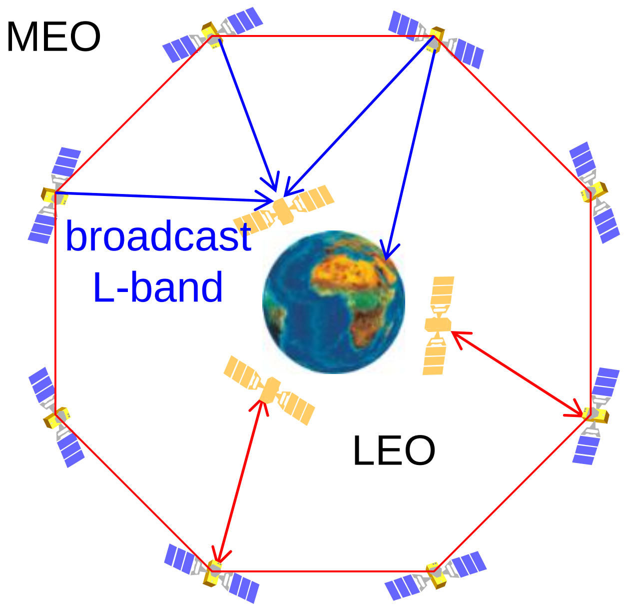
Optical Technologies for Global Satellite Navigation and Time Metrology

Christoph Günther

DLR

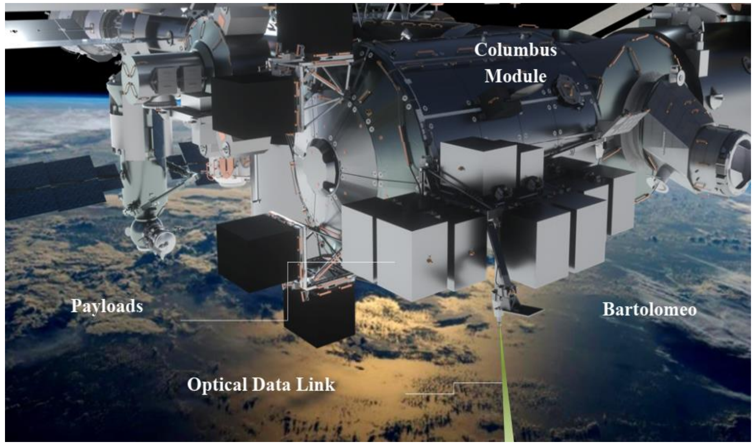
Kepler System in a Nutshell

- Reuse of the Galileo orbital slots -> migration scenario
- MEO – MEO optical two-way links within the orbital plane
- Ultra stable time references – cavity stabilized lasers
- Inter plane connectivity through LEO Satellites (constellation of 6 satellites at 1209 km)
- Iodine clocks on the LEO for autonomous time keeping up to roughly 1 hour
- Observation of the L-band signal from outside the atmosphere
- One ground station to preserve the alignment with earth rotation (not at the pole!) and with UTC
- GFZ: radial error < 1 cm: Michalak, Neumayer, Koenig

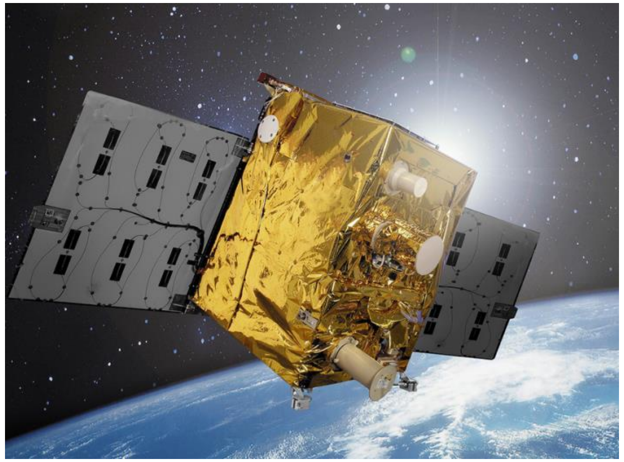


Verification and Validation Plans

- Time and frequency transfer in the Lab 2020 (talk Session B5 by Surof et al.)
- Time and frequency transfer in the test range Weilheim – Hohenpeißenberg 10.4 km in 2020
- Definition of a verification mission in **LEO Orbit**
  - launch 2023
  - optical terminals, (cavity), iodine clock, frequency comb
- OTTEx proposal for **MEO Orbit**
  - launch 2025
  - optical terminals, cavity, frequency comb



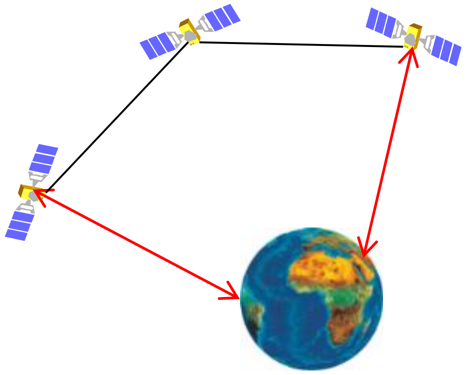
ISS-Bartolomeo



COFROS Satellite

Options for Time and Frequency Transfer

Kepler configuration



slower angular change
larger distances

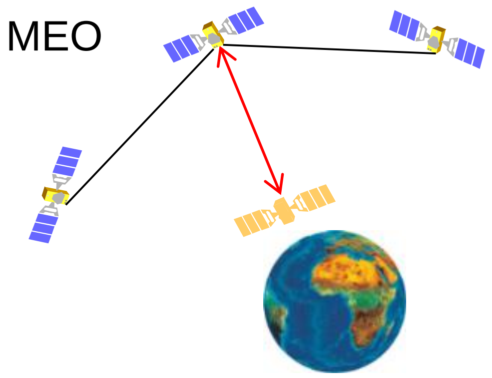
Performance driver

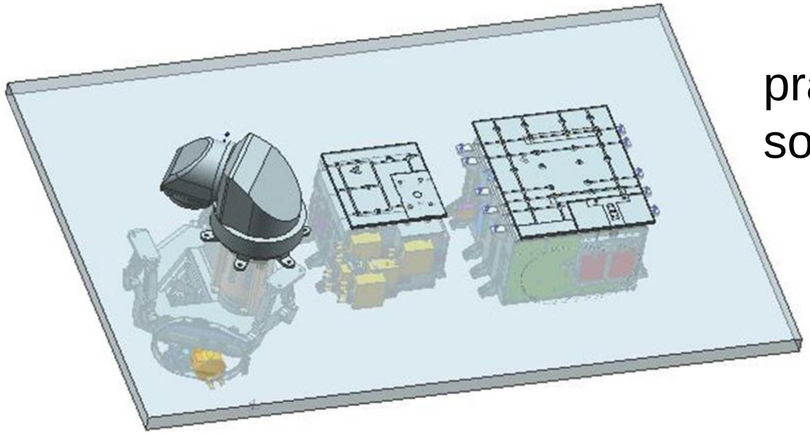
- uncompensated vibrations
  - of the satellites
  - of the terminals
- terminal performance
- laser stabilized on cavity
- atmosphere (spatial and time decorrelation)

