# Developing two-way free-space optical communication links to connect atomic clocks on the ground with atomic clocks in orbit.

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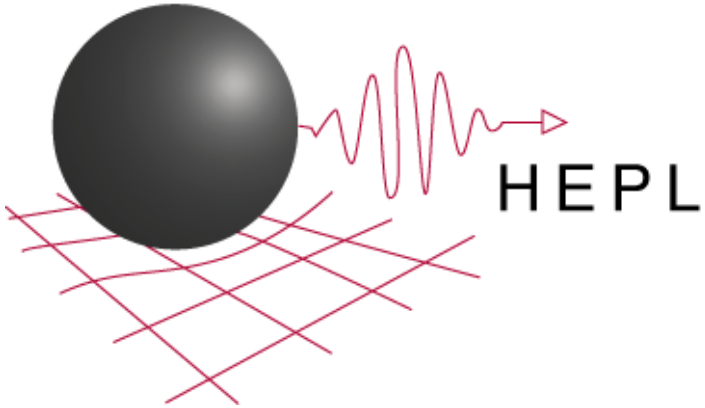
Michael Taylor
Supervisor: Prof. Leo Hollberg

Fundamental Physics



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# Optical Time and Frequency Transfer to Space

## Goal: 1ps time transfer from orbit to anywhere on earth
## 1mm range determination to orbit

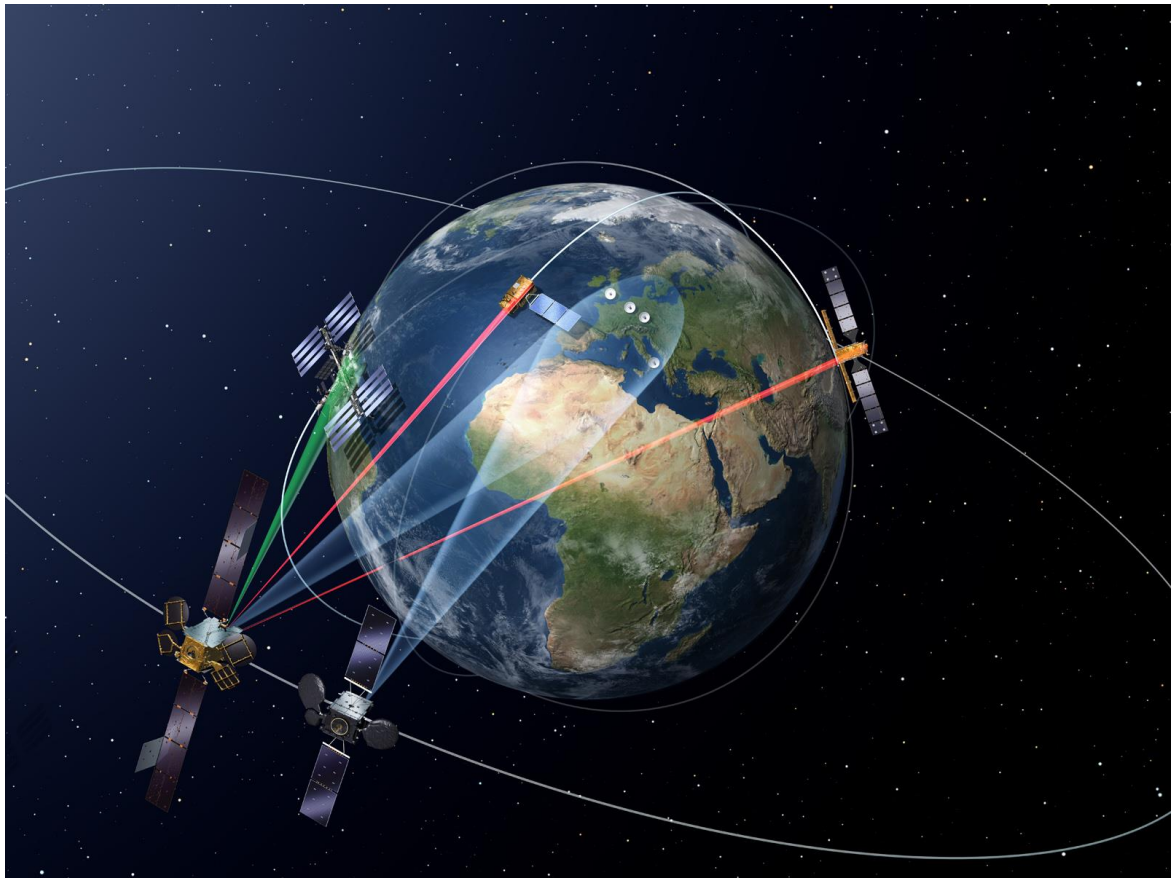


Image credit ESA: European_Data_Relay_System_EDRS.jpg

# Better Time Transfer to Orbit

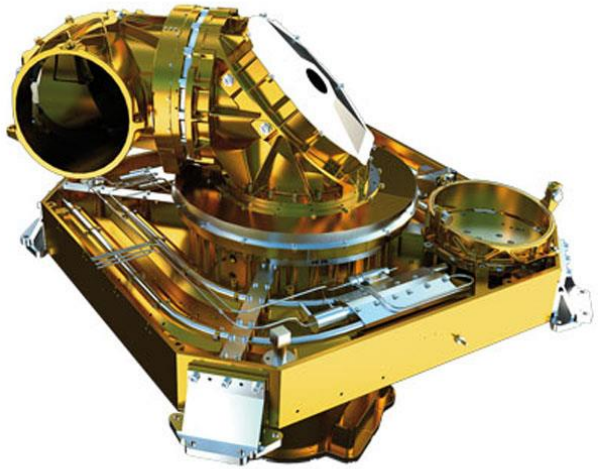
- Clock based tests of relativity
- Measure stability of atomic clocks in orbit
  - ACES/PHARO cold atom clocks to ISS soon!
- Precision orbit determination
- Geodesy
  - mm level sea level rise
