TNO innovation for life

SATELLITE COMMUNICATION WITH OPTICAL WAVES

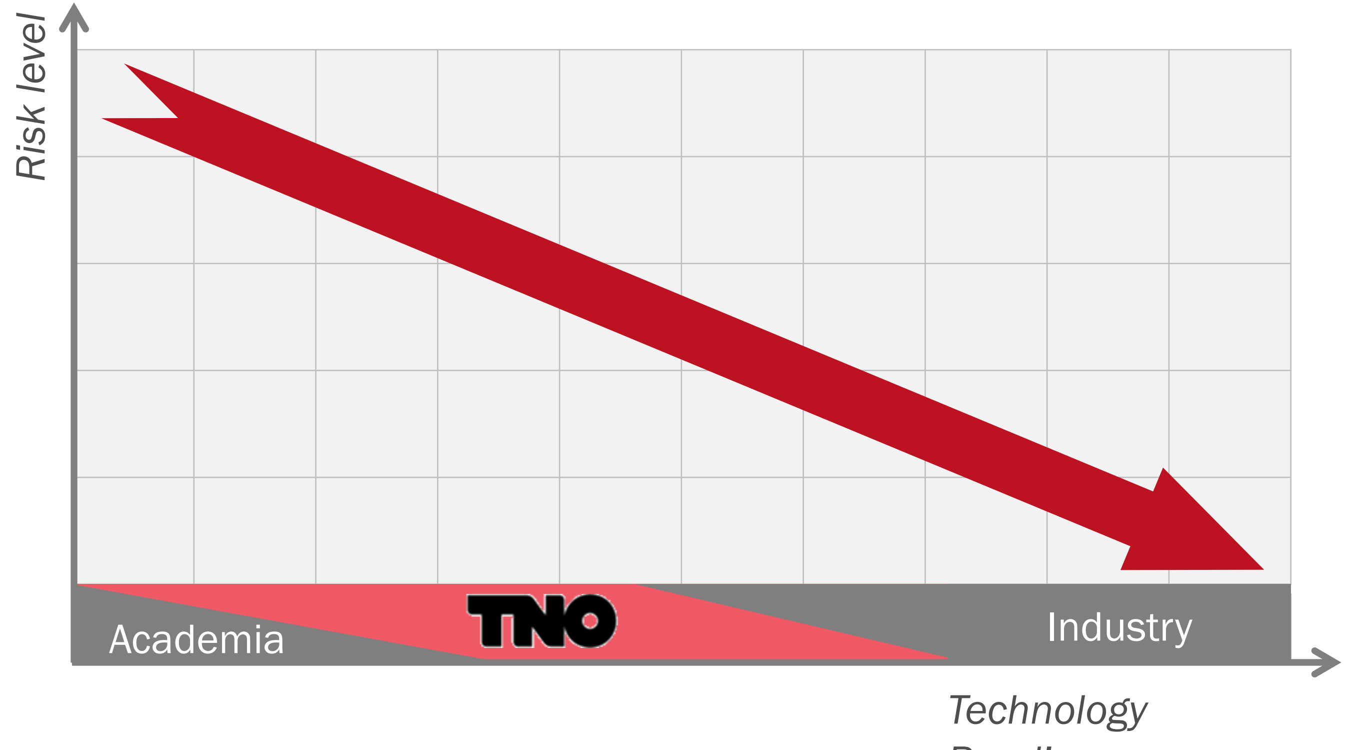
– POTENTIAL AND CHALLENGES –

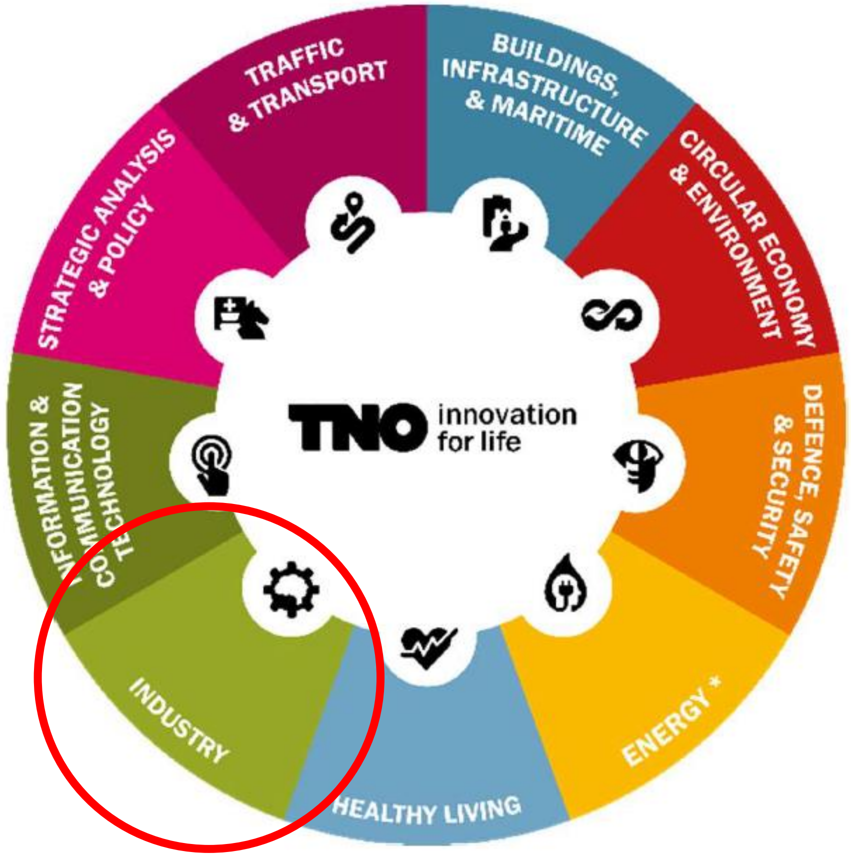
NIEK DOELMAN

- TNO SPACE & LEIDEN UNIVERSITY

TNO

- Founded in 1932
- Independent not-for-profit organization, bridging gap between academia and industry
- Annual Turnover ~500Meur: **~30% from Dutch government rest from industry**
- Around 3.000 employees (mainly MSc, PhD)
- Organized in 9 focus area's/units.





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SATELLITE COMMUNICATION WITH OPTICAL WAVES

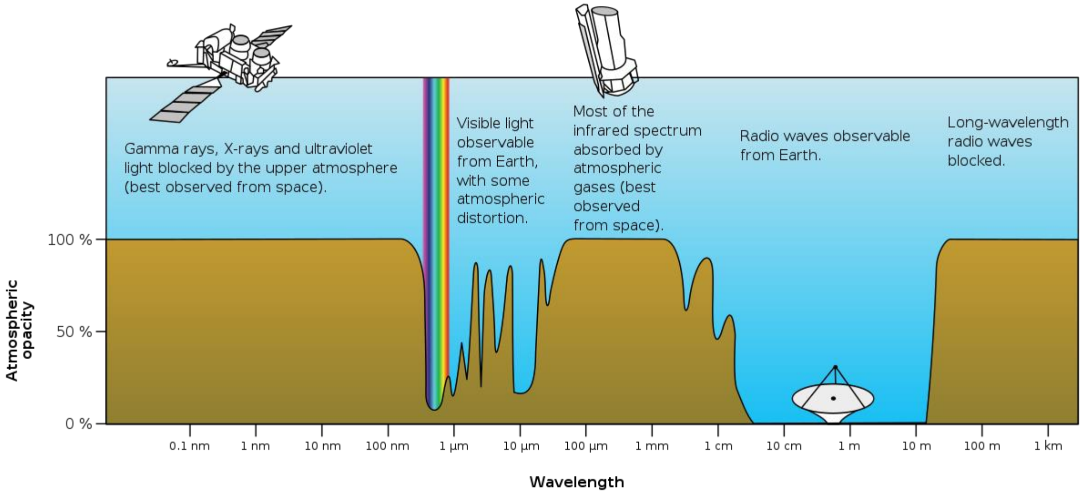
TNO innovation for life

FROM RADIO-FREQUENCY WAVES TO OPTICAL WAVES

POTENTIAL

HIGH FREQUENCY RF BANDS

- EHF 30 - 300 GHz waves: 10 – 1 mm
- THF 0.3 - 3 THz waves: 1 - 0.1 mm



OPTICAL BANDS

- 1.064 μm 282 THz
- 1.550 μm 194 THz

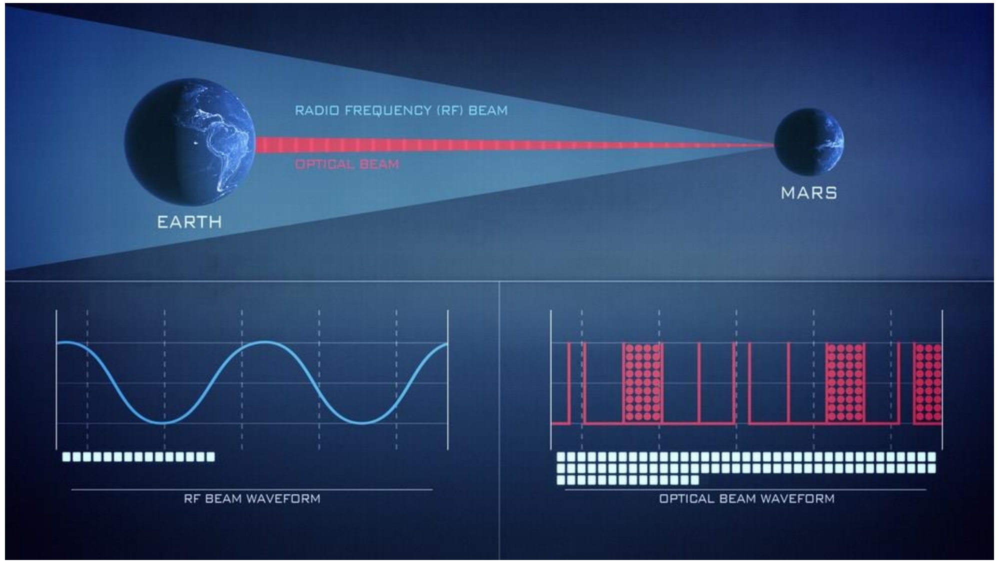
} order ~1000 faster/ shorter wavelength

IMPACT

- Shannon's capacity: $\text{Capacity} = \text{Bandwidth x } \log_2\left(1 + \frac{\text{Signal}}{\text{Noise}}\right)$
- Transmission (Friis): $\text{Transmission coefficient} \sim \left(\frac{\mathrm{D}_{Tx}\,\mathrm{D}_{Rx}}{\lambda\, L}\right)^2$

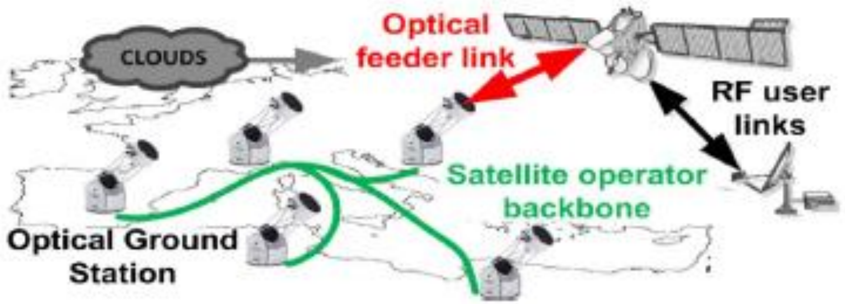
OPTICAL WIRELESS COMMUNICATION
Main Advantages

- High Speed: data rates (> 100 Gbps) with small Transmitter (Tx)/ Receiver (Rx)
- Secure: Immunity to interception, jamming, interferers and piracy
- Secure: enables the use of free space Quantum Key Distribution
- SWaPC: lower volume, lower weight (space), lower cost /bit
- Bandwidth: abundant, unregulated bandwidth
- Network: terrestrial fibre optics already available /enabler
- ... more



