TERRE - OCÉAN - ESPACE

Time/Distance metrology
based on free-space lasercom link

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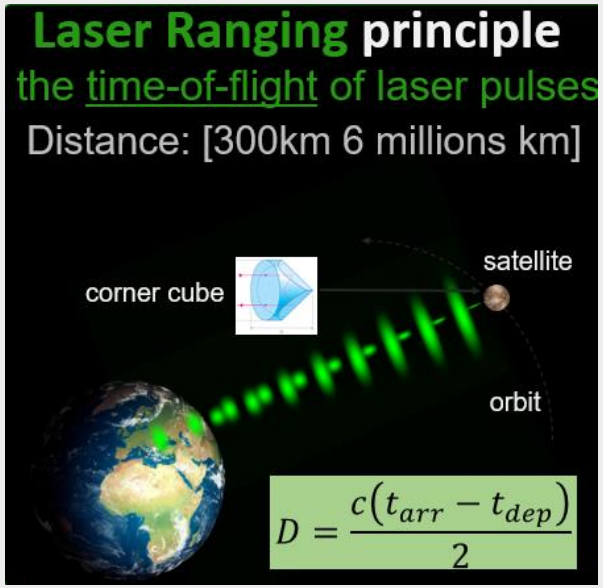
1. MeO Optical Ground Station – Sciences

- **Satellite Laser Ranging**
  (GNSS, Geodesy Satellites, Debris …)
- **Lunar Laser Ranging**
  (Moon Reflectors + LRO)
- **Time Transfer by Laser Link**
  (T2L2, Chomptt, **LRO**, **Hayabusa, ACES**…)
- **Satellite – OGS LaserCom**
  (SOTA, OPALS, **OSIRIS**, NorSatTD…)
- **QuantumCom demonstration**
- **Imaging / Astrometry**
  (Adaptive Optics, Intensity Interferometry)
- **T/F transfer by Fiber network**
  (**T-Refimeve** European fiber network)

1. MeO Optical Ground Station – Ranging Performance



Classic SLR system

- Laser Pulse rate : 5 Hz – 1 kHz
  Pulse width : 10 – 100 ps
  Power : several W
- Detection : Single-Photon PhD
  Event Timer
- Clock : 100 ns / UTC
  $\Delta f/f < 10^{-14}$

⇨ **[300km – 380 000 km]**
Accuracy ~ 10 mm
sensitivity ~ few mm

Limited by

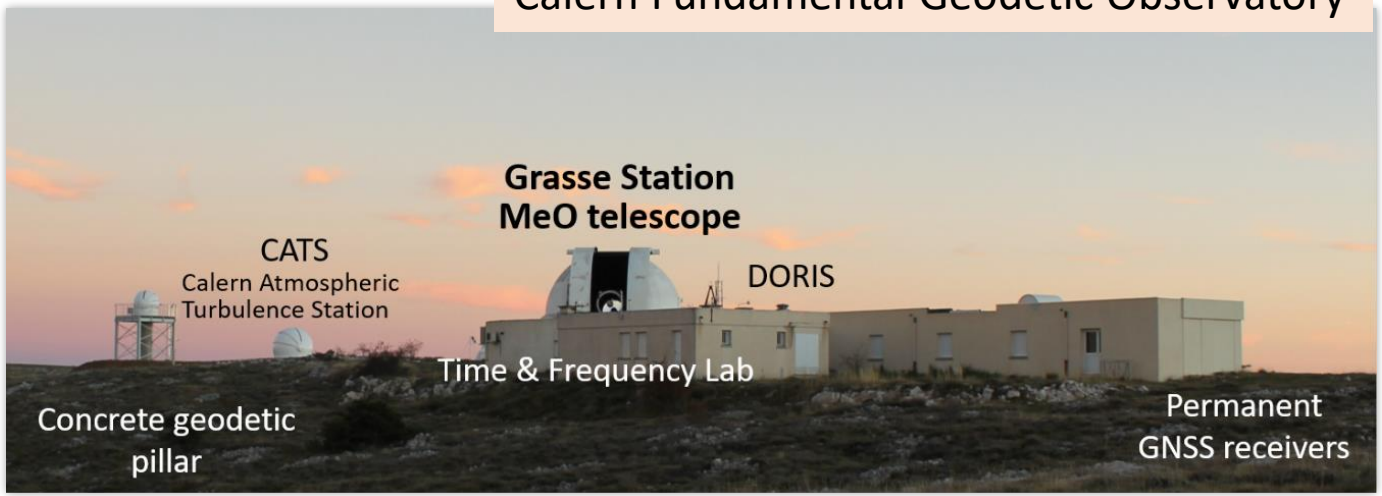
- Earth's atmosphere model
- Laser & detection system