  - plate motion, mapping earths gravity (GRACE-FO)
- High stability reference for other satellites
  - Enhance capabilities of GNSS, satellite formations, commercial small satellite systems, deep space ranging
- Joint Comparison of optical atomic clocks across the world

# Optical Link vs GNSS

USAF GPS block IIIA, retrieved from https://en.wikipedia.org/wiki/GPS_Block_IIIA#/media/File:GPS_Block_IIIA.jpg

- GNSS Observations:
  - 1Mchip/s symbol rate, + 1.5GHz carrier
  - CNR ~50dB-Hz
  - ~1nS timing uncertainty for long enough average
  - ~30cm range
  - Disrupted by ionosphere

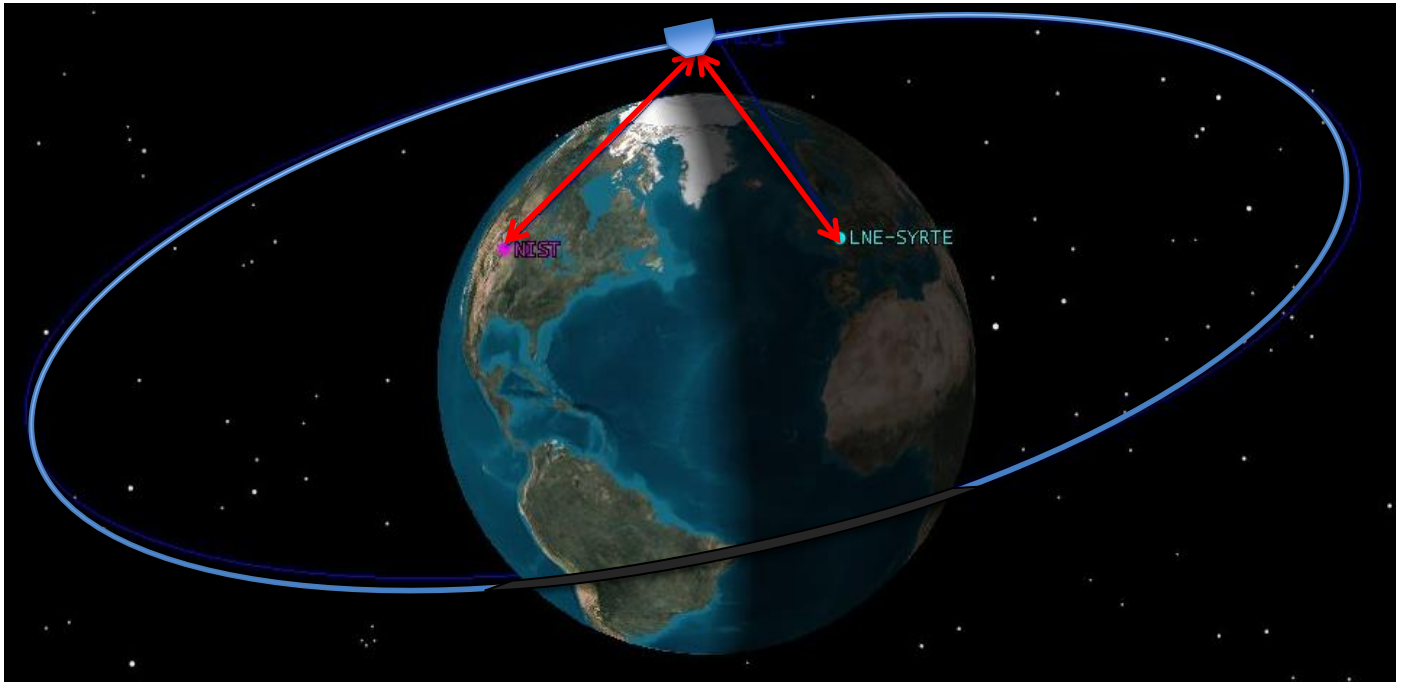
- Optical Signal:
  - 1Gbaud symbol rate, coherent detection on 193.5THz carrier possible
  - CNR ~110dB-Hz
  - Better than 1pS timing in clock recovery
  - Disrupted by atmosphere
  - Much stricter pointing requirement



