Challenges of Free-Space Quantum and Optical Time Transfer

Presented by: David Mitlyng, CEO, Xairos

The Basics of Time Transfer

All time transfer requires two elements:

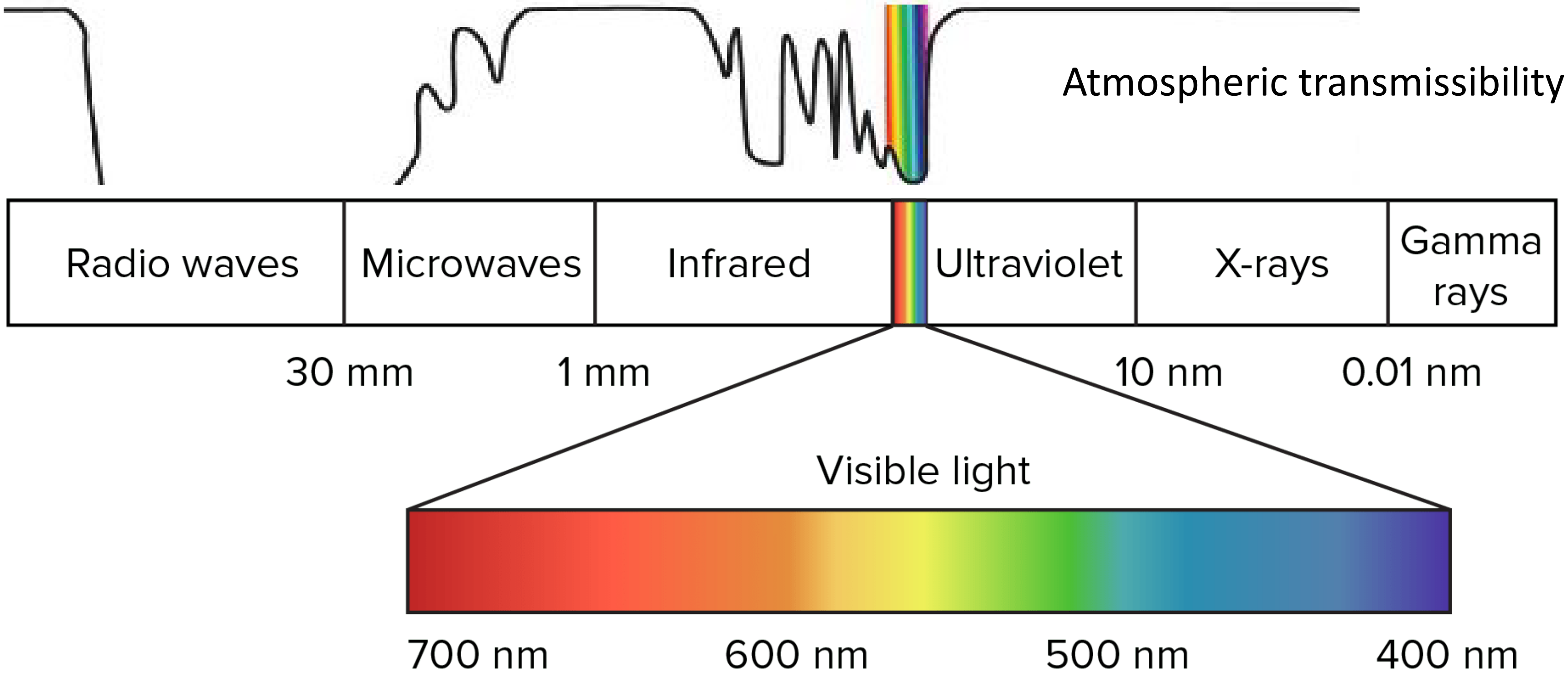
- A timing mark
- Communications of the time

The evolution of time transfer follows the same path as communications:

- Visual
- Cables
- RF
- Network
- Optical => next step to better accuracy and resiliency

