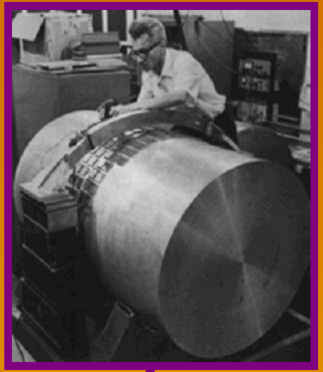
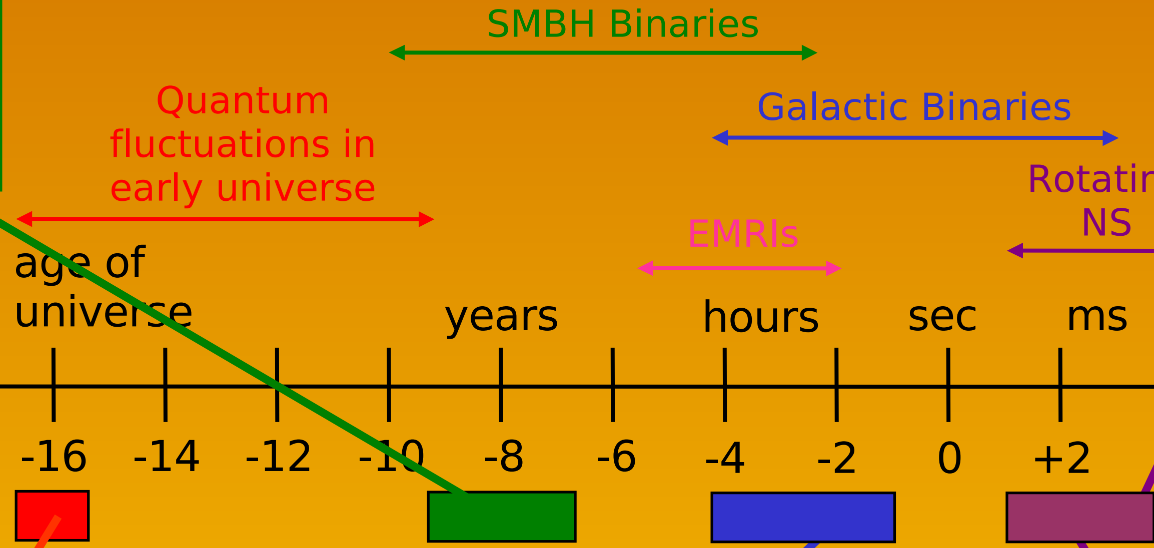
GW-Detection