GGOS needs: millimetric accuracy for global positioning

⇨ **improve measurement sensitivity at short time range (ms)**

& perform laser ranging at two-color

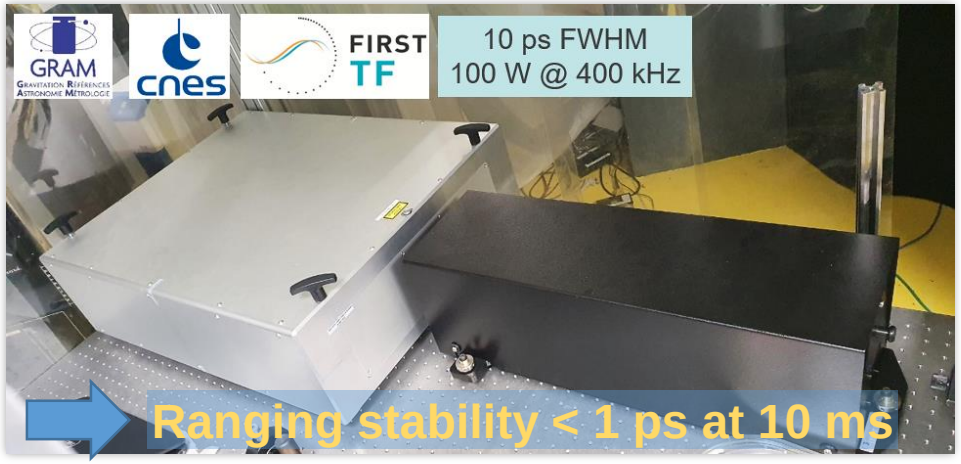
Calern Fundamental Geodetic Observatory



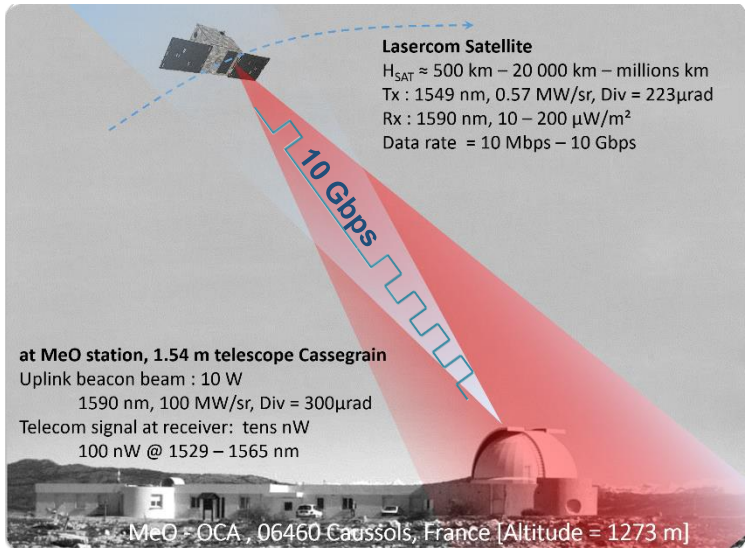
1. MeO Optical Ground Station – Ranging Performance

➔ SLR at High rate (up to 100 kHz – MHz)

- ✓ 10 ps, 400 kHz laser pulse
- ✓ High-speed SPAD
- ✓ High-speed event-timer



➔ Laser ranging based on free-space laser communication (lasercom)



10 Gbps

Laser Pulse rate : 5 GHz >> 400 kHz
Pulse width : 100 ps

Flexible Data format or modulation code

& multi-channels 850 nm, 1310 nm, band C

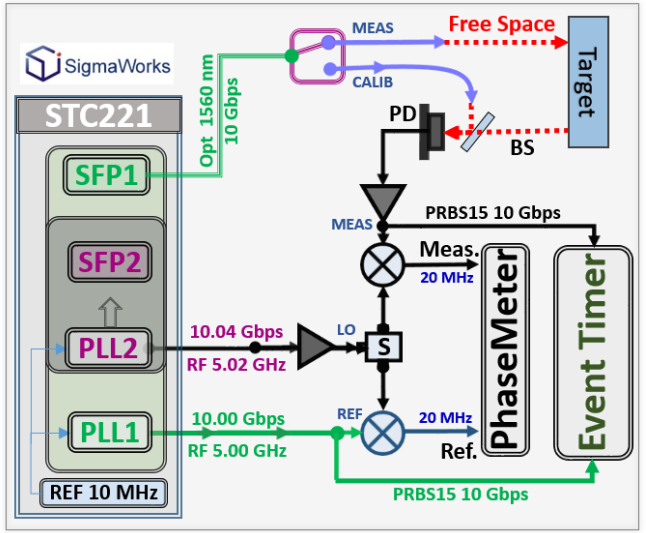
FIRST TF cnes

MetroCom
high-resolution & high-accuracy time/distance measurement from lasercom

2. MetroCom – Measurement principle

Using lasercom signal,
Combining
Phase (10 Gbps, Λ = 60 mm)
→ relative, resolution ~ µm
Time-of-Flight (10 Gbps)
→ absolute, resolution ~ 10 mm

➔High sensitivity + absolute distance measurement



Optical/Electrical High-speed Switch
SFP1 Telecom module optical source
PLL1 Phase-Lock-Loop RF electrical source
PD Photodiode Telecom detector
BS Optical Beam Splitter
S Electrical Splitter
Amplifier
Mixer

Phase Measurement

OOK 101010... debit = 10 Gbps
REF
MEAS
Demodulated + Filtered
PhaseMeter
➔Phase difference
$\Delta\varphi = (\varphi_{Meas.} - \varphi_{Ref.})$
Relative distance
$2 \times \Delta d = \frac{c}{n \times debit/2} \times \frac{\Delta\varphi}{2\pi}$

Time-of-Flight-Measurement

PRBS 1001011010... 10 Gbps
REF
MEAS
Synchronization pic generation
Event Timer
➔Time tagging stop-start
$\Delta t = [t_{start} - t_{stop}]$
Absolute distance
$2 \times d_{tof} = \Delta t \times \frac{c}{n}$

High sensitivity absolute distance

$d = \Lambda \times \left\{ \left\lfloor \frac{d_{tof}}{\Lambda} \right\rfloor + \frac{1}{2} \times \frac{\Delta\varphi}{2\pi} \right\}$ with $\Lambda = \frac{c}{n \times debit/2}$

The core material, STC221+301 developed by SigmaWork, generates 10 Gbps signals for both measurements (phase and ToF)

