Extremely High Speed Avenues for Space Communications: Optical & W-band Waves

Dr. Ricardo Barrios

8th ASMS/14th SPSC
Palma de Mallorca, Spain
Sep 5th, 2016

DLR

Abstract

Extremely High Speed Avenues for Space Communications: Optical & W-band Waves

Dr. Ricardo Barrios & Dr. Pantelis-Daniel Arapoglou, 8th ASMS/14th SPSC, 5 Sep 2016

The current telecommunications marketplace is experiencing an ever increasing demand for high-speed services, and the traffic demand for satellite broadband is expected to grow six-fold by 2020. As part of the continuous migration towards higher frequency bands, Optical & W-band waves offer the promise of unprecedented bandwidth compared to current commercial solutions, leveraging enough bandwidth capable to cope with mid and long-term requirements. Together they can realize extremely high speed avenues for space communications in inter-satellite and feeder link applications.

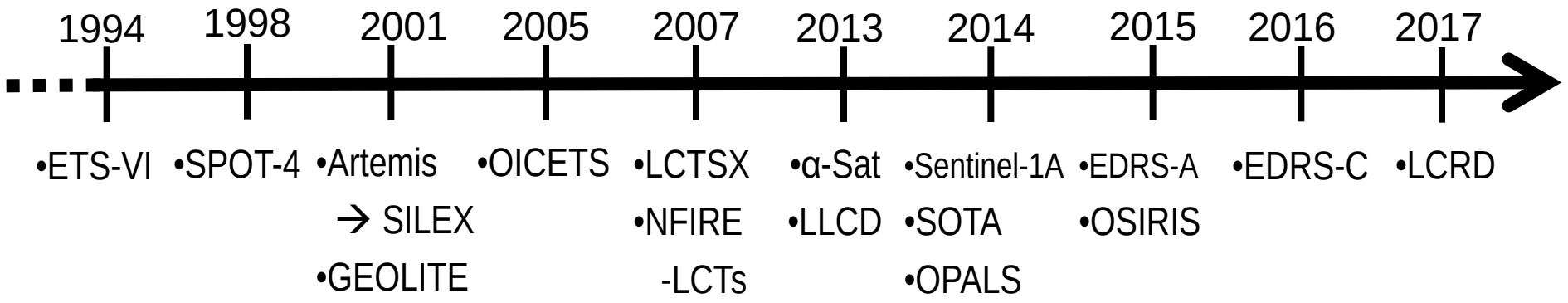
This tutorial focuses on giving a thorough overview of the different aspects and challenges to be taken into account when implementing GEO feeder links in the optical domain and W-band waves, including physical layer, channel model, modem, satellite payload and system level aspects. Particular attention is given to the feeder uplink scenario, which—as part of the forward link—presents itself as critical for the successful implementation of future extremely high throughput satellite systems. The tutorial will attempt to stress the practical challenges of these high frequency RF and optical technologies, proposing also ways forward in terms of necessary space and ground technology development, as well as open research directions.

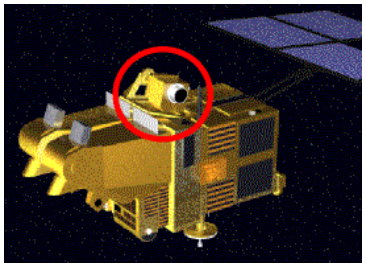
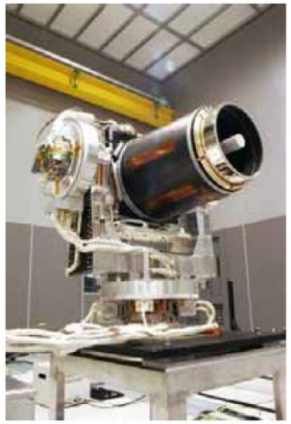
DLR

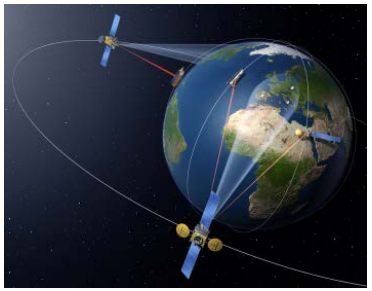
Outline

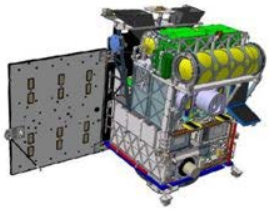
- ❑ Introduction to Lasercom for Space
- ❑ Technologies and Modulation Formats
- ❑ Atmospheric Effects
- ❑ Atmospheric-induced Fading Mitigation Techniques
- ❑ Optical GEO Feeder Links
- ❑ Summary

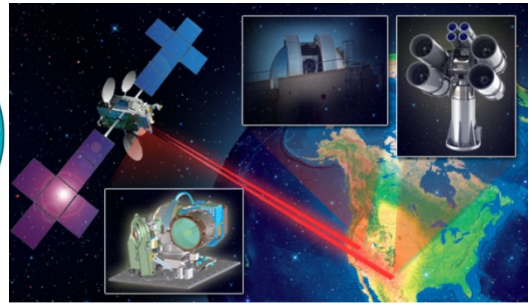
Timeline of Lasercom Space Missions
Selection





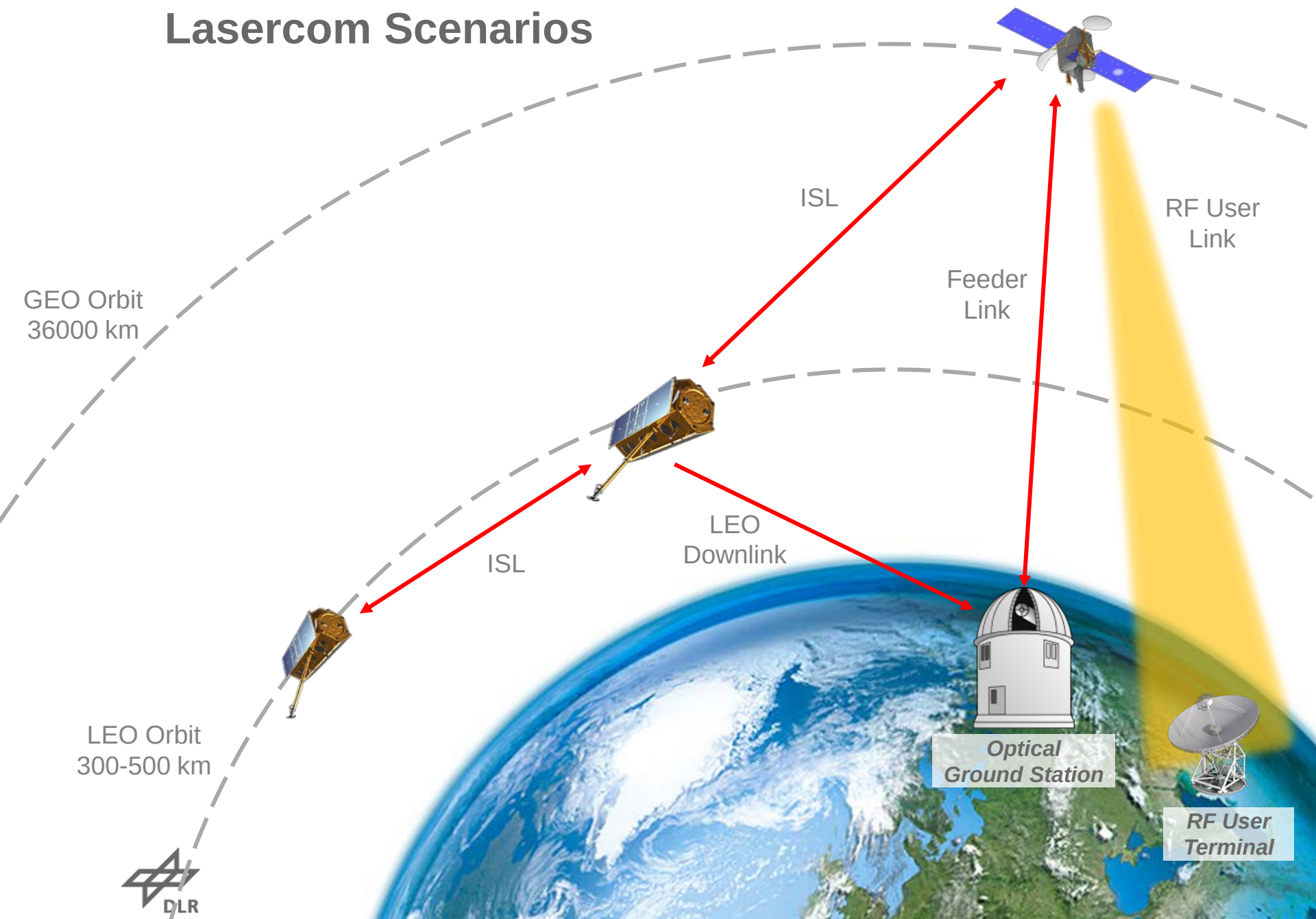




DLR

Pictures: ESA, JAXA, NICT, NASA, MIT, DLR

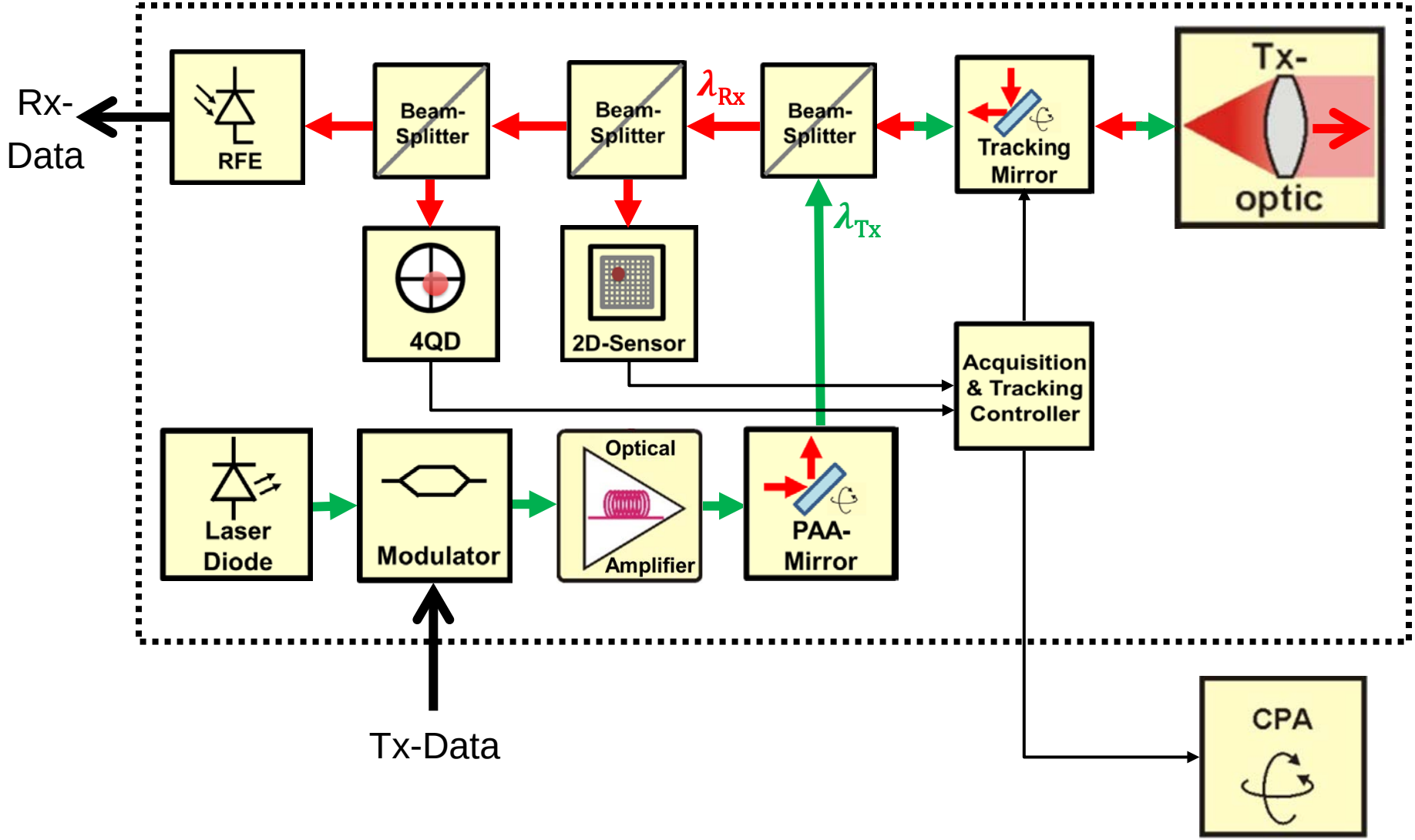
Lasercom Scenarios



Outline

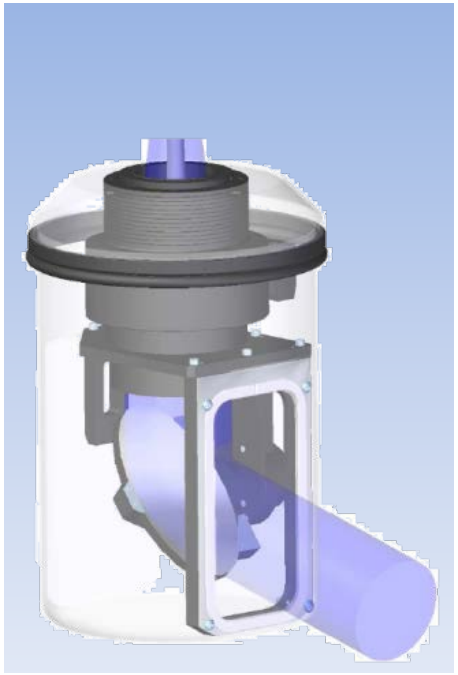
- ❑ Introduction to Lasercom for Space
- ❑ Technologies and Modulation Formats
- ❑ Atmospheric Effects
- ❑ Atmospheric-induced Fading Mitigation Techniques
- ❑ Optical GEO Feeder Links
- ❑ Summary