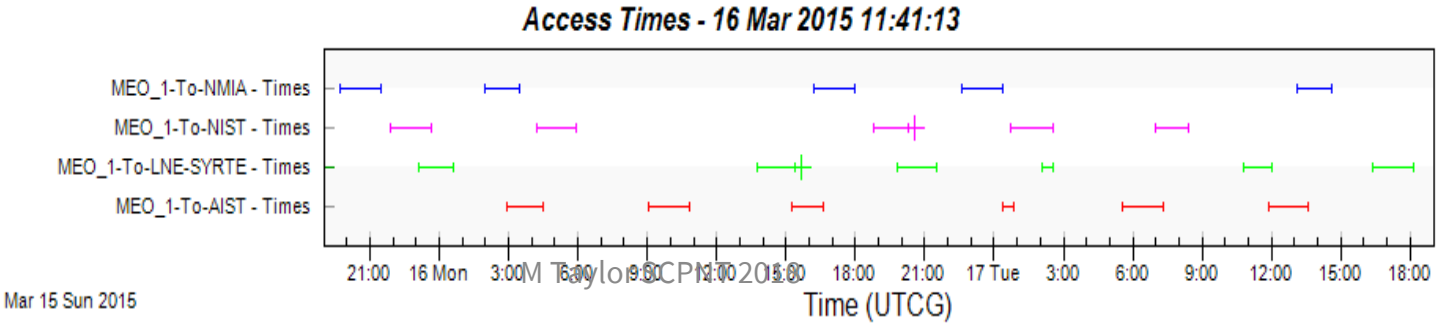
TESAT laser communications terminal. https://www.tesat.de/en/media-center/blog/information/83-news/616-advanced-capability-evolution-for-optical-laser-communication

# Comparing Atomics Clocks Around the World

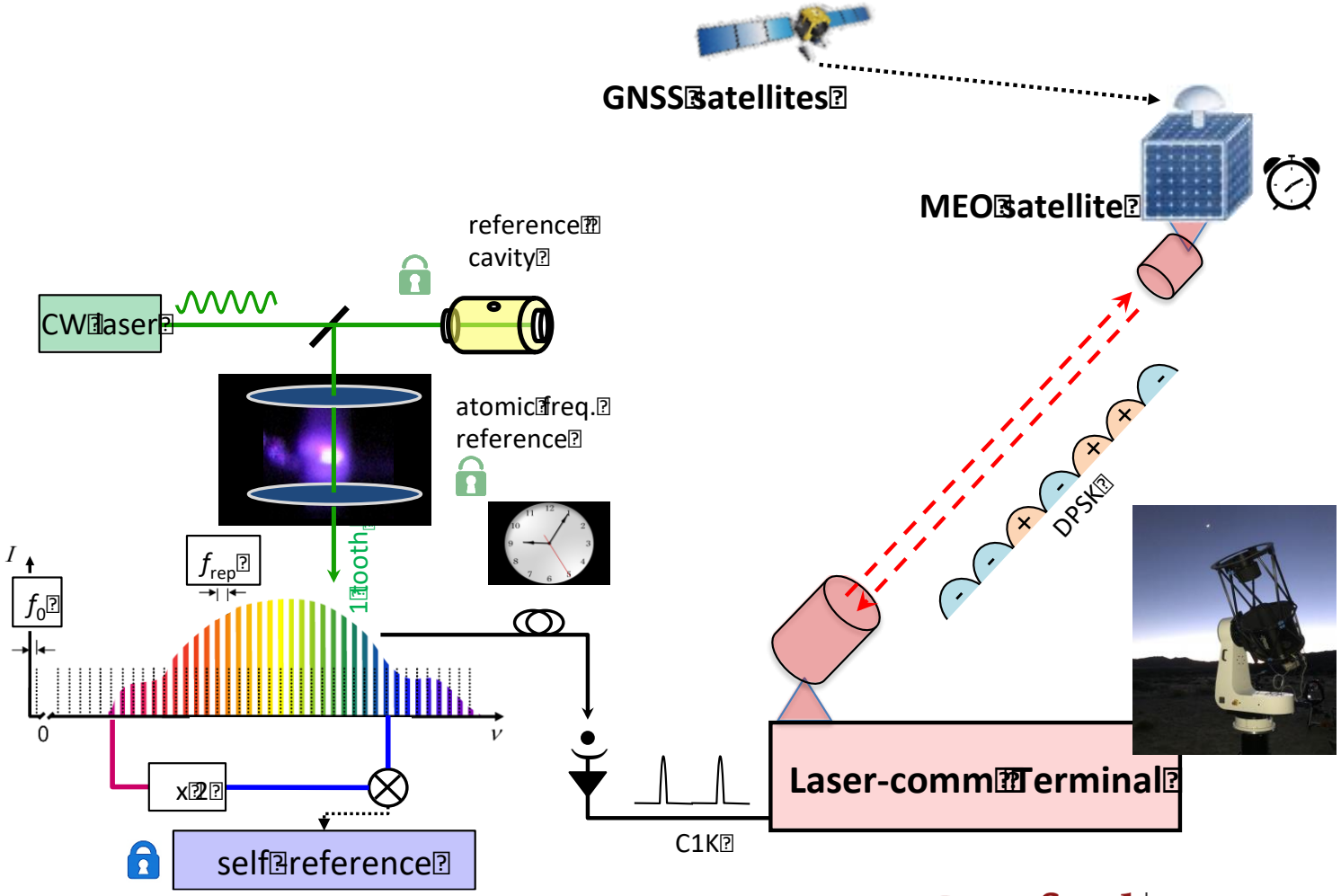
- Satellite in MEO orbit (~10,000km) provides common view between standards labs




Berceau, Paul, et al. "Space-time reference with an optical link." *Classical and Quantum Gravity* 33.13 (2016): 135007.



