The 9th Symposium on Frequency Standards and Metrology @ Kingscliff, NSW, Australia

中国科学技术大学
University of Science and Technology of China

Time and frequency dissemination over 113 km free-space

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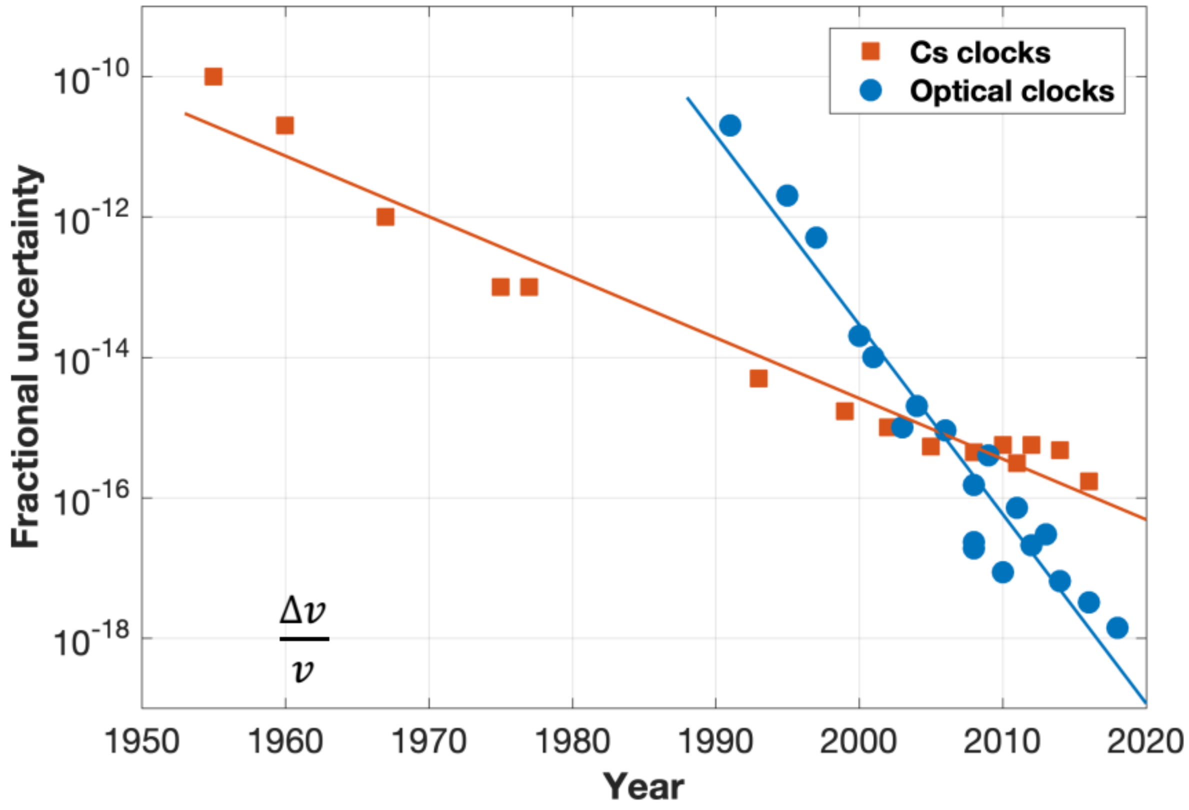
Outline

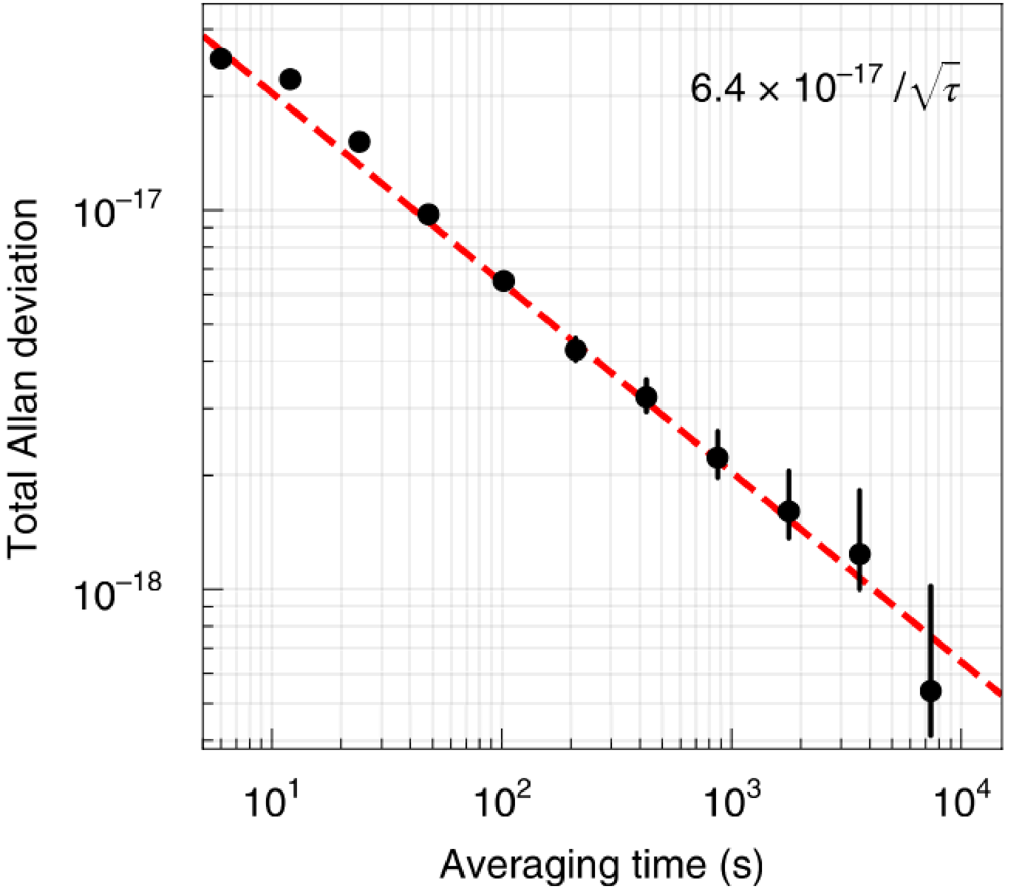
- Background & Motivation
- Experimental Setup
- Measurement Results
- Summary and Outlook

Background

- ➢ **Frequency uncertainty around 1E-18，2 orders better than the primary frequency standards**
- ➢ **Frequency instability reaches E-19@10000s**



Lu+,Al+,Yb, Sr Clocks



Oelker, E., et al. (2019).." Nature Photonics **13(10): 714**

Background

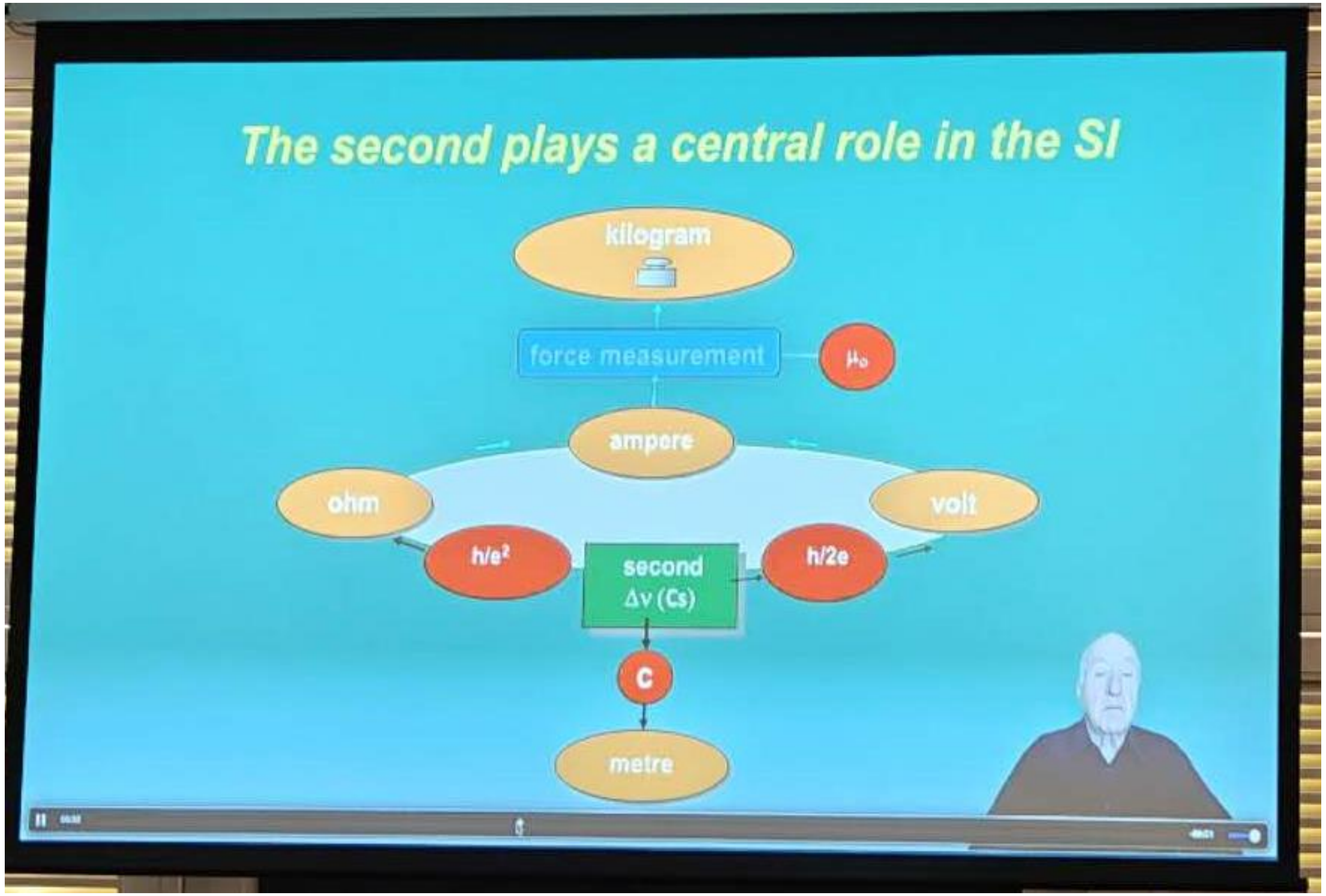
Many research opportunities will arise with better access to optical clocks and better dissemination methods,

uncertainty level	Application opportunity
1E-14	holdover
1E-15	spectroscopy/dark matter/secure com/holdover
1E-16	cosmology
1E-17	dark matter/connected interferometry
1E-18	positioning/real time geodesy/new clocks
1E-19	geodynamics
1E-20	relativistic geodesy/alternative theories of gravitation

METROLOGIA - Roadmap towards the redefinition of the second 2023

Background

Better optical clocks and better dissemination methods are important for metrology.



Jacques Vanier

On Monday

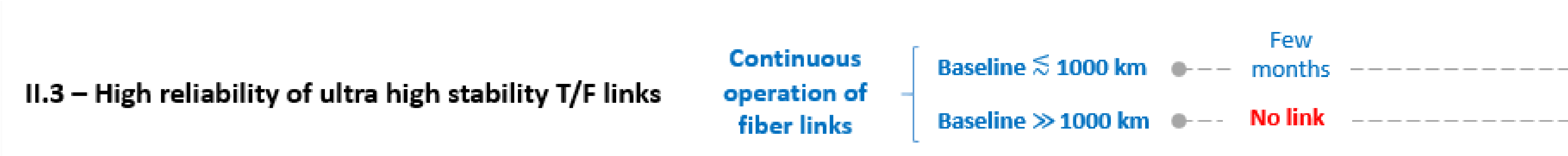
Redefinition of second may happens around 10 years, so better comparison link is required..

METROLOGIA - Roadmap towards the redefinition of the second 2023

Background

Fiber-based T/F dissemination: Europe, Australia, Japan, China

- Complex
- Expensive

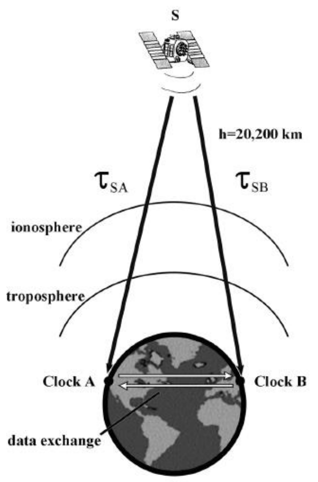


Talk of "Roadmap towards a redefinition of the SI second"

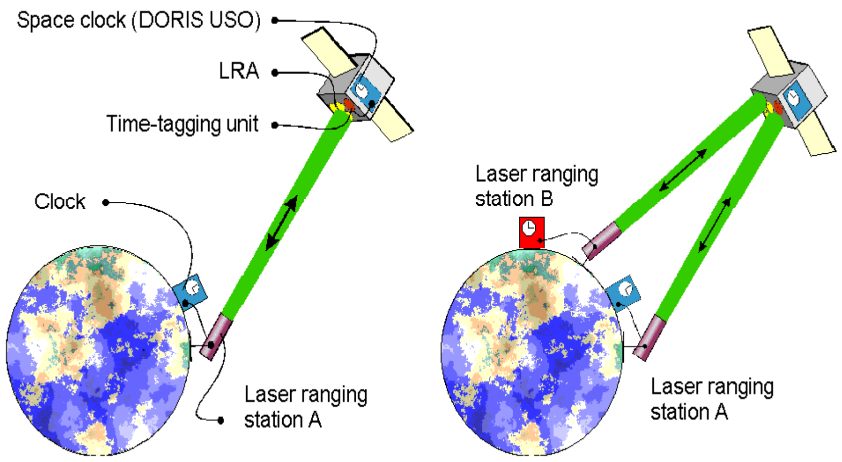
Global scale link: free space, double length (6dB)

Satellite-based time-frequency transfer

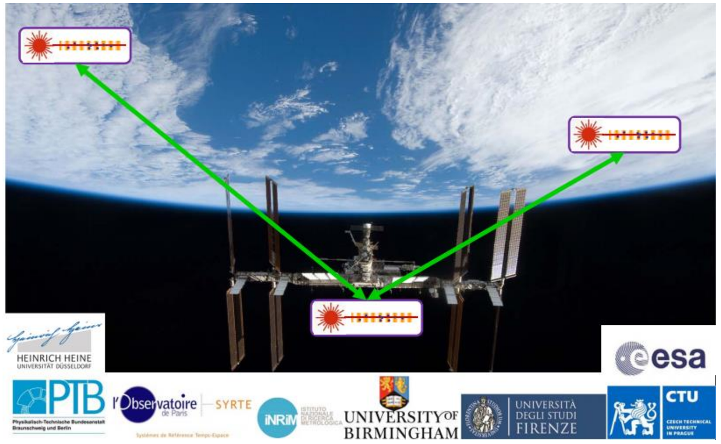
The existing satellite-based T/F transfer link cannot meet the requirements of optical clock comparison.



