Free-Space Optical link via a balloon for clock comparison

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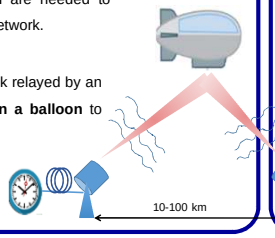
Abstract

Current optical clocks reach incertitude levels as low as 10^{-18} in terms of fractionnal frequency. In the meantime, work is on the way to make them transportable.

Numerous applications will take advantages of such characteristics, such as **chronometric geodesy**, that will enable geopotential mapping over a region with centrimetric level acuracy.

Transportable, flexible and easily deployable optical link over 10 to 100km are needed to supplement the fibre metrology network.

We develop such a free space link relayed by an **optical transceiver mounted on a balloon** to avoid line-of-sight obstruction.



1. Introduction and State of the art

TOFU: **U**ltrastable **O**ptical free space **F**requency **T**ransfer, via the phase of a continuous 1542nm laser.

Free space optical (vs. fiber) link → high **phase and power noise levels and bandwidths** :

- **Atmospheric turbulence** ($\Delta f/f \sim 10^{-13}$ up to 500Hz)
- Balloon & payload motion (**Doppler effect** $\Delta f/f \sim 10^{-11}$)

TOFU folded link to a balloon

- Retroreflector onboard the balloon = passive payload
- Emitter & receiver co-located => easy local phase noise verification
- Reaches **8.10^{-19} uncertainty after 20s integration time [1]**

Next step: build an active flying terminal

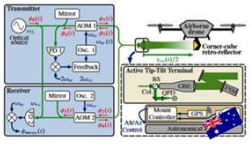
- Onboard power coupling into a fibre
- Point-to-point architecture
- Opens the way for a 3-point operational architecture

Worldwide demonstrated free space links :

- Point-to-point vs. folded
- Ground to ground vs. ground-air
- Continuous vs. pulsed laser

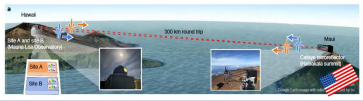
Shen et al, 2022

113km point-to-point link (type I) between 2 static terminals with 89dB power loss. Time & frequency transfer. Reaches 10^{-19} frequency instability using optical frequency combs.



Dix-Mathews et al, 2023

1.3km folded link (type III) to a corner cube onboard a flying drone. Frequency transfer via a continuous laser's phase, reaching $2.5.10^{-18}$ fractionnal frequency stability after 3s integration time, despite drone motion up to 0.3m/s.

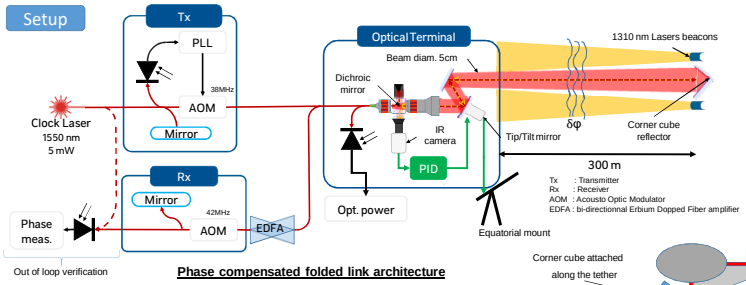


Caldwel et al, 2023

300km round trip folded link between two closely located (type II) optical terminals. Time and frequency transfer using frequency combs.

2. Phase-stabilized folded link to a balloon

Setup



Phase compensated folded link architecture

Airborne payload

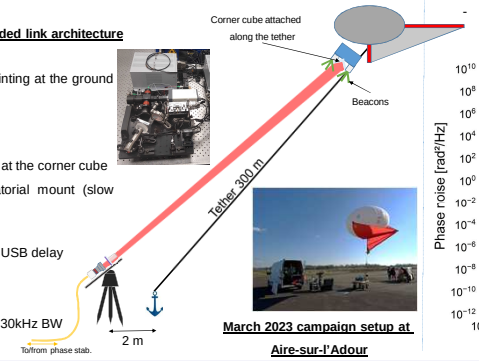
- Corner cube aligned with the tether for passive pointing at the ground terminal
- 4 laser diode beacons with λ=1330nm

Optical terminal

- Common Tx & Rx transceiver : fine optical pointing at the corner cube
- Actuators : tip-tilt mirror (+/-1mrad HF) + equatorial mount (slow motion)
- IR camera : beacons image acquisition (200fps)
- Pointing bandwidth **limited at 25Hz** due to camera USB delay

