Phase extraction for LISA heterodyne interferometry and deep frequency modulation interferometry

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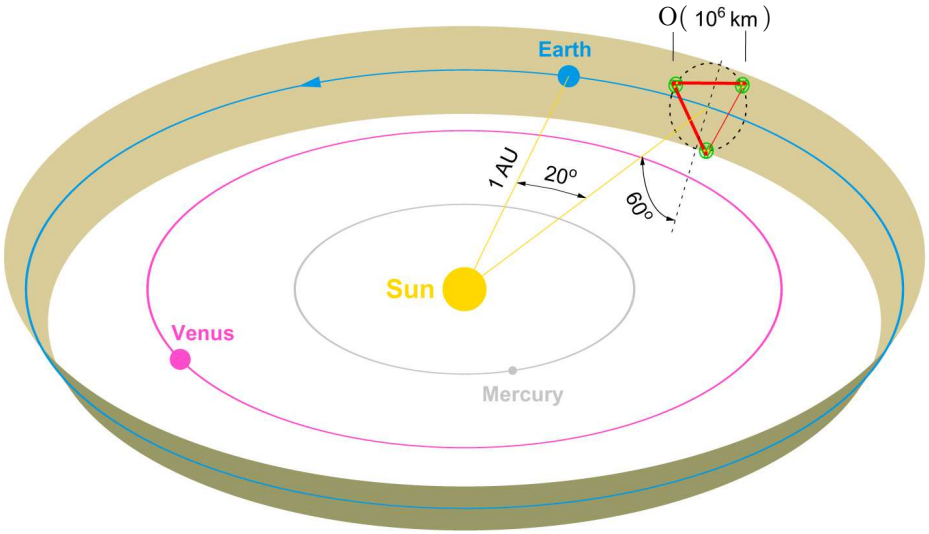
LISA phase extraction

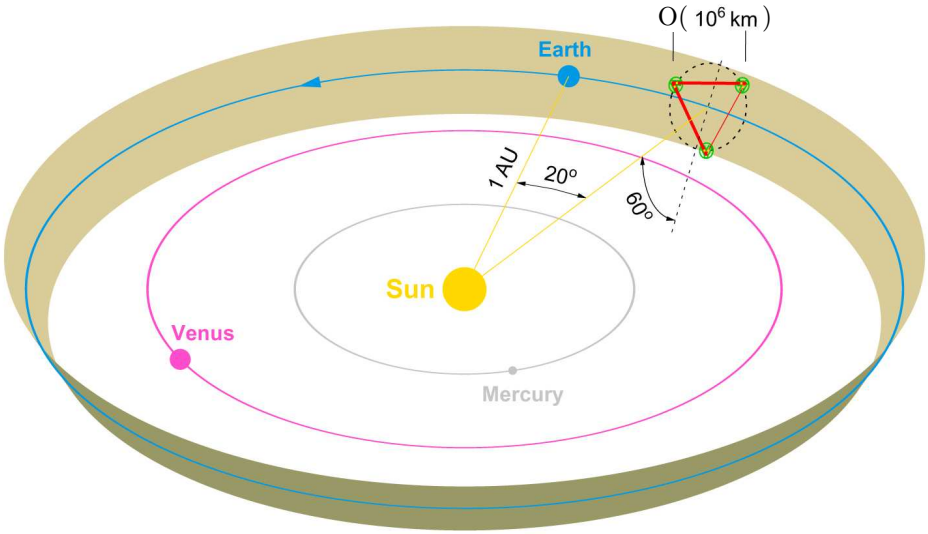
LISA



- Detect gravitational waves in mHz regime
- Operates with heterodyne interferometers

→ Phase extraction: LISA phasemeter (PM)

Related LISA specifictations

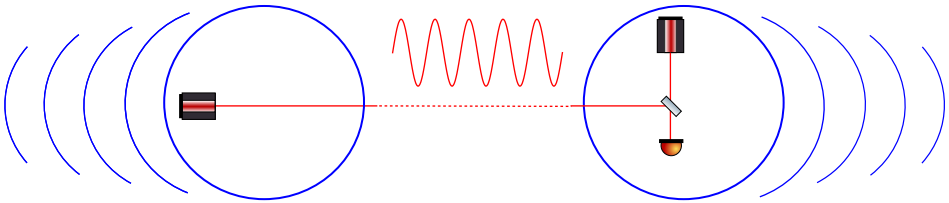


- Several million km armlengths
- Independently changing with up to several m/s
- Heterodyne interferometry with $\frac{\text{pm}}{\sqrt{\text{Hz}}}$ precision

$\rightarrow$ 3 (a.o.) technical issues and related requirements for PM

Issues $\rightarrow$ requirements

- $\frac{\text{pm}}{\sqrt{\text{Hz}}}$ interferometry $\rightarrow$ Phase readout contribution: $2\pi \frac{\text{urad}}{\sqrt{\text{Hz}}}$
- Doppler shift $\rightarrow$ Phase readout w. MHz bandwidth

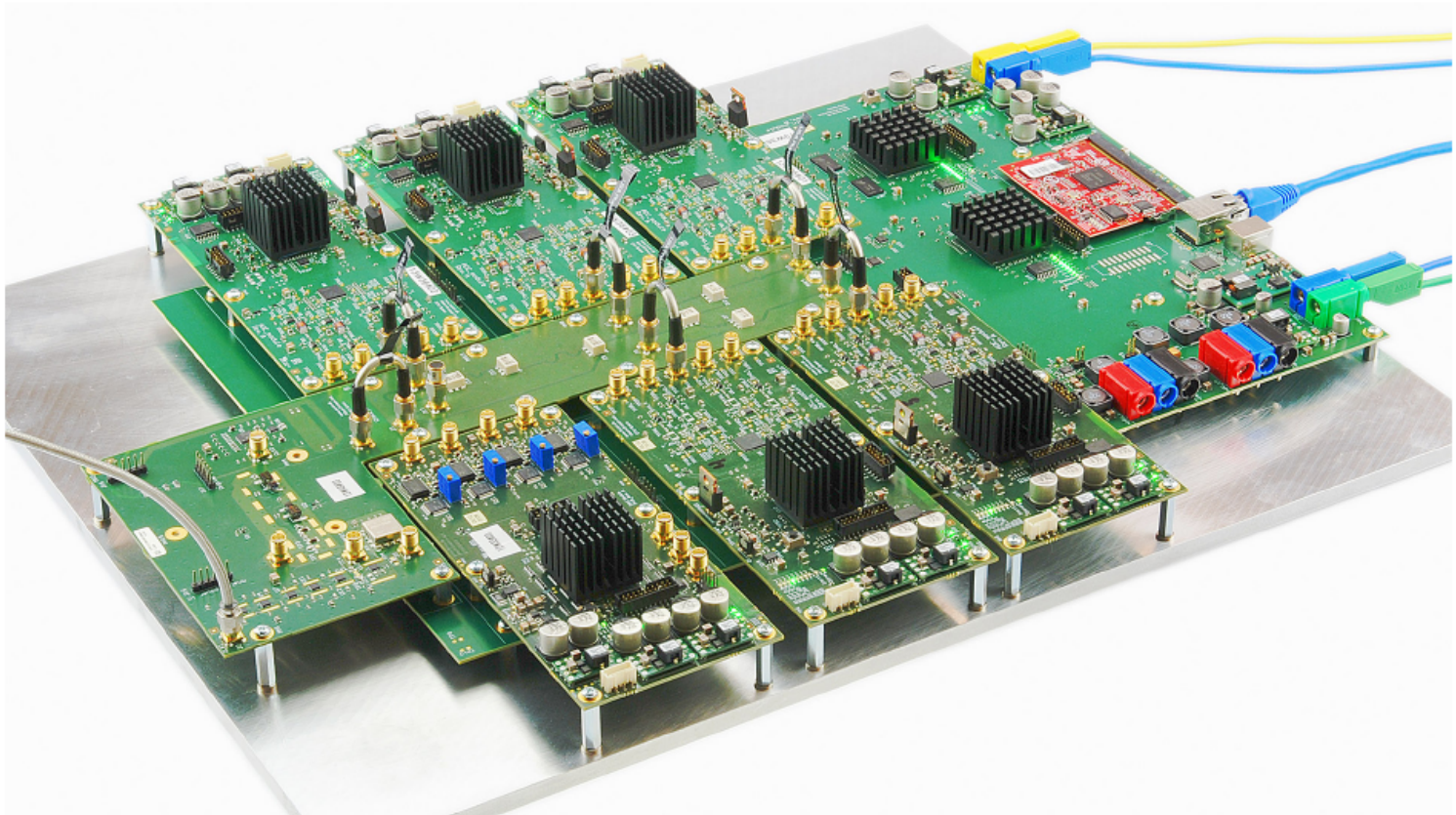


- Freq. noise amplification $\rightarrow$ Phase readout w. high dynamic range

$$\delta x = \frac{\Delta L}{f} \delta f$$

The phasemeter

- European implementation as elegant breadboard model:
- Core: FPGAs running DPLLs



- How to test it?

