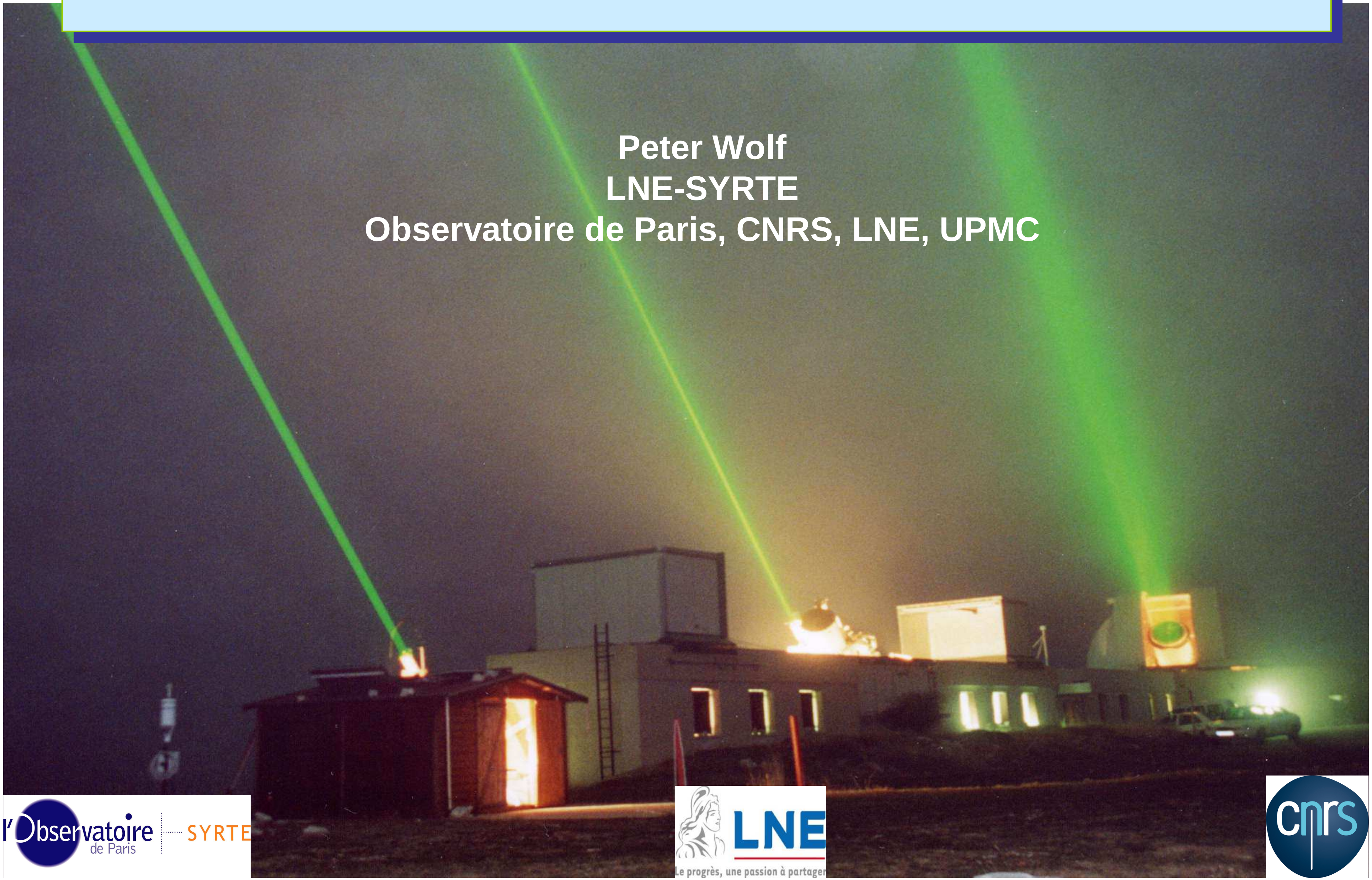
# Time and Frequency Links for STE-QUEST

**Peter Wolf**
**LNE-SYRTE**
**Observatoire de Paris, CNRS, LNE, UPMC**

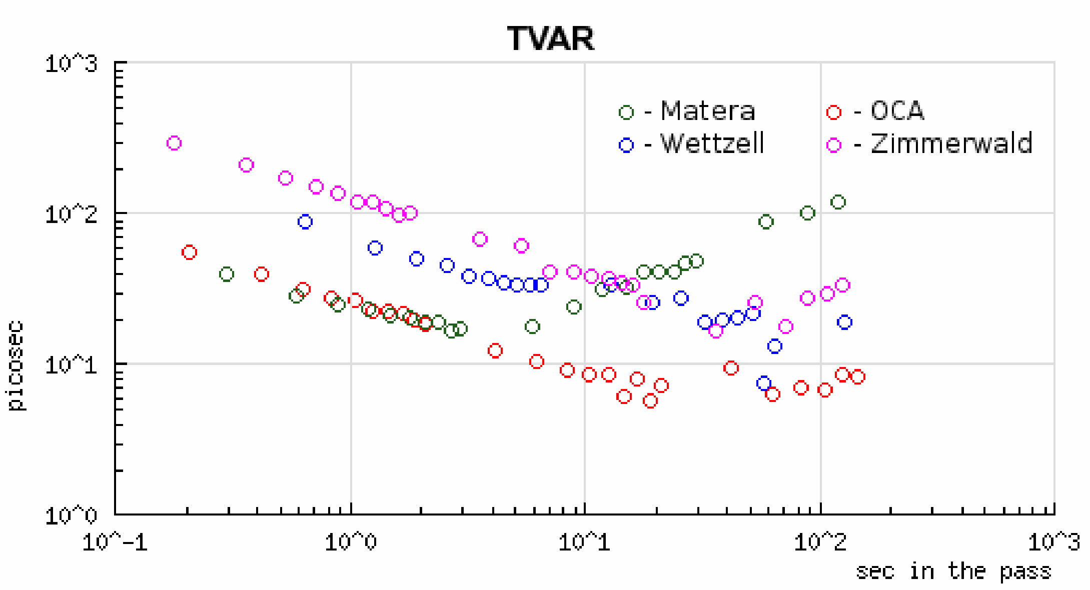


# Outline

1. Best “present” links and STE-QUEST requirements
2. The ACES MWL extension for STE-QUEST
3. “Continuous” optical links
4. The STE-QUEST optical link
5. Next steps
6. Conclusion