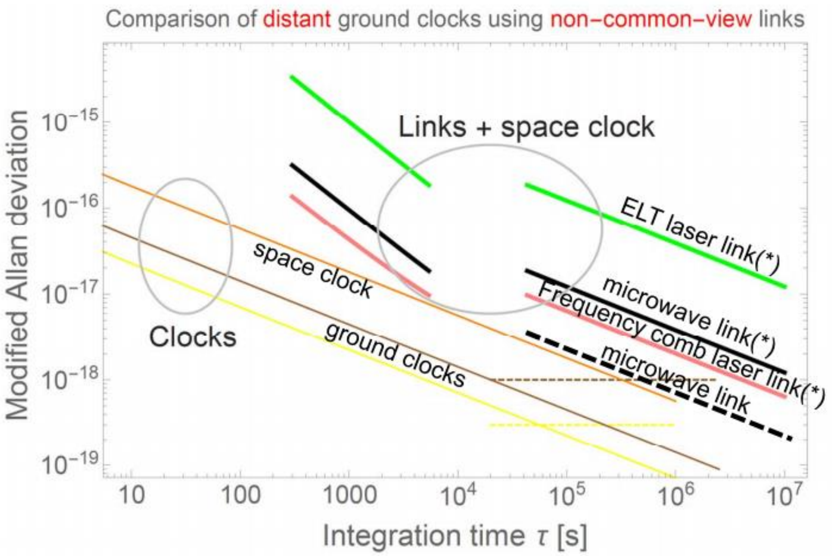
Satellite CV



T2L2



I-SOC



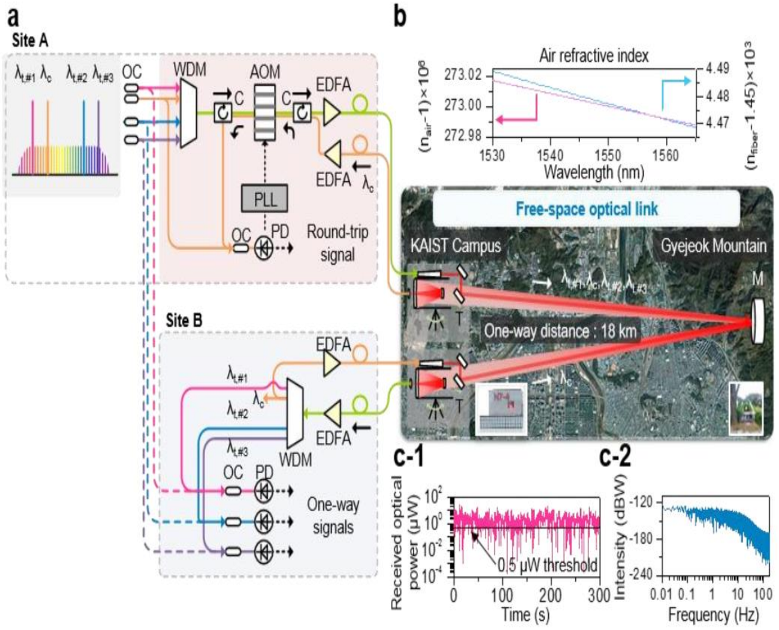
T/F link	Intability
GPS (CV)	1×10^{-15}@1 day
Time to laser link (T2L2)	1×10^{-16}@1 day (2013)
I-SOC (planning)	10^{-17}@10,000s，10^{-18}@10day

Research progress of high-precision T/F link on the ground

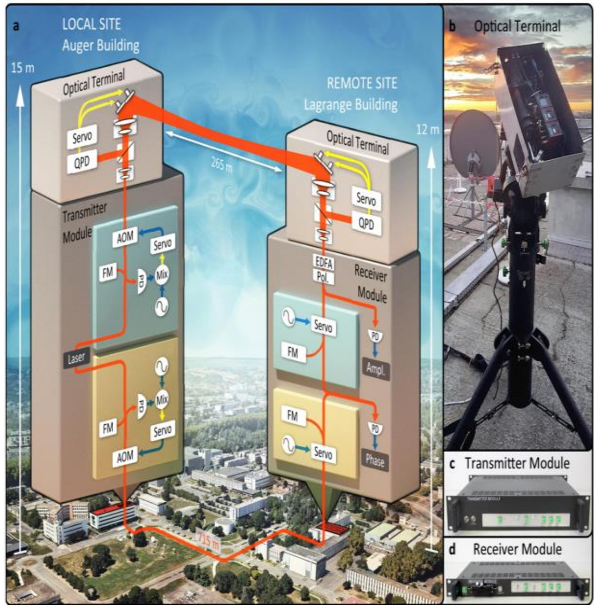
Ultra-stable laser frequency transfer

- 2019， South Korea KAIST, multi-wavelength ultra-stable optical frequency and microwave transfer locked by optical comb, 18km, 4E-15@0.1s; no long-term stability limited by link influence
- 2021, Joint team of Australia and France achieved 265m freespace ultra-stable optical frequency transfer， 1.6E-19@40s。 2022， increased to 2.4km， 6.1E-21@300s。

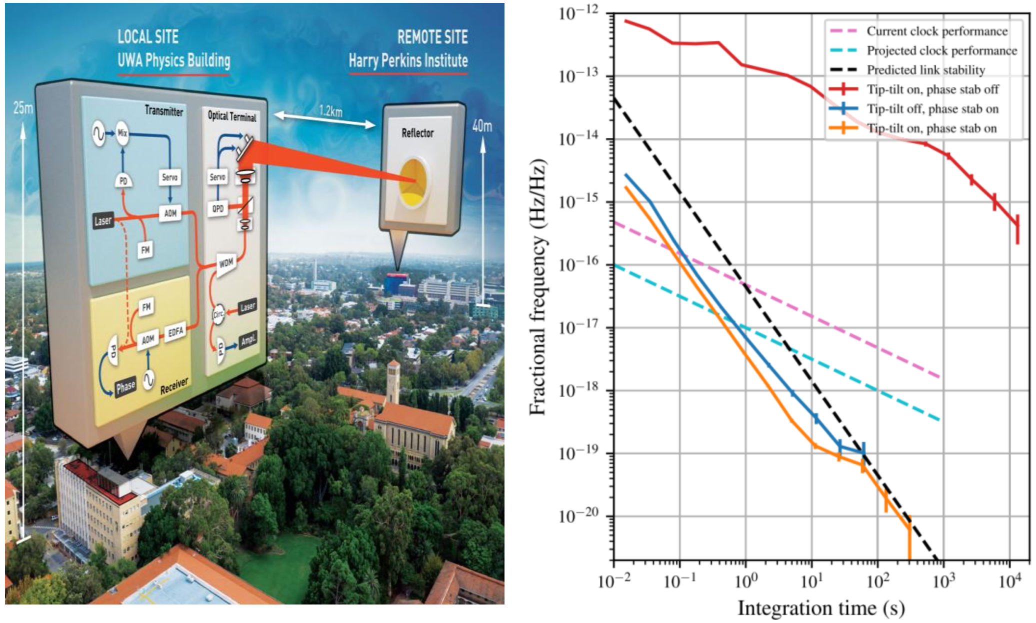
■ Low ambiguous range (drawback)



Nat Commun. 10:4438 (2019)



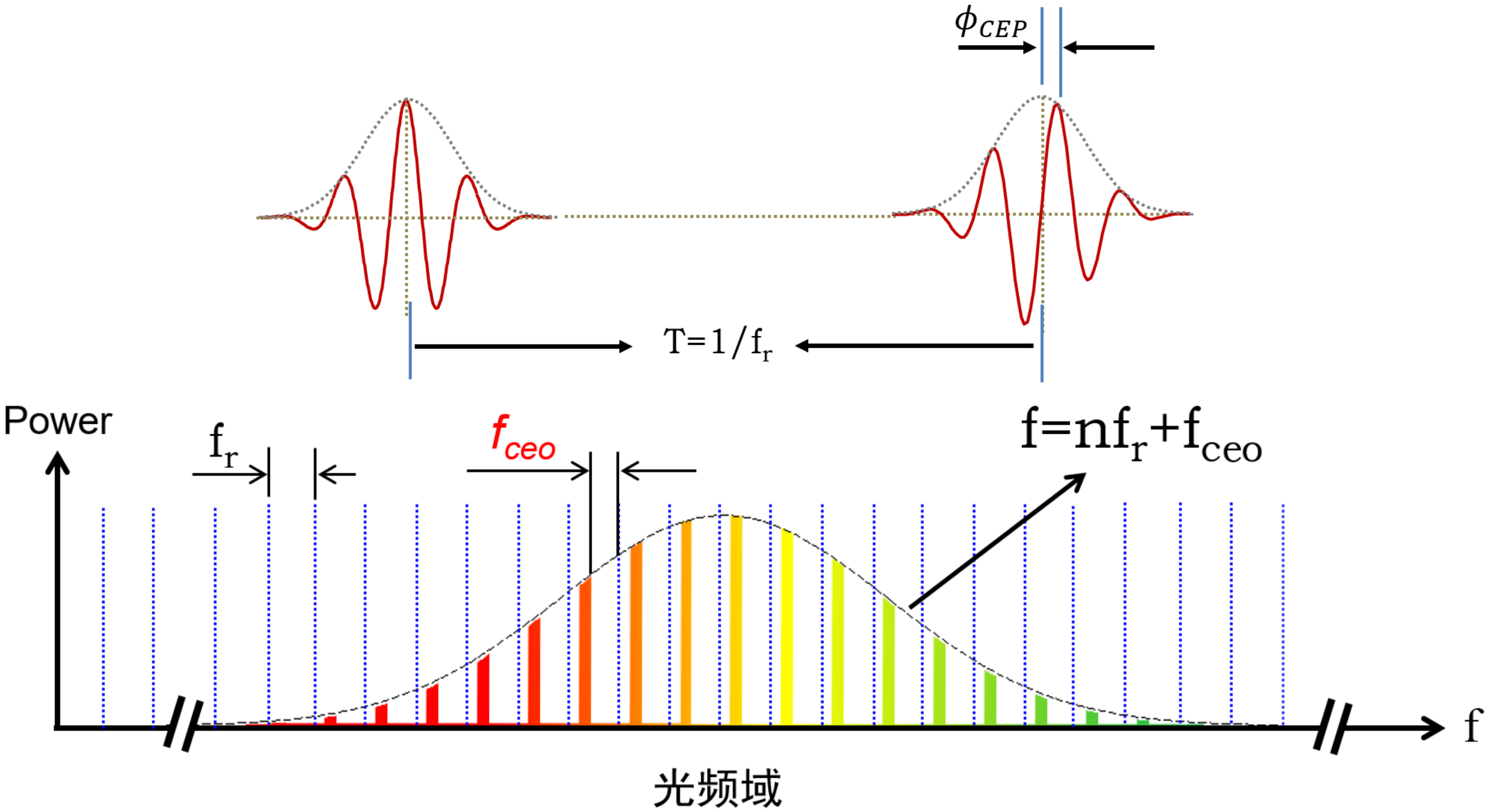
Nat. Commun. 12:515 (2021)

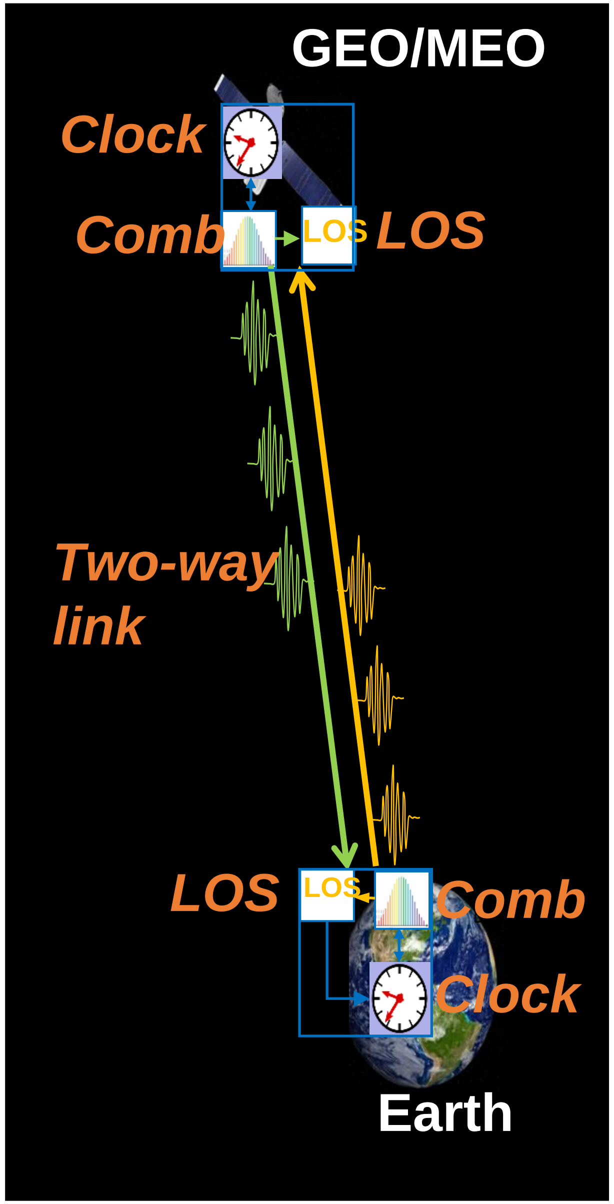


PRL 128, 020801 (2022)