# Two-Way Satellite Optical Time Frequency Transfer using Optical Communications Links



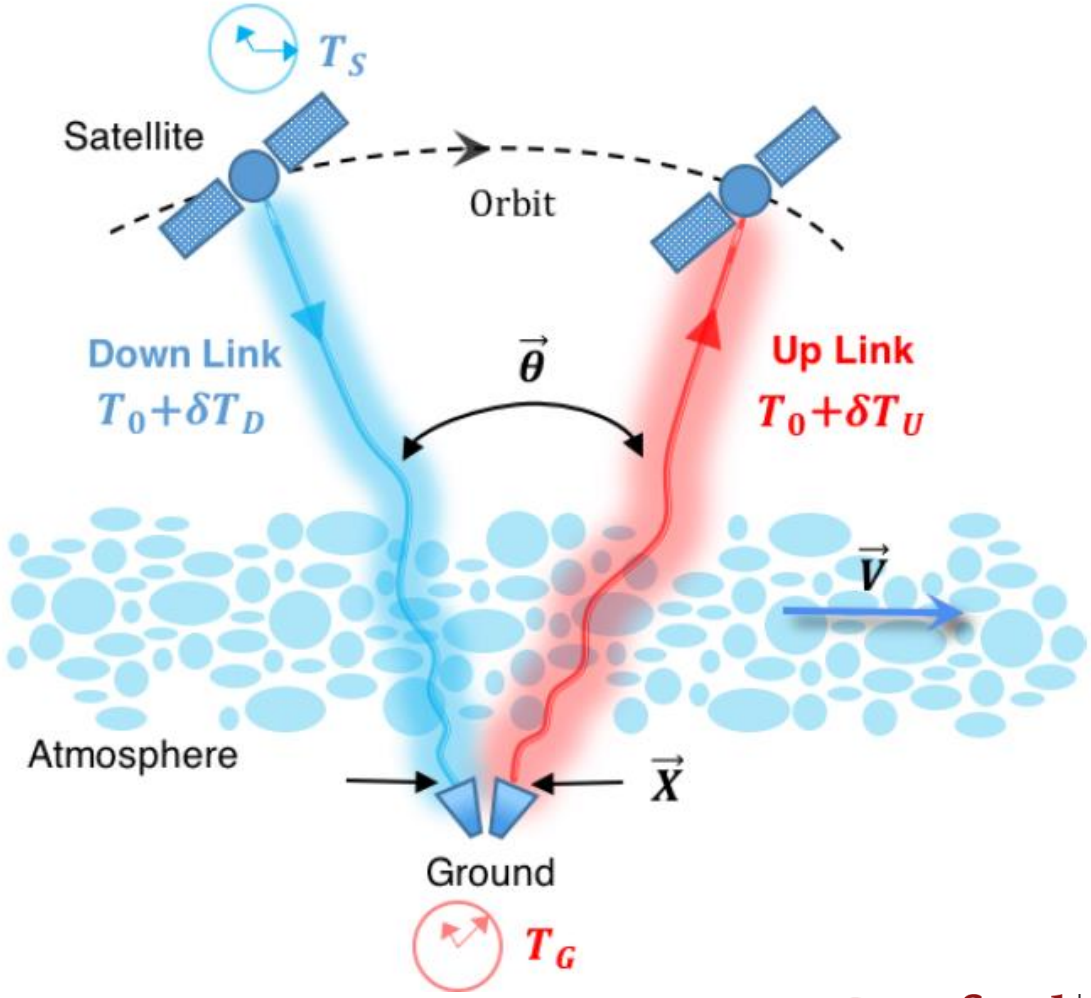
# Two Way Satellite Time Transfer: Ground to Space

- Two way measurement between ground and space clocks:

$$2\left(\phi_G(t) - \phi_S(t)\right) + \left(\phi_{G\to S}(t) - \phi_{S\to G}(t)\right) + \frac{n_S(t)}{A_G(t)} + \frac{n_G(t)}{A_S(t)}$$

- Comparison depends on:
  - $\Delta\phi_{GS}$ ground/space clock phase difference
  - $\Delta\phi_{S\leftrightarrow G}$ residual two way path non-reciprocity
  - Noise $n(t)$ scaled by incoming signal intensity $A(t)$
    - A signal fade in **either** direction will cause an increase in uncertainty on the two way measurement

# Partial Reciprocity in Ground to Space Links




Belmonte, Aniceto, et al. "Effect of atmospheric anisoplanatism on earth-to-satellite time transfer over laser communication links." Optics express 25.14 (2017): 15676-15686.



