Free-Space Optical link for clock comparison

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Abstract

The emerging generation of optical clocks holds great perspectives for fundamental physics and open up new fields of applications, such as chronometric geodesy. These clocks, reaching residual frequencies instabilities in the low 10^{-18}, required means of comparison in the optical frequency domain. Mainly optical fiber links can reach sufficient performances, but are the limiting factor for applications in need of reconfigurable, rapidly deployable or in space links.

Our work aims to demonstrate a ground-to-ground stabilized free-space optical link via an airborne relay. We are currently working on a 600 m folded free space link, achieving stability of 10^{-18} after 20 s of integration, and on it's airborne version.

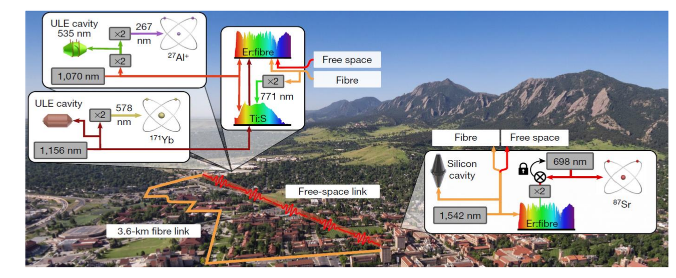
This Poster present our link design and results as well as development perspectives toward our end goal.

1. Introduction and State of the art

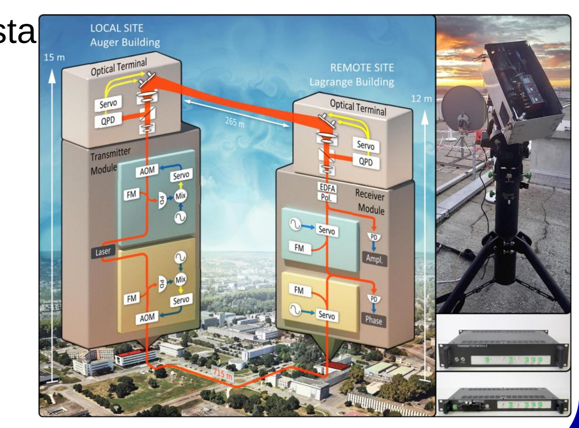
- Such link might be used for fundamental physics tests, chronometric geodesy (comparing clocks with 10^{-18} stability → retrieve geopotential with 1 cm elevation resolution), time and frequency metrology
- This link will be useful to compare transportable optical clock (currently in development)
- Main Difficulty : overcome airborne carrier motion and atmospheric turbulences by optical path and phase compensation
- Our work is split in smaller experiments that decompose the final ground-to-ground via airborne relay link.