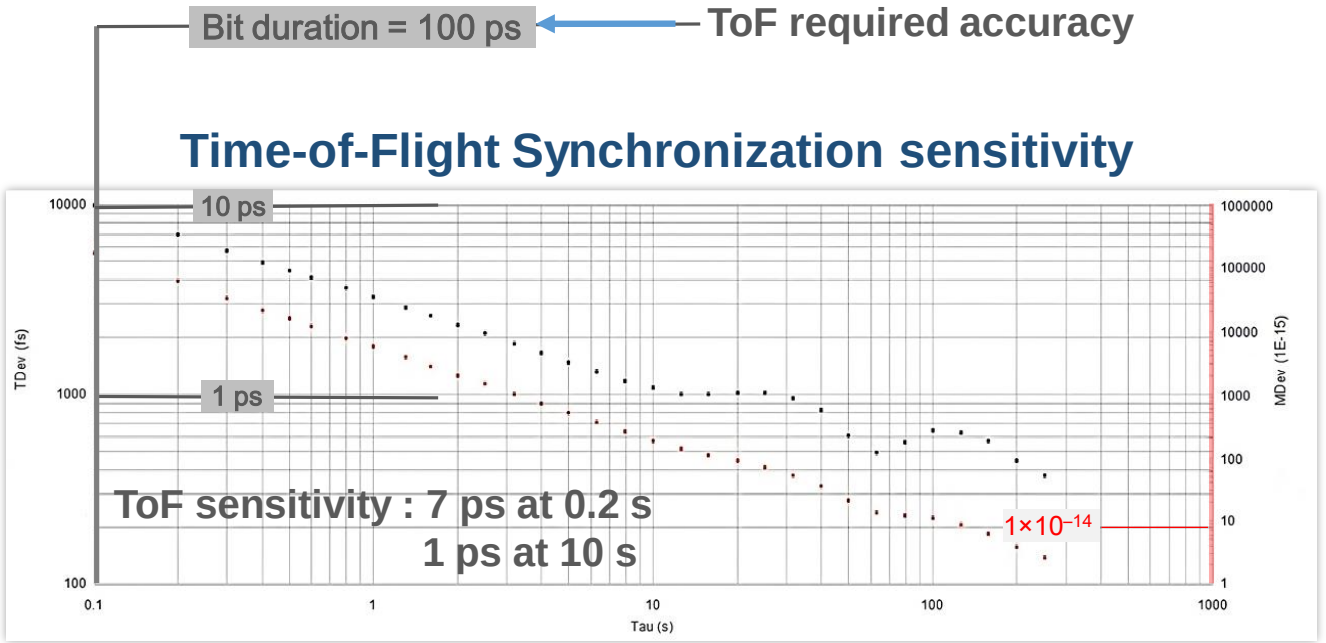
- ✓ Laser source for both measurement is telecom source SFP10G (COTS)
- ✓ Data format + bit rate are programmable by FPGA
- ✓ Time-of-Flight measurement is performed by the same instrument

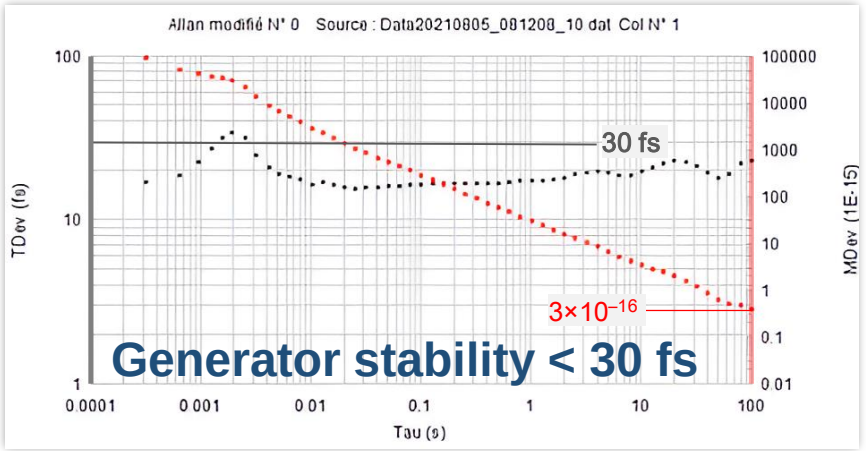
⇨ Telecom signal generator + synchro with low phase noise, synchronized with external reference…

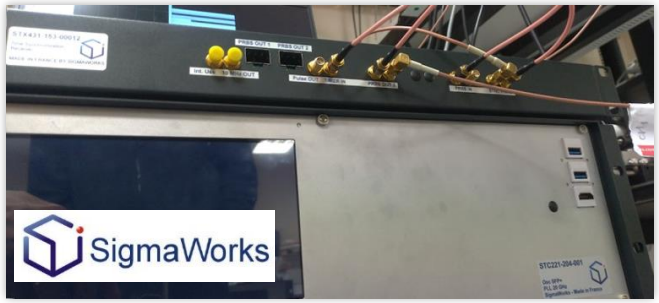
2. MetroCom – Measurement principle

SigmaWork generators architecture + performance

- Fréquence de sortie : 50 MHz – 20 GHz
- Fréquence d'entrée : 5 – 1400 MHz
- Bruit de phase 15 GHz @ 100 kHz = -110 dBc/Hz
- Bruit intégré < 55 fs RMS
- Sensibilité thermique : < 0.2 ps /°C
- Dynamique PLL fractionnée : 32 bits
- Sortie PLL : 2 paires différentielles
- Référence externe synthèse : Single ended
- Puissance de sortie optique : 0 dBm module SFP
- Longueur d'onde : module SFP sélectionné