# Best “present” links and STE-Q requirements

- Existing techniques: GNSS, TWSTFT, T2L2, ground fibre
- Near future: ACES-MWL, ACES-ELT



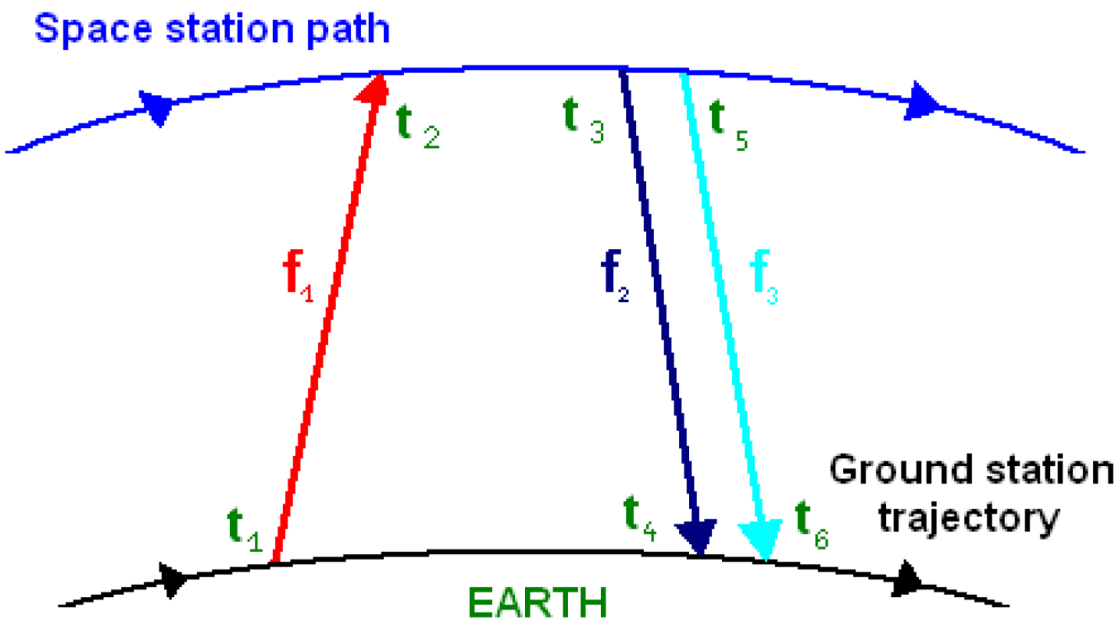

T2L2 Ground to space

Jason2 Quartz vs. ground clocks

- T2L2 is a two-way pulsed optical link (532 nm)
- Typically 10 to 2000 pulses per second
- Best performances MDev ≈ $5 \times 10^{-11}$ @ 1 s

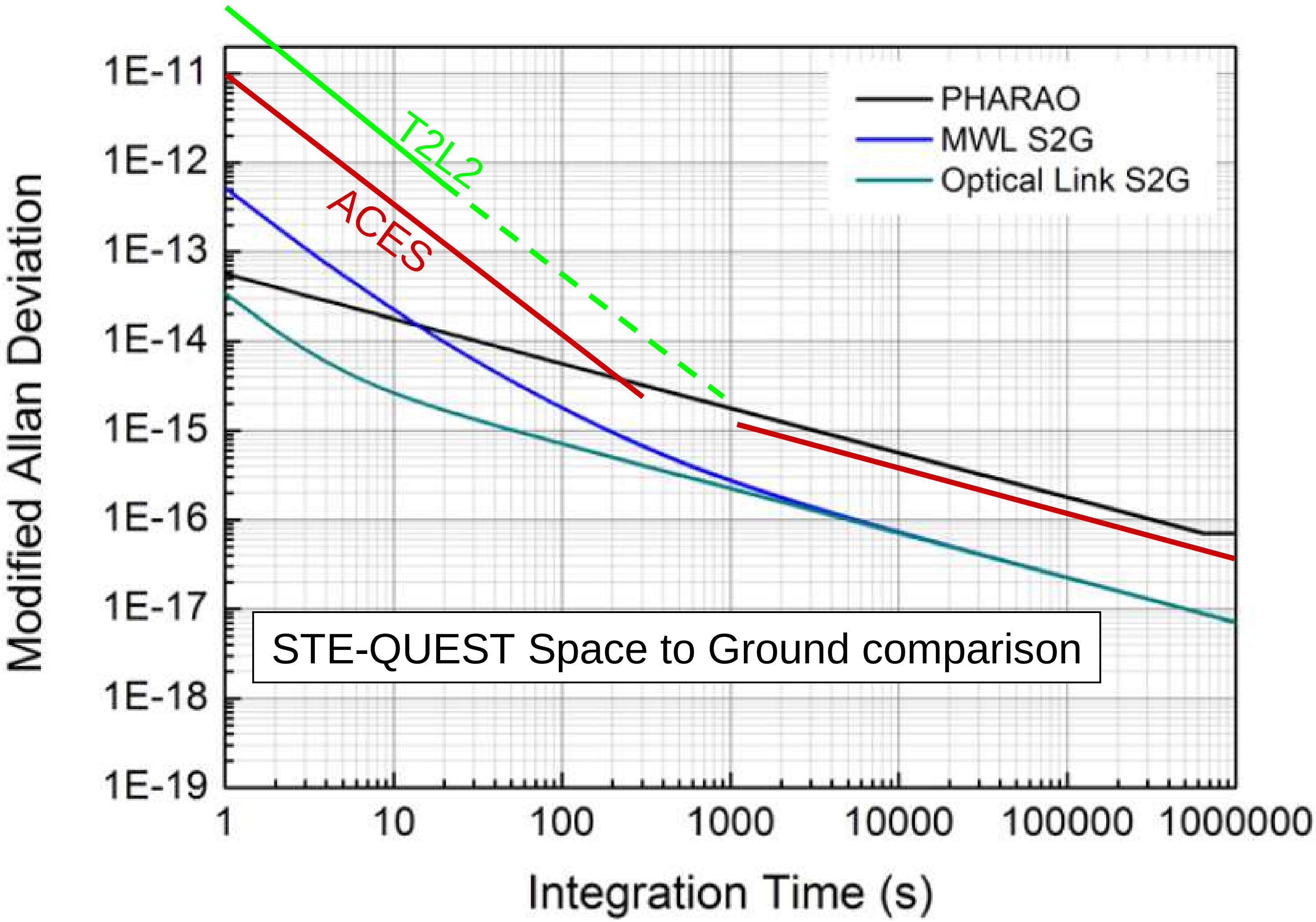
# Best "present" links and STE-Q requirements