LEO verification mission

single step time transfer
earlier availability

Inter-Terminal Noise and Offsets

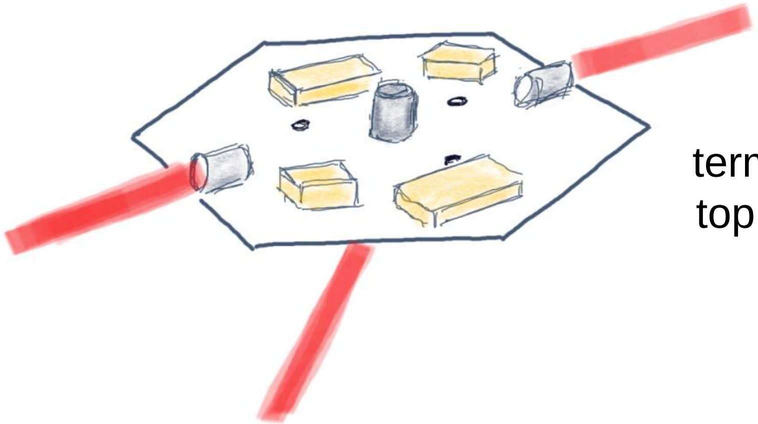




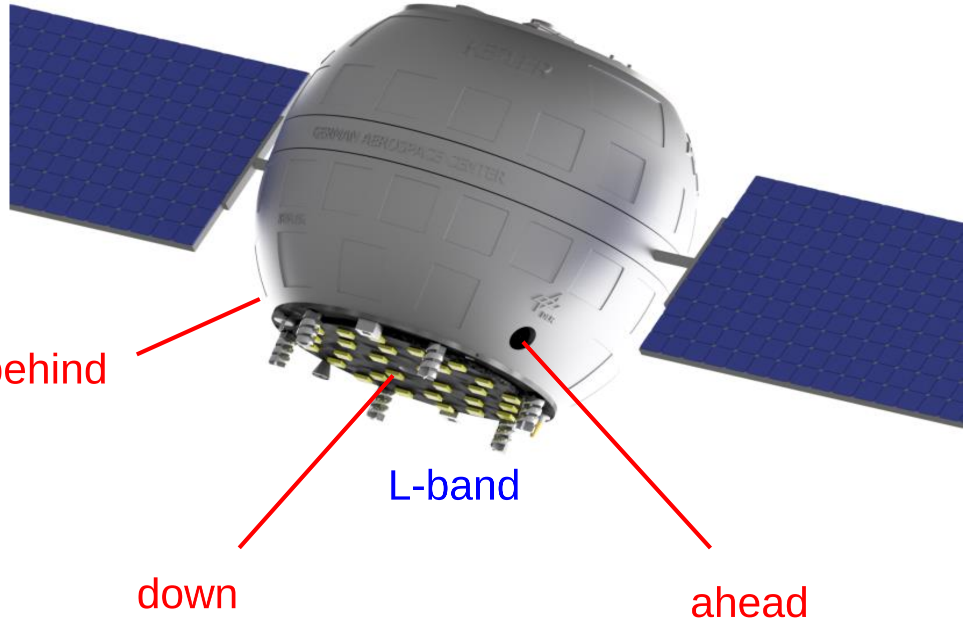
pragmatic solution

TESAT Spacecom
LEO/GEO 2020

Potentially stable configuration

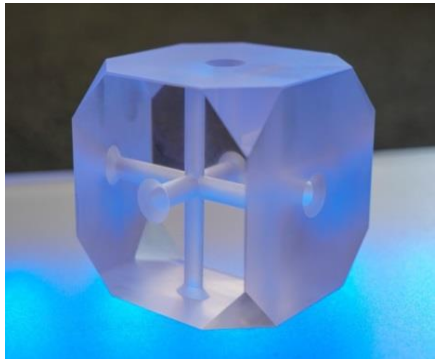


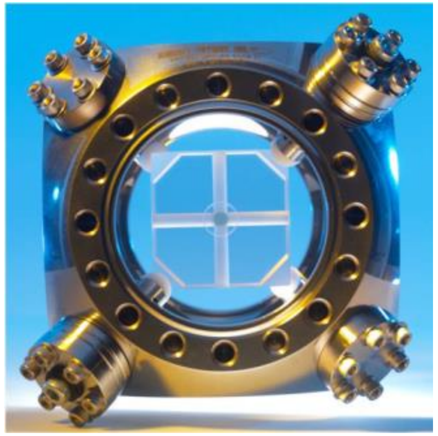
terminal, top view



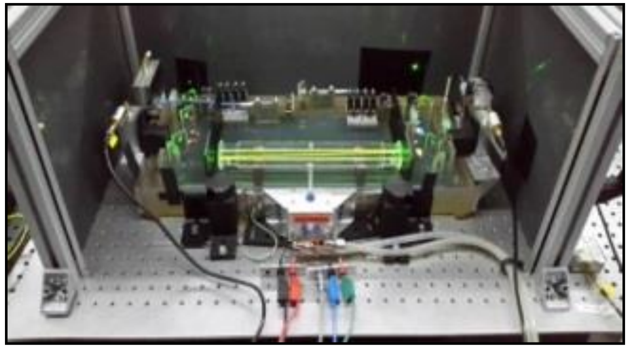
Cavities (all satellites) and Iodine Clocks (LEO)