Two signals vs. Three signals

- No absolute test possible (lack of reference)
- Test phasemeter against itself: split/null measurements:
  - Split into identical signal: $s_a = \varphi_1 \quad s_b = \varphi_1$
  - Two channel comparison: $s_a - s_b \stackrel{!}{=} 0$
- Common noise or nonlinearities cannot be detected

  $\rightarrow$ Three-signal test
- Combine initial phase signals φ_1, φ_2, φ_3 to three intermediate ones

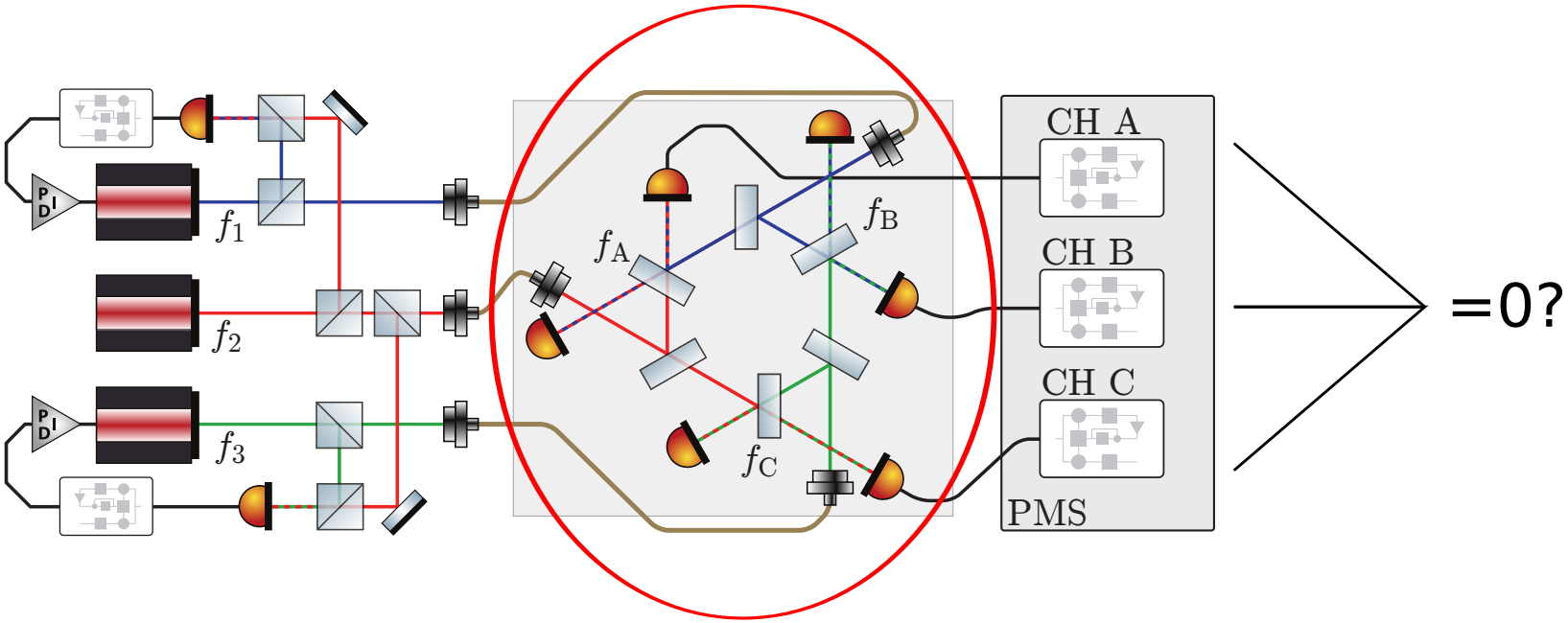
$$s_a = \varphi_1 - \varphi_2 \qquad s_b = \varphi_2 - \varphi_3 \qquad s_c = \varphi_1 - \varphi_3$$

- Measure s_a,s_b and s_c in different Phasemeter channels and add up:

$$s_a + s_b + (-s_c) \stackrel{!}{=} 0$$

Optical three-signal test

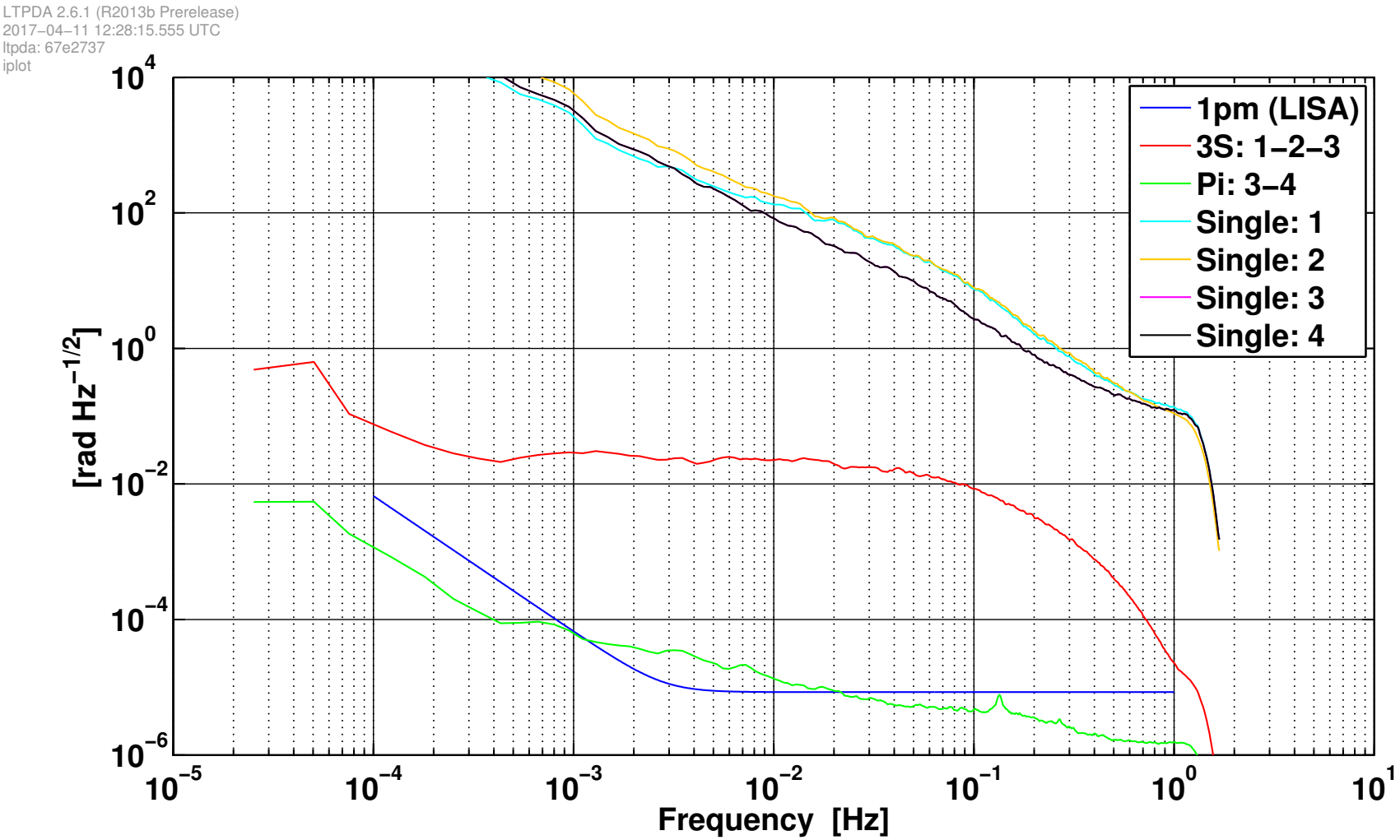
→ Optical testbed: hexagonal optical bench with 3 recombination beamsplitters