ACES-MWL: two-way link with three frequencies (KU and S band)
Specs: MDev ≈ $9 \times 10^{-12}$ @ 1s

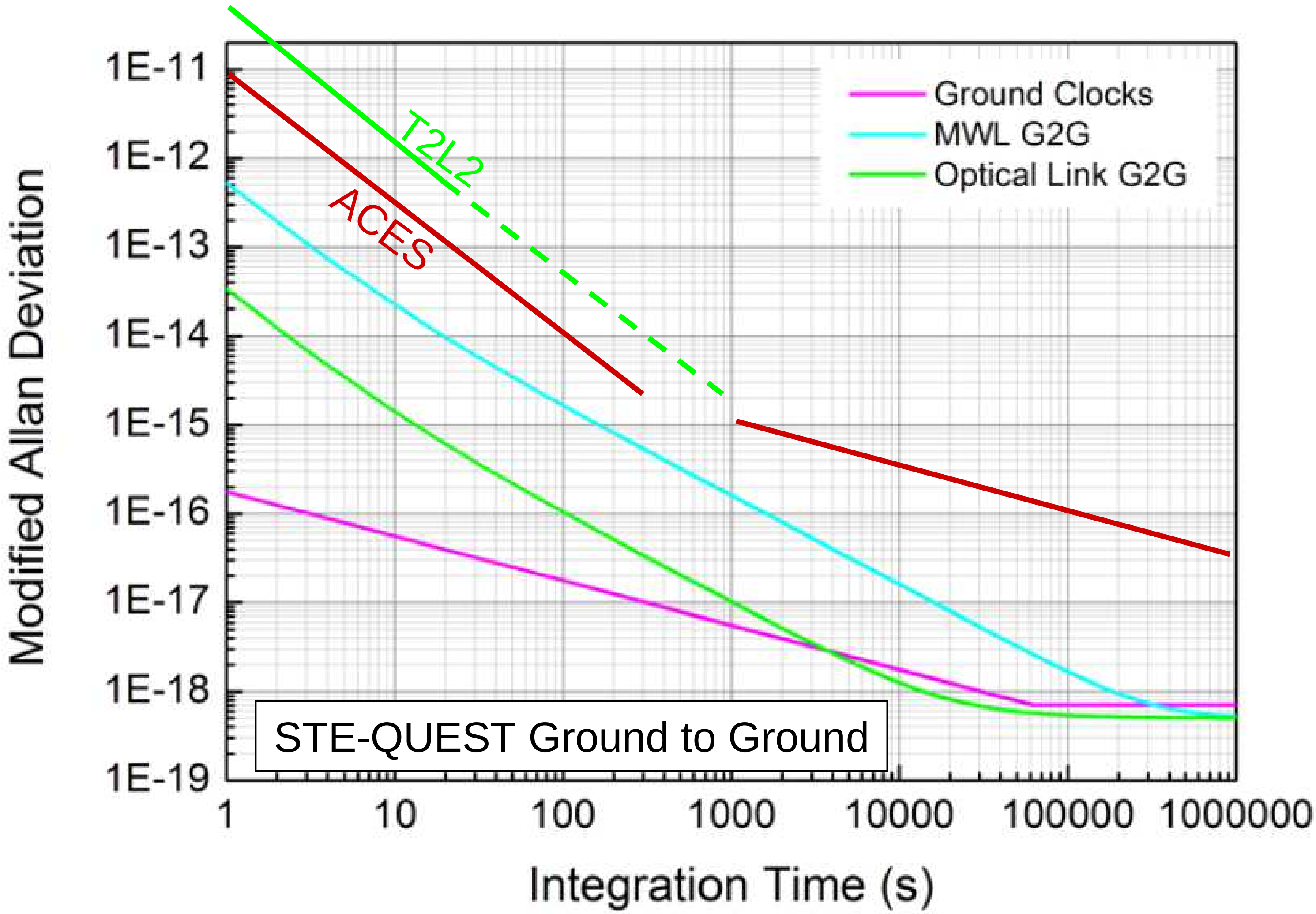



$f_1$ = 13.5 GHz modulated by PRN code at 100 Mchip/s
$f_2$ = 14.7 GHz modulated by PRN code at 100 Mchip/s
$f_3$ = 2.25 GHz modulated by PRN code at 1 Mchip/s