pulsar timing



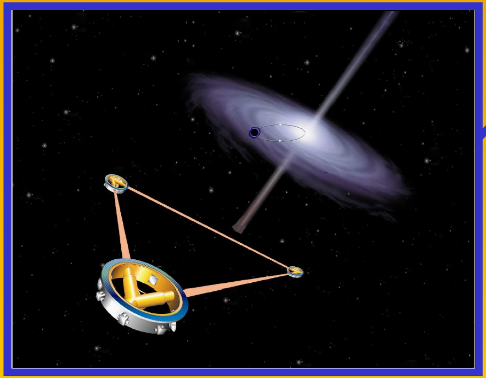
bars



ground-based interferometers

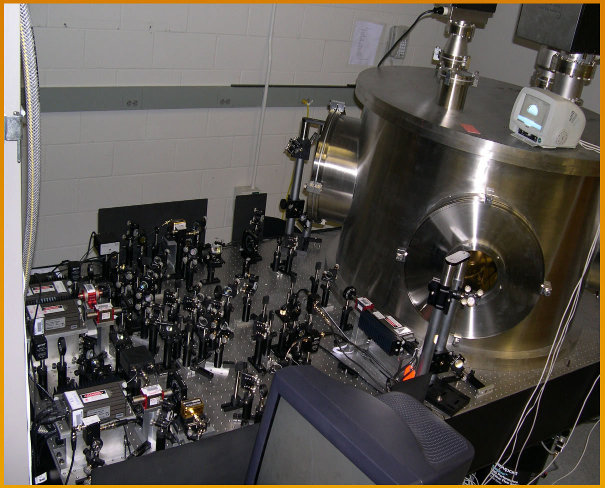
CMB polarization

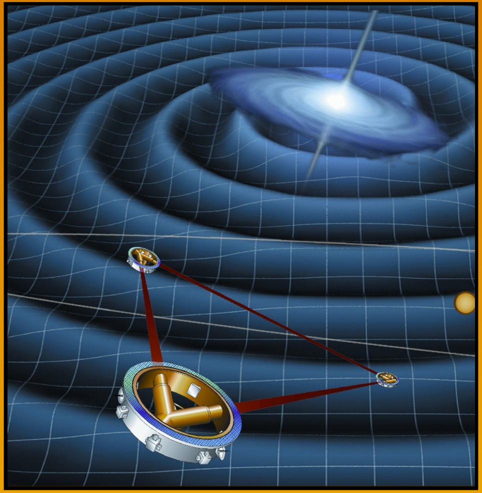
G0900657-v1

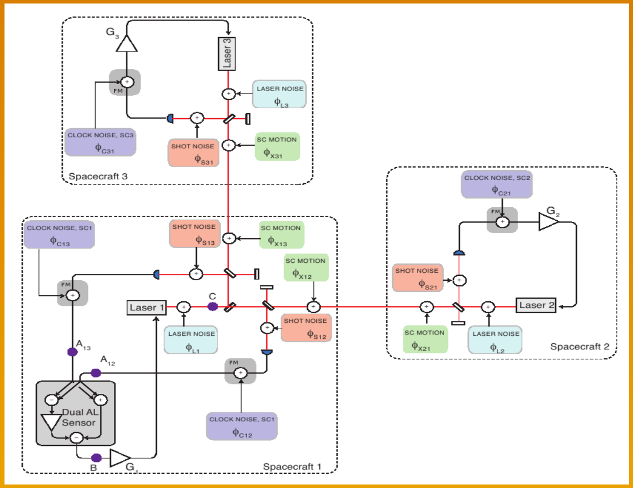


space-based interferometers

The long baseline Interferometry of LISA







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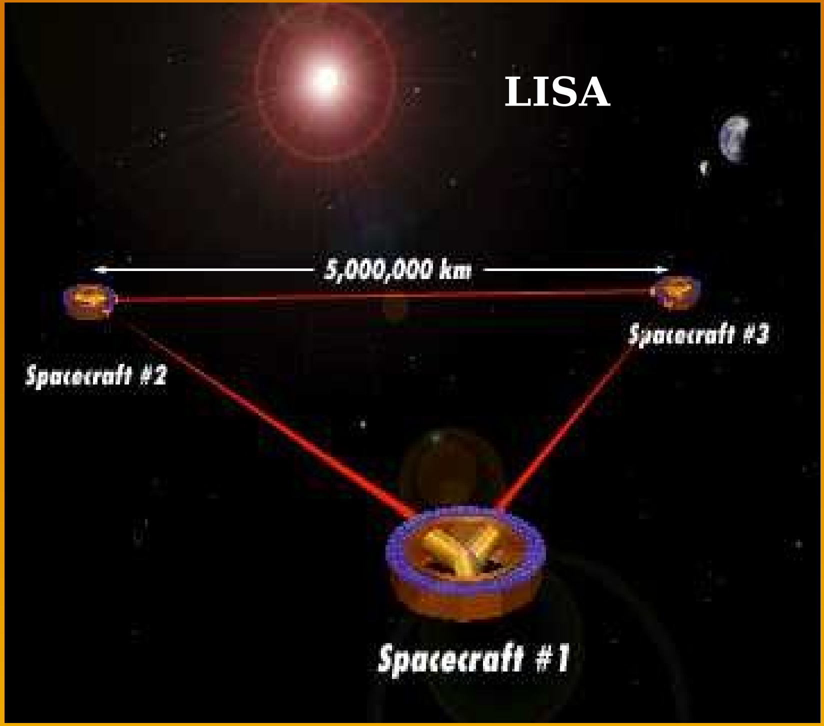
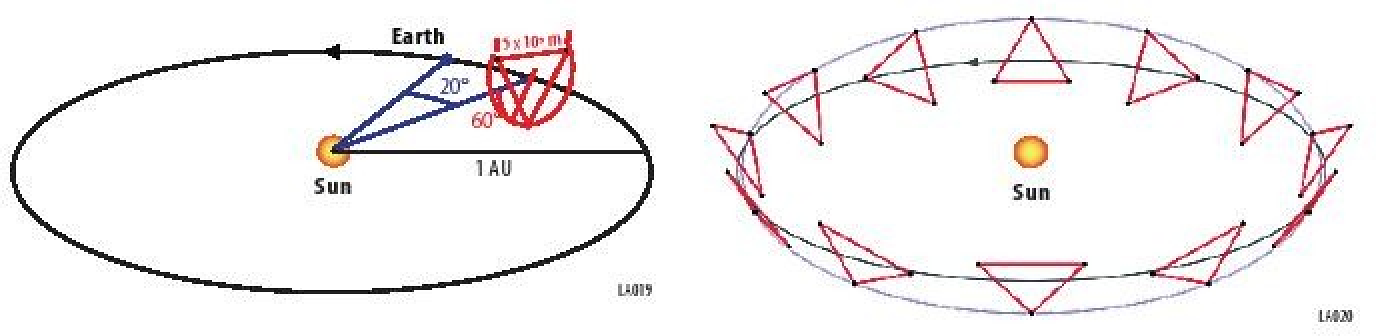
May 2009

LISA Technology

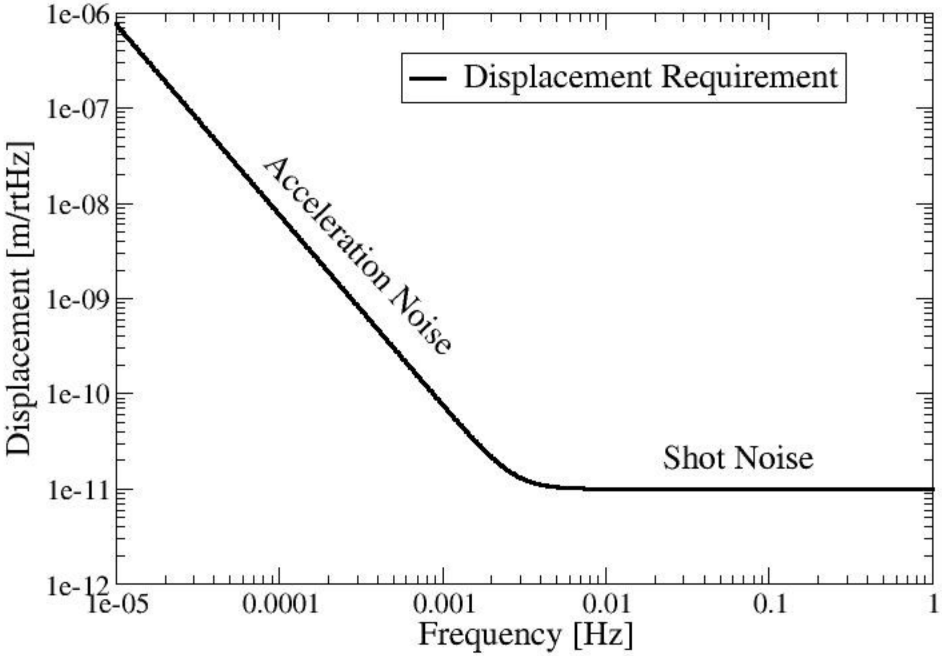


- 3 spacecraft constellation
- S/C separated by 5×10^6 km
- Two Drag-free proof masses inside each S/C
  (Drag-free in sensitive direction)
- Earth-trailing solar orbit
- 5 year operational lifetime



LISA

Limiting Noise sources:



Below 3mHz:

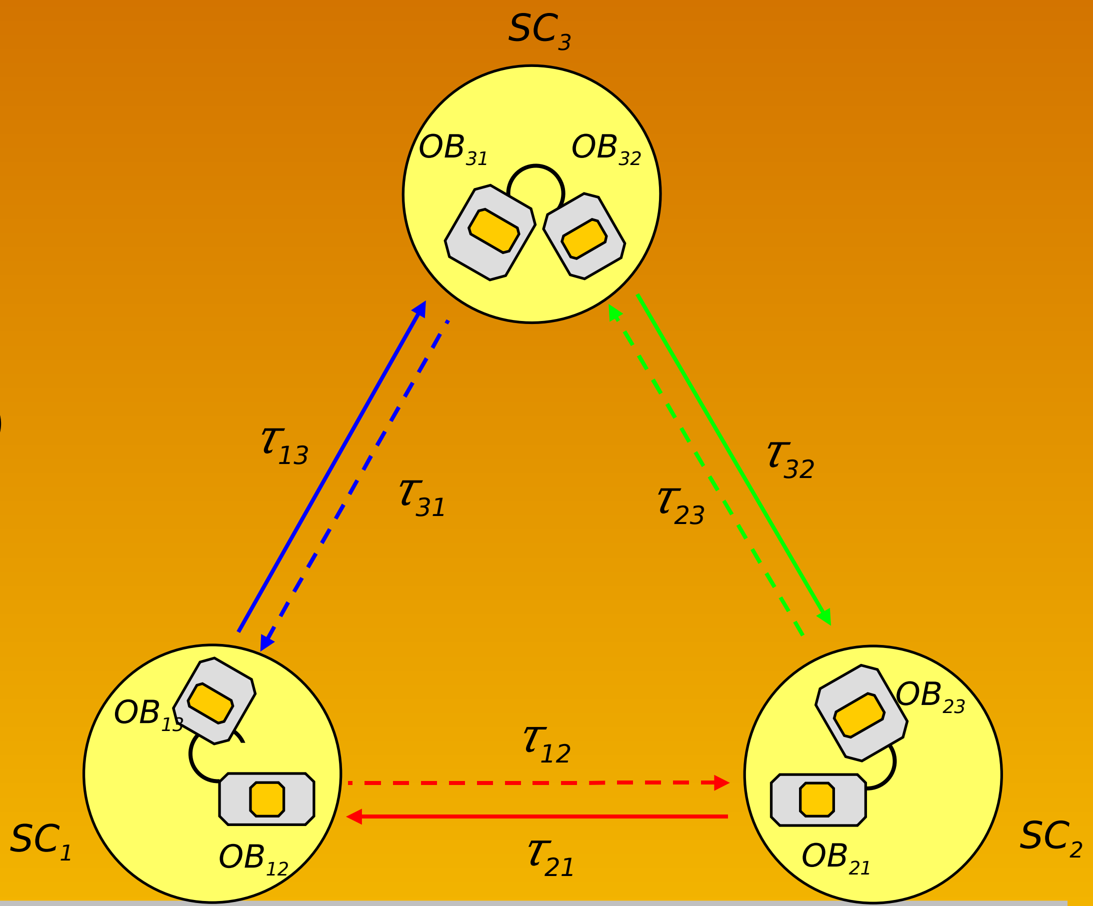
- acceleration noise $3x10^{-15}m/s^2/rtHz$
    - ➢ $1/f^2$ displacement noise of 12pm/rtHz @3mHz

Above 3mHz:

- Limited by shot noise based on 40pW received light
    - 40cm telescope

LISA Interferometry

Goal: Measure changes in the distance between proof masses



Staged approach:

- Interferometry between PM and optical bench (OB)
- Interferometry between OBs on different S/C
- Measure differential laser phase noise on each S/C (create a beam splitter)

Note:

- 10pm/rtHz ~ 10^{-5}cycl./rtHz for $\lambda = 1\mu m$
- relative S/C motion +/- 10m/s → Doppler shifts of +/-10MHz

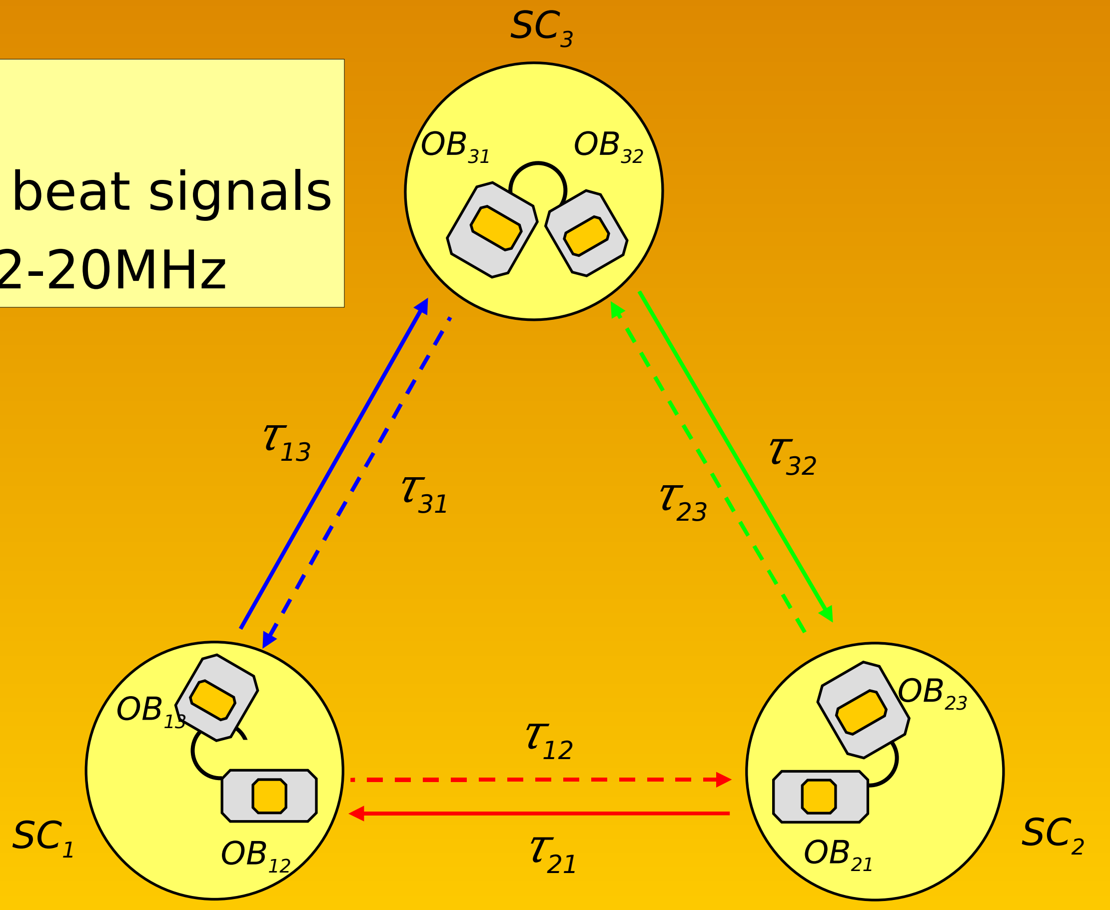
LISA Interferometry

Note:

- 10pm ~ 10^{-5}cycl. for $\lambda = 1\mu m$
- relative S/C motion +/- 10m/s ➡ Doppler shifts of +/-10MHz

LISA Signals:

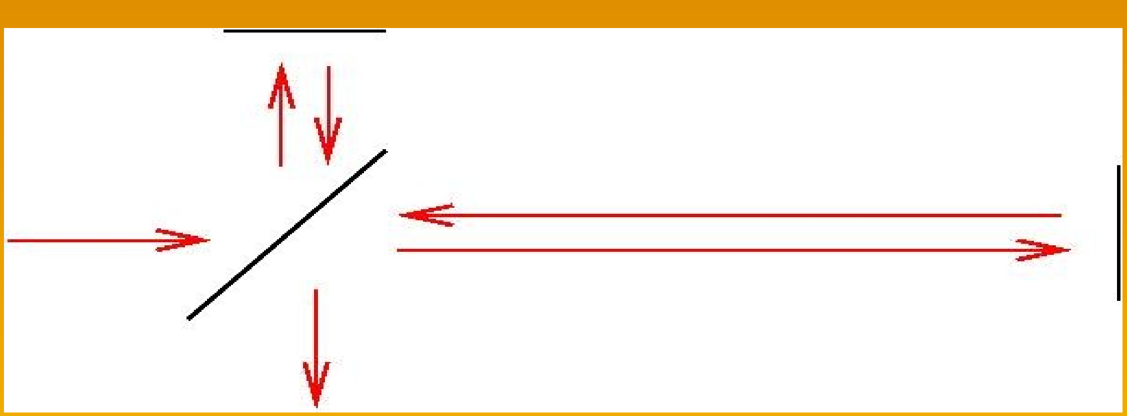
- Phase evolution in laser beat signals
- Beat frequencies betw. 2-20MHz



LISA Interferometry

Interferometer measure a phase difference:

- Length changes $k\delta L$
- Frequency changes $2\pi\delta\nu\Delta L/c$ => $\phi(\omega)\,(e^{-i\omega L1/c}-e^{-i\omega L2/c})$



Time Domain:

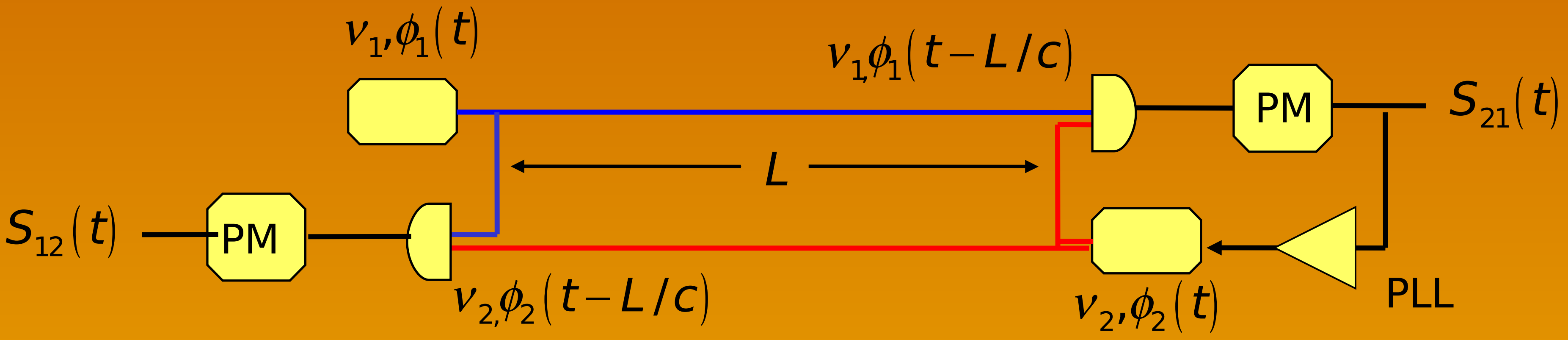
$\phi(t-L_1/c)-\phi(t-L_2/c)$

LIGO: $\Delta L\sim 0$ Intrinsic Common mode rejection of $\delta\nu$

LISA: $\Delta L\sim 50\,000$ km would require $\delta\nu < 60\mu$Hz/rtHz

- Need to subtract phase noise in postprocessing

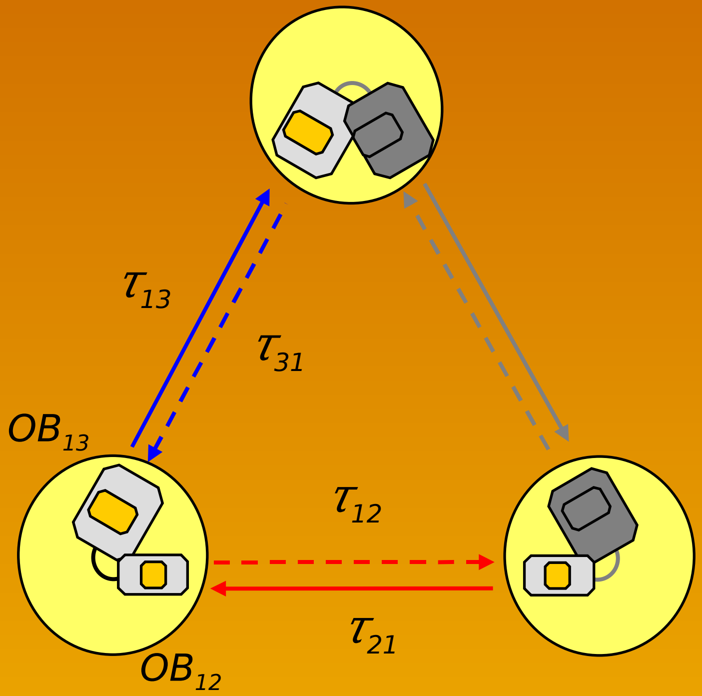
Measuring a LISA arm



- Beat Signal on SC$_2$: $A\sin\left[2\pi\nu_{12}t + \phi_1(t - L/c) - \phi_2(t)\right]$
- PM Signal on SC$_2$: $S_{21}(t) = \phi_1(t - L/c) - \phi_2(t)$
- PLL condition: $\phi_2(t) = \phi_1(t - L/c)$
- Beat Signal on SC$_1$: $A\sin\left[2\pi\nu_{12}t + \phi_1(t) - \phi_2(t - L/c)\right]$
- PM Signal on SC$_1$:

$$\begin{aligned} S_{12}(t) &= \phi_1(t) - \phi_2(t - L/c) \\ &= \phi_1(t) - \phi_1(t - 2L/c) \end{aligned}$$