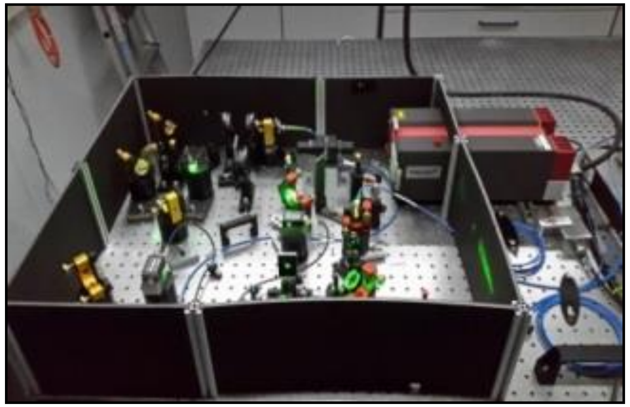
Cavity-stabilized laser
NPL, Airbus, ESA



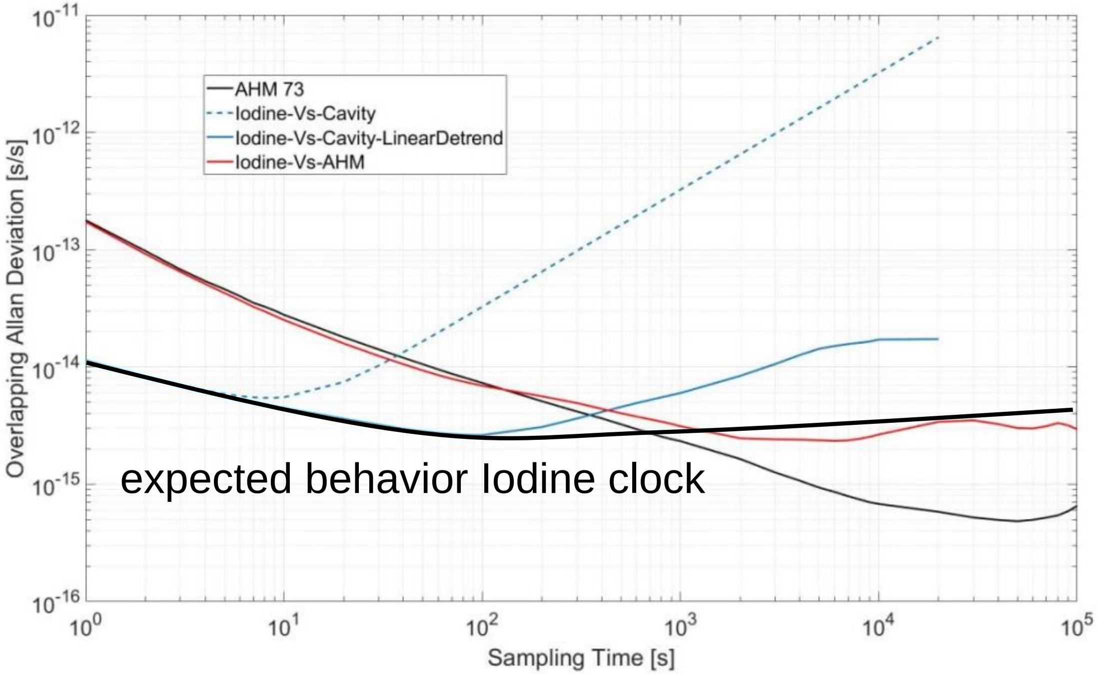


Iodine reference
Schuldt, Braxmaier



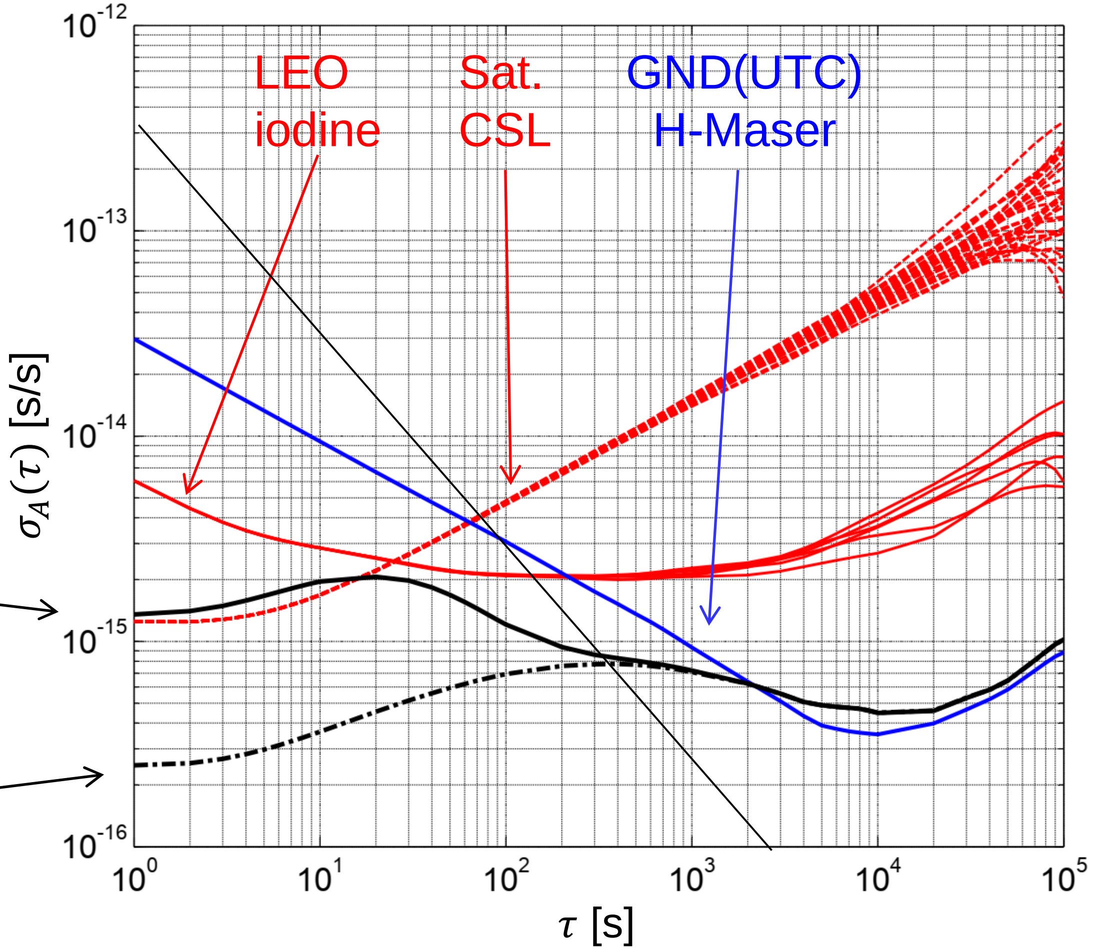


Characterization of stability
Schmidt, Schuldt