# Best "present" links and STE-Q requirements



# Best "present" links and STE-Q requirements



## The ACES-MWL extension for STE-QUEST
### (see also poster by T. Feldman)

• Studied in ESA-ITT-AO6404 – Phase 1 finished (TimeTech, DLR, SYRTE, ONERA, PTB, NPL)
• Phase 2 (breadboarding) calls expected soon

Difficulties:
• Larger distance (S/N) and its variation
• Doppler dynamics
• Ionosphere
• Turbulence
• Phase cont. during dead times

Solutions:
• Build on ACES-MWL experience
• Increase frequencies (Ka-band, X-band)
• Increase chip rates
• Model higher order ionospheric terms
• Mitigate turbulence (troposphere) by two-way configuration

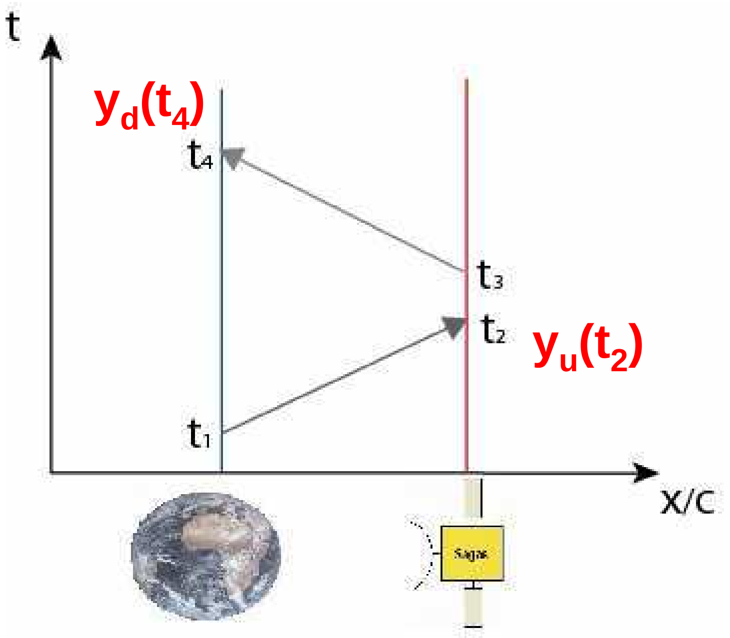
# “Continuous” free space optical links

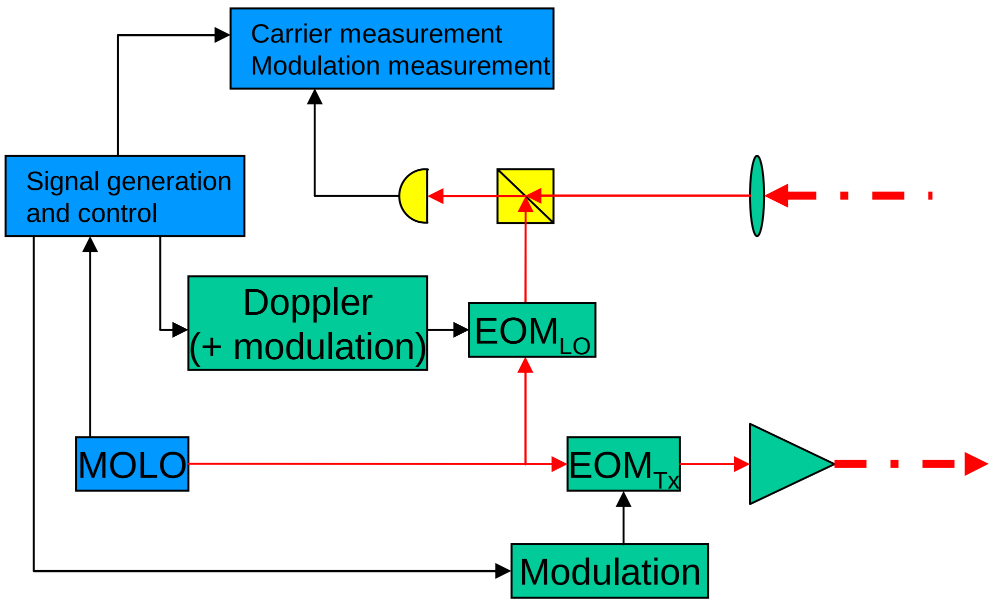
- Increasing frequency of pulsed optical links is not an option (limited by pulse width and repetition rate)
- Continuous links in optical fibres (phase coherent or modulated) have shown very good performance, well compatible with STE-QUEST specs.
- First experiments in free space (SYRTE-OCA, NIST) show promising results, turbulence limited.
- Space-space and space-ground coherent links for optical communications (> Gbit/s) have been demonstrated (TRL=9)
- The application of such techniques to time/frequency transfer for space missions (STE-QUEST and beyond) is being studied under ESA contracts.