Optical comb-based T/F link

Comb-based T/F link scheme：





- ➢ Broad-band optical signal
- ➢ Highly coherent

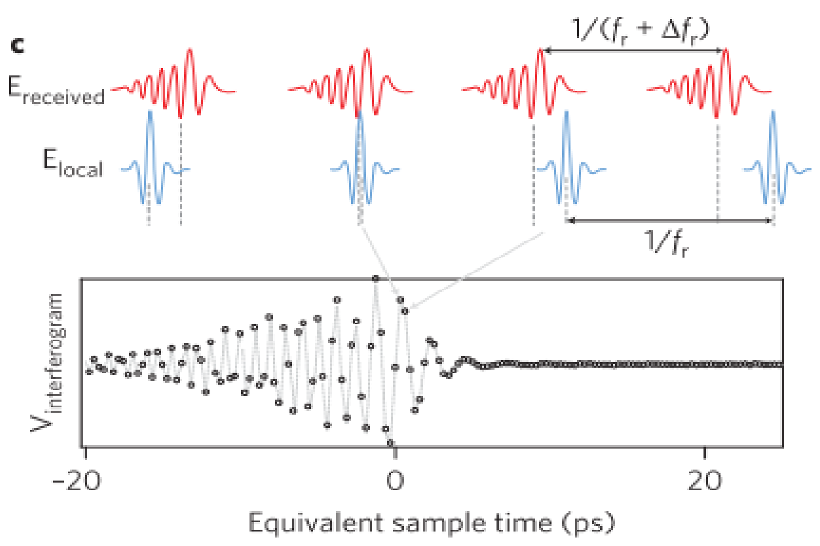
Enlarge ambiguous range

Optical comb-based T/F link

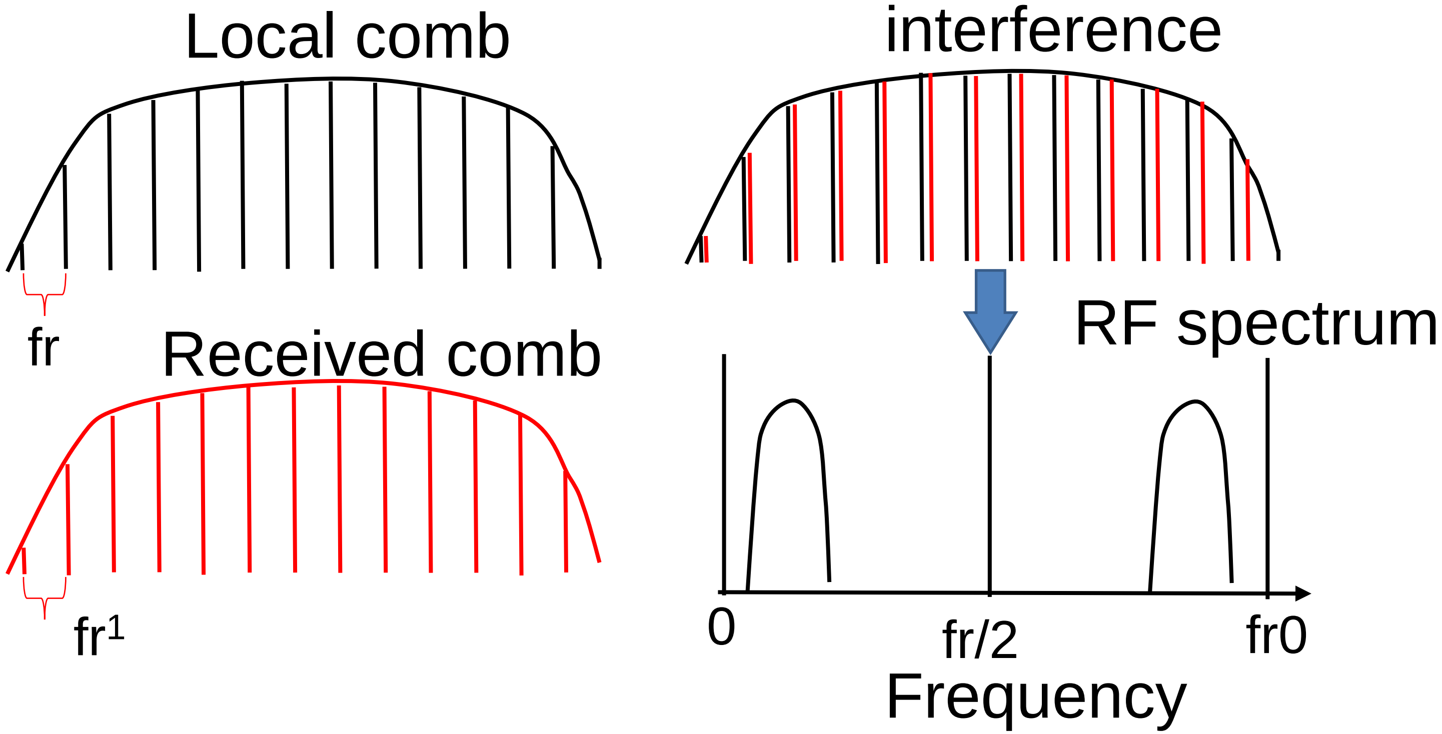
Comb-based T/F link scheme

- Local comb locked to clock, which stability is transformed to comb
- Linear optical sampling(LOS) to extract the arrival time of the signal comb

Drawback: low photon efficiency



[Nat. Photonics 7, 434–438 (2013)]

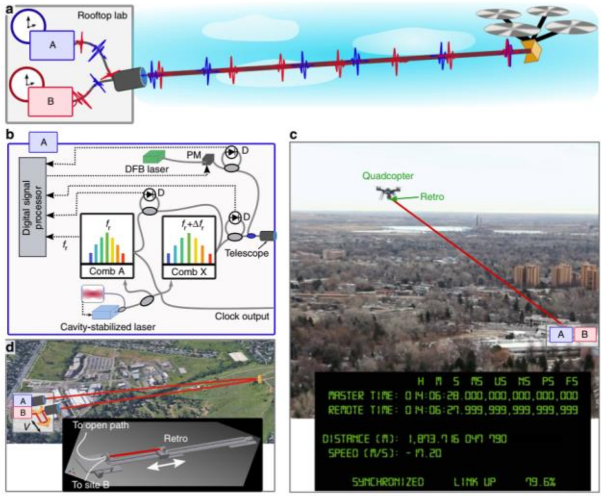


Research progress of high-precision T/F link on the ground

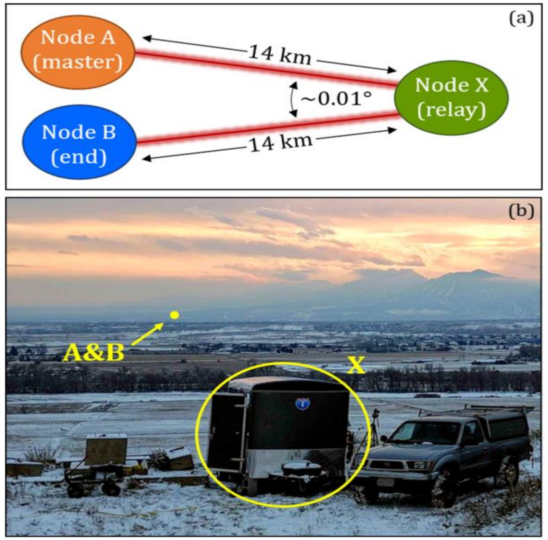
NIST group pioneering works based on optical comb

- **2013, scheme first proposed** [Nat. Photonics 7, 434–438 (2013).]
- **2016，round-trip 12km atmosphere，5E-19@1000s**
- **2019，flying quadcopter，24m/s, E-18@100s**
- **2020, 14 km freespace，three-node network，6E-19@200s**
- **2021，BACON，free space and fiber optical comparison network，5E-18@10000s**

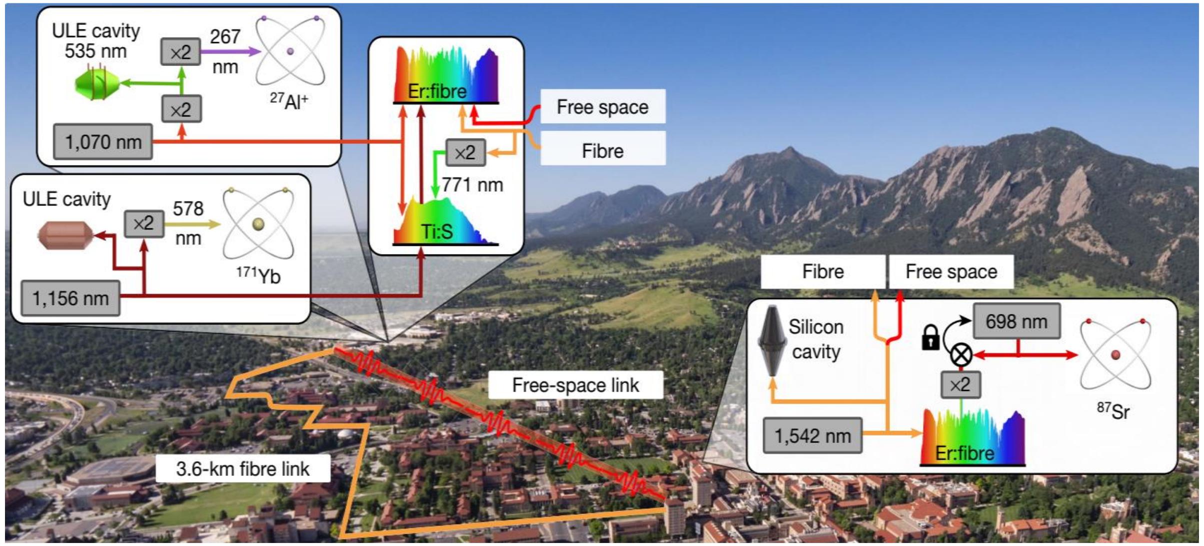
Appl. Phys. Lett. 109, 151104 (2016)



Nat. Commun. 10, 1–7 (2019).

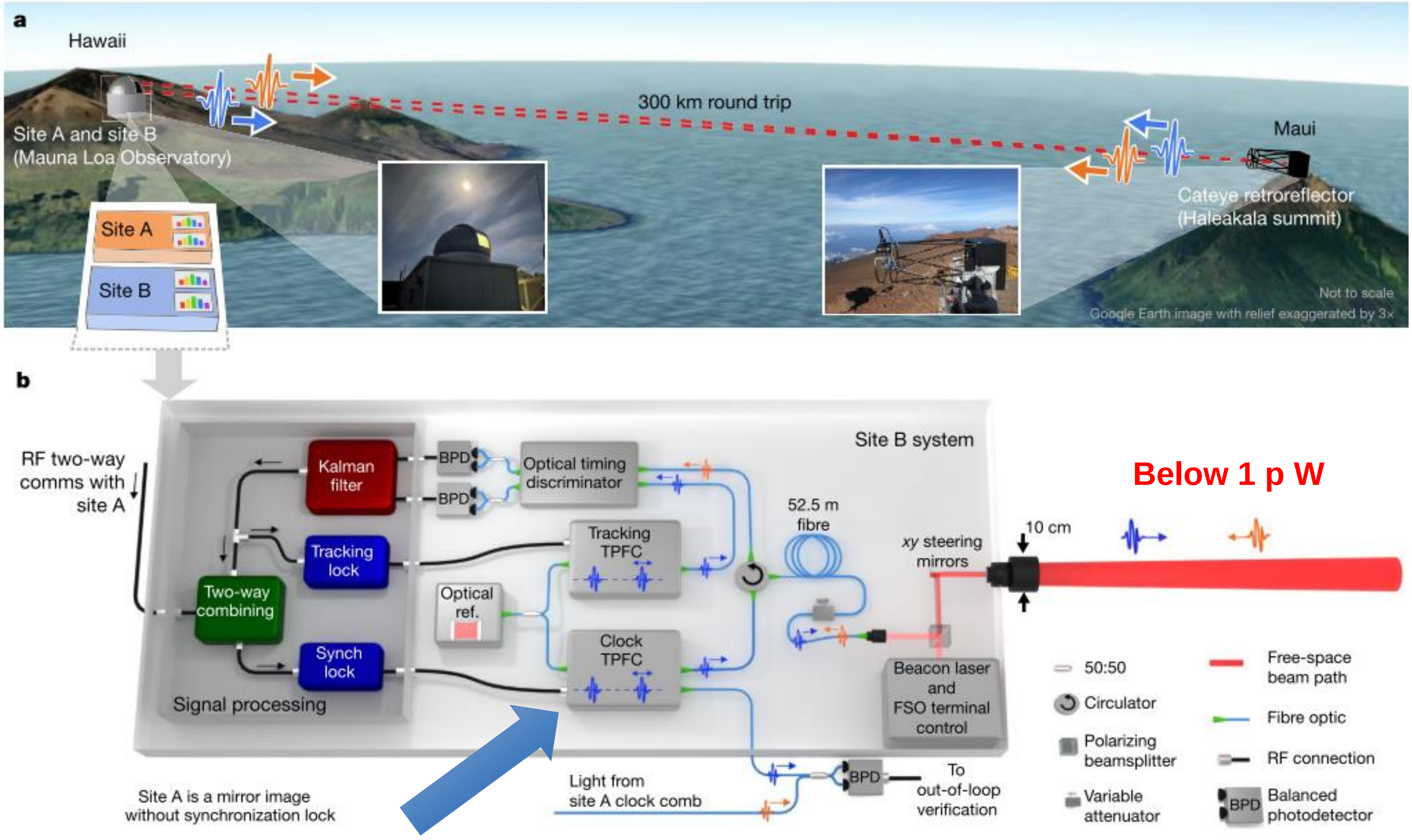


APL Photon. 5, 076113 (2020)



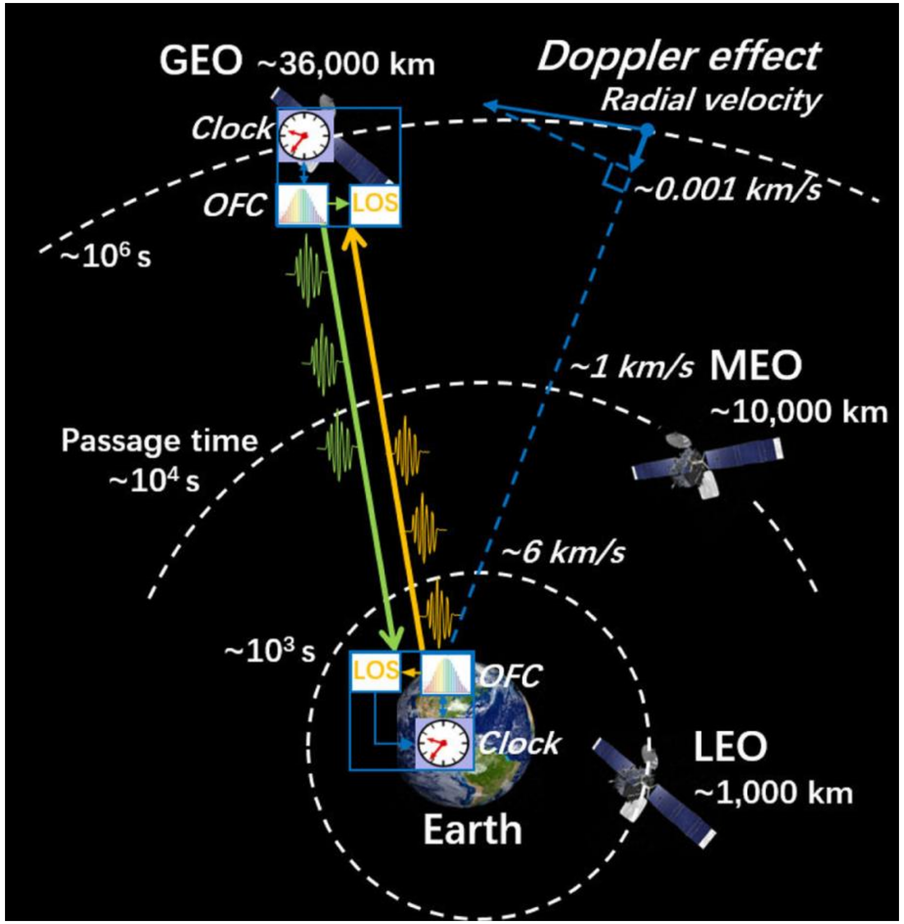
Nature. 591:564-569 (2021)

