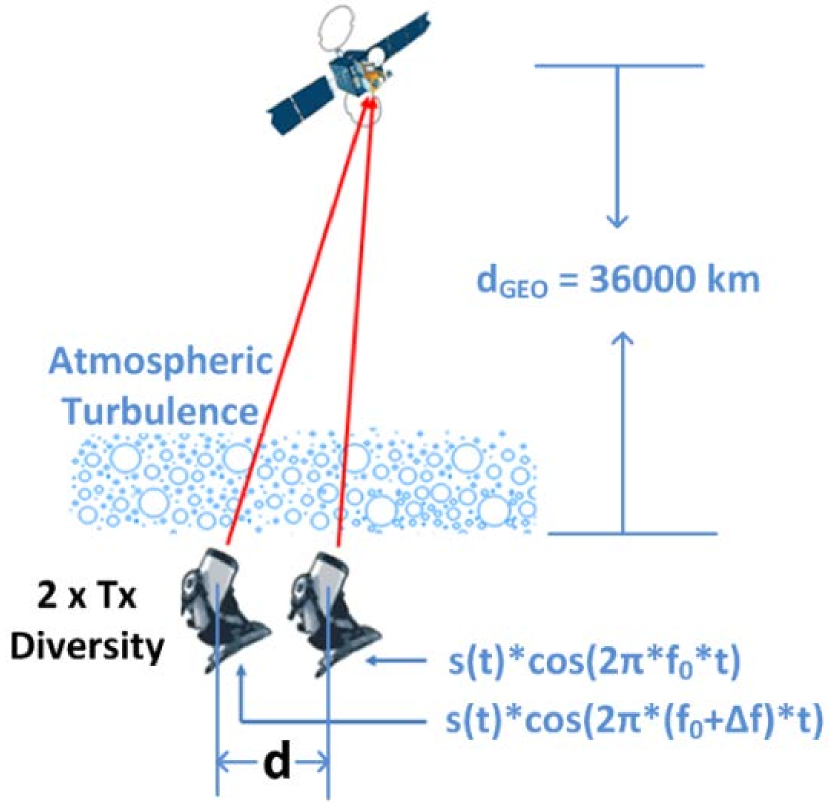


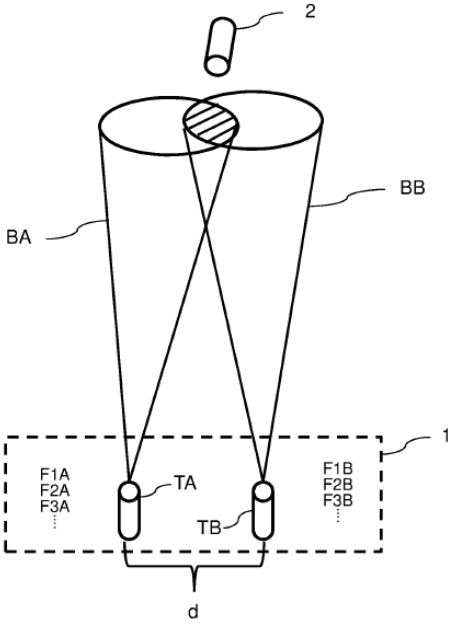
no scintillations

→ Methods for Spectral Separation of Tx-signals required

Mustafa, “Optical Transmitter Diversity Scheme with Increased Spectral Efficiency for Geostationary Satellite Feeder-Links”, PhD-Topic

1) Tx-Diversity with Wavelength-Division





- avoids the spectral overlap (→ interference)
- requires no modification in Rx
- **but is spectrally inefficient**

Example for spectral–INefficiency through channel separation:

28Gbps IM/DD needs ~30GHz plus conventional filtering slopes,

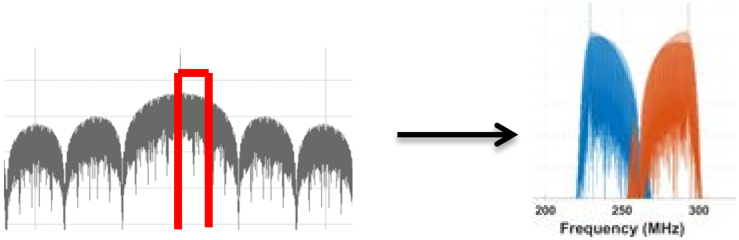
with 4x Tx-Diversity this requires 200GHz/28Gbps