Components of full-duplex Space Laser Terminals

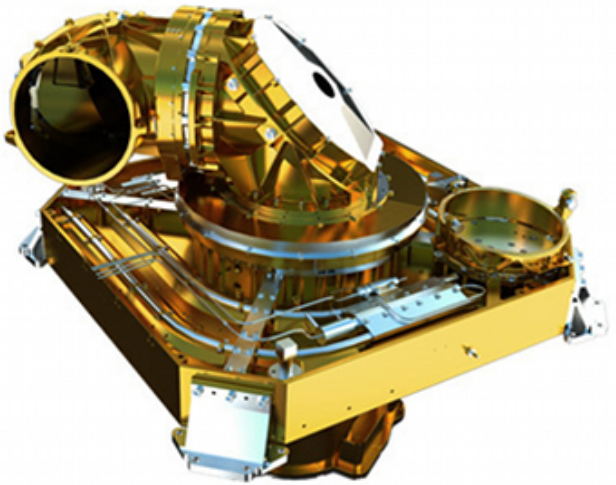


Coarse Pointing Assembly Examples

Azimuth-Elevation Gimbal (OICETS)



One-Mirror



Periscope (Alphasat)

Optical Ground Stations

❑ 1m Class

❑ 40cm Class Rx
❑ 15cm Class Tx

20cm-MOGS

❑ 60cm Class

Pictures: ESA, ViaLight, NASA, DLR.

Modulation Formats

Optical Intensity Detection (incoherent)

- Direct Detection (**IM/DD**) with On-Off Keying (OOK)
  - Low-to-medium sensitivity.
  - High data-rates.
  - Low implementation effort.
  - → short range with atmosph. (LEO)
- **PPM** (Pulse Position Modulation)
  - sensitivity limit (photon counting)
  - high implementation effort
  - limited data-rate
  - → long-range medium-rate (Exploration)

Complex Field Detection (coherent)

- Self-homodyne-DPSK with **PreAmp**
  - high sensitivity (in Phot./bit)
  - high data-rates
  - requires plane Rx-wave
  - atmosphere is a challenge
  - → long range space links (GEO)
- **with local oscillator**: hom./heterodyne-BPSK, QAM

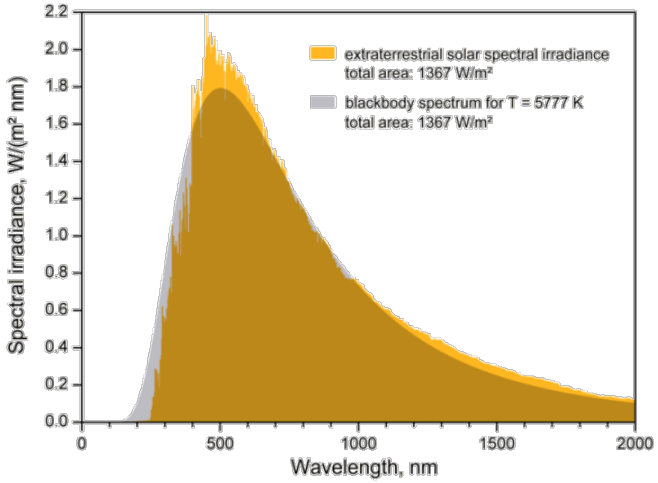
Outline

- ❑ Introduction to Lasercom for Space
- ❑ Technologies and Modulation Formats
- ❑ Atmospheric Effects
- ❑ Atmospheric-induced Fading Mitigation Techniques
- ❑ Optical GEO Feeder Links
- ❑ Summary

Atmospheric effects

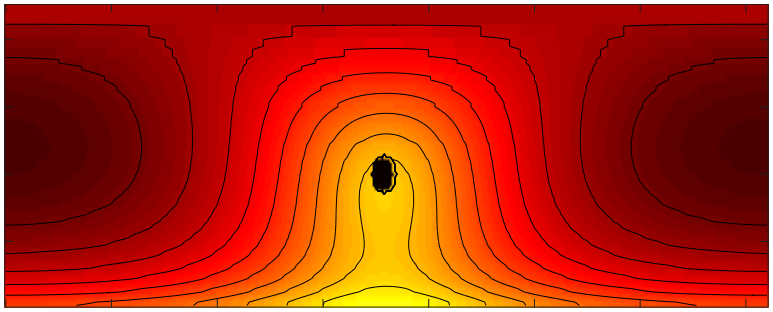
- Atmospheric attenuation.
  - Large time scales. Considered constant.
  - Related with visibility.
  - Dominated by fog, clouds, rain, snow, dust.
  - The attenuation coefficient is made up of four parts:

$$\sigma = \alpha_m + \alpha_a + \beta_m + \beta_a$$

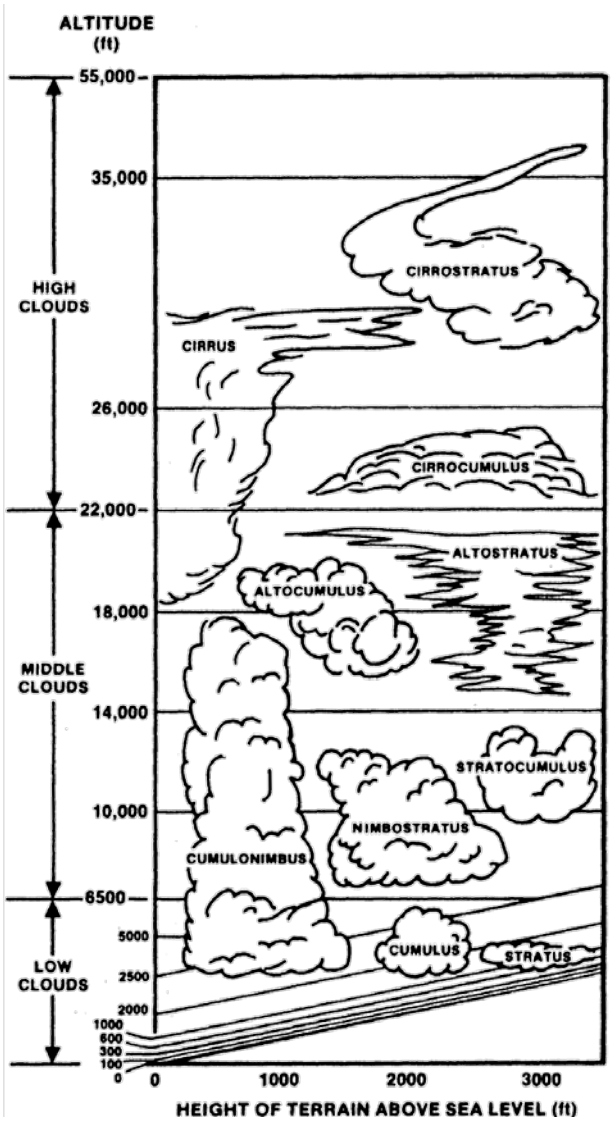


- Background noise
  - Direct Sun or moonlight (also planets) in the receiver FoV may cause link outages.
  - Sky radiance.

- Atmospheric turbulence
  - Small time scale. Random in nature.
  - Caused by wind and temperature gradients.



Atmospheric Attenuation



Attenuation Effects

Scattering:

Rayleigh-Scattering
Electron-Resonance

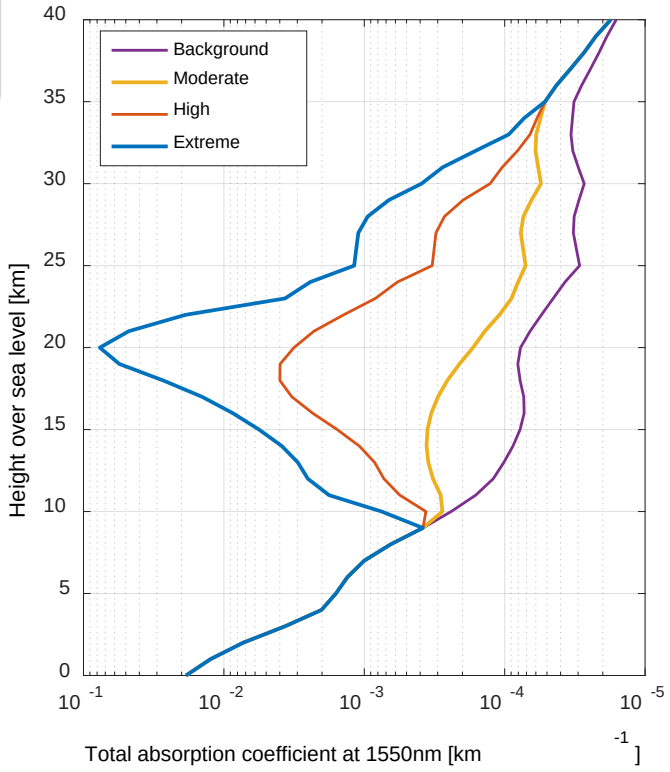
Mie-Scattering
Aerosols and Droplets

Absorption:

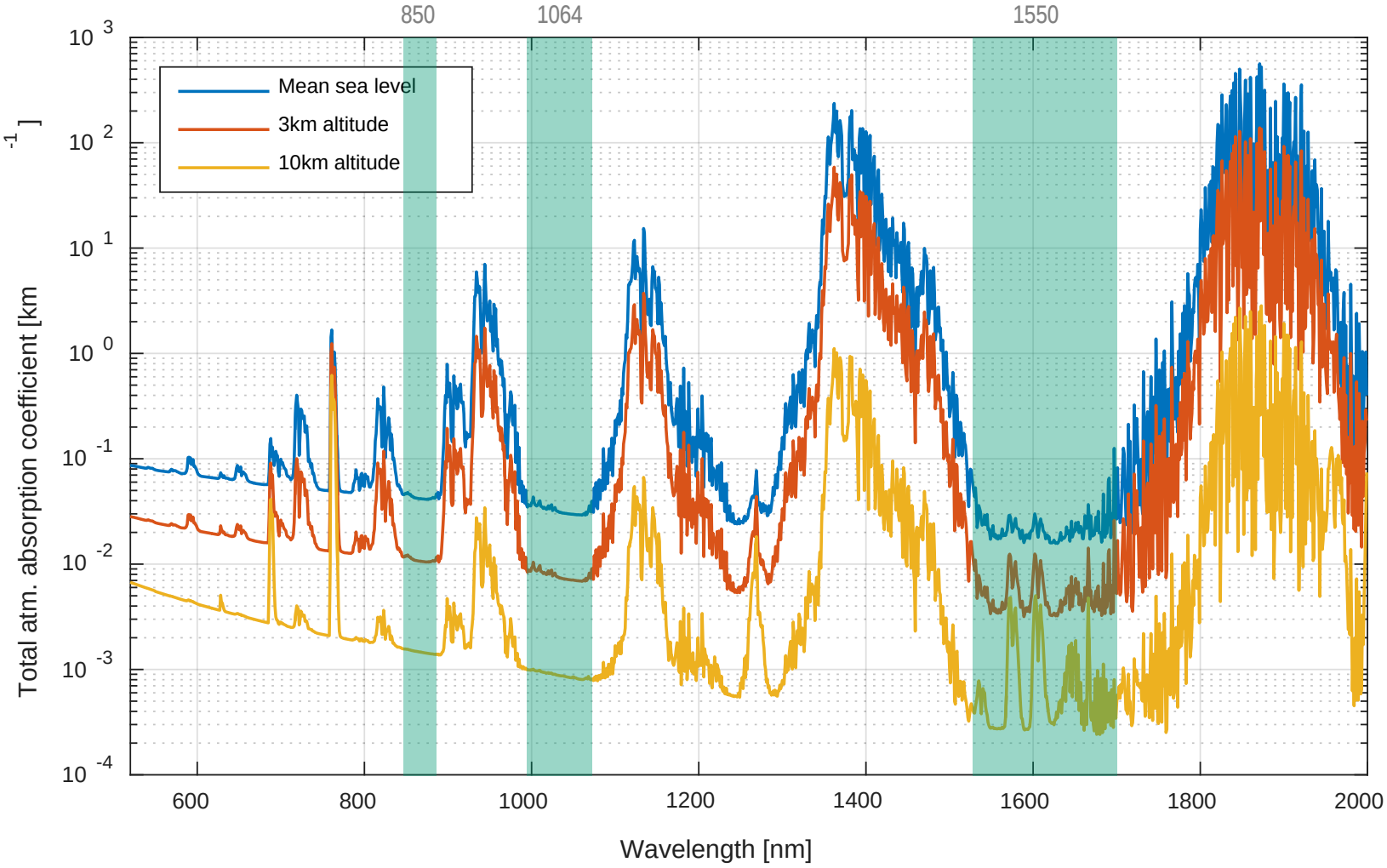
Molecular Absorption

Absorption by Aerosols
volcanic ash, sand

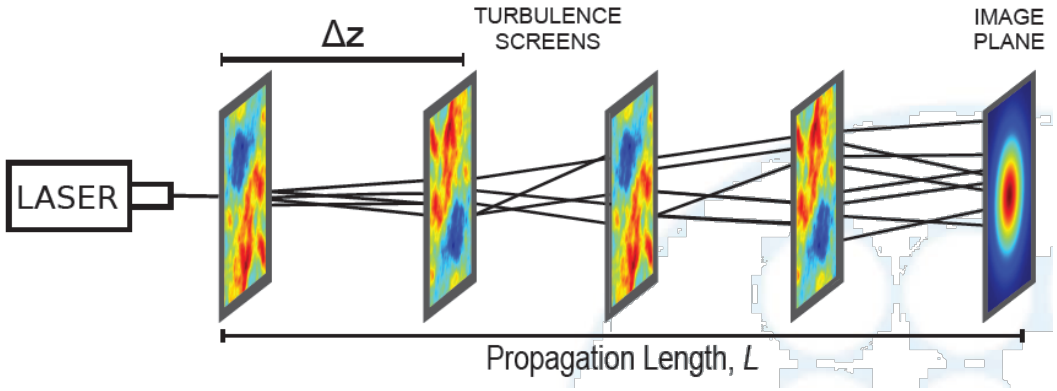
Free-Space Loss

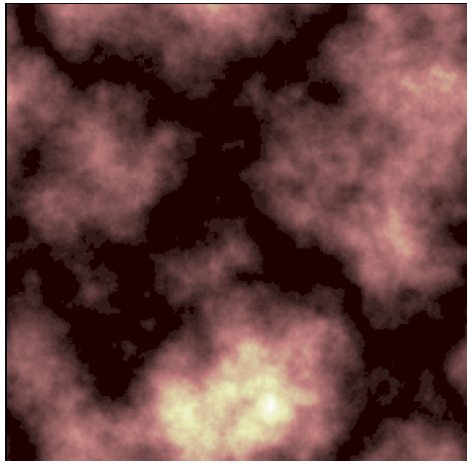


Atmospheric Transmission

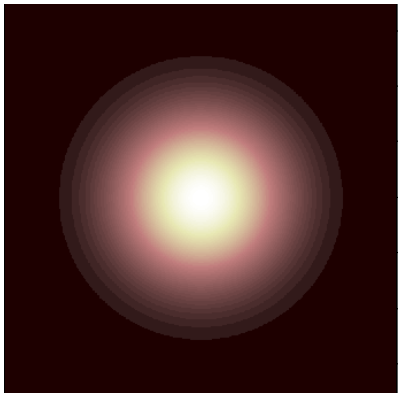


What happens when an optical beam passes through turbulent air?

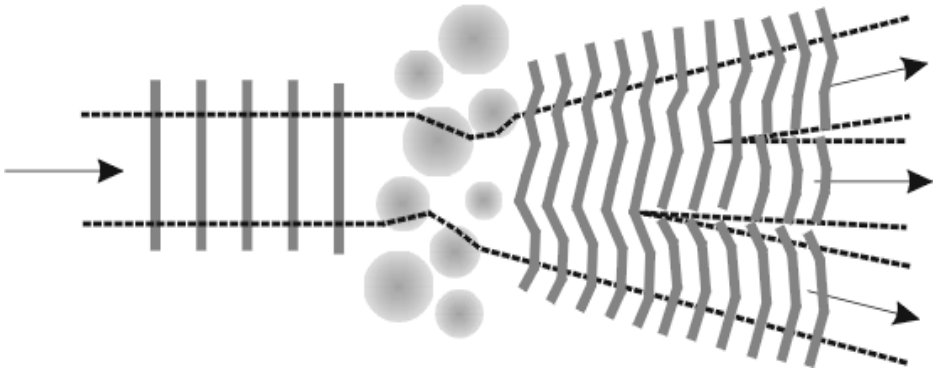




Turbulence screen example

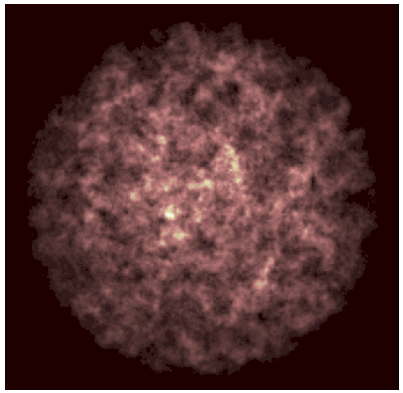


collimated laser beam at Tx



turbulent volume with IRT-strength

Wavefront distortion → Interference



Far-field intensity-speckles

C_n^2 profile Defines IRT strength

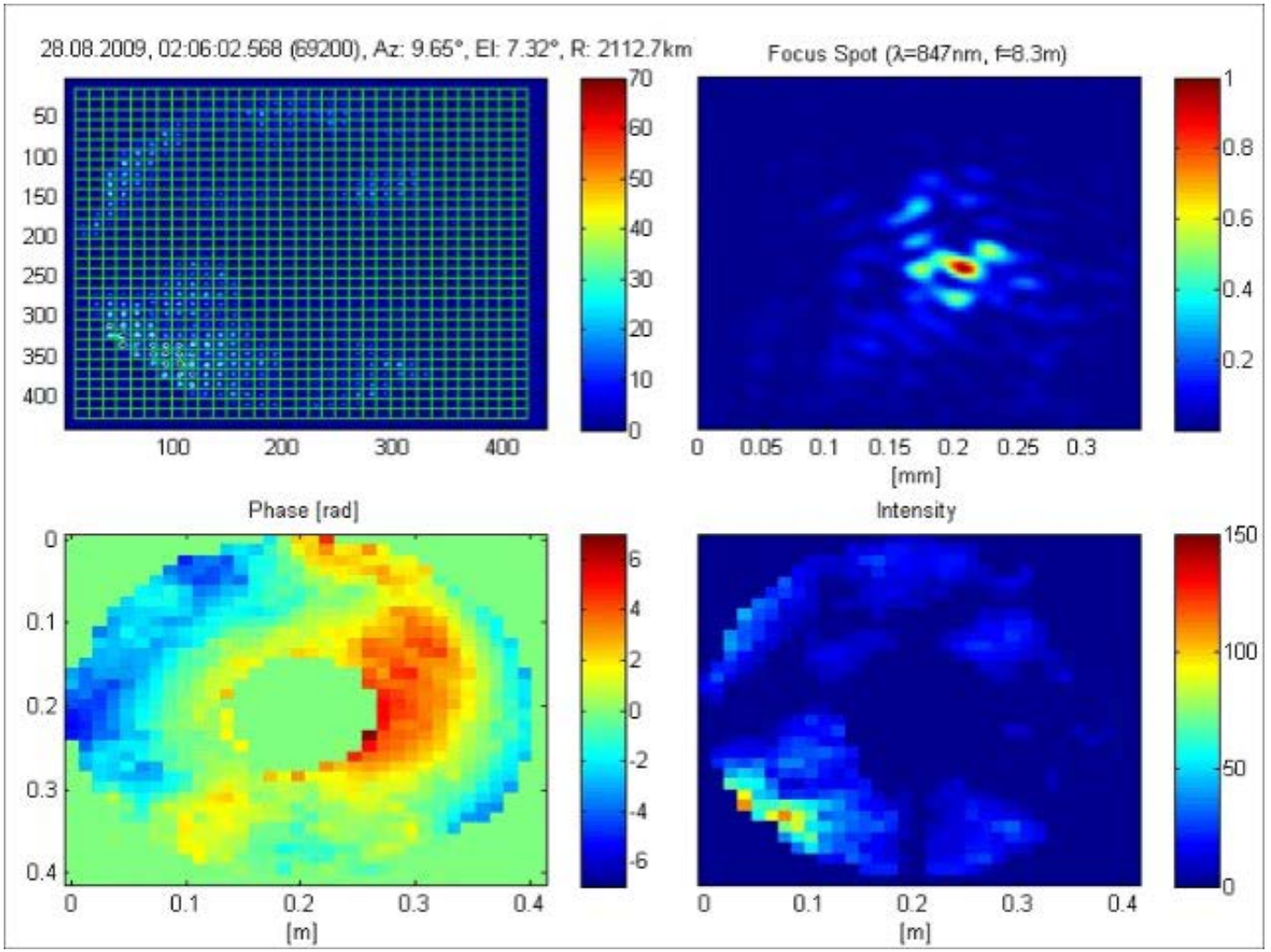
Turbulence Characterization
KIODO 2009

Shack Hartmann

Focus spot

Reconstr. phase

Intensity



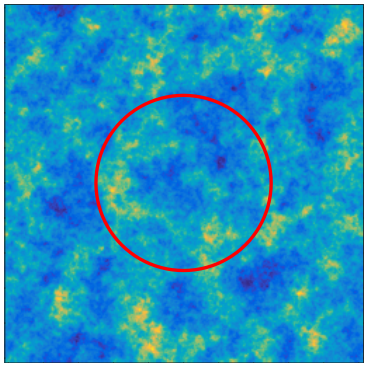
Outline

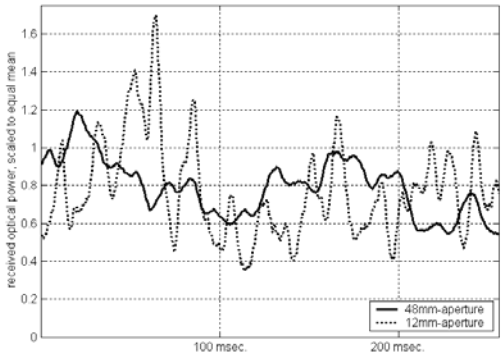
- ❑ Introduction to Lasercom for Space
- ❑ Technologies and Modulation Formats
- ❑ Atmospheric Effects
- ❑ Atmospheric-induced Fading Mitigation Techniques
- ❑ Optical GEO Feeder Links
- ❑ Summary

Downlink Mitigation Strategies

❑ Aperture Averaging

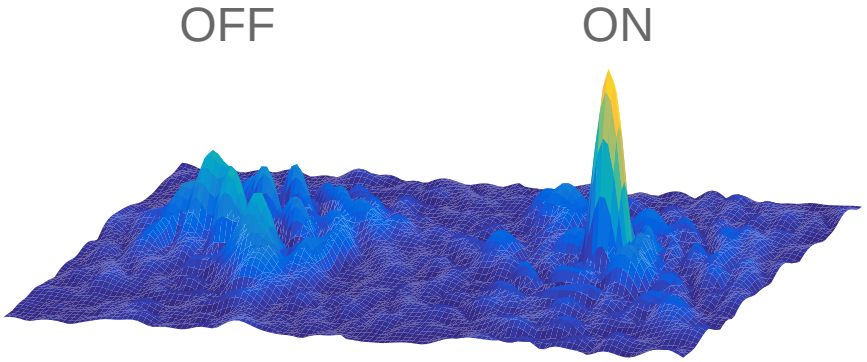
- Larger Rx aperture reduces variance of Rx power in magnitude and spectrum.
- Rx aperture is larger than the average structure size of the Rx field.

