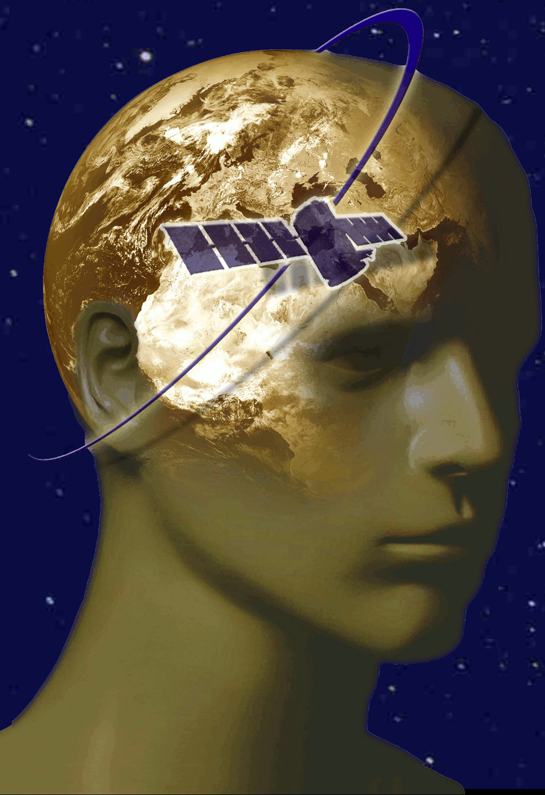
Test of the **gravitational redshift** with satellites **Galileo 6 and 7**

Journée GPhys

2015, July 6th

Observatoire de Paris



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Observatoire de Paris

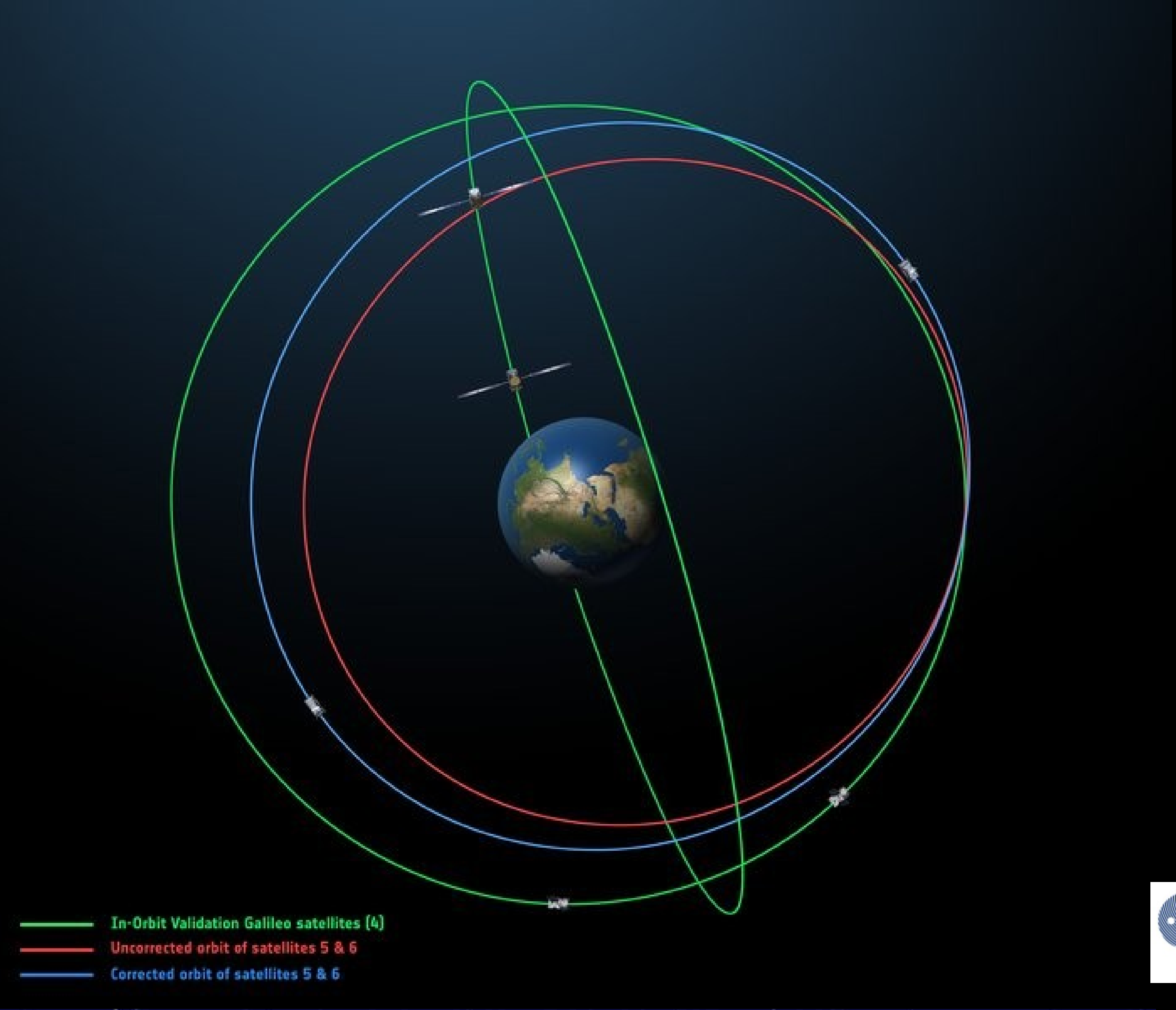
Université Pierre et Marie Curie

- **Galileo satellites 5 and 6** were launched with a Soyuz rocket on 22 august 2014 on the wrong orbit due to a technical problem
- Launch failure was due to a **temporary interruption of the** joint hydrazine **propellant supply** to the thrusters, caused by freezing of the hydrazine, which resulted from the proximity of hydrazine and cold helium feed lines.
- **Last launch** of Galileo satellites 7 and 8 occured on **friday 27 march**

esa
European Space Agency

GALILEO EGNOS

Navigation solutions powered by Europe



European Space Agency

- For a Keplerian orbit one shows that :

$$\tau(t) = \underbrace{\left(1 - \frac{3Gm}{2ac^2}\right) t}_{\text{constant frequency bias}} - \underbrace{\frac{2\sqrt{Gma}}{c^2} e \sin E(t)}_{\text{eccentricity correction}} + \mathrm{Cste}$$