Communications Methods

The Electromagnetic Spectrum



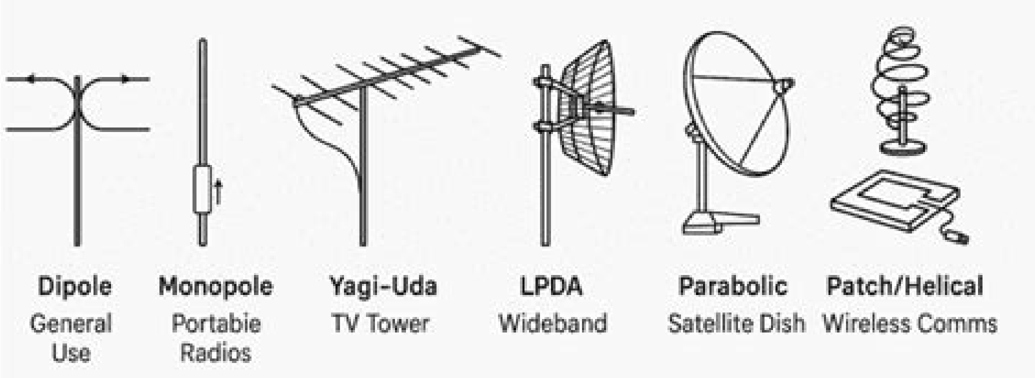
RF Transmission

RF antennas converts alternating electric currents into radio waves

Antenna size inversely proportional to wavelength

MM-wave (between microwave and infrared waves) antennas in work

Free-Space



Guided

RF signals transmitted with copper wiring, coax cables, waveguides

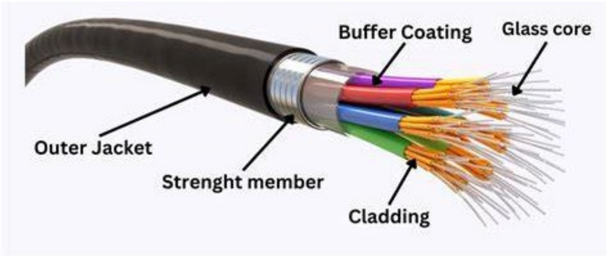
Optical Transmission

Free-Space

Masers and lasers for transmission

Optical pointing and tracking mechanisms required

Guided



Fiber optic cables

Optical and Quantum Time Transfer

GNSS and Time Transfer is RF

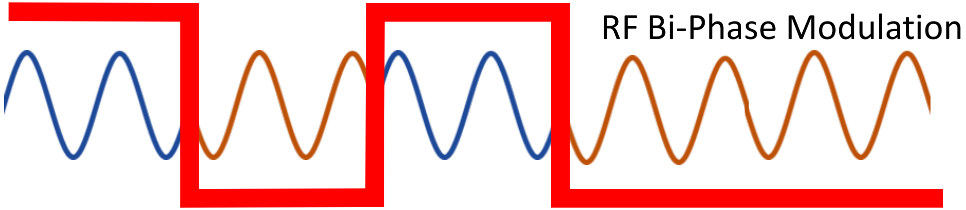
System	Country/Region	Signal Bands (Frequency / Wavelength)	Published Accuracy (Open Service)	Satellites (nominal)	Orbit Type
GPS	United States	L1: 1575.42 MHz (~19.0 cm) L2: 1227.60 MHz (~24.4 cm) L5: 1176.45 MHz (~25.5 cm)	~3–5 m horizontal (SPS); <1 m with dual-frequency / SBAS	31 operational (24-satellite baseline)	MEO, 20,200 km, 6 planes, 12-hr period
GLONASS	Russia	L1: ~1598–1606 MHz (~18.7 cm) L2: ~1242–1249 MHz (~24.1 cm) L3: 1202.025 MHz (~24.9 cm)	~5–10 m horizontal	24 (full constellation)	MEO, 19,100 km, 3 planes, 11.25-hr period
Galileo	European Union (ESA/EUSPA)	E1: 1575.42 MHz (~19.0 cm) E5a: 1176.45 MHz (~25.5 cm) E5b: 1207.14 MHz (~24.8 cm) E6: 1278.75 MHz (~23.4 cm)	~1 m (Open Service); <20 cm (High Accuracy Service)	24 + spares (~28 on-orbit)	MEO, 23,222 km, 3 planes, 14-hr period
BeiDou (BDS-3)	China	B1I/B1C: 1561.1/1575.4 MHz (~19 cm) B2a/B2b: 1176.5 / 1207.1 MHz (~25 cm) B3I: 1268.52 MHz (~23.6 cm)	~2–5 m globally; ~1–2 m in Asia-Pacific; cm-level via PPP-B2b	35 (3 GEO + 3 IGSO + 24 MEO)	Hybrid: MEO (21,500 km), IGSO, GEO
QZSS	Japan (regional augmentation)	L1 C/A, L1C, L2C, L5, L6 (1575.42 / 1227.60 / 1176.45 / 1278.75 MHz)	~1 m standalone; cm-level with CLAS / MADOCA	4 currently; 7 planned by ~2026	QZO (inclined elliptical, "quasi-zenith") + GEO
NavIC (IRNSS)	India	L5: 1176.45 MHz (~25.5 cm) S-band: 2492.028 MHz (~12.0 cm) L1 being added	~5 m over India / primary service area; ~10 m extended	7 (constellation being modernized to NavIC-2)	3 GEO + 4 GSO/IGSO (regional)

