Signal-in-Space Range Error analysis of the simulated broadcast ephemerides for the KEPLER system

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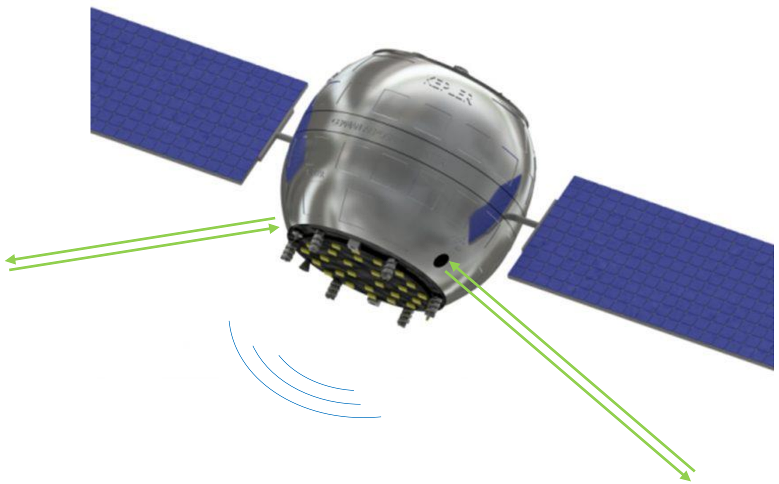
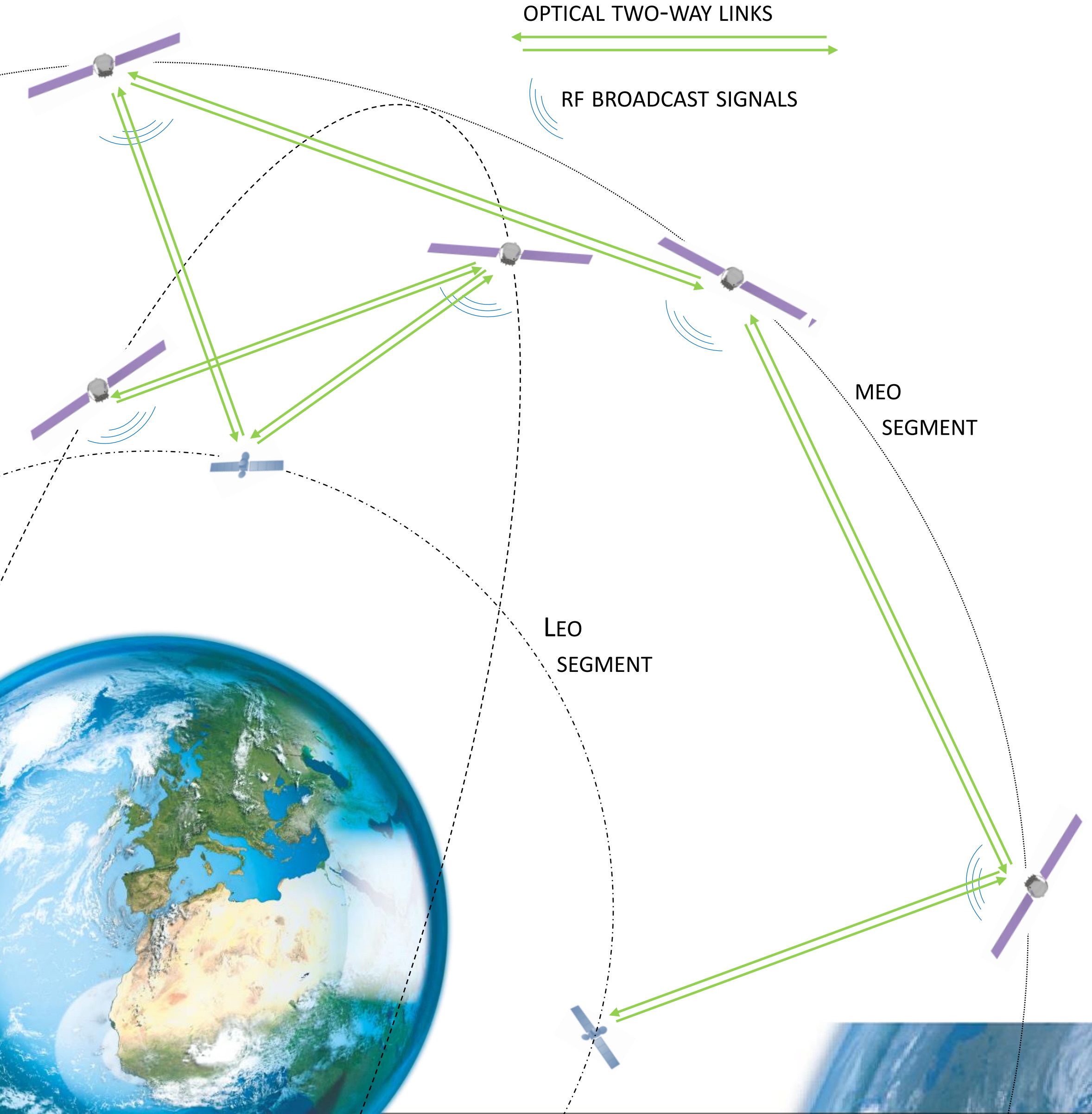
Knowledge for Tomorrow

Outline

- Kepler system
- ODTS results
- Prediction system
  - Orbits, clocks and ERPs for Galileo and Kepler
  - Galileo with modelling errors – emulation of actual SiSRE
- Analysis of simulated broadcast ephemeris
  - Fit errors
  - Quantization (truncation) errors
  - Reduction of the quantization errors
- Conclusions



Kepler – a next generation GNSS and processing architecture



- MEO segment – Galileo-like satellites
- Complementary LEO segment – 6 satellites at altitude of 1200 km
- Optical inter-satellite links (OISLs)
  - two-way time transfer
  - autonomous ps-level in-space clock synchronization
  - inter-satellite ranging with mm-level precision
  - high data rates 50 – 100 Mbps

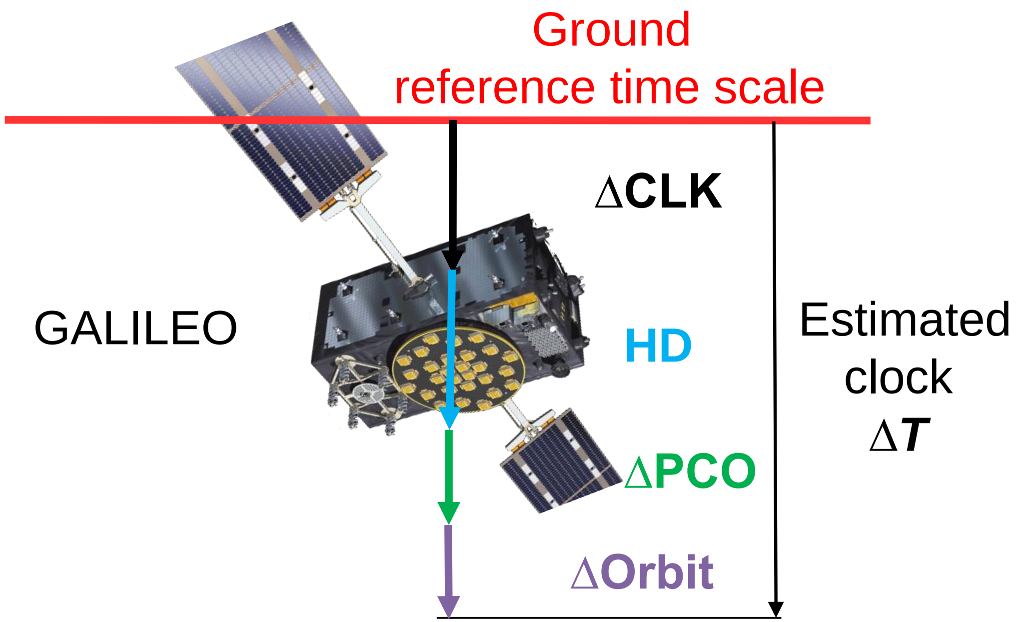
✓ Enhanced orbit determination via inter-satellite ranging