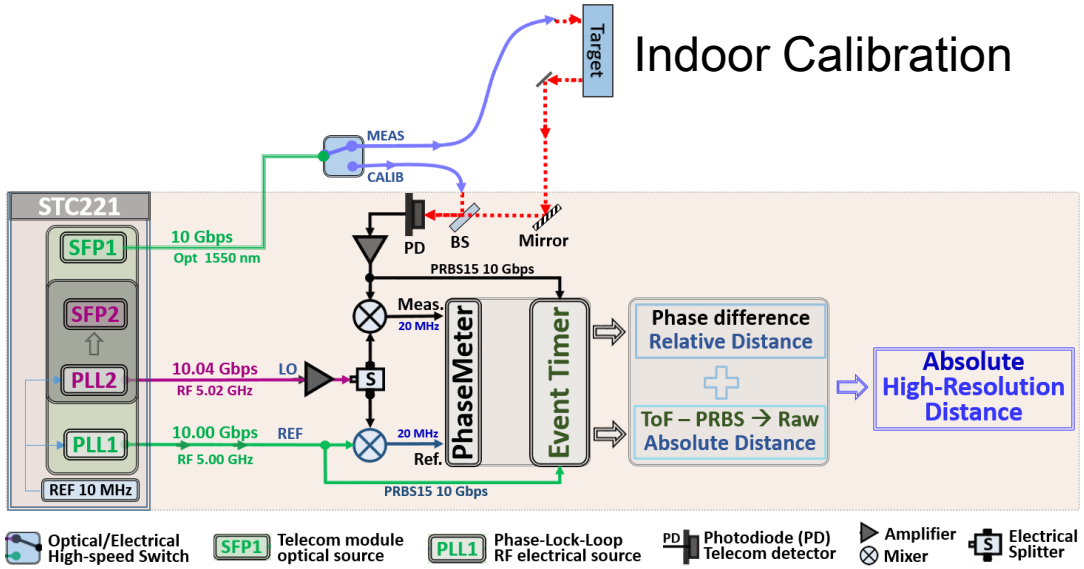


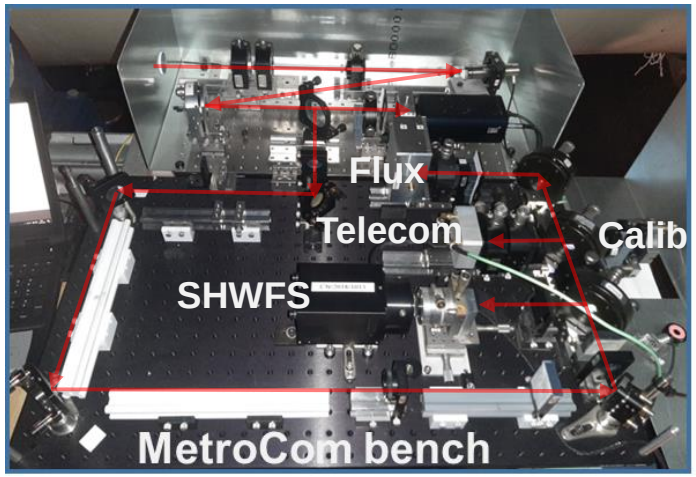
ToF 1U

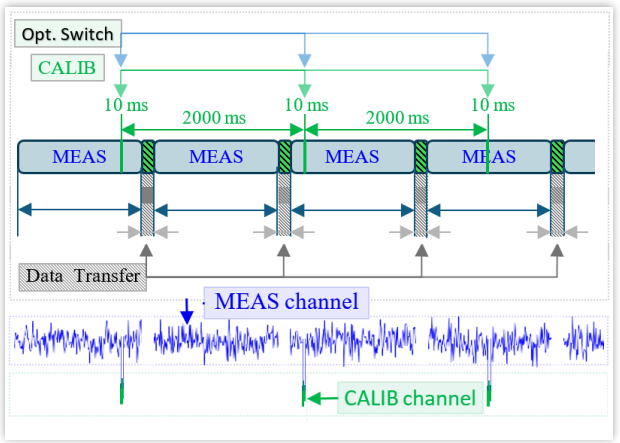
Phase 3U

2. MetroCom – Calibration performance

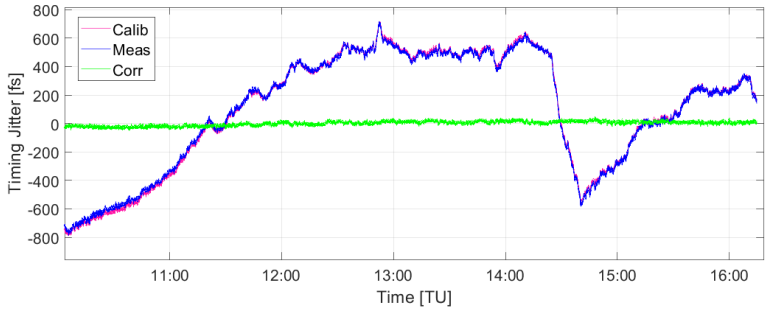
Indoor Calibration



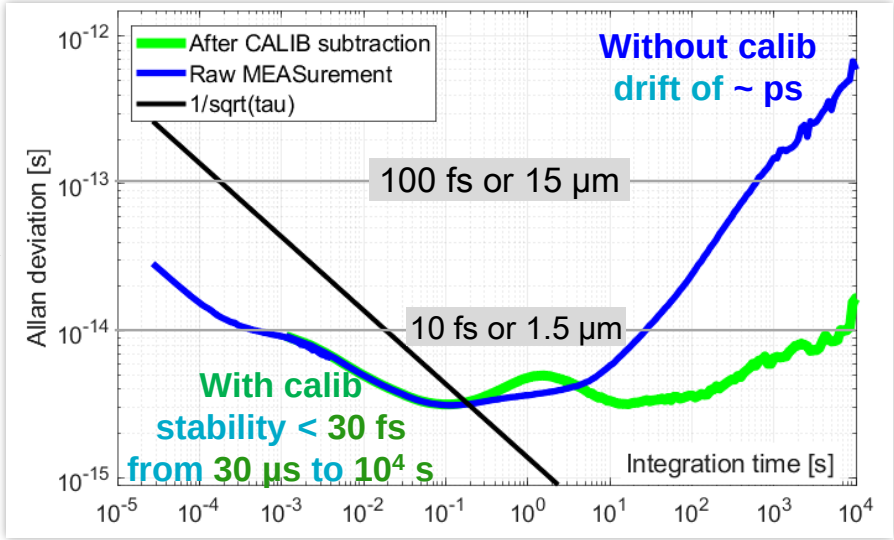




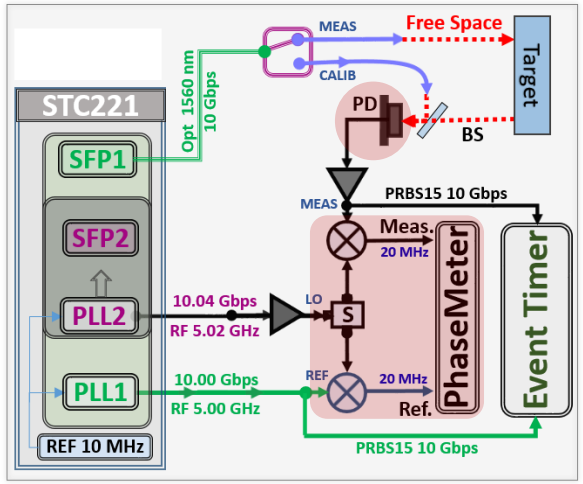
With room temperature fluctuation of 3 °C



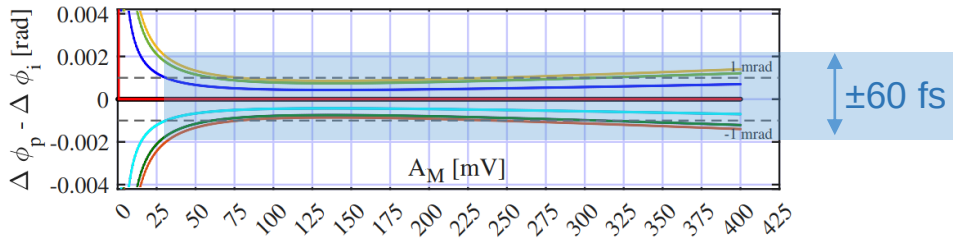
Calibration is measured every second, during 10 ms



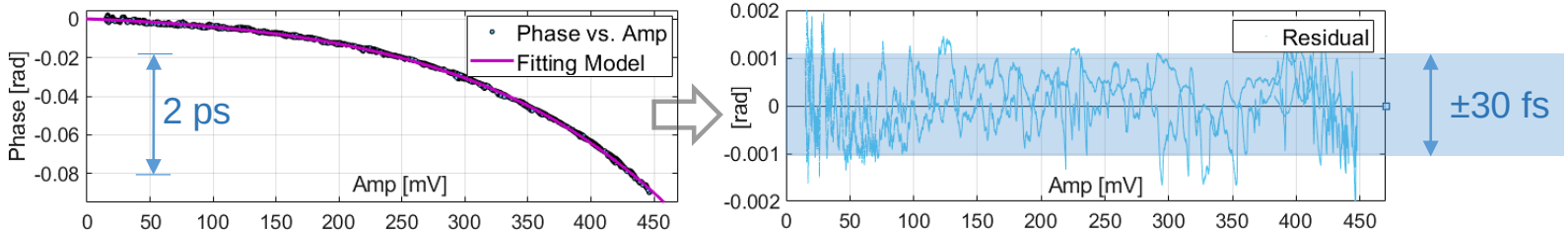