Quantum vs RF and Optical Time Transfer

RF
Time Transfer

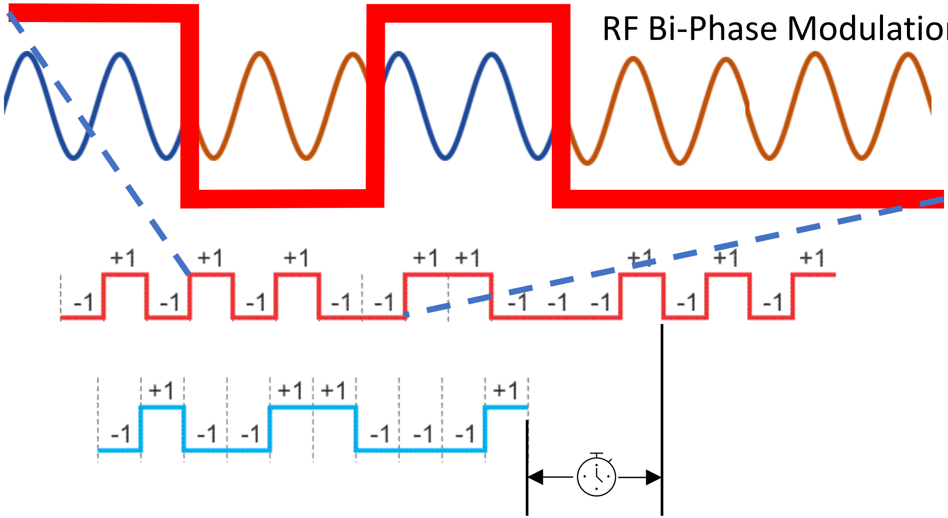
Quantum vs RF and Optical Time Transfer

RF
Time Transfer



Quantum vs RF and Optical Time Transfer

RF
Time Transfer



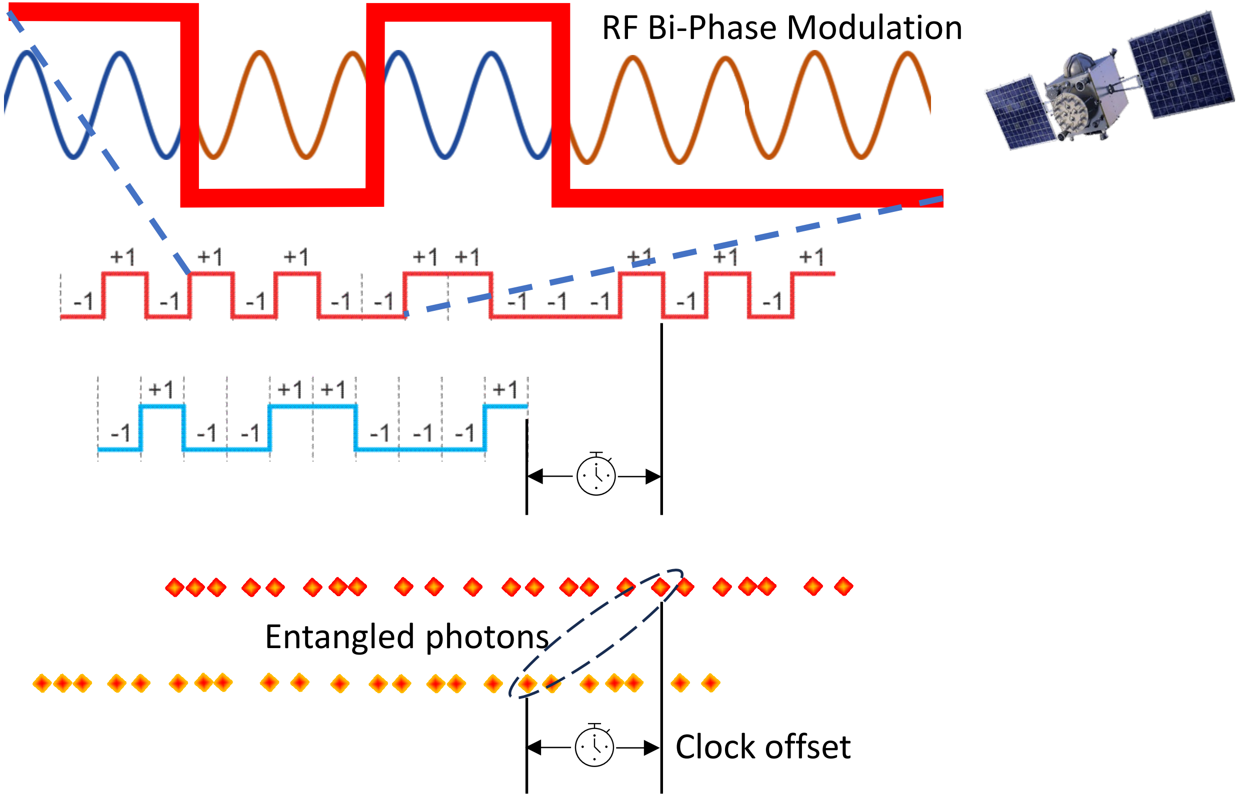
RF or Optical
Time Transfer via
modulated signal

Quantum vs RF and Optical Time Transfer

RF
Time Transfer

RF or Optical
Time Transfer via
modulated signal

Quantum Time
Transfer

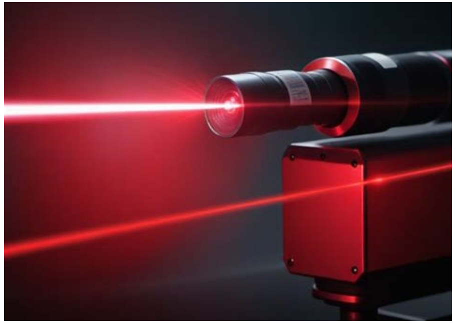


FSOC Terminal Design

Basics of Optical Transmission

Creating light is easy =>

For efficient communications coherent directed light is needed =>



Free-space optical communications (FSOC) terminals connect free-space laser links

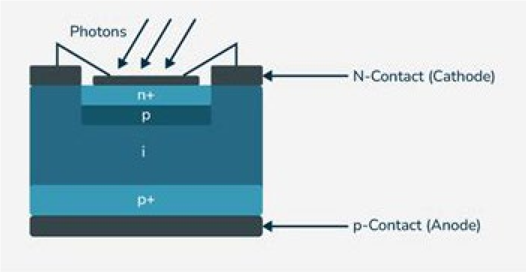
- Creating (laser) and detecting (avalanche photo diode) coherent light is easy
- Maintaining link while directing this light is the major challenge

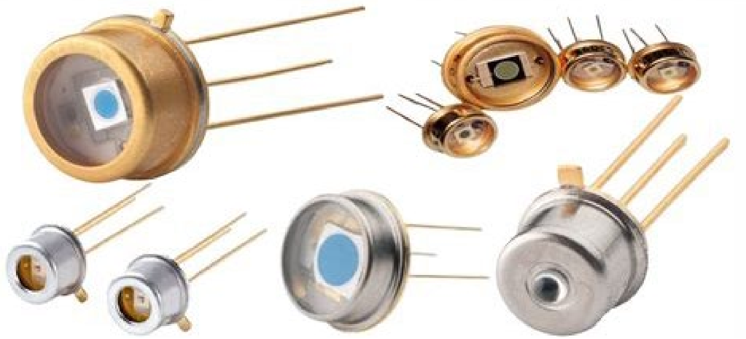
The Challenge of Free-Space Optical Transmission

The fundamental challenge: maximizing the amount of light that is received over long distance and hits the avalanche photo diode (APD) that is typically 5 mm

Wavelength range from 300 nm to 1700 nm

- Silicon => 300 nm and 1100 nm
- Germanium => 800 nm and 1600 nm
- InGaAs => 900 nm to 1700 nm





FSOC Terminal Elements

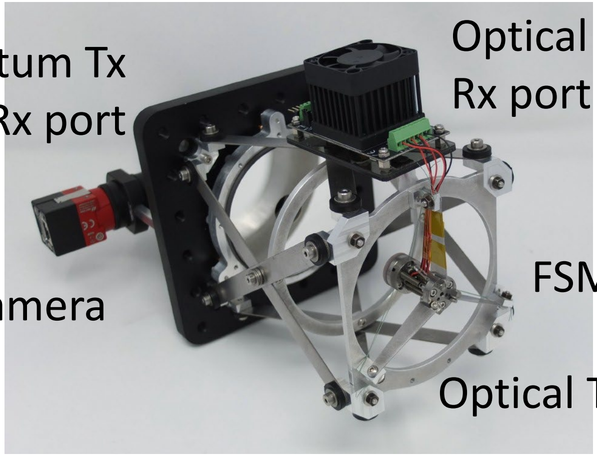
Optical transmitter (seed laser, amplifier, modem) – typically 1550 nm

