Optical Technologies for Global Satellite Navigation and Time Metrology

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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
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

Potentially stable configuration

MEO

pragmatic solution

TESAT Spacecom
LEO/GEO 2020
Cavities (all satellites) and Iodine Clocks (LEO)

Cavity-stabilized laser
*NPL, Airbus, ESA*

Iodine reference
*Schuldt, Braxmaier*

Characterization of stability
*Schmidt, Schuldt*

[Graph showing expected behavior of iodine clock]
Clock Models and Time Synchronization

Ensemble mean of the composite clock

\[ \sigma_A (\tau) [s/s] \]

- LEO
- iodine
- Sat.
- CSL
- GND(UTC)
- H-Maser

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

Implicit ensemble mean

Trainotti, Giorgi, Furhtner
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

- Laser stabilized on cavity
- RIO Laser stabilized on comb
- Beat unit 1
- Terminal
- Beat unit 2
- Counter
- Computer

Menlo Frequency Comb

Kollim.

~ $8 \times 10^{-15} / \tau$

Terminal ADEV

- Iodine clock
- Roundtrip beat
- RIO lock beat
- Kollim, Term., FSM
- Kollim, PAAM, Term., FSM, 36 murad

Overlapping Allan Deviation [s/s]

Sample Interval [s]
What can we hope for?
Is it useful?

- 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)?

Yt lattice clocks

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expected measurement after fiber stabilization
≈ 8 \times 10^{-15} / \tau
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Hinkley et al., *Science* 2013
The Influence of the Atmosphere

round trip < 200 ms
accumulated error < few fs on each of the measurements
$\sim n \times 10^{-14}/\tau$

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

- $\sigma_{\text{code}} \sim 25 \mu m = 75 fs$
- $\sigma_{\text{carrier}} \sim 2.5 as$

- Performance limited by the satellite, by the terminal and by the cavity

BPSK modulation

1 data bit = 511 chips

~40 ps

20 ns

1.064 µm ~ 3 fs

information
50 Mbps

1 data bit

~40 ps

20 ns

1.064 µm ~ 3 fs
Optical Atmospheric Ground Tests

Image taken from DWD Hohenpeißenberg (SAT)

Cavity+ Comb
Sat RX
Sat TX

ref.

10.4 km

Ground

Cavity+ Comb
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?

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