LISA Interferometry



- Identical measurement in 2nd arm
- SC_2 and SC_3 act as transponders

$$S_{12}(t) = \phi_1(t) - \phi_1(t - \tau_{12} - \tau_{21})$$

$$S_{13}(t) = \phi_1(t) - \phi_1(t - \tau_{13} - \tau_{31})$$

- Time-Delay Interferometry

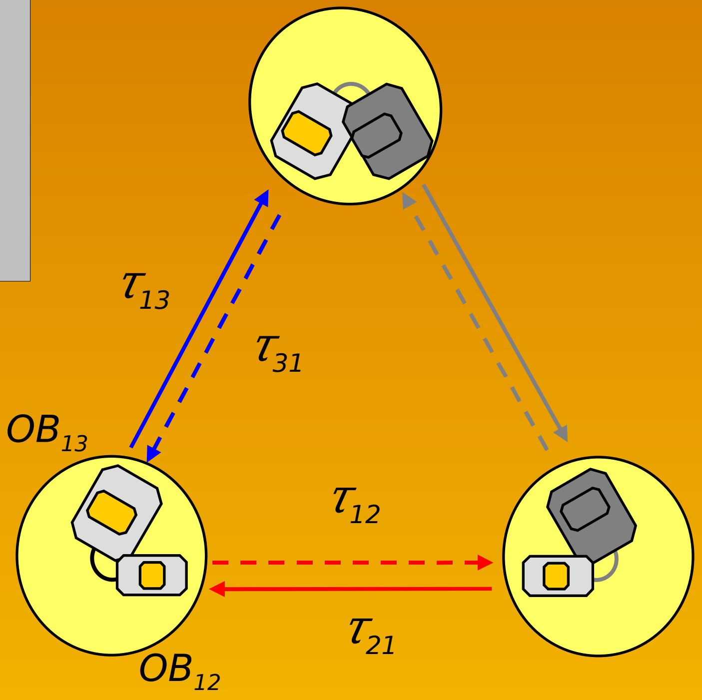
$$X(t) = S_{12}(t) - S_{13}(t) - S_{12}(t - \tau_{13} - \tau_{31}) + S_{13}(t - \tau_{12} - \tau_{21})$$

  - All $\phi(t)$, $\phi(t-\tau)$, ... - terms show up twice with opposite sign and cancel
  - First-order insensitive to laser phase noise

LISA Interferometry

What do we need to make this work?

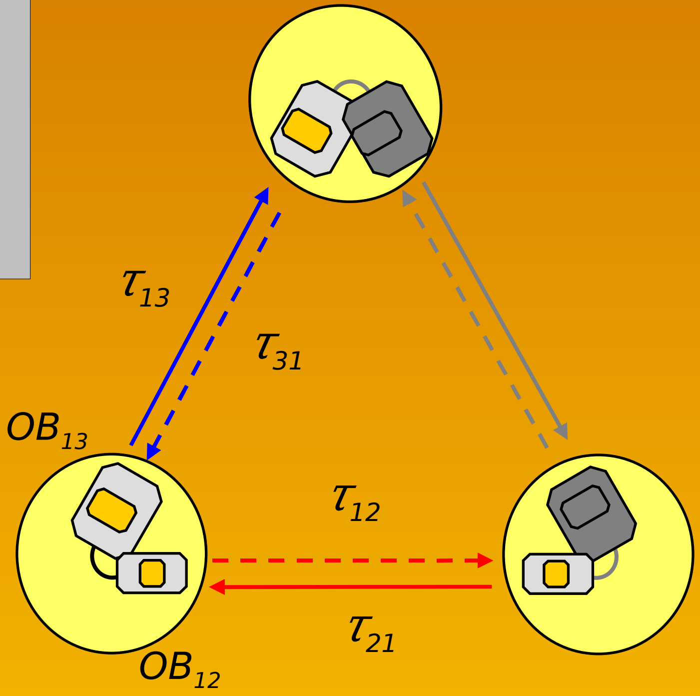
- Do we have to have low noise transponders (mirrors) at the far ends?



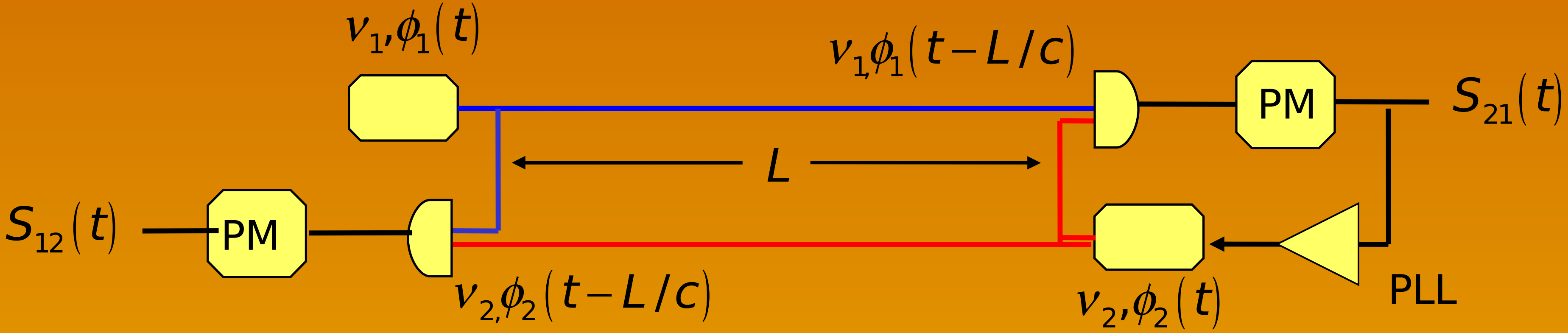
LISA Interferometry

What do we need to make this work?