- One need an **accurate clock** to measure the constant frequency bias
- The eccentricity correction is a periodic term → **use the stability of the clock to "average" the random noise**
- Limitations are due to mismodeled **systematics effects**

- RMS deviation between theory and experiment is **~ 2.2 %**
- Evidence of **systematic bias** during some particular passes

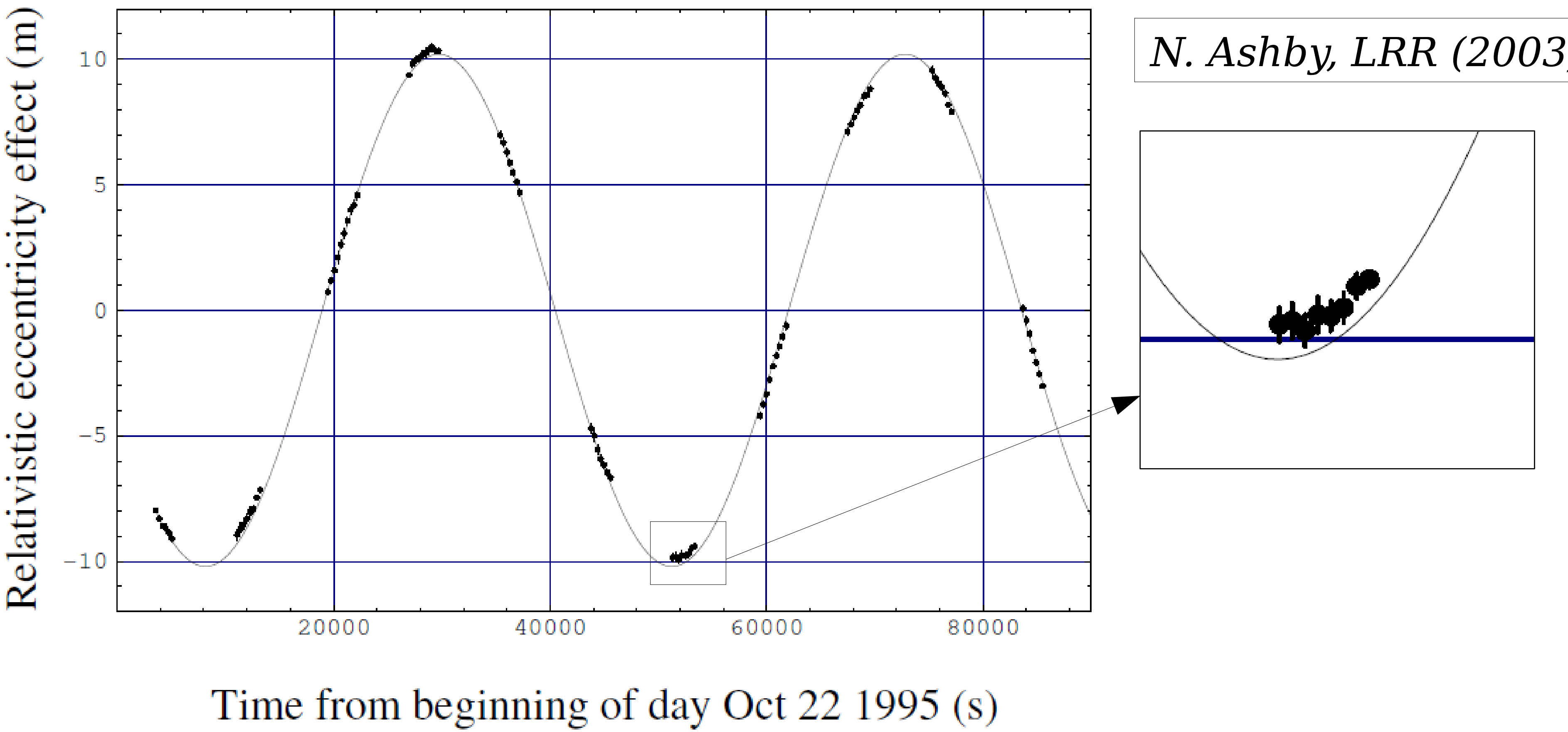
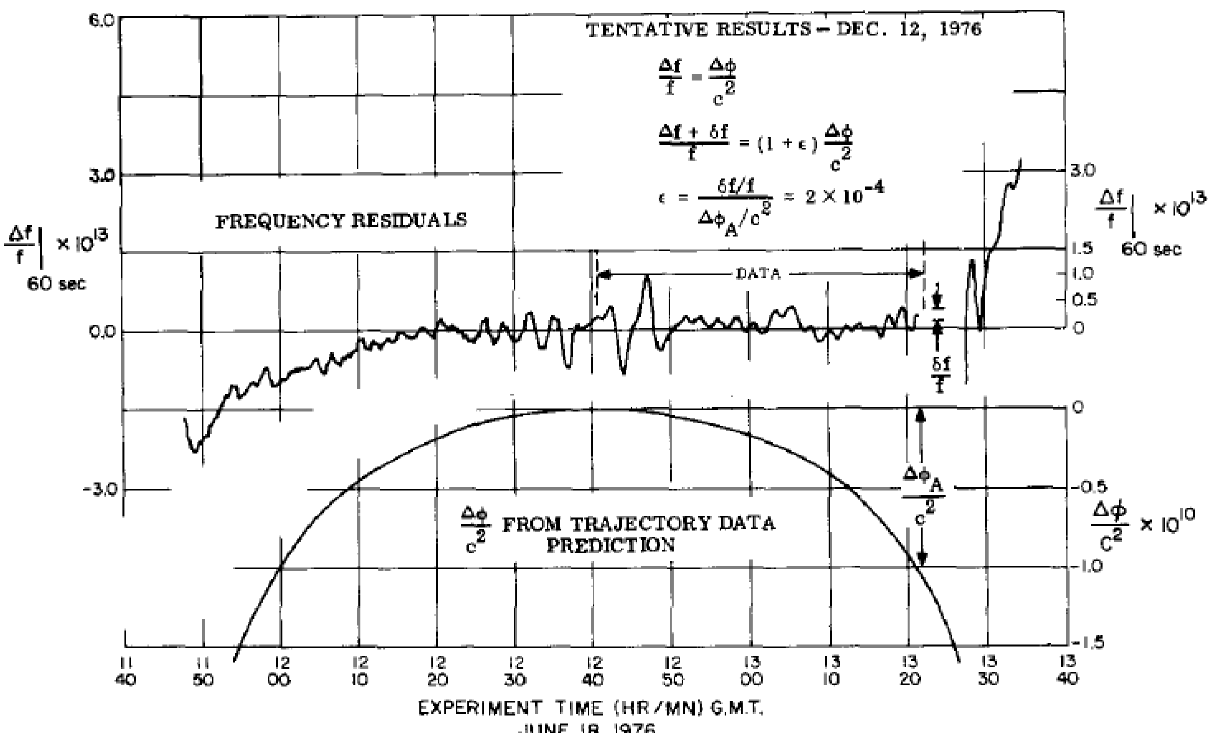
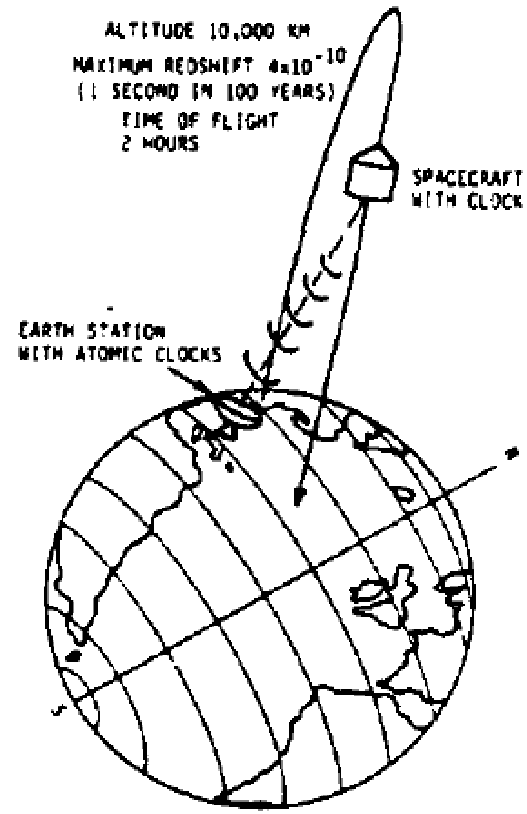