Credits: NASA

OPTICAL WIRELESS COMMUNICATION
Challenges



Poulenard 2015

- Requires clear Line-of-Sight … clouds for instance demand a grid of ground stations
- Requires high precision pointing … much smaller beam spot
- Atmospheric conditions … absorption, scattering, …

  atmospheric turbulence leads to intensity fluctuations, beam wander, beam spread
- Eye safety limits ~50 W/m^2 (1064 nm) and 1000W/m^2 (1550 nm)
- Some technology still @ low maturity … e.g. high-power multiplexing, amplifiers, ..
- Standards missing / in progress
- Additional RF/optics conversion needed
- On-board (satellite) high-speed processing needed
- …

FIRST (OPERATIONAL) OPTICAL SATELLITE LINK

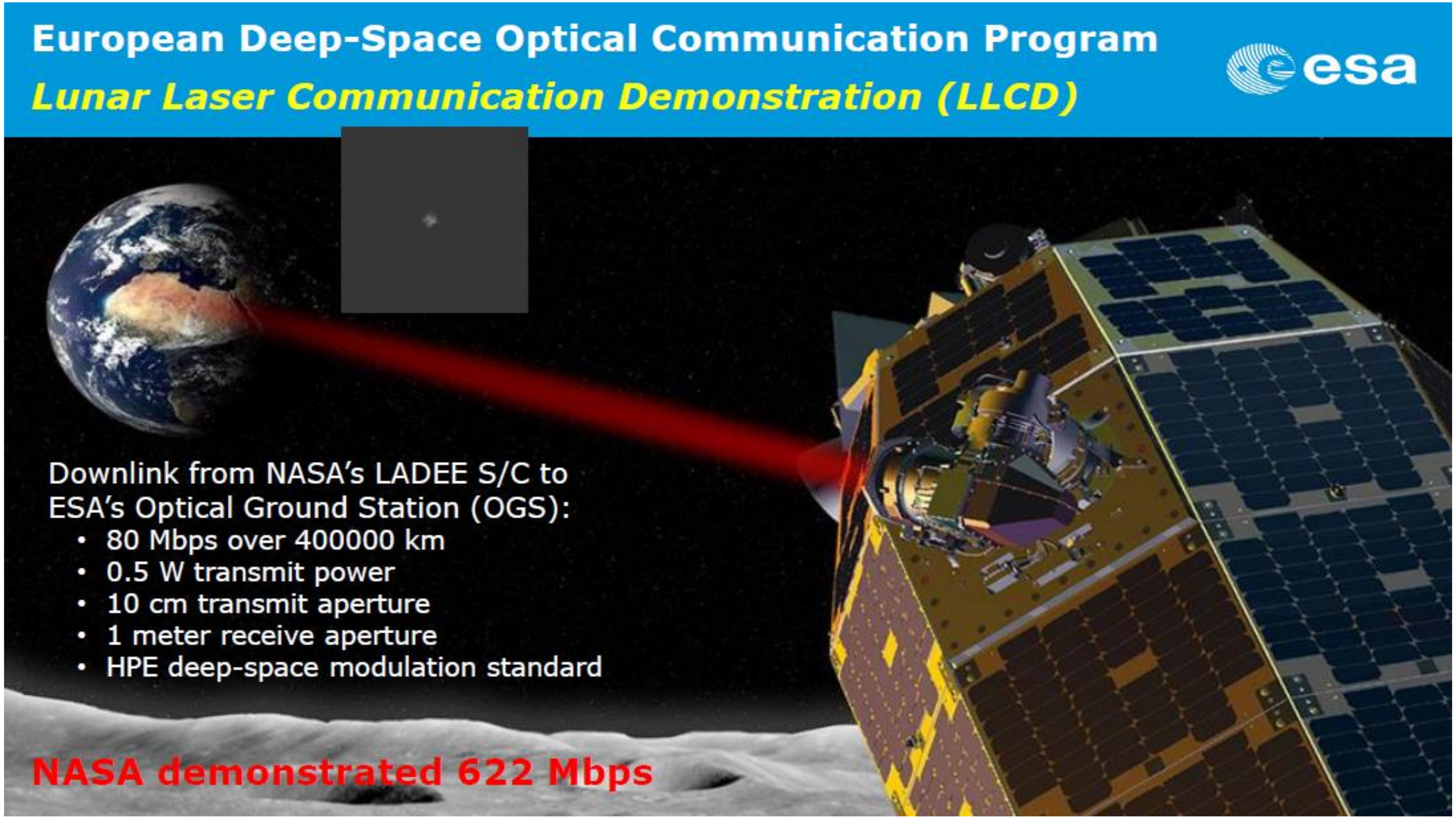
- European Data Relay Satellite (EDRS) System

Credits: Airbus 2021

- Secure data transfer up to 1.8 Gbps
- Data relay from Low Earth Orbits (700km) to GEO-stationary
- Relay up to 40 TB of data
- Data from Observation satellites, aircraft, unmanned aerial vehicles and other mobile

EARLY OPTICAL SATELLITE LINKS

Lunar Link



Credits: ESA

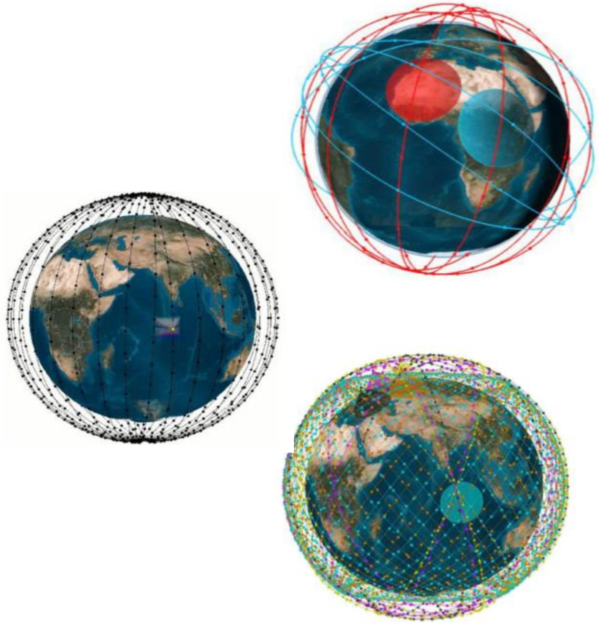
OPTICAL SATELLITE COMMUNICATION

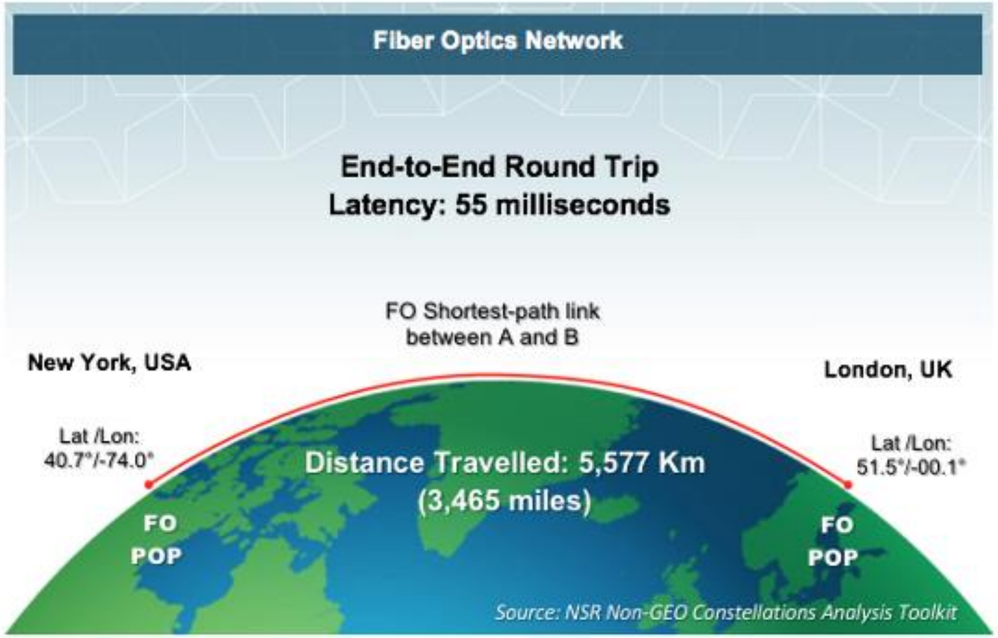
Details of a Ground to LEO Satellite Link

- Specifics of optical wireless over very long distance
- PHY-layer perspective

LEO SATELLITE CONSTELLATIONS
HIGH THROUGHPUT AND LOW LATENCY

- Various LEO satellite configs under construction ..
- Objective: high-throughput broadband services with low latency
- … latency advantage over fiber network

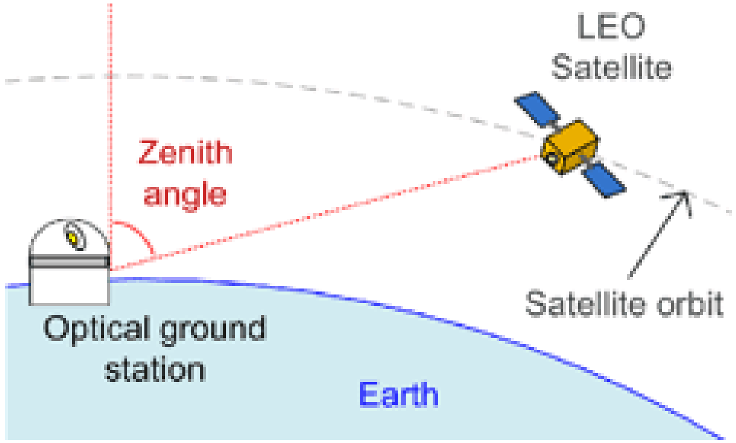




SATELLITE - GROUND LINK

DOWNLINK BUDGET

LINK to LEO Satellite	
Geometrical	Tx Antenna Gain
	Rx Receiver Gain
	Free-space Loss
	TOTAL Geometric
Optical inaccuracies	Optical aberrations in Tx
	Optical aberrations in Rx
	Pointing Boresight error
	Pointing Precision
	TOTAL Inaccuracies
Atmospheric	Absorption/ scattering
	Wavefront error
	Irradiance fluctuations
	TOTAL Atmospheric
Total	



Ref: Takemoto 2015 ICSOS

- **Free-space Loss**
  - Range effect: $L_R = \left(\frac{\lambda}{4\pi L}\right)^2$ ... -252 dB (Zenith) .... -260 dB (20deg elevation)
  - LEO satellite at 500 km orbit, 1550 nm wave
- **Antenna Gains**
  - Gain: $G \approx \left(\frac{\pi D}{\lambda}\right)^2$ ground: +126 dB space: +110 dB
  - Limited apertures: ground: 0.5 – 1 m (very large: 4m),

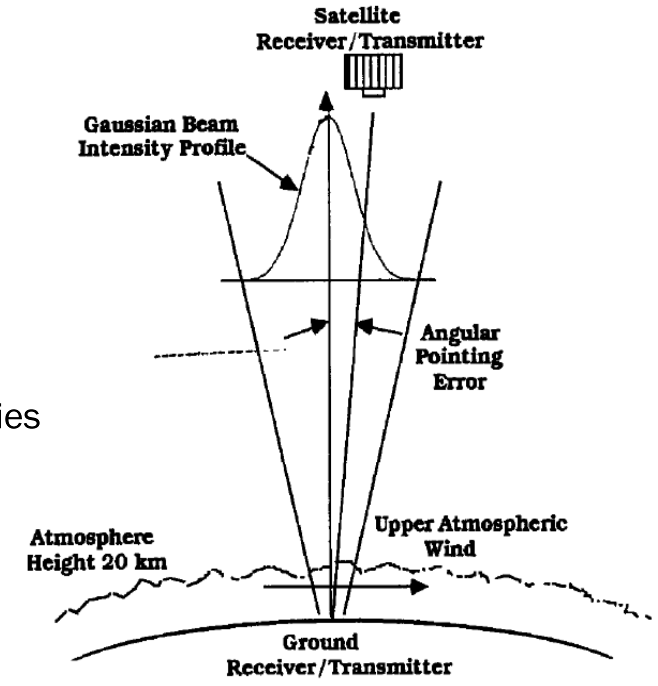
    space: 0.1 - 0.2 m (very large: 1m)