2. MetroCom – Systematic Errors Sources



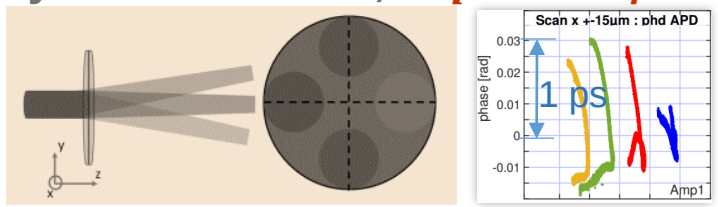
- **Electrical cross-talk** in demodulation system → cyclic error on $\Delta\varphi$
  (– 64 dB REF → MEAS & – 71 dB MEAS → REF)
  By filtering low-amplitude signal, cyclic error < 60 fs (10 µm)



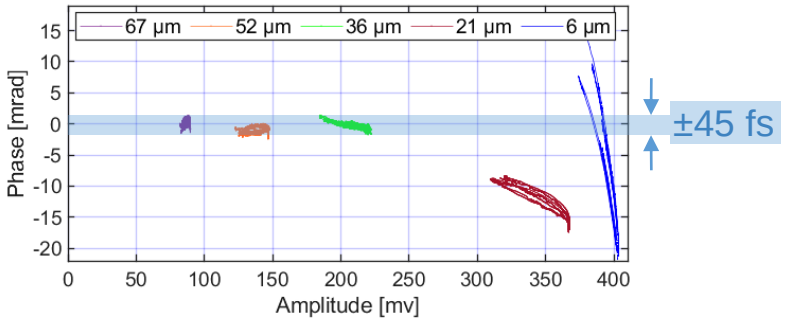
- **Amplitude to phase coupling:** ΔAmp → $\Delta\varphi$ or AM/PM
  (Amp variation caused by atmospheric turbulence in free-space)
  By measurement and correction, AM/PM < 30 fs (5 µm)



