Searching for Dark Matter with Galileo atomic clocks

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Outline

- Introduction
- Theoretical approach
- Statistical analysis
- First theoretical results

Introduction

- Atomic clocks are a good tool to search a uniform-in-time drifts of fundamental constants

=> Such transient in time changes of fundamental constants can be induced by Dark Matter objects

=> Network of correlated atomic clocks (GPS) can be used to search DM objects

$$\frac{\delta\omega(r,t)}{\omega_c} = \sum_X K_X \frac{\delta X(r,t)}{X}$$

- Scalar interaction (φ) between DM and atoms of clocks induces shifts in effective values of fundamental constants:

- fine structure constant α,
- the ratio of the light quark mass to the quantum chromodynamics m_q/Λ_{QCD},
- the electron and proton (fermion) masses m_e and m_p

$$\frac{\delta X(r,t)}{X} = \Gamma_X \varphi^2(r,t)$$

Model

- 24 Galileo satellites with atomic clocks (H-maser) on boards
- 3 months of data

- Clocks give time by counting number of oscillations and multiplying them by the period

- Experimentally relevant quantity is the total phase accumulated by the quantum oscillator $\varphi_0(t) = \int_0^t \omega_0 dt'$

- Interaction with DW leads to a shift in the oscillator frequency:

$$\varphi(t) = \int_0^t \big(\omega_0 + \delta\omega(t')\big)dt'$$

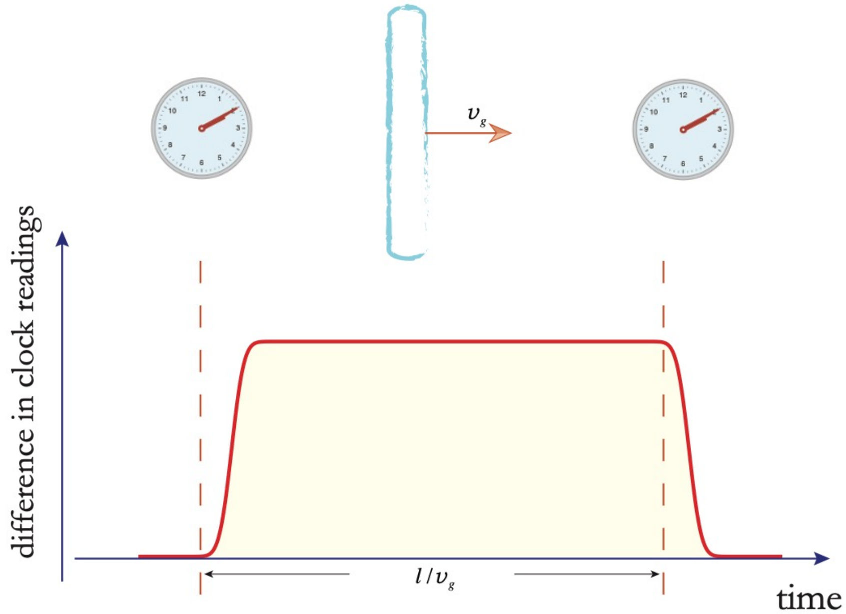
Comparison signal from two clocks

Before DW arrival, clocks are synchronized => $\Delta\varphi(t) = 0$

- DW passing the first clock introduces a phase difference
  $\Delta\varphi(t) \sim d/v_g$

  DW propagates through the clock network with v_g:

$$\Delta\varphi(t) \sim \int_{-\infty}^{t} \left(f\left(t' - \frac{l}{v_g}\right) - f(t') \right) dt' = \omega_0 \Delta t(t)$$

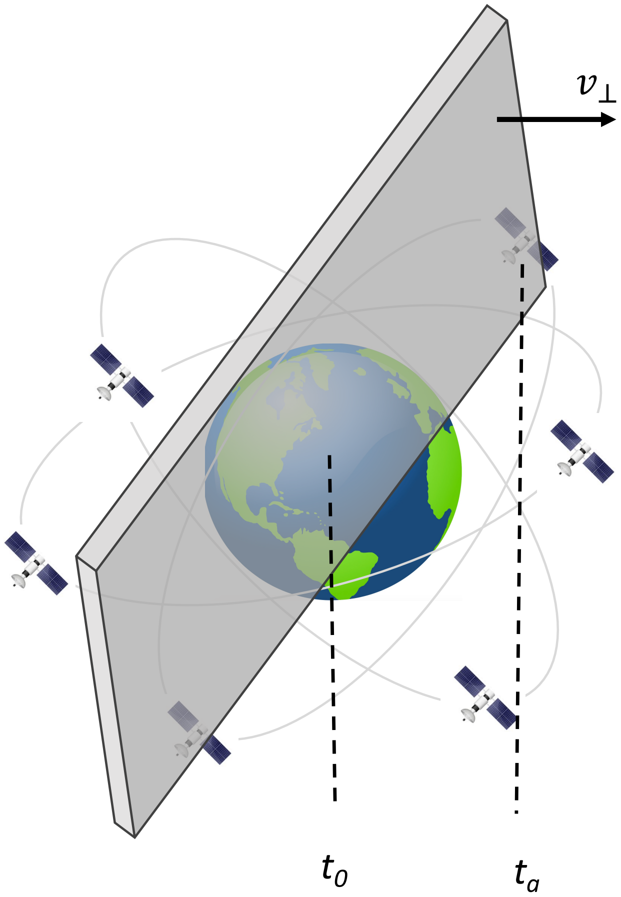


A. Derevianko, M. Pospelov, Nat. Phys. **10**, (2014)

- After passing the second clock, the phase difference vanishes

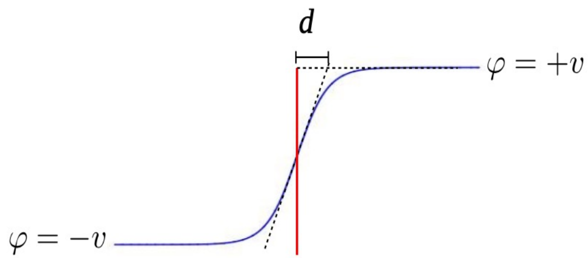
=> Monitoring correlated time difference $\Delta t(t)$ between two clocks, one can search for DM