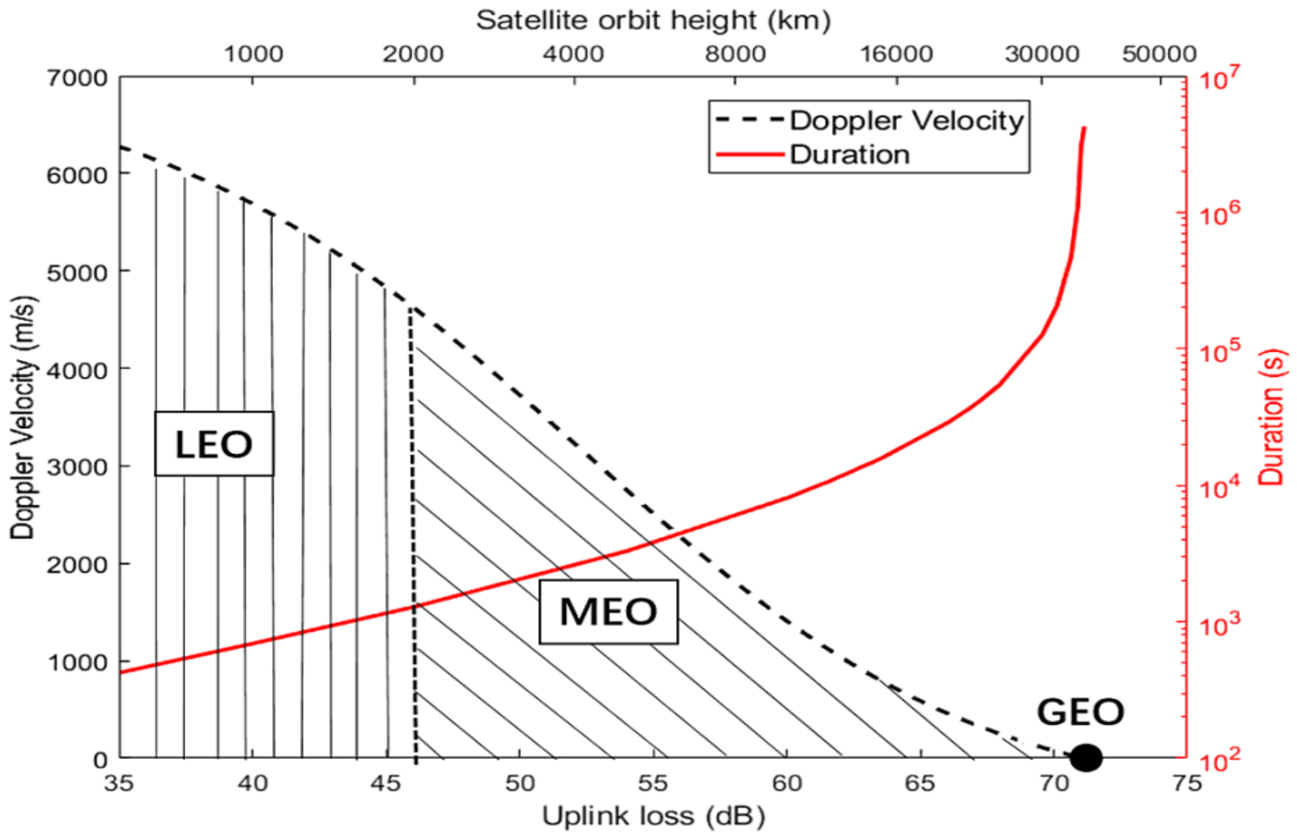
Research progress of high-precision T/F link on the ground



Different satellite orbit types consideration

MEO/GEO is better than LEO for longer duration, larger common view range, and lower relativistic effects.



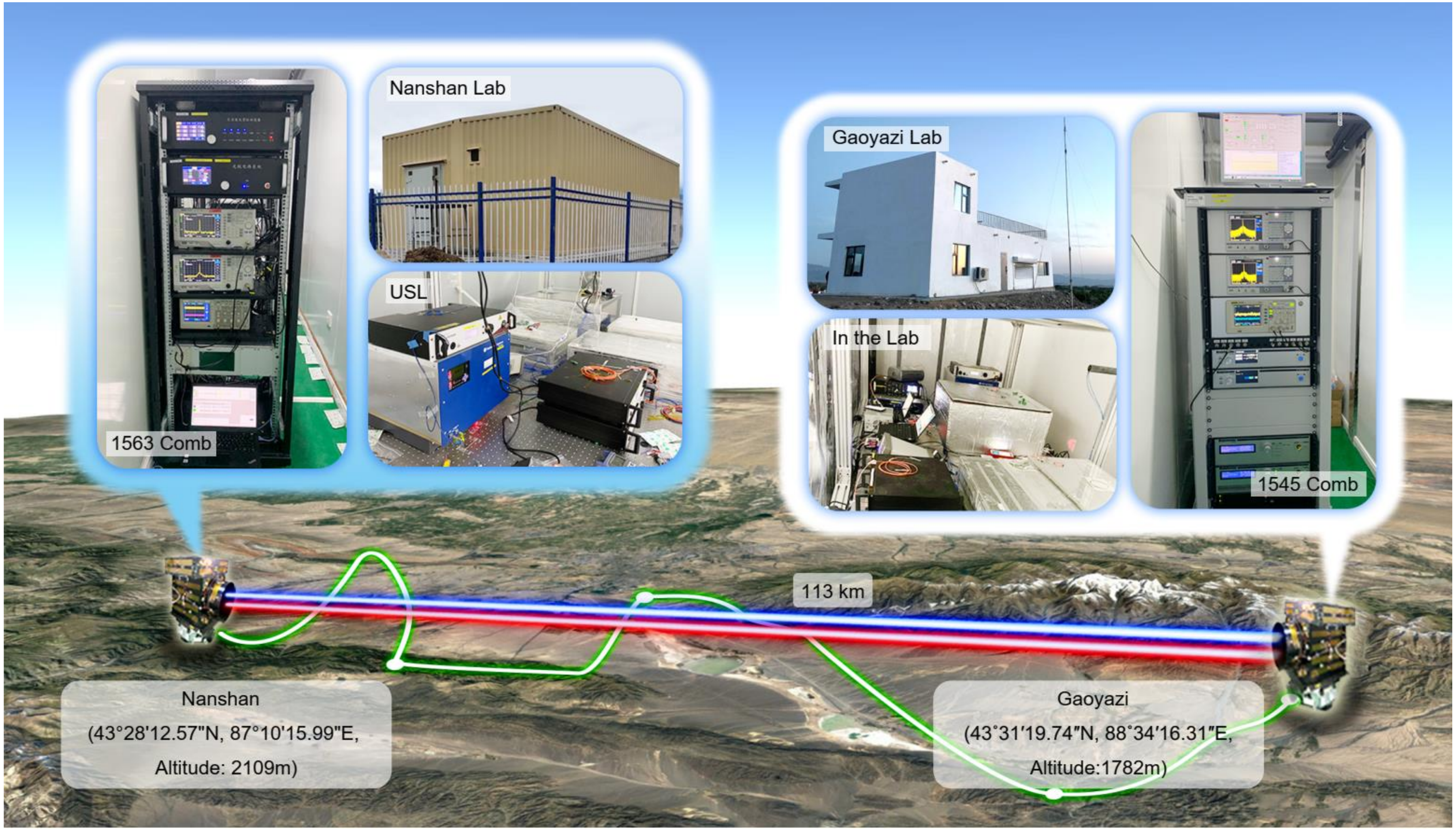


The most challenges are large link loss, atmospheric noise.

Qi. Shen Optica 8, 471(2021)

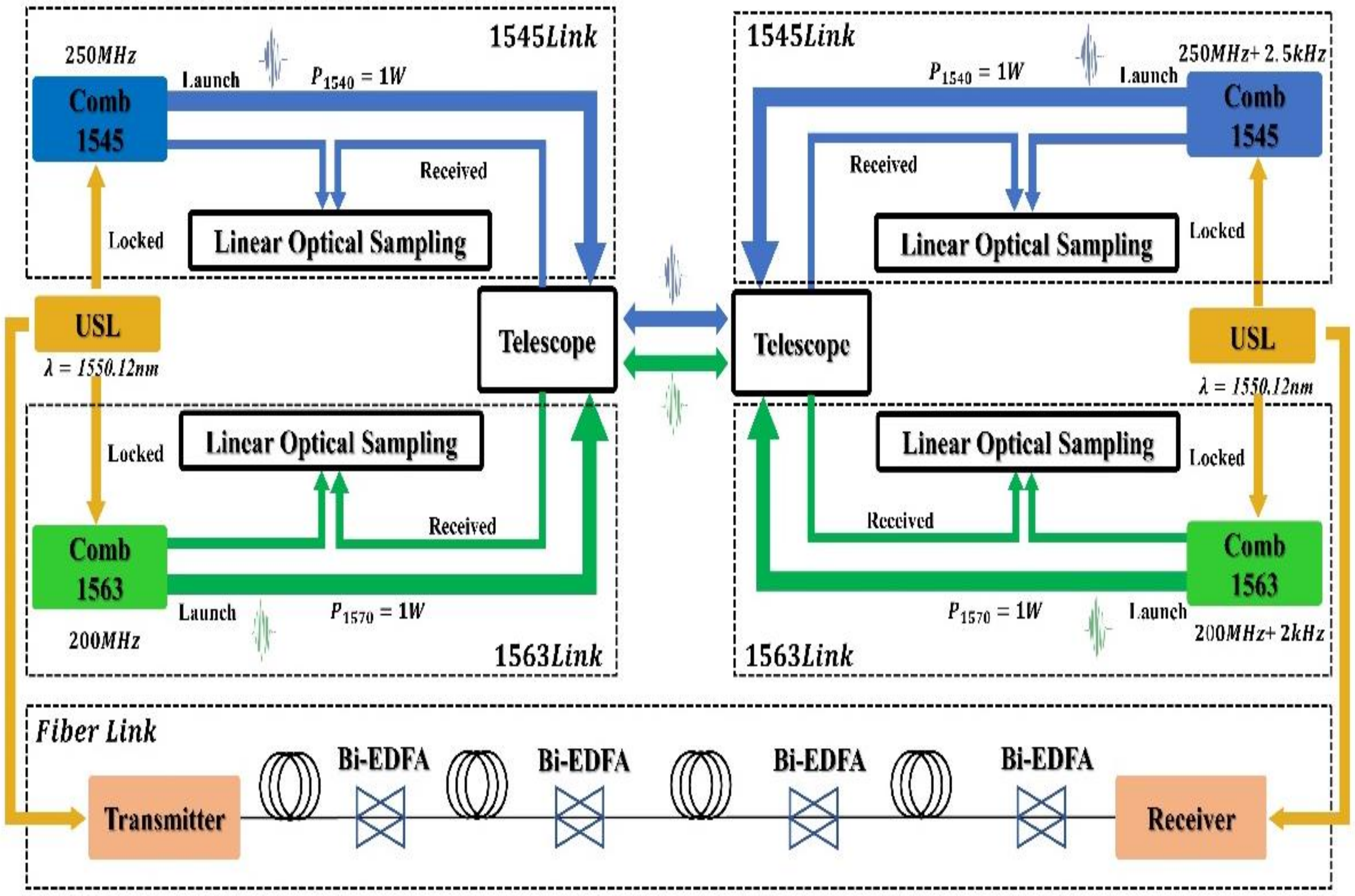
Experimental Setup

113 km point-to-point straight line free-space link



Qi. Shen et. al.. *Nature*, 610: 661–666

113 km point-to-point straight line free-space link



System setup:

- Ultra stable laser、1545/1563 comb、Linear optical sampling (LOS) optics and electronics
- Telescope
- Fiber optical transfer terminal

Two independent two-way comb links:

- 1545nm link: comb repetition rate/diff. 250 MHz/ 2.5kHz
- 1563nm link: comb repetition rate/diff. 200 MHz/ 2kHz

An independent optical fiber frequency transfer link:

- Fully verify and evaluate the performance of space transfer links

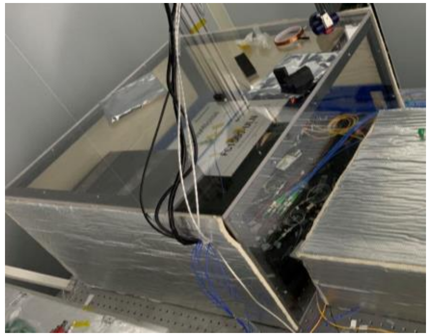
113 km point-to-point straight line free-space link

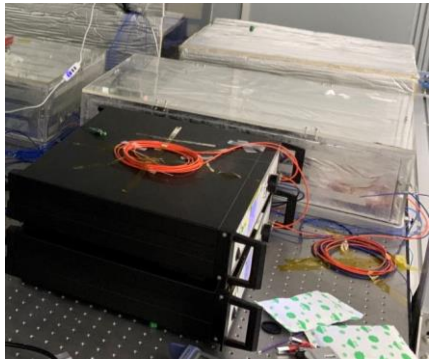
1545 comb :

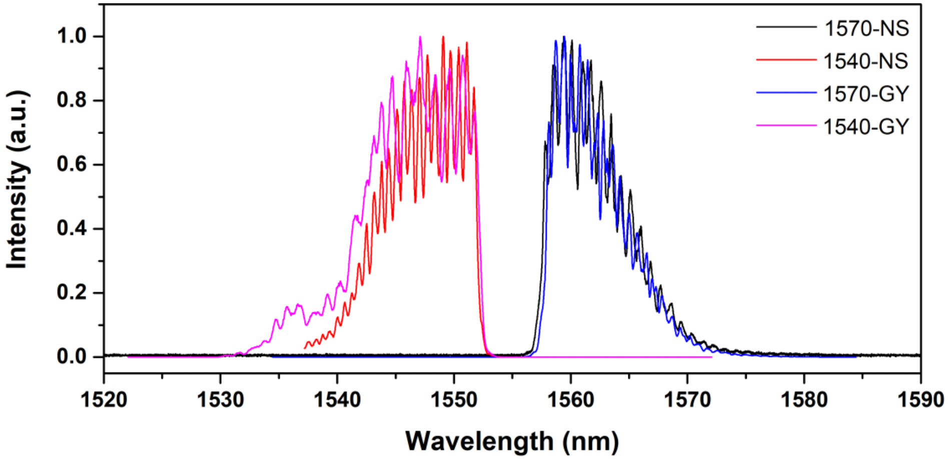
- Commercial product from Menlo. System Inc.
- Homemade amplifier to 1W output power
- MDEV: 1E-16@1s； 6E-21@10000s
- 3dB wavelength： 10 nm； 70/90 ps pulse width

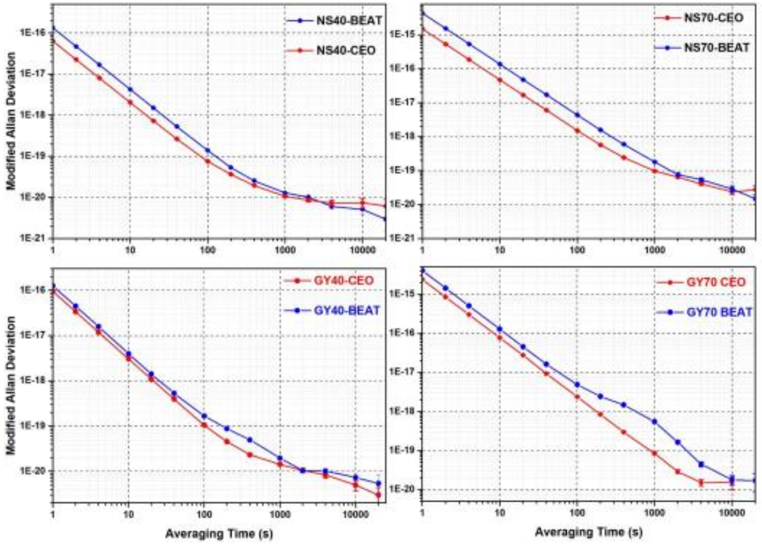
1563 comb :