→ whole C- plus L-Band (8THz) can only transmit 1.1Tbps…

"Verfahren zur optischen Datenübertragung von einer Sendeeinrichtung zu einer Empfangseinrichtung, insbesondere von einer Bodenstation auf der Erdoberfläche zu einem Satelliten", Giggenbach, German Patent DE 10 2013 226 736

More Sophisticated Diversity-Division Methods:

- Dual Vestigial Single Side Band Filtering



Mata-Calvo, Giggenbach, Fuchs, Mustafa, „Fading-Mitigation bei Sender-Diversität in atmosphärisch-optischen Freistrahlverbindungen mit Einseitenbanddatenmodulation“, DPA - applied

- Polarisation Division

Giggenbach, Mata-Calvo, “Diversitätsverfahren zur Minderung der Amplitudenstörungen in optischen Satelliten-Uplinks mit Überlagerungsempfang“, DPA 20130710 - applied

- Phase-Variation Division

Fuchs, Giggenbach, Mata-Calvo, "Verfahren zu optischen Breitband-Freistrahlkommunikation unter Verwendung von Sender-Diversität", DE 20 2014 219 344, German Patent Office

- Space-Time Coding (Alamouti), for Optical Links

Alamouti, “A Simple Transmit Diversity Technique for Wireless Communications”, IEEE JOURNAL ON SELECT AREAS IN COMMUNICATIONS, VOL. 16, NO. 8, OCTOBER 1998

Inherent to all Tx-Div Methods: Power-Inefficient due to Small Tx-Apertures / Large Spots …

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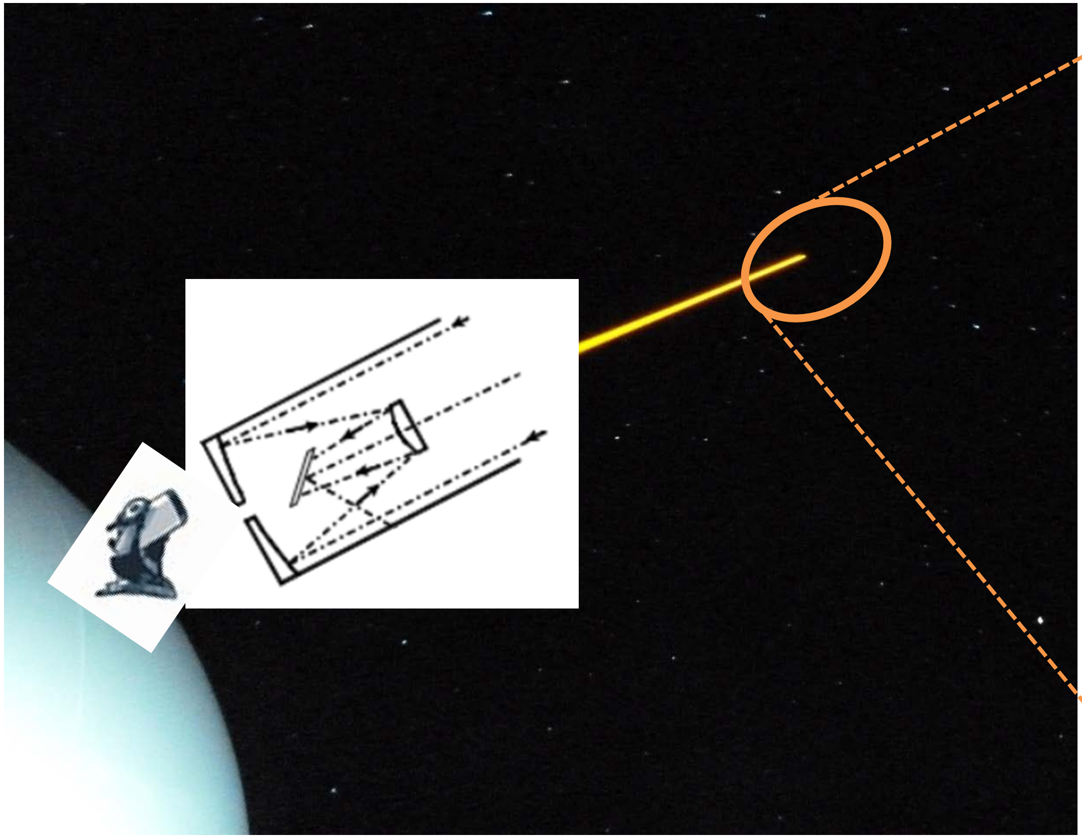
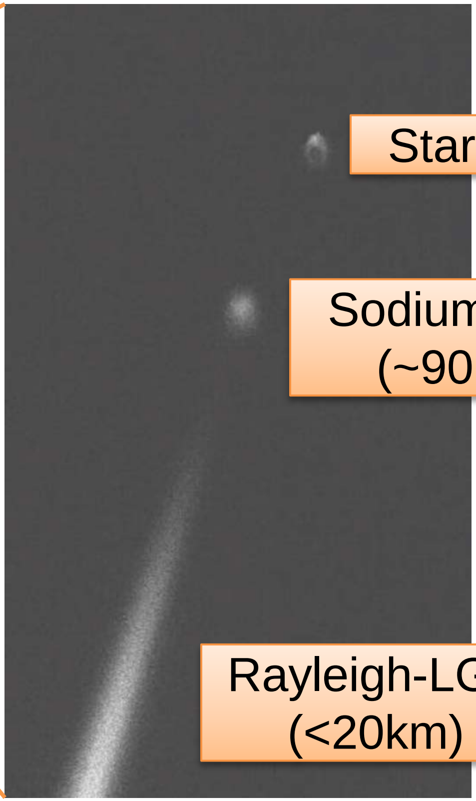
Fading Reduction without Spatial Diversity