Phase stabilization unit

- Michelson unbalanced architecture
- Digital Phase Lock Loop (D-PLL) + AOM actuator : 30kHz BW
- Rx and Tx co-located => out-of-loop verification



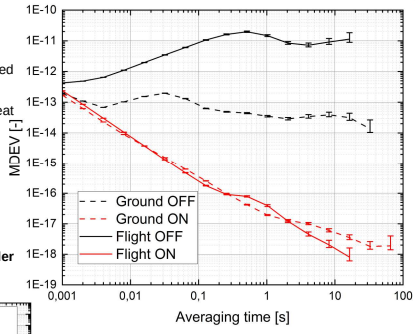
March 2023 campaign setup at Aire-sur-l'Adour

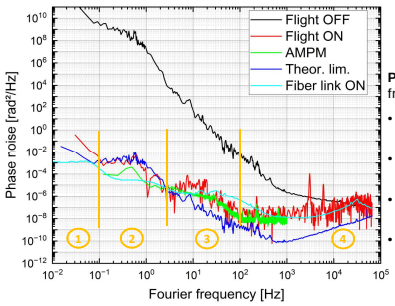
Results

Phase stabilization

Up to 20-minute long phase time series were acquired during the campaign with no power loss.

- System performance : MDEV of the out of loop beat note fractional frequency
- Reaches **8.10^{-19} after 20s** integration time, **PLL ON**
- 300m ground link for horizontal/vertical comparison
- Open loop main phase noise source :
  - GROUND : air index fluctuations (**turbulence**)
  - FLIGHT : balloon & payload motion (**Doppler effect**)





Noise characterization

Phase noise power spectral density reveals the link's frequency stability limiting factors:

- **Phase noise correction delay**: fundamental limit reached between 0.1 and 3Hz (2)
- **Thermal uncompensated effects**: below 0.1Hz (1), e.g. in the out-of-loop measurement fibre
- Amplitude to noise conversion (**AMPM**) between 3 and 100Hz (3), due to mixing in the measurement chain
- At higher frequencies (4), the PLL itself is limitating (as compared with a 300m fiber link).

3. Active airborne terminal flight tests

Next step : *active terminal* onboard the balloon

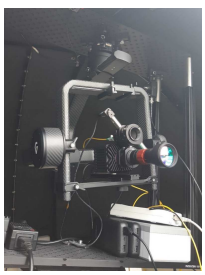
→ couple the received laser beam into a monomode fibre

→ Tests at Aire-sur-l'Adour August 2024

Terminal design

- Commercial **gimbal** : 2-axis pointing actuator
- Visible camera : ground beacons imaging
- µ-computer
- Fibre collimator + photodiode
- 1330nm laser beacons

Max. weight : 8kg (balloon limitation)



Setup

Results

Functional tests

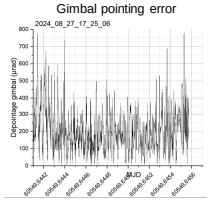
- Software, power, wifi control
- The gimbal remains locked to ground station for hours of operation

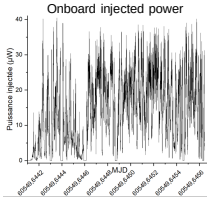
Laser power stabilization

- Depending on weather conditions
- → Better with constant stable wind
- Gimbal max depointing +/-1mrad
- → 500µrad required
- → Frequent power extinctions

Campaign rex

- Need for a second pointing stage
- Ground terminal limitating too





4. Coming next

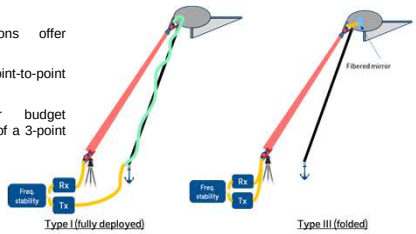
Next step : **March 2025**

Goals :

1. **Onboard tip-tilt mirror** design
2. **Ground functionnal tests** : TT ability to compensate for gimbal pointing error
3. **In flight tests** at Aire-sur-l'Adour
4. Try & attach a **fibre along the tether**
5. **Point-to-point phase stabilization** (with fully deployed & folded architectures)

Both configurations offer advantages :

- I : genuine point-to-point link
- III : power budget representative of a 3-point link



[1] Maron Nicolas, Fernandez Sébastien et al., "Free space optical link to a tethered balloon for frequency transfer and chronometric geodesy," Opt. Express **32**, 4267-4276 (2024)