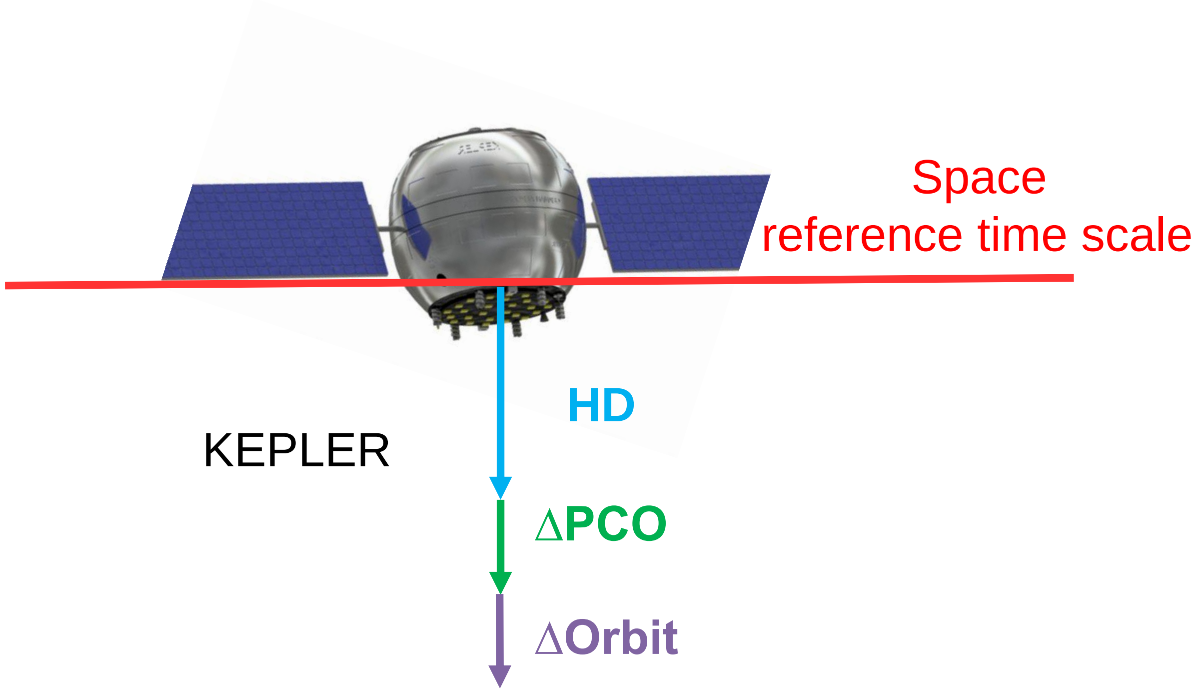
✓ Reduced, regional ground segment

✓ Signal-in-space quality enhancement

✓ Faster and more accurate global positioning and timing services

Galileo vs. Kepler concept





- **Reference time scale –** defined by a fixed ground clock
- **Satellite iono-free 'clocks' estimated epoch-wise**
  - Δ*T* absorbs
  - ✓ Clock proper **ΔCLK**
  - ✓ Hardware delay **HD**
  - ✓ 95% of radial phase center offset error **ΔPCO**
  - ✓ Large part of orbit radial error **ΔOrbit**

- **Reference time scale –** defined by synchronized MEO clocks
- **Satellite clocks not estimated – fixed to null in POD**
  - Cannot absorb HDs, PCO and orbit radial errors
- Different HDs = L-band signals are not synchronized

Precise calibration of HDs and PCOs is essential

Signal-in-Space Range Error (SiSRE)

GALILEO: Global average SiSRE value, dual frequency, ionosphere-free

$$SiSRE = \sqrt{(w_R \Delta R - \Delta T)^2 + w_{AC}^2(\Delta A^2 + \Delta C^2)}$$

ΔR is orbit radial error
ΔC is orbit cross-track error
ΔA is orbit along-track error
} difference to ‘true’ antenna phase center in ECEF
ΔT is ‘clock’ estimation error
Weights $w_R = 0.98 \;\; w_{AC} \approx 1/8$

KEPLER: Synchronized satellite clocks → no clock estimation error → ΔT split into:

- Ionosphere-free satellite hardware delay calibration error ΔHD^s
- Clock synchronization error Δt_{sync} provided by synchronization sub-system

$$SiSRE = \sqrt{\left(w_R \Delta R - \Delta HD^s - \Delta t_{sync}\right)^2 + w_{AC}^2(\Delta A^2 + \Delta C^2)}$$

- ΔHD^s = 0, hardware delays assumed precisely calibrated

Orbit Determination & Time Synchronization (ODTS)

Simulated ODTS for Galileo and Kepler

- Up to 18 Galileo Sensor Stations (GSSs)
- Kepler clocks synchronized
- L-band code + phase + OISLs
- Real-world models and parametrization
- Modelling errors (SRP, gravity …)
- 4 scenarios analysed

Scenario
1. Galileo (reference)
2. Kepler fast-track OISLs MEO2MEO
3. Kepler fast-track OISLs MEO2MEO + 6 LEOs (L-band)
4. Kepler OISL MEO2MEO + 6 LEOs (L-band) + OISLs MEO2LEO

Orbit Determination & Time Synchronization (ODTS)

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Kepler results

- An order of magnitude SiSRE improvement
- Sub-cm SiSRE with just 1 – 2 stations
- Little impact of LEOs on SiSRE
- LEOs required for signal monitoring

SiSRE (ODTS)

Scenario	18 GSSs	2 stations OBER+REUN	1 station OBER
1. Galileo (reference)	2.4 cm	X	X
2. Kepler fast-track OISLs MEO2MEO	0.2 cm	0.5 cm	1.3 cm
3. Kepler fast-track OISLs MEO2MEO + 6 LEOs (L-band)	0.2 cm	0.5 cm	0.9 cm
4. Kepler OISL MEO2MEO + 6 LEOs (L-band) + OISLs MEO2LEO	0.3 cm	0.4 cm	0.7 cm

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Orbit and clock prediction – an outlook

- Operational GNSS provides navigation message with predicted orbits+clocks for real time navigation
- ODTS is a basis for generating predictions

Question

What orbit prediction SiSRE can be expected from Kepler?

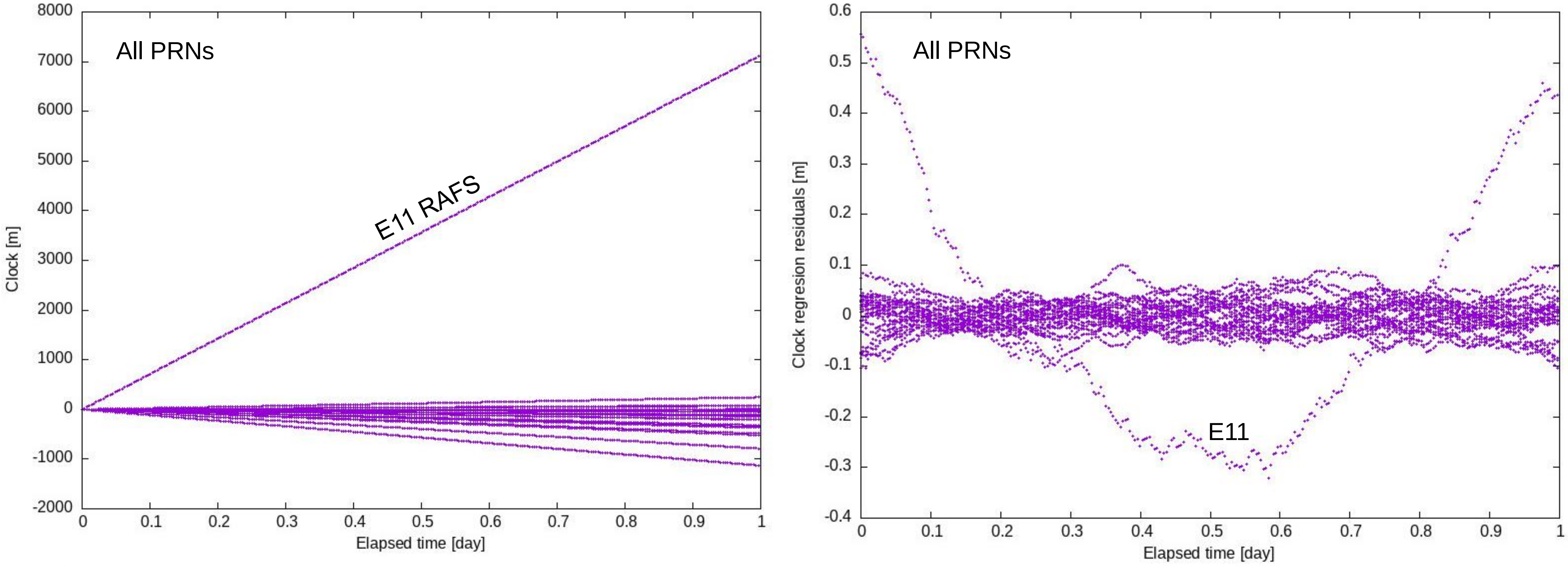
To answer

We are developing a prediction simulator including

1. Prediction of satellite clocks
   - Galileo realistic clock model
   - Kepler clock synchronization noise only (3 mm)
2. Prediction of Earth rotation parameters
3. Dynamic prediction of satellite orbits