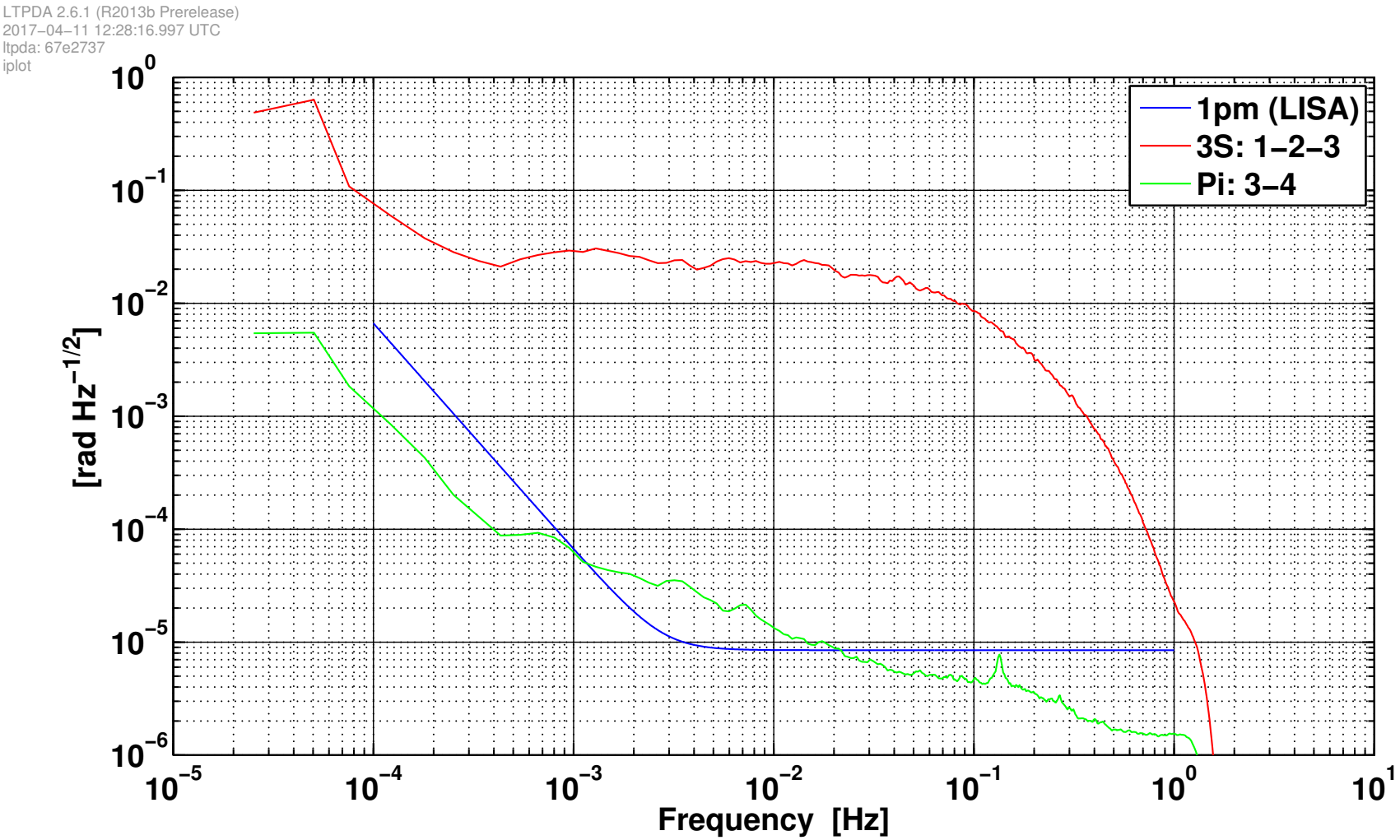
Optical three-signal test

→ Optical testbed: hexagonal optical bench with 3 recombination beamsplitters

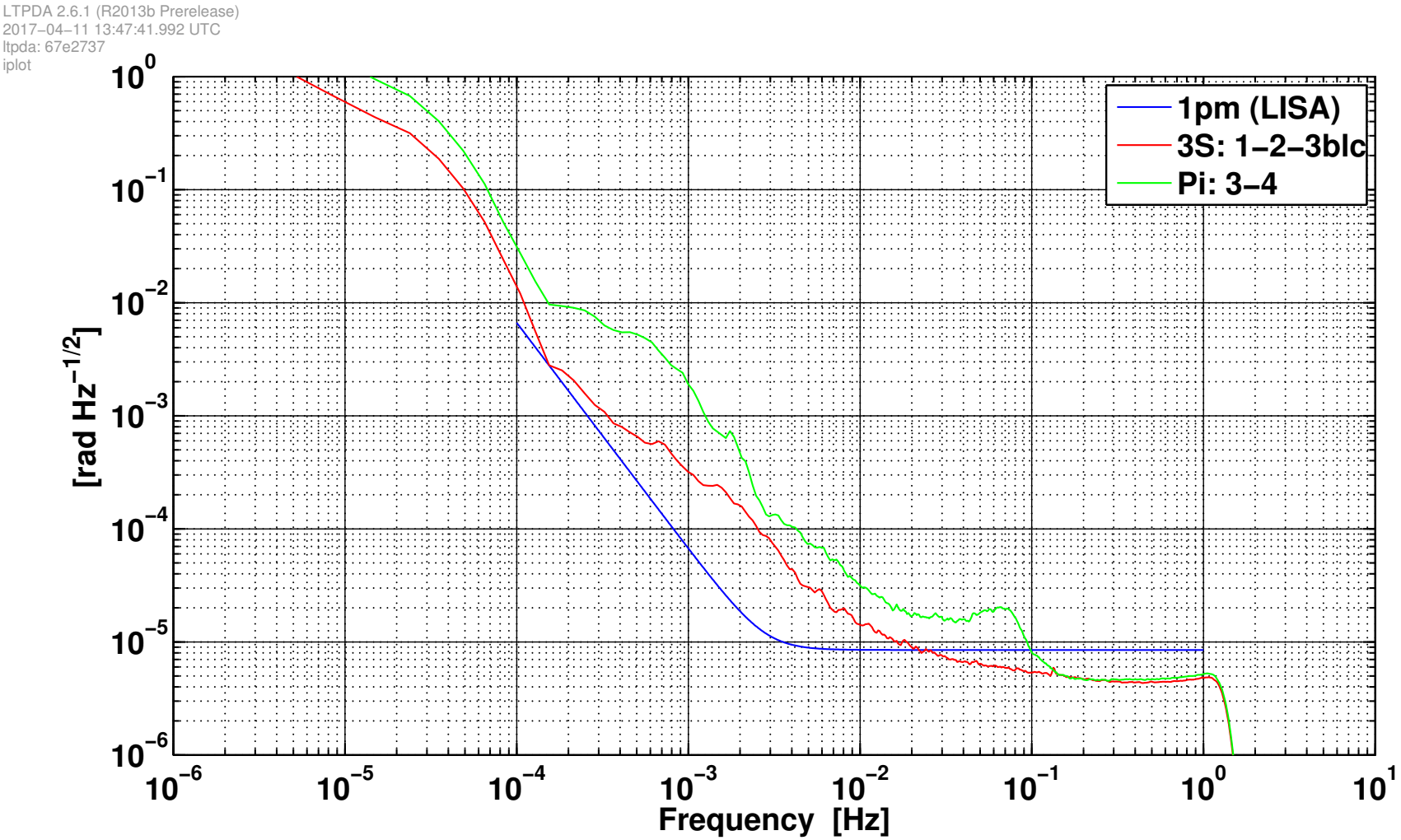
Initial measurement



Initial measurement

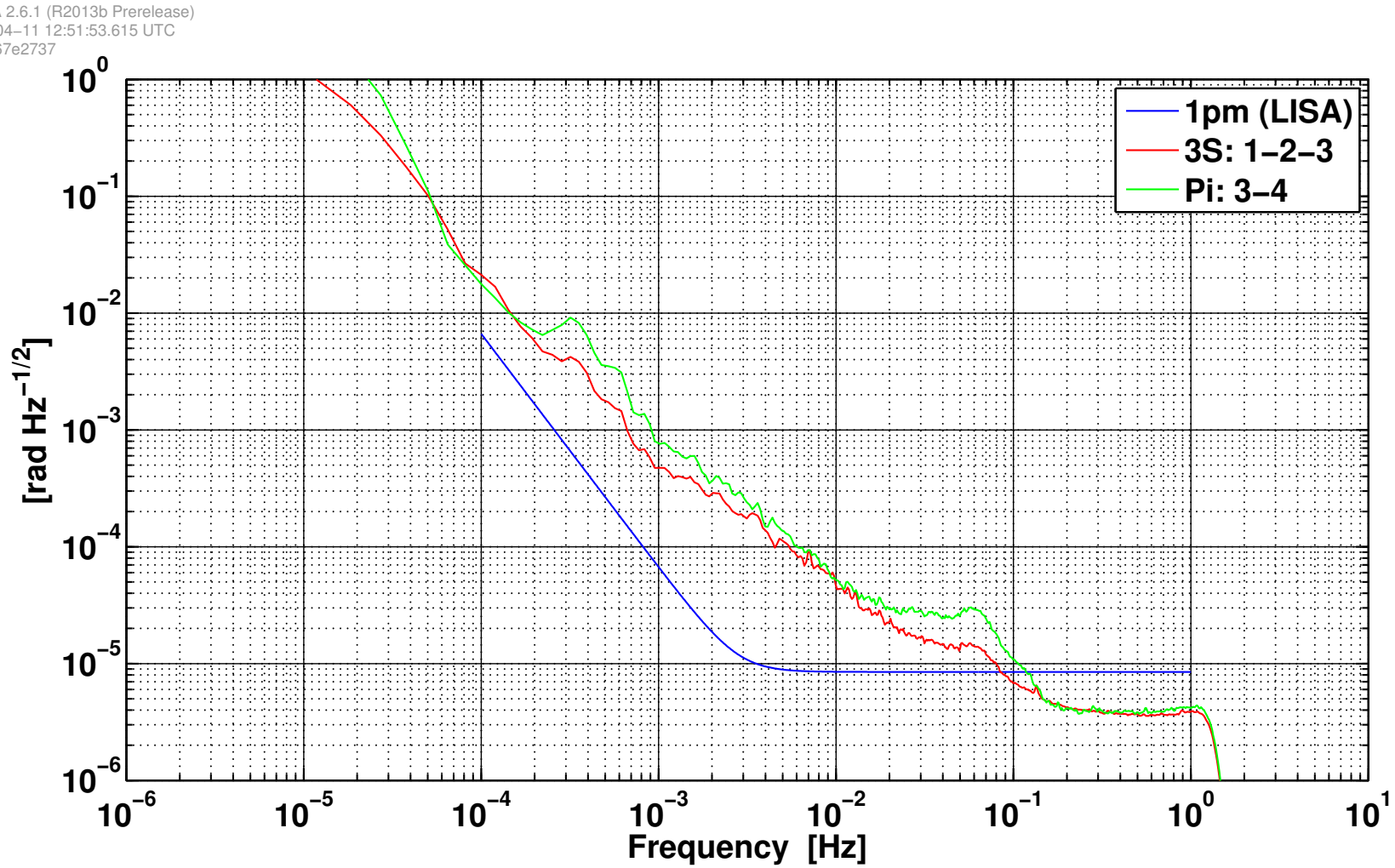


After some sweat and time



With sweep and high dynamic range