Signal simulation



DM signal: $\varphi(z, V, d) = V \cdot \tanh\left(\frac{z}{2d}\right)$

$$V^2 = \frac{3}{2} v_{gal} \Im d \rho_{\rm DM}$$



The distance between DW and an aircraft *a:*

$$z_a(t, v_\perp, t_0) = -v_\perp(t - t_0) - \boldsymbol{r}_a(t)\boldsymbol{n}_\perp$$

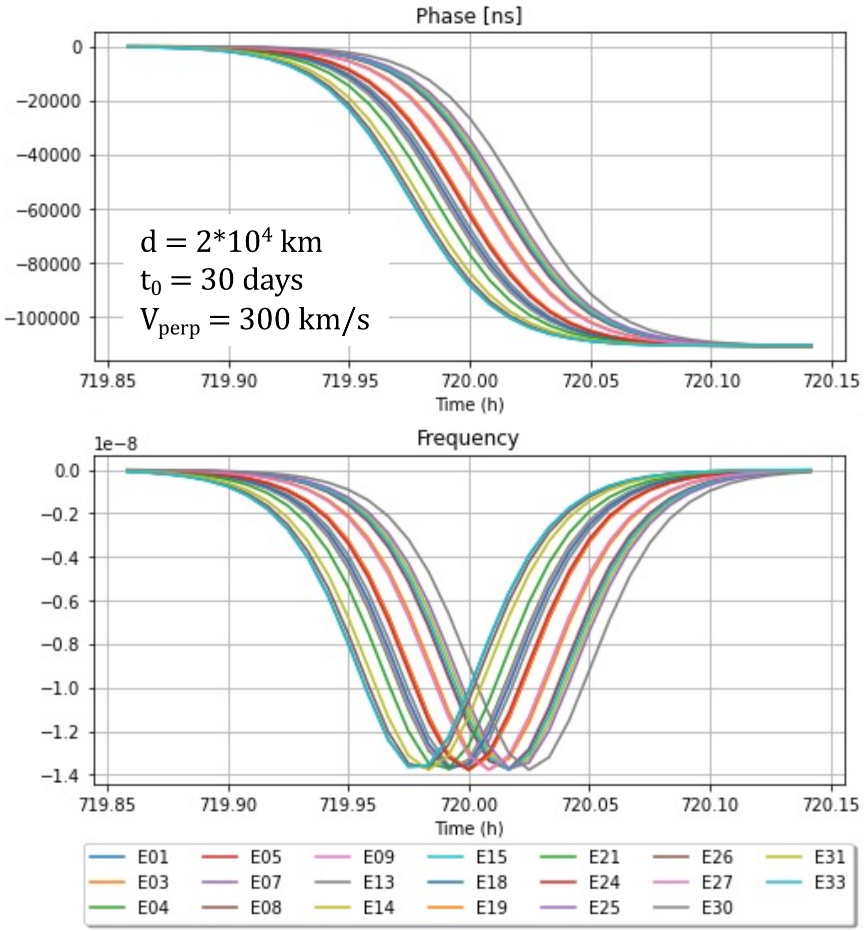
Signal from DW: $S_a(t) = \int_{-\infty}^{t} \Gamma_a^{\rm eff}(\varphi^2(z_a(t', v_\perp, t_0), V, d) - V^2)dt'$

The first-order difference:

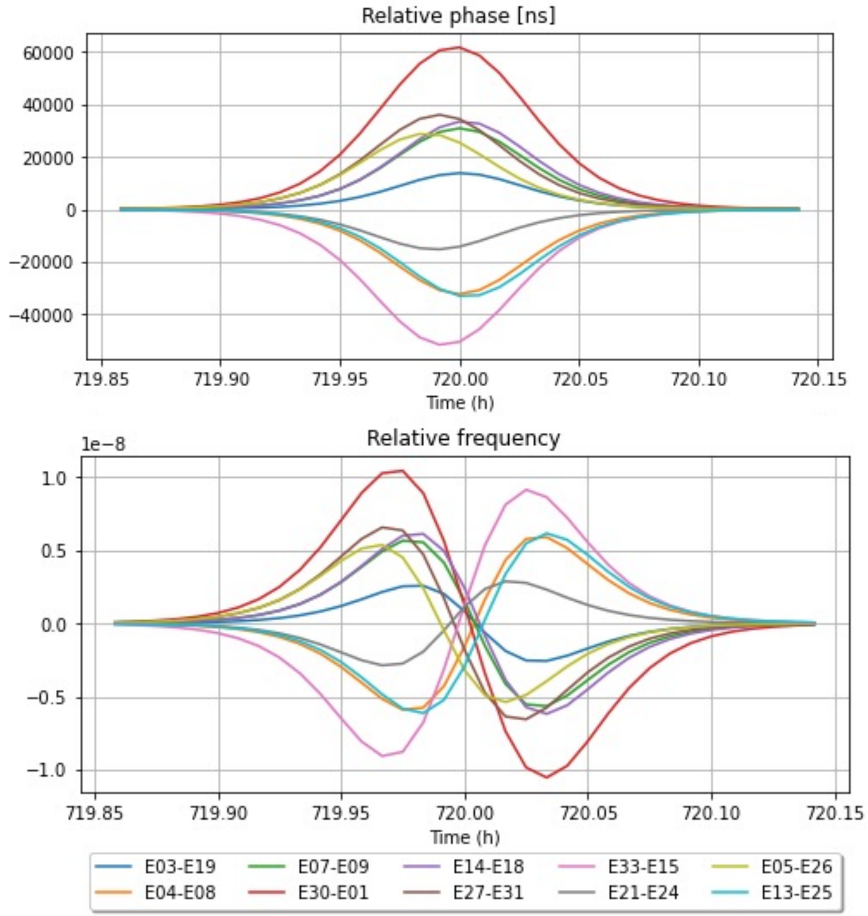
$$\Delta S(t) = S(t) - S(t - \Delta t) = \int_{t-\Delta t}^{t} \Gamma_a^{\rm eff}(\varphi^2(z_a(t', v_\perp, t_0), V, d) - V^2)dt'$$