Uplink Beam Control by Pre-Distortion: requires Laser-Guide-Stars (Sodium- or Rayleigh-Backscatter)

Classical (axially observed) LGS does not see tilt

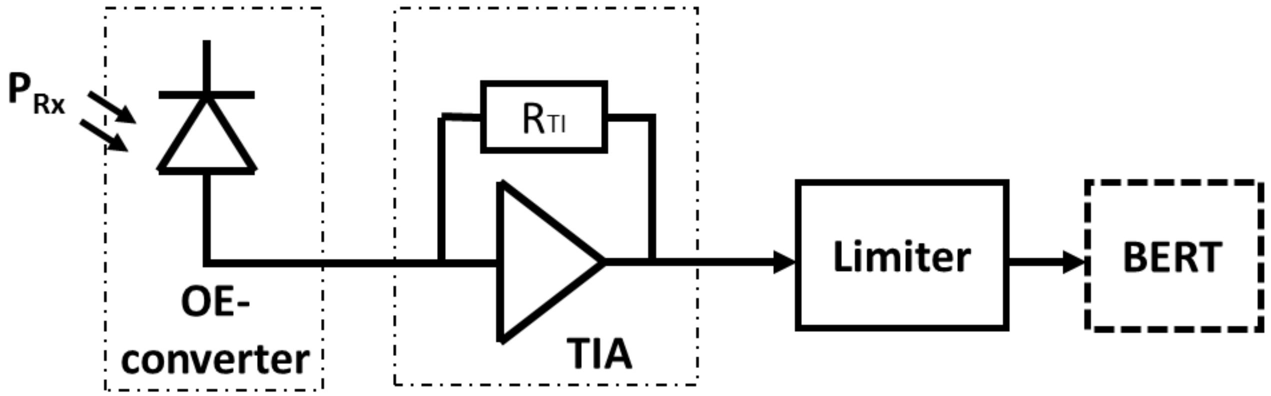




IKN participated in ESO's LGS measurement campaign on Tenerife & LaPalma

Mata Calvo, Bonaccini Calia, Barrios, Centrone, Giggenbach, Lombardi, Becker, Zayer, "*Laser Guide Stars for Optical Free-Space Communications.*" Proceedings of SPIE, Photonics West 2017