# Continuous link example: Mini-DOLL

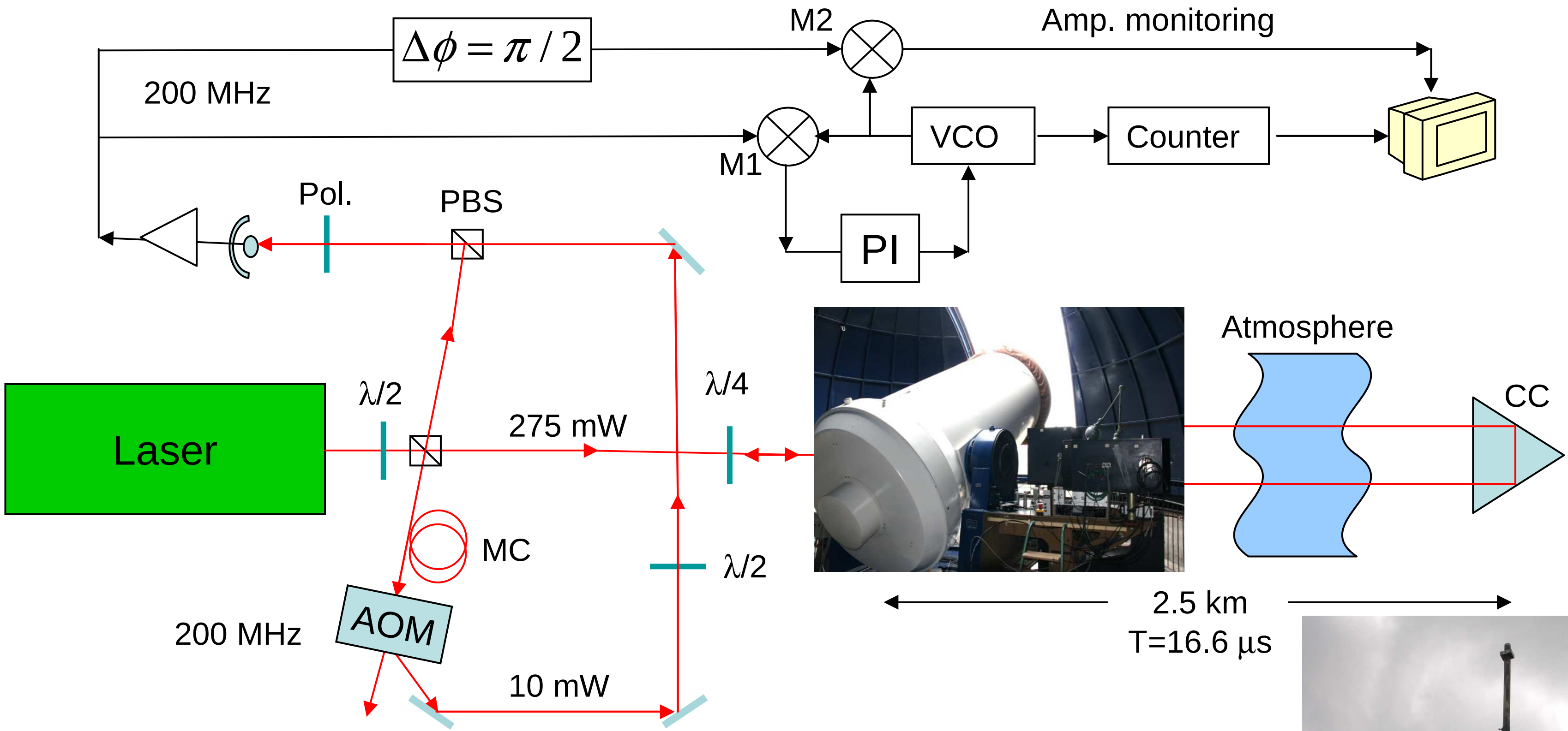
**Principle of DOLL (Deep space Optical Laser Link):**

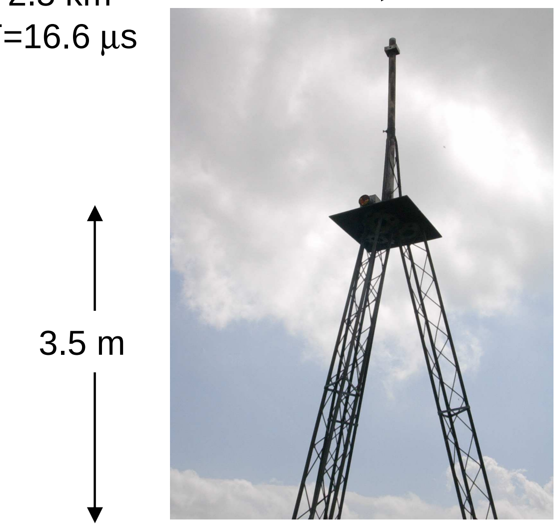
- two way, phase coherent optical link for timing and ranging
- heterodyne measurement of $\Delta y$ between local and incoming signal
- Doppler ranging: $2\Delta v/c = (y_u + y_d)$ + corr.
- Frequency transfer: $2\Delta f/f = (y_u - y_d)$ + corr.
- In practice more complex (Doppler compensation, stray light, turbulence, ….)



# Ground tests (2009) in ranging mode to study atmospheric limitations *(see also Poster by N. Chiodo)*



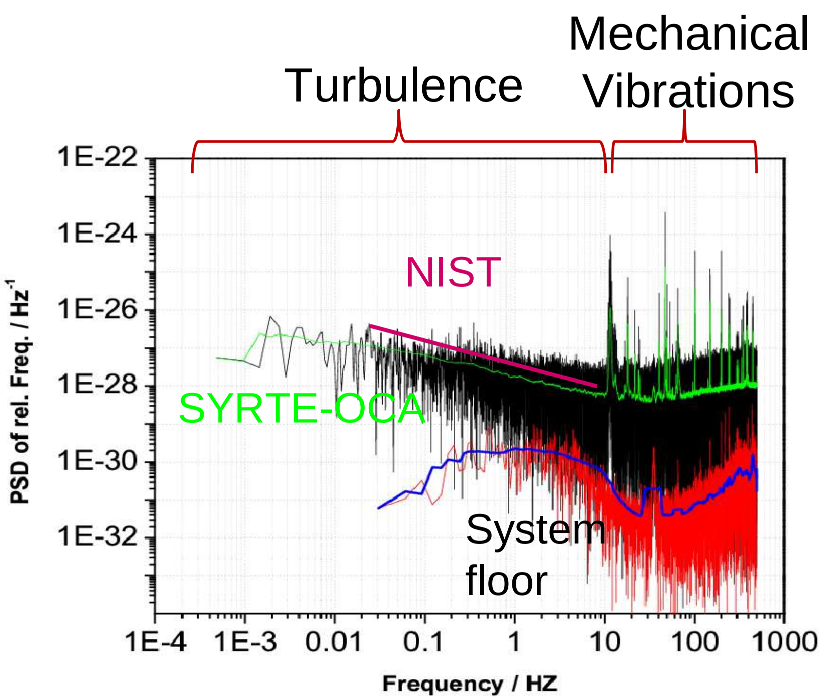

- Single terminal with passive corner cube
- Full atmospheric contribution
- Telescope diameter: 1.5 m
- Beam diameter: 380 mm