Figure 5: *Comparison of predicted and measured eccentricity effect for SV nr. 13.*

R. Vessot et al., GRG 1979, PRL 1980, AdSR 1989

- Test of the redshift on a **single parabola**
- Continuous **two-way microwave link** between a spaceborne hydrogen maser clock and ground hydrogen masers
- Frequency shift verified to $7*10^{-5}$
- **Gravitational redshift verified to $1.4*10^{-4}$**





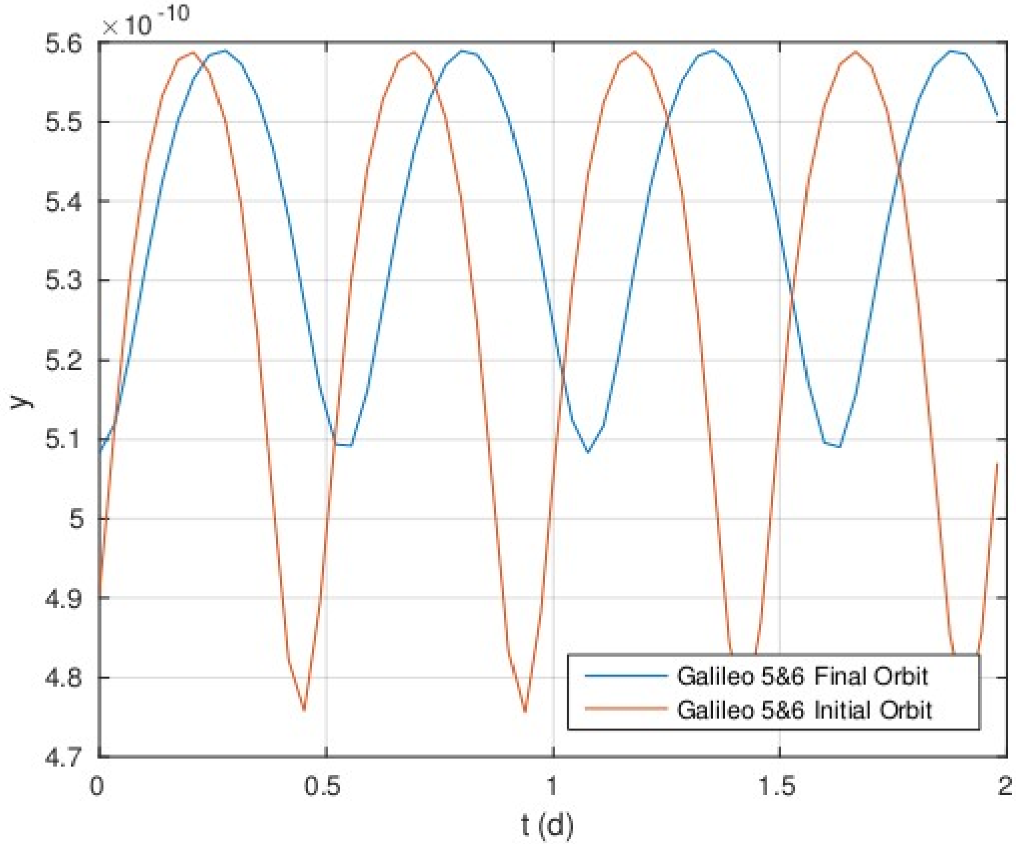
Simulation of :

1. Galileo 5 and 6 **orbits**
2. Realistic **onboard clock noise**
3. **Gravitational Redshit Signal** (including a Local Position Invariance violation, random noise and systematic effects)

Analysis of the simulated signal with two different methods :