Opto-Electrical Receiver Characteristic and the Scintillating Channel



LN-Scintillation-PDF of AMPlitude and INTensity/PoWRer:

$$A(P) = A_0(P) \cdot e^{\chi(P)+j\Sigma(P)} \qquad I(P) = A_0^{\,2} \cdot e^{\Psi(P)+\Psi^*(P)} = A_0^{\,2} \cdot e^{2\cdot\chi(P)}$$

Rytov: LogAmp χ is normally distrib. : $p(\chi) = \frac{1}{\sqrt{2\pi\cdot\sigma_\chi^{\,2}}}\cdot e^{-\left[(\chi-\mu_\chi)^2/2\sigma_\chi^{\,2}\right]}$

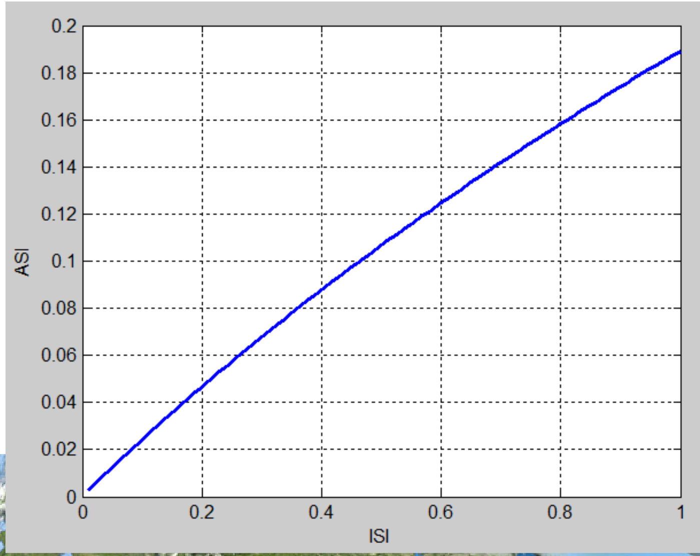
„function of a RV“

Amplitude is Log-Norm (LN) distrib.: $p(A) = \frac{1}{A\cdot\sqrt{2\pi\cdot\sigma_\chi^{\,2}}}\cdot e^{-\frac{(\ln(A)-\langle\chi\rangle)^2}{2\sigma_\chi^{\,2}}} \longrightarrow \sigma_A^2 = e^{\sigma_\chi^{\,2}} - 1$

since AMP is LN → also INT (or PWR in OGEOFL) is LN:

Intensity-PDF is also Log-Norm distr: $p(I) = \frac{1}{2\cdot I\cdot\sqrt{2\pi\cdot\sigma_\chi^{\,2}}}\cdot e^{-\frac{\left(\ln\frac{I}{I_0}-2\langle\chi\rangle\right)^2}{8\cdot\sigma_\chi^{\,2}}} \longrightarrow \sigma_I^{\,2}\Big|_{\mu=-2\sigma^2} = e^{4\sigma_\chi^{\,2}} - 1$

…by comparing $\sigma_\chi^{\,2}$, $\sigma_A^{\,2}$, $\sigma_I^{\,2}$: $\sigma_A^2 = \left(\sigma_P^2 + 1\right)^{\frac{1}{4}} - 1$



… is sensitivity-run of coherent and APD-RFEs

… more effective than 4x Tx-Div !