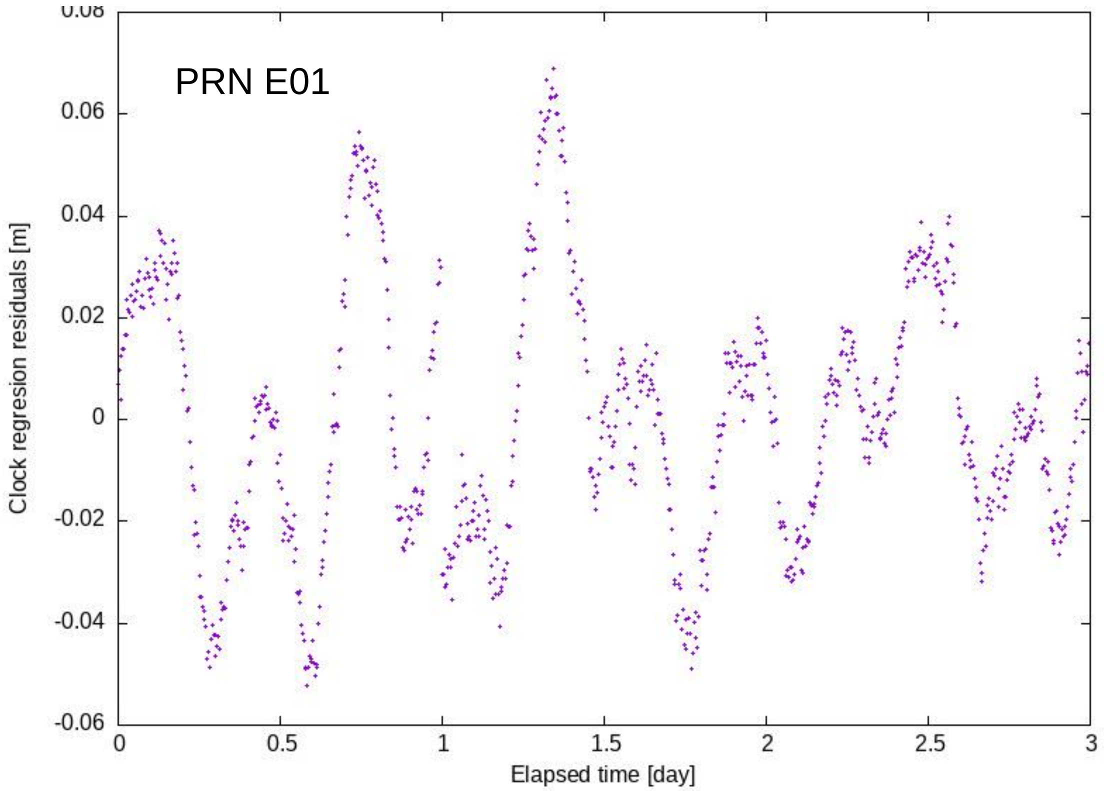
Galileo clocks

Clocks estimated by CODE 2020/09/20



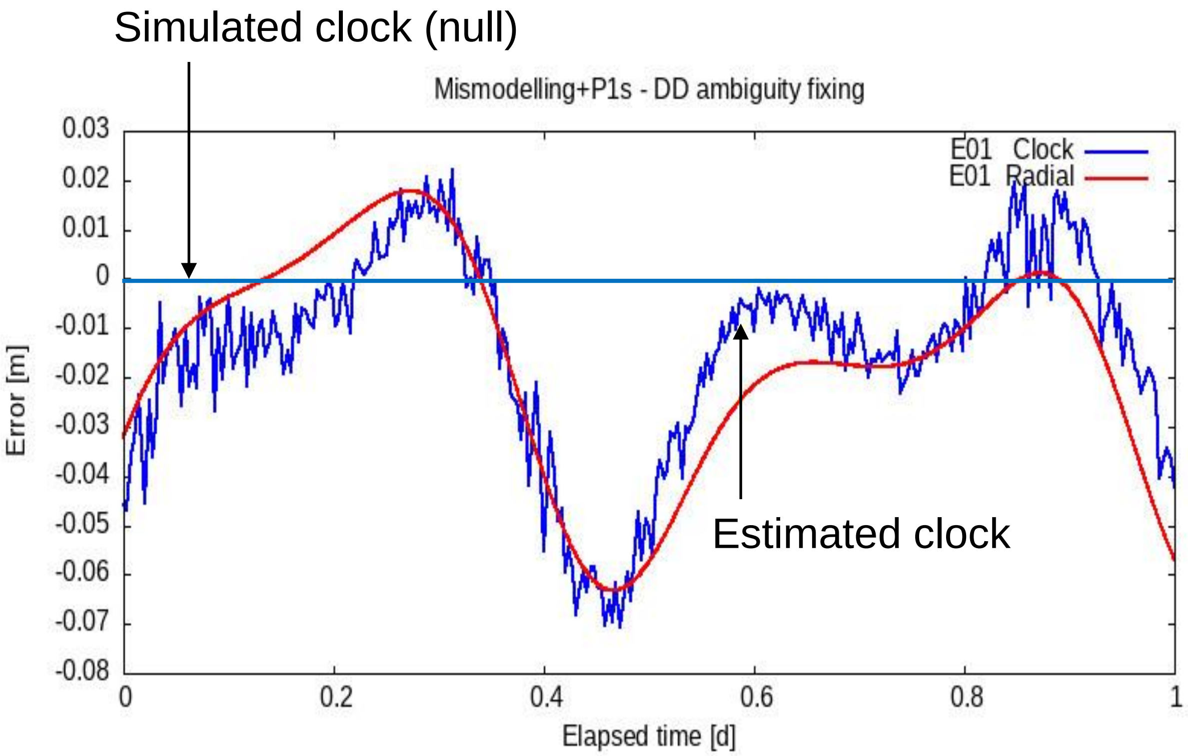
Galileo PHM clocks

CODE clocks 2020/09/20-23



- High-pass filter to remove systematic effects synchronous with the orbital period
- 0.6 cm RMS after filtering

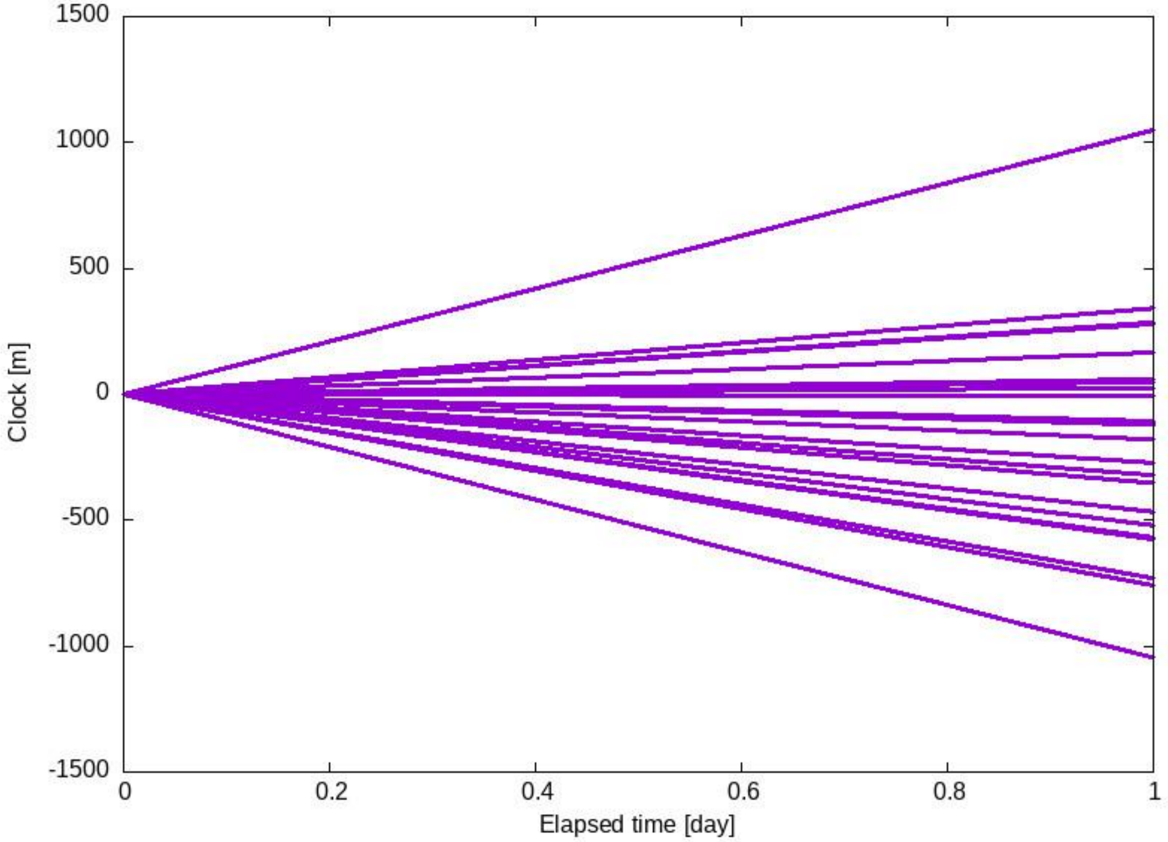
Simulated Galileo POD with modelling errors