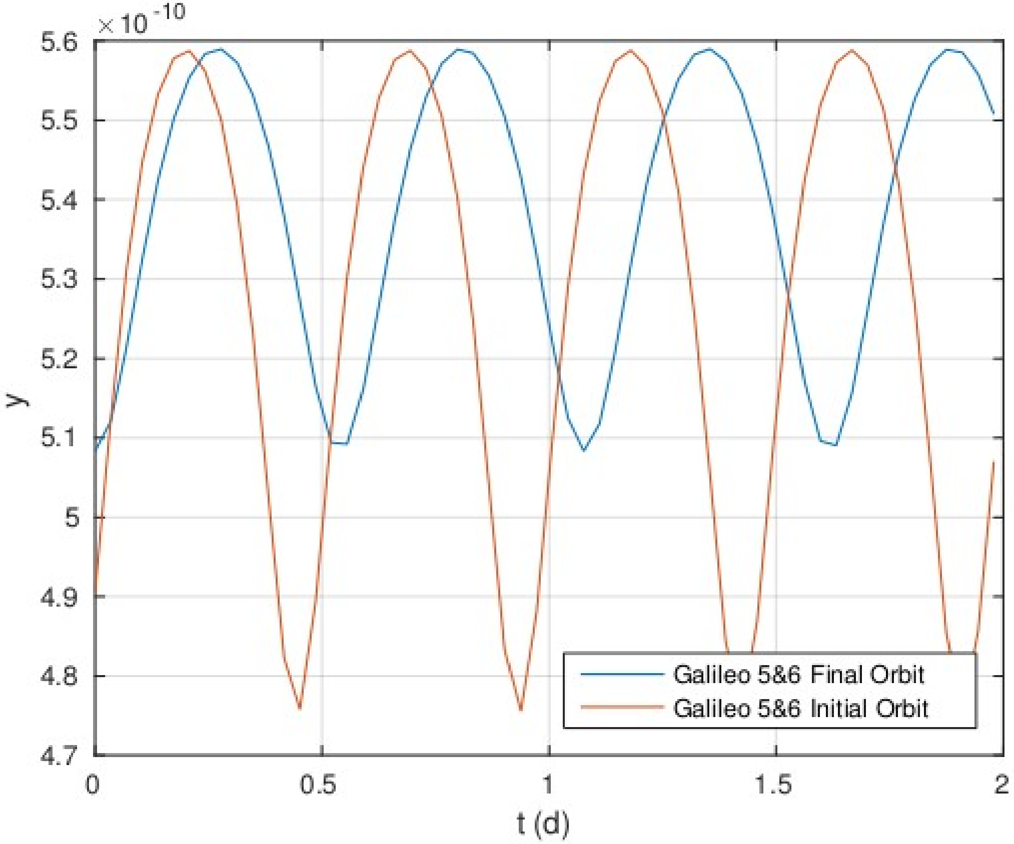
1. **Matched Filtering** in the frequency domain
2. **Linear Least-Square + Monte-Carlo** in the time domain

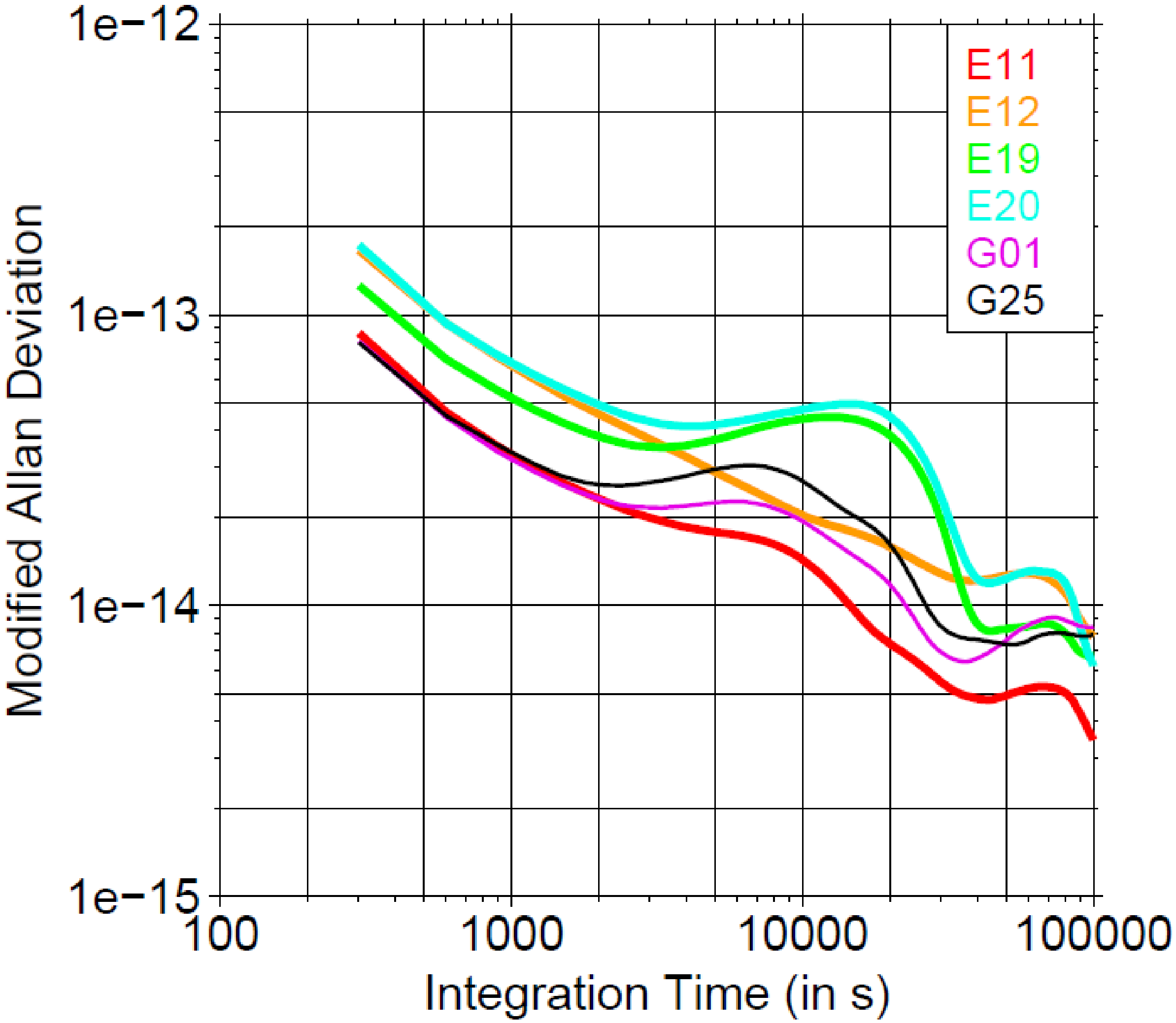
- Wrong orbit due to a technical problem : **eccentric orbit** (~0.16 today, ~0.23 initially)
- Two-Lines Elements (TLE) + Kepler equation for a duration of 2 years