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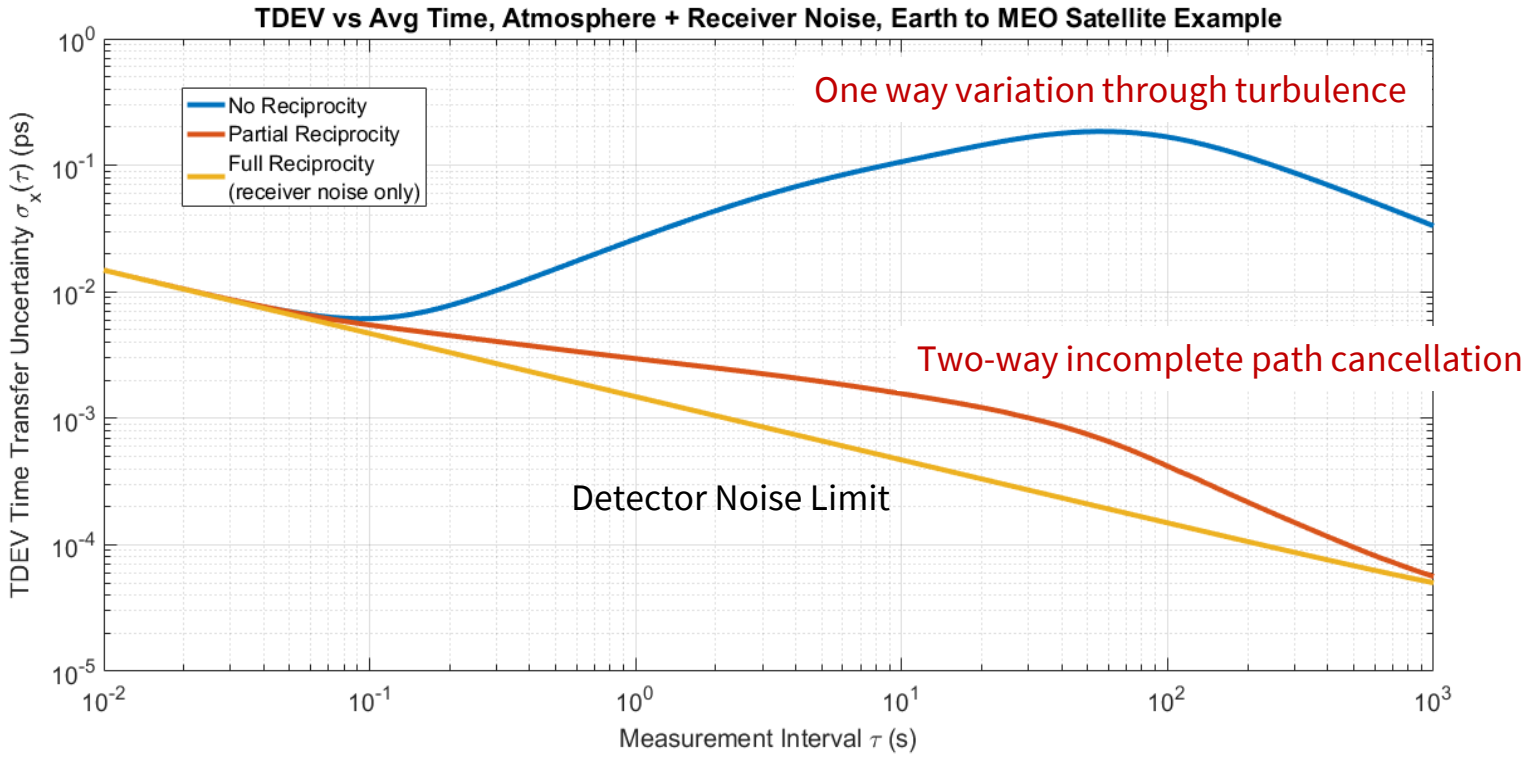
# Partial Reciprocity Earth-MEO Satellite