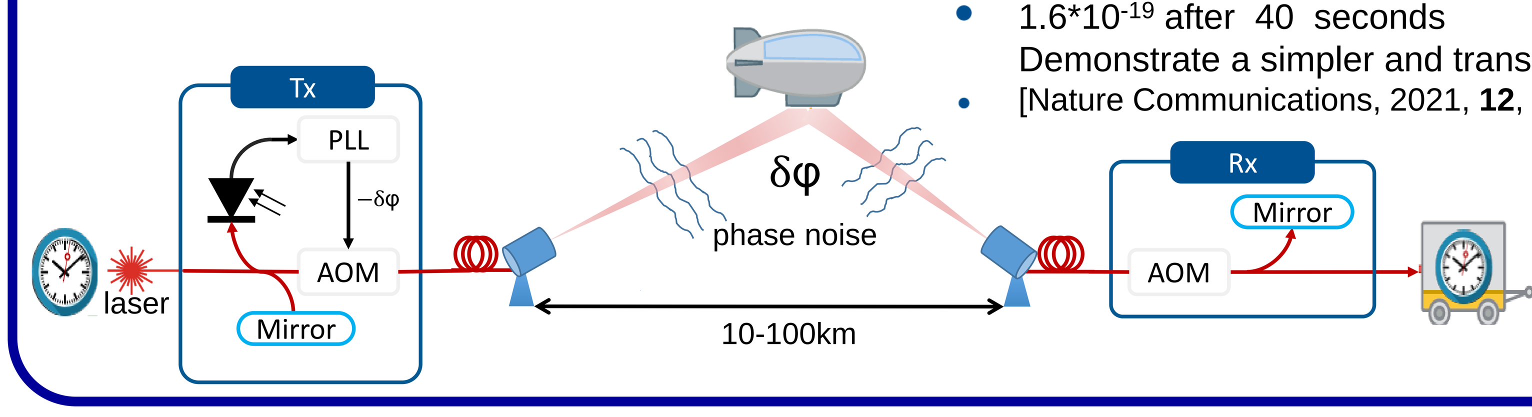
Point-to-point links demonstrated

- NIST
  Frequency comb free space link span over 1.5 km and reach 10^{-18} instability after few hundred seconds
  Used to compare two clocks in a network of three
  [Nature, doi : 10.1038/s41586-021-03253-4]
- Folded link on a flying quadcopter
  [Nature Communications, 2019, 10, 1819]