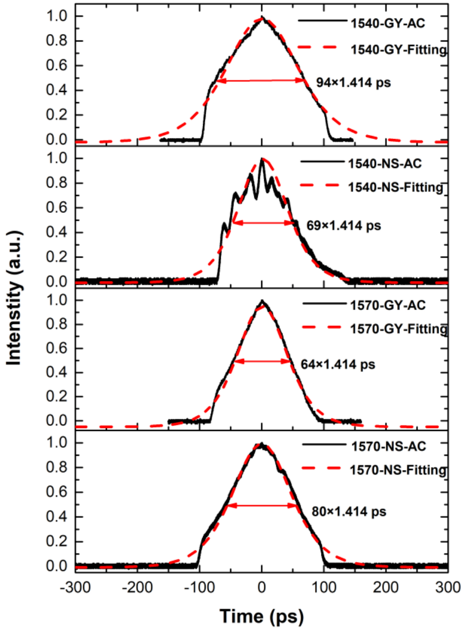
- Homemade： 1W output power
- MDEV: 2E-15@1s； 1E-20@10000s
- 3dB bandwidth： 7 nm； 60/80 ps pulse width







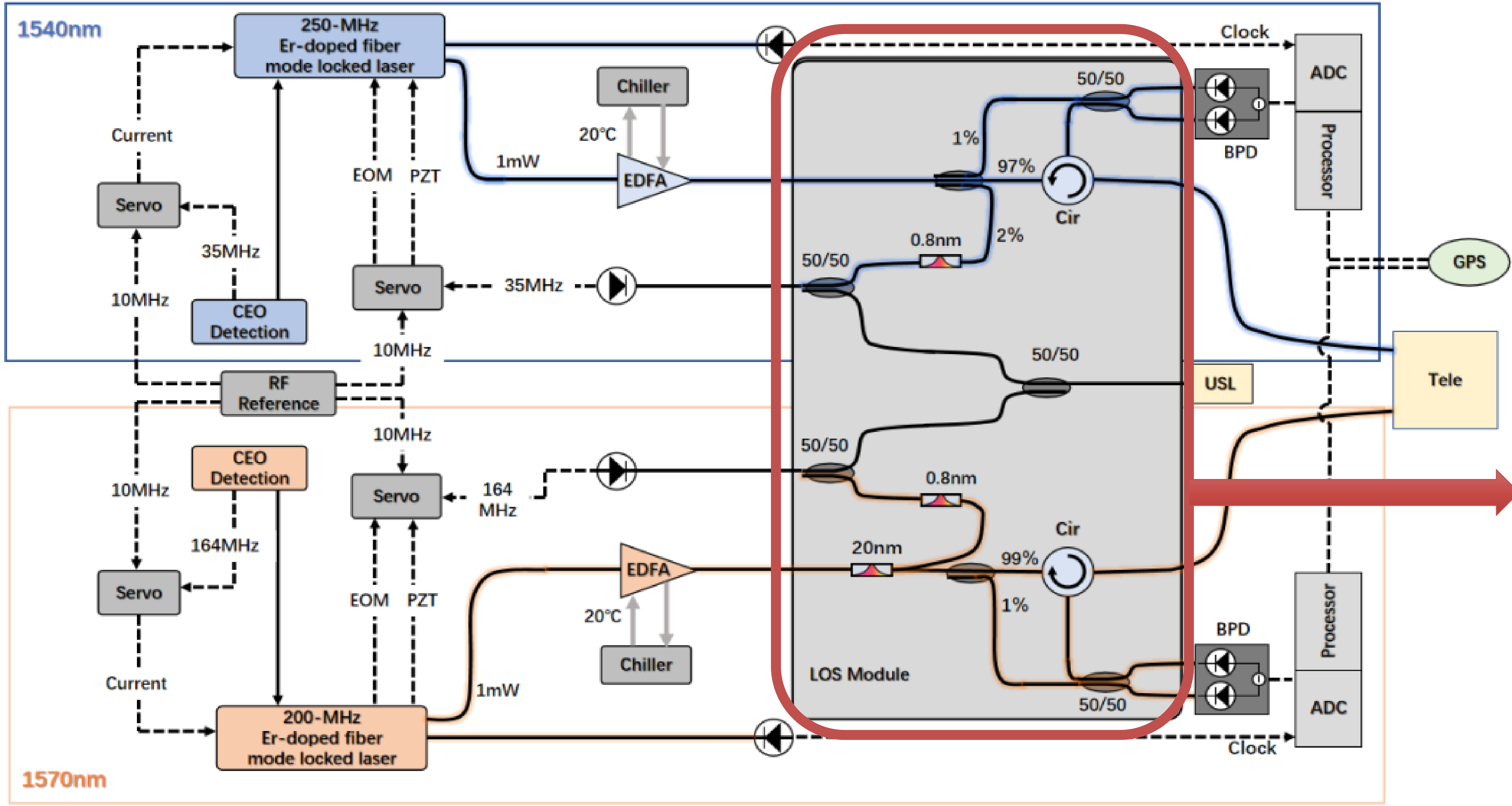


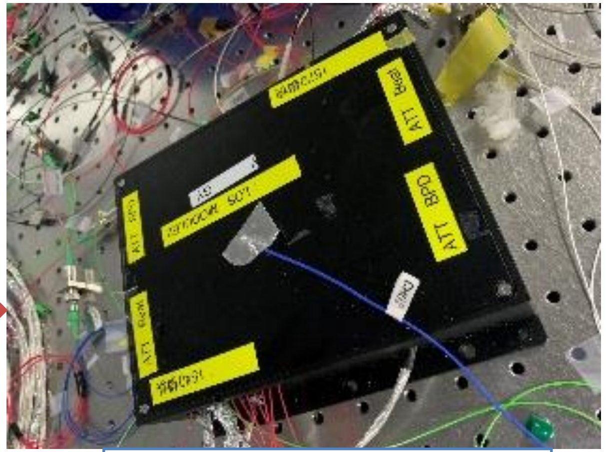


113 km point-to-point straight line free-space link

LOS optics:

- Integrated fiber optical module design with circulator
- Temperature control: 7 mK std



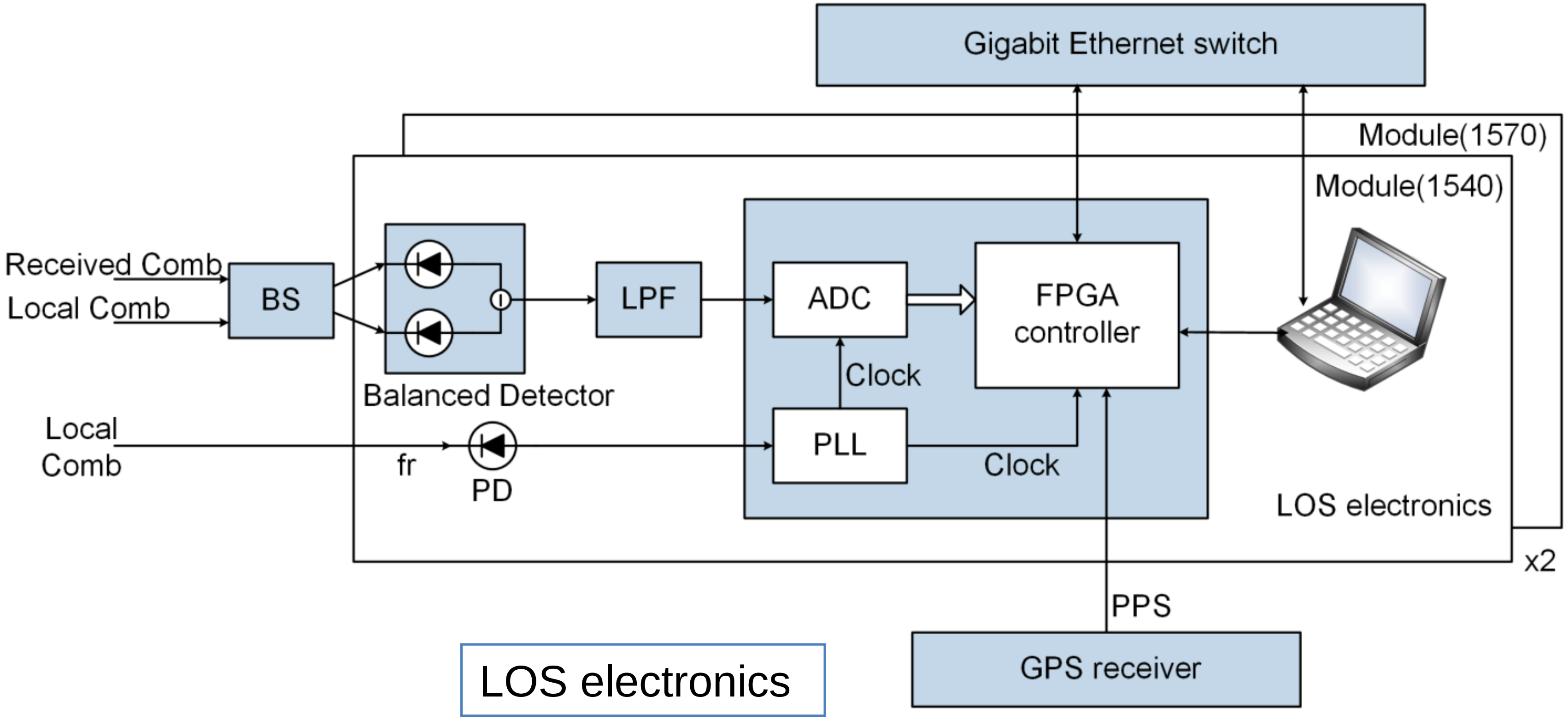


LOS optics module

113 km point-to-point straight line free-space link

LOS electronics :

- Balanced detector: NEP < 10 pW/sqrtHz， Gain: 40kV/W
- ADC: 14 bits; FPGA controller
- One data frame includes 1024 sampling points
- Remote start synchronize by GPS pps with 30 ns jitter

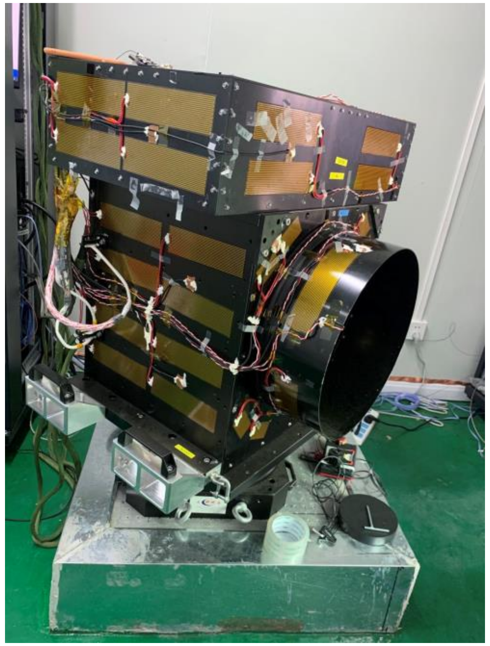


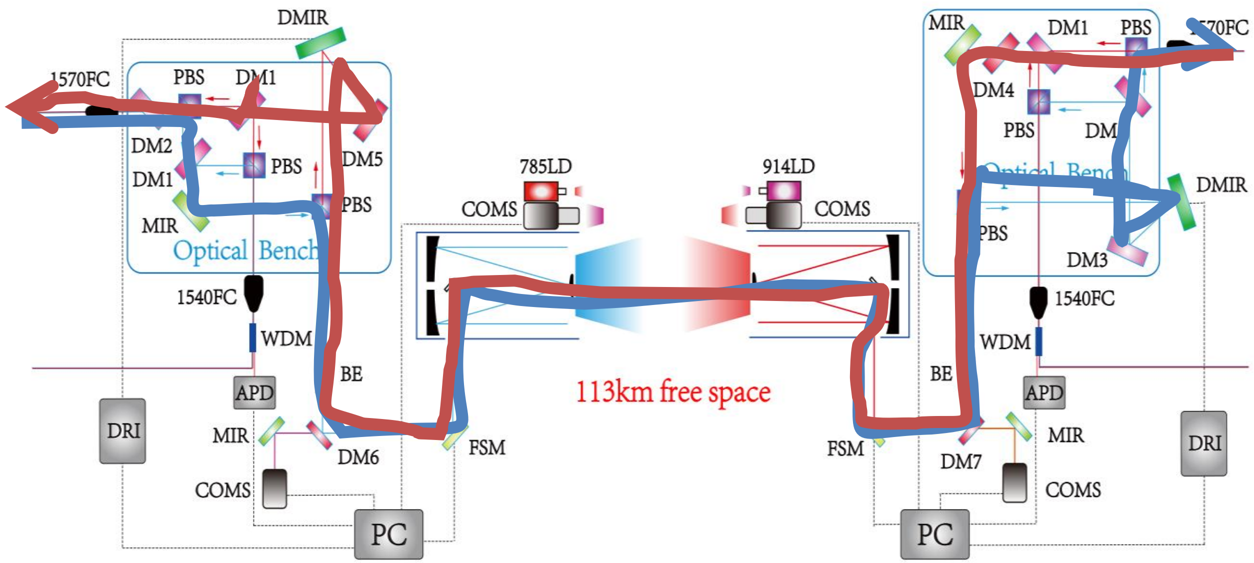
LOS electronics

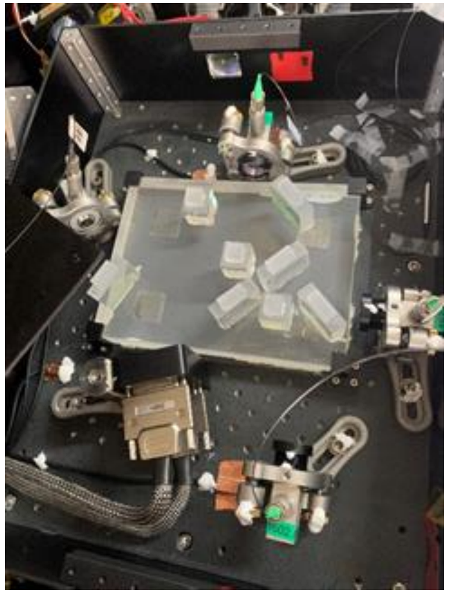
113 km point-to-point straight line free-space link

Optical transceiver telescope :

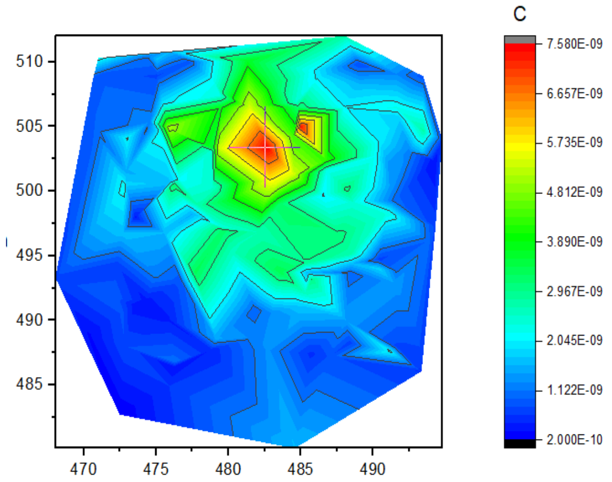
- 400 mm diameter, focal length of 1600 mm
- Full-angle divergence: 12 urad indoor; 30-50 urad after 113 km free space link
- Orthogonal polarization scheme to separate two directional signals, to simulate the nonreciprocal situation due to satellite point-ahead angle
- Adaptive optics with deformable mirror: increase single-mode coupling efficiency
- Optical bench technique employed with temperature control