SATELLITE - GROUND LINK

DOWNLINK BUDGET

LINK to LEO Satellite	
Geometrical	Tx Antenna Gain
	Rx Receiver Gain
	Free-space Loss
	TOTAL Geometric
Optical inaccuracies	Optical aberrations in Tx
	Optical aberrations in Rx
	Pointing Boresight error
	Pointing Precision
	TOTAL Inaccuracies
Atmospheric	Absorption/ scattering
	Wavefront error
	Irradiance fluctuations
	TOTAL Atmospheric
Total	

- **Optical wavefront errors**
  - Distorted beams, due to optical component inaccuracies
  - Wavefront error of 200nm, leads to ~3 dB loss
- **Pointing issues**
  - Boresight error: ..slope of the Gaussian…
  - and jitter: ..spot 'dancing' in receiver plane
- **Absorption and scattering effects / molecular and aerosol**
  - Extinction factor
  - Scales with 'number density of air constituents'
  - Integrated effect (over path)
  - Typical value: 1-2 dB



Ref: Andrews 1995

Ref: Kaushal 2017

$$\gamma(\lambda) = \underbrace{\alpha_m(\lambda)}_{\text{Molecular absorb. coeff.}} + \underbrace{\alpha_a(\lambda)}_{\text{Aerosol absorb. coeff.}} + \underbrace{\beta_m(\lambda)}_{\text{Molecular scatt. coeff.}} + \underbrace{\beta_a(\lambda)}_{\text{Aerosol scatt. coeff.}}$$

IMPACT OF ATMOSPHERIC TURBULENCE

BEAM DISTORTION

- Temperature/ pressure variations lead to fluctuations (spatial & temporal) in index-of-refraction
  - Cn2 profile – strongest at ground level
  - Power spectrum – fast fall-off for higher spatial frequencies
- Giving pathlength fluctuations → wavefield phase fluctuations
- and amplitude fluctuations (after some propagation)

EFFECTS ON OPTICAL BEAM

1. Beam spread; wider spot @ receiver
   - On top of diffractive effect
2. On-axis scintillation (amplitude fluctuations)
3. Beam wander; spot 'dancing' in receiver plane
   - also yielding intensity fluctuations

Ref: Andrews 1995

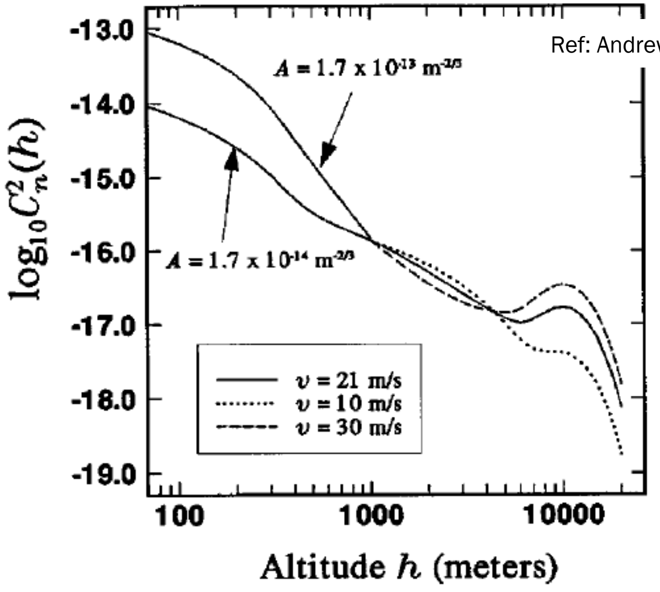
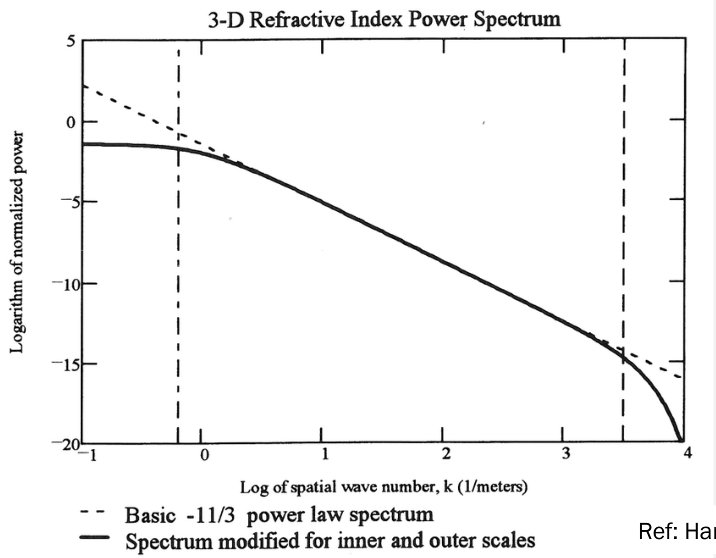


Fig. 2. $C_n^2(h)$ profile associated with the H–V day model as a function of altitude h. The values of A shown represent C_n^2 near ground level, whereas v denotes high-altitude wind speed.



Ref: Hardy 1998

ATMOSPHERIC TURBULENCE

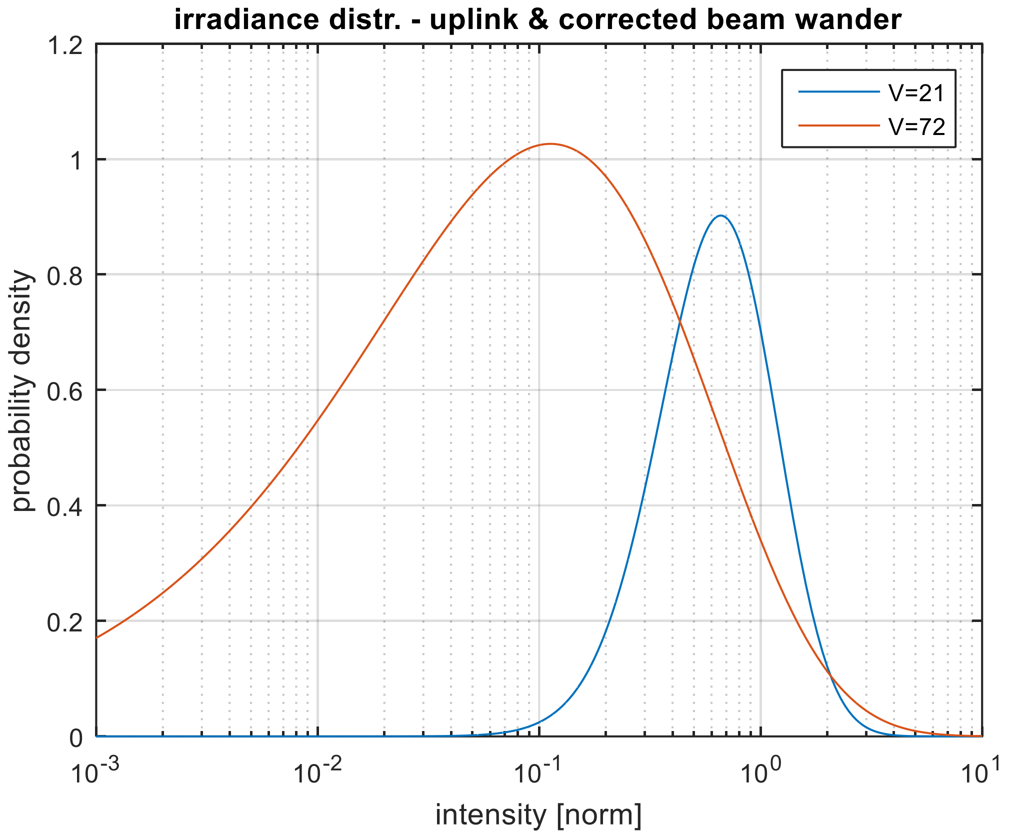
EFFECT ON LINK BUDGET

1. Average Loss
2. Instantaneous intensity fluctuations
   (fading channel)

IMPORTANT PARAMETERS

1. Turbulence strength
2. Elevation angle
3. Slant range
4. Uplink vs. downlink
5. Beam size/ type

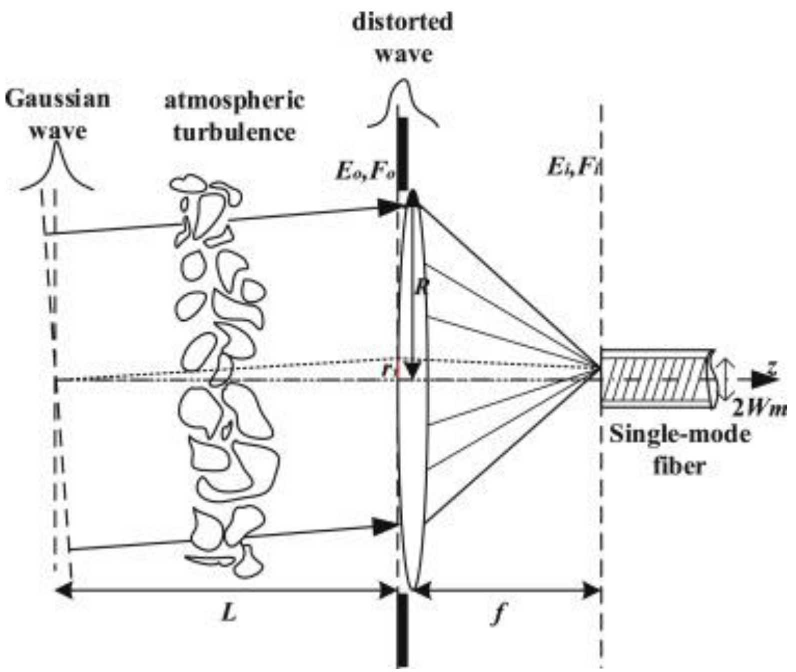
Model of intensity fluctuations



- Cn2 Model: Hufnagel-Valley with variable pseudo-wind at 11 km
- Values: [21 72]
- Uplink to satellite
- Other: Tx waist (0.35m), Zenith angle (1 rad), wavelength (1550 nm), AO beam wander correction under PAA angle

DISTURBED WAVEFRONTS AND FIBER COUPLING

1. Wave intensity profile should match mode of fiber
2. Wave distortion may seriously reduce coupling efficiency
3. Nominal case: coupling efficiency of 0.81
   - Spatial Match of Gaussian wave profile with fiber mode



Ref: Lu 2019

WAVEFRONT PHASE CORRECTION NECESSARY !

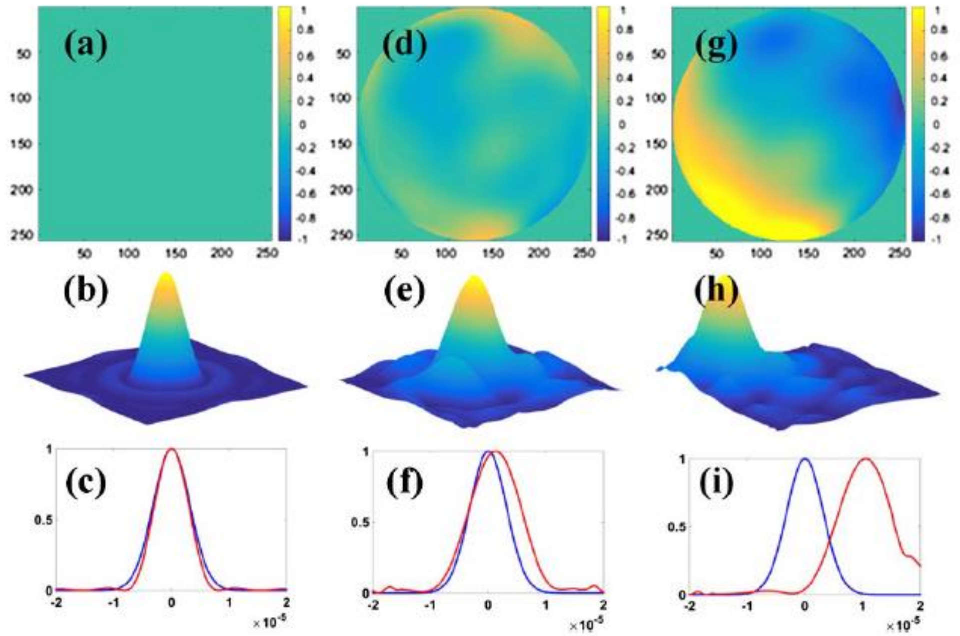


Fig. 4. Schematic of the fiber coupling over different turbulence.