[*SYRTE-OCA, Djerroud et al. Opt. Lett. (2010)*]

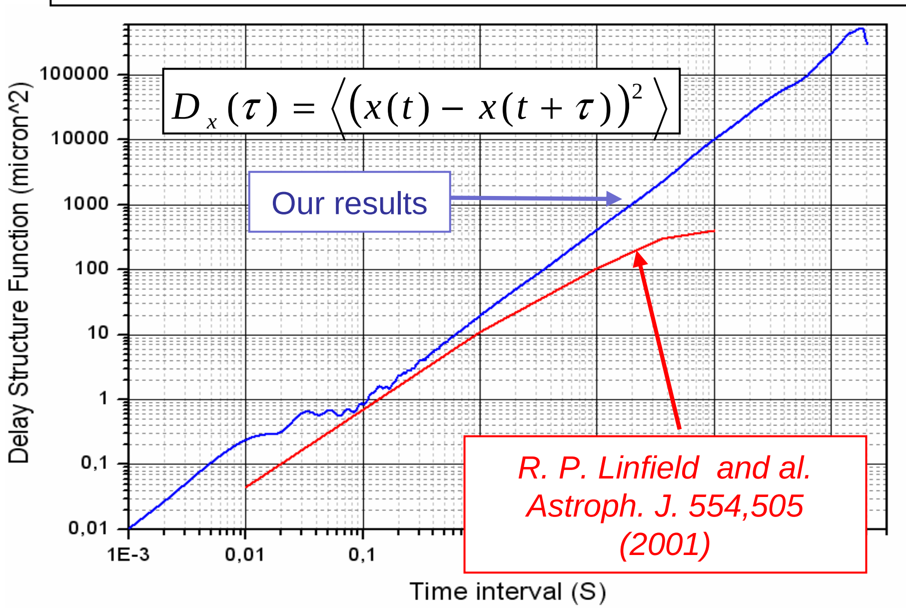
# Turbulence limit


NIST 2012

[*Giorgetta, Nat. Phot. 2013*]