Signal simulation

- Thin DW ($d < 10^4$ km)

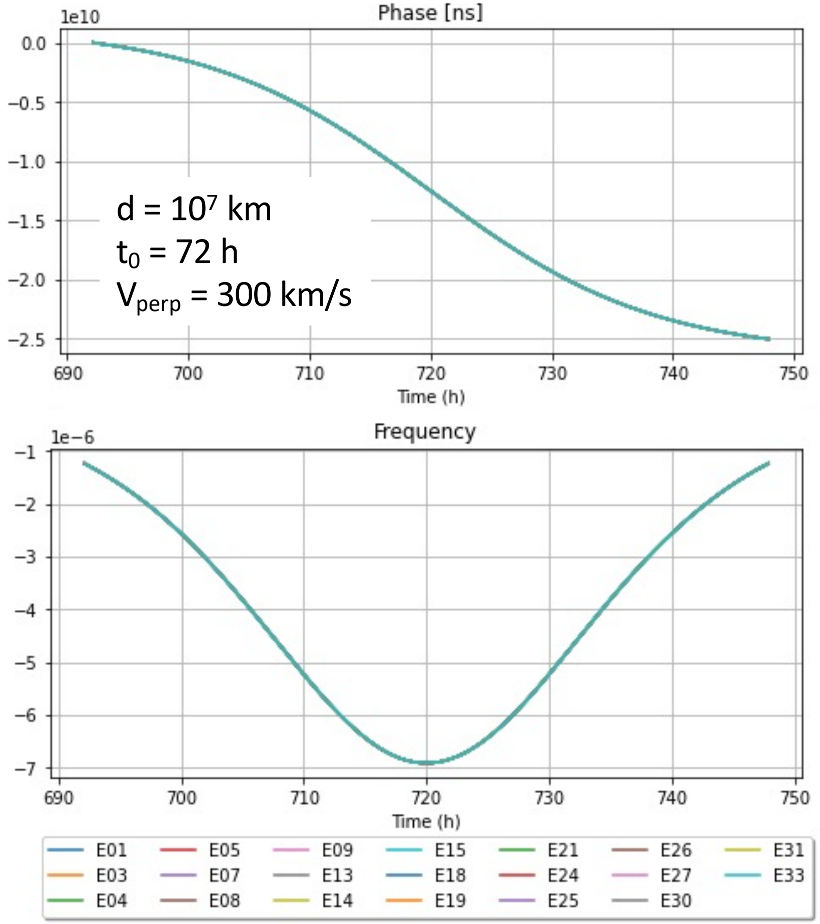


Relative differences

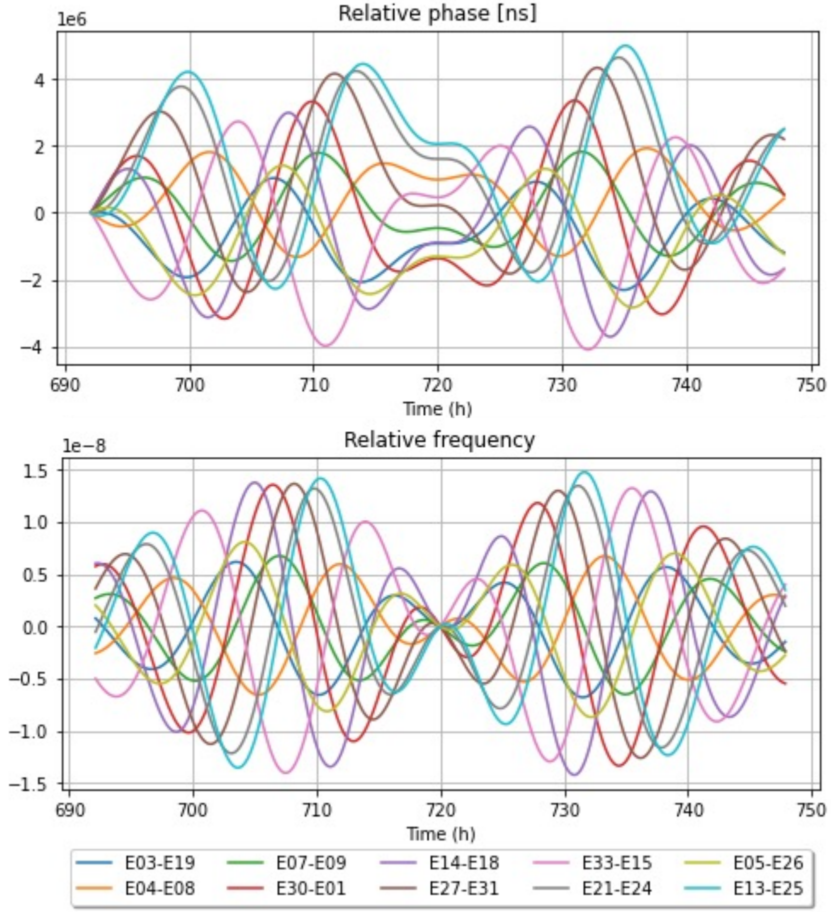


Signal simulation

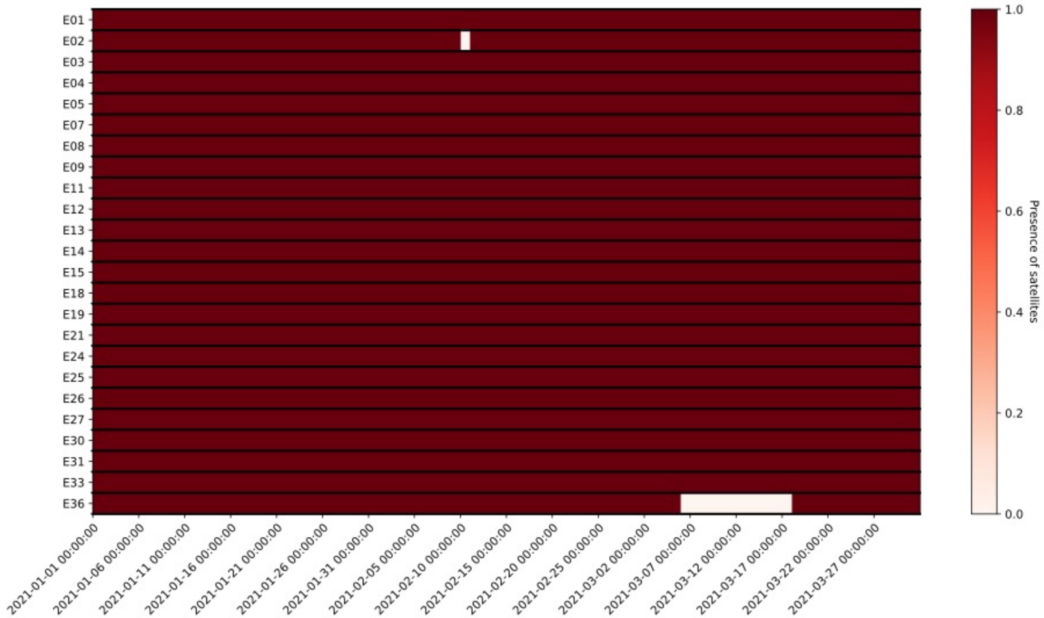
- Thick DW (d > 10^4 km)