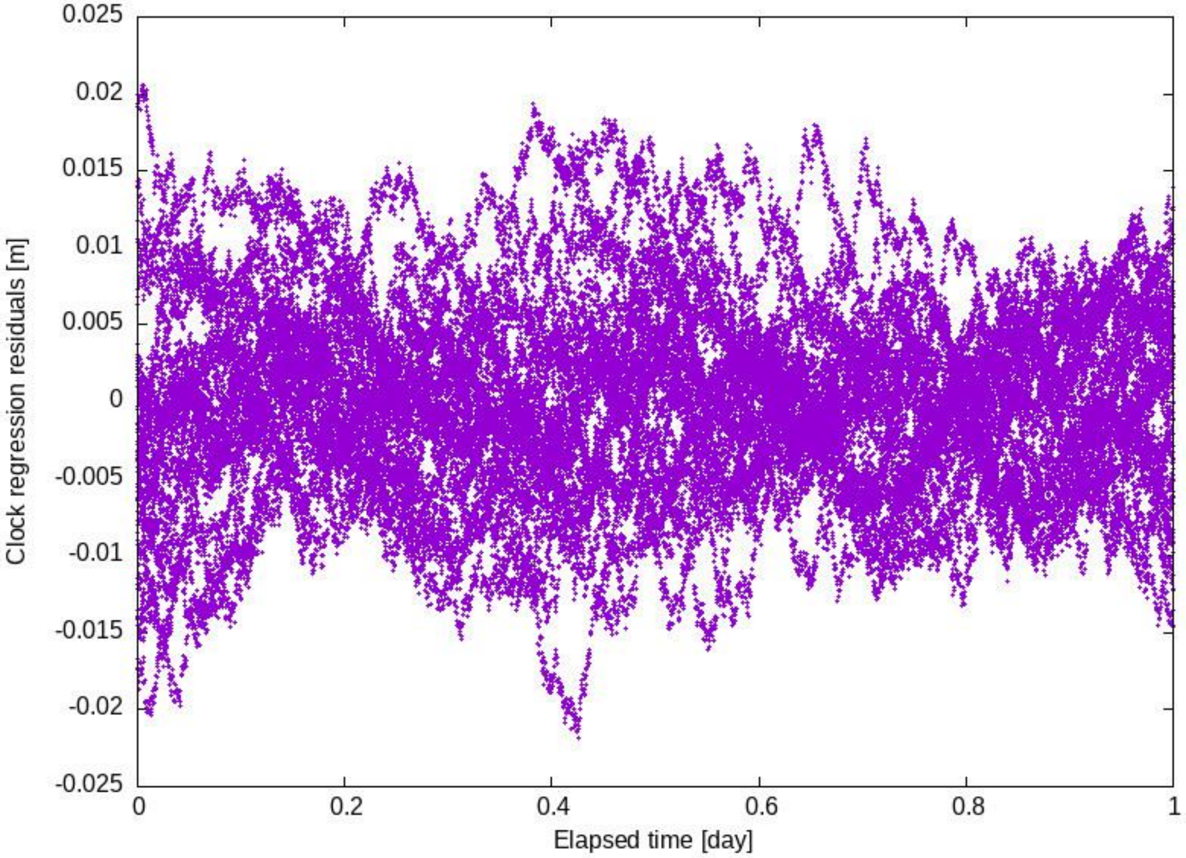


- Estimated clock is clearly correlated with orbit radial error

Galileo clock simulation

PHM simulated with two-state clock model



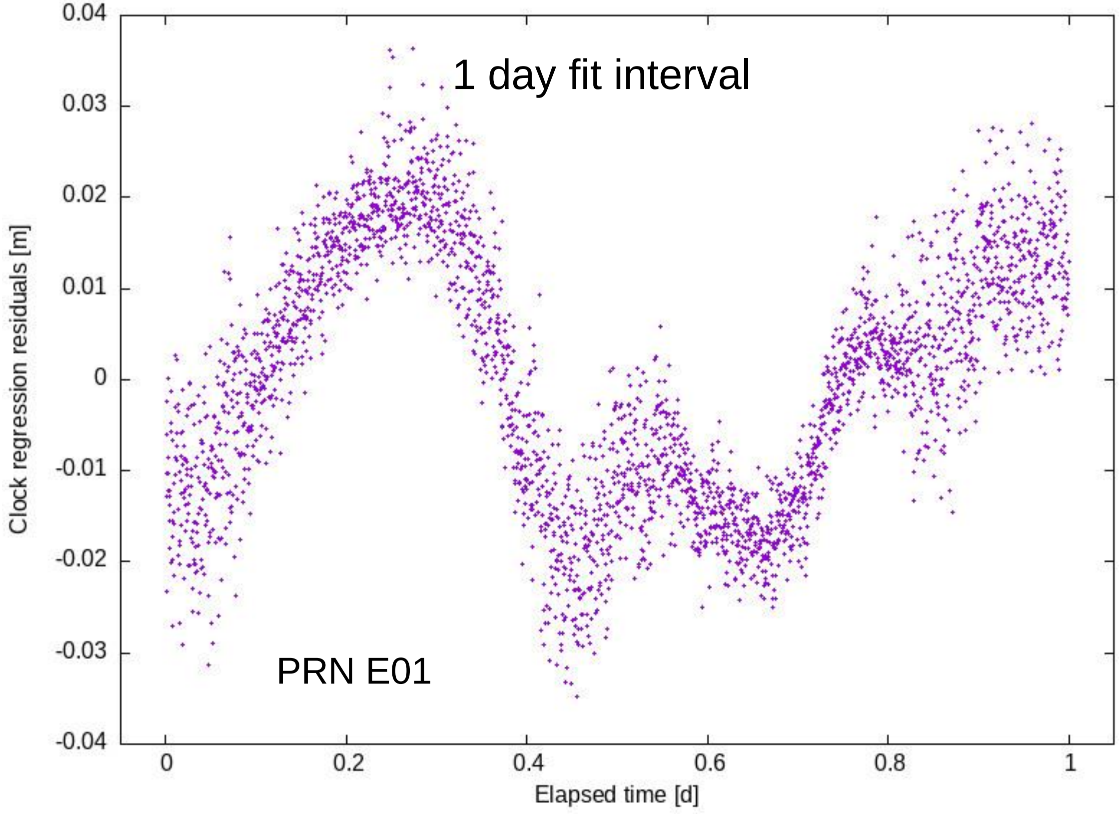


- OADEV 10^{-14} @ 10^{3} s
- 0.6 cm RMS

1. Prediction of Galileo clock

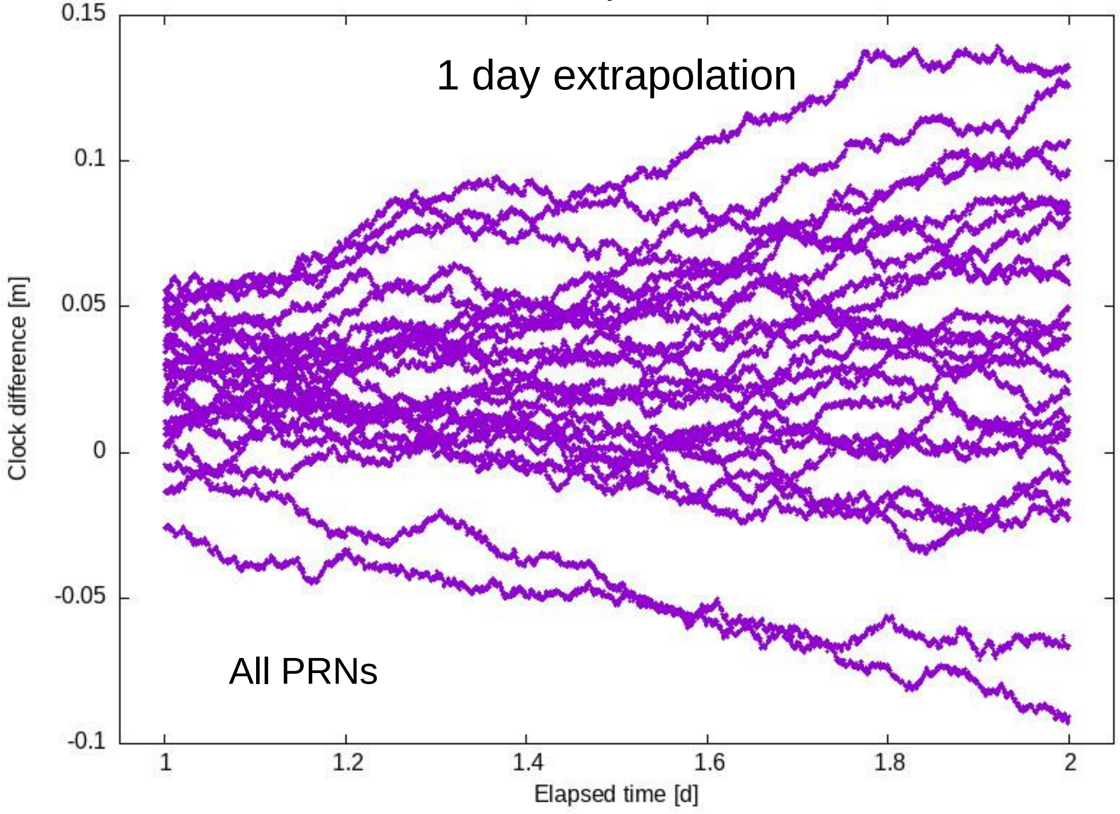
Galileo with perfect models

Linear fit to the clocks estimated in POD



- Deviations due to orbit radial errors