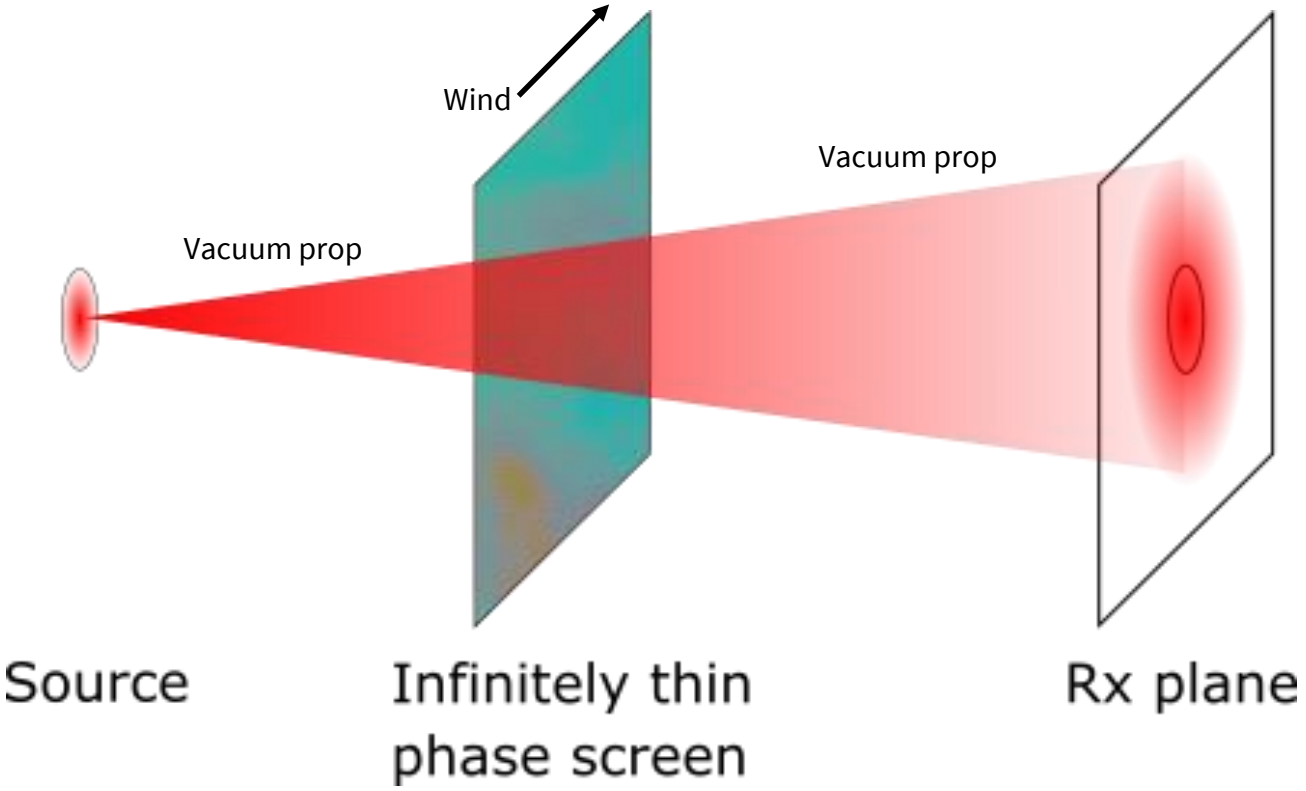
- Turbulence causes small optical path length variations that lead to timing uncertainty during long averaging periods



# What 1km of Turbulence Looks Like

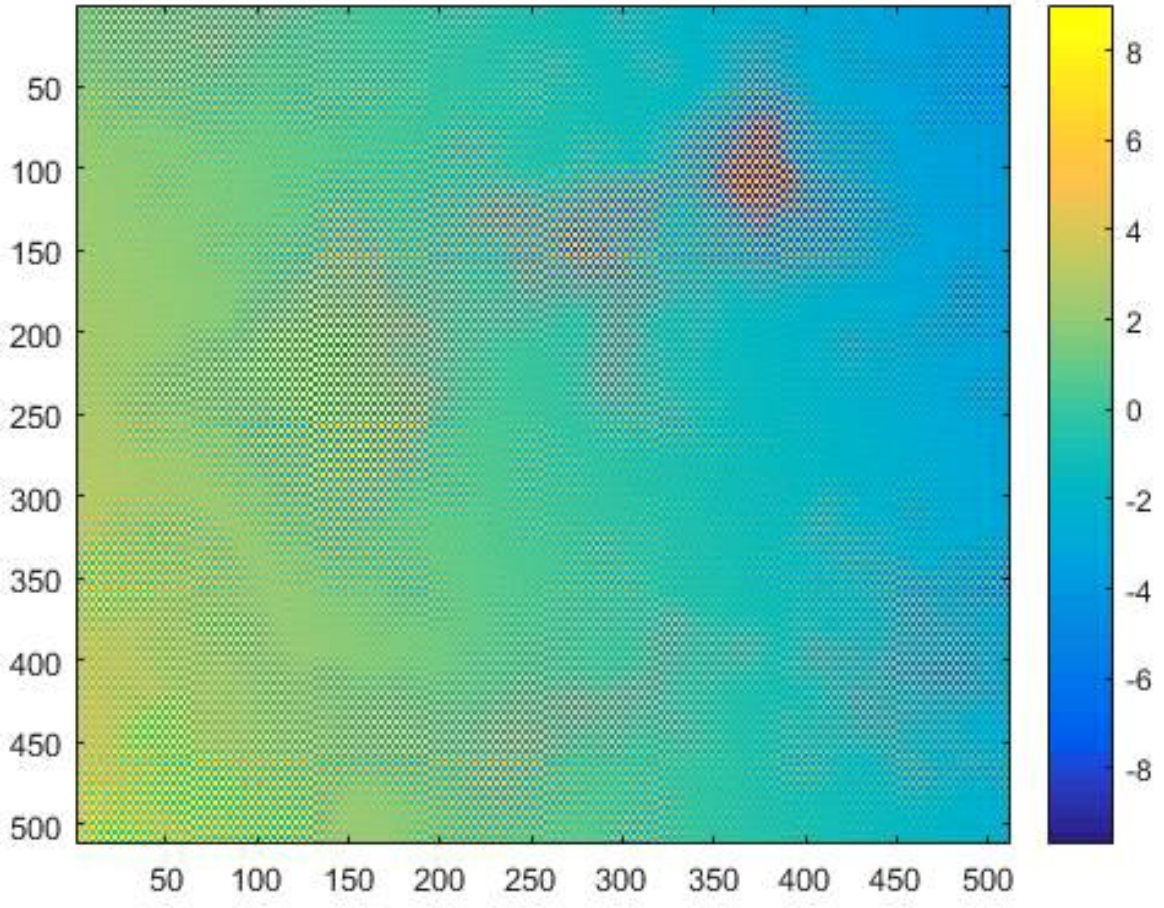
# Simulating Optical Propagation Through Turbulent Atmosphere