Ref: Chen 2015

ADAPTIVE OPTICS
WORKING PRINCIPLES

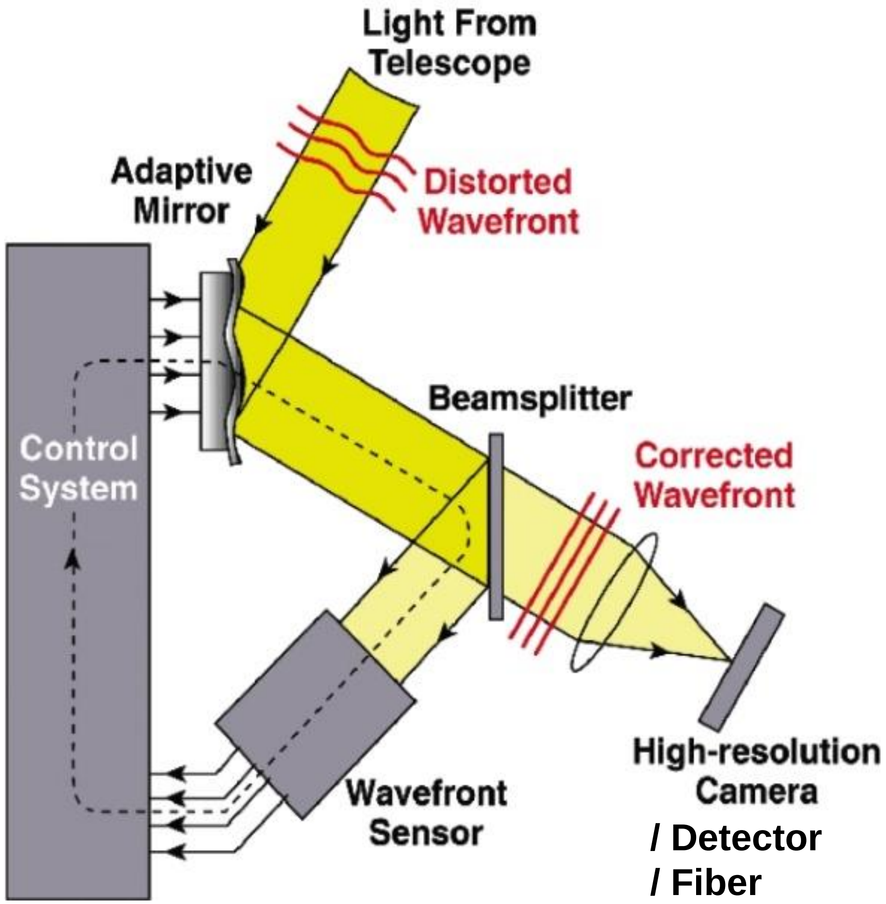
PRINCIPLES

1. Measure phase distortion at receiver
2. Compute (instantaneous) wavefront correction
3. Apply phase correction by 2D deformable mirror

PROPERTIES

1. Real-time feedback loop
2. 2D spatial correction for a 3D effect
3. Relatively complex solution, with high-end components

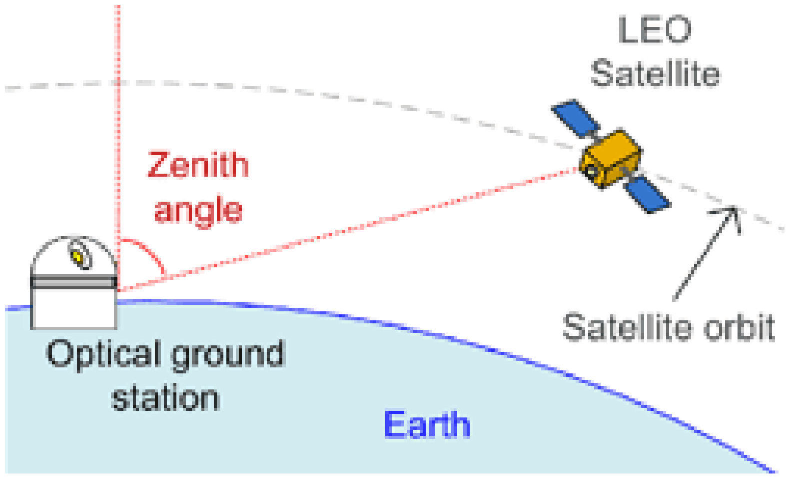
(indispensable in large astronomical telescopes)



Movie: https://www.youtube.com/watch?v=3BpT_tXYy_I from 1m20

SATELLITE TO GROUND LINK

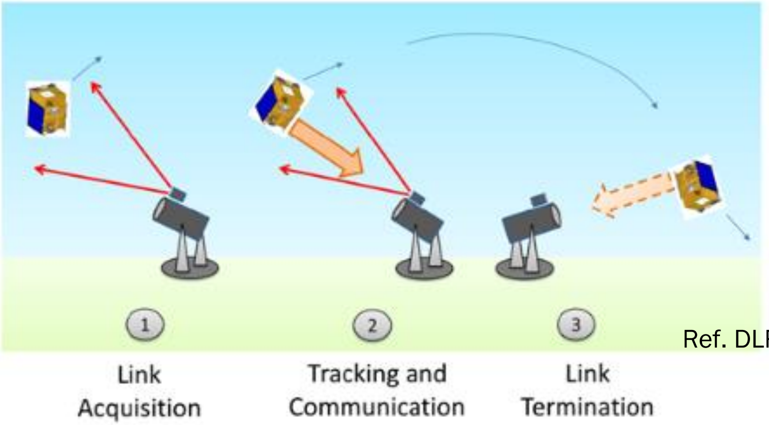
DOWNLINK BUDGET



LINK Down LEO Satellite (500 km) – 1550 nm - Zenith – Rx 0.4m			
Geometrical	Tx Antenna Gain	**109.7**	Tx aperture = 0.15m / Beam divergence 9.2 µrad (half angle)
	Rx Receiver Gain	**118.2**	Rx aperture = 0.4 m
	Free-space Loss	**-252.2**	Slant range = 500 km
	TOTAL Geometric	-24.3	
Optical inaccuracies	Optical aberrations in Tx	-0.7	Wavefront Error = 100 nm (RMS)
	Optical aberrations in Rx	-1.2	Transmission Rx optics system = 0.75
	Pointing Boresight error	-0.6	Offset = 2.5 µrad
	Pointing Precision	-1.1	Jitter is 2.5 µrad (RMS)
	TOTAL Inaccuracies	-3.7	
Atmospheric	Absorption/ scattering	-0.9	Visibility = 20 km, Scale parameter = 4km
	Wavefront error	-1.8	Mismatch for fiber coupling & nominal factor 0.81 / with Adaptive Optics system at 75% rejection
	Irradiance fluctuations	-0.5	Margin for outage probability of 1%
	TOTAL Atmospheric	-3.2	
Total		-31.2 dB	

SATELLITE TO GROUND LINK

DOWNLINK BUDGET



Ref. DLR

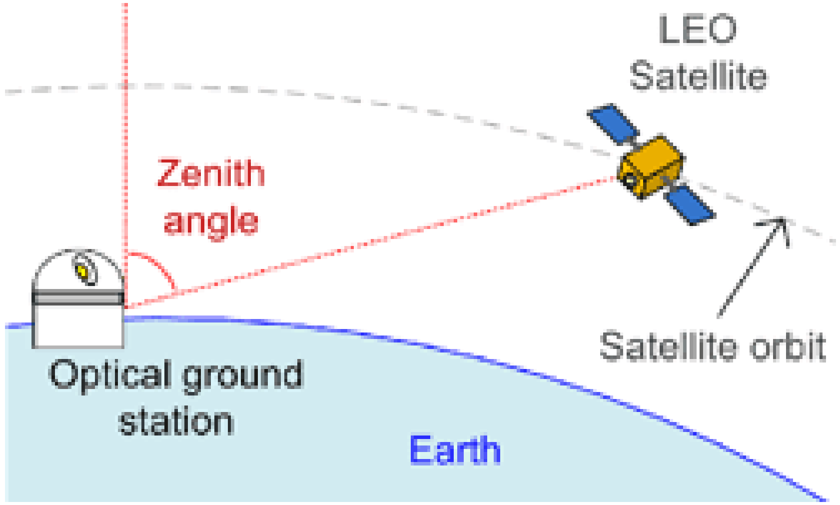
LINK Down LEO Satellite (500 km) – 1550 nm - extreme angles – Rx 0.4m				
		Zenith	20 deg elevation	
Geometrical	Tx Antenna Gain	109.7	109.7	Tx aperture = 0.15m / Beam divergence 9.2 µrad (half angle)
	Rx Receiver Gain	118.2	118.2	Rx aperture = 0.4 m
	Free-space Loss	-252.2	-259.7	Slant range = 500 km vs. 1192 km (Orbit at 500km)
	TOTAL Geometric	-24.3	-31.9	*7.6 dB higher loss*
Optical inaccuracies	Optical aberrations in Tx	-0.7	-0.7	Wavefront Error = 100 nm (RMS)
	Optical aberrations in Rx	-1.2	-1.2	Transmission Rx optics system = 0.75
	Pointing Boresight error	-0.6	-0.6	Offset = 2.5 µrad
	Pointing Precision	-1.1	-1.1	Jitter is 2.5 µrad (RMS)
	TOTAL Inaccuracies	-3.7	-3.7	*unchanged*
Atmospheric	Absorption/ scattering	-0.9	-2.6	Visibility = 20 km, Scale parameter = 4km
	Wavefront error	-1.8	-3.6	Longer atmospheric path/ Adaptive Optics system at 75%
	Irradiance fluctuations	-0.5	-2.4	Margin for outage probability of 1%
	TOTAL Atmospheric	-3.2	-8.6	*5.4 dB higher loss*
Total		-31.2 dB	-44.2 dB	*13 dB higher loss*

Main effects:
- Longer path
- More atmospheric distortion

SATELLITE TO GROUND LINK

DOWNLINK BUDGET – INCREASED RX APERTURE

	Rx 0.4m		Rx 0.8 m		
	Zenith	20 deg elevation	Zenith	20 deg elevation	
Tx Antenna Gain	109.7	109.7	**109.7**	**109.7**	Tx aperture = 0.15m / Beam divergence 9.2 µrad (half angle)
Rx Receiver Gain	118.2	118.2	124.2	124.2	Rx aperture = 0.8 m
Free-space Loss	-252.2	-259.7	**-252.2**	**-259.7**	Slant range = 500 km vs. 1192 km (Orbit at 500km)
TOTAL Geometric	-24.3	-31.9	-18.3	-25.9	*6 dB gain with twice the diameter*
Optical aberrations in Tx	-0.7	-0.7	**-0.7**	**-0.7**	Wavefront Error = 100 nm (RMS)
Optical aberrations in Rx	-1.2	-1.2	**-1.2**	**-1.2**	Transmission Rx optics system = 0.75
Pointing Boresight error	-0.6	-0.6	**-0.6**	**-0.6**	Offset = 2.5 µrad
Pointing Precision	-1.1	-1.1	**-1.1**	**-1.1**	Jitter is 2.5 µrad (RMS)
TOTAL Inaccuracies	-3.7	-3.7	**-3.7**	**-3.7**	*unchanged*
Absorption/ scattering	-0.9	-2.6	**-0.9**	**-2.6**	Visibility = 20 km, Scale parameter = 4km
Wavefront error	-1.8	-3.6	-3.9	-9.4	Higher error variance (D^(5/3)) / (Adaptive Optics at 75%)
Irradiance fluctuations	-0.5	-2.4	-0.2	-1.1	Effect of Aperture Averaging
TOTAL Atmospheric	-3.2	-8.6	-5.0	-13.1	*up to 4.5 dB higher loss*
TOTAL	-31.2 dB	-44.2 dB	-27.0 dB	-42.7 dB	*Limited gain for low elevation angles*