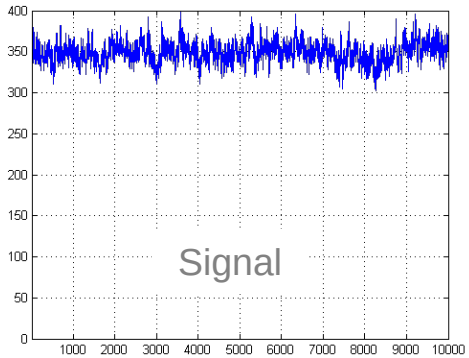


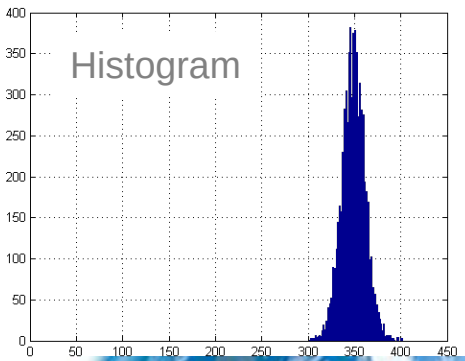


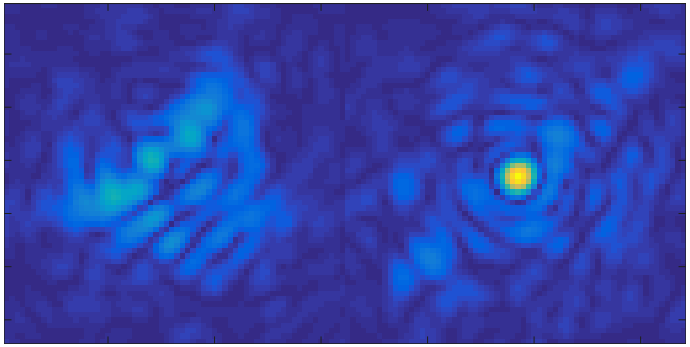
❑ Adaptive Optics

- Enables SMF coupling, or Heterodyning with LO.
- Requires real time correction of atmospheric phase distortions.





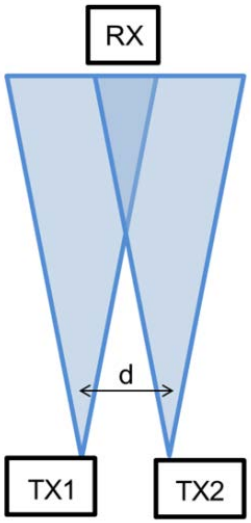


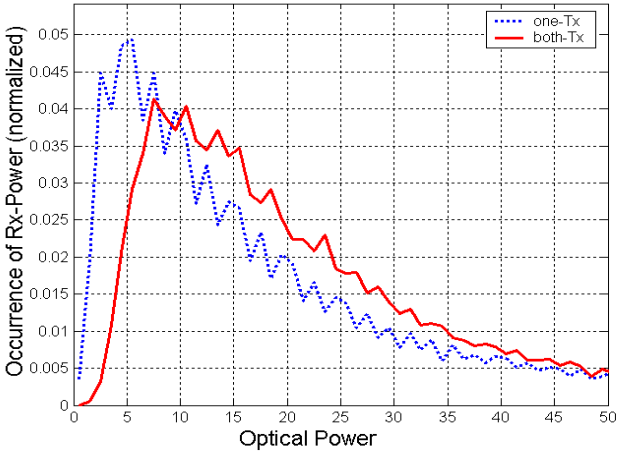


Uplink Mitigation Strategies

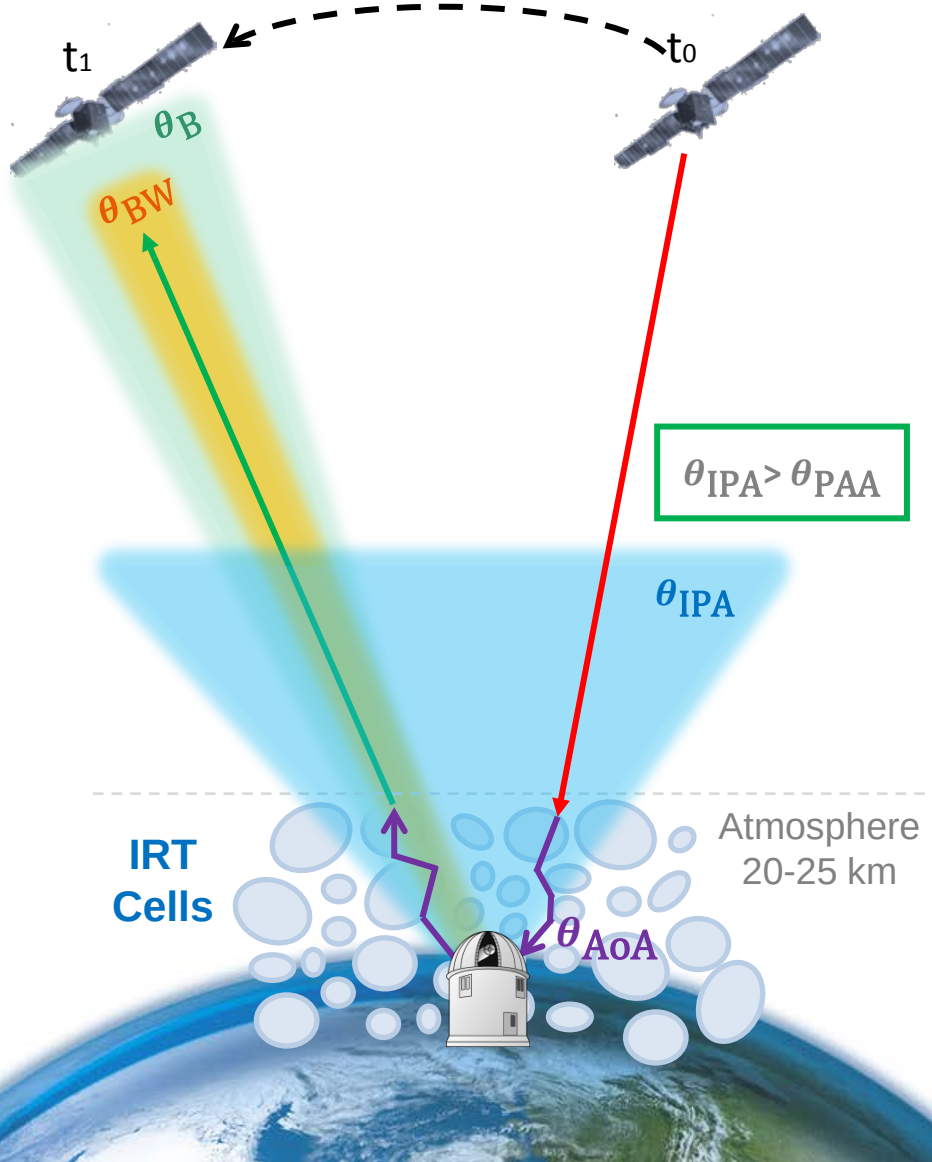
❑ Transmitter diversity

- Multiple separated Tx lasers undergo different atmospheric paths.
- Non-coherent detection averages out atmospheric effects.
- Separation defined by Fried parameter.





❑ Pre-distortion Adaptive Optics



DLR

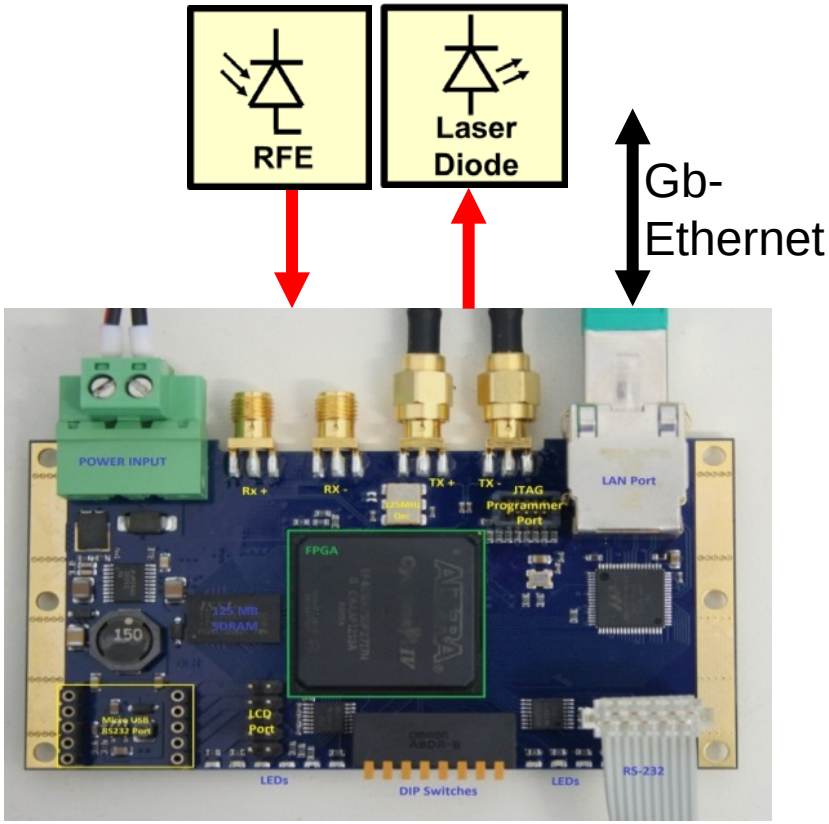
Error Correction Codes
Downlink and uplink

Delay-Tolerant Transmission Management (only non-realtime scenarios)

Low-overhead ARQ for lossy return channel

Interleaved Packet-Layer FEC (Burst Errors from IRT-Fading, 1..10ms)

Robust Data-Recovery and Bit-Level FEC



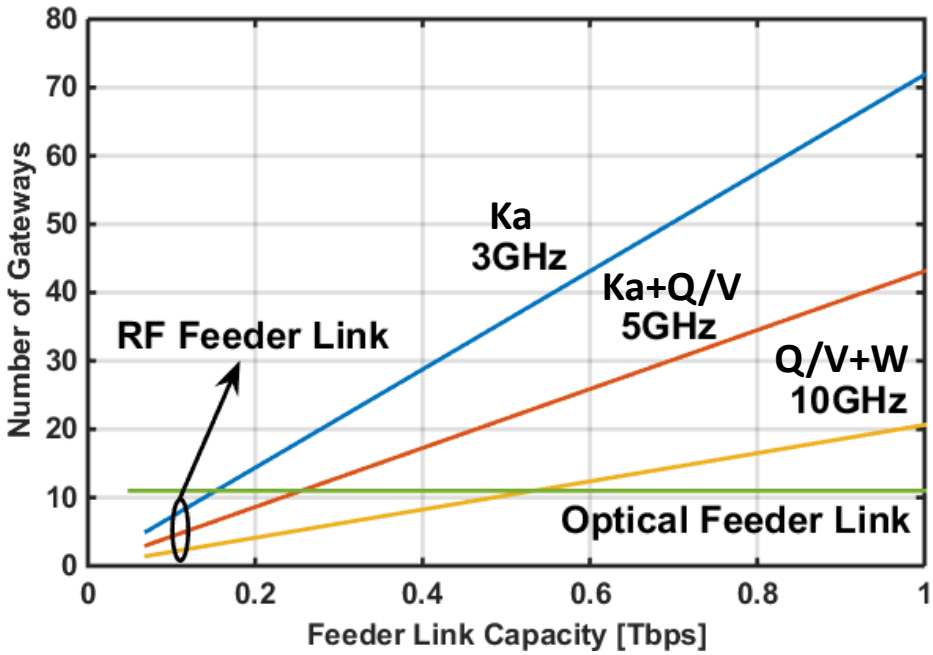
FPGA-Implementation of Laser-Ethernet-Transceiver (LET)

Outline

- ❑ Introduction to Lasercom for Space
- ❑ Technologies and Modulation Formats
- ❑ Atmospheric Effects
- ❑ Atmospheric-induced fading Mitigation Techniques
- ❑ Optical GEO Feeder Links
- ❑ Summary

Motivation for Optical GEO Feeder Links in Future Satellite Com. Systems

- Terabit-per-second SatComm is required in future (EU Digital Agenda by 2020)
  - Every EU-citizen at least 30Mbps
  - 50% with 100Mbps or more.
- Number of required RF ground stations grows linear with throughput
- Optical Feeder Links provide >1Tbps over one optical ground station
- Number of OGSs in the network is driven by robustness against cloud blockage
  - **At least one OGS must be available**



*[*] RF feeder link assumes all spectrum usage in **Ka** band (blue line), **Ka+Q/V** band (red line) and **Q/V+W** band (yellow line). OGEOFL (green line) can provide Terabit capacity with only one OGS.*