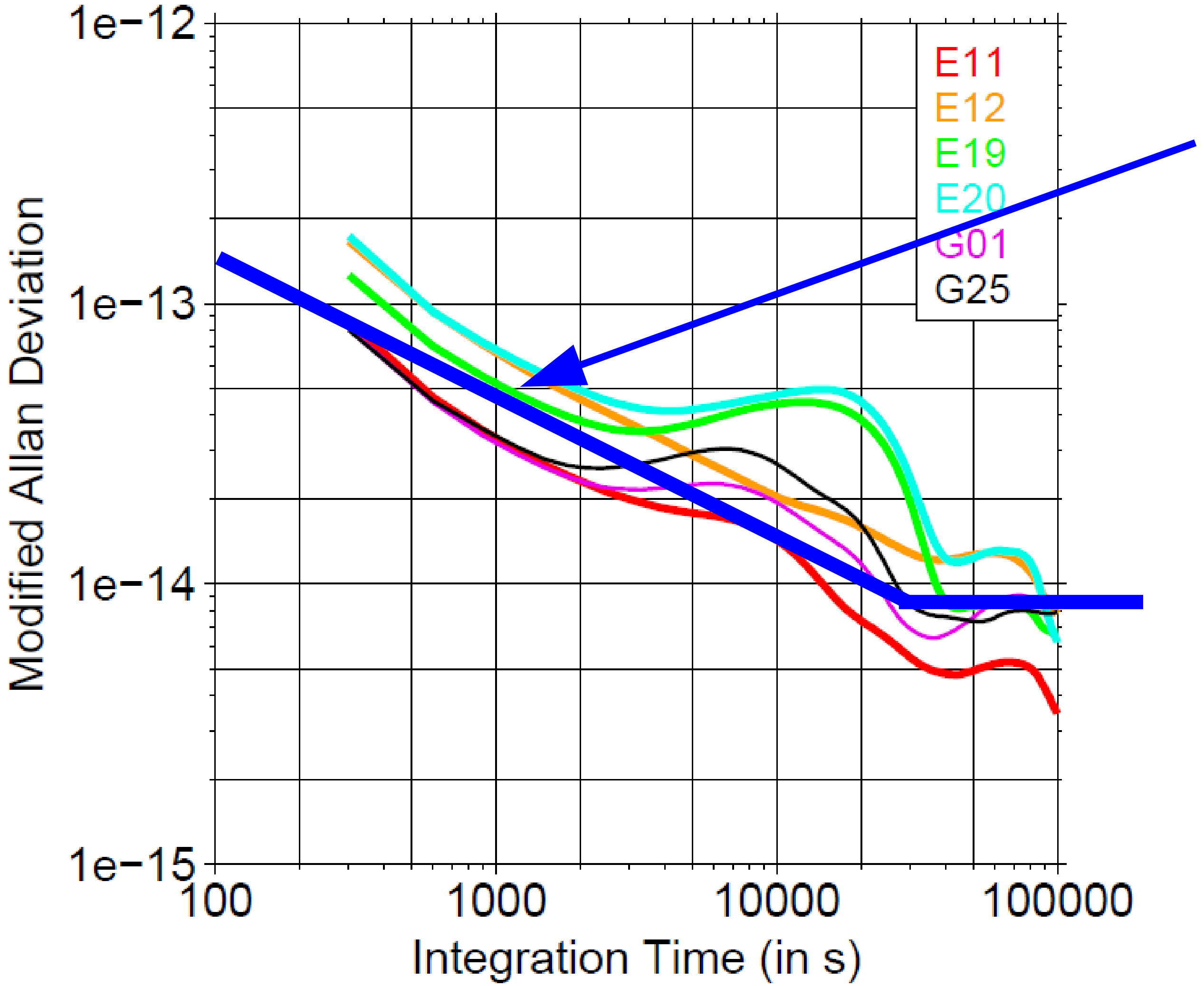
- Simple phenomenological model for LPI violation (C. Will, LRR 2014)
- Alpha is = 0 in GR
- GP-A limit : alpha < 1.4x10^{-4}