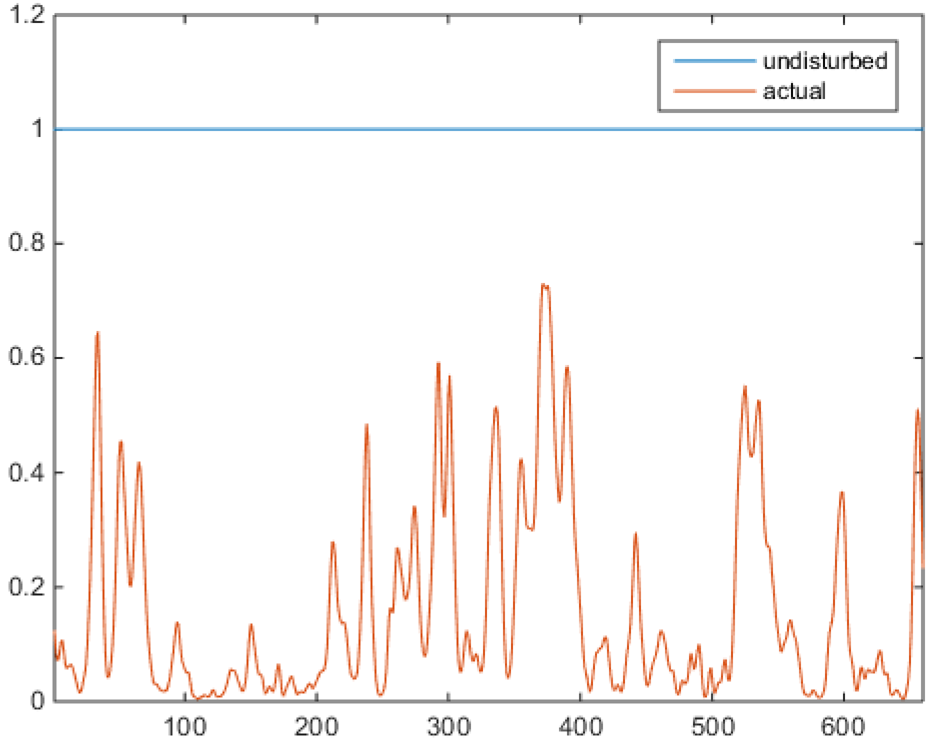


Main effects:
- Receiver gain
- More atmospheric distortion at low elevations

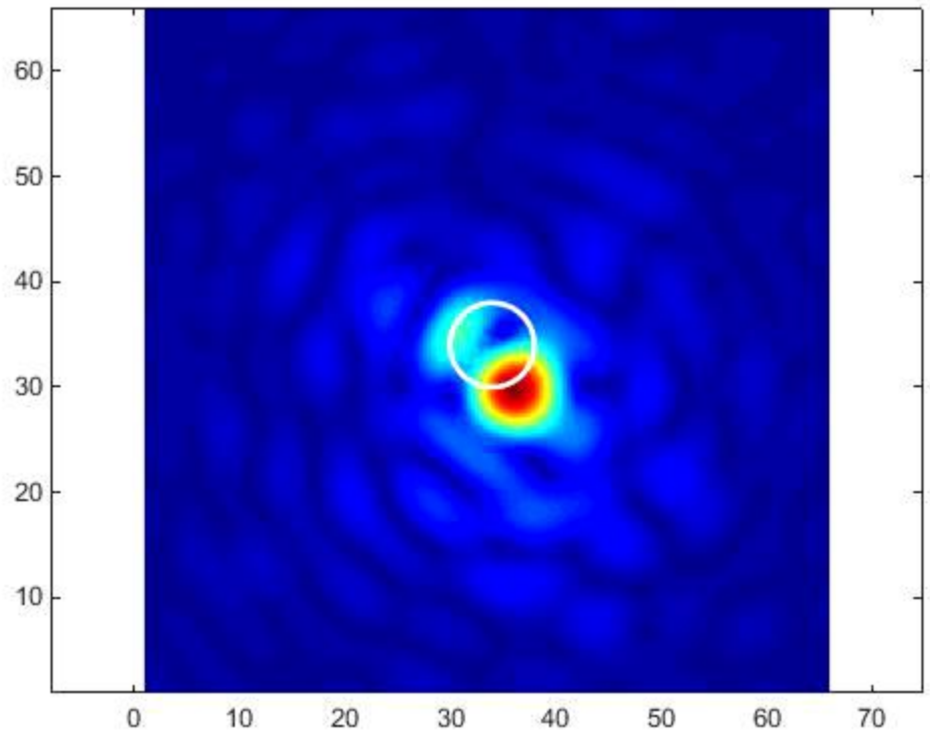
TURBULENCE INDUCED DISTORTIONS

ROLE OF RECEIVER APERTURE

1. Small Rx aperture



Received power

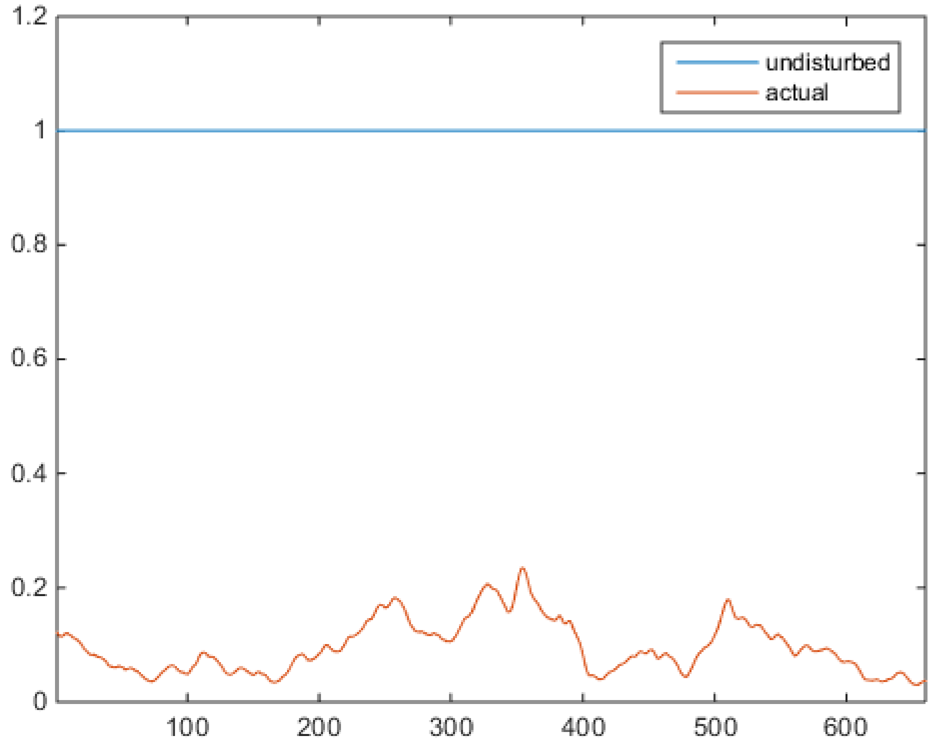


Disturbed spot (atmospheric turbulence

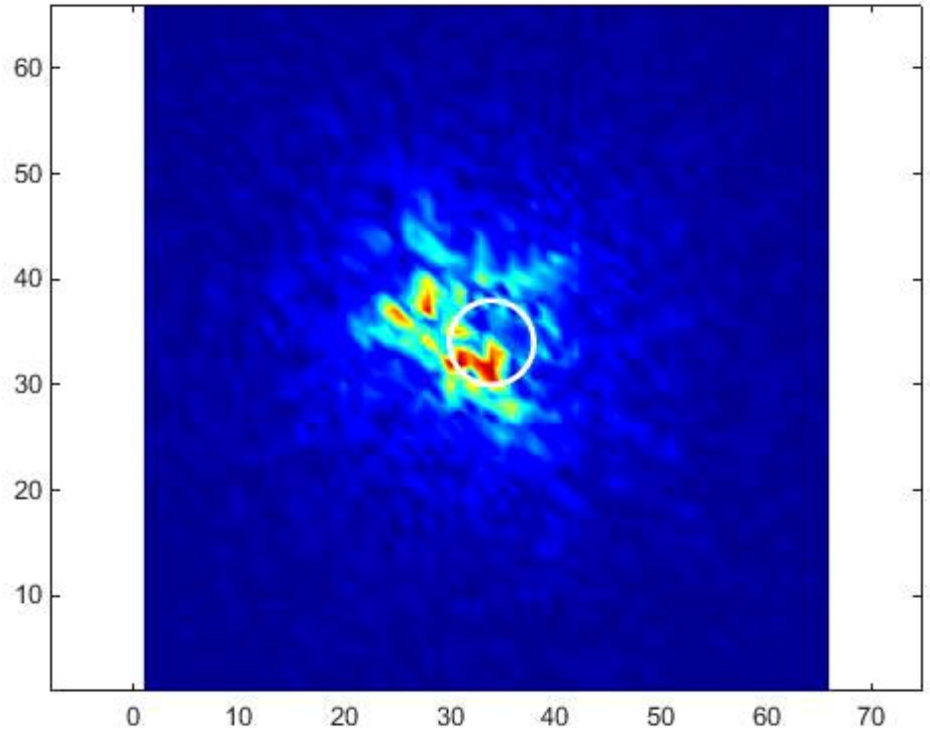
TURBULENCE INDUCED DISTORTIONS

ROLE OF RECEIVER APERTURE

2. 4 times larger Rx aperture



Received power

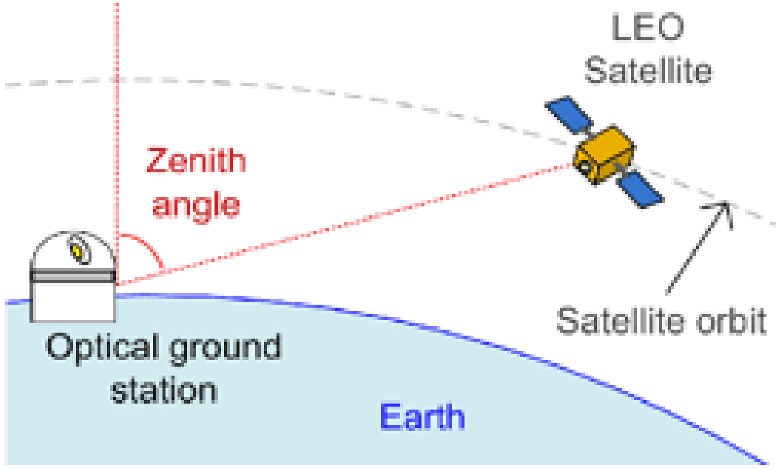


Disturbed spot
(atmospheric turbulence

GROUND TO SATELLITE LINK

UPLINK BUDGET – regular sized Tx (0.8m) and Rx (0.15m)