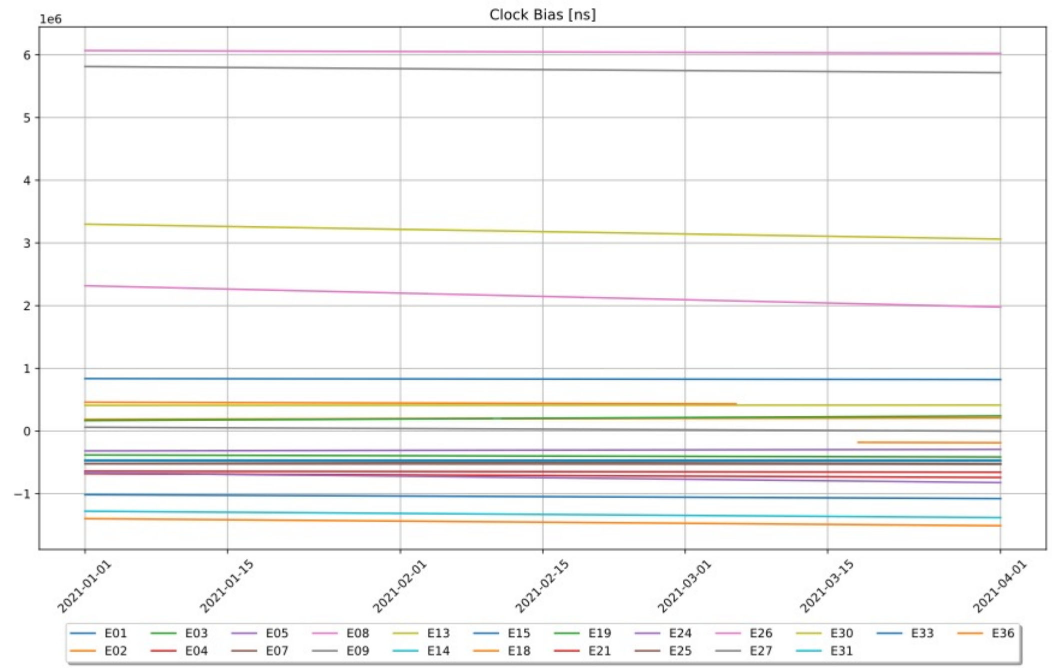


Relative differences



Presence of data





- 2 satellites have missing data

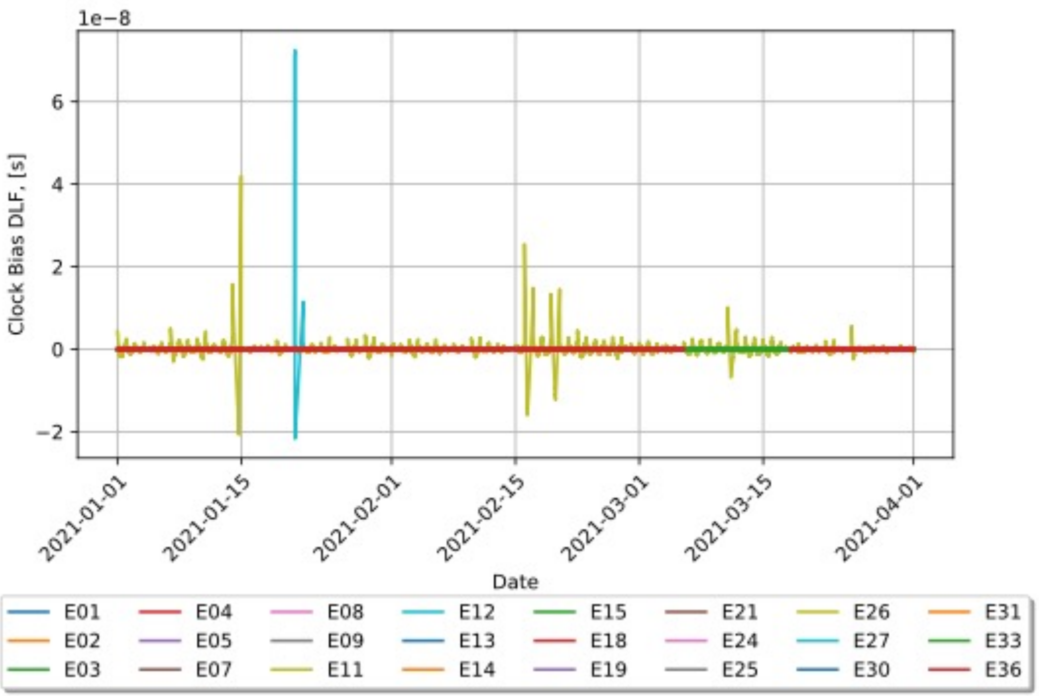
=> We removed them from the analysis

- Different linear drift for each clocks

=> should be removed