Optical receiver (APD, amplifier)

Optical telescope – collimates and concentrates light

Pointing, acquisition and tracking (PAT) – coarse gimbal, fine steering mechanism (FSM), quad-cell or camera detector, beacon

Support electronics and structure



FSOC Design Considerations

→ Aperture diameter - transmit and receive gain (collecting area)

  → Beam divergence – set by wavelength and aperture (larger = narrower beams)

    → Pointing and tracking – tight beam requires tight PAT control

→ Wavefront quality

  → Surface and alignment tolerances, thermal gradients

  → Adaptive optics

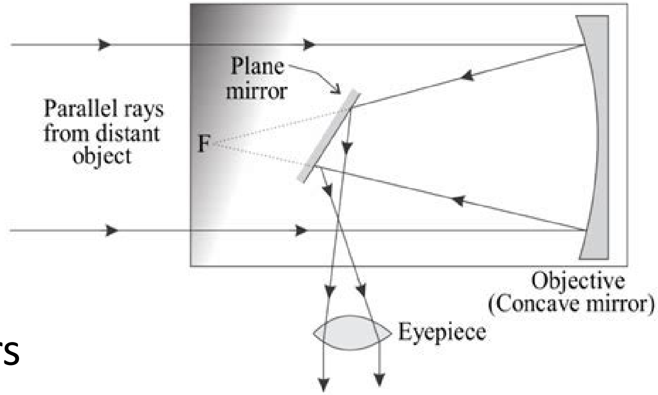
→ Dynamic range

  → Isolation between Tx and Rx paths

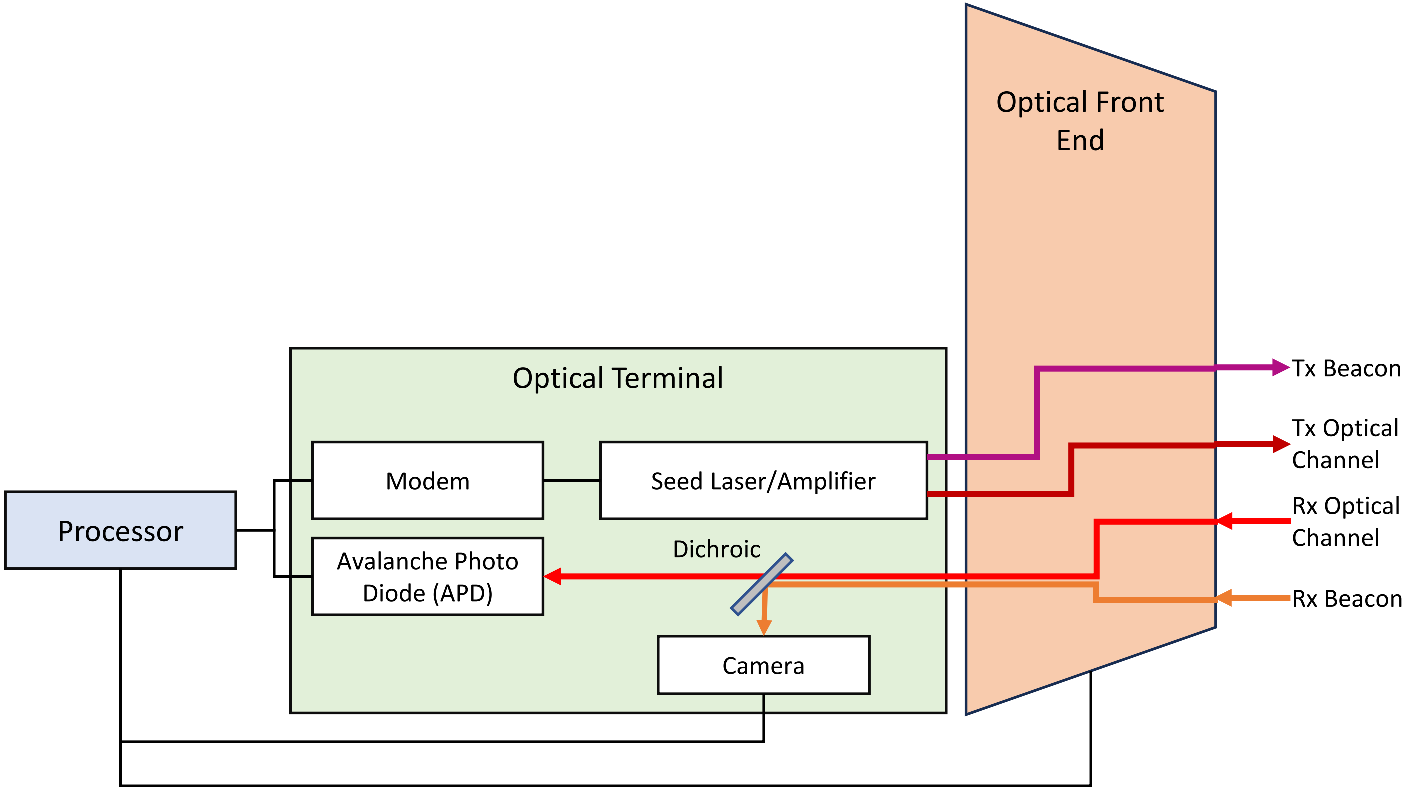
  → APD choice

→ Field of view - coarse gimbals and fine steering mirrors

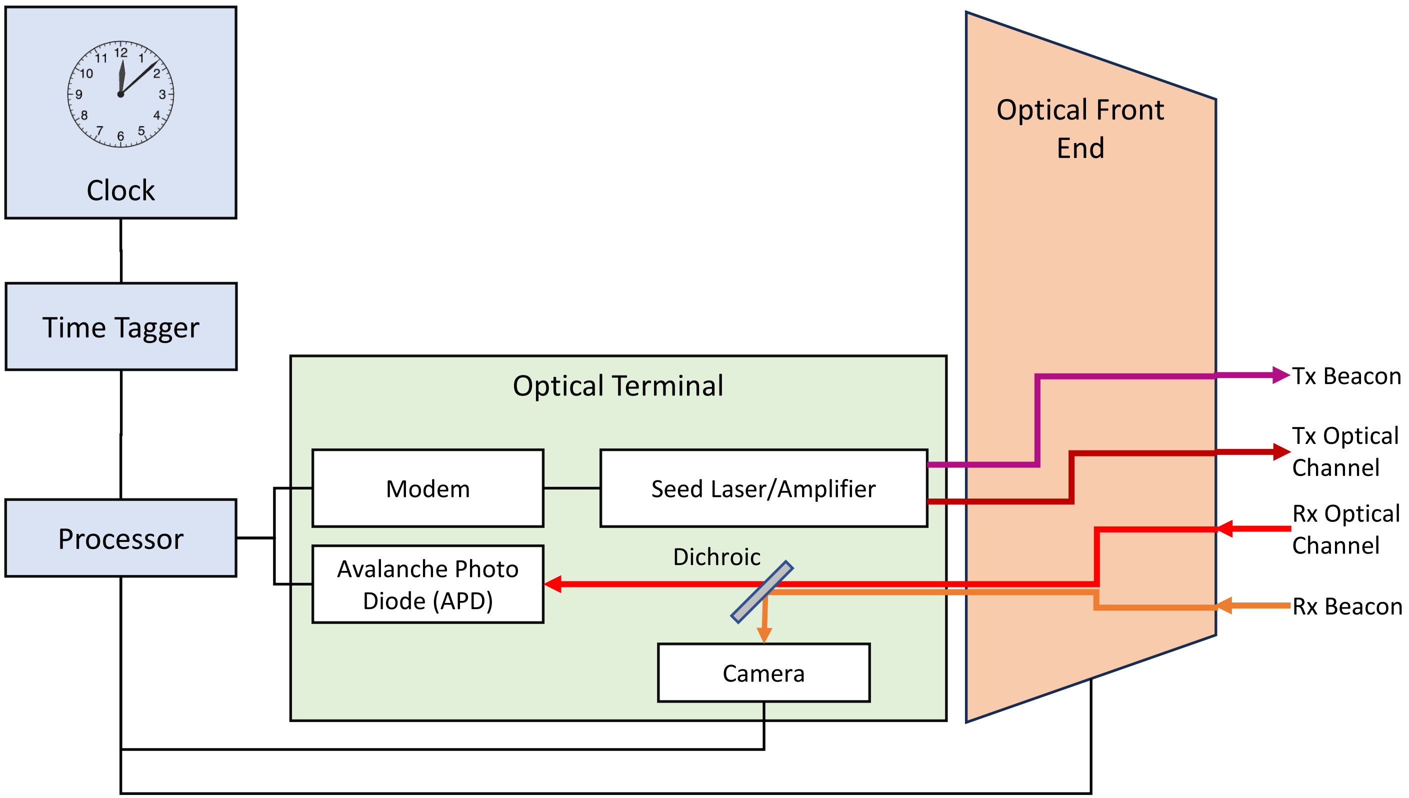
→ Compactness -> aperture - refractive, reflective (Cassegrain, off-axis), or hybrid