Kyosemi detector, $\Delta Spot$ → $\Delta\varphi$

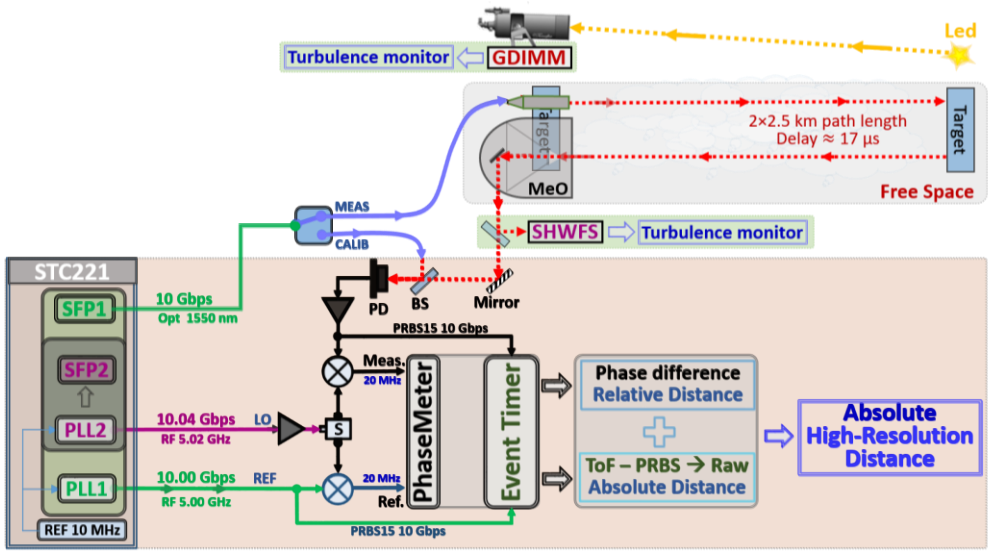


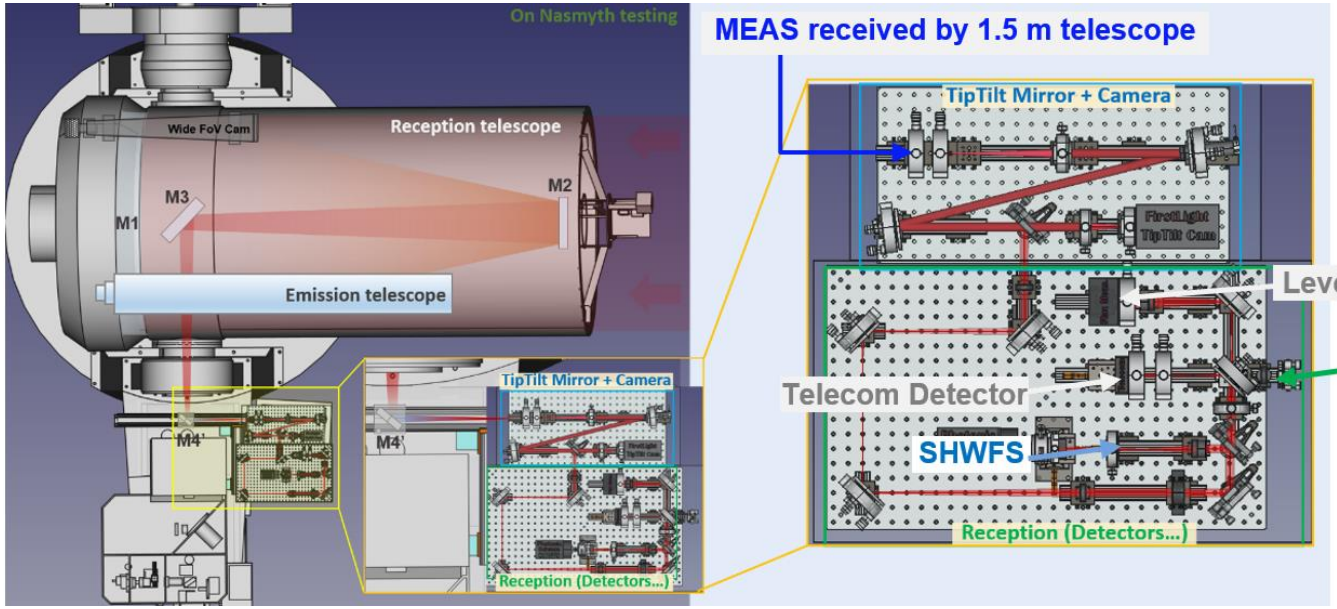
SigmaWork telecom detector

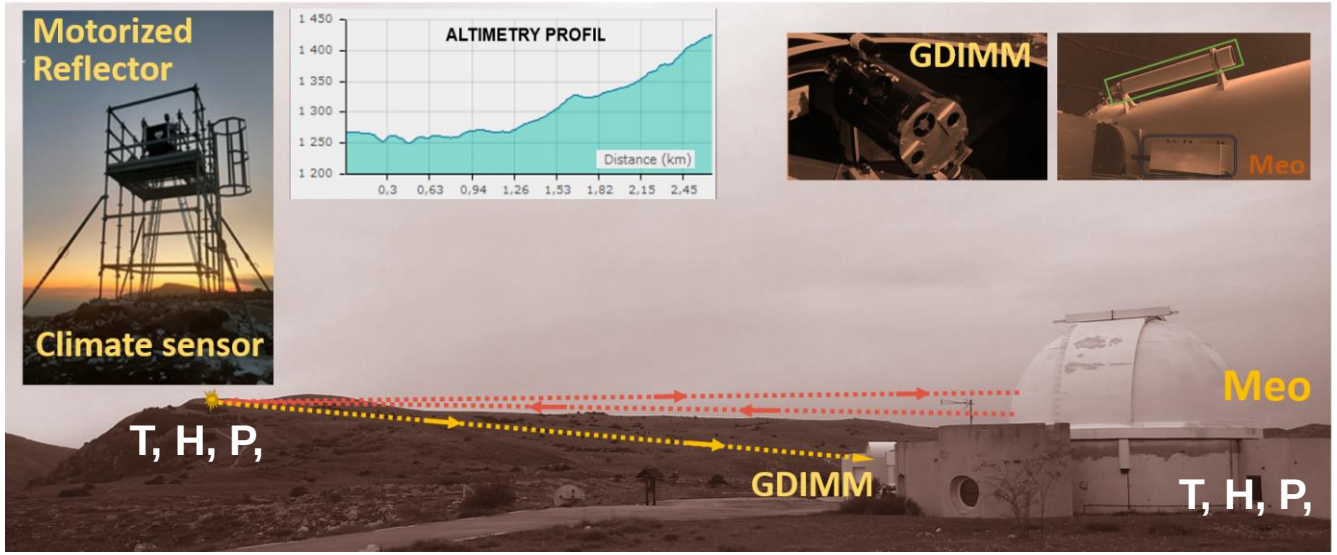


- **Telecom photodiode – Spot position to phase coupling:** $\Delta Spot$ → $\Delta\varphi$
  (Phase changes when spot position move on PhD detection zone)
  By de-focusing the spot size, $\Delta Spot$ → $\Delta\varphi$ < 45 fs (7 µm)
  or by using mono-mode fiber coupling, $\Delta Spot$ → $\Delta\varphi \approx 0$