- Add single channel noise and sweep carrier frequency at error point



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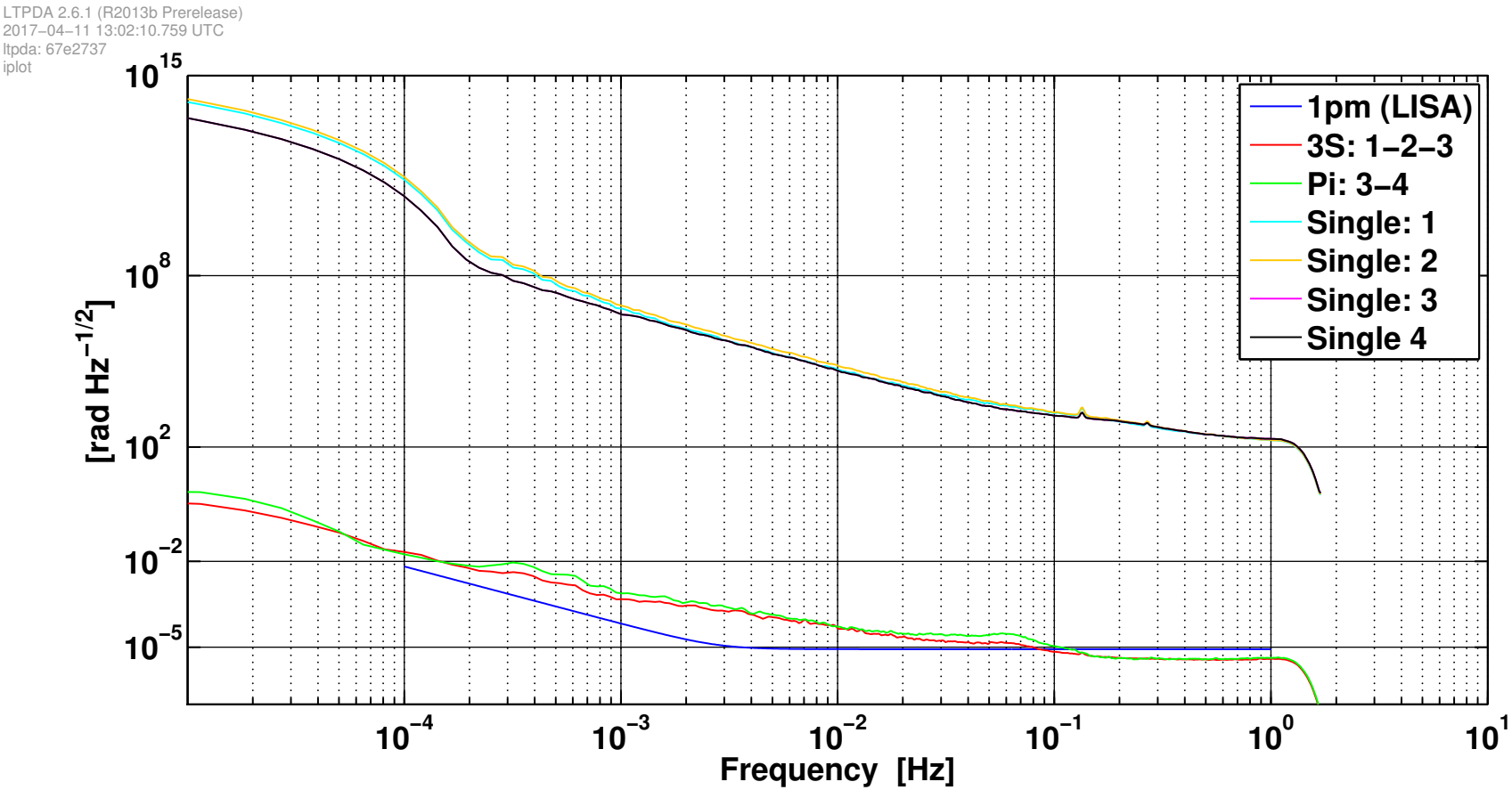

With sweep and high dynamic range

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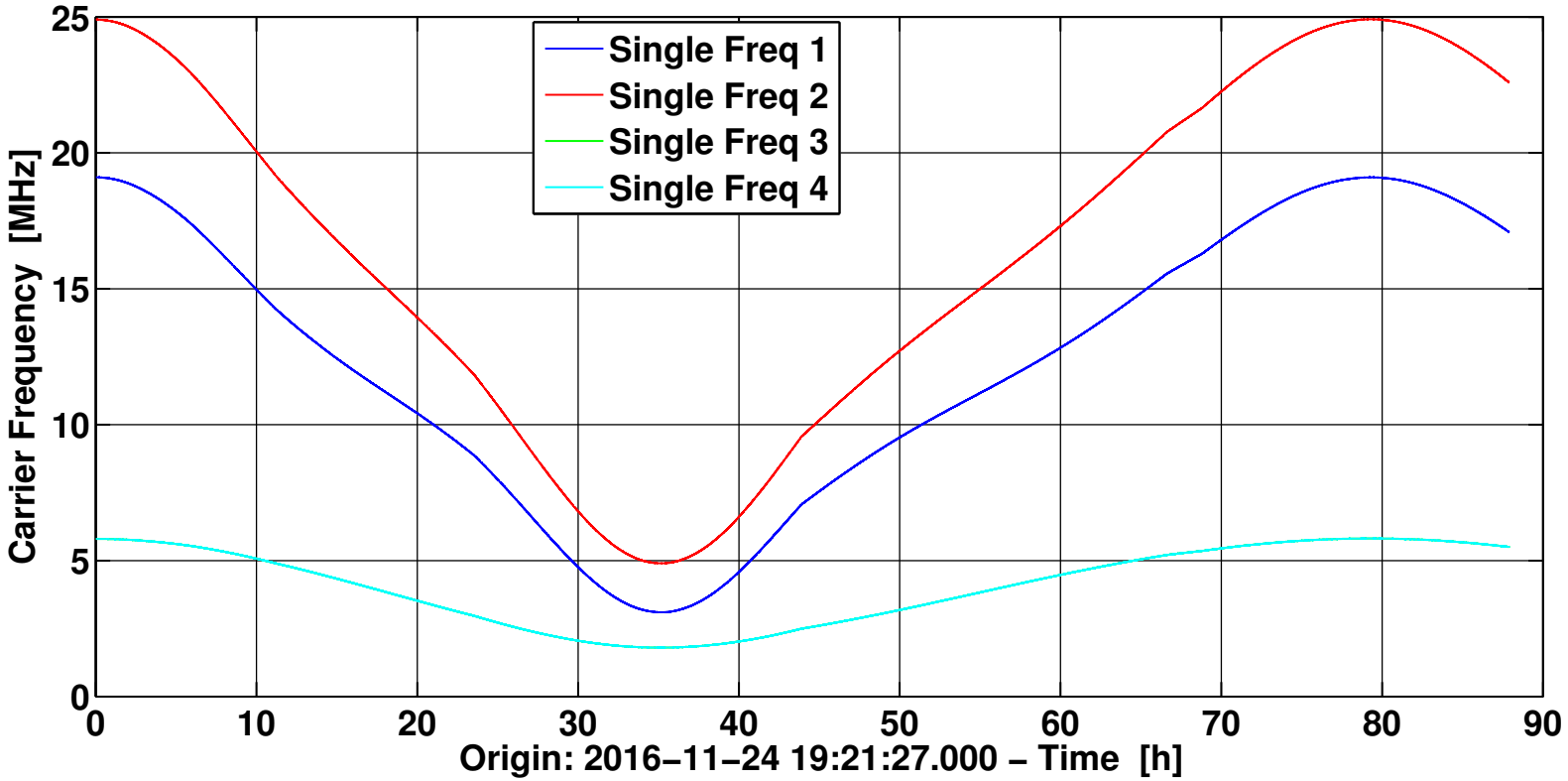
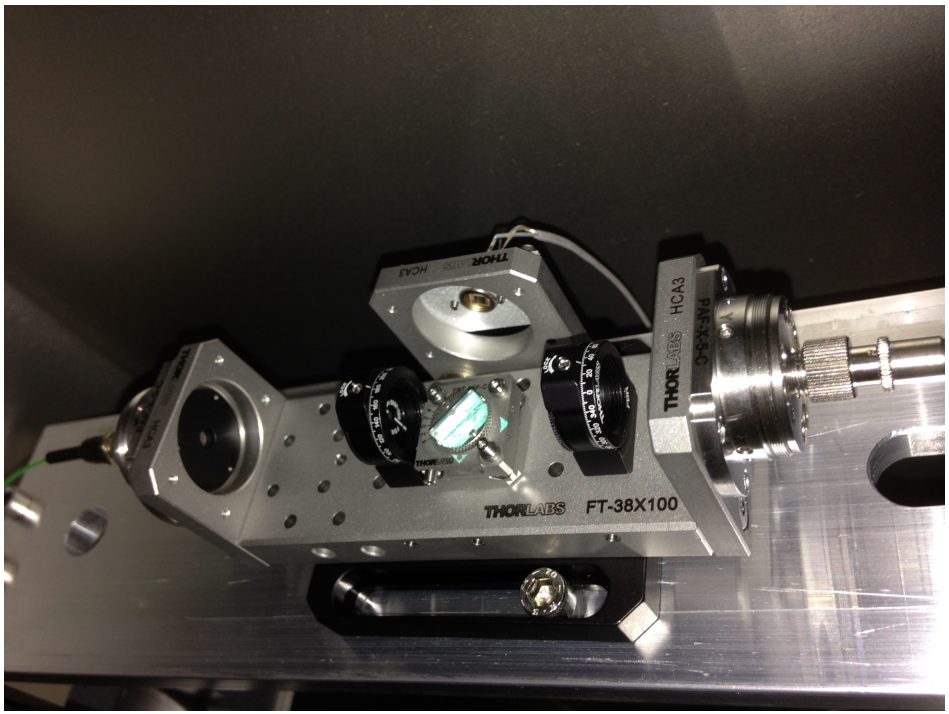