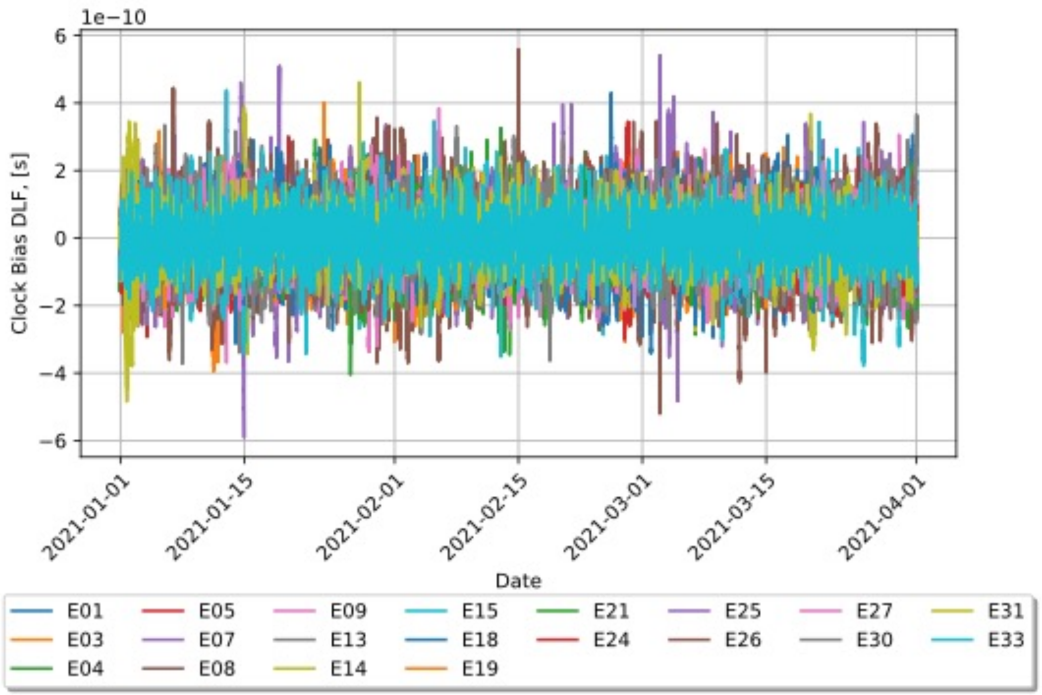
Pre-process

From Clock Bias, we remove daily linear fit



2 clocks have problems:

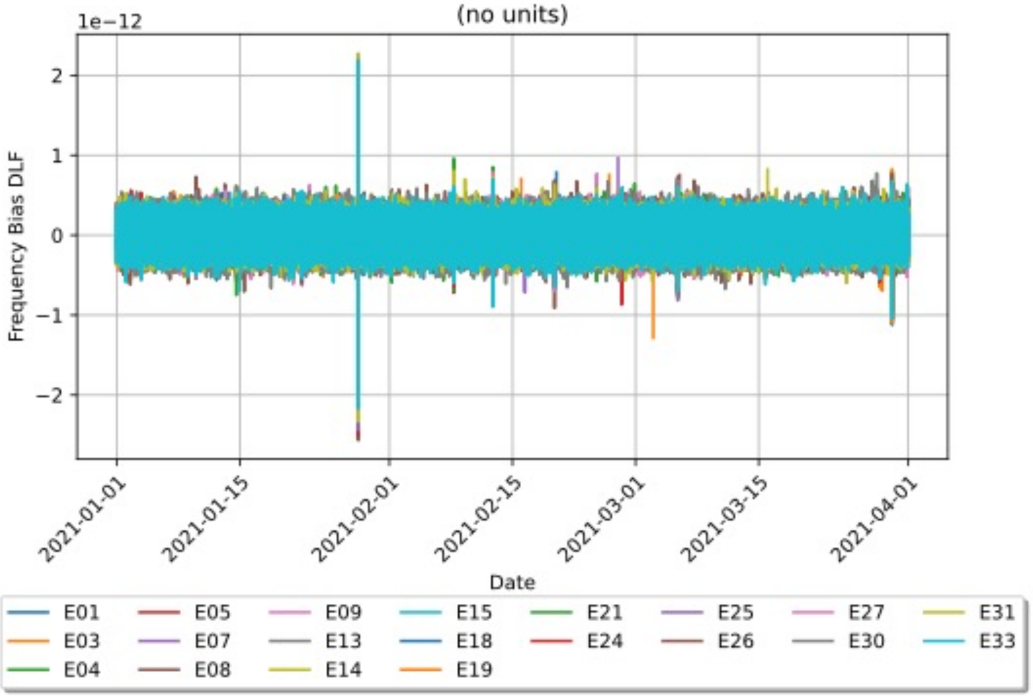
- E11 works with Rb clock,
- E12 has a big jump



Clock bias with removed daily linear fit after removing E02, E11, E12, E36 clocks