- Do we have to have low noise transponders (mirrors) at the far ends?
  - No, we only have to measure $\phi(t)$ at the far ends and then subtract them.



Measuring a LISA arm



- Beat Signal on SC$_2$: $A\sin\left[2\pi\nu_{12}t+\phi_1(t-L/c)-\phi_2(t)\right]$
- PM Signal on SC$_2$: $S_{21}(t)=\phi_1(t-L/c)-\phi_2(t)$
- PLL condition: $\phi_2(t)=\phi_1(t-L/c)$ $+\delta\phi(t)$
- Beat Signal on SC$_1$: $A\sin\left[2\pi\nu_{12}t+\phi_1(t)-\phi_2(t-L/c)\right]$
- PM Signal on SC$_1$: $S_{12}(t) = \phi_1(t)-\phi_2(t-L/c)$ $-\delta\phi(t\text{-}L/c)$

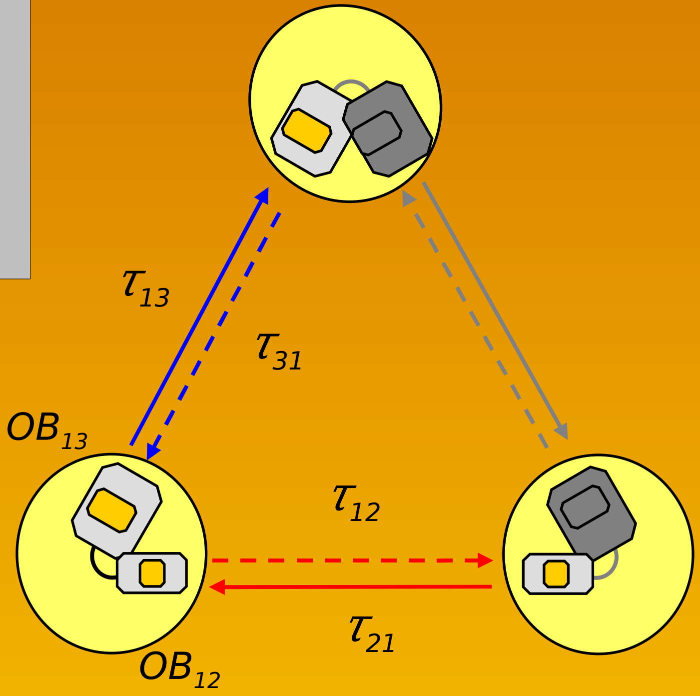
$$= \phi_1(t)-\phi_1(t-2L/c)$$

LISA Interferometry

What do we need to make this work?

- Do we have to have perfect transponders (mirrors) at the far ends?
  - ➢ No, we only have to measure ϕ(t) at the far ends and then subtract them.

- Do we have to have the same phase noise enter in both arms? (Beamsplitter)

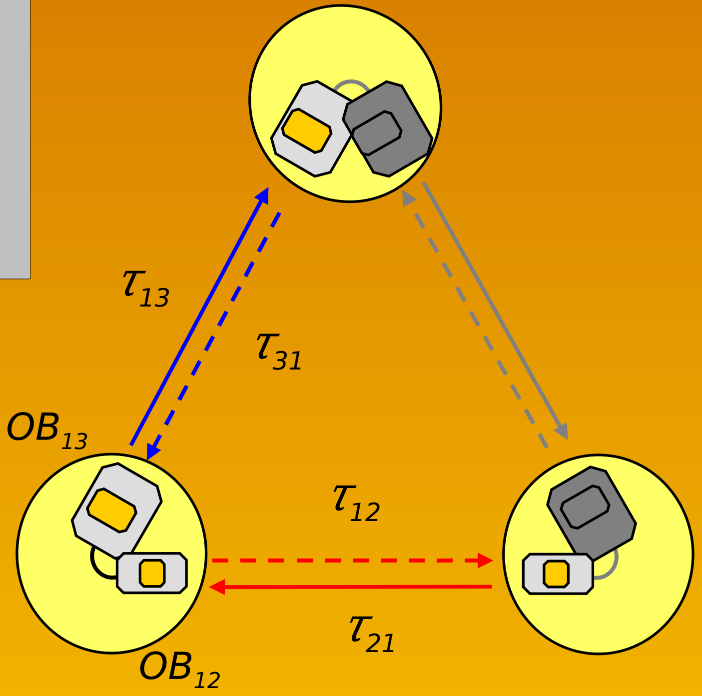


LISA Interferometry

What do we need to make this work?

- Do we have to have perfect transponders (mirrors) at the far ends?
  - No, we only have to measure $\phi(t)$ at the far ends and then subtract them.

- Do we have to have the same phase noise enter in both arms? (Beamsplitter)
  - No, we only have to measure the differential phase noise and subtract that as well.



LISA Interferometry

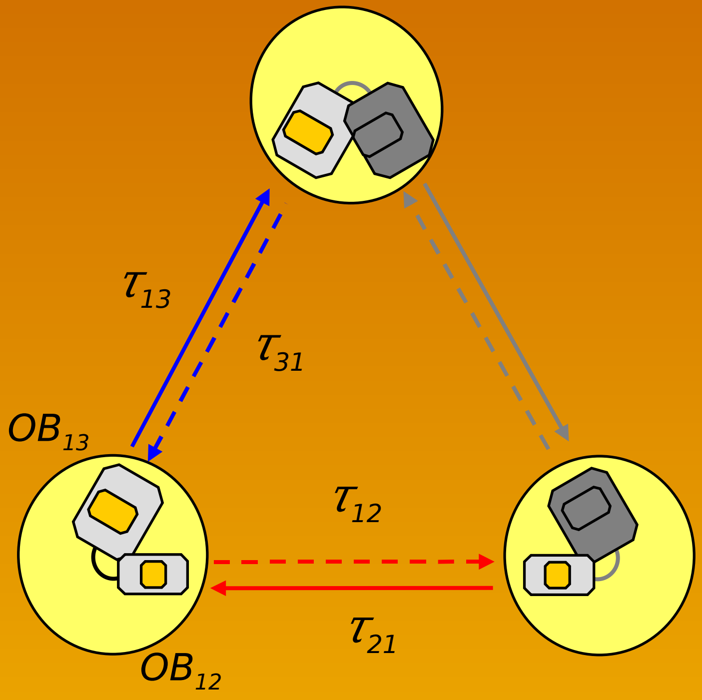
- Repeat measurement in two arms

- SC_2 and SC_3 act as transponders

$$S_{12}(t) = \phi_1\left(t\right) - \phi_1\left(t - \tau_{12} - \tau_{21}\right)$$

$$S_{13}(t) = \phi_1\left(t\right) - \phi_1\left(t - \tau_{13} - \tau_{31}\right)$$

$$+\Delta\phi_{12}(t)\text{-}\Delta\phi_{12}(t\text{-}\tau_{13}\text{-}\tau_{31})$$