Latest work: polarization control

- Limitation at low freqs: likely due to non-linear polarization

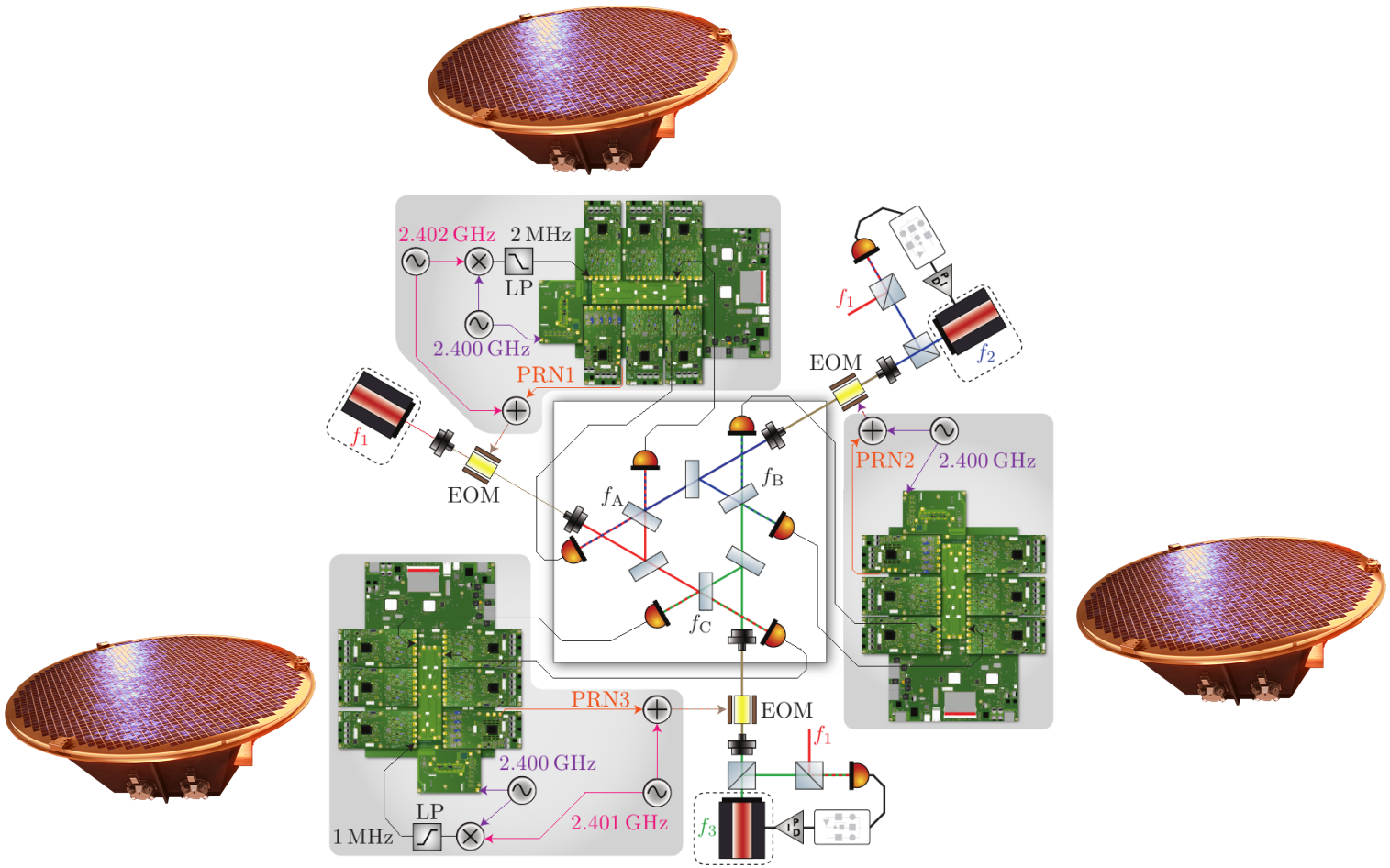
→ Can be caused by mating sleeves

- Use fiber benches to get hold on polarization



Outlook

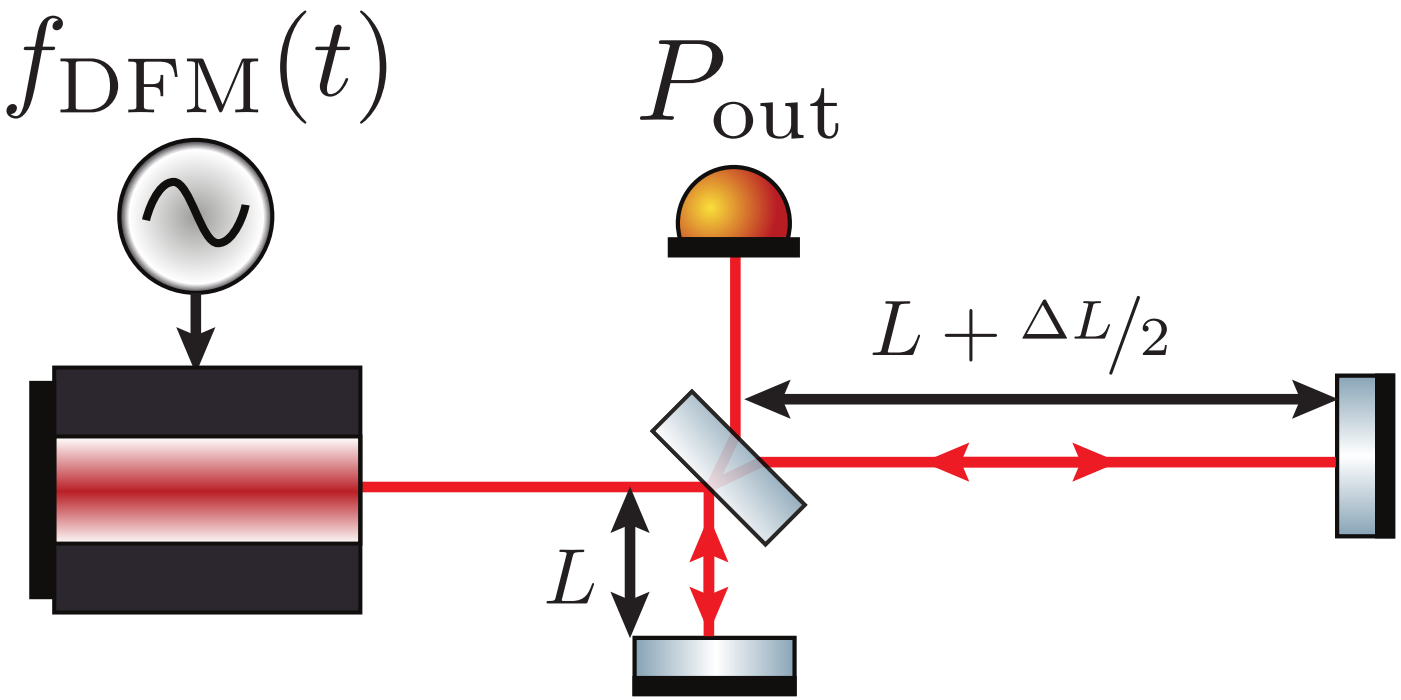
- LISA metrology experiment (Talk Daniel Penkert)



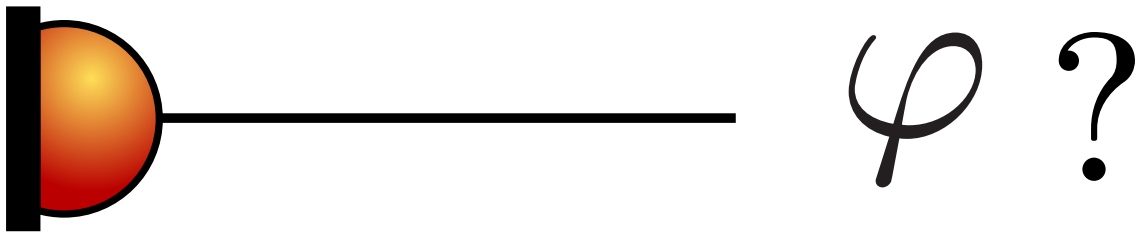
Phase readout for Deep Frequency Modulation Interferometry

Introduction

- DFMI setup (Details: Talk Katharina Isleif)