Linear extrapolation error



- Decimeter-level clock prediction error after 1 day

2. Prediction of Earth rotation parameters (ERPs)

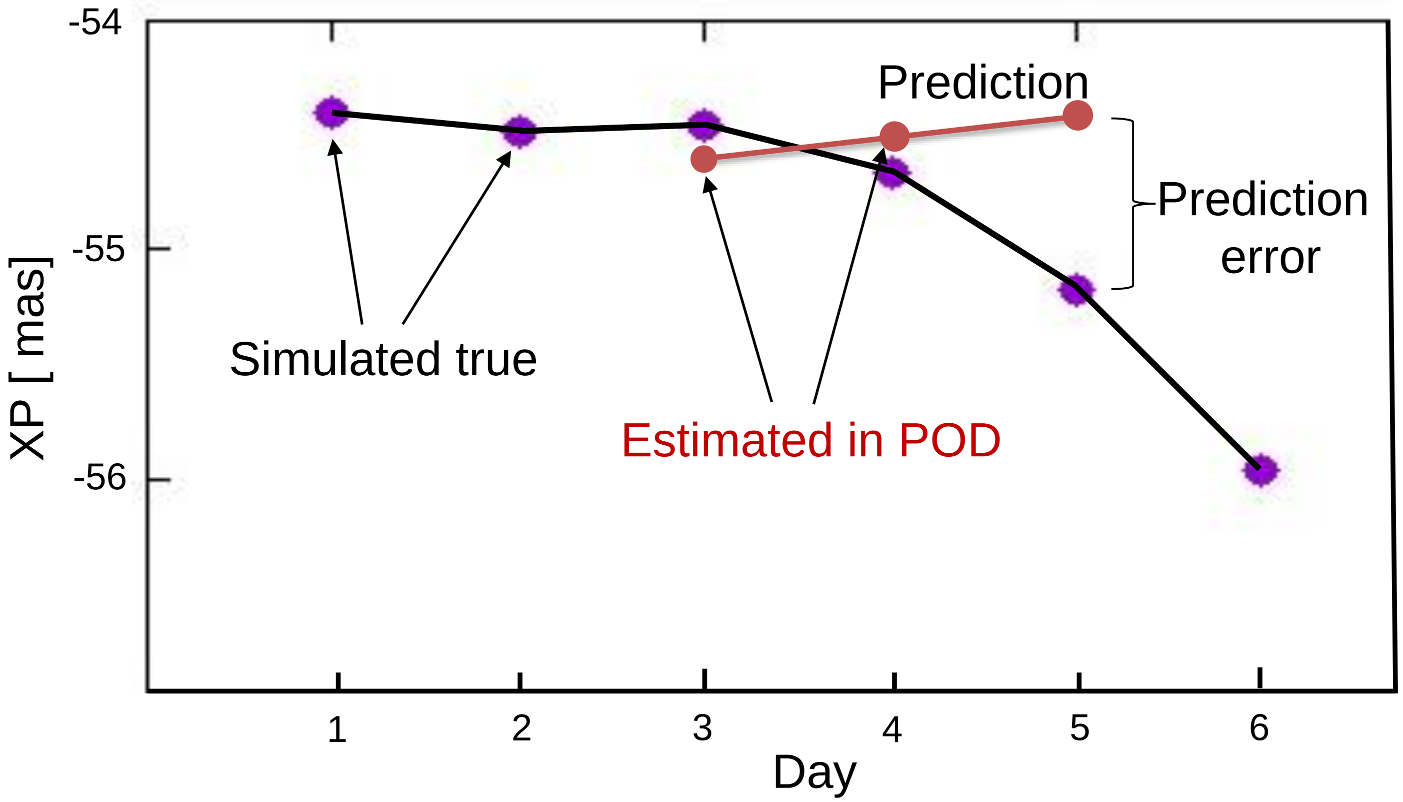
Simulation

- Daily ERP time series from IERS EOP08C04 series
- Pole offsets XP, YP
- Length of day (LOD)
- Linear interpolation between days

Prediction

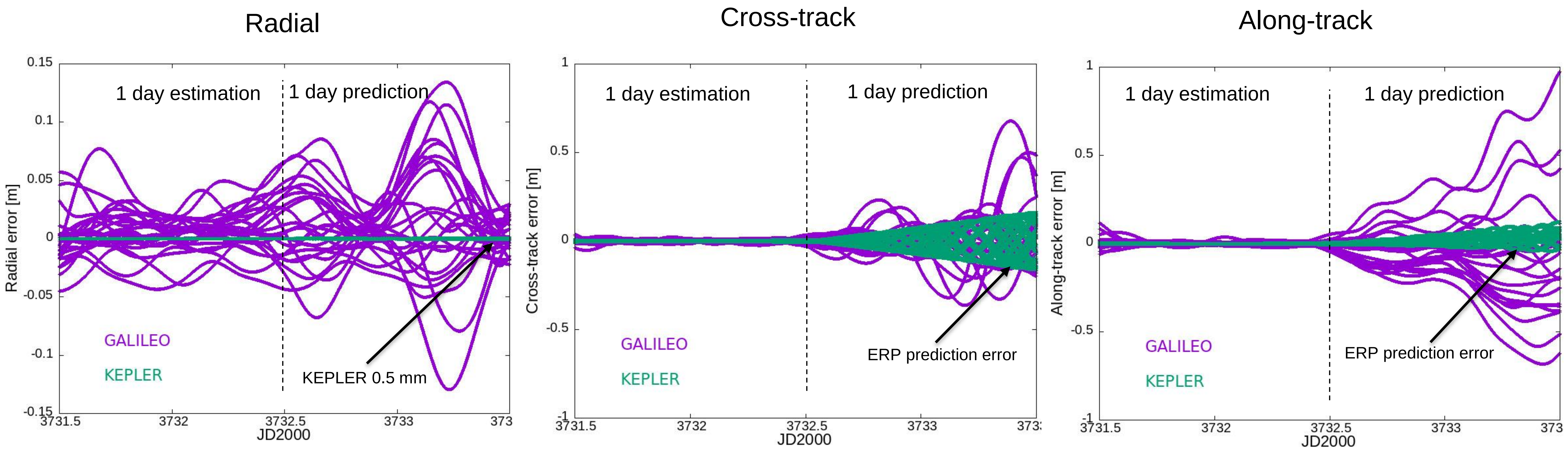
- Linear extrapolation
- Based on points estimated in POD
- Difficult to predict
- Linear prediction error