2. MetroCom – Implementation with MeO telescope

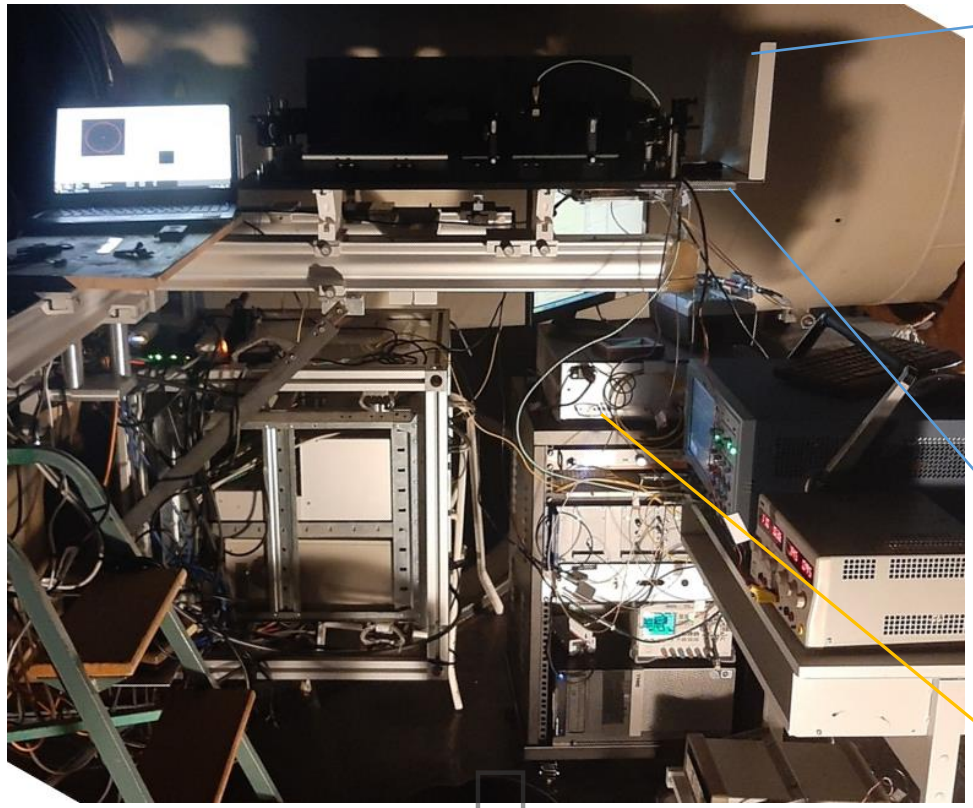


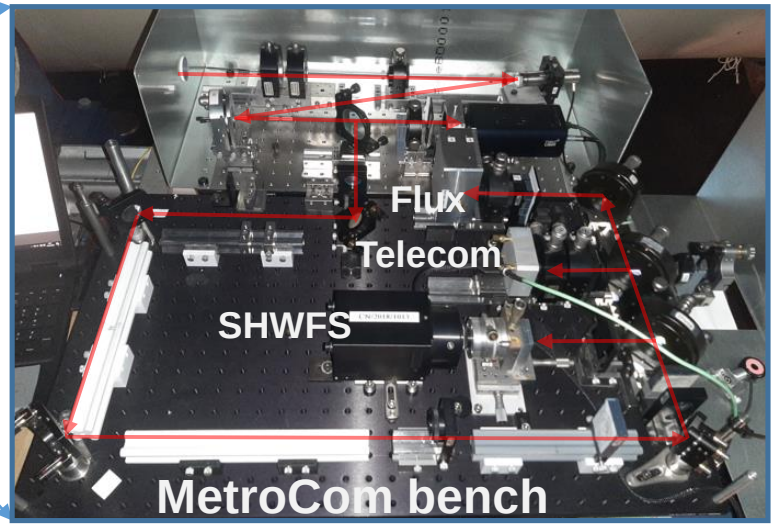


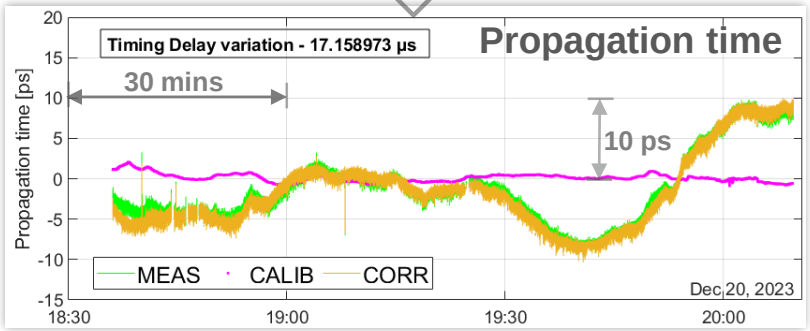


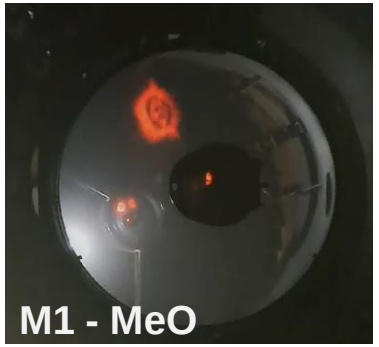
- **Test measurement sensitivity**
  (over turbulence + 2×2.5 km)
- **Timing jitter measurement**
  (caused by atmospheric turbulence)
- **Physic of Atmospheric turbulence effect**
  (theoretical model vs measurement)
- **Propagation-time variation at long term**
  (comparing with refraction index – T,H,P)