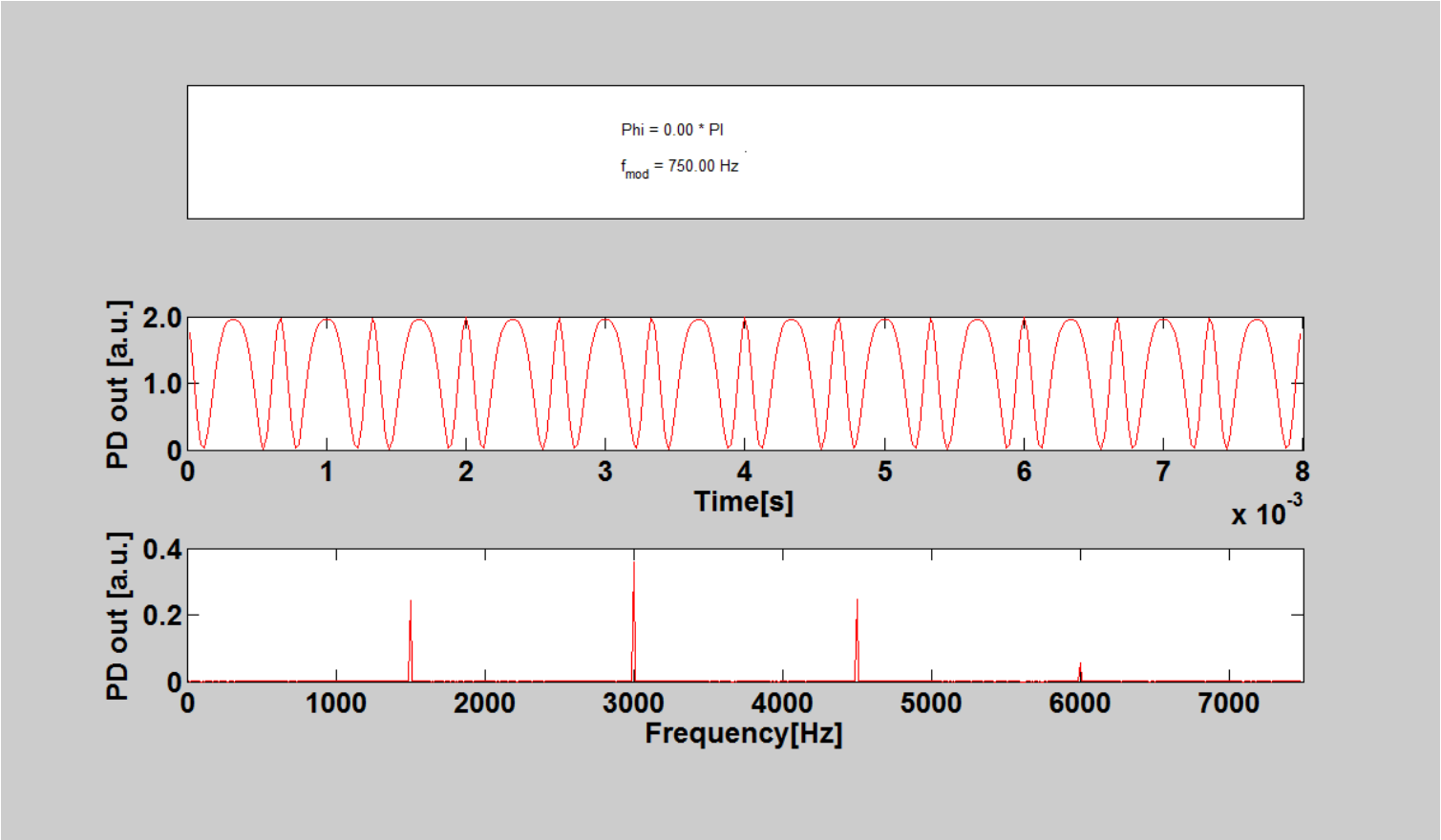


DFMI readout



- Signal: $V_{\mathrm{PD}} = A \cdot (1 - \cos(m \cdot \cos(2\pi\varphi) - \psi))$
- Fourier components at $x \cdot f_{mod}$

DFMI readout



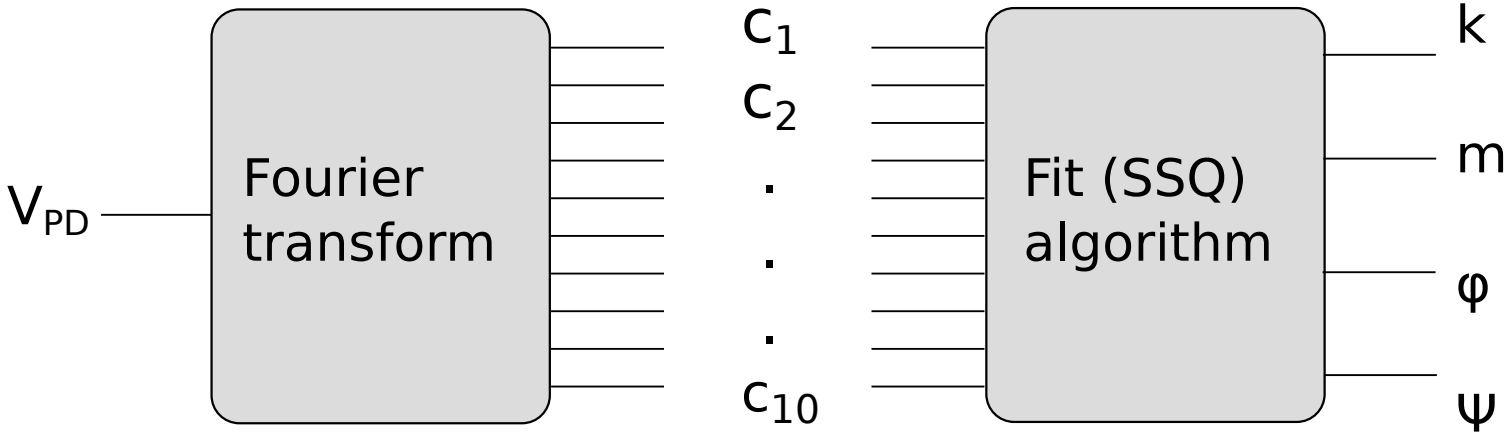
DFMI readout

- Fourier components:

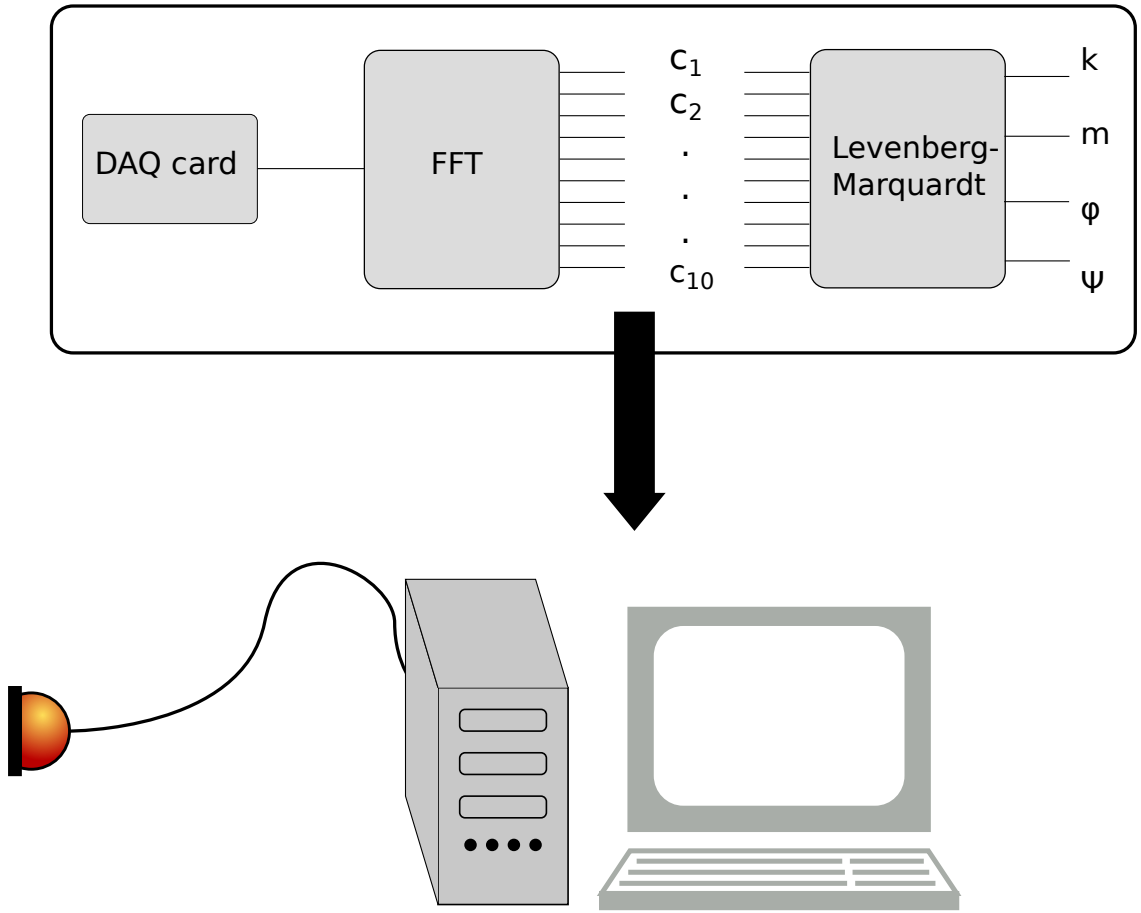
$$c_n = a_n e^{in\psi}$$

$$a_n = \begin{cases} k \sin(\varphi) (-1)^{\frac{n+1}{2}} J_n(m) & \text{if } n \text{ is odd,} \\ k \cos(\varphi) (-1)^{\frac{n}{2}} J_n(m) & \text{if } n \text{ is even.} \end{cases}$$