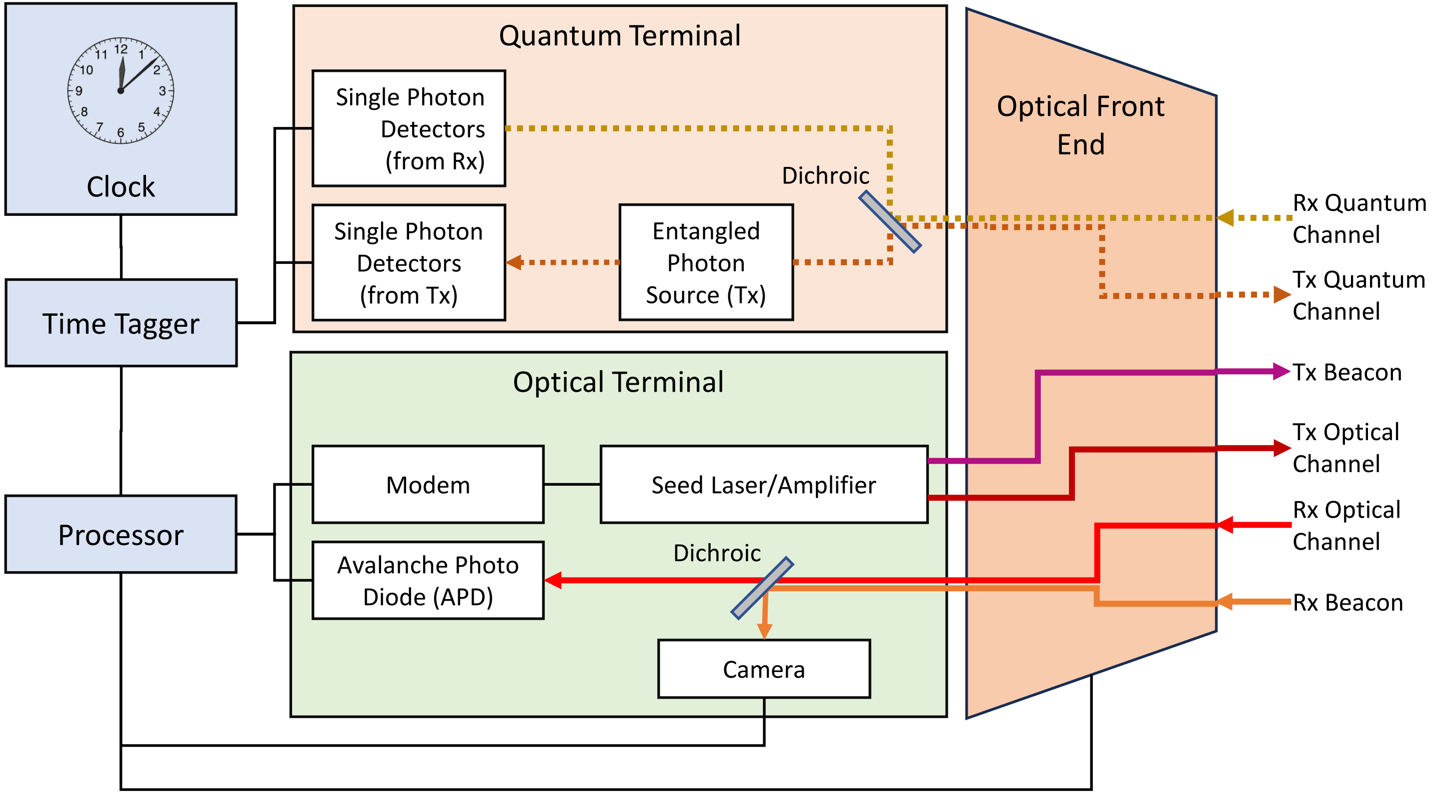
FSOC Terminal Block Diagram



Optical Time Transfer Block Diagram



Optical and Quantum Time Transfer Block Diagram



Challenges

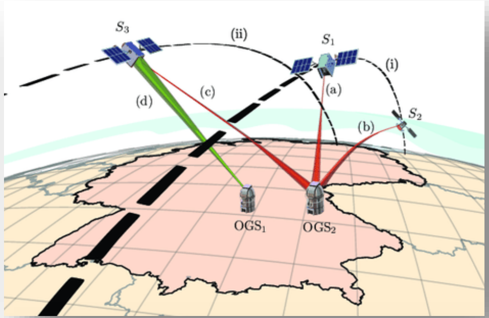
Space-Based Quantum and Optical Links

Same issues that impact free-space quantum and optical time transfer have been solved by the FSOC community

- FSOC design – aperture, telescope, PAT

New considerations:

- Link budget
- Concept of operations
- Doppler effects
- Point-ahead angle
- Constellation design



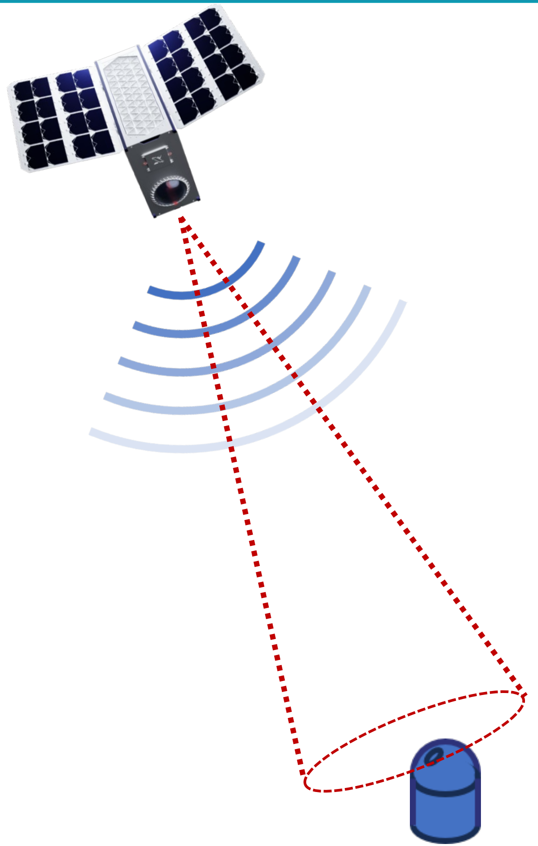
Link Budget

Antenna gain is replaced by transmitter and receiver gain

Scintillation and atmospheric losses are more critical

Key input parameters:

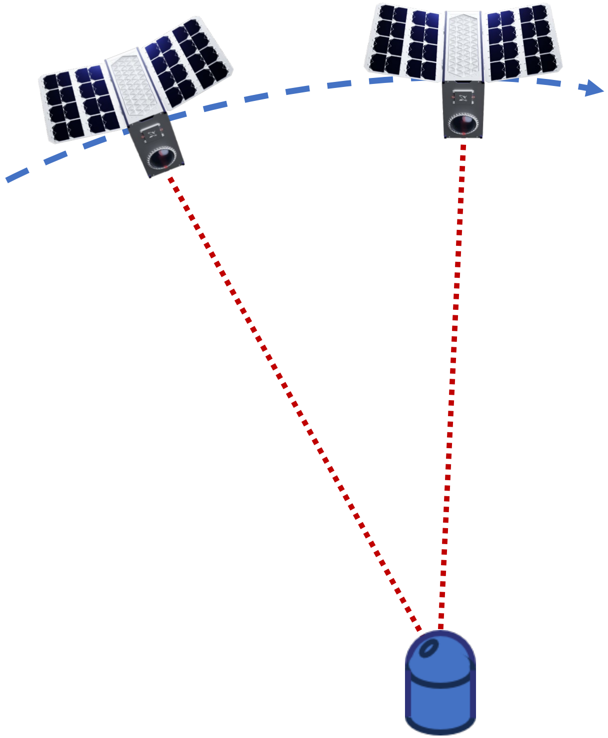
- Laser output power
- Laser transmit beam divergence angle
- Free-space loss
- Pointing/jitter loss
- Atmospheric and scintillation loss
- Receiver optics diameter and sensitivity



Point-Ahead Angle

The point-ahead angle of the FSOC link must be calculated to account for the relative motion between satellite and ground (or other satellite)

Requires a priori knowledge of the relative position between the transmitter and receiver