$$\tilde{y}(\alpha) = -(1+\alpha)\frac{GM}{c^2 r_s}$$





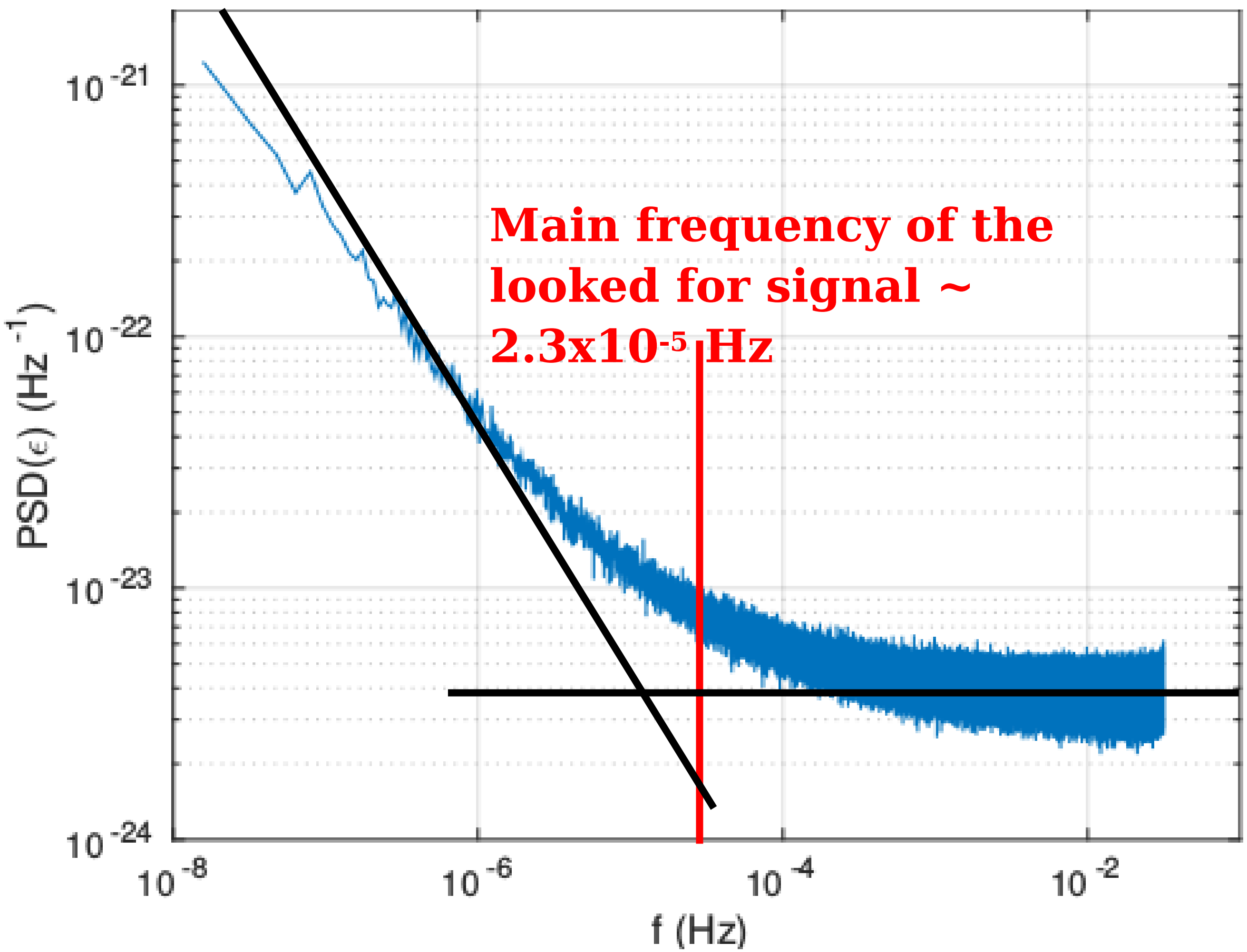
L. Prange et al., IAG Potsdam Proceedings, 2014, accepted for publication



MDEV of the simulated clock noise

- White noise ~5x10-14 @ 1000s
- Flicker noise ~8x10-15

L. Prange et al., IAG Potsdam Proceedings, 2014, accepted for publication



PSD of the simulated clock noise

- White noise $\sim 4\times10^{-24}$
- Flicker noise $\sim 4\times10^{-29}$ @ 1 Hz $\sim 2\times10^{-24}$ @ signal frequency

Matched filtering method

Sensitivity is the inverse of the signal-to-noise (SNR) ratio ρ, which is maximized with **matched filtering**

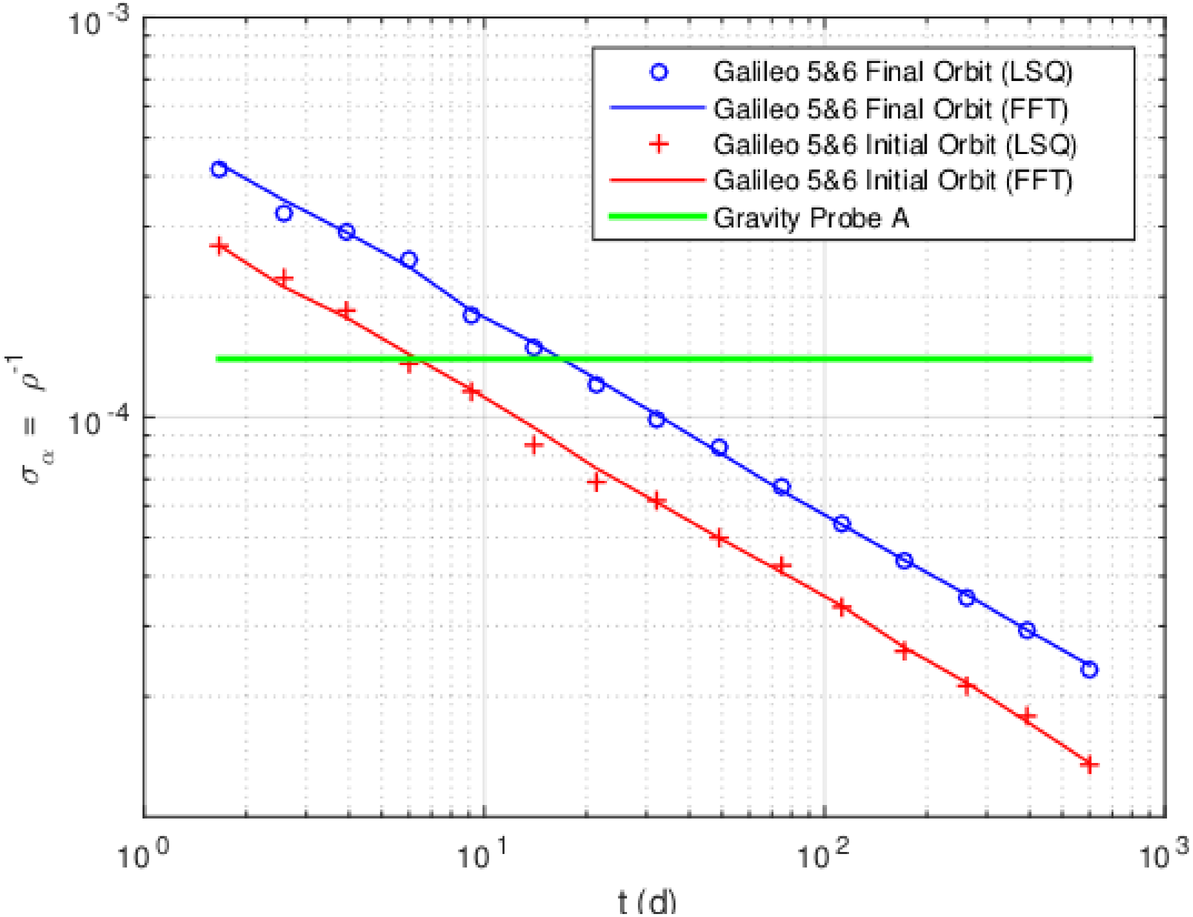
$$\rho^2 = \int_{-\infty}^{+\infty} \frac{|\tilde{X}(f)|^2}{S_N(f)} \mathrm{d}f$$