Clock Models and Time Synchronization

Ensemble mean of the composite clock



Kepler time scale
$\sigma_A < 2 \times 10^{-15}$

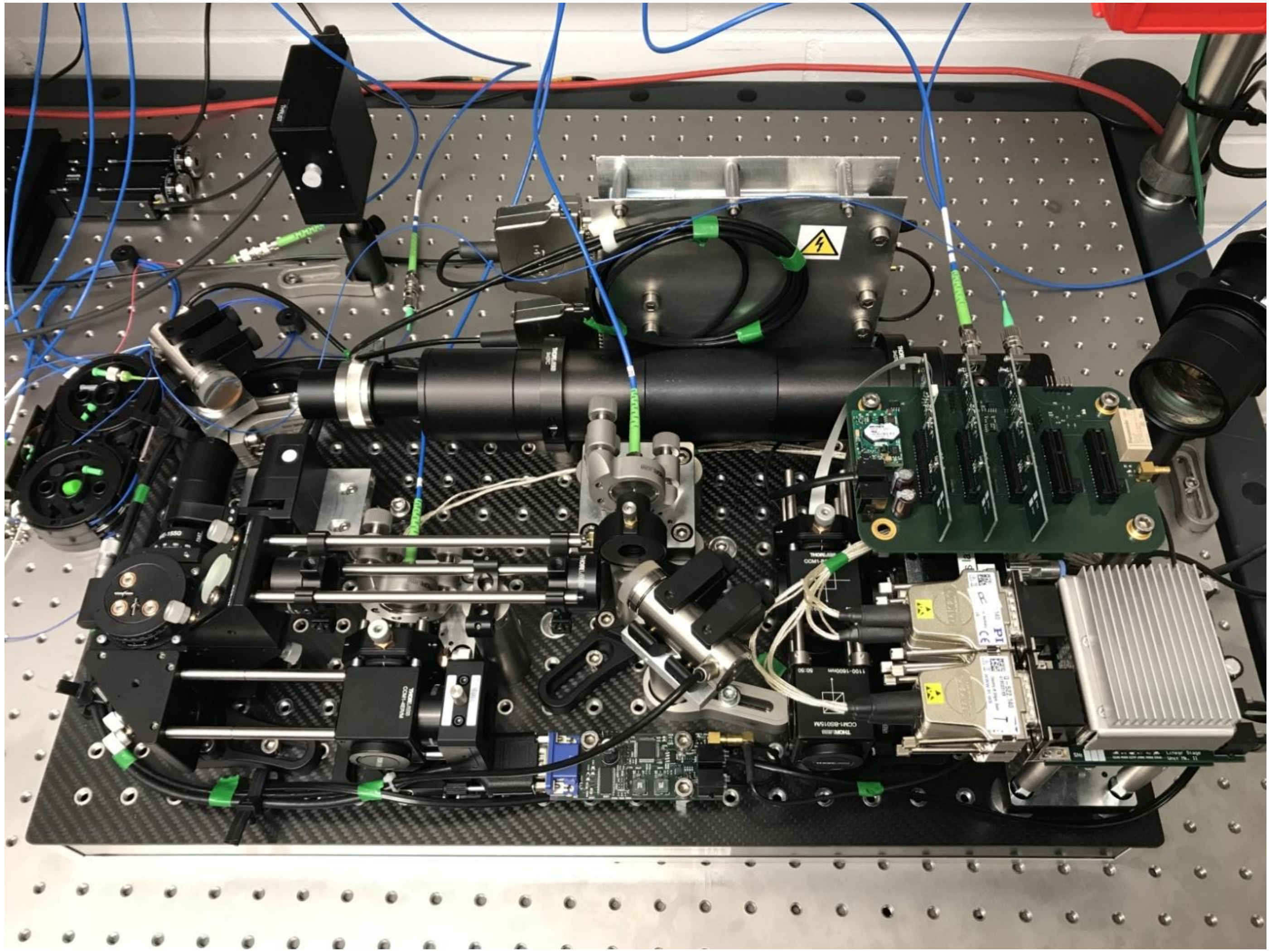
Implicit ensemble mean

Trainotti

Trainotti, Giorgi, Furthner
Detection and Identification of Faults in Clock Ensembles