2. MetroCom – Implementation with MeO telescope







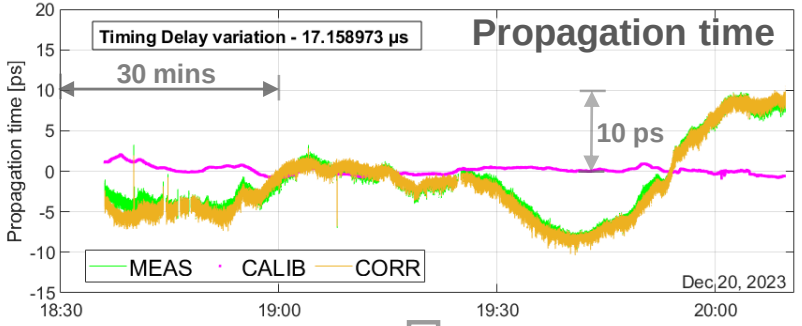


3. MetroCom – Result & Discussions

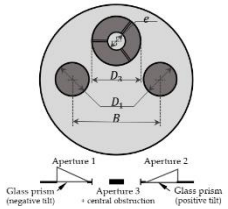
At short time range ms to seconds → Physic of turbulence modeling

$$\sigma_T^2 = 26.31/c^2 \times C_n^2 \mathcal{L}_0^{5/3}\, L/2$$

C_n^2 (by GDIMM and SHWFS) from 0.5×10^{-15} up to $3\times10^{-15}\ m^{-2/3}$
→ $\sigma_T = 0.2$ to 0.5 ps rms on the propagation delay when $\mathcal{L}_0 = 13$ m

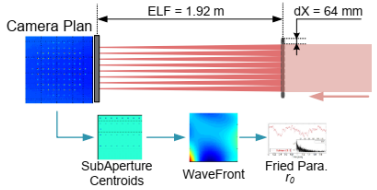


GDIMM measurement – 50 m from MeO telescope



- ✓ angle-of-arrival (AA),
- ✓ Fried parameter r_0,
- ✓ turbulence strength C_n^2
- ✓ and particularly outer scale $\mathcal{L}_0$.

SHWFS measurement – on axis of lasercom beam



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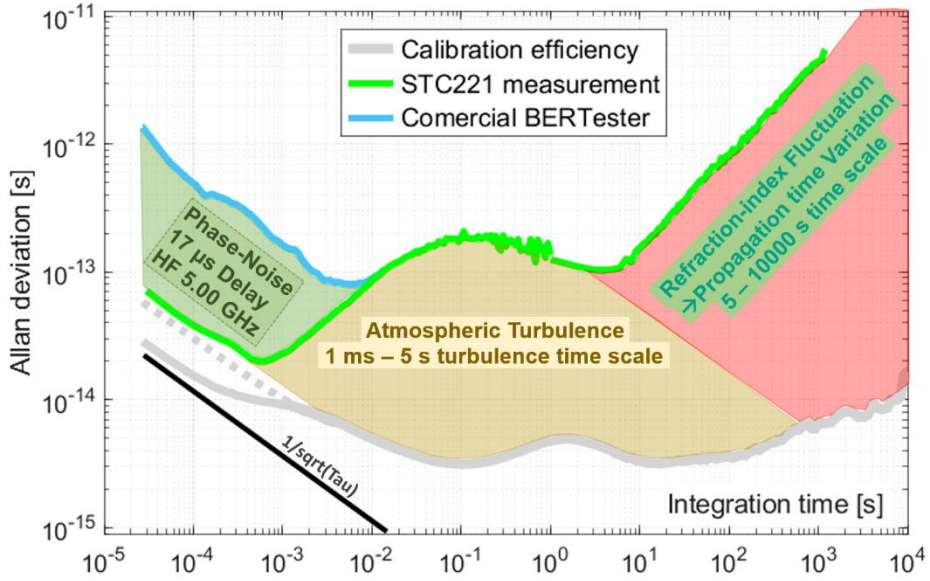

Meteorological (T,H,P at MeO & at 2.5 km) → refraction group-index variation at long time range 5 – 10^4 s

$$L = \frac{1}{2}\times\left(\frac{\phi}{2\pi}+k\right)\times\frac{c}{n\times f_{RF}} \quad \text{and} \quad n(\lambda,t,p,x,p_w) - 1 = K(\lambda)\cdot D(t,p,x) - p_w \cdot g(\lambda)$$

le cnam LNE

- 1.10^{-6} /°C : 1mm/km/°C
- 3.10^{-7}/hPa : 300 µm/km/hPa
- 10^{-7} /10%RH : 100 µm/km/(10%RH)

4. MetroCom – Conclusion & Prospects

- **Phase measurement sensitivity < 30 fs (1.5 µm) from 30 µs to 10000 s**
- **Time-of-Flight, PRBS synchronization sensitivity ~ 7 ps (10mm) at 0.2 s**
- **Implementation of a test-bench with telecom signal generator**
- **Error sources characterization & mitigation, < 60 fs**
- **Free-space test with MeO telescope on 2×2.5 km slant path**
- **Timing jitter caused by atmospheric turbulence: modeled & measured at short and long time range**

- **Combining with ToF measurement on Free-Space**
  (with measurement & calibration process)
- **Two-color measurement**
  (850 nm + 1565 nm or 1310 nm + 1565 nm)
- **Monomode-fiber coupling, using Adaptive Optic**
  (to eliminate spot/phase coupling on detector)

Acknowledgements: We would like to thank First-TF & CNES for their support