- $\tilde{X}(f)$: Fourier transform of the (ideal) signal
- $S_N(f)$: PSD of the random noise

Linear least-square method

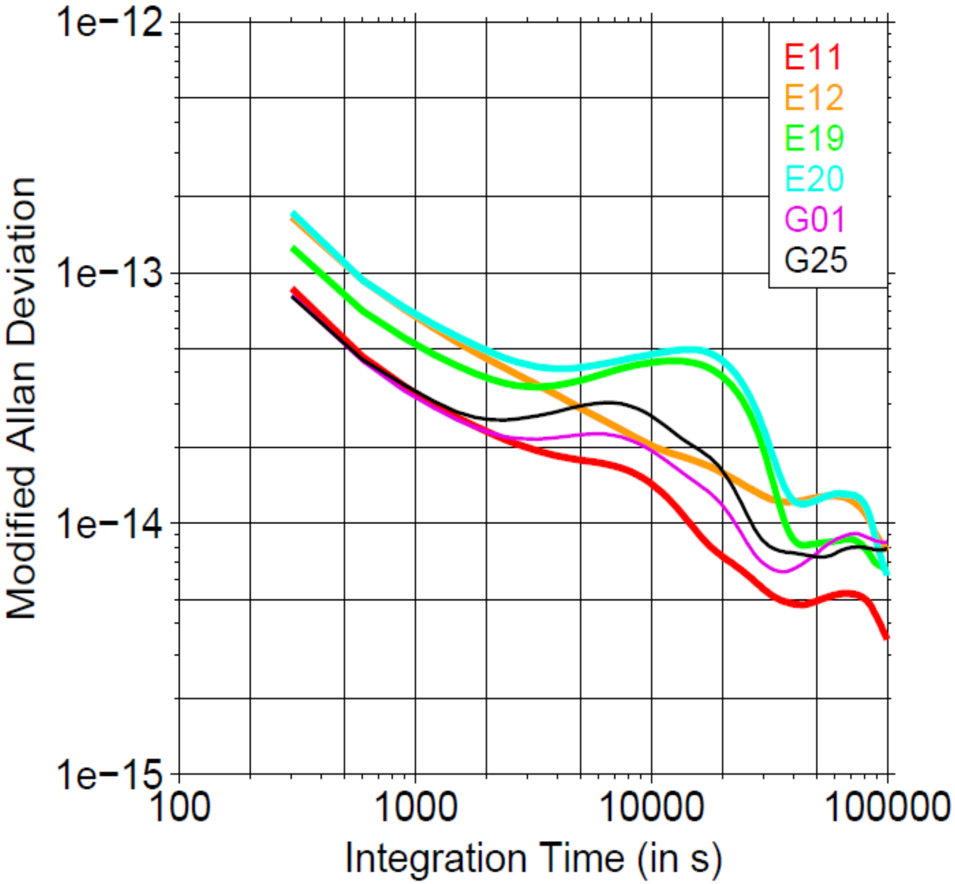
Find the minimum of the merit function χ^2 with respect to alpha

$$\chi^2 = \sum_{i=1}^{N} \left[(y(t_i) + \epsilon_i + \epsilon_{\mathrm{sys}}) - (\tilde{y}(\alpha; t_i) + A) \right]^2$$



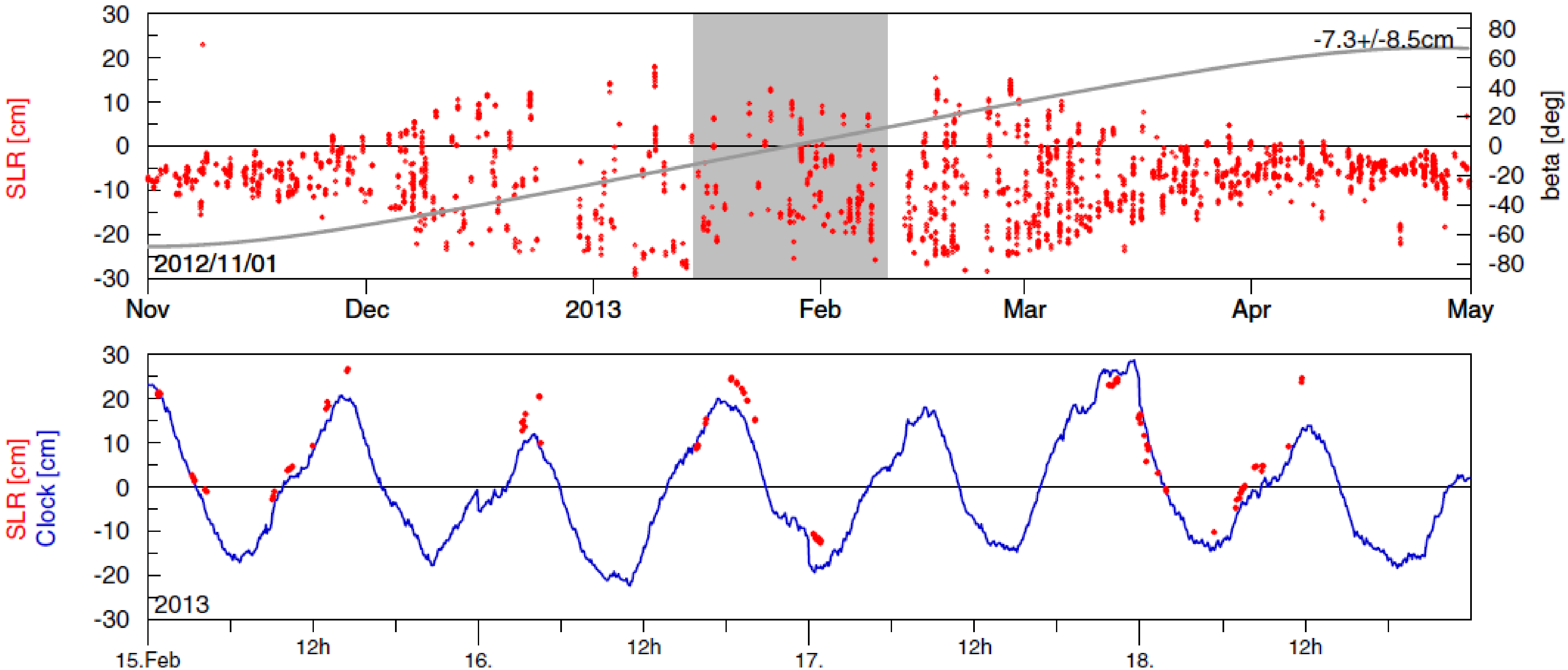
- *The best actual limit on grav. redshift (GP-A) is reached after ~2 weeks with Galileo 5*
- *After one year of integration the sensitivity is ~3x10-5 → a factor of 5 better than GP-A, which was a dedicated experiment (expected sensitivity of ACES-PHARAO is 2-3x10-6)*