ION GNSS 2019, Session E6

Optical Inter-Satellite Terminal Prototype



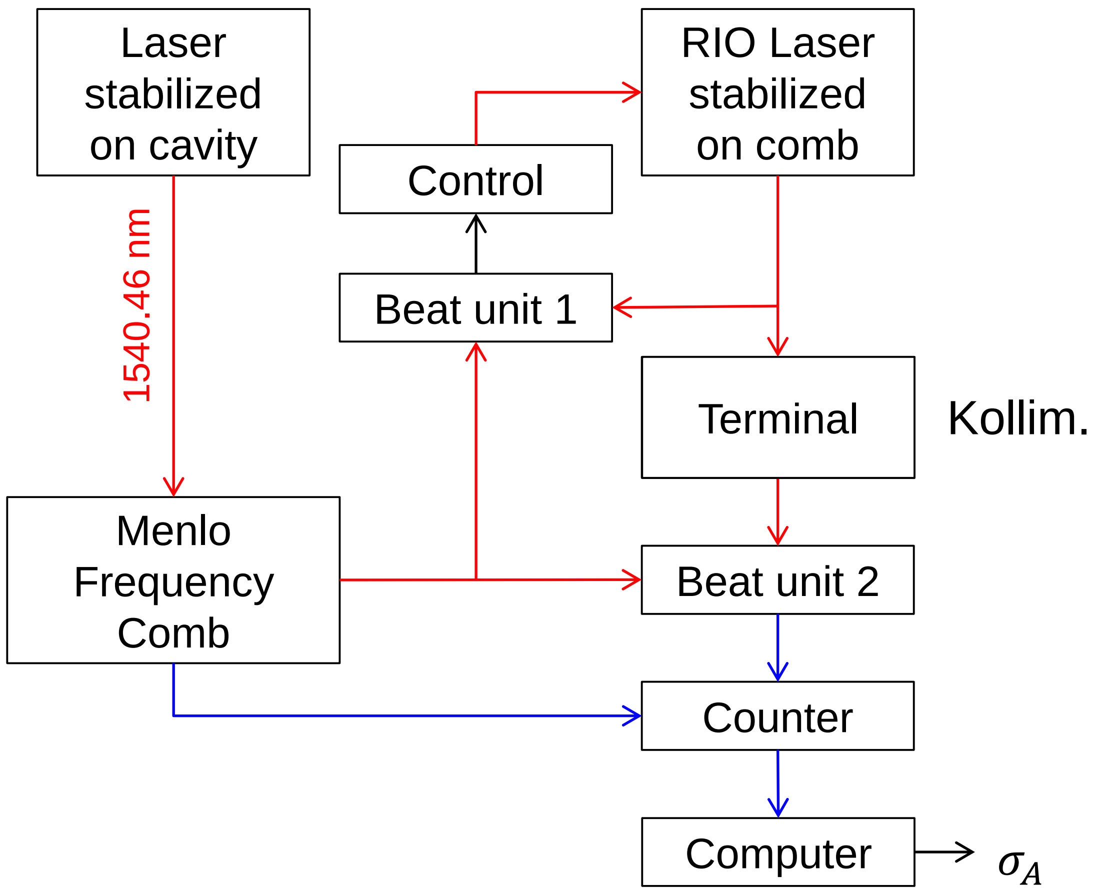
Surof, Poliak, Schmidt, Mata Calvo, Furthner

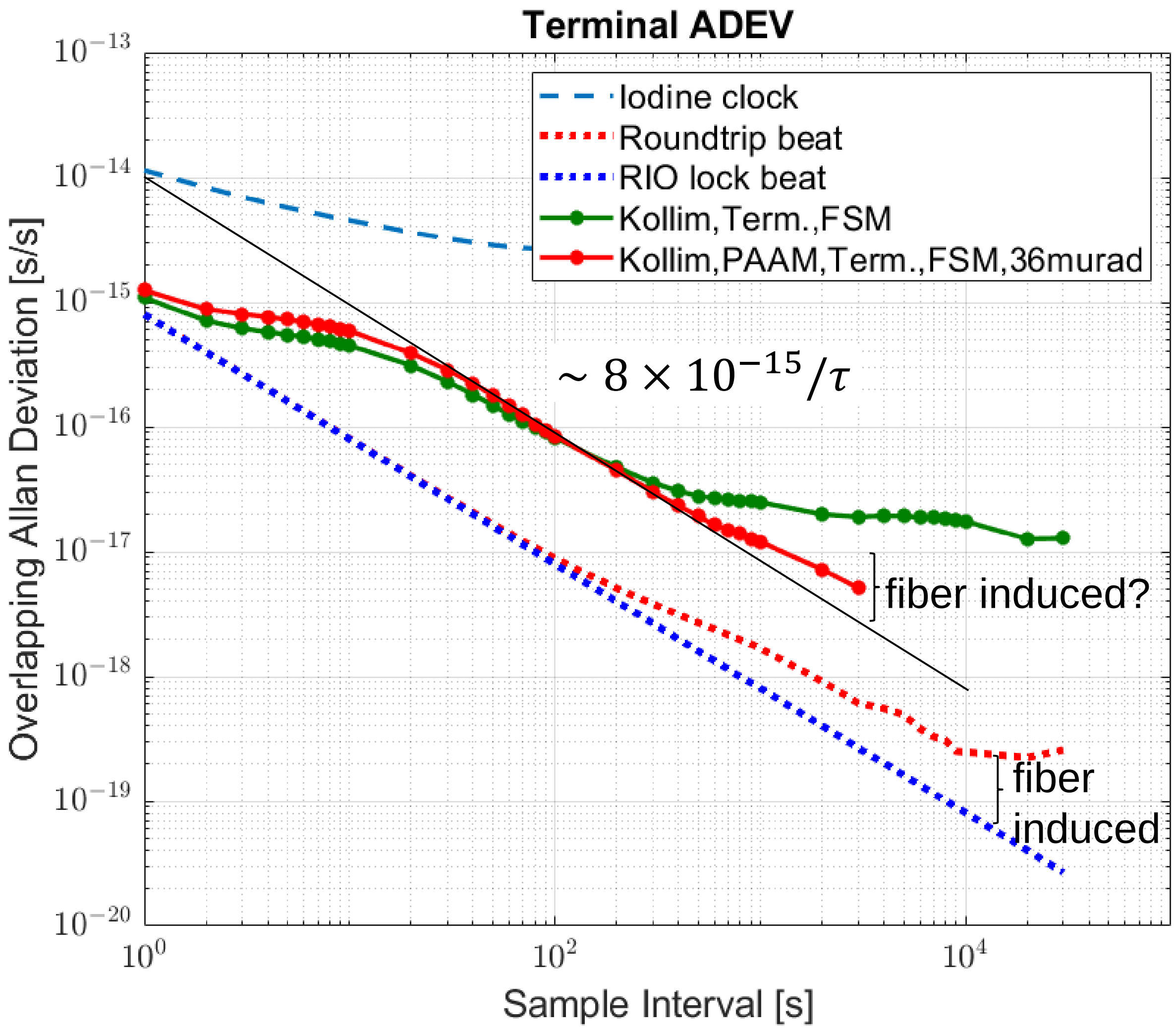
See also:
Surof, Poliak, Mata Calvo, Richerzhagen, Wolf, Schmidt