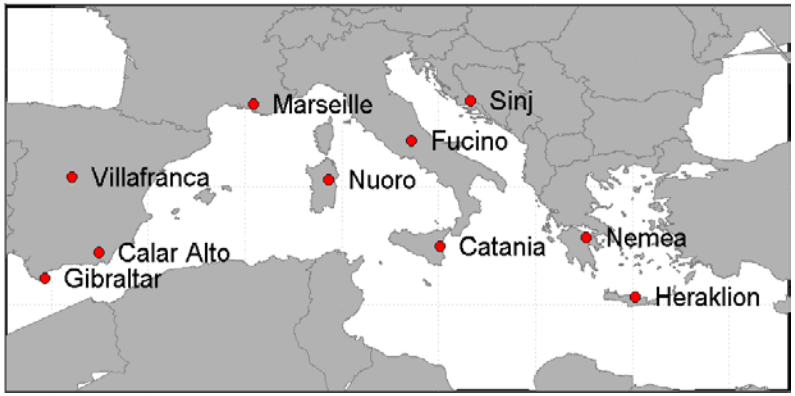
Cloud-Blockage Mitigation OGS-Network Availability

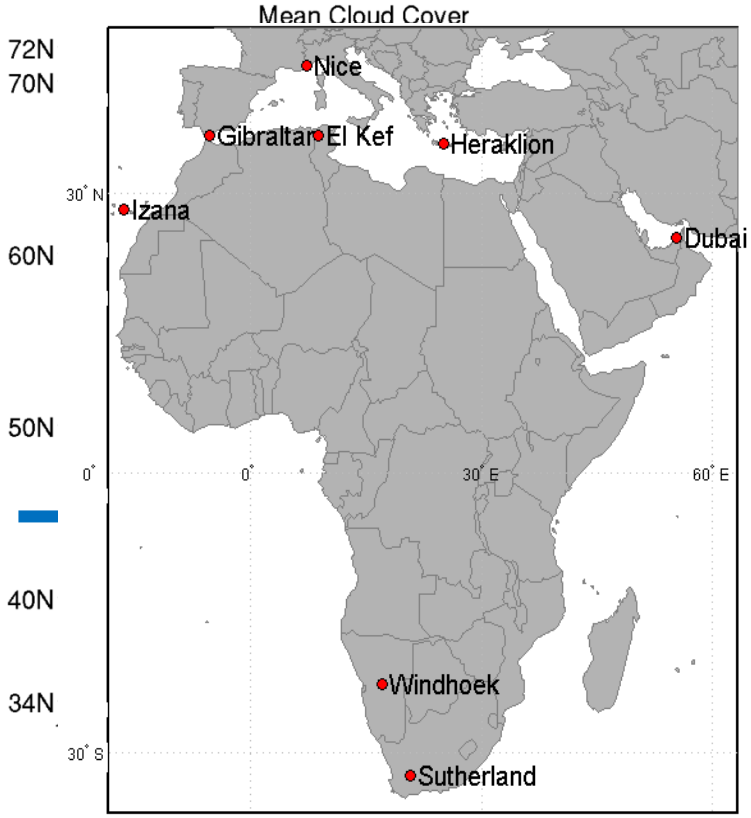
11 European stations

Availability = 99.67 %

10 Mediterr. stations

Availability = 99.89 %



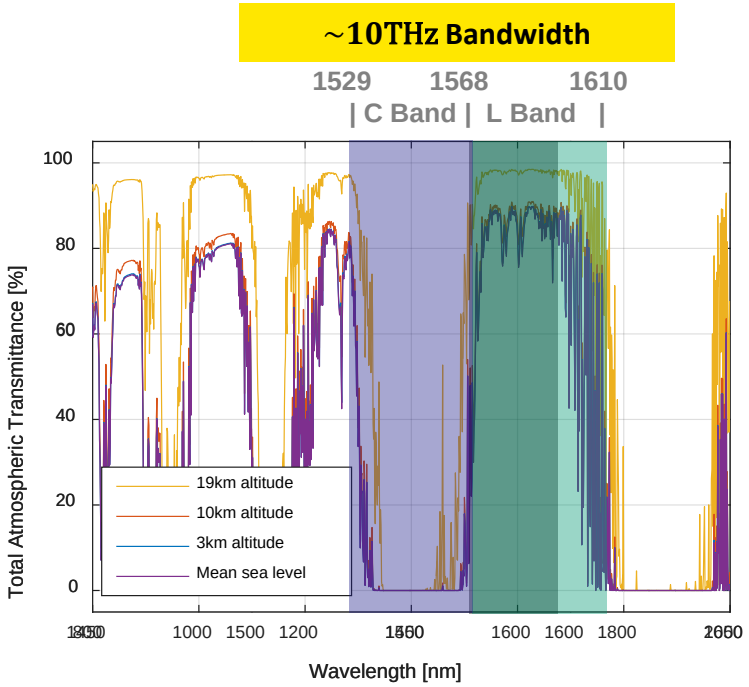


8 stations Inter-Continental

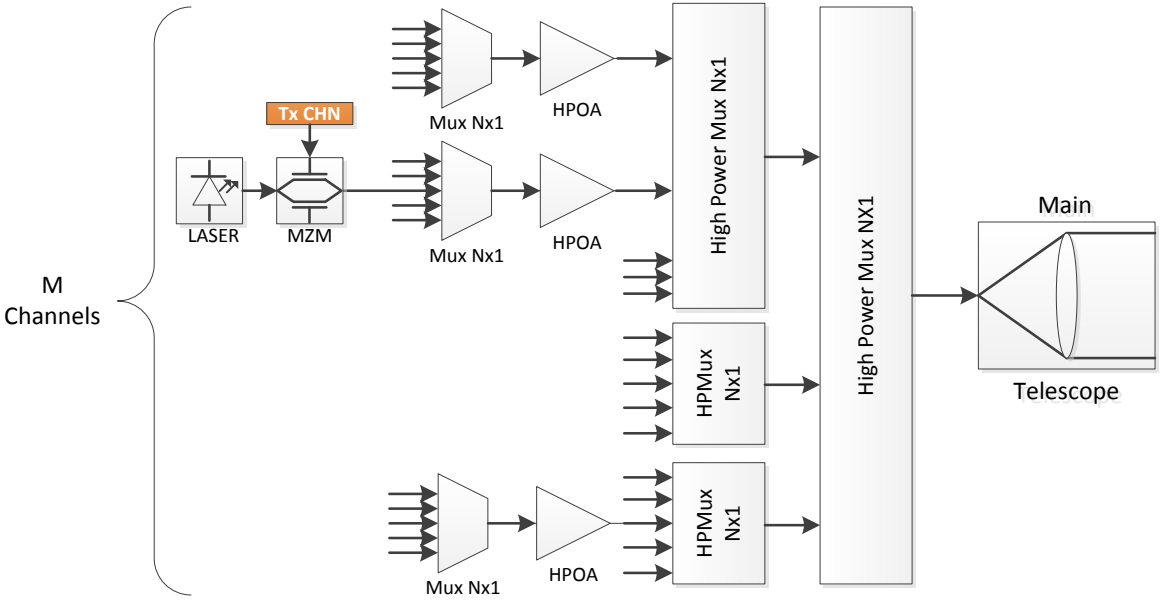
Availability = 99.971 %

Data-basis: Satellite images and simultaneous ground observations (from 1990 to 2006)

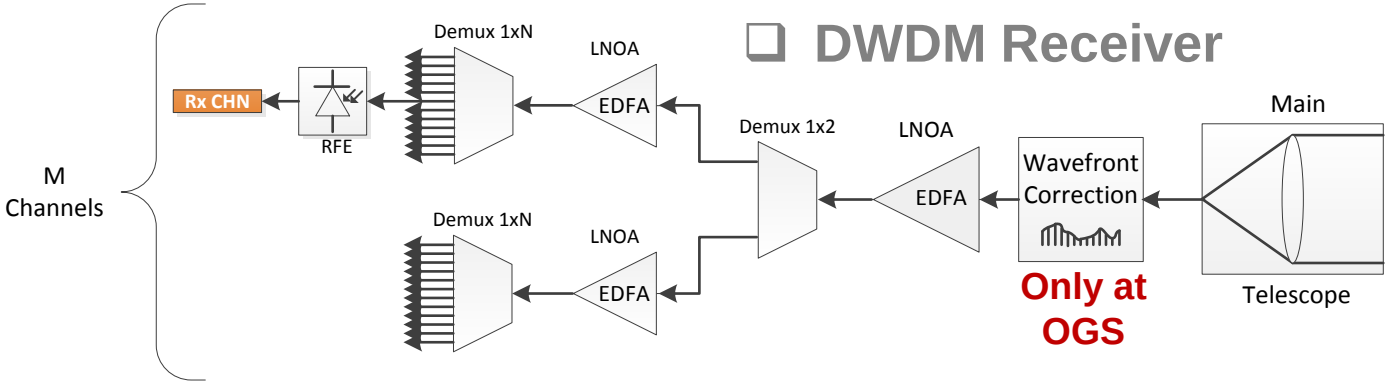
DWDM-System for Optical GEO Feeder-Links



❑ DWDM Transmitter



❑ DWDM Receiver



θ_{AoA}: Angle-of-Arrival
θ_{PAA}: Point-Ahead Angle
θ_{BW} : Beam Wander
θ_{IPA}: Isoplanatic Angle

Ground-GEO Optical Channel

$\theta_{PAA} \sim 18\mu rad$

GEO Orbit
36000 km

t_1

~253ms (700m)

t_0

θ_{BW}

θ_{IPA}

θ_{AoA}

Signal

Histogram

Signal

Histogram

Atmosphere
20-25 km

IRT
Cells

Strong Fading due
to beam wander

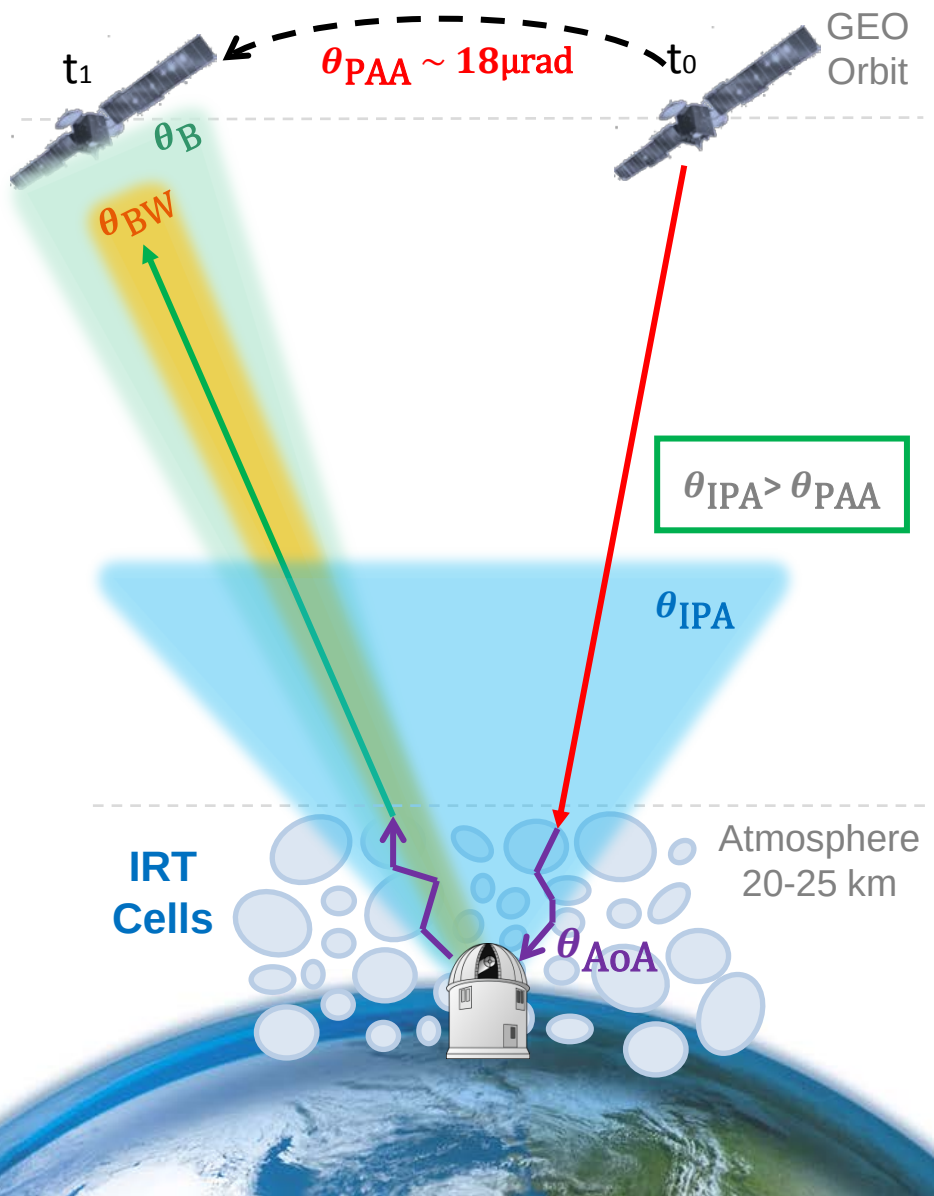
DLR

θ_{AoA}: Angle-of-Arrival
θ_{PAA}: Point-Ahead Angle
θ_{BW} : Beam Wander
θ_{IPA}: Isoplanatic Angle
θ_B: Beam divergence