Illustration of ERP prediction approach



3. Prediction of orbits + ERPs

Galileo 18 GSSs vs. Kepler fast-track 2 GSSs
Perfect models

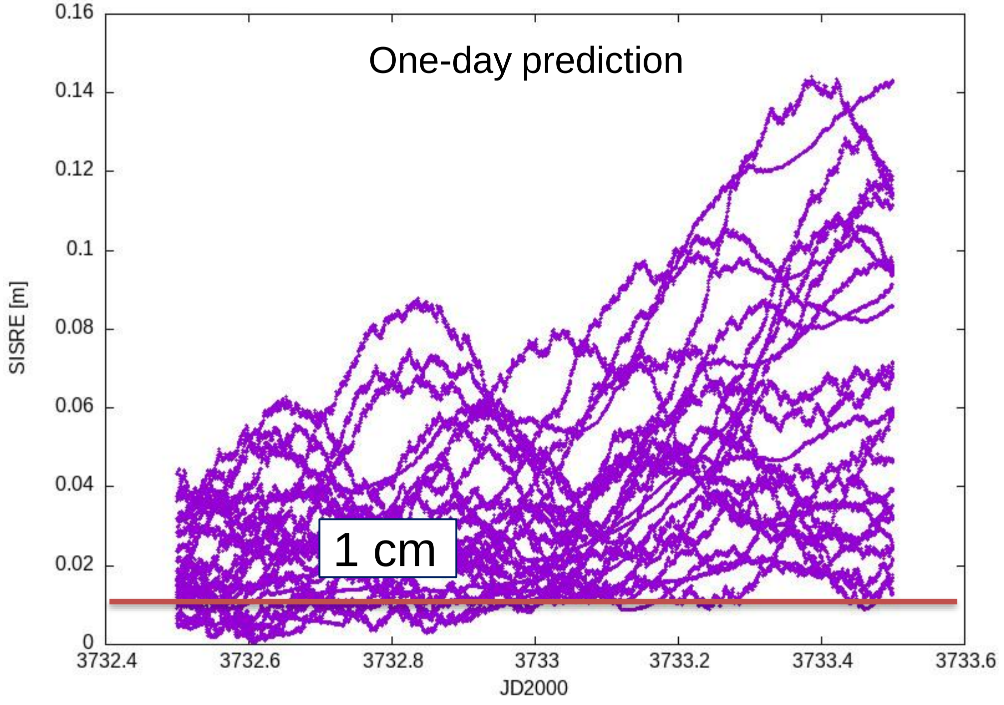


- Joined impact of dynamic orbit and ERPs prediction errors
- Kepler – extremely small radial prediction error
- Along- and cross-track components are affected by ERP prediction errors – at ~decimeter level after 1 day

Prediction SiSRE

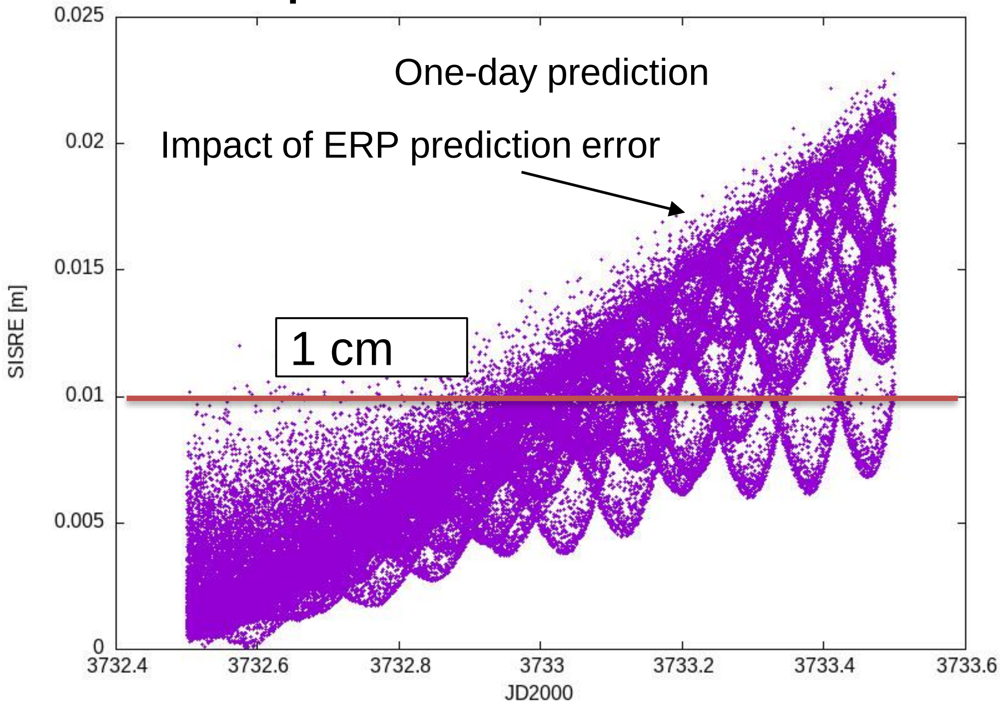
Perfect models

Galileo with 18 stations



- Decimeter-level prediction SiSRE after one day

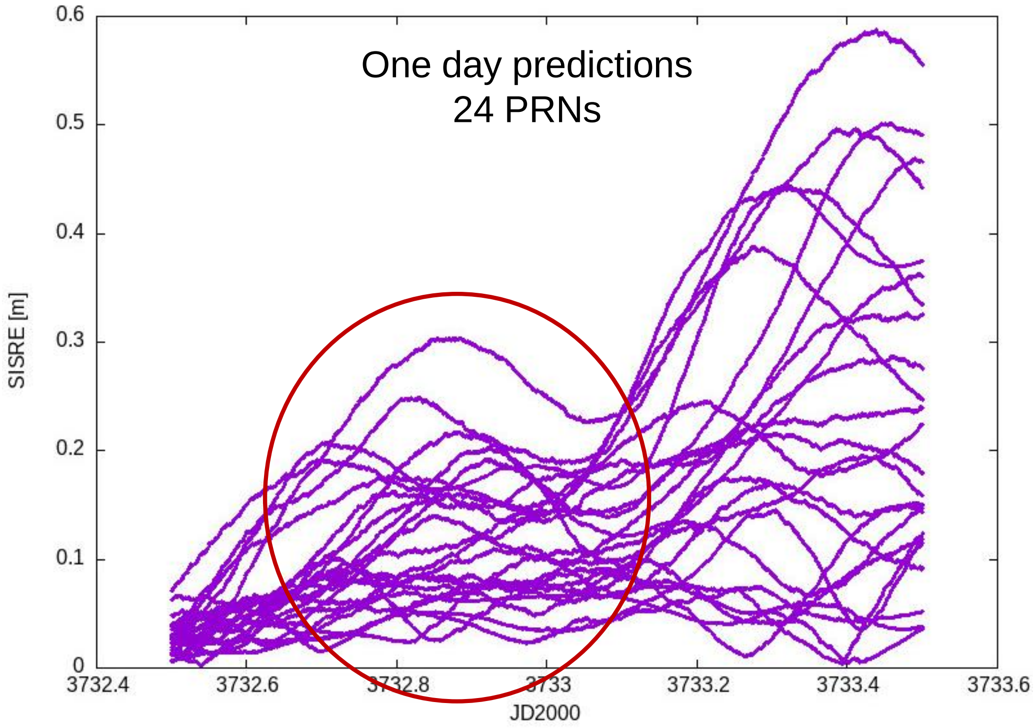
Kepler fast-track with 2 stations



- ✓ Clocks keep synchronized within 3 mm noise
- ✓ Significant improvement in SiSRE(PRD)

Galileo prediction SiSRE with modelling errors

- Actual Galileo broadcast SiSRE ~17 cm
- Attempt to simulate this
  - ODTS + prediction with modelling errors
  - Clock extrapolation based on 6h fit