- The two very different methods agree on the sensitivity of the test
- We proved mathematically that $\sigma_\alpha = \rho^{-1}$
- **Problem** : all systematic effects that mimic the gravitational redshift signal will induce a bias in the estimation of alpha → fake violation of LPI



Bump in the MDEV → systematic effect at orbital frequency due to a **radial error in the estimated orbit** (Montenbruck et al., J.Geo., 2014)

→ mimick a grav. redshift violation !



- Systematic effect shows a **dependency with the sun elevation angle**, ie. the direction of Sun w.r.t. the satellite orbital plane (Montenbruck et al., J.Geo., 2014)
- At least 75 % of this effect due to **mismodeling of Solar Radiation Pressure** (SRP), other effects could be due onboard temperature variations

Systematic effects

- Systematic effect due to mismodelling of the SRP :
  - Effect at orbital frequency with a frequency shift (1/year) (linked to the direction of the Sun
  - Amplitude modulation at frequency (1/year)

$$\epsilon_{\rm sys} = A \sin((n_{\rm sat} + \omega_{\rm year})t + \phi_1)(1 + B(\cos(\omega_{\rm year} t + \phi_2) - 1)),\ \omega_{\rm year} = 2\pi/{\rm year}$$

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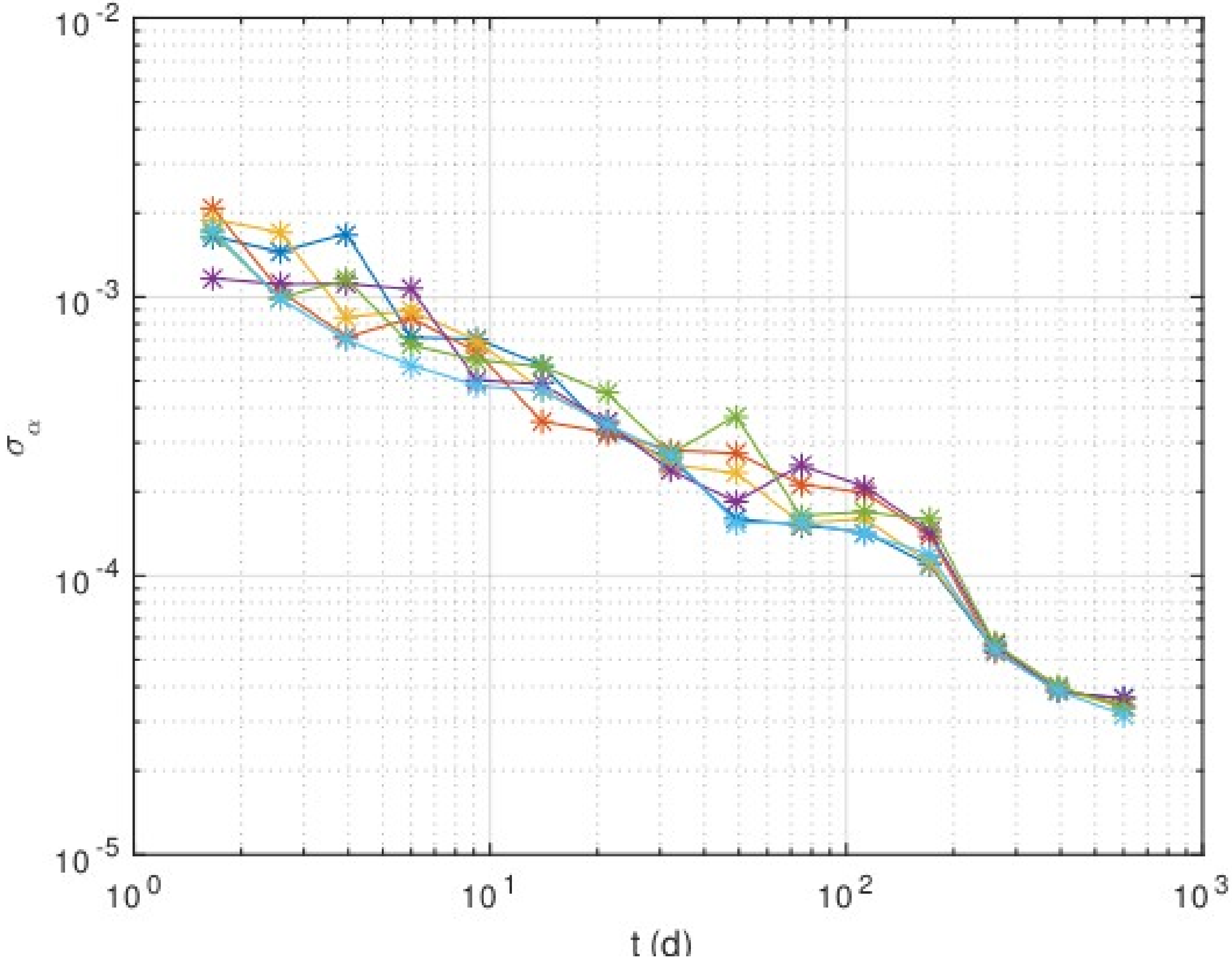

Decorrelation between fit parameters occurs for 1 year integration time

Conclusion

- it will be possible, with Galileo satellites 5 and 6, and at least one year of data, to improve on the GP-A (1976) limit on the gravitational redshift test, down to an accuracy around $3\text{-}5\times10^{-5}$
- Detailed study of random and systematics effects (article submitted)