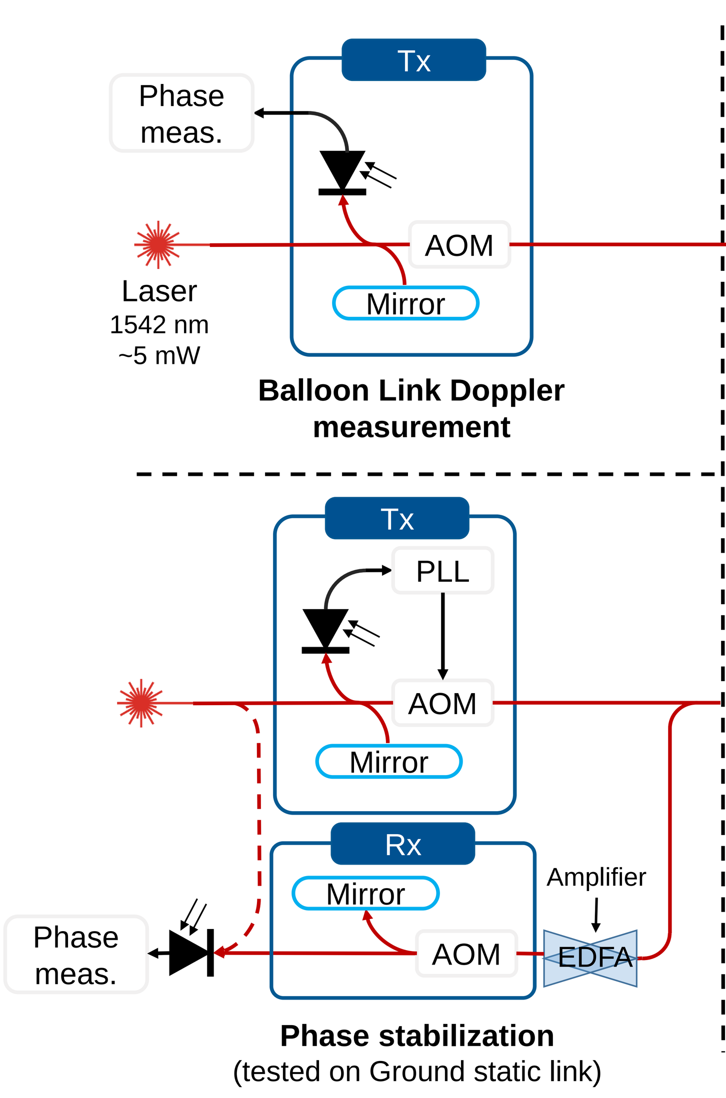


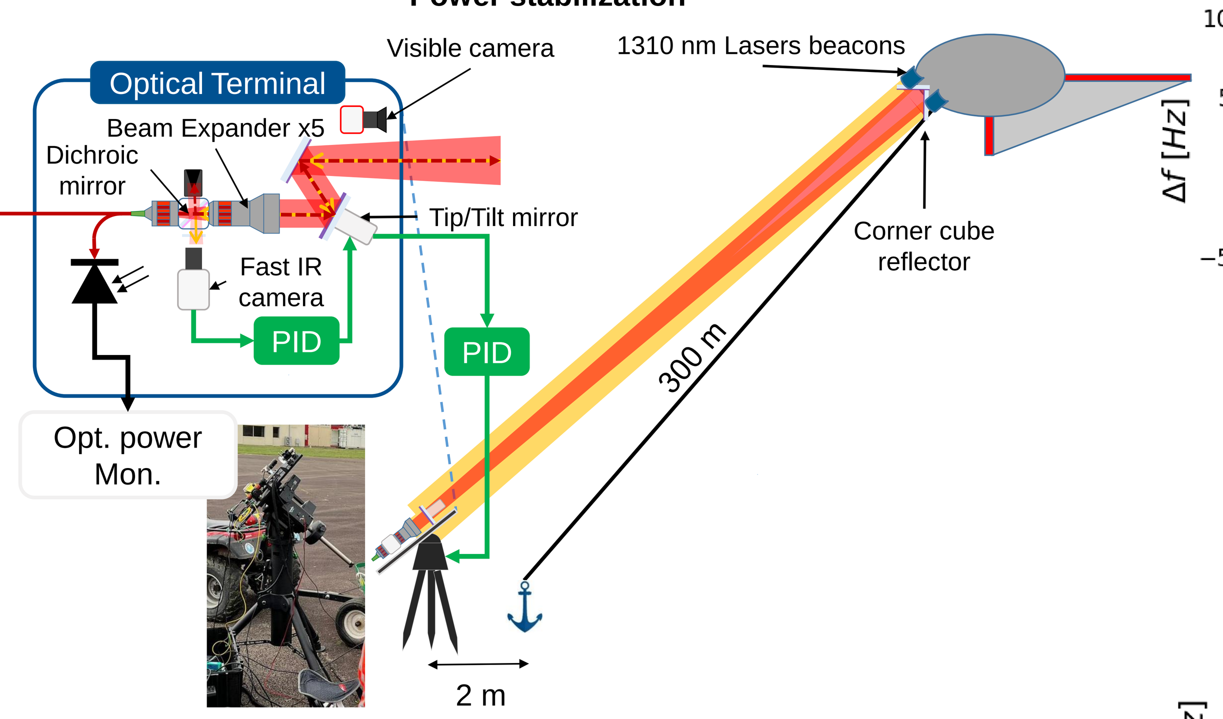
- KAIST
  Coherent frequency comb free-space link span over 1.4 km and reach instability of 10^{-18} after few tens of seconds
  [Optics Communications 504 (2022) 127481]
- UWA/CNES/SYRTE
  Coherent free-space link span 300 m and reach instability of 1.6×10^{-19} after 40 seconds
  Demonstrate a simpler and transportable design
  [Nature Communications, 2021, **12**, 515]





2. Free-Space Folded Link



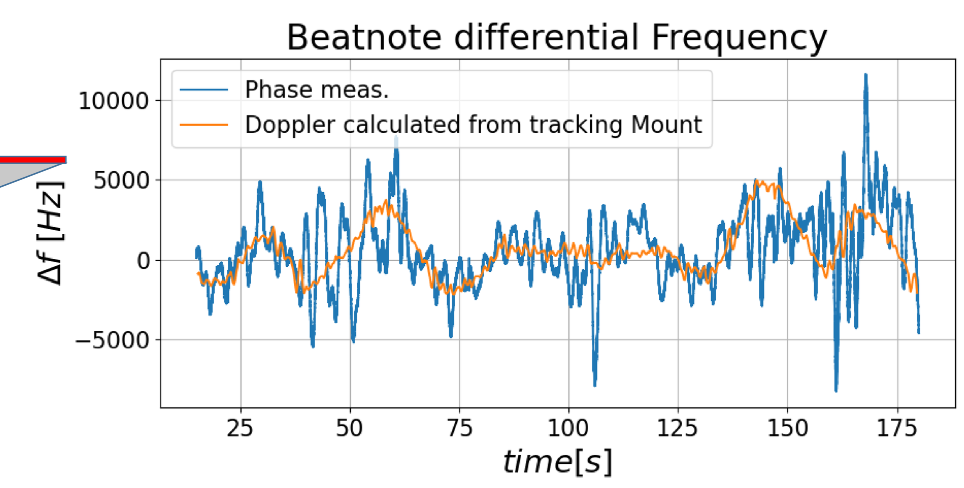


A visible camera with a large field of view (6 °) is used for target acquisition.