Galileo Quarterly Performance Report Q2-2022

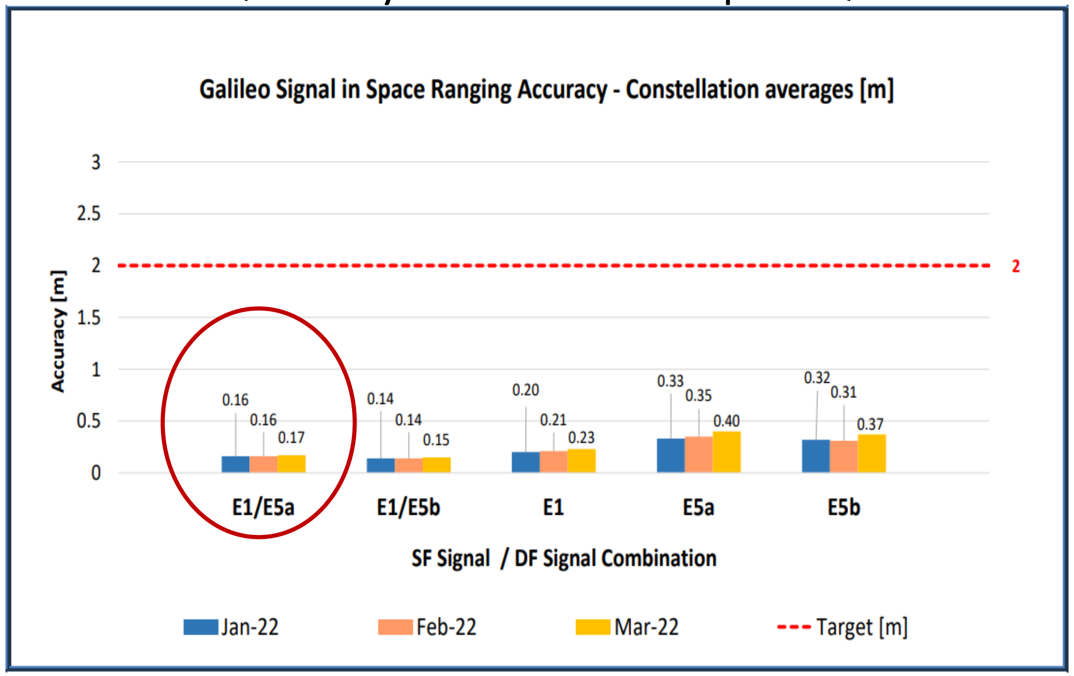


Figure 8 : Monthly Galileo SIS Ranging Accuracy (95th percentile) "over all satellites" (constellation average), measured during the reporting period

- Unclear if the modelling errors are realistic
- Not analyzed further

Broadcast orbit parameters

F/NAV parameters

- 6 Keplerian parameters
- 3 rate parameters
- 6 amplitudes of harmonic corrections

Accuracy analysis

- LSQ fits to **perfect*** dynamic orbits (all PRNs)
- Fit windows between 10 min and 4 h
- Fit windows sliding every 5 min over 1 day orbits
- Reconstructed orbits wo/w parameter truncation
- Orbit RMS errors in radial/cross/along-track direction
- SiSRE values

* Fit accuracy weakly depends on the quality of the dynamic orbit

Galileo OS SIS ICD v1.2

Parameter	Definition	Bits	Scale factor	Unit
M_0	Mean anomaly at reference time	32*	2^{-31}	semi-circles**
Δn	Mean motion difference from computed value	16*	2^{-43}	semi-circles/s**
e	Eccentricity	32	2^{-33}	N/A
$A^{1/2}$	Square root of the semi-major axis	32	2^{-19}	meter$^{1/2}$
Ω_0	Longitude of ascending node of orbital plane at weekly epoch***	32*	2^{-31}	semi-circles**
i_0	Inclination angle at reference time	32*	2^{-31}	semi-circles**
ω	Argument of perigee	32*	2^{-31}	semi-circles**
$\dot{\Omega}$	Rate of change of right ascension	24*	2^{-43}	semi-circles/s**
$\dot{i}$	Rate of change of inclination angle	14*	2^{-43}	semi-circles/s**
C_{uc}	Amplitude of the cosine harmonic correction term to the argument of latitude	16*	2^{-29}	radians
C_{us}	Amplitude of the sine harmonic correction term to the argument of latitude	16*	2^{-29}	radians
C_{rc}	Amplitude of the cosine harmonic correction term to the orbit radius	16*	2^{-5}	meters
C_{rs}	Amplitude of the sine harmonic correction term to the orbit radius	16*	2^{-5}	meters
C_{ic}	Amplitude of the cosine harmonic correction term to the angle of inclination	16*	2^{-29}	radians
C_{is}	Amplitude of the sine harmonic correction term to the angle of inclination	16*	2^{-29}	radians

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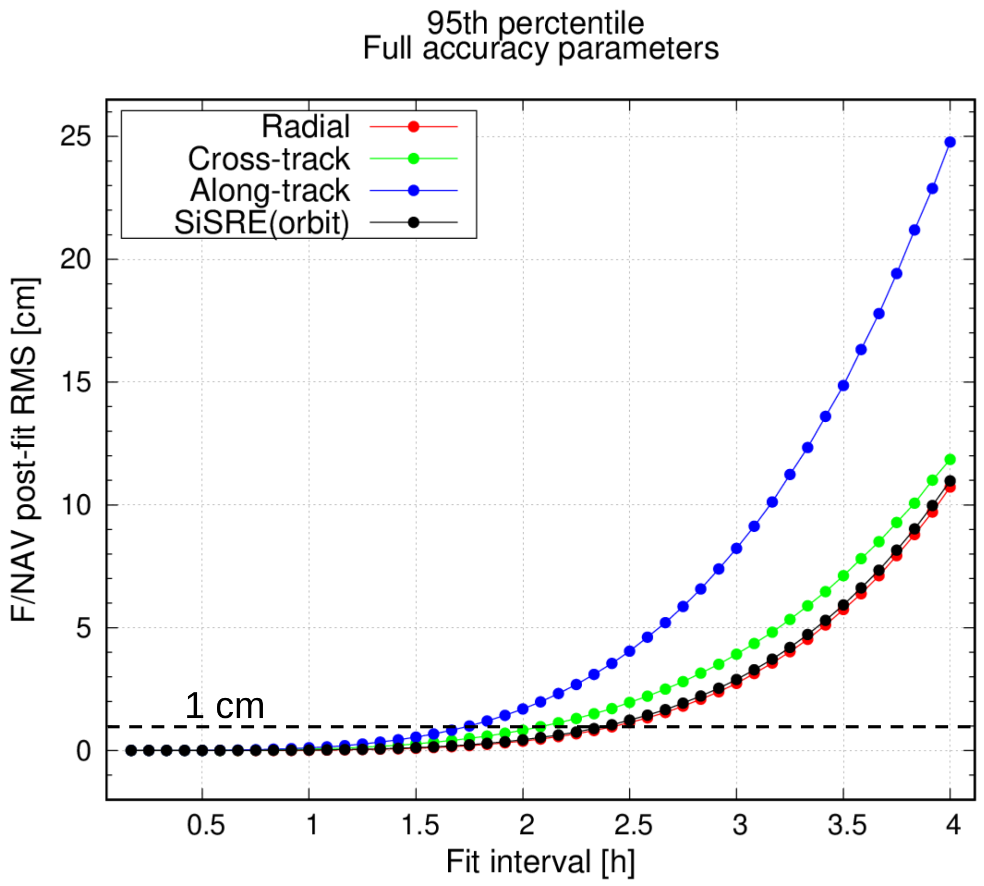
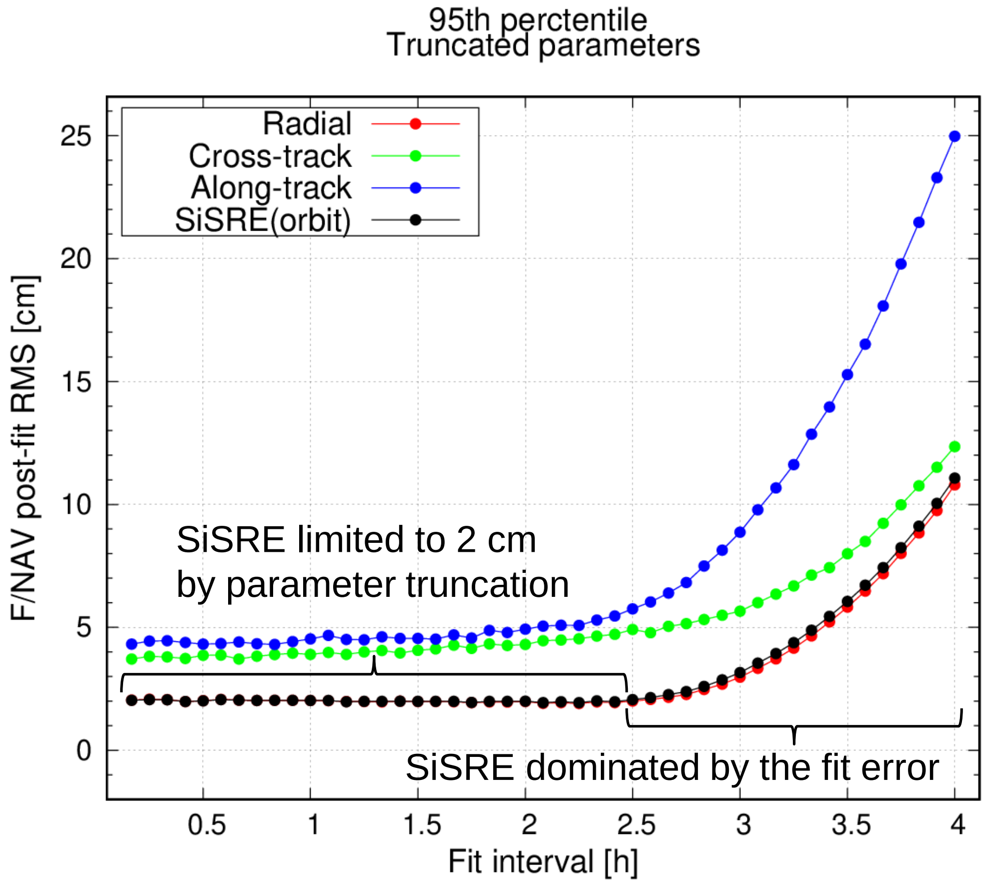
Orbit fit accuracy of the F/NAV broadcast parameters