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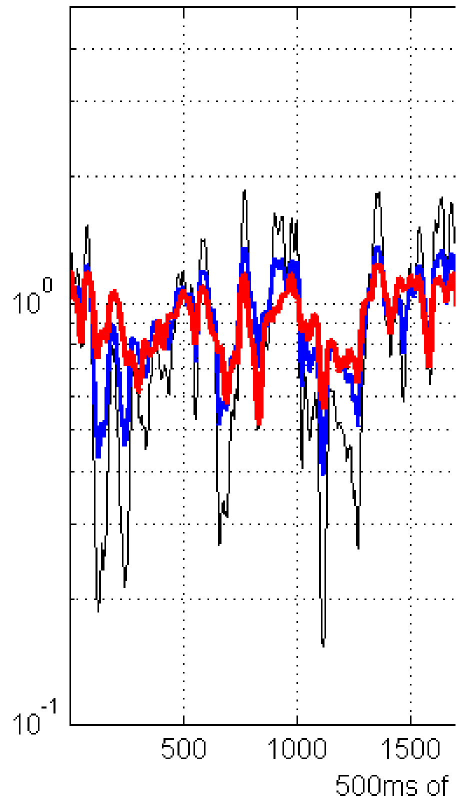
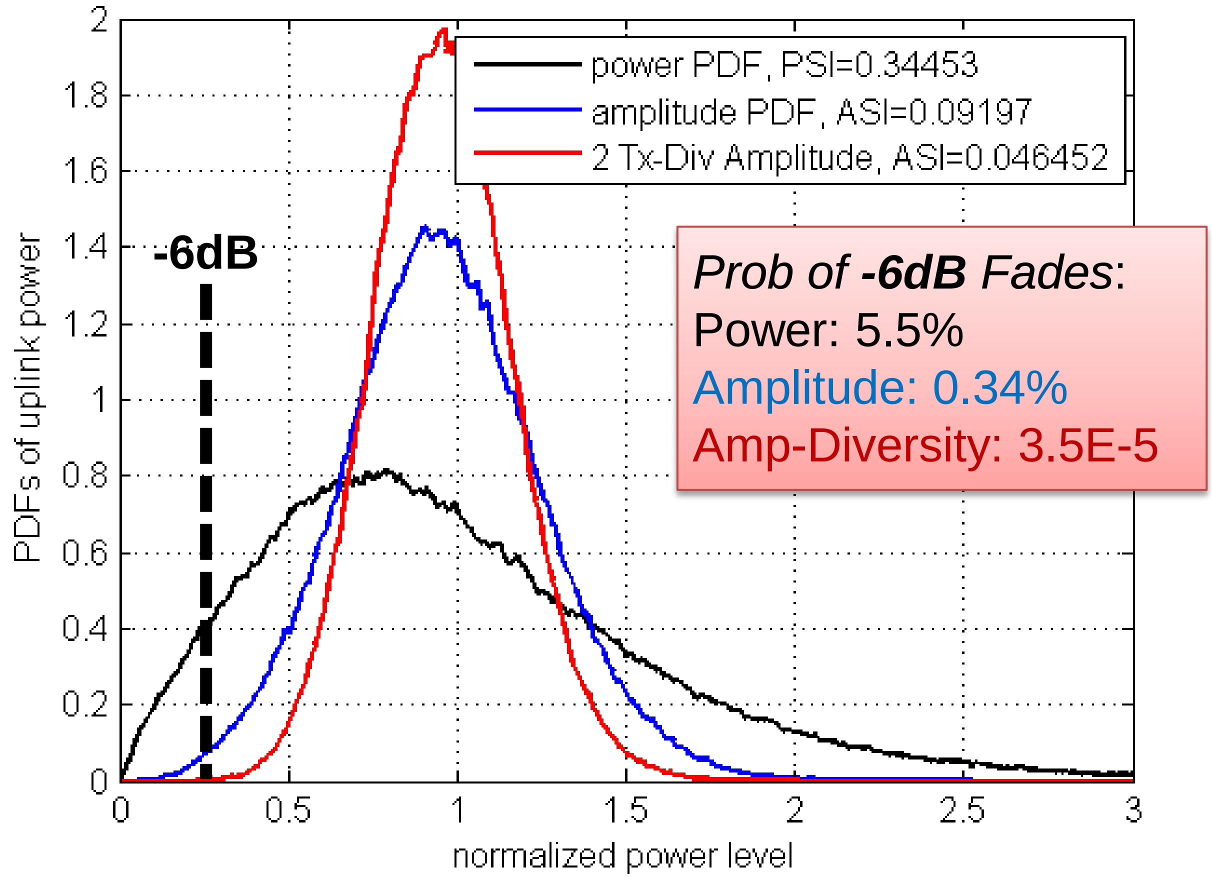
SUMMARY: Simulated Signals: 2x Amplitude-Diversity
*Scintillation * Pointing-Jitter*





*Prob of **-6dB** Fades*:
Power: 5.5%
Amplitude: 0.34%
Amp-Diversity: 3.5E-5

Simulation according to ArtemEx - Measurements

"Power Vector Generation Tool for Free-Space Optical Links - PVGeT", Giggenbach, Parthasarathi, Shrestha, Moll, Mata-Calvo, ICSOS-2017

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