Laboratory Characterization of Optical Inter-satellite Links for Future GNSS

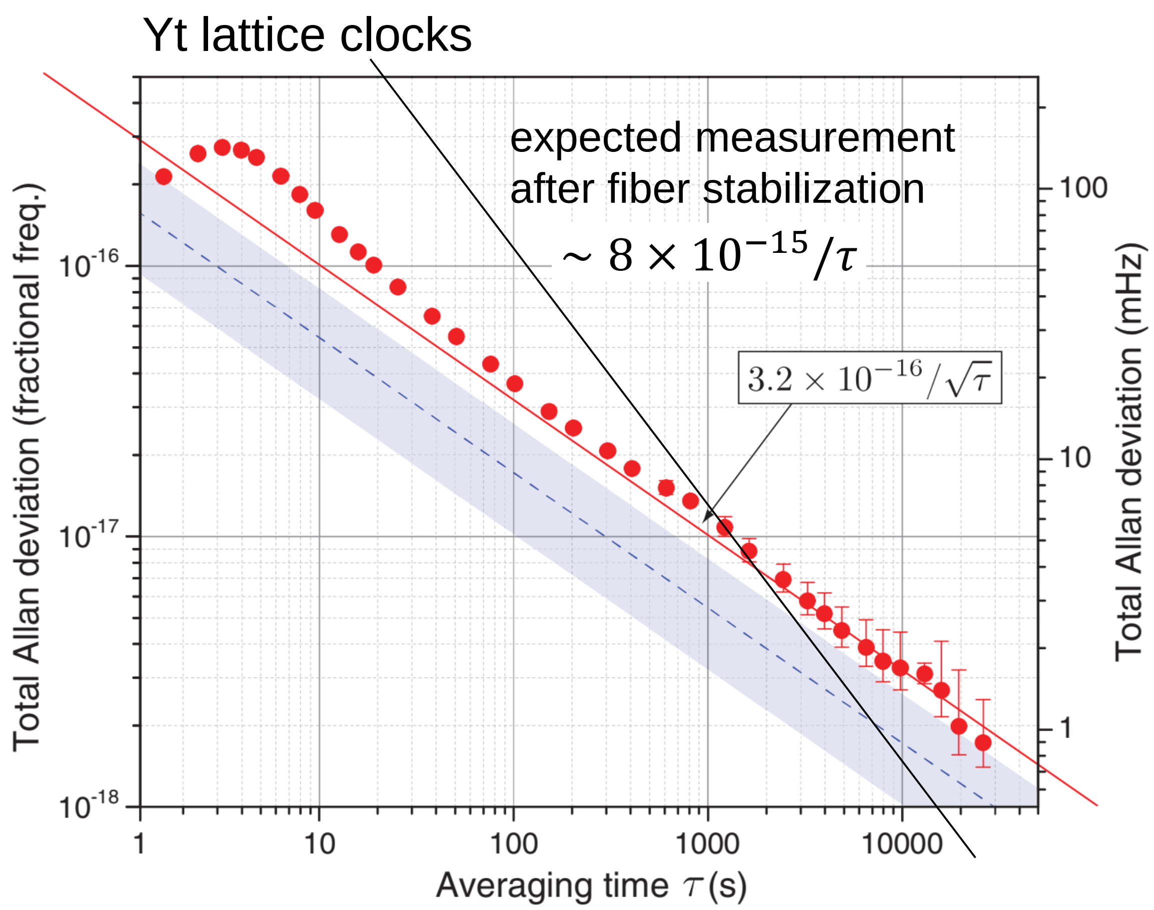
ION GNSS 2019, Session B5

Measurement Setup





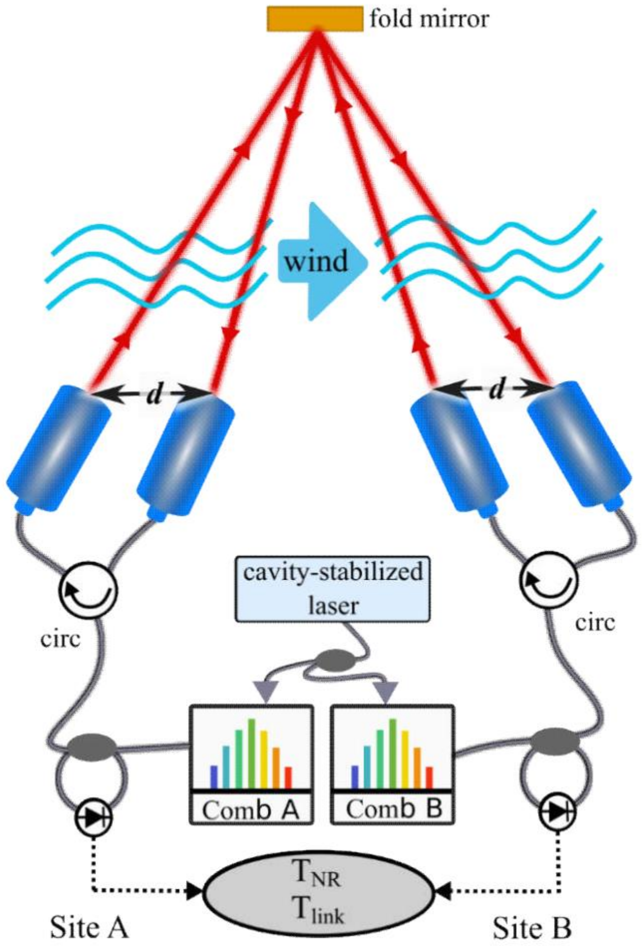
What can we hope for?
Is it useful?