Uplink Transmission Approaches
Pointing by tracking

- Downlink reference can be used to point the uplink.
  - Beam wander can be compensated.
  - Smaller uplink divergence is possible → Larger Tx Gain
- Correlation between down- and up-link paths is not perfect.
  - Residual beam wander.
- Correlation coefficient follows

$$\gamma \propto \exp\left[-\left(\frac{\theta_{PAA}}{\theta_{IPA}}\right)^{5/3}\right]$$



DLR

θ_{AoA}: Angle-of-Arrival
θ_{PAA}: Point-Ahead Angle
θ_{BW} : Beam Wander
θ_{IPA}: Isoplanatic Angle
θ_{B}: Beam divergence

Uplink Transmission Approaches
Open loop pointing

$$G_T = (\pi D_T / \lambda)^2$$

Transmitter gain

Free-space Loss

Receiver gain

$$P_R = P_T G_T \eta_T \tau_{ATM} L_{FS} L_{SR} L_{BW} G_R \eta_R$$

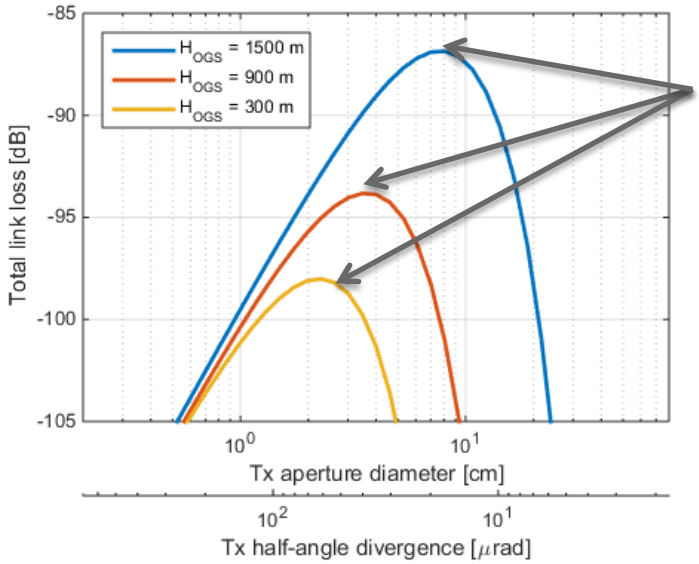
Atm. Attenuation

Strehl ratio Loss

$$L_{SR} = 10\log_{10}\left(1+(D_T / r_0)^{5/3}\right)^{-6/5}$$

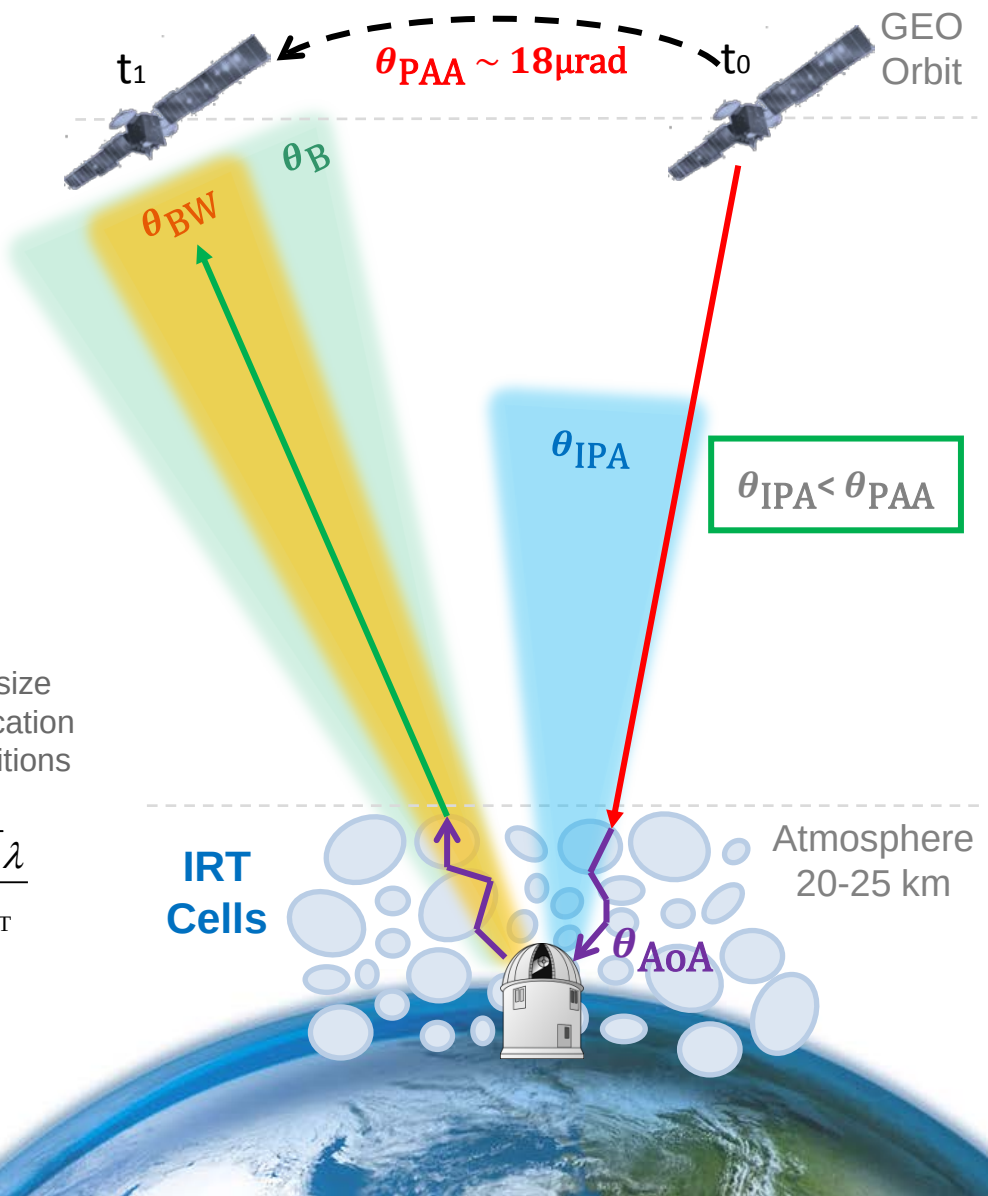
Beam Wander Loss

$$L_{BW} = \exp\left(-G_T \theta_{BW}{}^2\right)$$



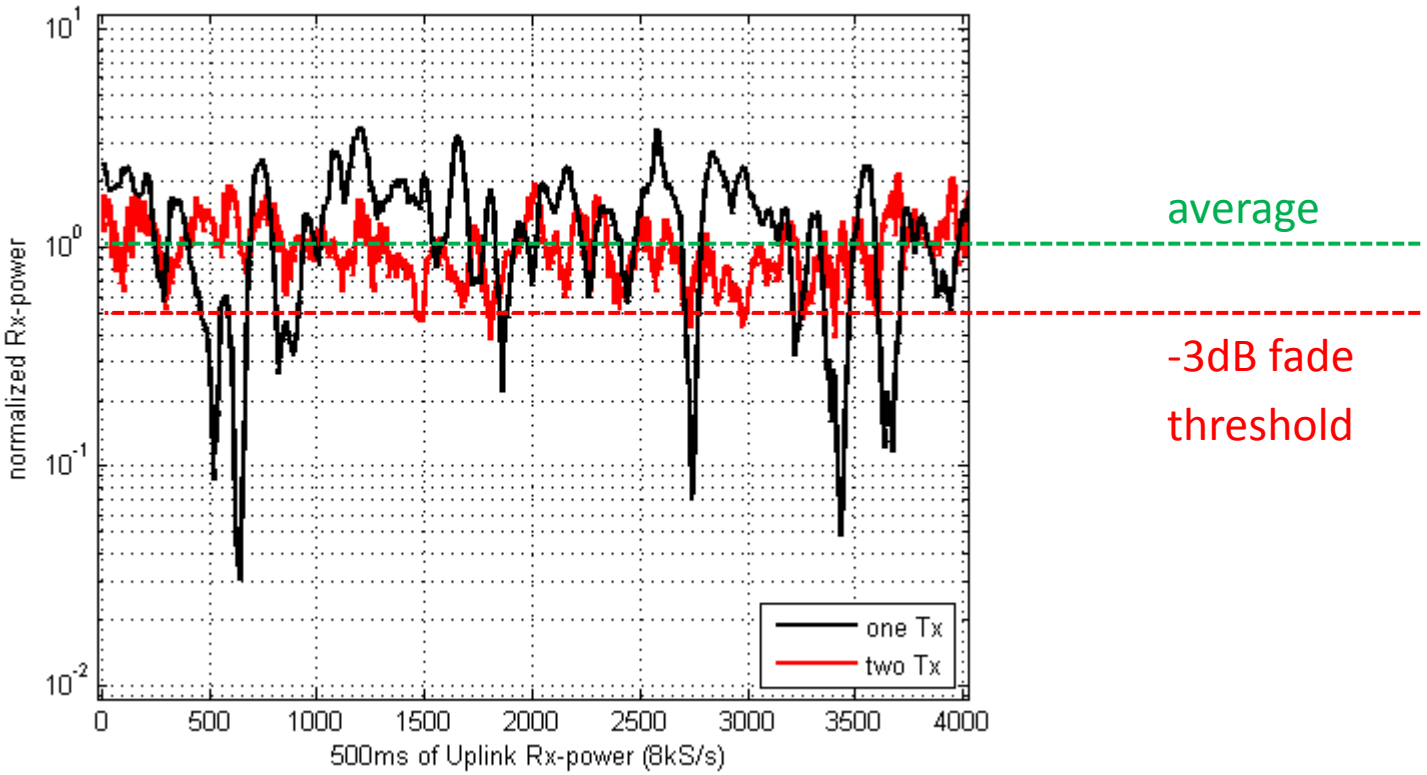
Optimum Tx size depends on location and atm. conditions

$$\theta_{DIV} = \frac{2\sqrt{2}\lambda}{\pi D_T}$$



Measured Uplink Received Power at GEO

Rx-Power with second Tx-Beam



Alternative Solution:
Probing with Laser Guide Star

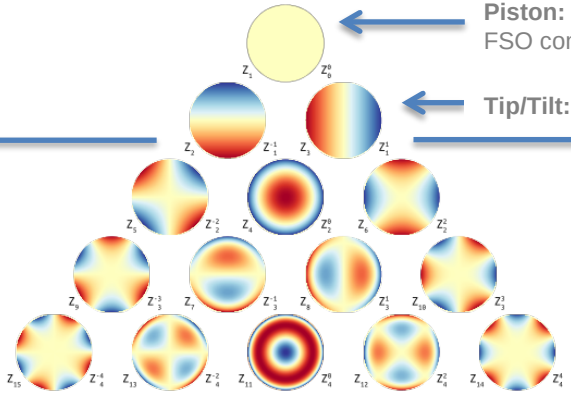
Mata-Calvo et al. "Transmitter diversity verification on ARTEMIS geostationary satellite," Proc. SPIE 8971, pp. 897104, 2014.

Uplink Transmission Approaches
Pre-distortion Adaptive Optics

Lower modes
Relative error
~80%

Higher modes
Relative error
~20%

Absolute error
still significant



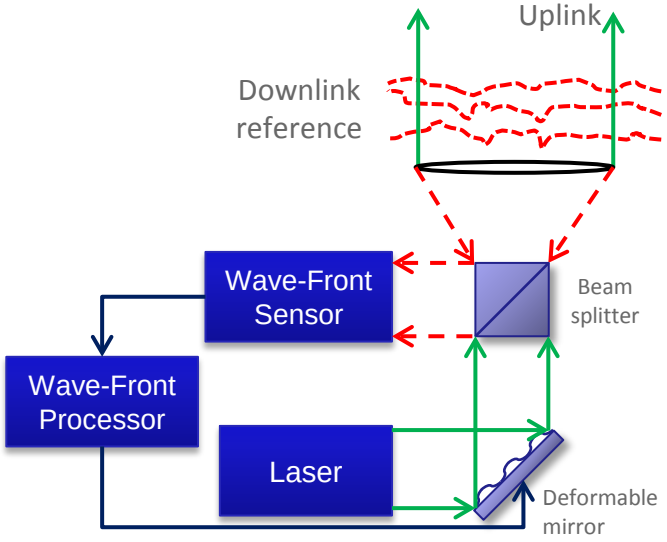
Piston: Not relevant in FSO communications

Tip/Tilt: Beam wander

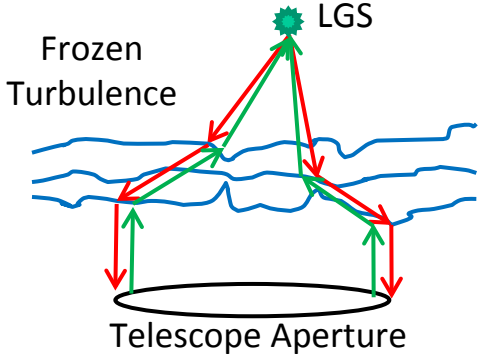
Higher modes produce only scintillation

- Phase distortions can be represented by Zernike modes.
- Correction of only higher modes might not provide enough improvement.
  - Beam wander correction either by divergence optimization or pointing by tracking.