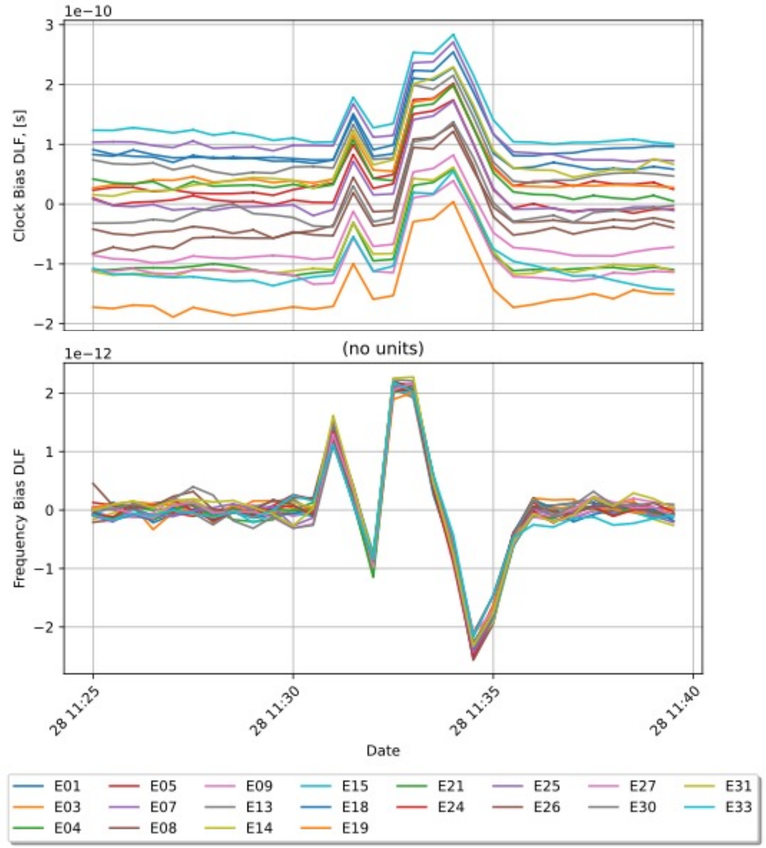
Pre-process

From Clock Bias, we also can calculate a derivative, which corresponds to frequency



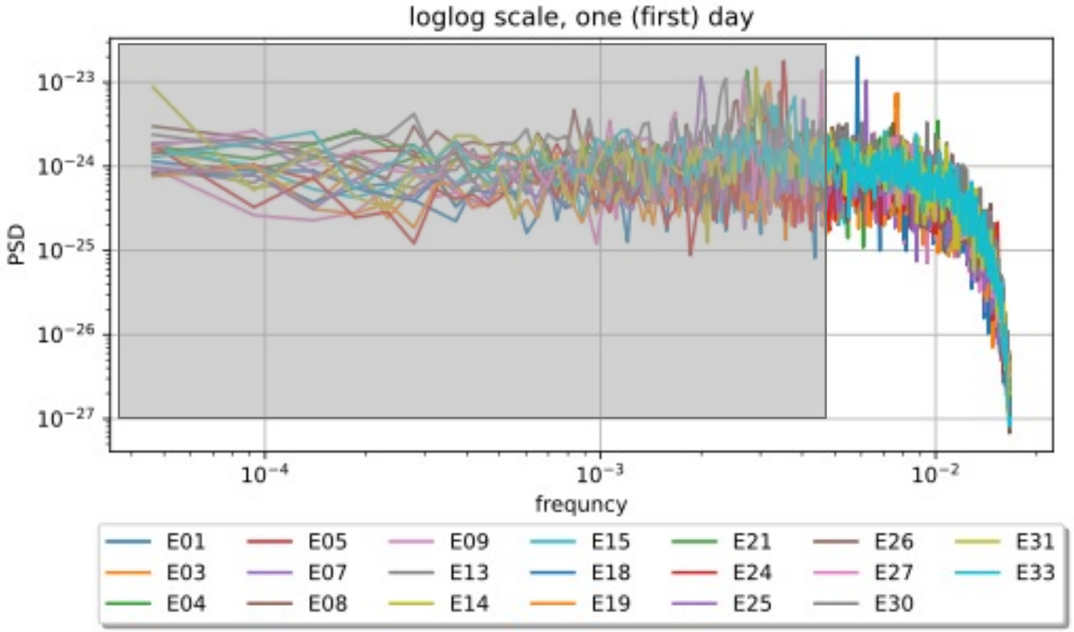
Frequency bias with removed daily linear fit after removing E02, E11, E12, E36 clocks