- Phase screens represent cumulative perturbations from propagation



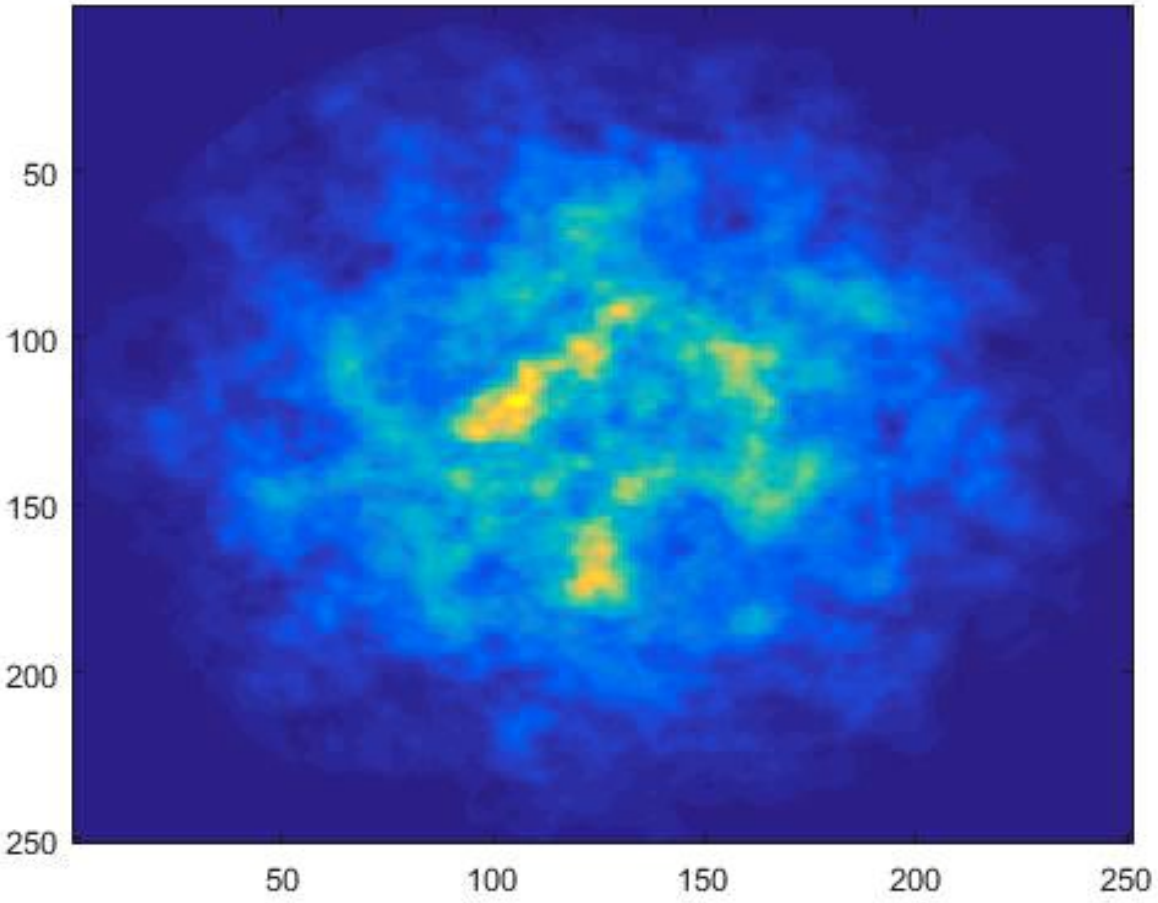
# Infinite Kolmogorov Phase Screen Example