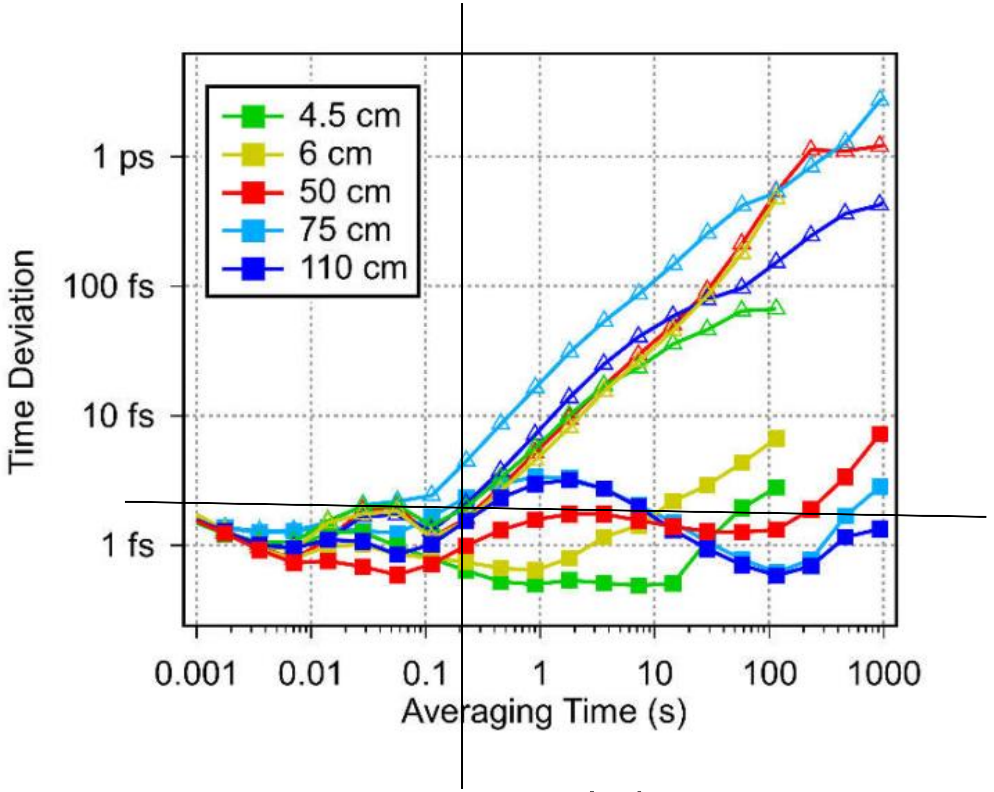


Hinkley et al., *Science 2013*

- What do we need for establishing an optical definition of the second?
- What do we need for an optical UTC standard?
- What if this standard was space based?
- What can we use precise time distribution for otherwise?
  - Relativistic geodesy?
  - Benefits compared to the tracking of probe masses (satellites)?