Jump from a ground reference clock

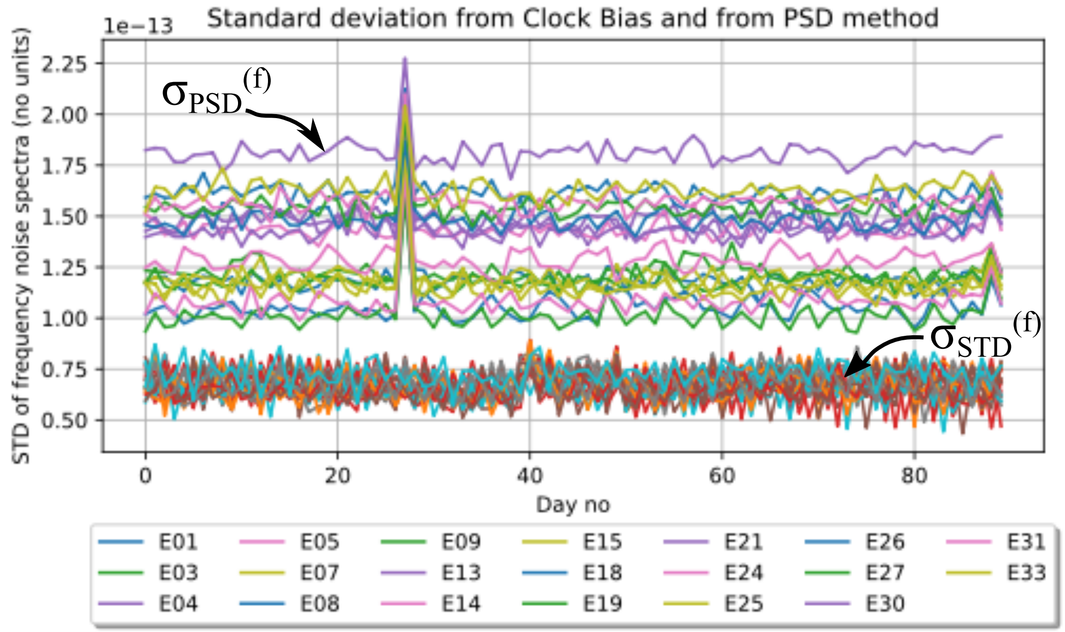


Noise characterization

PSD (Welch method) for one day



σ for linear region for each satellite for every day



=> white noise

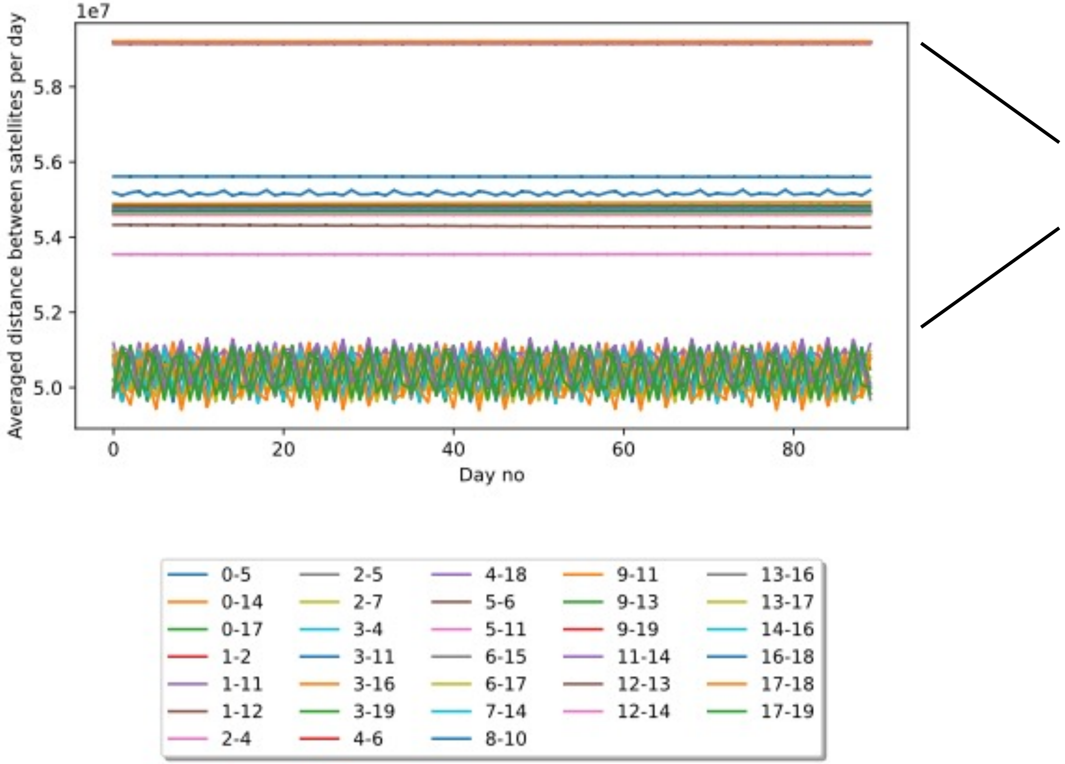
$$\sigma_{\mathrm{PSD}} = \sqrt{\frac{b_0 \cdot f_s}{2}}$$

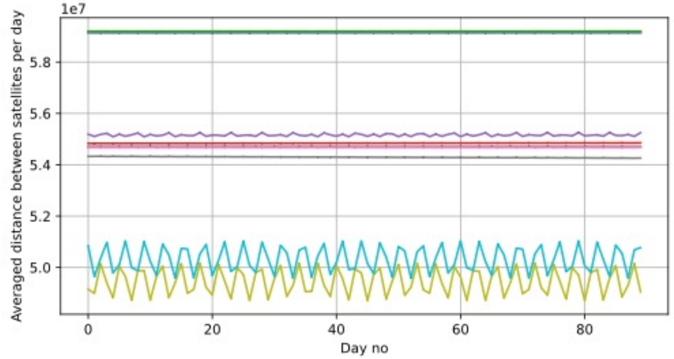
$f_s = 1/30$

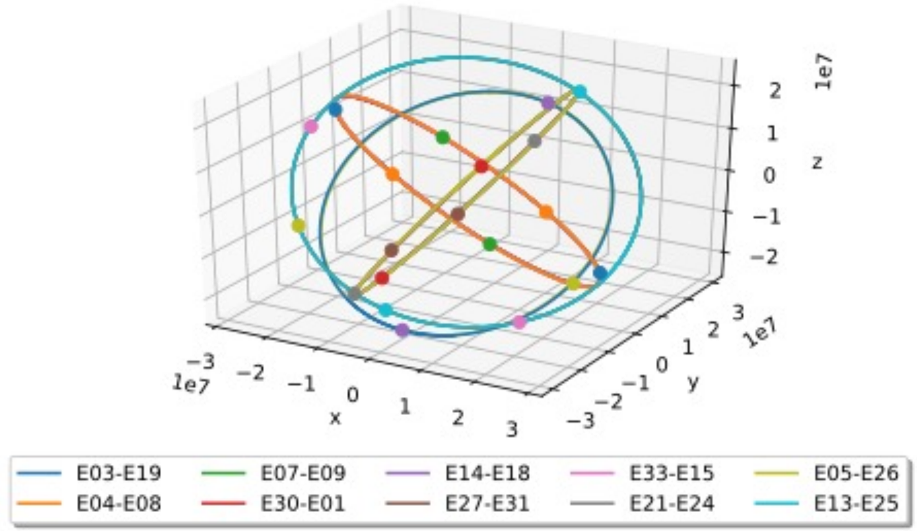
Comparison with sigma from clock files

$$\sigma_{\mathrm{STD}}^{(f)} = \frac{\sigma_{\mathrm{STD}}^{(t)}}{\Delta T}$$

Choosing independent pairs







Relative phase and frequency differences

Data Analysis: frequentist approach

1. Posterior probability $p \equiv p(D_t|\varphi(\zeta)) = Cp(\zeta)\exp\left(-\frac{1}{2}[d-s]^T \boldsymbol{C}^{-1}[d-s]\right)$

ζ defines DW parameters: incident direction, velocity, encounter time

C is the covariance matrix

d – data

s $\sim hs(t_{0j}, d_j, \mathbf{v}_{perp,j})$ – simulated signal

2. We work with independent pairs

$d_i = d_a - d_b$

$s_i = s_a - s_b$

$\Rightarrow C_{ii} = \sqrt{\sigma^2_{\mathrm{PSD},a} + \sigma^2_{\mathrm{PSD},b}}$, i is pair of clocks a and b