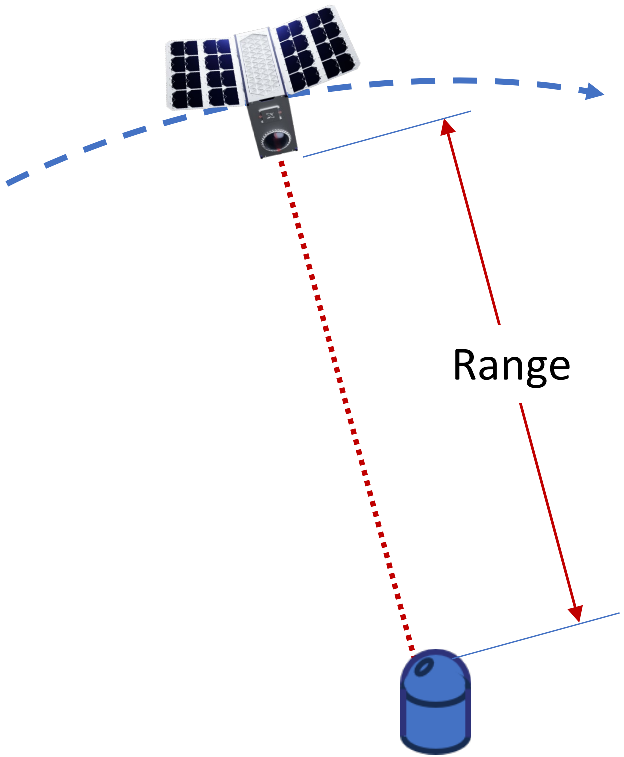


Doppler Effects

The Doppler Effect is the change in frequency or wavelength of a wave in relation to an observer moving relative to the source of the wave

Doppler shift in the optical domain deteriorates the communication performance but tends to become a dominating factor for accurate quantum and optical time transfer

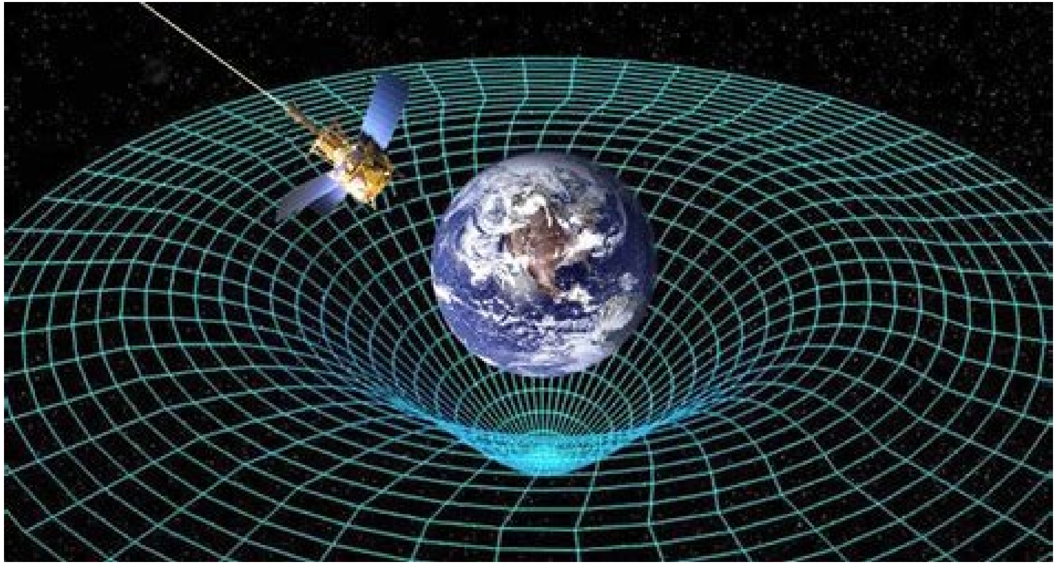
Compensation requires a priori knowledge of the range rate between the two objects



Relativistic Effects

Relativistic effects account for the warping of space and time

This affects clock synchronization between satellites and ground stations and tends to domination as better accuracy is necessary

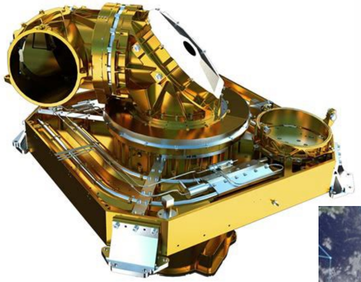


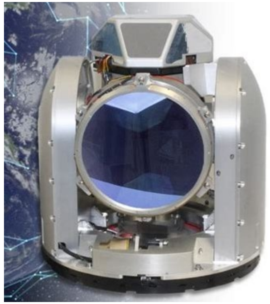
State-of-the-Art

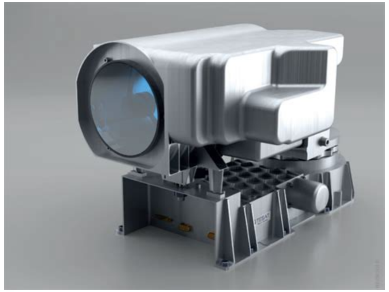
Space-based Optical Communications

Multiple designs now on-orbit spurred by:

- Standards set up Space Development Agency and European Space Agency
- Mega constellations like Starlink
- Earth observation and sensing satellites that generates lots of data