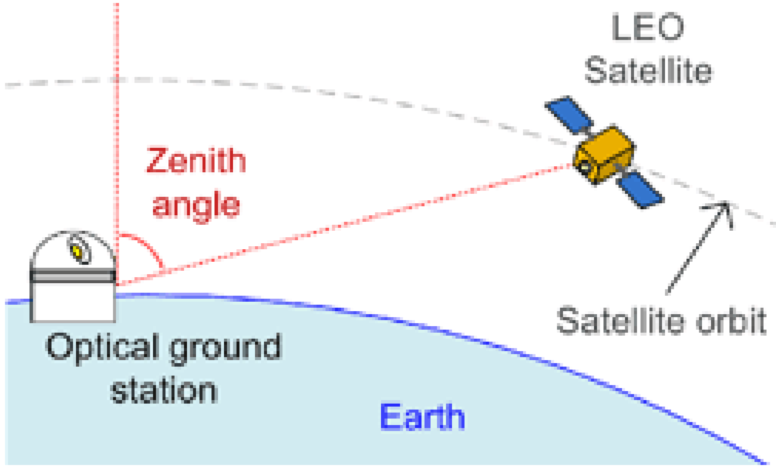
LINK to LEO Satellite (500 km) – 1550 nm - Zenith angle			
Geometrical	Tx Antenna Gain	124.2	Tx aperture = 0.8 m
	Rx Receiver Gain	109.7	Rx aperture = 0.15 m
	Free-space Loss	-252.2	Slant range = 500 km
	TOTAL Geometric	-18.3	*unchanged*
Optical inaccuracies	Optical aberrations in Tx	-0.7	Wavefront Error = 100 nm (RMS)
	Optical aberrations in Rx	-1.2	Transmission Rx optics system = 0.75
	Pointing Boresight error	-17.8	Offset = 2.5 µrad- Tx gain dependent
	Pointing Precision	-9.6	Jitter is 2.5 µrad (RMS) – Tx gain dependent
	TOTAL Inaccuracies	-29.4	*Pointing sensitivity*
Atmospheric	Absorption/ scattering	-0.9	Visibility = 20 km, Scale parameter = 4km
	Wavefront error	-	Irrelevant, due to high coherence radius (>> 1m)
	Additional Beam Spread	-15.6	Turbulence-induced widening of the beam
	Irradiance fluctuations	-10.8	100% Pre-corrected Beam wander
	TOTAL Atmospheric	-27.2	
Total		–75.0 dB	*~ 48 dB additional loss due to Atmospheric distortion and Pointing errors*



Main effects of reversing Tx Rx size
- Same geometric loss
- Very sensitive to pointing errors
- High impact of turbulence

GROUND TO SATELLITE LINK

UPLINK BUDGET – reduced Tx (0.2m) and Rx (0.15m)



LINK to LEO Satellite (500 km) – 1550 nm - Zenith angle			
Geometrical	Tx Antenna Gain	112.2	Tx aperture = 0.2 m
	Rx Receiver Gain	109.7	Rx aperture = 0.15 m
	Free-space Loss	-252.2	Slant range = 500 km
	TOTAL Geometric	–30.3	*12 dB higher loss*
Optical inaccuracies	Optical aberrations in Tx	-0.7	Wavefront Error = 100 nm (RMS)
	Optical aberrations in Rx	-1.2	Transmission Rx optics system = 0.75
	Pointing Boresight error	-1.1	Offset = 2.5 µrad
	Pointing Precision	-1.8	Jitter is 2.5 µrad (RMS)
	TOTAL Inaccuracies	-4.9	
Atmospheric	Absorption/ scattering	-0.9	Visibility = 20 km, Scale parameter = 4km
	Wavefront error	-	Irrelevant, due to high coherence radius (>> 1m)
	Additional Beam Spread	-5.5	Turbulence-induced widening of the beam
	Irradiance fluctuations	-0.8	100% Pre-corrected Beam wander
	TOTAL Atmospheric	-7.2	
Total		–42.4 dB	*~33 dB better with a 4 x smaller Tx*

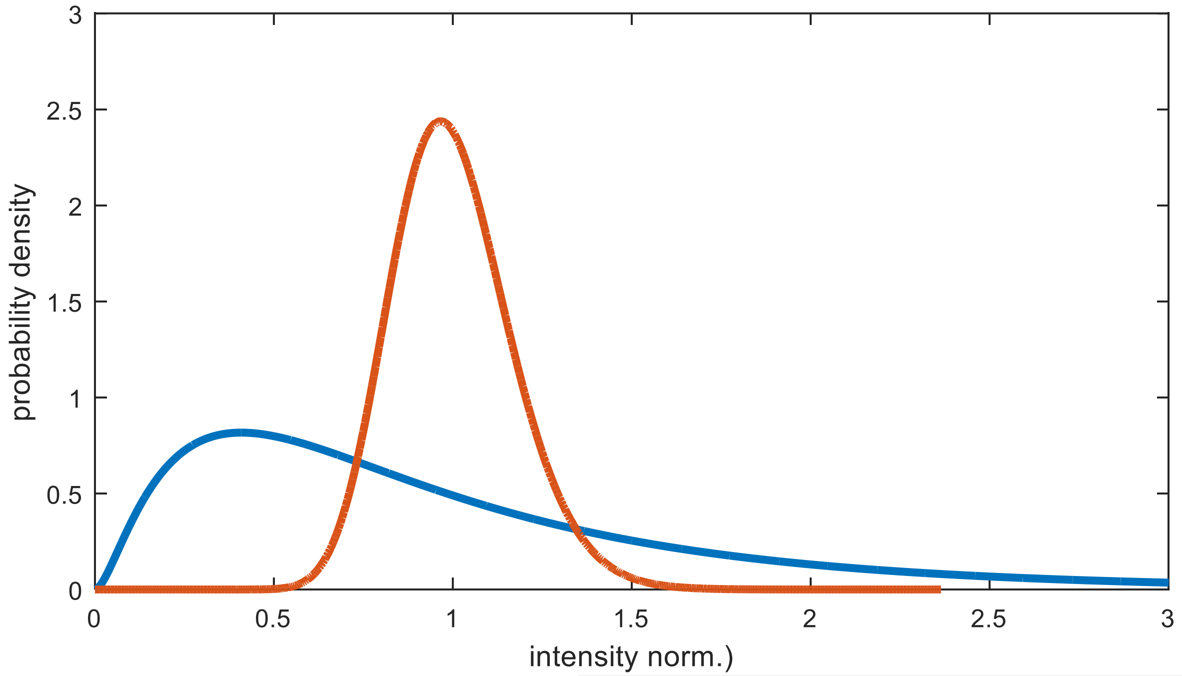
Main effects smaller Tx
- Lower gain
- Less sensitive to pointing errors
- Smaller impact of turbulence

REDUCING THE EFFECT OF TURBULENCE

INTENSITY FLUCTUATIONS / FADING

POTENTIAL APPROACHES

1. Aperture Averaging
   - Increase of (ground-) Rx aperture reduces intensity fluctuations, b
2. Diversity / spatial and or temporal
   - For instance: multiple Tx beams to average out fading effects
3. Adaptive Optics
   - Works for beam spreading, fiber coupling, limited (still) for intensit
4. Interleaving and Error Correction
   - Can be very eff
5. Network orches
   - Requires netwo



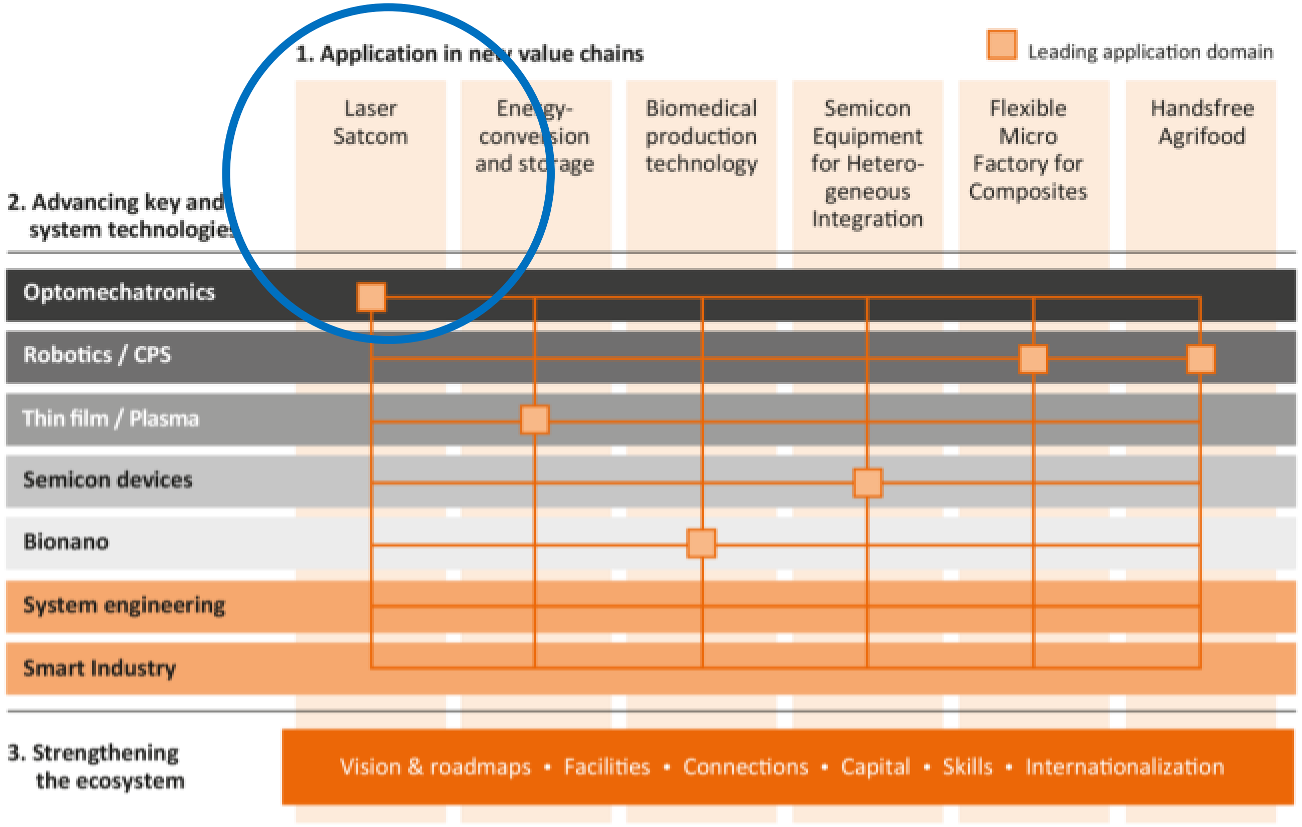
- Improve the curve ... Adaptive Optics, Spatial Diversity
- Deal with the curve ... Forward error correction, Interleaving, Adaptive transmission,
- Find a better curve (link) ... Network orchestration

NATIONAL DEVELOPMENTS
Groeifonds

- NXTGEN HighTech proposal
- Funded for 450 Meuro (April 2022)