- Wind blowing evolving turbulence across propagation path



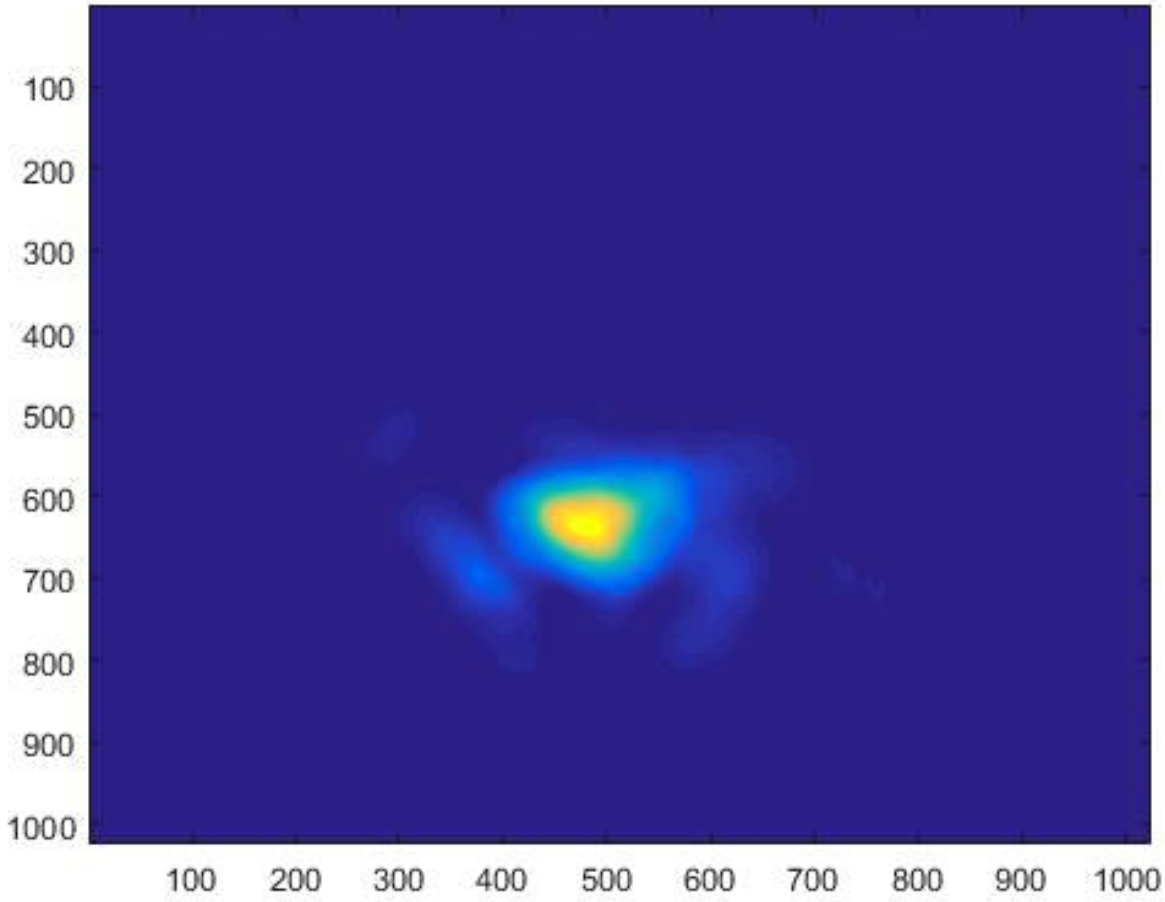
# Downlink Beam Scintillation

- Downlink beam coherence is broken up through turbulence, many light and dark spots running over aperture produce signal fades



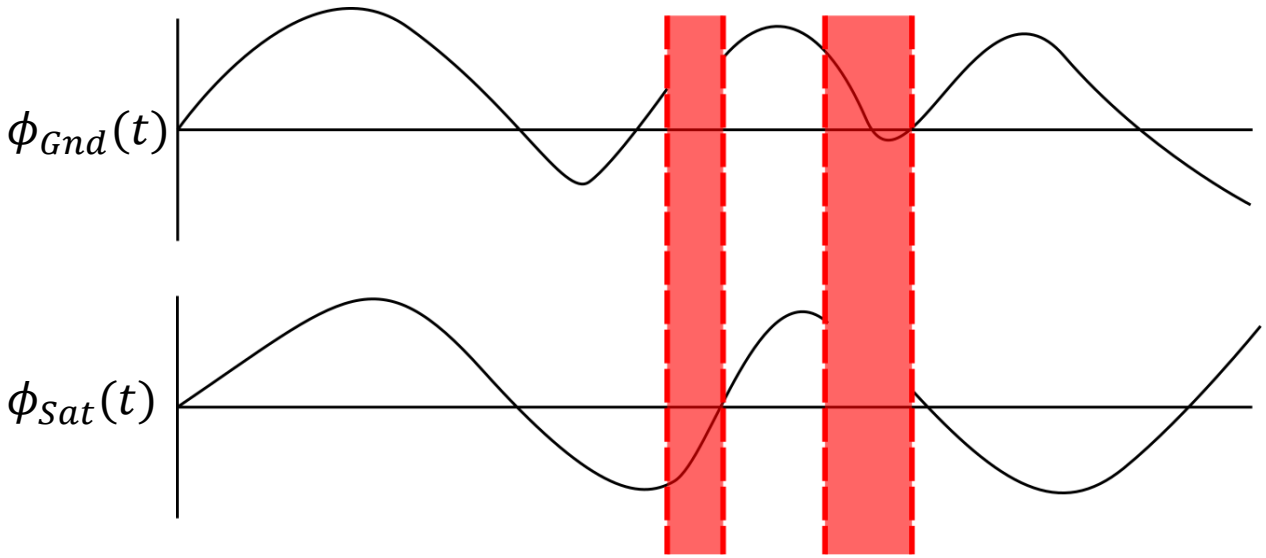
# Uplink Beam Wander

- Refraction through turbulence causes beam steering, potentially large and long fades at satellite



# Simulating Two-Way Satellite Time Transfer

- Time series of simulated intensity and phase measurements on ground and at satellite
- Identify performance penalty due to partial reciprocity




Fading on either end drops two-way comparison

# Conclusions

- Satellite optical communications links can be used for precision time transfer and ranging
  - 1ps timing achievable with current space hardware
- Partial reciprocity of the atmosphere limits achievable time-transfer performance
  - Limit closer to fs level, noticeable on coherent detection systems
- Satellite optical uplinks are an important research topic for communications and time-transfer
  - Limited ability to correct uplink from downlink
  - Beam wander a significant challenge

# Thank You!

Questions?