Pre-distortion AO system



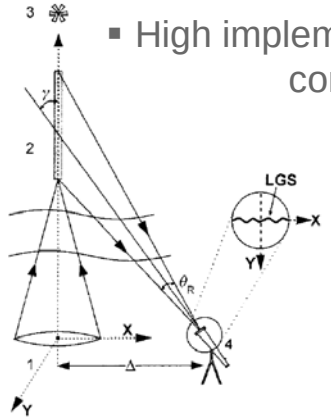
Laser Guide Star (LGS)



- Round-trip ~0.6ms. Tilt time ~100 ms.
- For Tx/Rx shared aperture up- and downlink sees same tilt.
- **Classic LGS cannot measure tilt.**

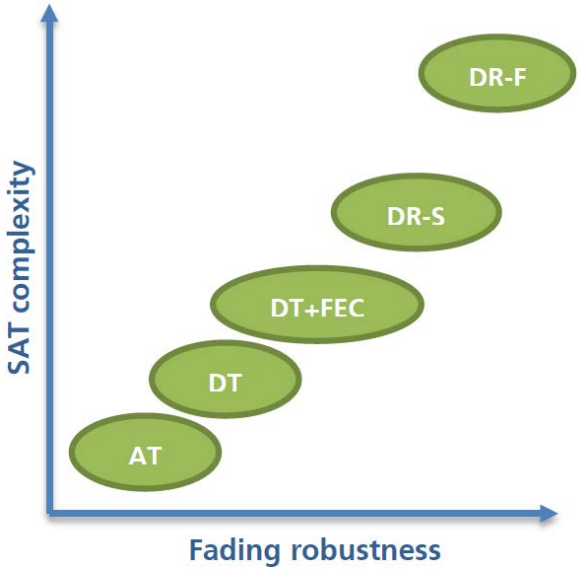
LGS Tilt correction

- Bistatic approach breaks up- and downlink correlation.
- Min. 2 Rx to retrieve tilt info.
- High implementation complexity.



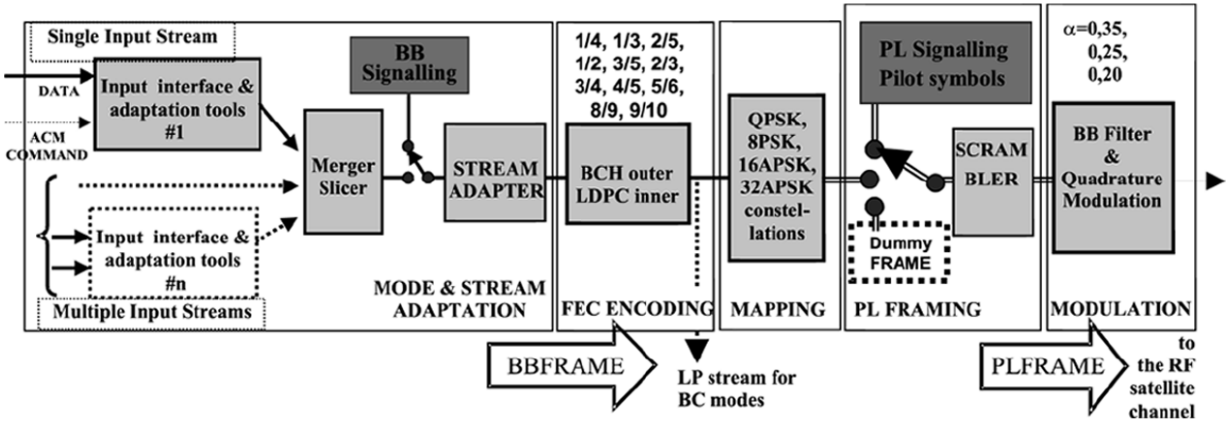
DVB-S2 Signal

❑ Uplink Transmission Schemes

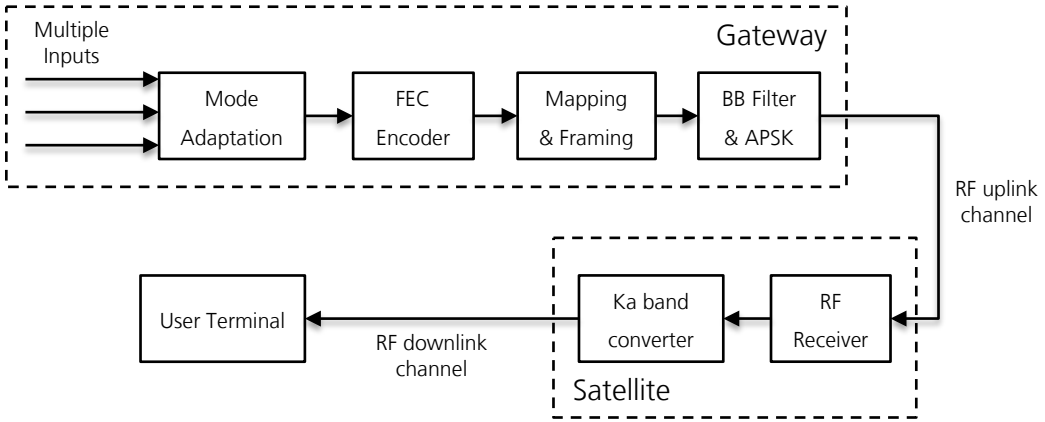


- AT: Analog Transparent
- DT: Digital Transparent
- FEC: Forward Error Correction
- S: Soft
- F: Full

❑ Functional block diagram of the DVB-S2 system



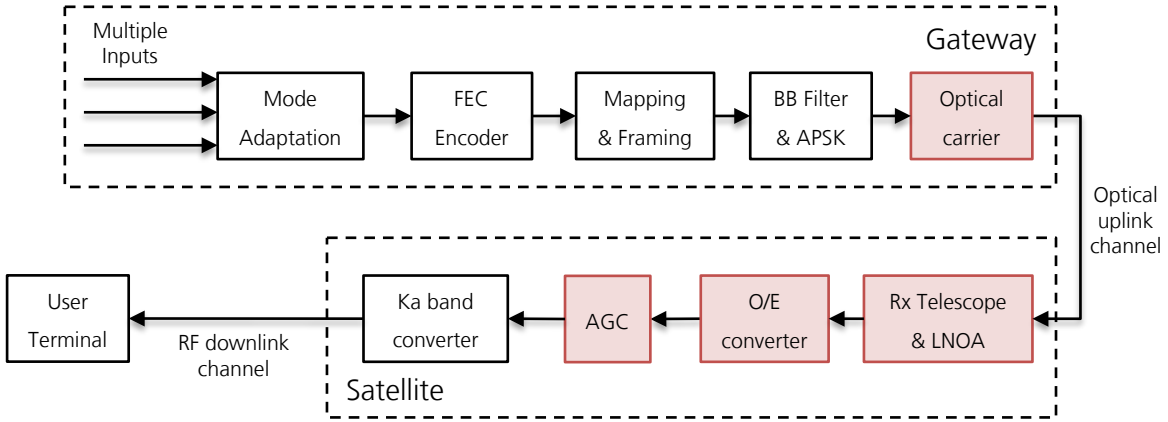
❑ Simplified block diagram including the satellite and user in the chain.



Transparent Options

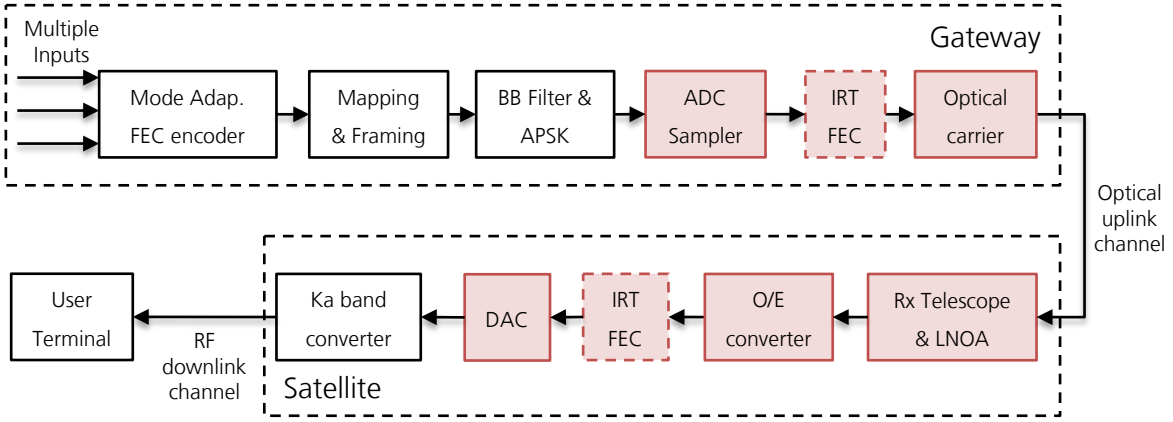
- Minimum impact on sat payload.
- Due to high Tx powers HPOA nonlinearities can be a problem.
- No protection against long fades.

❑ Analog transparent transmission scheme for DVB-S2 signals



- Processing power needed onboard.
- Specific protection against IRT fading possible.
- Considerable bandwidth expansion.

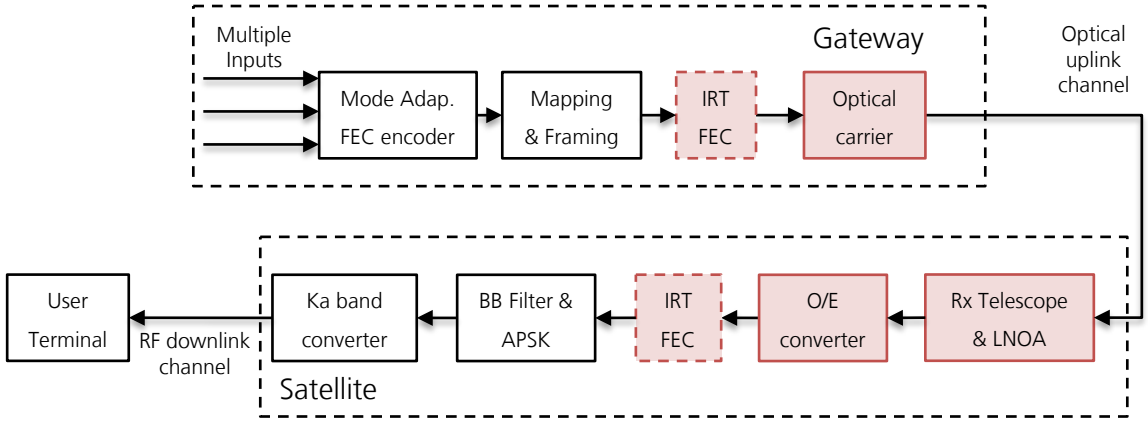
❑ Digital transparent transmission scheme for DVB-S2 signals. Dashed blocks are optional.



Digital Regenerative Options

- Lower bandwidth reqs. compared to DT option.
- Excellent protection against fading.
- Major impact on sat payload.
- Transparency is almost lost.
- SWaP penalty due to BB-to-Ka onboard conversion.

❑ Digital soft-regenerative transmission scheme for DVB-S2 signals.