NXT GEN HIGHTECH

The proposed solution: towards a coherent, leading high tech equipment ecosystem



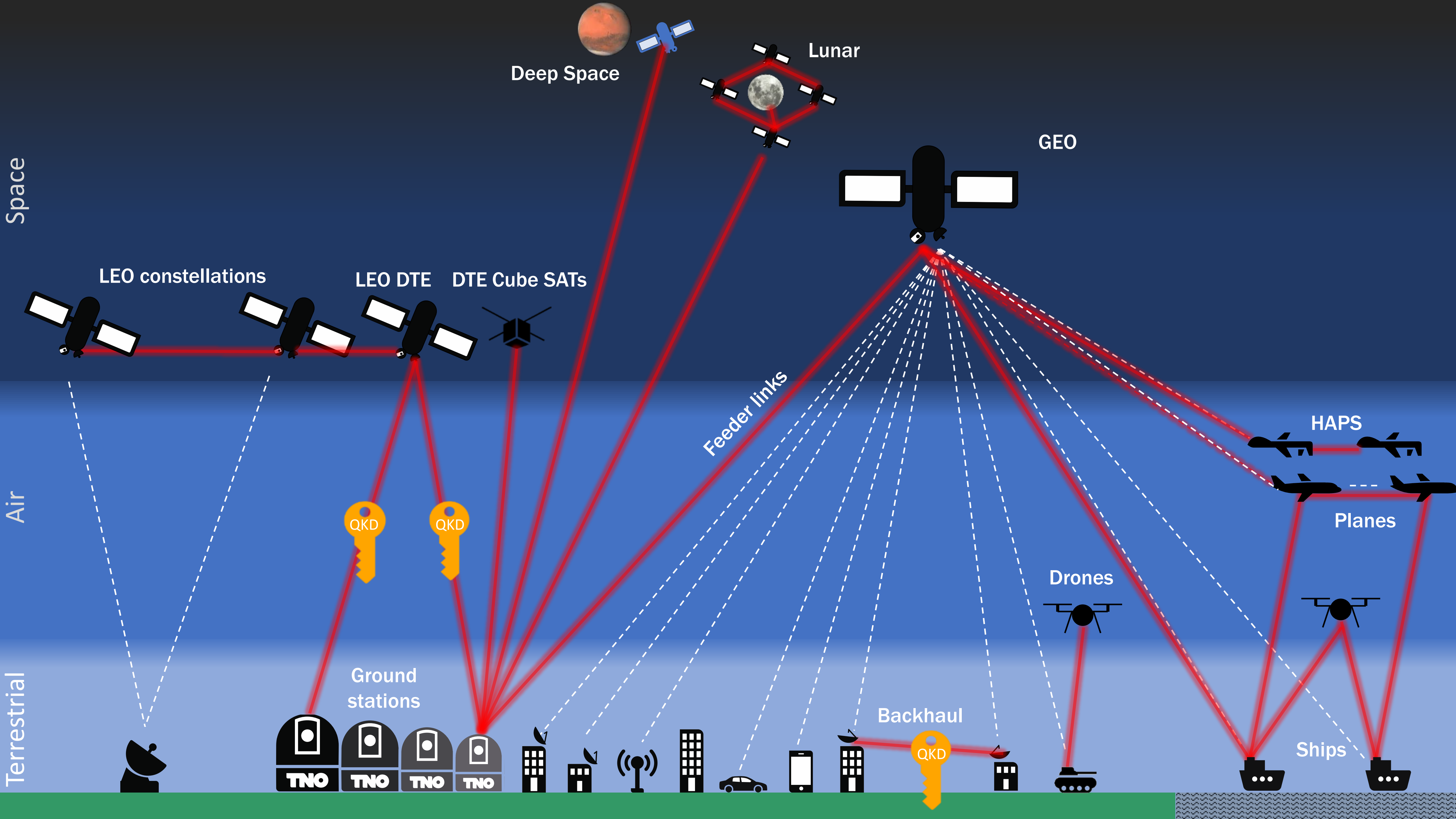
Starting right away with over 340 companies and knowledge institutions

The parties participating in NXTGEN HIGHTECH consist of 189 SMEs (including 75 young start-ups and scale-ups), 130 larger companies and 23 knowledge institutions. Roughly 1500 researchers and innovators are contributing. With a letter of intent these organisations have shown their commitment

NL National research program – Optical Wireless Superhighways

- Funded by NWO (Dutch Research Council)
- Wireless links: from indoor links to satellite links
- 5 universities, 15 PhD students
- Period: 2022-2026
- Active participation by industry (~20 parties)

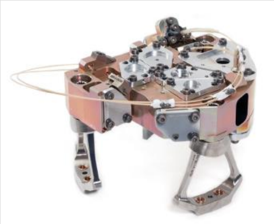
- <u>Research high-lights</u>
  - Beam steering
  - Device localization
  - Diversity to reduce fading
  - Software defined networks
  - Multi-beam terminal
  - Key authentication
  - Low noise detection
  - Adaptive beam correction



Space
Air
Terrestrial
Deep Space
Lunar
GEO
LEO constellations
LEO DTE
DTE Cube SATs
Feeder links
HAPS
Planes
Drones
QKD
QKD
Ground
stations
TNO
TNO
TNO
TNO
Backhaul
QKD
Ships

Portfolio Space

Tesla Optical bench



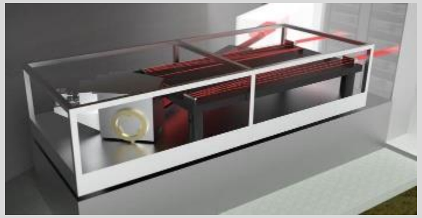
LEOCAT optical head

CubeCAT

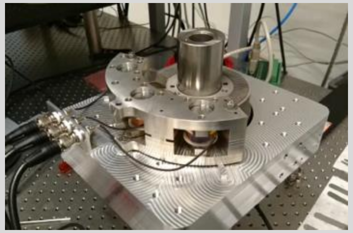
Fine steering mirror

TOmCAT Tbit class terminal

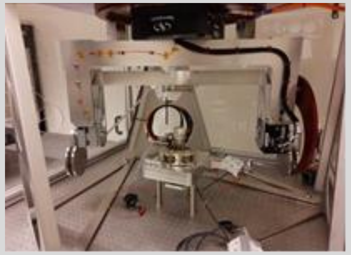
Bulk multiplexer



Course pointing assembly



Pointing testbed

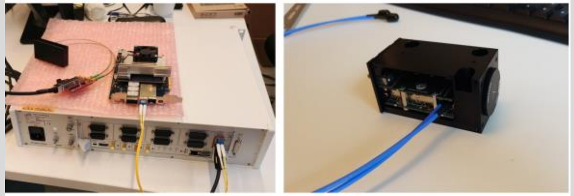


OC Lab

GoCAT Gbit class terminal

Deformable mirror

Modems/ detectors

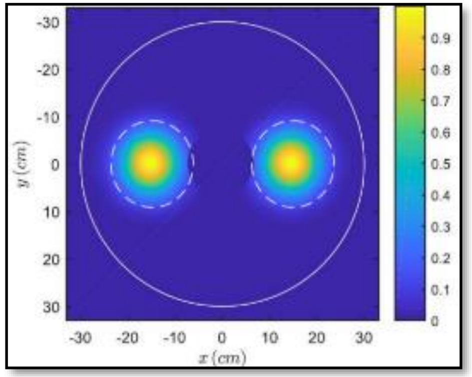


FEEDER LINK GND TO GEO SATELLITE

- Terabit Optical Communication Active Terminal = TOmCAT

- **Key aspects**:
  - Adaptive Optics (AO) for pre-correction of atmospheric disturbances
  - Uplink, 13 channels x 100 Gbit/s, C-band
  - Downlink, 7 channels x 100 Gbit/s, L-band
  - 50 Watt per channel uplink
  - Bulk optics multiplexing

- **Telescope**:
  - Rx aperture: 600 mm
  - Tx sub-aperture: 200 mm (2x)
  - Total transmitted power: 650 Watt



Partners:

AIRBUS DEFENCE & SPACE

VDL

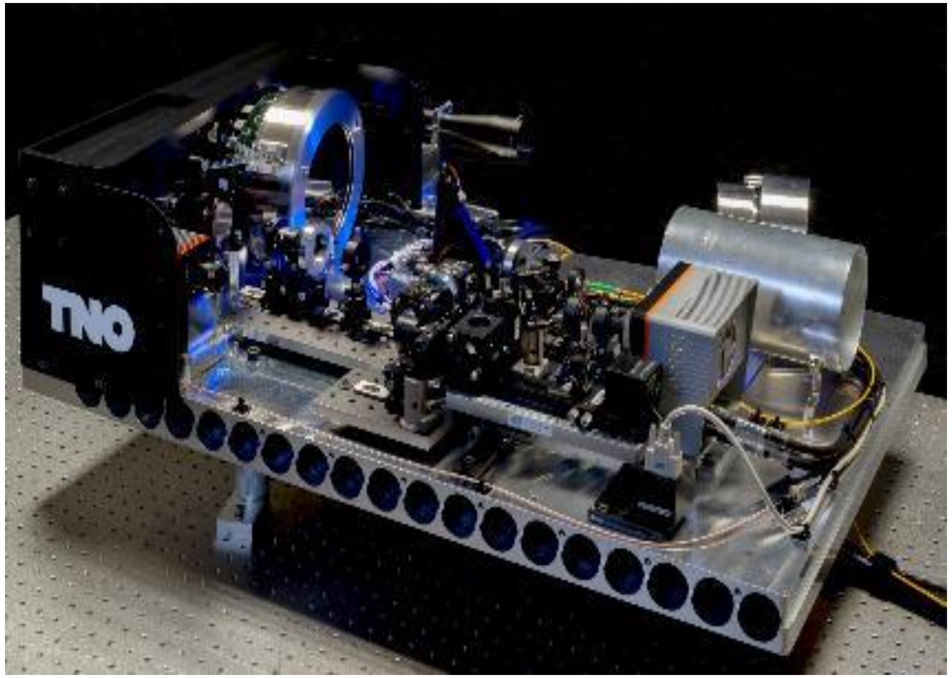
DEMCON

esa

telecom artes 4.0 programme

hittech

C-STS



AIRBORNE LCT DEMONSTRATOR

TNO innovation for life

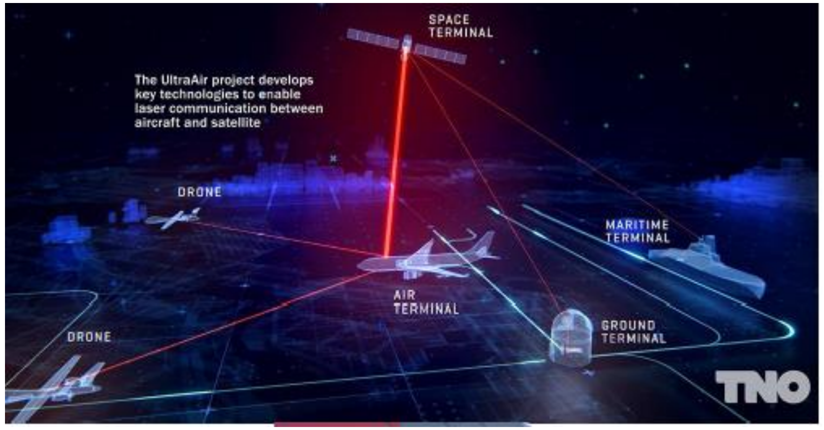
- Air based Laser Communication Terminal = Air-LCT
- Compatible with European Data Relay System (EDRS)
- Roadmap for full integration into aircraft
- Current status:
  - Demonstrator for optical communication through aircraft window

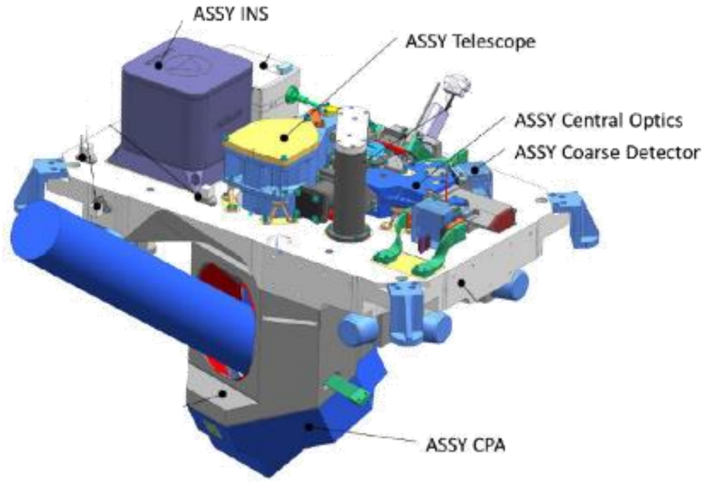
- Pointing Challenge !