- SiSRE below 1 cm for fit intervals up to 2.5 h
- Decimeter SiSRE for fit interval of 4 hours



- Steady 2 cm SiSRE for fit intervals up to ~2.5 h

Impact of single parameter quantization on SiSRE

Analysis

- 30 min fit windows to predicted orbits
- Sliding every 10 min in (0:15, 4:15) h

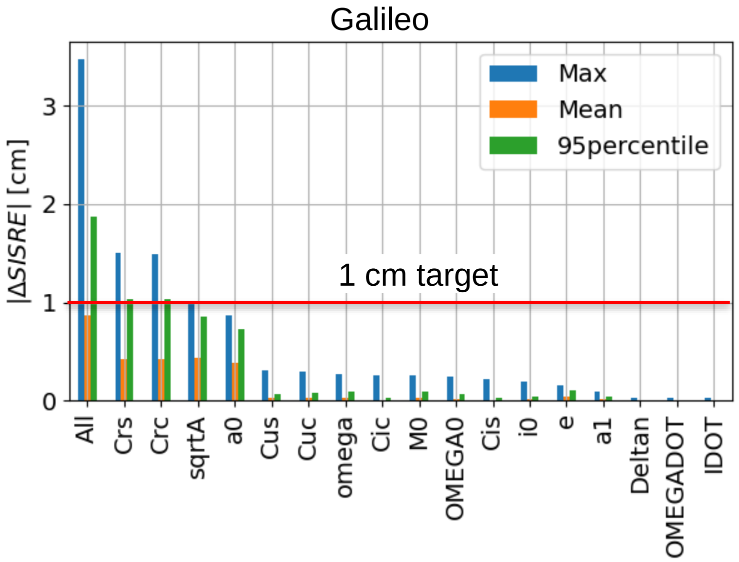
Largest impact

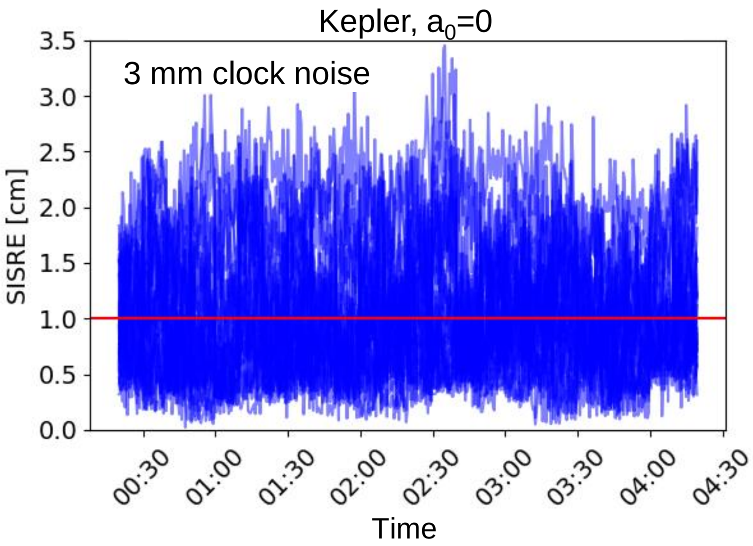
- Correction to radius Crs
- Correction to radius Crc
- Semi-major axis $\sqrt{A}$
- Clock bias a_0

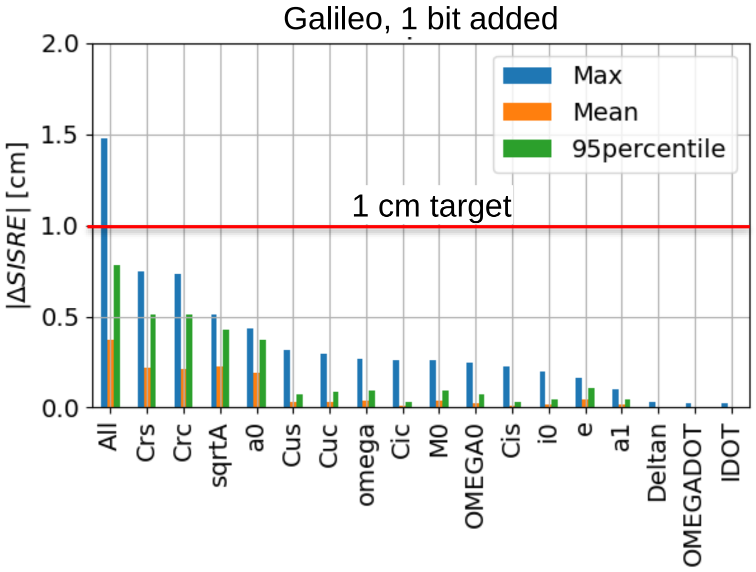
Solution

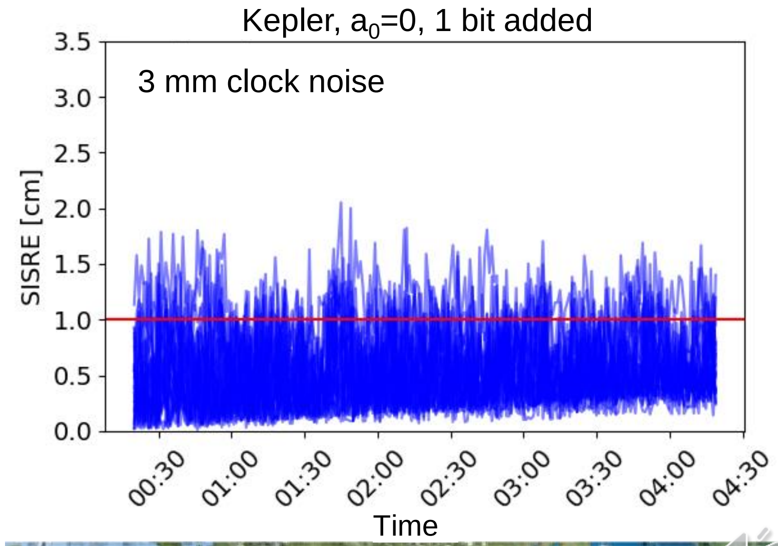
- add 1 bit and adapt scale factors

Parameter	Number of bits	Scale factor
Crs	16 → 17	2^{-5} → 2^{-6}
Crc	16 → 17	2^{-5} → 2^{-6}
$\sqrt{A}$	32 → 33	2^{-19} → 2^{-20}
a_0	31 → 32	2^{-34} → 2^{-35}









Conclusions

KEPLER GNSS

- Autonomous satellite clock synchronization via OISLs
- SiSRE ODTS improved by a factor of 10 compared to 2.4 cm for Galileo
- Sub-cm SiSRE ODTS with ground network limited to 1-2 stations
- LEO satellites not critical for ODTS functions in Kepler

Prediction system

- Prediction of satellite clocks, orbits and Earth rotation parameters
- Initial results with perfect models and modelling errors for Galileo only
- Kepler prediction SiSRE of 1 cm

F/NAV broadcast parameters

- Orbit fit errors
  - Sub-cm for fit intervals up to 2.5 h
  - Decimeter-level for fit interval of 4 h
- Quantization errors
  - Limit broadcast orbit accuracy
  - Steady 2 cm orbit errors for fit intervals up to 2.5 h
  - Reduction to 1 cm by allocating 1 bit more for 4 parameters : Crs, Crc, $\sqrt{A}$ and a_0

Thank you for watching!

Contact

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