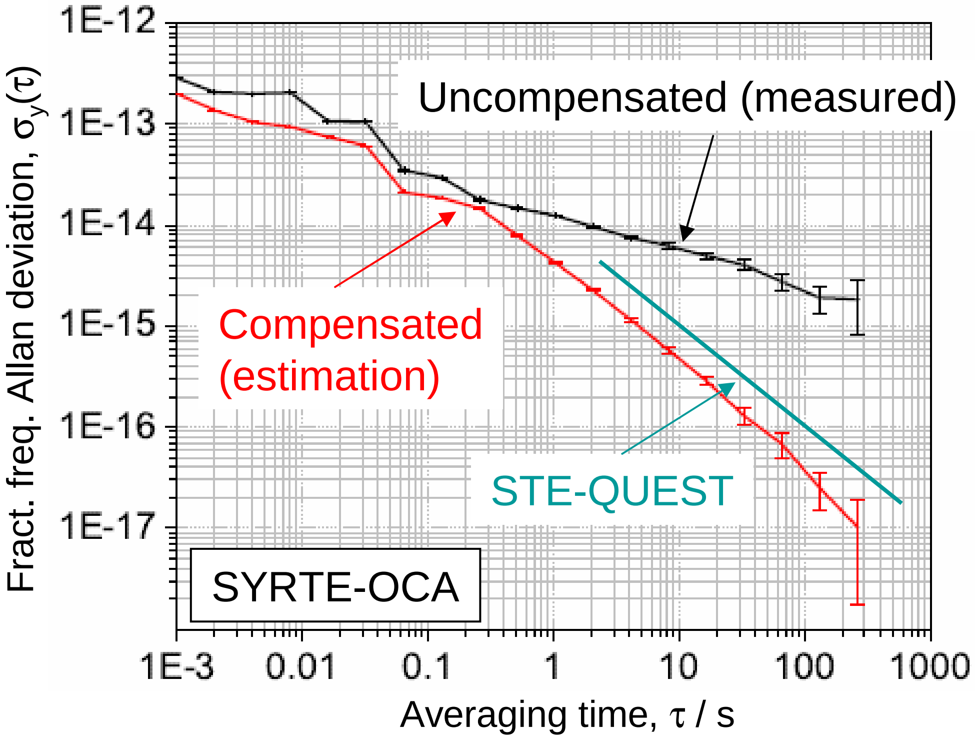


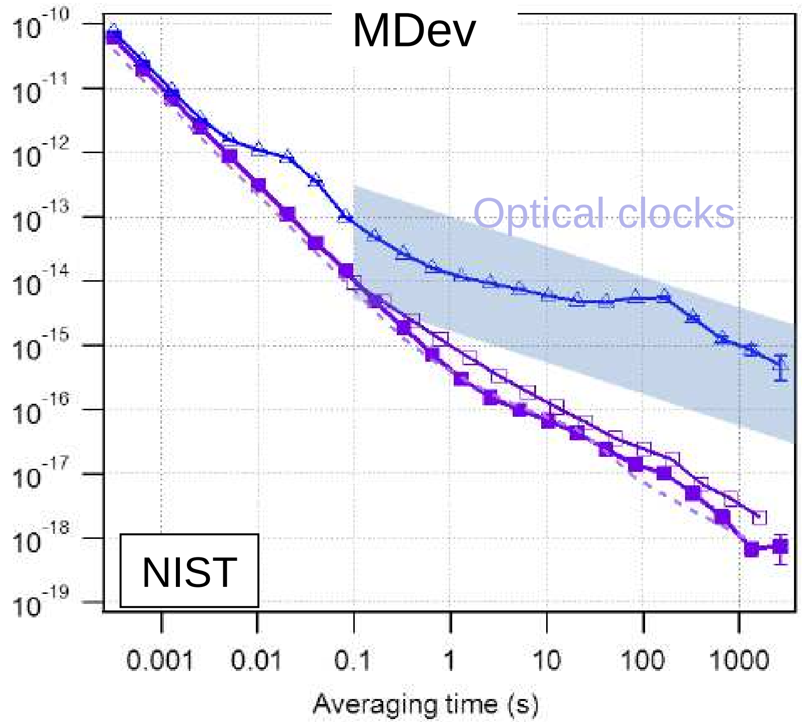

Turbulence noise very similar to stellar interferometry measurements



# Two-way compensation of turbulence

- Assume geostationary satellite ($T \approx 250$ ms)
- Calculate $(y(t)\text{-}y(t+T))/2$ from our ground ↔ ground link and look at its statistics:




- OK at turbulence limit and **if** two-way compensation works (temporal + spatial)
- Require sites with low turbulence (astronomical observation sites)
- Investigate adaptive optics schemes to mitigate cycle slips

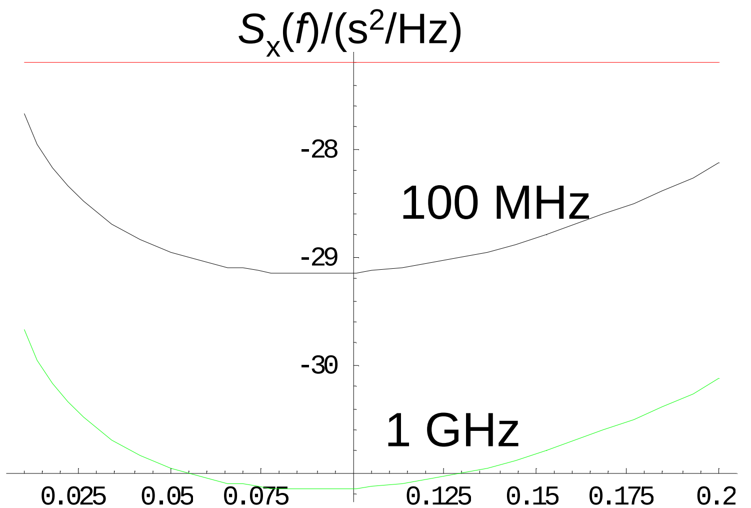
# STE-QUEST optical link (preliminary design choices)

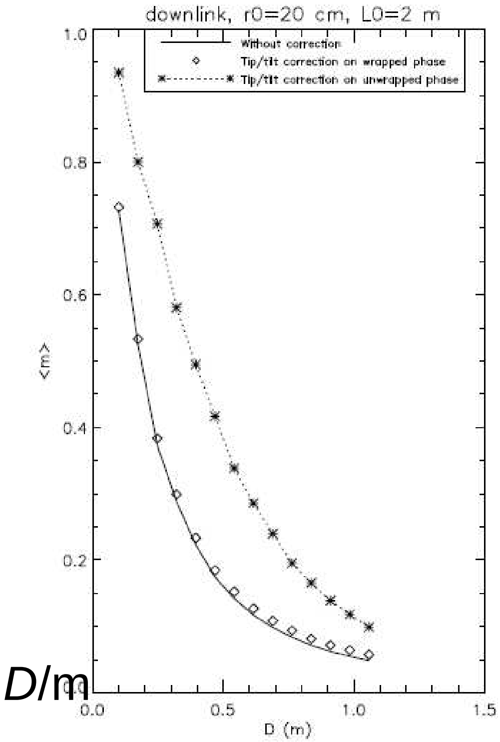
- Nd-YAG lasers at 1064.5 nm (TESAT-LCT heritage)
- S/C telescope $D$ = 125 mm, S/C $P_e$ = 1 W (TESAT-LCT heritage)
- modulation frequency 1 GHz, detection BW = 3 GHz (can be reduced)
- optional carrier phase measurement
- dual ground telescope:
  - emission: $D$ = 0.09 m, $P_e$ = 25 W
  - reception: $D$ = 0.4 m

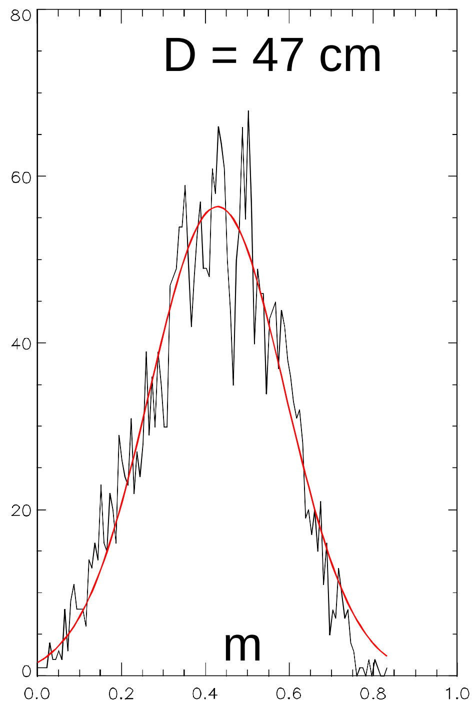
  (→ SLR heritage, eg. Yargadee: 0.16 m / 1 m
  Graz: 0.1 m / 0.5 m )


# STE-QUEST optical link (some design drivers)

- Existing technology in space and on ground (TESAT, eLISA, SLR)
- Phase noise and turbulence limitations
- Pointing errors
- Link budgets