Optical bench

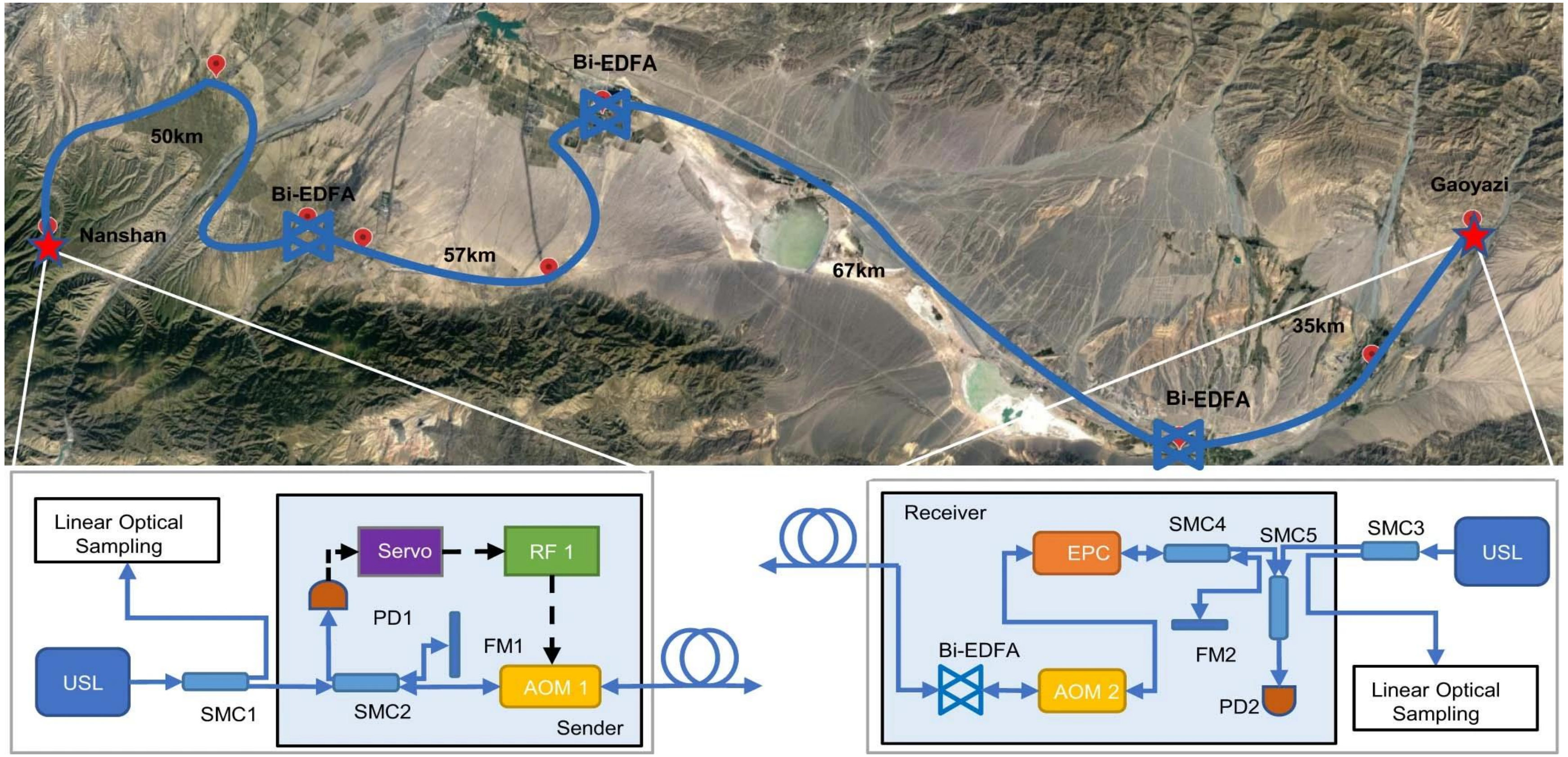


Divergence test result

209 km fiber optical frequency transfer link

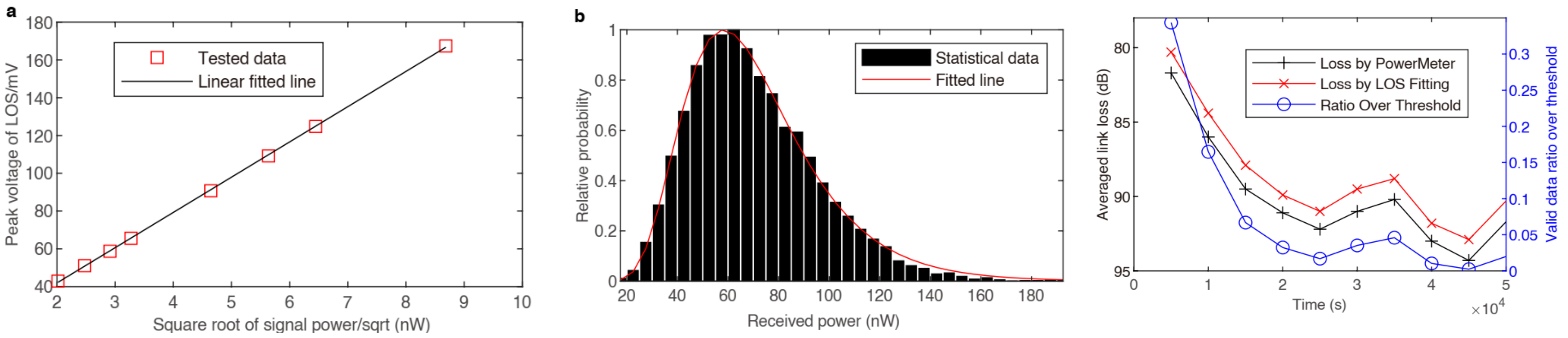
Fiber optical frequency transfer link:

- Total length 209km, which transmits the Nanshan ultra-stable laser frequency to Gaoya
- Link loss is 65dB, add 4 bidirectional amplifier to suppress the link loss: 3 in the link, 1 in the Gaoya
- Sharing the same ultra-stable laser clock with free space T/F links
- The in-loop instability of frequency transfer is better than 1E-20@10,000s



Received signal power and link loss estimation and calibration:

- Received power (nW) much less than reflected Local power, cannot be measured real time by powermeter. A power estimation method is proposed.
- Calibration: $V_{peak} + V_{offset} \propto \sqrt{P_s}.$
- Indoor calibrate: linear relation between peak voltage and sqrt Signal Power
- Outdoor estimation: log-normal distribution; the average power can be estimated by this distribution and the valid data ratio
- Verification: With sending comb power reduced, both power meter and this estimation method are compared to be consistent.



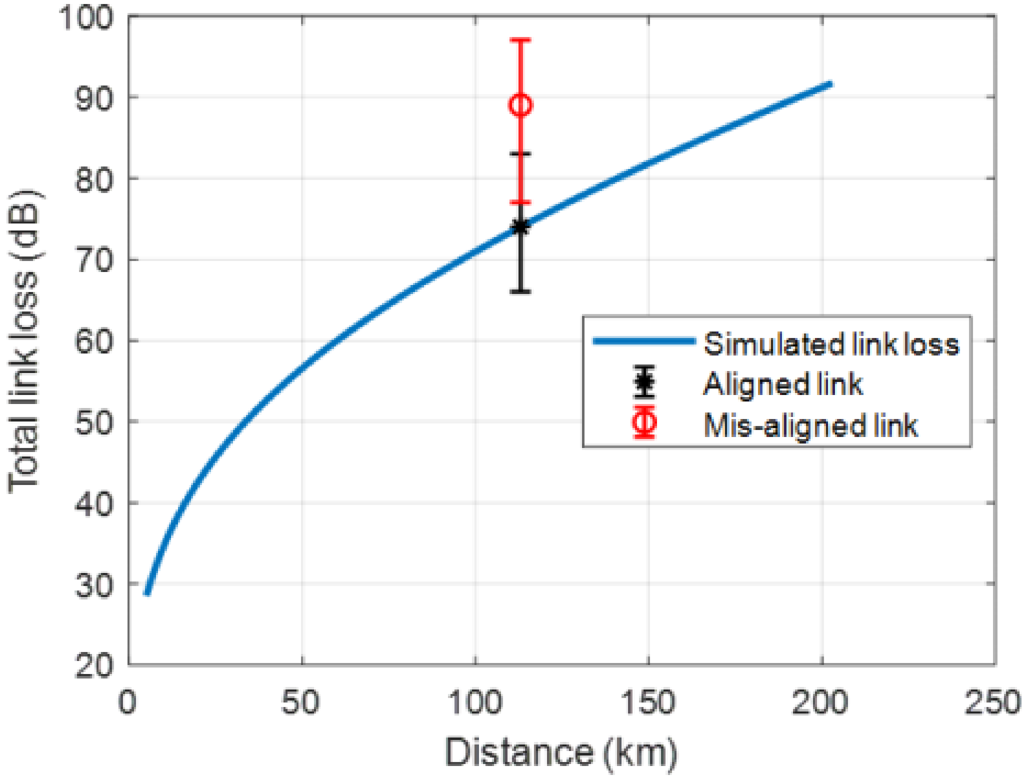
113 km point-to-point straight line free-space link

Characteristic of the 113 km link loss :

- Typical average loss 74 dB, consistent with the theoretical calculation
- $$\eta_{link} = \eta_{los}\eta_{tele\_link}$$
$$= (\eta_{los\_t}\eta_{los\_r})(\eta_{tele\_t}\eta_{geo}T_{atm}\eta_{tele\_r}\eta_{sm}\eta_{atp})$$

- the LOS optics loss of 4 dB
- the telescope optical efficiency of 4.8 dB
- the geometric attenuation of 21.8 dB
- the atmospheric attenuation of 12.5 dB
- the single-mode coupling attenuation of 27.9 dB
- the ATP loss of 3 dB
- Table 1: Input parameters for the total link calculation

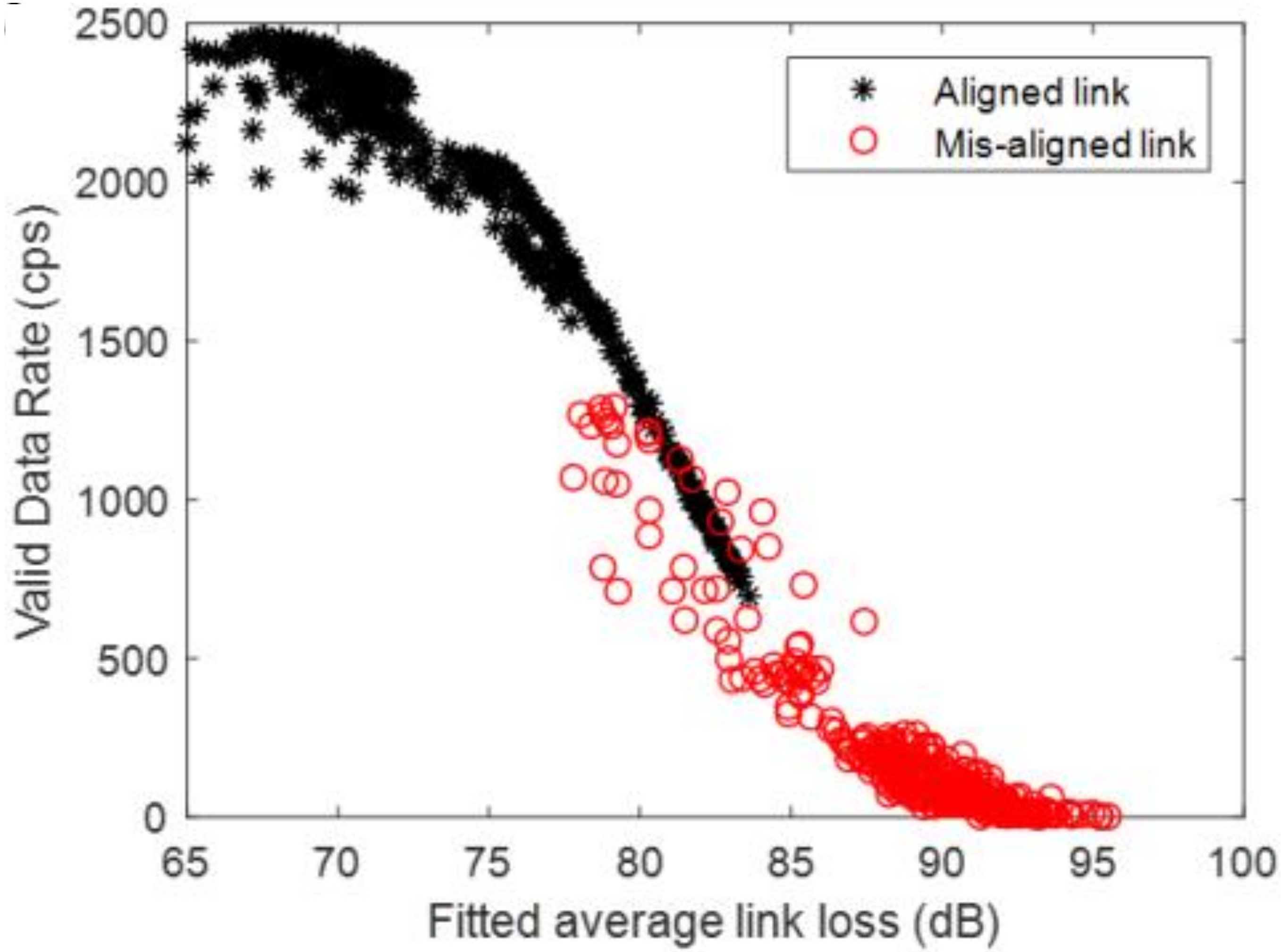
Symbols	Parameters	Values
θ_t	divergence angle	40 μrad
V	visibility	40 km
λ	wavelength	1550 nm
C_n^2	refractive-index structure	4E-16
D_r	receiver lens diameter	400 mm
f	focal length of the receiver	1.584 m
W_m	fiber-mode field radius	5 μm



113 km point-to-point straight line free-space link

Characteristic of the 113 km link :