3. Posterior on the signal amplitude (Dt: templates with θ, φ, v_{perp}, d, t_0)

$$h_\zeta = \frac{\boldsymbol{d}^T \boldsymbol{C}^{-1}\boldsymbol{s}(\zeta)}{\boldsymbol{s}^T(\zeta)\boldsymbol{C}^{-1}\boldsymbol{s}(\zeta)} = \frac{\sum_{i,k}^{Ncp}\sum_{j,l}^{D_t} d_j^i (C^{-1})_j s_l^k(\zeta)}{\sum_{i,k}^{Ncp}\sum_{j,l}^{D_t} s_j^i(\zeta) d_j^i (C^{-1})_j s_l^k(\zeta)}$$

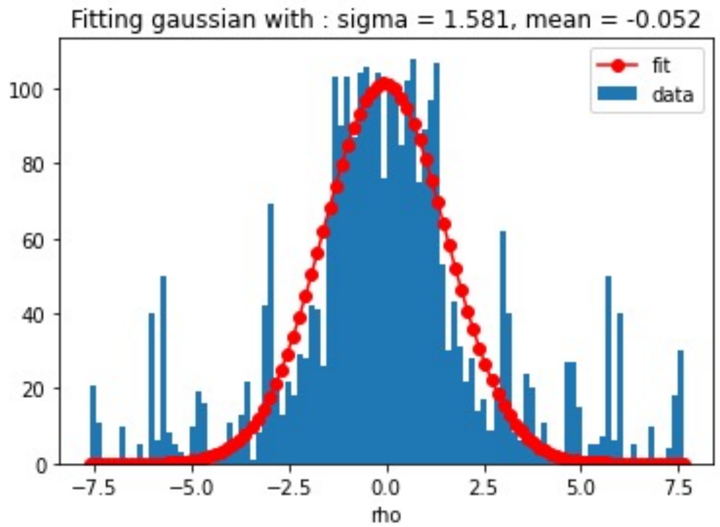
$$\sigma^2_{h_\zeta} = \frac{1}{\boldsymbol{s}^T(\zeta)\boldsymbol{C}^{-1}s(\zeta)}$$

Signal to Noise Ratio $\mathrm{SNR} = \frac{h_\zeta}{\sigma_{h_\zeta}} = \frac{\boldsymbol{d}^T\boldsymbol{C}^{-1}\boldsymbol{\varphi}(\zeta)}{\sqrt{\boldsymbol{\varphi}^T(\zeta)\boldsymbol{C}^{-1}\boldsymbol{\varphi}(\zeta)}}$

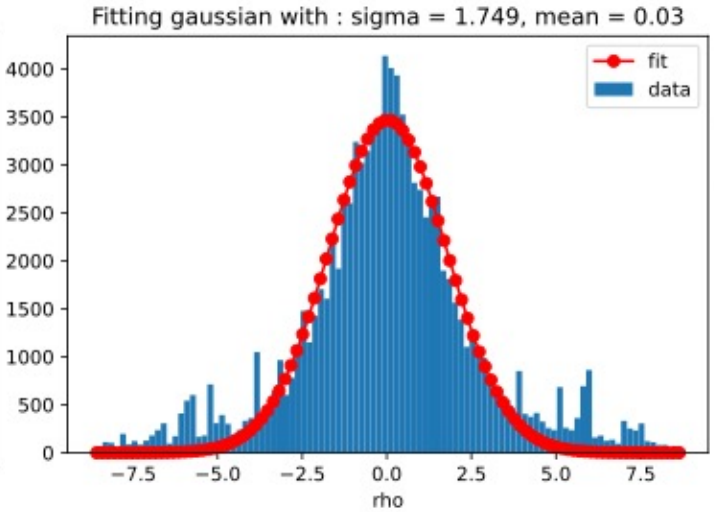
Data Analysis: frequentist approach

1. Forming templates for 5 parameters: (t_0, d, v, θ, φ) => calculation SNR on event free simulated data

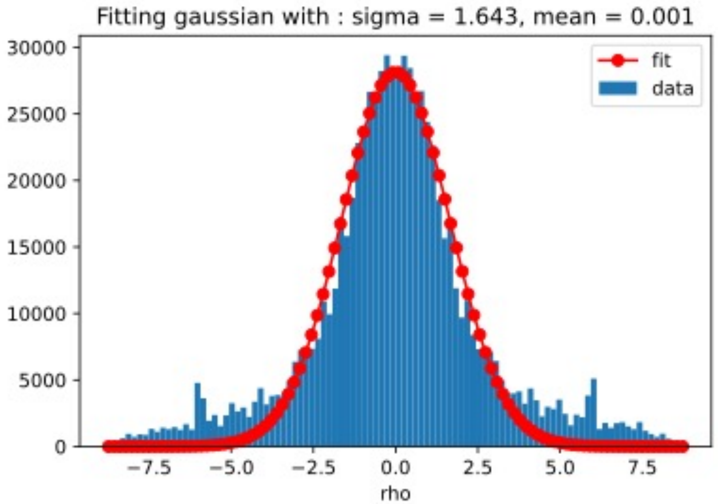
5^5 templates



10^5 templates



15^5 templates



=> Gaussian distribution

Still need to be done…

- Estimate a threshold value

$$1 - \left[\mathrm{erf}\left(\frac{\rho_{\mathrm{thresh}}}{\sqrt{2}}\right)\right]^{N_{\mathrm{templates}}} = 0.05$$

- SLR campaign has provide high quality of the clock data with very small residual with respect to daily linear fits .

- In the case of a positive event of DW signal, we will need to exclude the signal from an orbital error. This will be possible by analysing SLR residual. This comparison can be done.

Conclusions

- Our analysis can be applied to any model describing the interaction of the usual Maxwell Lagrangian with scalar fields beyond the Standard Model

- The tangential profile of DM field gives more information about interaction process

- Our model allows to consider thick domain walls which was not considered before

Thank you for your attention!