A Tip/Tilt mirror is used to compensate low frequency atmospheric turbulences and to track target motion (fast tracking). It is driven by a fast IR camera (1° field of view)

Our Terminal is build on an astronomical mount to ensure the target is always in the reach of the Tip/Tilt mirror (slow tracking)

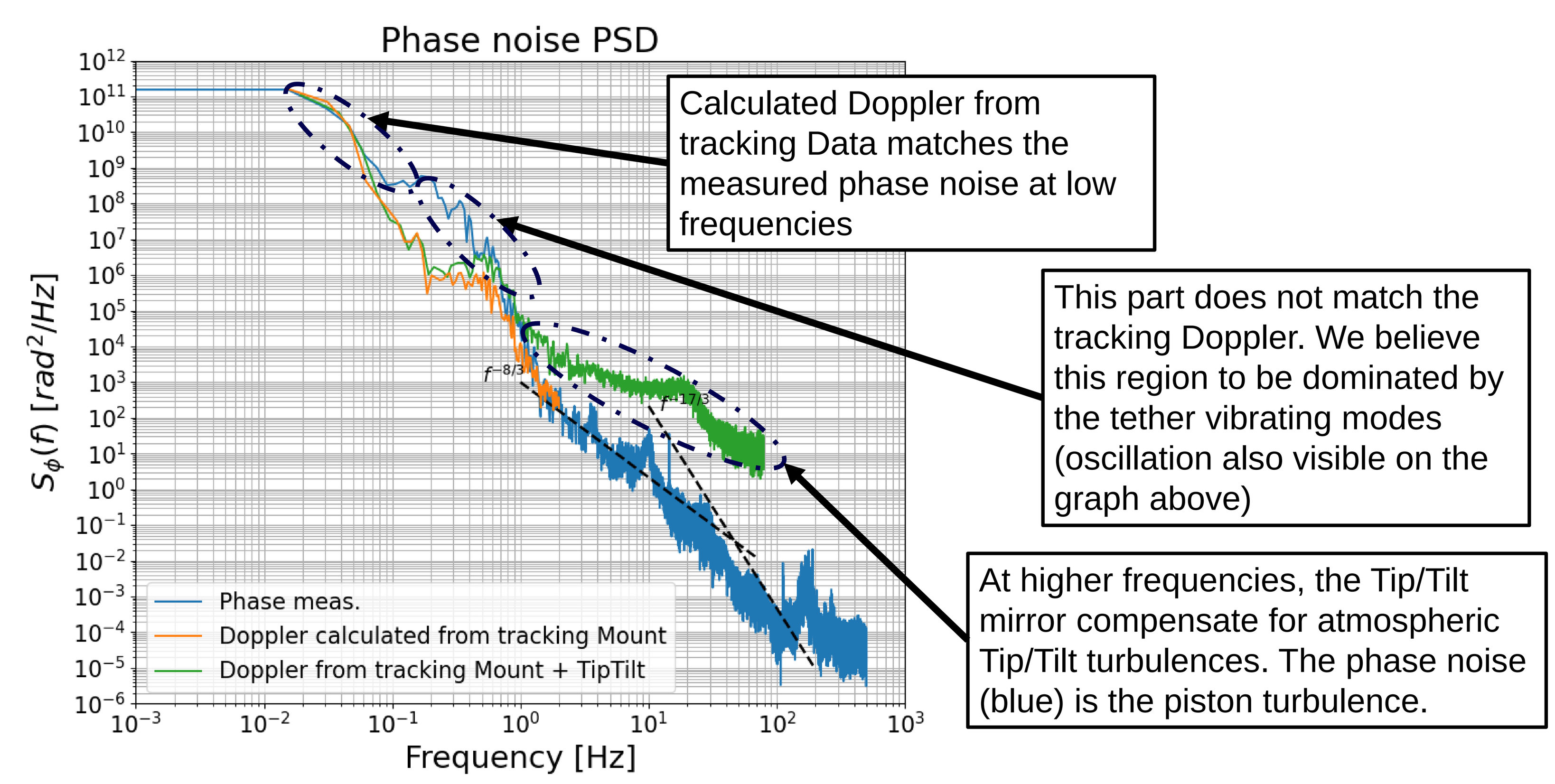
Frequency transfer is based on conventional fiber link with active compensation (Unbalanced Michelson). The phase noise δφ accumulated in the link (long arm) is measured by a heterodyne detection against a local short arm. A phase lock loop (PLL) then compensate it by driving an acousto-optic modulator accordingly. (see diagram in Introduction)