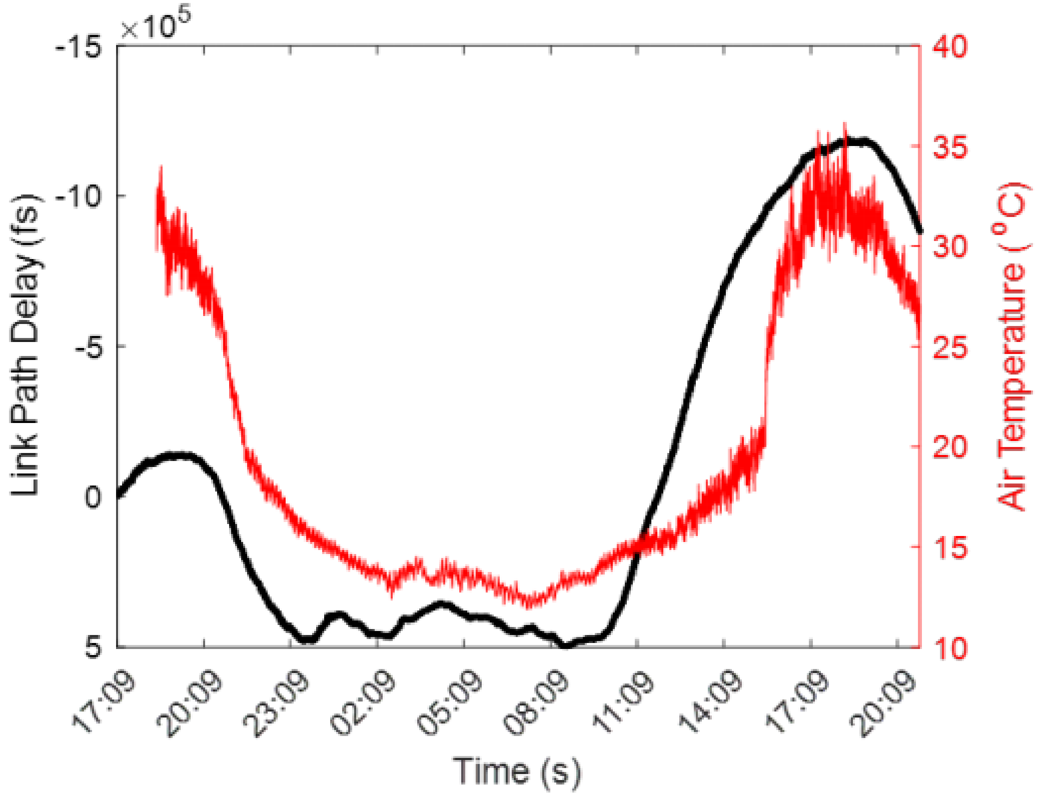
- Valid data rate reduce with loss increase;
- Received signal data rate can be 100 cps with 90 dB (1 nW)

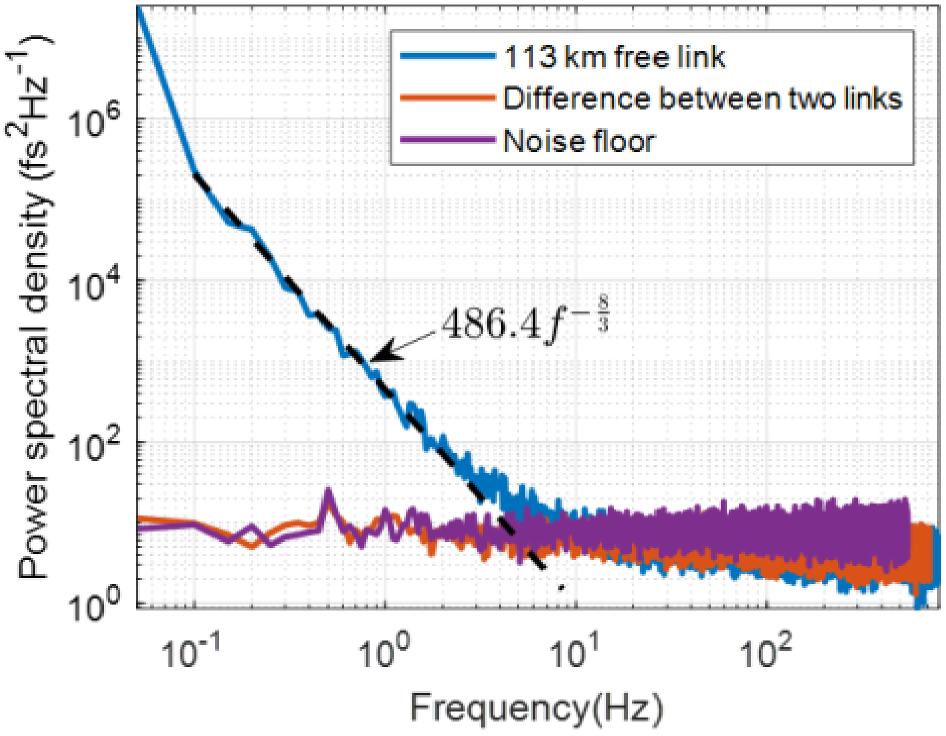


113 km point-to-point straight line free-space link

Link delay drift and PSD :

- Link delay drift: >1ns in 24 hours, mainly caused by air temperature
- Noise power spectra density (PSD) of the free link exhibits a single power-law decay at a curve consistent with proposed atmospheric model
- Residual noise of the two-way link is same as the system floor with indoor shorted-fiber

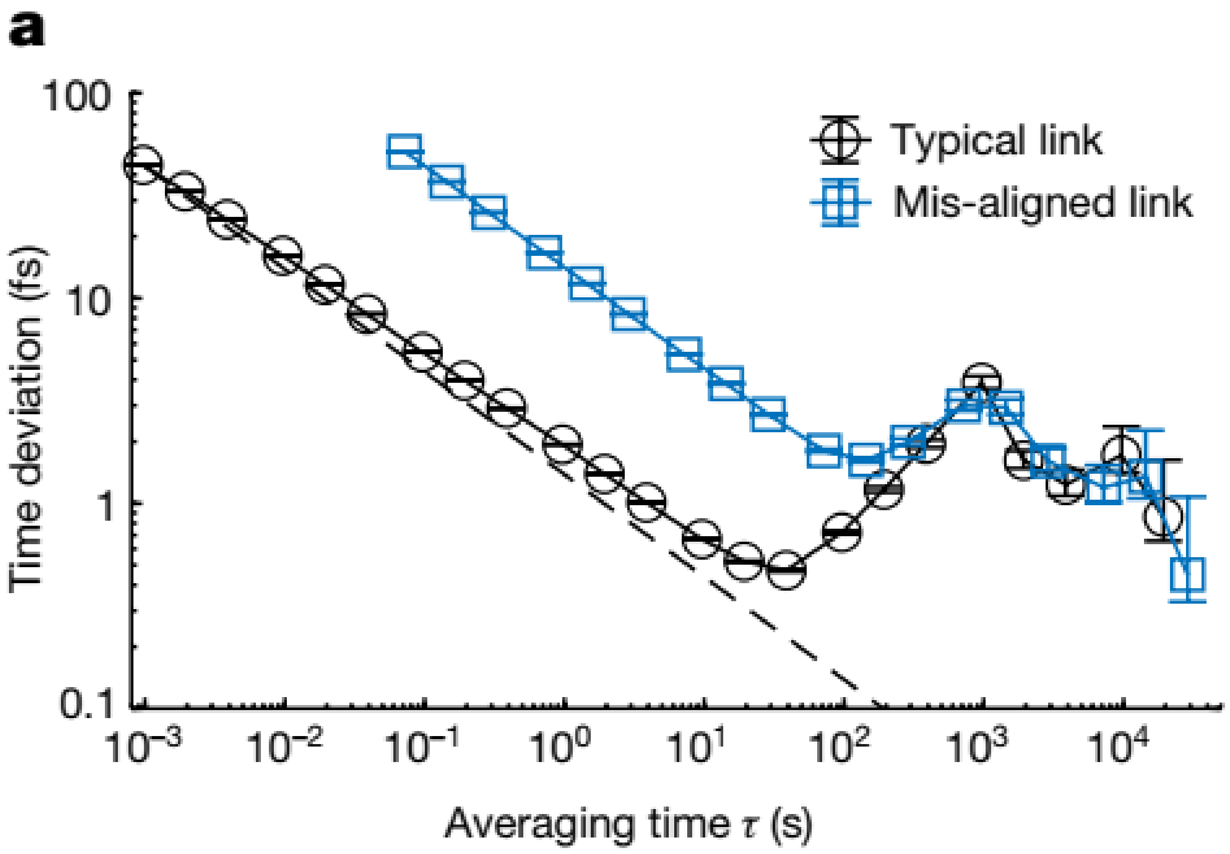




113 km point-to-point straight line free-space link

Time transfer:

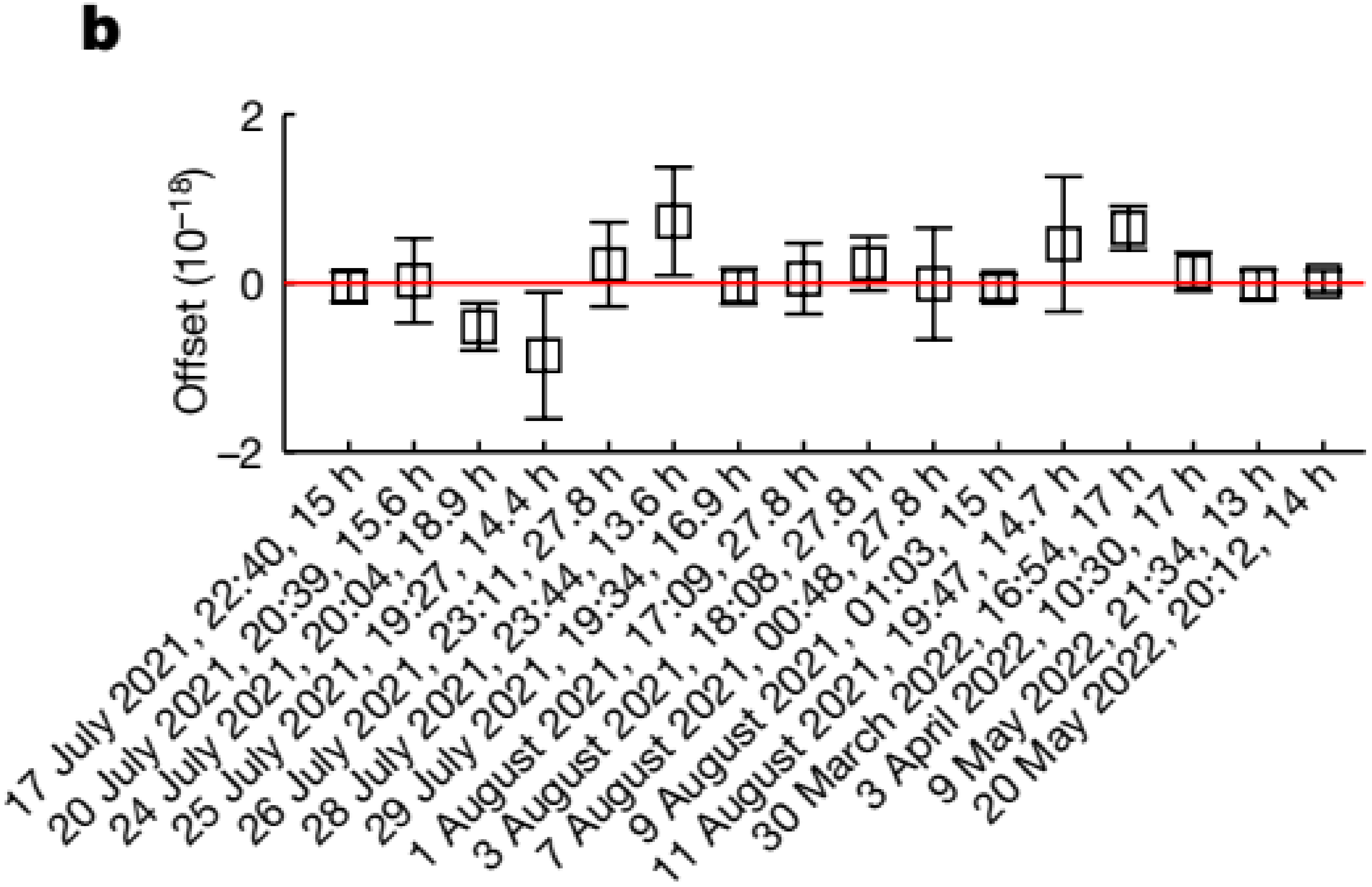
- TDEV: down to 0.5 fs at 40s from 40 fs at start
- Thermal drift limits TDEV to 1 fs, bumps around 1000 s due to air conditioner
- Mis-aligned link 89 dB; Typical link 74 dB



113 km point-to-point straight line free-space link

Time transfer:

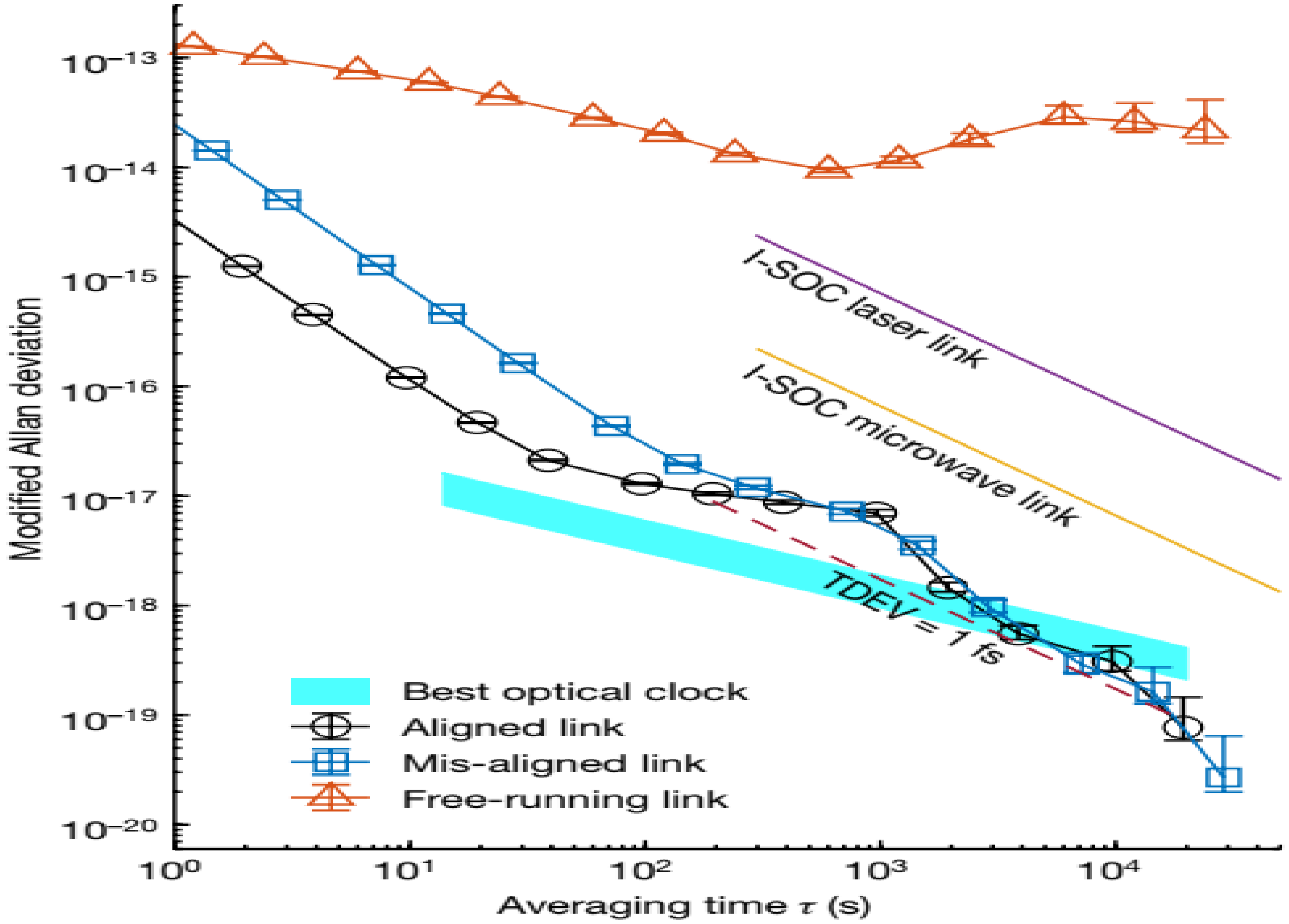
- 16 data sets, Summer 2021 and Spring 2022, 5 months
- Systematic fractional offset: 6.5E-20 $\pm$ 3.5E-19 (1σ)