- Fit parameters with model to measured Fourier coefficients



DFM readout: embedded hardware



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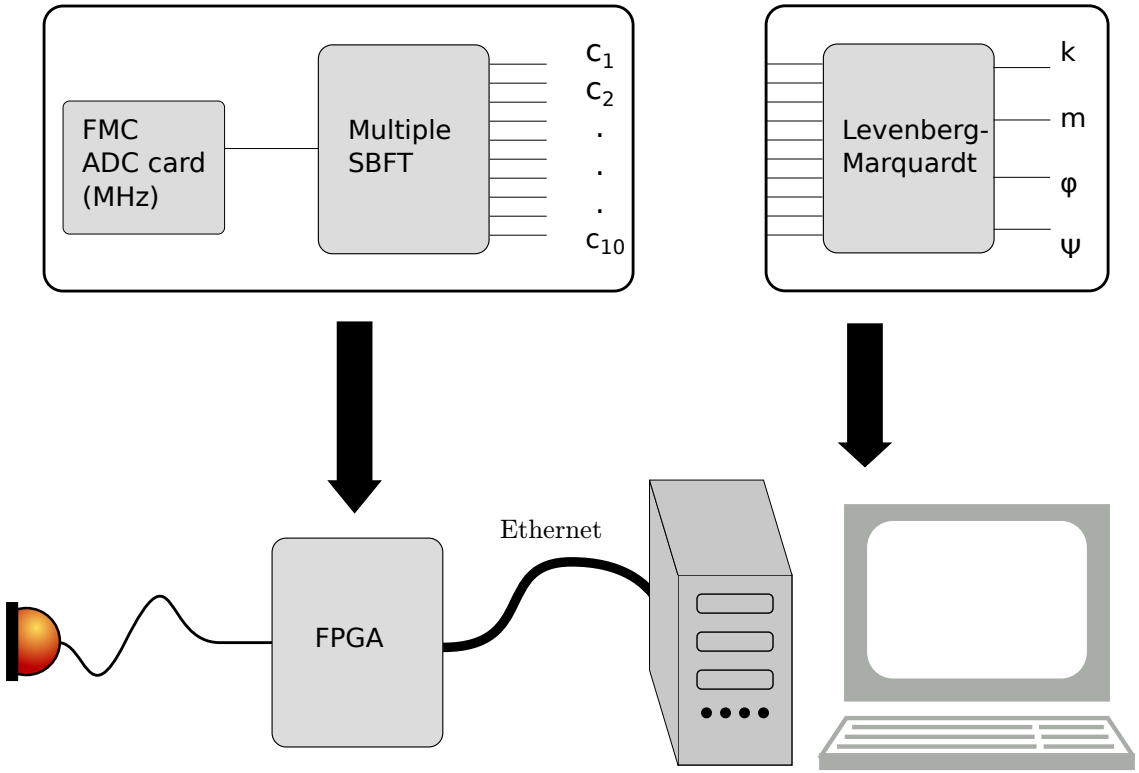
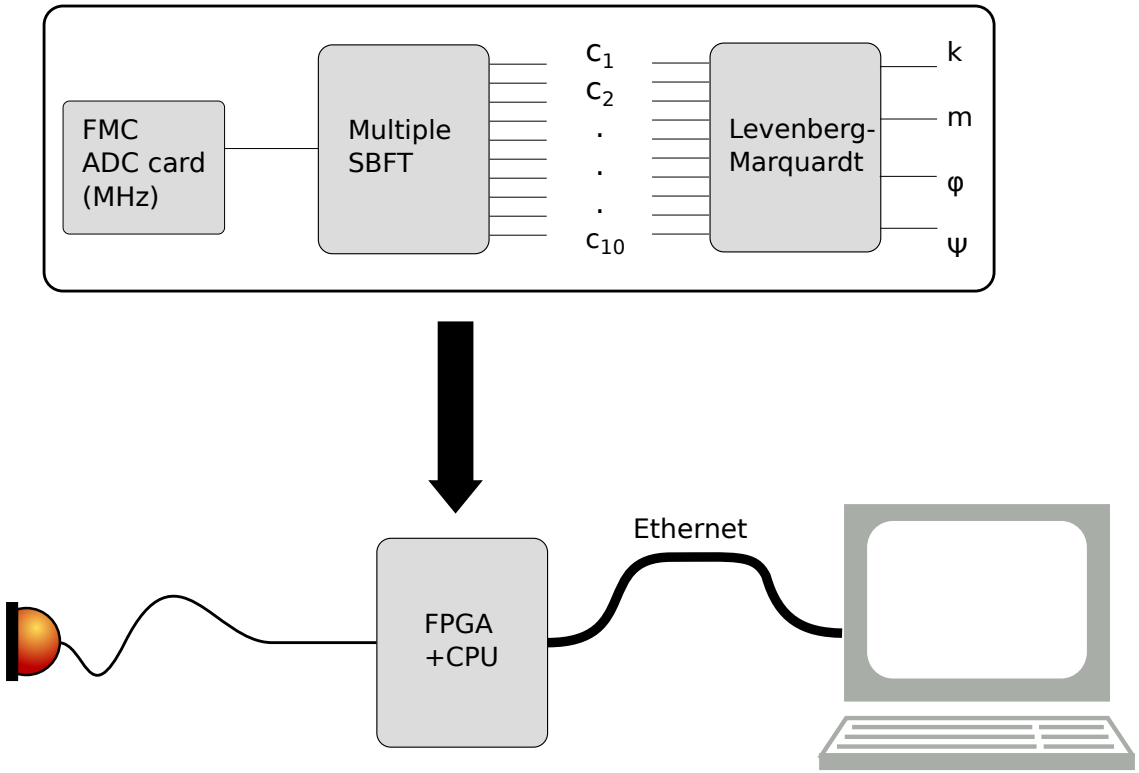
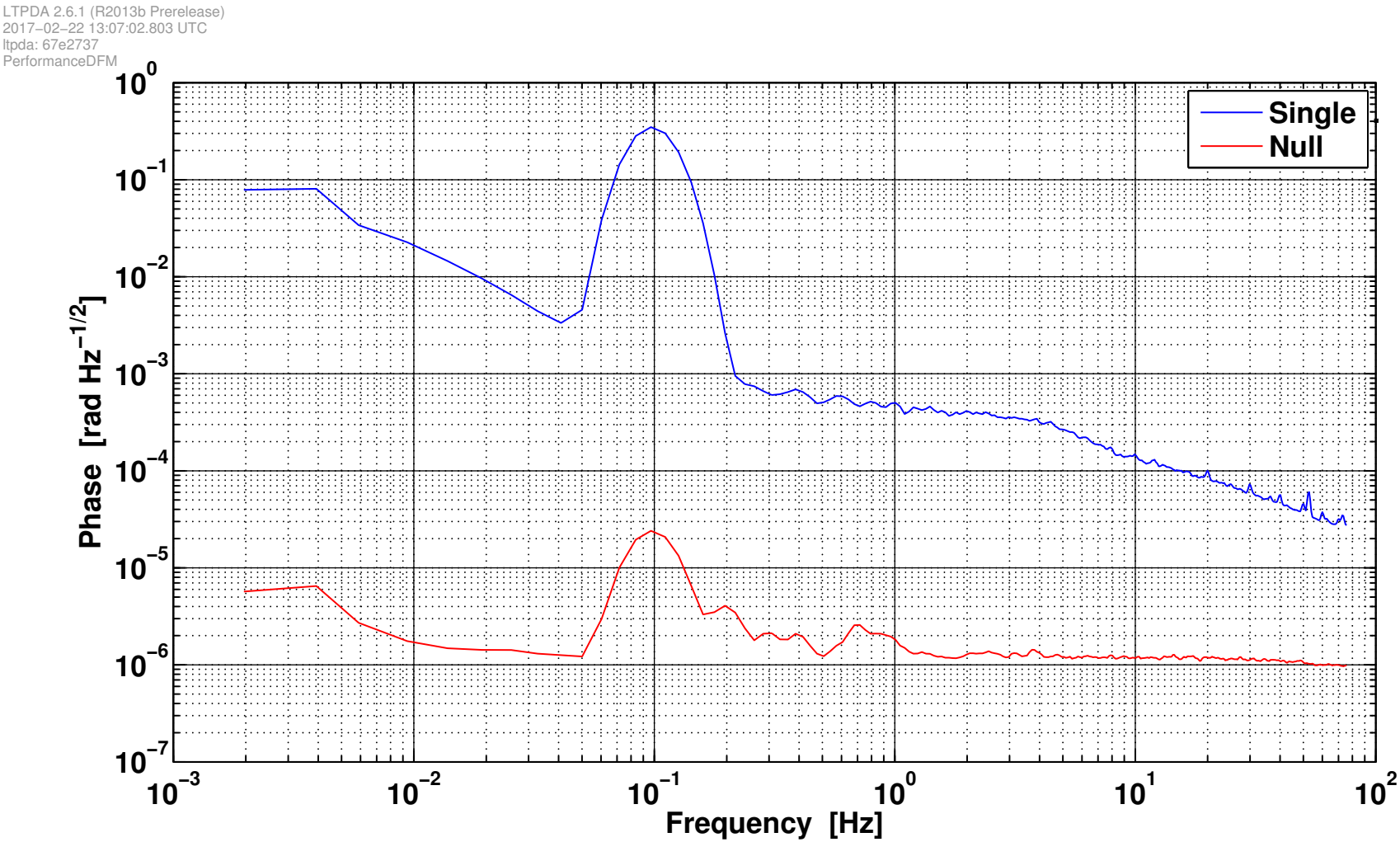