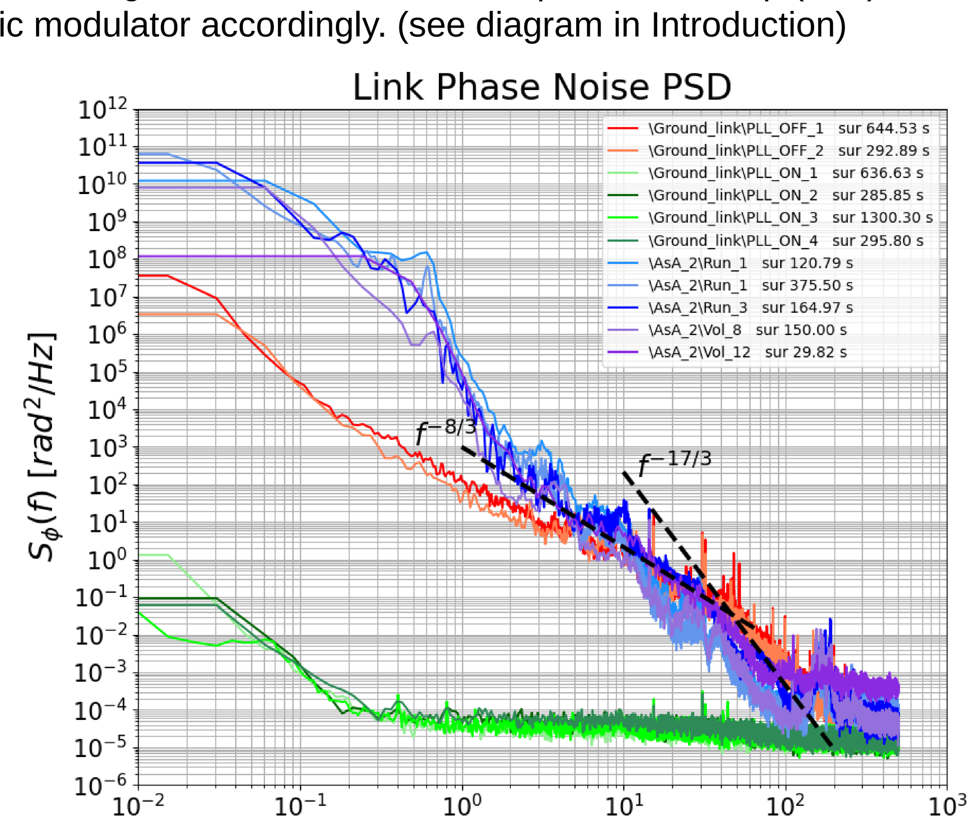


On the two graph here, we focus on a balloon link data.

Given the link geometry and tracking data, one can calculate the Doppler effect induce by the balloon motion.