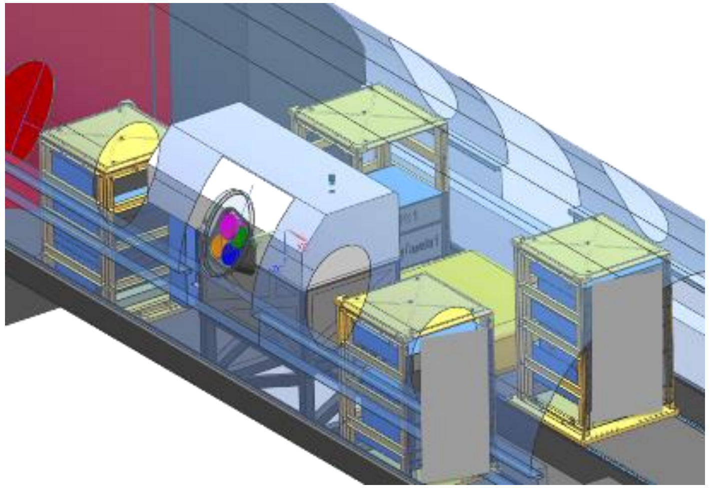
- TNO Dynamical Optical Performance Evaluation = DOPE analysis
  - Design based on end-to-end modelling, including:
    - Optical modelling,
    - FEM modelling,
    - Dynamics
    - Control modelling,
    - Error sources

Dutch Industrial partner:

AIRBUS DEFENCE & SPACE







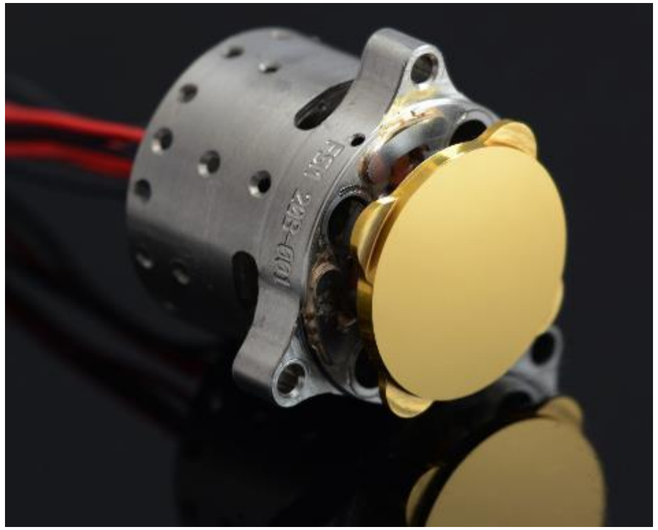
ENABLING TECHNOLOGY – FSM

TNO innovation for life

Dutch Industrial partner:

DEMCON

- Fine/Fast Steering Mirror = FSM
- TNO inhouse designed
  - custom developed reluctance actuators, redundant coil windings
  - hysteresis free flexural bearing
  - mirror angle control via eddy current sensors
  - dedicated thermal design enabling high optical power relay
- Applications:
  - CubeCAT terminal
  - LEOCAT terminal
  - Multi-purpose TNO breadboards for demonstration purposes
- Space qualified:
  - Vibration tested
  - Thermal vacuum tested *(mechanical performance and outgassing)*
- Status:
  - Commercially available product through FSO Instruments



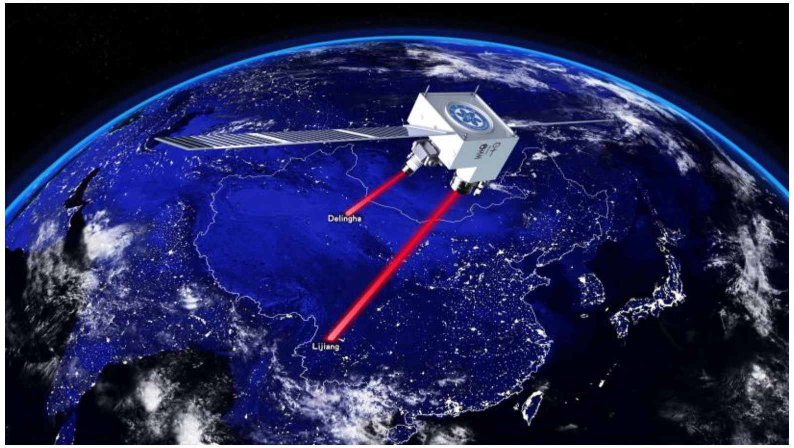
Tip/tilt range	±2°, i.e. ±34,9 mrad (optical)
Bandwidth (-3 dB)	> 1 kHz
Jitter	< 1 µrad
Optical coating	Enhanced gold, >98% refl. @1550 nm
Max. optical power	~10 W
Mirror diameter	Ø20 mm (flatness <12 nm rms) Ø30 mm possible
Volume	Ø24 mm x 30 mm

LONG RANGE KEY DISTRIBUTION

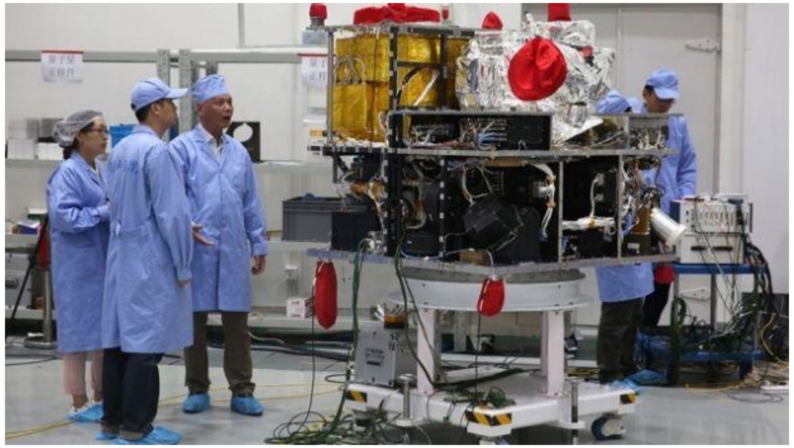
SECURE COMMUNICATION WITH QKD

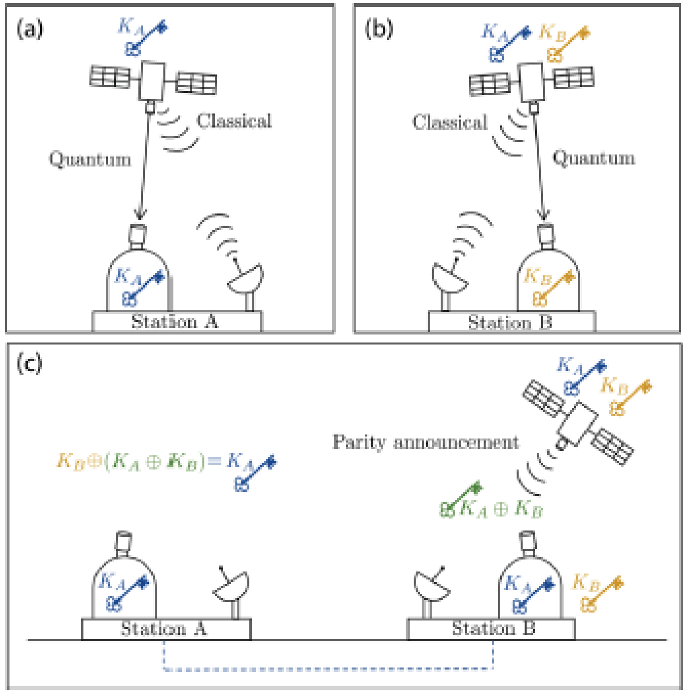
- Space/satellite based QKD
- Overcome distance limitation of fibers

Chinese quantum project QUESS showed it worked!

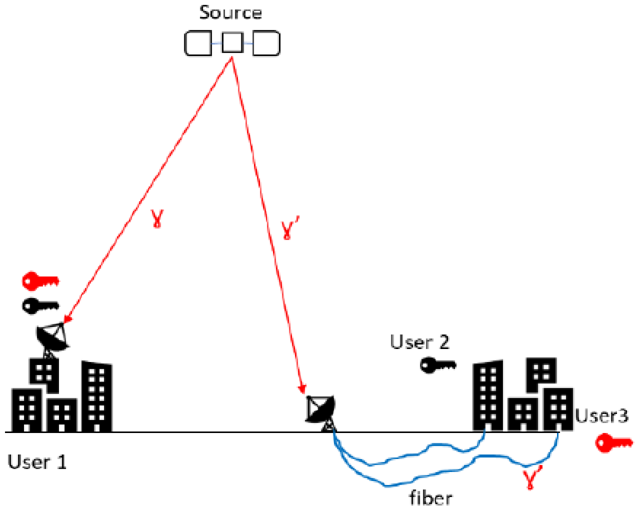


Micius **satellite**





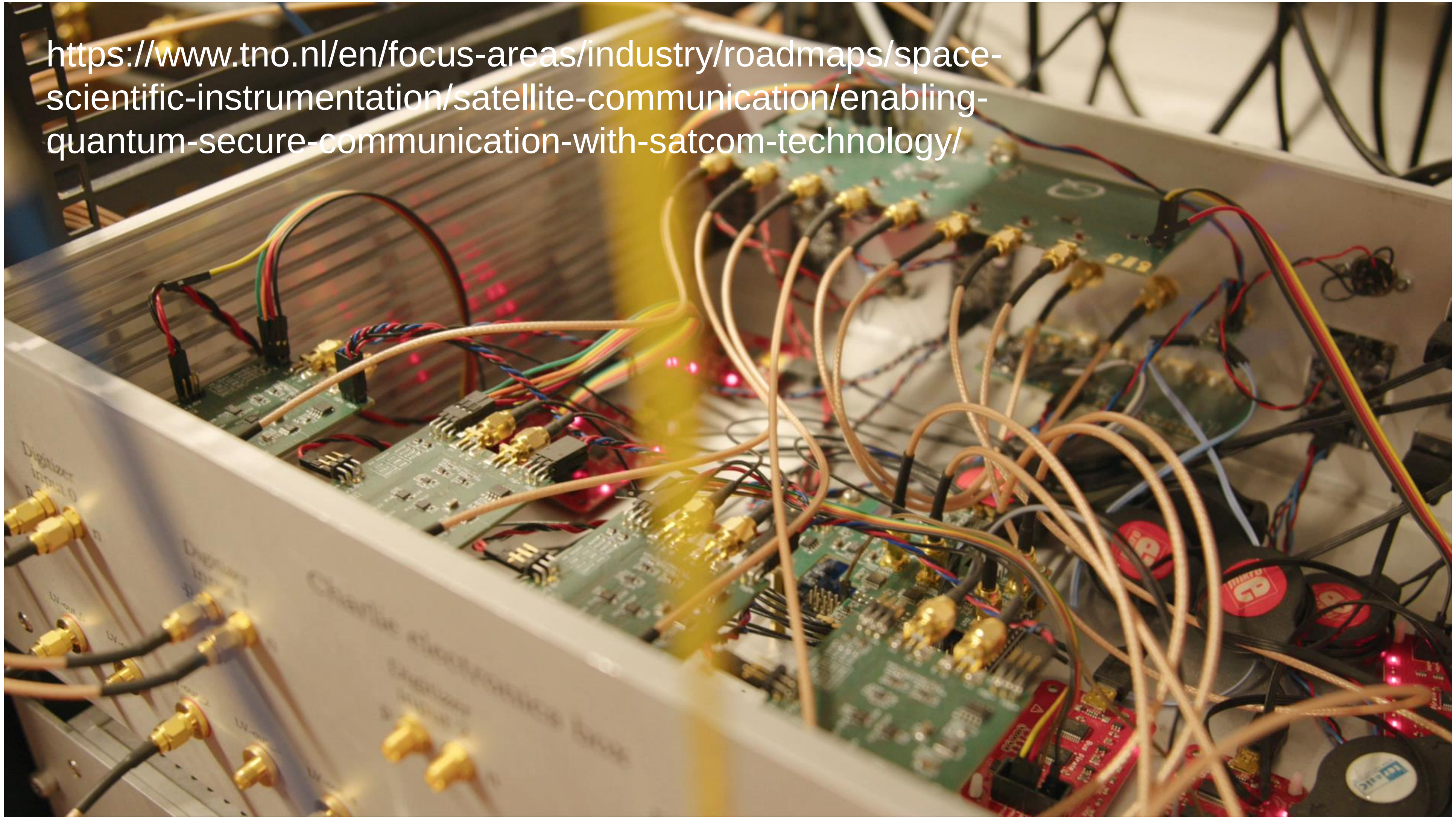
Bedington 2017



Courtesy Bob Dirks

QUANTUM KEY DISTRIBUTION

https://www.tno.nl/en/focus-areas/industry/roadmaps/space-scientific-instrumentation/satellite-communication/enabling-quantum-secure-communication-with-satcom-technology/



THANK YOU

TNO innovation for life