DFM readout: embedded hardware



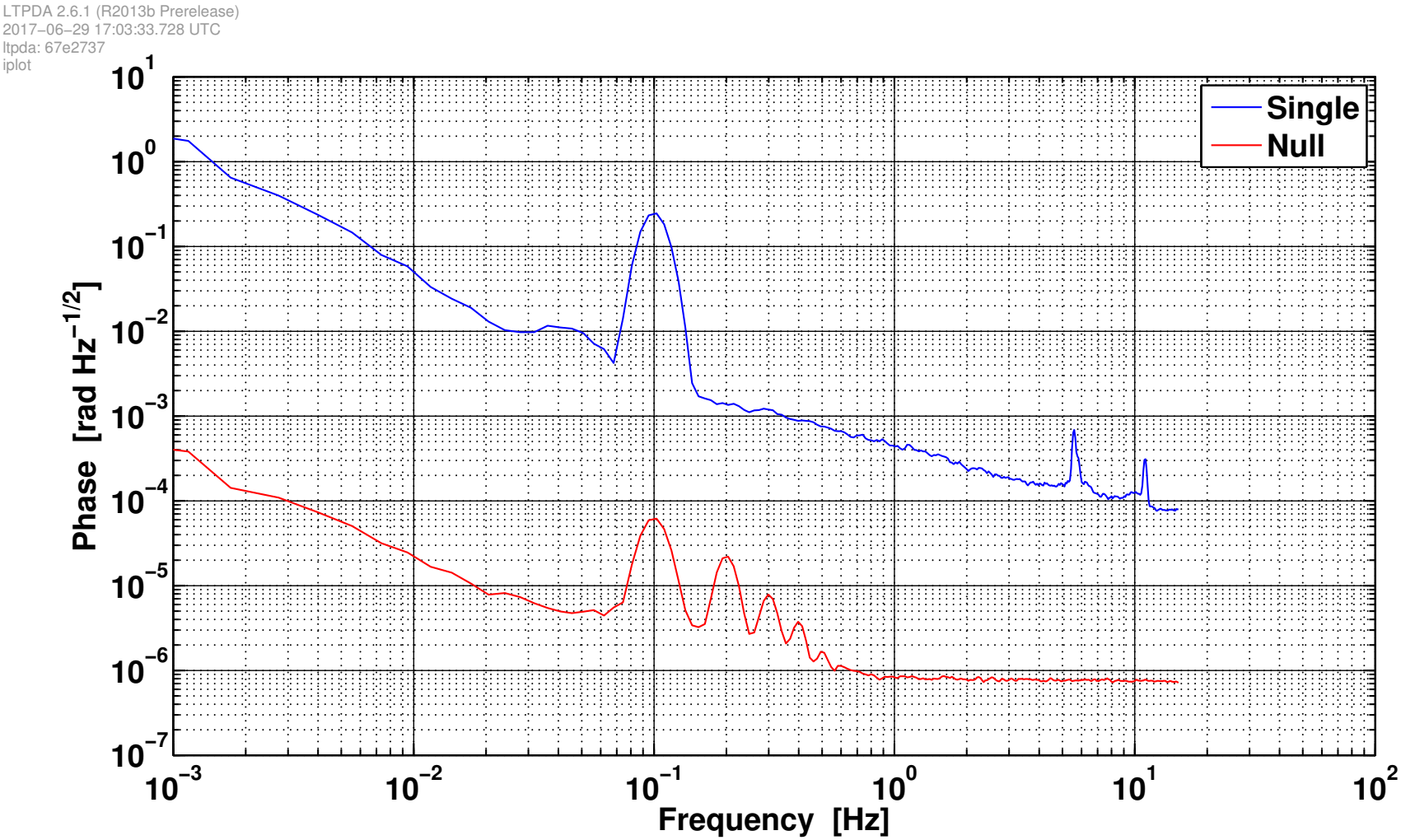
Electrical measurements

- Split measurement with modulation in electrical testbed

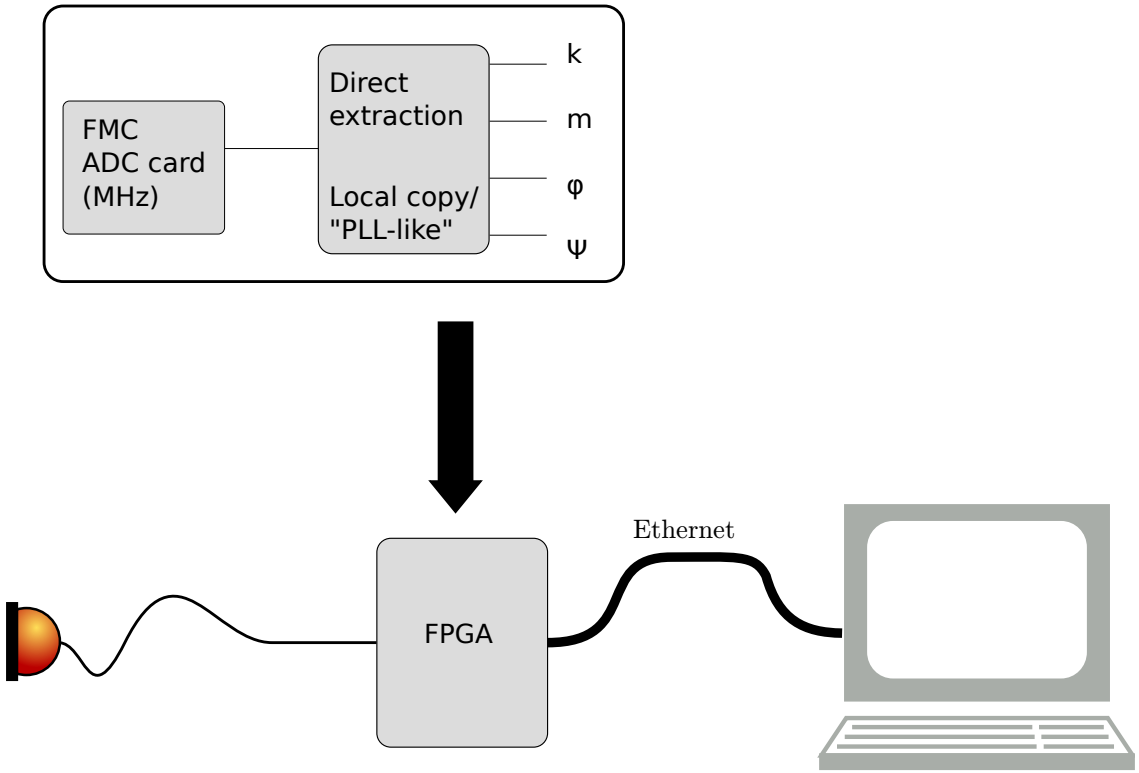


Measurements

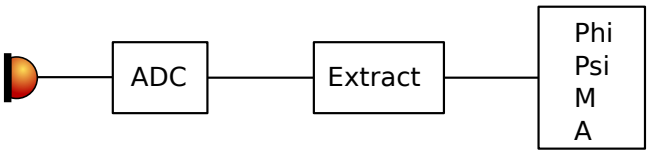
- Split measurement with optical setup and moving mirror

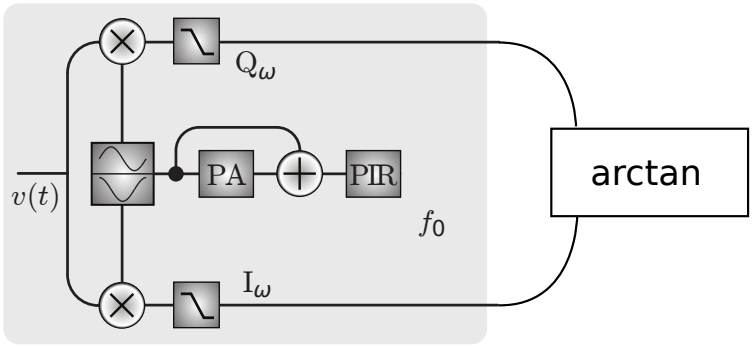


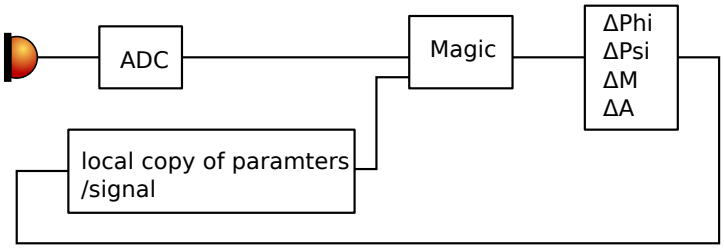
DFM readout: alternatives

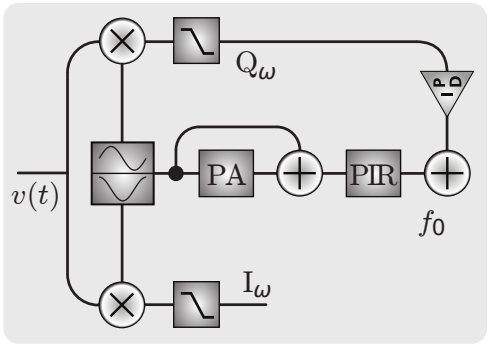


DFM readout: alternatives









Summary

Summary

- LISA phasemeter is being tested in optical three-signal testbed
  - → Measurement performance: getting close to LISA 1 pm
  - → Dynamic range up to 10 orders of magnitude
  - → Sweep with carrier frequencies between $\approx$ 5 - 25 MHz
- Long term goal: full metrology test (LIME) -> Talk by Daniel Penkert

- Embedded phasemeter for DFMI developed (spectral analysis + fit)
- Split measurements revealed $\frac{\text{urad}}{\sqrt{\text{Hz}}}$ noise floor with 3 order of magnitude dynamic range
- Other extraction algorithms under investigation

To be continued..

Thank you for your attention!

Image courtesy: NGO Yellow book, O.Gerberding, D. Penkert, K. Isleif