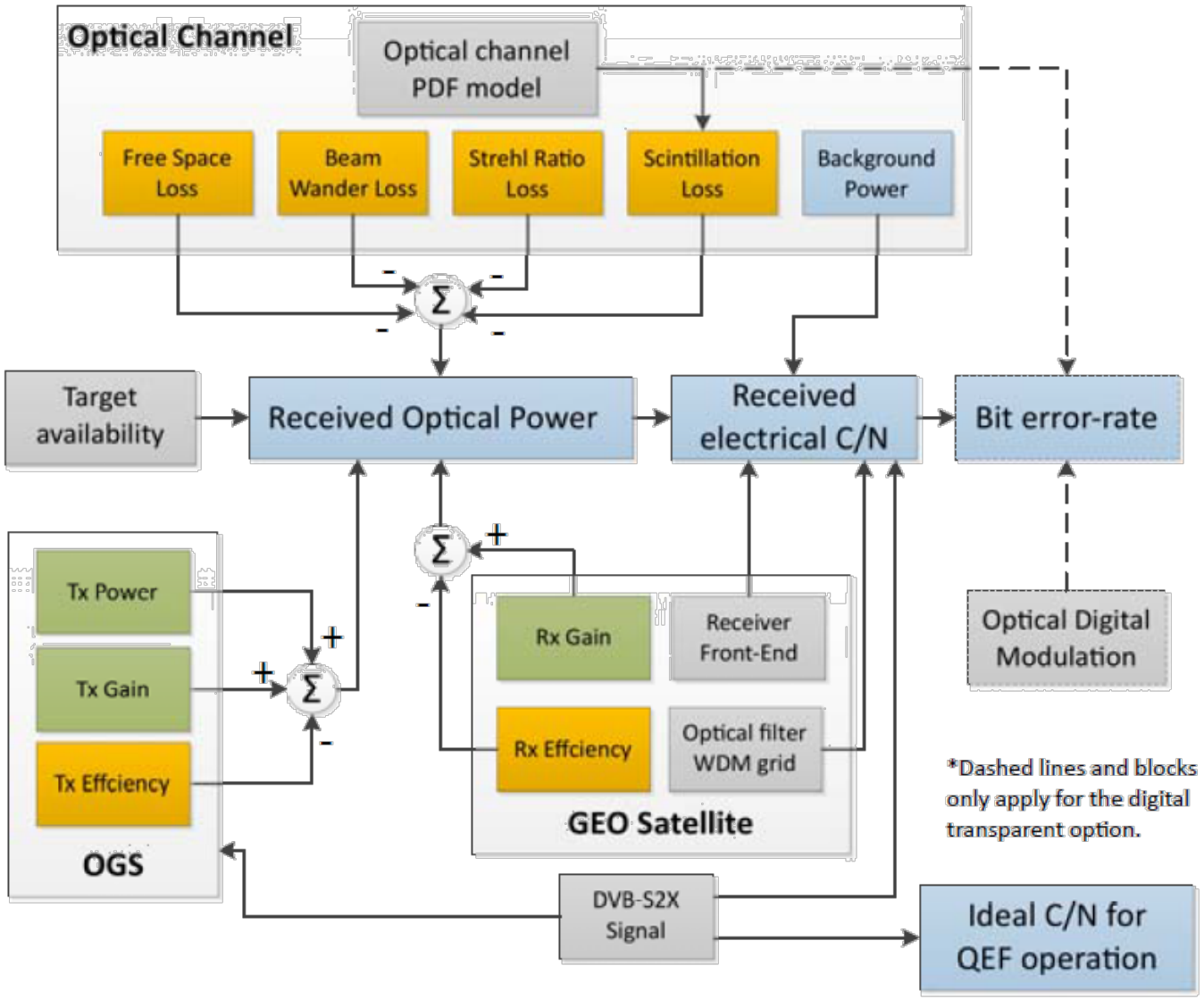


- Most robust in terms of BER.
- Maximum SWaP impact.
- No standard upgrades after Sat launch.

❑ Fully regenerative:

Data a is also transmitted in baseband over the optical carrier, but DVB-S2 modulation and coding blocks are included in the satellite RF chain to achieve most robust system against BER.

Link Budget

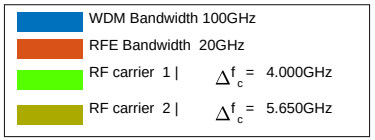

Optical Channel
Optical channel PDF model
Free Space Loss
Beam Wander Loss
Strehl Ratio Loss
Scintillation Loss
Background Power
Target availability
Received Optical Power
Received electrical C/N
Bit error-rate
Tx Power
Tx Gain
Tx Effciency
OGS
Rx Gain
Receiver Front-End
Rx Effciency
Optical filter WDM grid
GEO Satellite
Optical Digital Modulation
*Dashed lines and blocks only apply for the digital transparent option.
DVB-S2X Signal
Ideal C/N for QEF operation

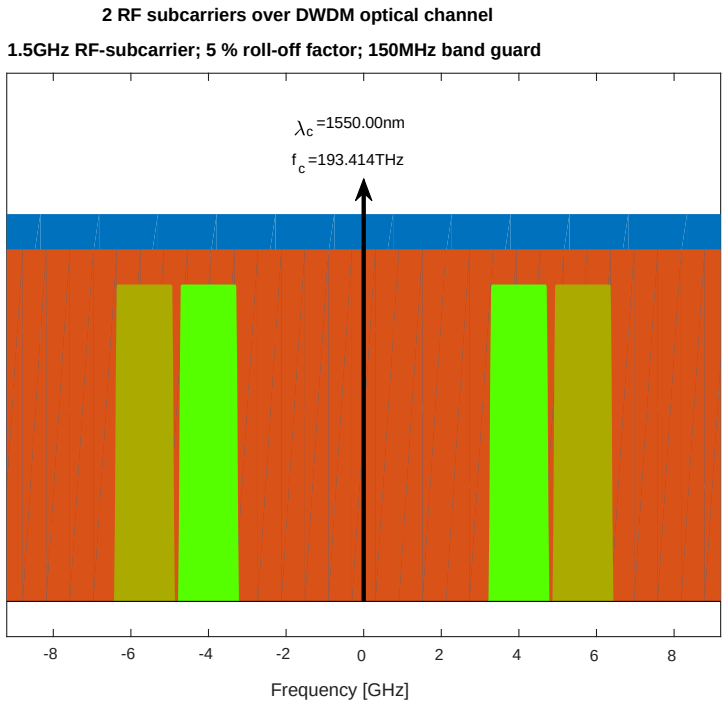
Link Budget
Analog Transparent Example

Parameter	Unit	Tenerife	Tirana	Gibraltar	Paris
Tx antenna gain	dB	113.53	108.82	105.87	103.01
Transmitter loss	dB	-3.01	-3.01	-3.01	-3.01
Tx diversity gain	dB	0.00	0.00	0.00	0.00
Free-space loss	dB	-289.66	-289.75	-289.68	-289.89
Atmospheric attenuation	dB	-0.14	-0.28	-0.34	-0.49
Cloud margin	dB	-3.00	-3.00	-3.00	-3.00
Strehl ratio loss	dB	-1.14	-1.14	-1.11	-1.09
Beam wander loss	dB	-5.19	-5.19	-5.02	-4.93
Scintillation loss	dB	-2.19	-3.75	-4.16	-5.76
Tx antenna gain	dB	114.10	114.10	114.10	114.10
Receiver loss	dB	-3.01	-3.01	-3.01	-3.01
Fiber coupling loss	dB	-1.07	-1.07	-1.07	-1.07
Total link loss	dB	-80.79	-87.29	-90.44	-95.14
Total OGS Tx power	dBm	44.77	44.77	44.77	44.77
Received power	dBm	-36.02	-42.52	-45.67	-50.37
Carrier-to-noise ratio	dB	23.85	16.53	12.45	5.39

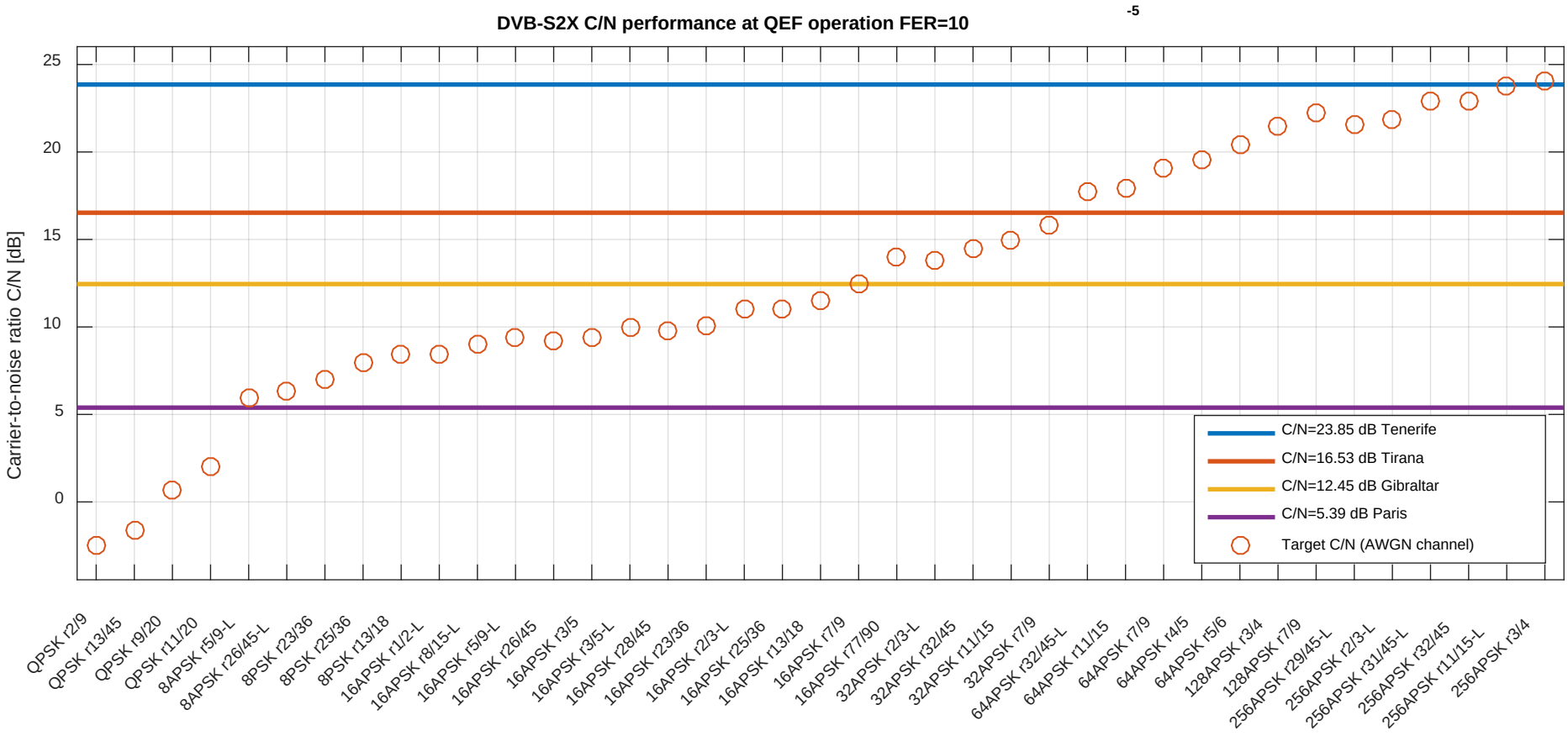
- OGS Tx optical power per lambda 30W.
- One lambda per beam.
- BW 1.45GHz per beam.
- DWDM Grid: 100-50-25 GHz
- RFE photodetector at SAT BW=20GHz
- SAT: EDRS-A @ 9ºE

- Uplink IF in RF C-band 4-8GHz.





Link Budget
Analog Transparent Example



DLR

DVB implementation guidelines; part 2 - S2 Extension (DVB-S2X). Doc. A171-2, 2015.

Selected References

- R. Mata-Calvo, P. Becker, D. Giggenbach, F. Moll, M. Schwarzer, M. Hinz, and Z. Sodnik, “Transmitter diversity verification on Artemis geostationary satellite,” in *Free-Space Laser Communication and Atmospheric Propagation XXVI*, 2014, vol. 8971, p. 897104.
- S. Dimitrov, B. Matuz, G. Liva, R. Barrios, R. Mata-Calvo, and D. Giggenbach, “Digital Modulation and Coding for Satellite Optical Feeder Links,” in *7th Advanced Satellite Multimedia Systems Conference (ASMS)*, 2014.
- D. Giggenbach, “Optical Satellite Feeder Links for Terabps Throughput.” DLR Institute of Communications and Navigation, Presentation, on elib.dlr.de
- Sylvain Poulenard, Michael Crosnier, and Angélique Rissons, “Ground Segment Design for Broadband Geostationary Satellite With Optical Feeder Link,” J. OPT. COMMUN. NETW. 7(4), pp. 325-336, 2015.
- N. Perlot, T. Dreischer, C. M. Weinter, and J. Perdigues, “Optical GEO Feeder Link Design,” in *Future Network & MobileSummit 2012 Conference Proceedings*, 2012.
- D. Giggenbach, P. Becker, R. Mata-Calvo, C. Fuchs, Z. Sodnik, and I. Zayer, “Lunar Optical Communications Link (LOCL): Measurements of Received Power Fluctuations and Wavefront Quality,” in *Proc. International Conference on Space Optical Systems and Applications (ICSOS)*, 2014.
- D. Giggenbach, R. Barrios, F. Moll, R. Mata-Calvo, S. Bobrovskyi, F. Huber, N. Johnson-Amin, F. Heine, and M. Gregory, “EFAL: EDRS Feeder Link from Antarctic Latitudes - Preliminary Results of Site Investigations, Availability, and System Requirements,” in *International Conference on Space Optical Systems and Applications (ICSOS)*, 2014.

Preguntas?