The Influence of the Atmosphere





round trip< 200 ms

accumulated error < few fs
on each of the measurements

$\sim \mathrm{n} \times 10^{-14}/\tau$

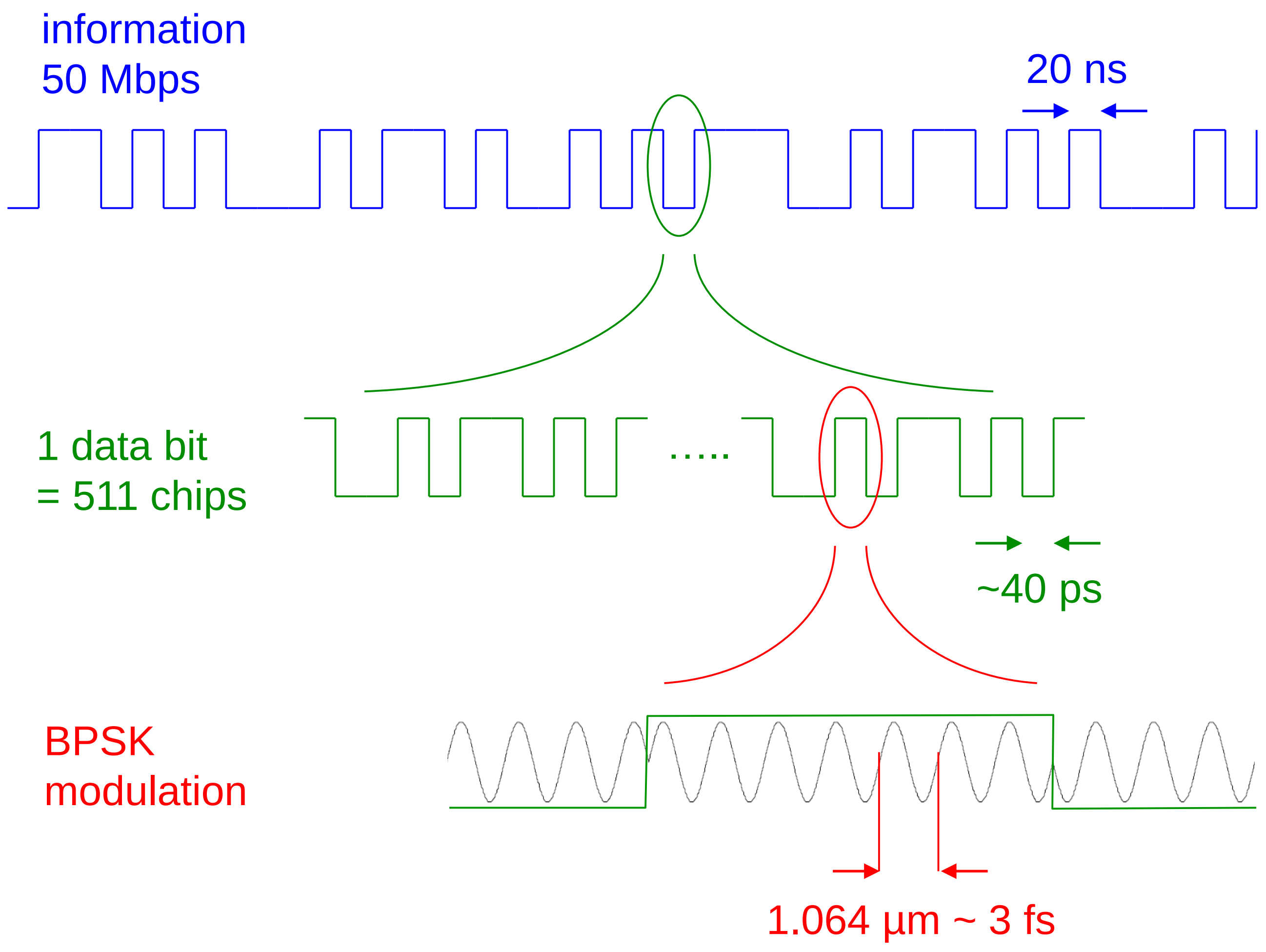
similar influence like terminal

Swann et al. arxiv:1811.10989.pdf

The Optical Signal = DSSS in the Optical Domain

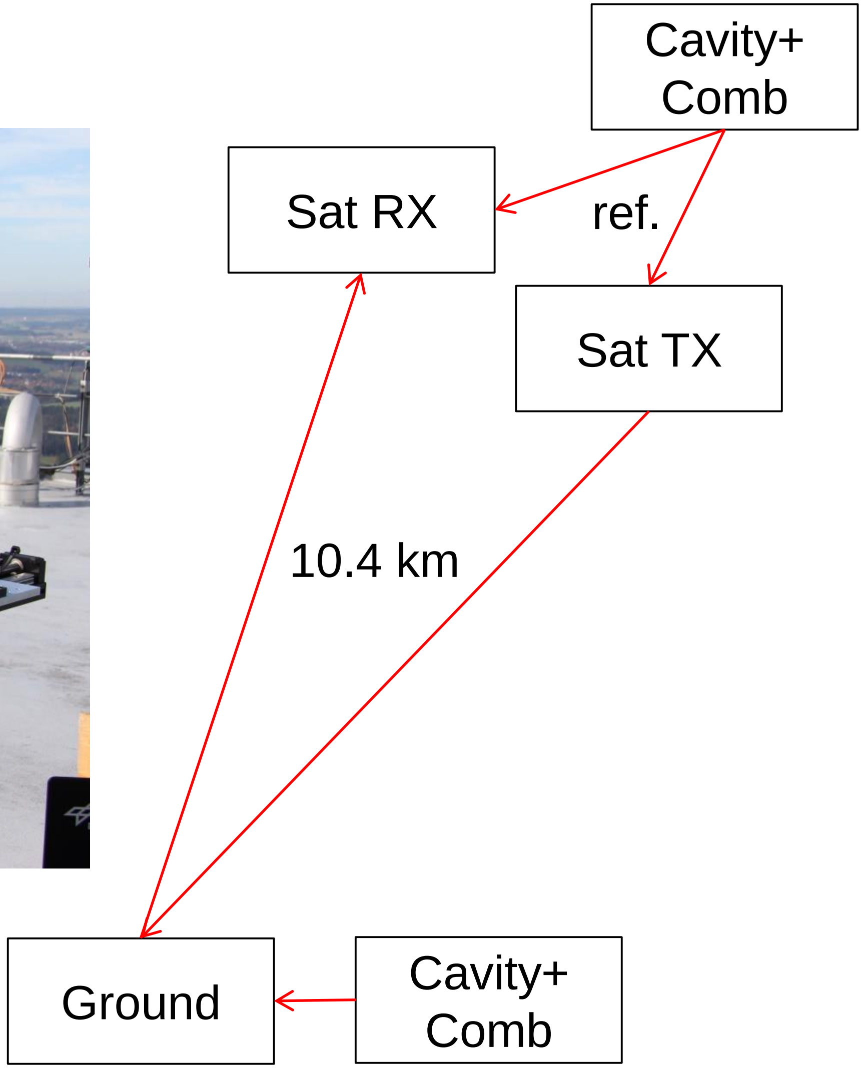
- Carrier frequency Nd:YAG
- Spread spectrum code: 511
- Bit modulation of 50 Mbps
- Duplex: polarization (and frequency)
- Chip rate: 25.51 Gcps
- Link budget assumes
  - Size of aperture 5-7 cm
  - Power < 5 W
  - driven by 50 Mbps
- $\sigma_{code} \sim 25\ \mu m = 75 fs$
- $\sigma_{carrier} \sim 2.5\ as$

  } @ 10 ksps (theory)
- Performance limited by the satellite, by the terminal and by the cavity



Optical Atmospheric Ground Tests

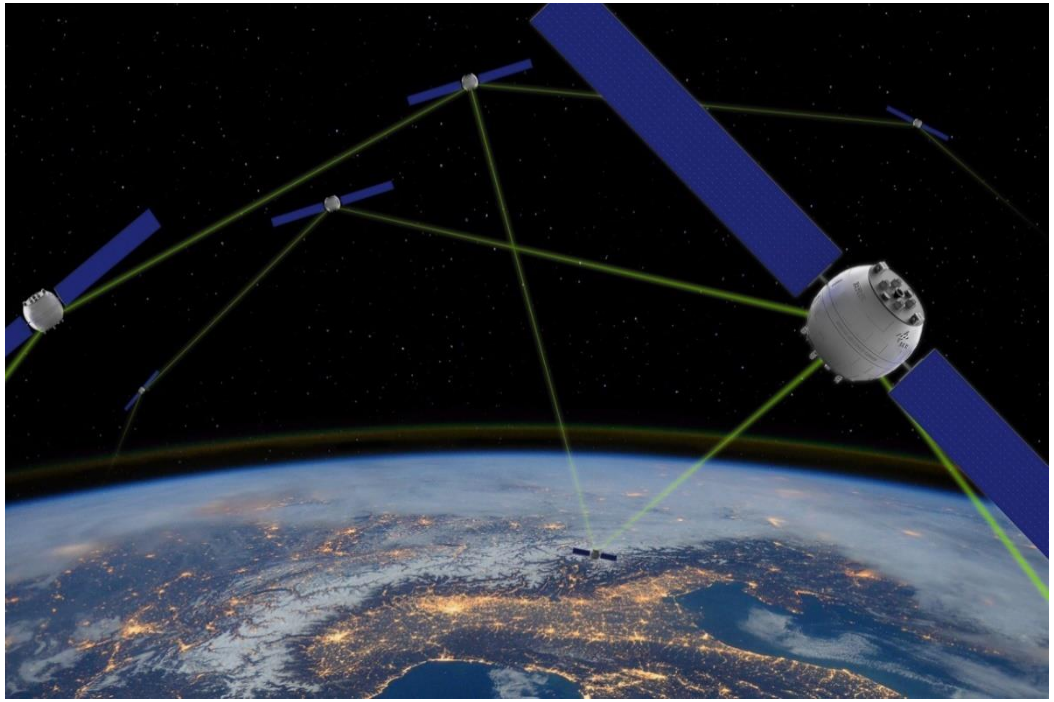
Image taken from DWD Hohenpeißenberg (SAT)



Impressions from the Test Sites…

Outlook

- Optical technologies for satellite navigation
  - very tight synchronization
  - selected precise ranges
  - high data transport capability
  - no jamming and spoofing
- How interesting are they for the time community?
  - At which level do we need to synchronize clocks?
  - Which geographic coverage, how often?
- How interesting is it for geodesy?



Acknowledgements

This work was performed in the project ADVANTAGE (Advanced Technologies for Navigation and Geodesy) project, and co-funded by the "Impuls- und Vernetzungsfond" of the Helmholtz Association under research grant ZT-0007.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

ADVANTAGE

DLR