- Uplink phase noise at apogee with 8 µrad pointing error as fct. of emission diameter
- Turbulence effect on downlink heterodyne efficiency [S/N = m $(S/N_{opt})$] from Monte Carlo simulations with PILOT software (ONERA)

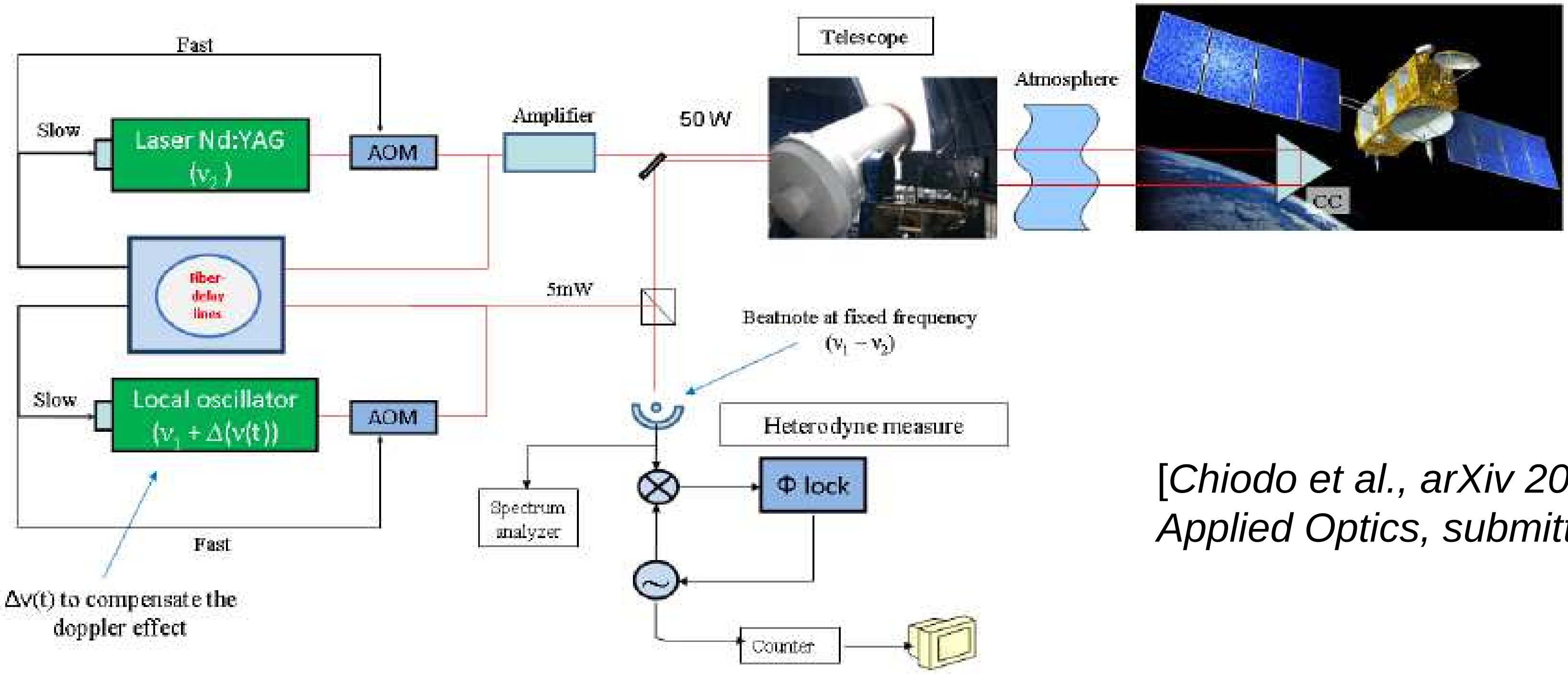
# Next Steps

Laboratory breadboarding of MWL and of optical « back-end »
- Demonstrate ACES-MWL upgrade in laboratory end-to-end test
- Demonstrate modulation/demodulation of optical carrier in realistic Doppler/Power environment

• Turbulence simulations to estimate limits of two-way compensation (essential for MWL and optical)
- time series of up and down link heterodyne phase fluctuations
- time series of up – down as fct. of temporal and angular separation
- explore various scenarios (wind speed and profile, turbulence strength and profile, outer scale, etc.

• Extension of ground-ground experiment to ground-space in particularly adverse conditions. First tests carried out in 2012/13.
- "replace" reflector at 2.5 km by satellite corner cube
- require stabilized laser to reach turbulence limit
- very low return power (< 1 pW); STE-QUEST ≈ 10 nW to 100 μW
- high Doppler (±12 GHz, 120 MHz/s); STE-QUEST about half that
- "double blind" pointing; STE-QUEST to lock to incoming signal (eg. TESAT-LCT)

# Extension to satellite *(Poster by N. Chiodo)*




[*Chiodo et al., arXiv 2013, Applied Optics, submitted*]

Encountered difficulties:

- Low return power ⇒ full 1.5 m telescope required ⇒ high order adaptive optics
- Pointing of reception (point ahead) ⇒ tip/tilt correction AO
- ILRS satellites not luminous enough for on-site AO system
- Unsuccessfully tried “double blind” pointing
- All of these problems are already solved for “high power” system (Opt. Telecom)

# Conclusion

• First design studies have shown that upgrade of ACES MWL (Ka band, faster modulation) is feasible (ESA study just finished).
• Breadboarding of STE-QUEST MWL to be started in upcoming ESA call.
• Optical link design based on existing telecom “front end” and modulation of optical carrier (ESA study just finished).
• Breadboarding of “back end” to be started in upcoming ESA call.

• Ground-ground optical free space links show performance well within STE-QUEST specs.
• Extension to ground-space with passive space segment (corner cube) difficult because of extremely low return power ($>10^4$ times less than STE-QUEST).
• Turbulence mitigation in two-way configuration remains an open question (extensive numerical simulation required).