We



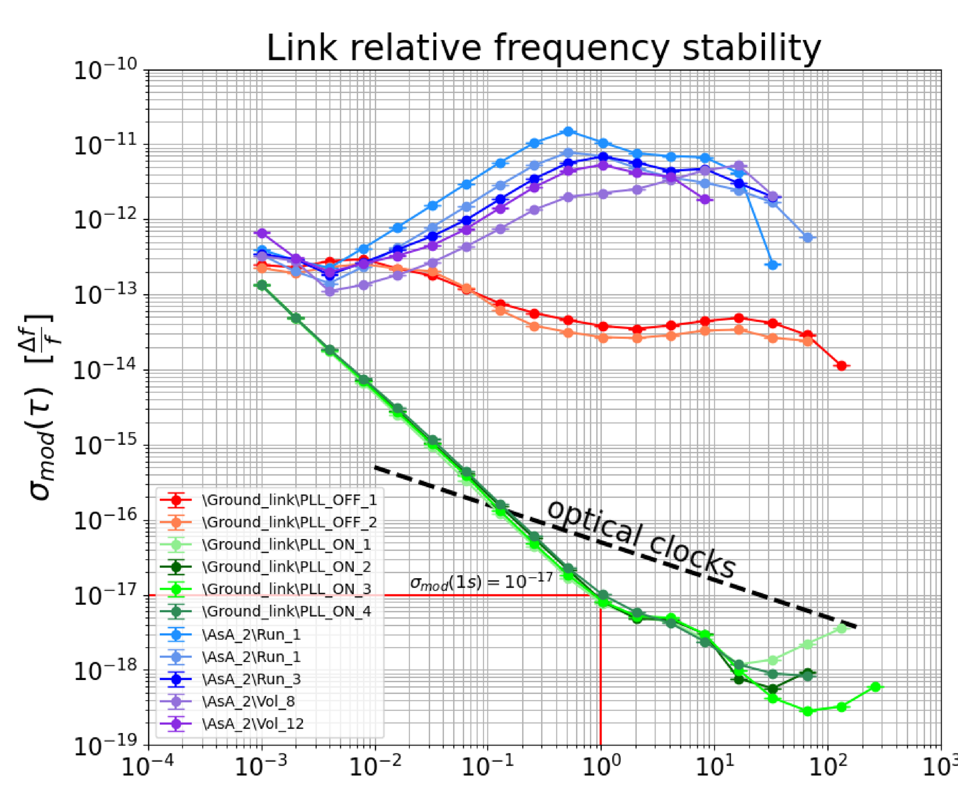


We were unable two use the phase stabilization on the balloon link due to power constraint. Instead, we use a simpler approach that still allow us to measure an uncompensated Balloon link.

We observe on the phase noise measurements of the balloon link (shades of blue) two power law slopes as expected by Kolmogorov turbulence theory ([doi : 10.1364/JOSAA.12.001559])

For comparison, are depicted here data from our Ground static link, with either the phase stabilization off (shades of red) or on (shades of green)

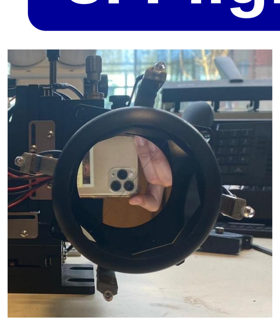
The flattening after 100 Hz is due to aliasing inherent to our phasemeter behavior.



The stabilized link has a residual frequency instability of 10^{-17} after 1 s and reaches 10^{-18} after 20 s of integration

After a few s of integration, the phase stabilization is hitting a thermal limitation. The system is thermally regulated but this part has room to be improved.
Still, the current performances on the static link (shades of green) are sufficient to compare distant optical clocks.

3. Flight payload



Demonstrating a folded link with an airborne corner cube reflector (CC) :

- The carrier is a 16 m³ Helikite, Balloon/Kite Hybrid.
- The laser beacons we use have a ± 10 ° angular emission lobe. (CC has ± 20 ° acceptance angle)
  → need a control to aim toward the on ground terminal
- The payload is equipped with 4 laser beacons.
  The payload is detected on the terminal camera using a barycenter algorithm.
  → mitigate CC rotation along its optical axis impact on the detection (power loss while using a single beacon)
- CC is mounted onto a rigid stick, which is inline between the balloon and its tether, ensuring that the CC is always roughly pointing toward the balloon anchorage point.
- Placing the ground terminal close the anchorage point ensure to stay within CC acceptance angle.

4. Outlook and conclusion

- The folded nature of our link implies that the science signal transmitted travel four times in the same portion of turbulent atmosphere instead of only twice on point-to-point link, for which the phase stabilization system is designed for. This potentially impairs the phase stabilization system.
- Furthermore, the corner cube implies almost perfect link geometry reciprocity. The point-to-point will potentially introduce non reciprocal optical paths, consequently degrading the phase stabilization performance.
- Our approach demonstrate a simpler architecture compare to free space frequency transfer links relying on frequency comb, yet yielding very comparable performance in term of residual frequency instabilities (10^{-18} after 20 s of integration, already sufficient for optical clock comparison) albeit on short static link.
- A disadvantage of our system compare to frequency comb techniques is the sensitivity to signal outages (deep fades) and corresponding phase loss.
- The first folded uncompensated link on a balloon was conducted successfully. Our next campaign is in preparation, this time we should have a phase stabilized link on the balloon.
- A light weight airborne terminal with active pointing will be required
- A fiber could be run along the balloon tether to stay within small balloon weight payload capacity (laser and phase stabilization system located on ground).

Up to date as of 22/09/2022