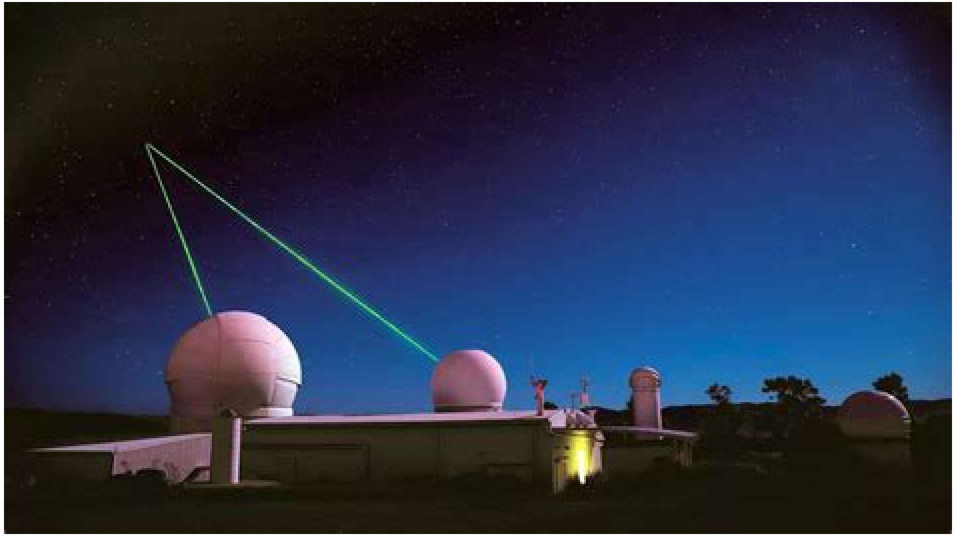




Satellite Laser Ranging

Satellite laser ranging (SLR) uses ultrashort pulses of light that hit a satellite (or other space objects) and bounce back to be caught by the station

Measures the round-trip time with the speed of light formula at millimeter level precision



Space-Based Optical Time Transfer

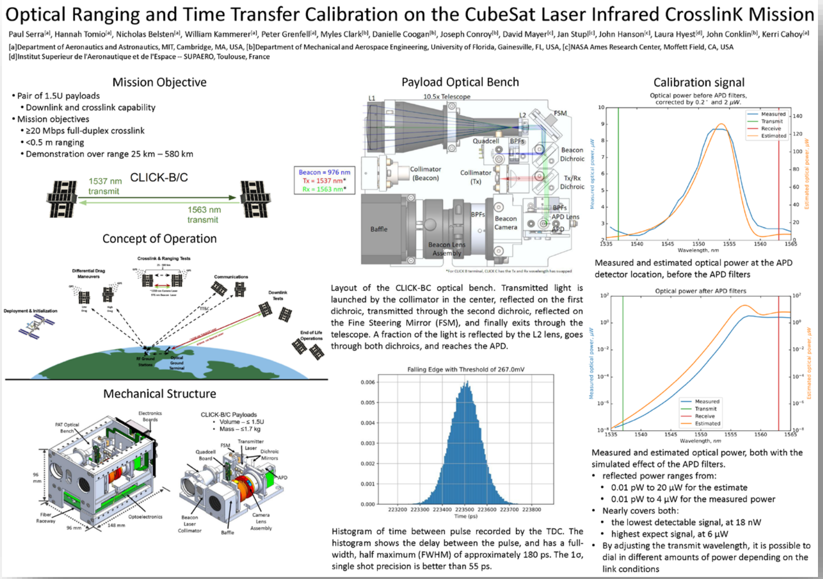
JASON-2 satellite with Time Transfer by Laser Link (T2L2) payload

CubeSat Laser Infrared CrosslinK (CLICK) B and C

ESA OPSTAR program

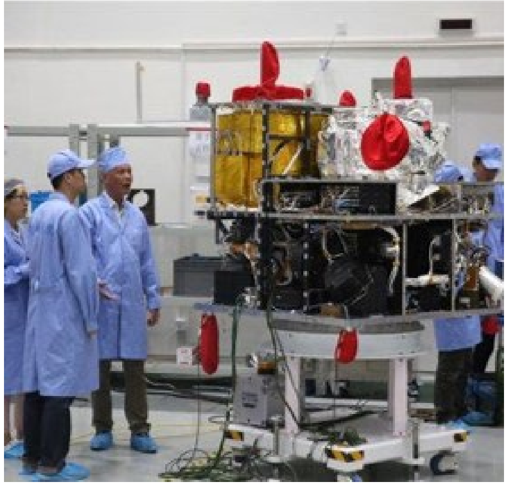
Optical comb development

- NIST demonstrations
- Optical Clock Orbiting in Space (FOCOS) mission



Space-Based Quantum Communications

Sponsor	Satellite	Wavelengths
China (Chinese Academy of Sciences)	Micius QKD demonstration satellite (launched 17 Aug 2016)	810 and 850 nm
	Space Lab Tiangong-2 quantum payload (launched 15 Sept 2016)	850nm
	Jinan 1 (launched 29 July 2022)	850nm
	Three LEO satellites (2025)	
	MEO and GEO satellites (2026)	
Europe (European Space Agency)	Eagle-1 QKD satellite led by SES (2026)	1565 nm
	QKD-GEO satellite led by Thales and Hispasat (2027)	
	TeQuantS led by Thales (Study Phase only)	
	IRIS^2 Secure Satellite Constellation with QKD links (2030)	
	QKDSat ESA private partnership with Honeywell UK (2027)	850nm
	SAGA (Security And cryptoGrAphic mission)	1550 nm
Canada (CSA)	Quantum Encryption and Science Satellite (QEYSSat) (2026)	785 and 1550 nm
Singapore (SpeQtral and CQT)	SpooQy-1 (launched 17 June 2019)	N/A – no space-to-ground link
	SPEQTRE (2025)	810 nm
	SpeQtral-1 (2025)	810 nm
UK (UK Space Agency)	QUARC (Study only)	808 nm
	SPOQC (2025)	NIR (DV) and Telecoms (CV)
	ROKS (Study only)	785 nm
	OPSAT Volt (with ESA)	785nm
Germany (DLR)	QUBE (launched 16 Aug 2024)	850 nm
	QUBE-II (2025)	850 nm
	QUICK^3	698 nm
United States (NASA, Boeing)	SEAQUE (launched 27 June 2024)	N/A – no space-to-ground link
	Q4S led by Boeing (2027)	N/A – no space-to-ground link



Thank You!

Contact: david@xairos.com