113 km point-to-point straight line free-space link

Frequency transfer:

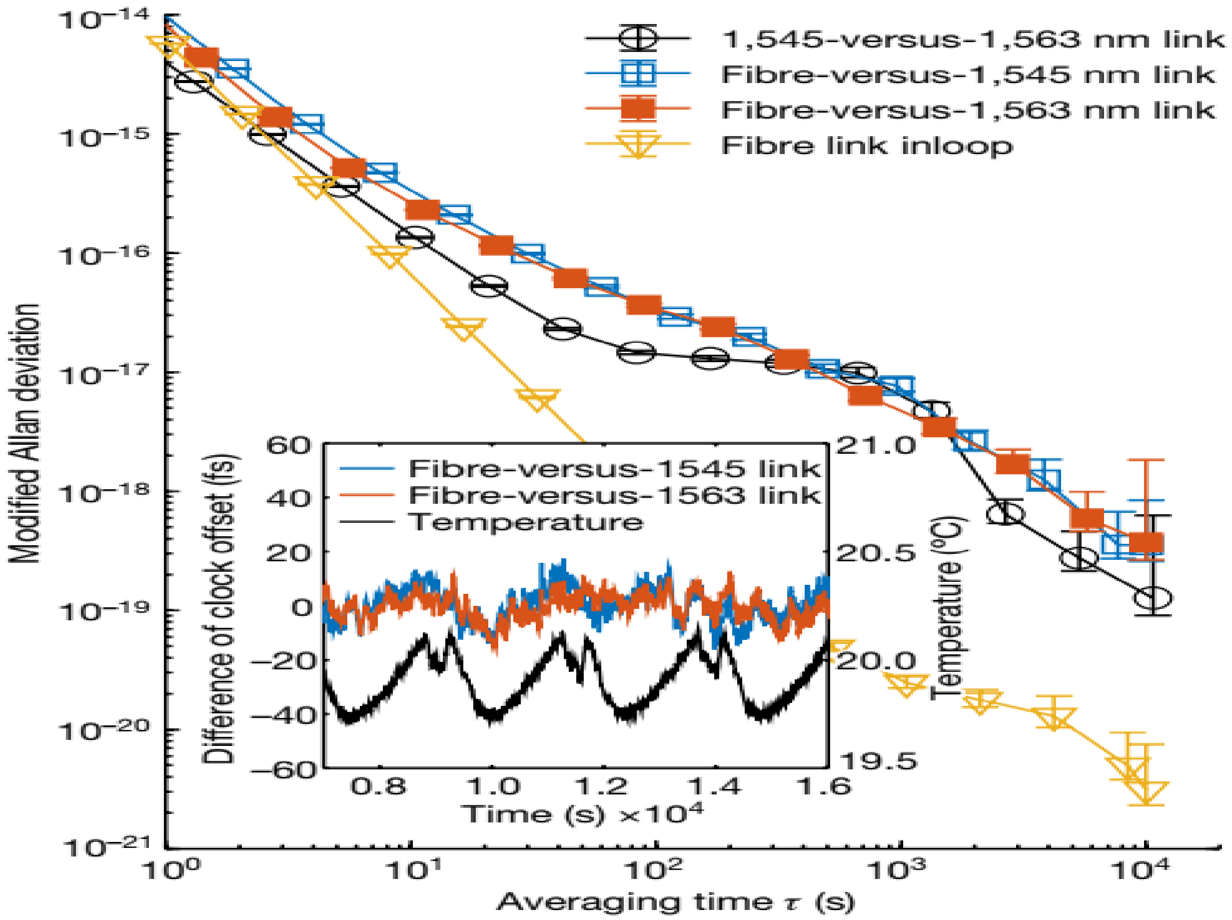
- MDEV: 2E-14~3E-15@1s;
  3E-19@10,000s;
- One way link: E-14@10,000s
- Better than optical clock after one hour
- Mis-aligned link 89 dB;
- Typical link 74 dB



113 km point-to-point straight line free-space link

Frequency transfer:

- Free-space link and fiber link results are consistent: < 4E-19@10,000s
- Thermal drift effects limit the link performance for long averaging times

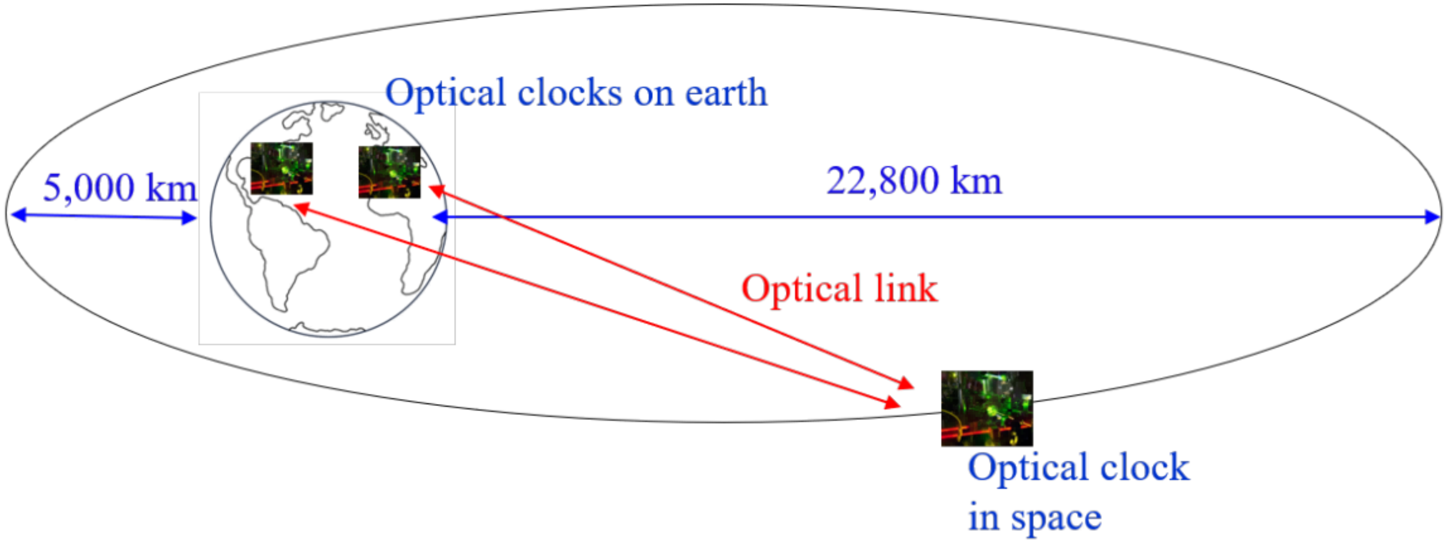


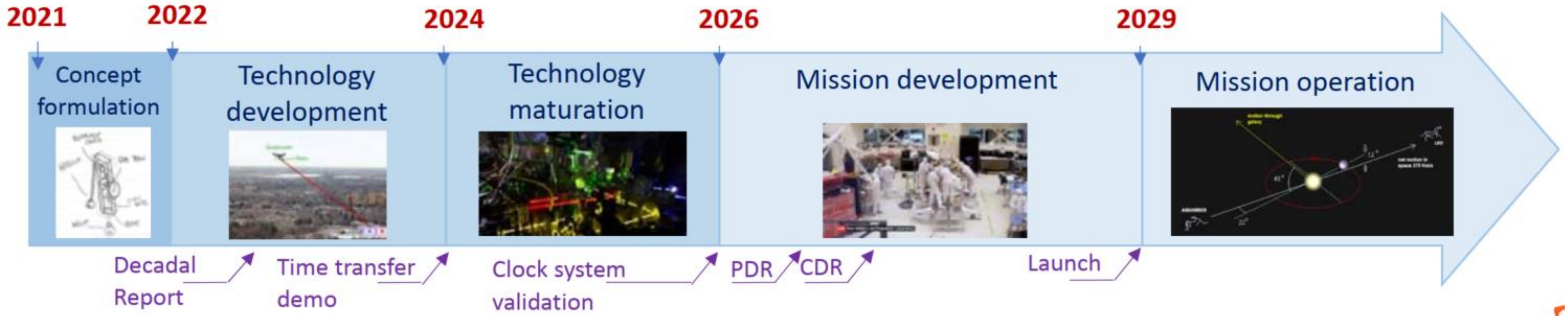
Summary

- A time–frequency dissemination over a 113 km free-space link have been implemented. The relative instability is below 4×10^{-19} at 10,000 s, whereas the link loss is up to 89 dB.
- Several key techniques have been used and verified:
  - ✓ High power low noise comb
  - ✓ High sensitive and high precision time measurement
  - ✓ High stable and high efficiency optical transceiver

Perspective

NIST/JPL（FOCOS）



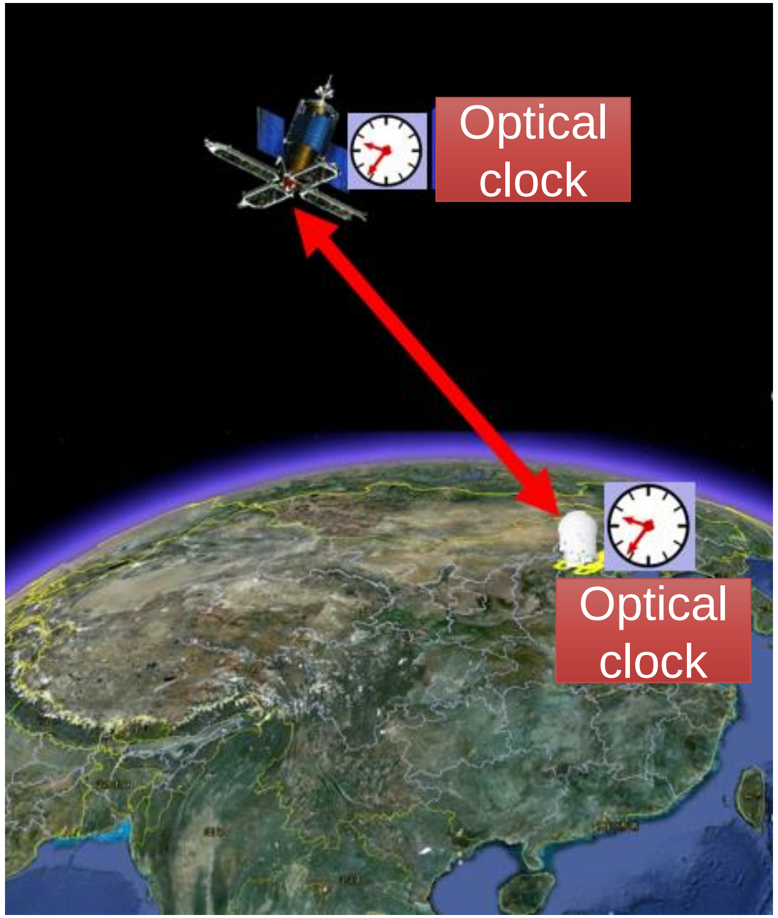


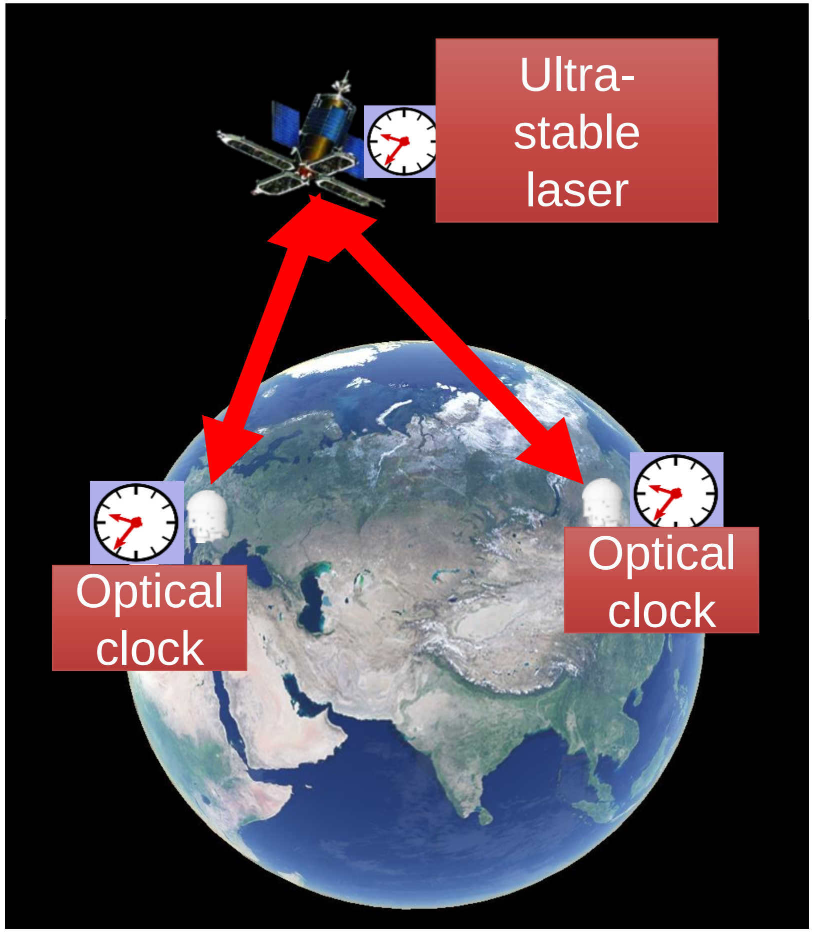
Quantum Sci. Technol. 7 (2022) 044002

Perspective

Satellite with Sr clock (<1E-17 uncertainty), OFC and two telescopes.

Launch time : 2026-2027





Satellite-ground and satellite common view optical clock comparisons at global scale

Looking for collaboration!

NIM (Beijing)
USTC(Hefei)
IATMST(Wuhan)
NTSC(Xian)

Tokyo University

SYRTE
PTB
NPL
……
Australia
Singapore
Hawaii

Email: hjiang1@ustc.edu.cn

Acknowledgements

113 km

NanShan

Gaoyazi

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The end,
Thank you for your attention!