- Time-Delay Interferometry

$$X(t) = S_{12}(t) - S_{13}\left(t\right) - S_{12}\left(t - \tau_{13} - \tau_{31}\right) + S_{13}\left(t - \tau_{12} - \tau_{21}\right)$$

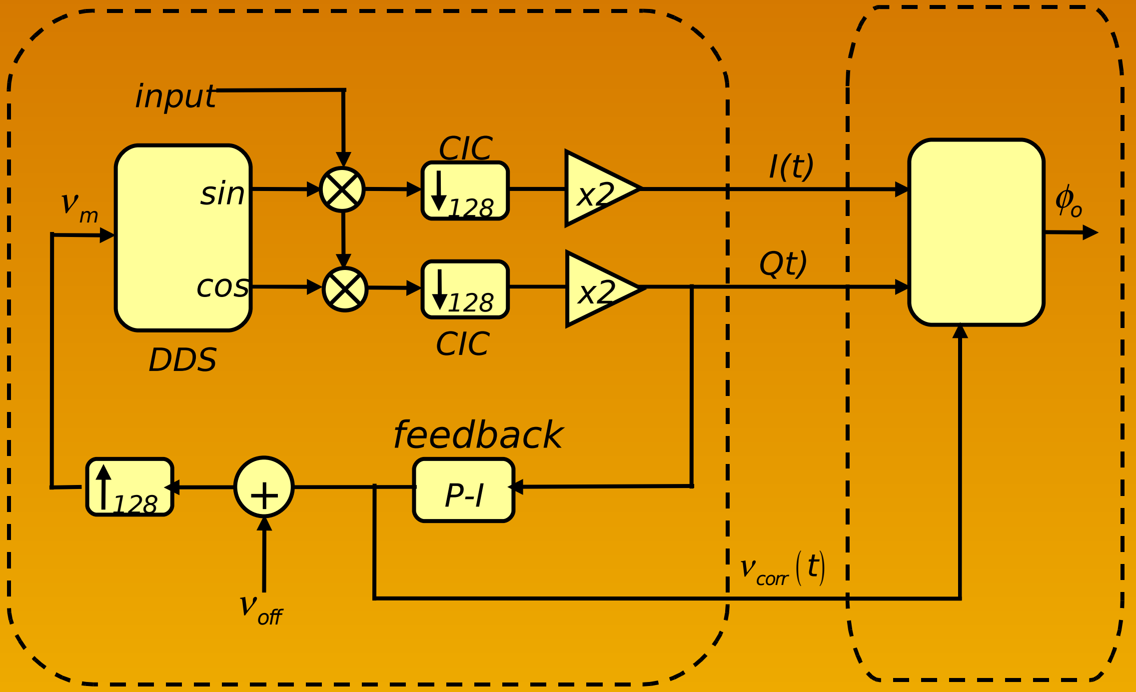
$$-\Delta\phi_{12}(t)+\Delta\phi_{12}(t\text{-}\tau_{13}\text{-}\tau_{31})$$

LISA Interferometry

What do we need to make this work?

- We need to be able to measure $\phi(t)$ in each signal with the necessary accuracy
  - ➢ Phasemeter

Phasemeter



Numerical Controlled Oscillator Phase Reconstruction

Phasemeter:

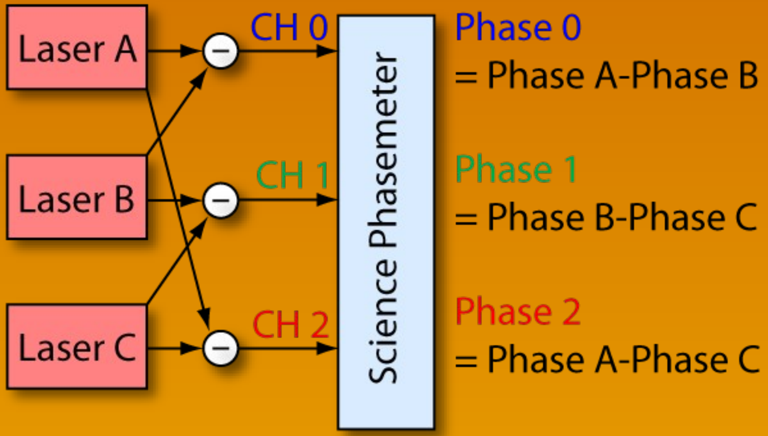
- Digital
- PLL with NCO

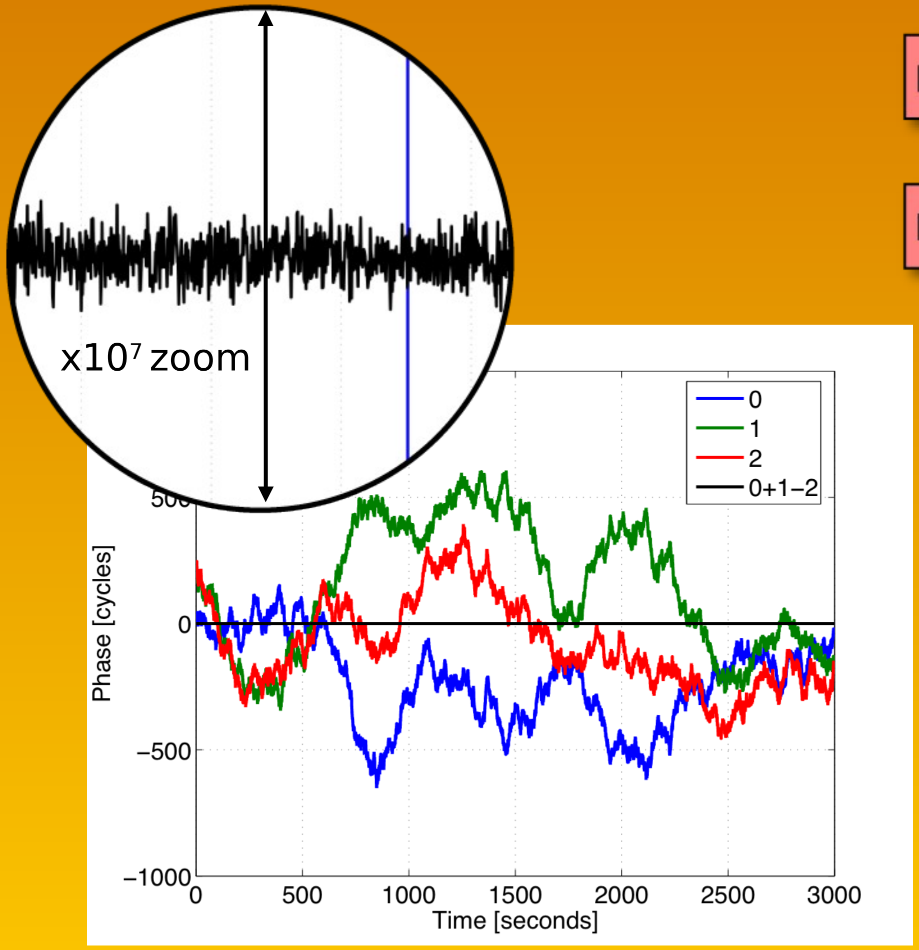
Measures the phase against the on board clock:

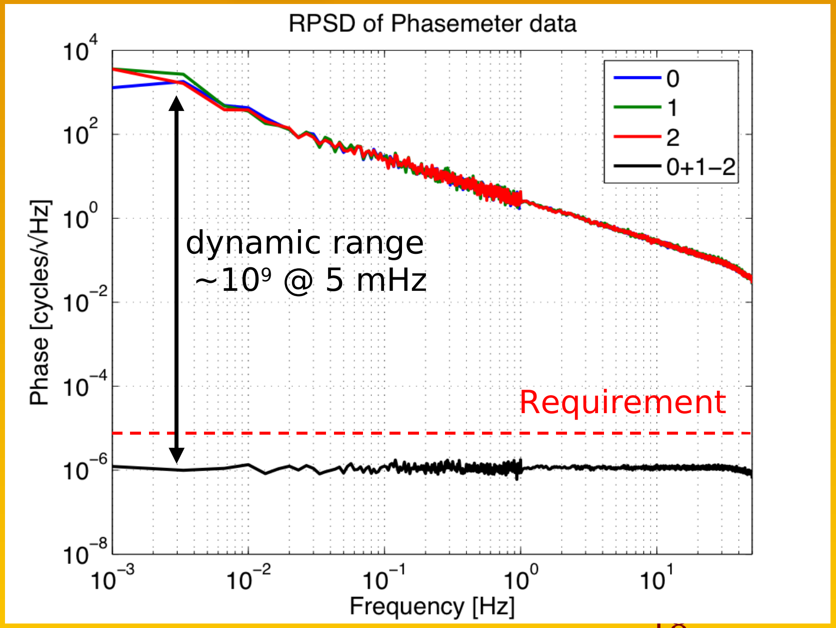
- Clock noise: $\delta\tau < 5x10^{-14}$ s/rtHz for 20 MHz beat
- Requires clock stabilization between S/C

LISA Interferometry

Status of Phasemeter:
- It works (Digital part)
- with respect to local clock







dynamic range ~10^{9} @ 5 mHz

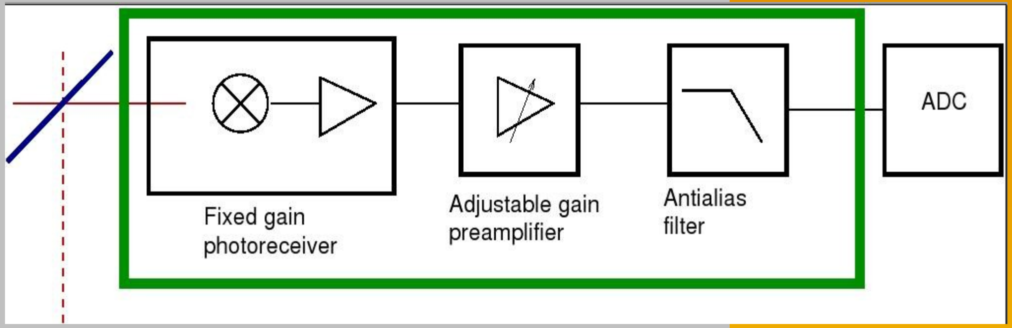
Courtesy of Daniel Shaddock (JPL)

LISA Interferometry

Status of Phasemeter:

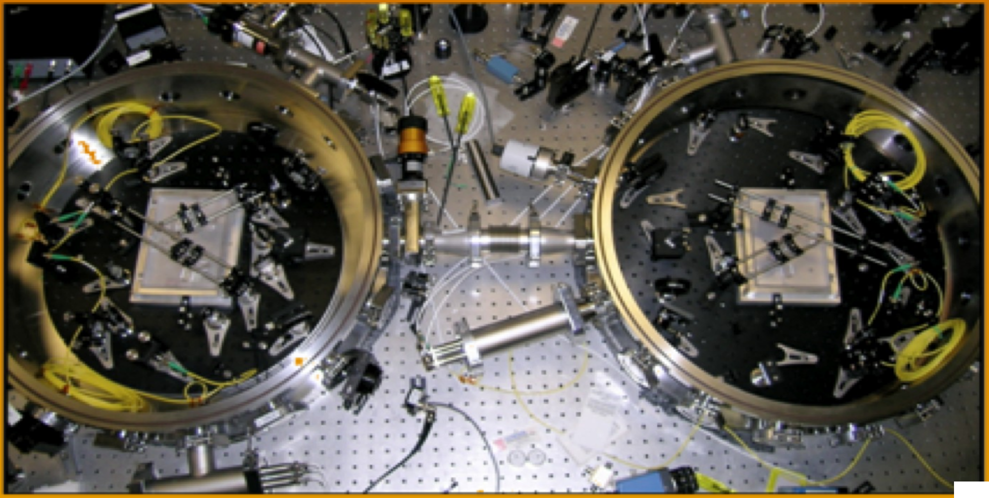
Analog Parts

- Photodiodes and Amplifiers
- Cables
- ADC timing
- …



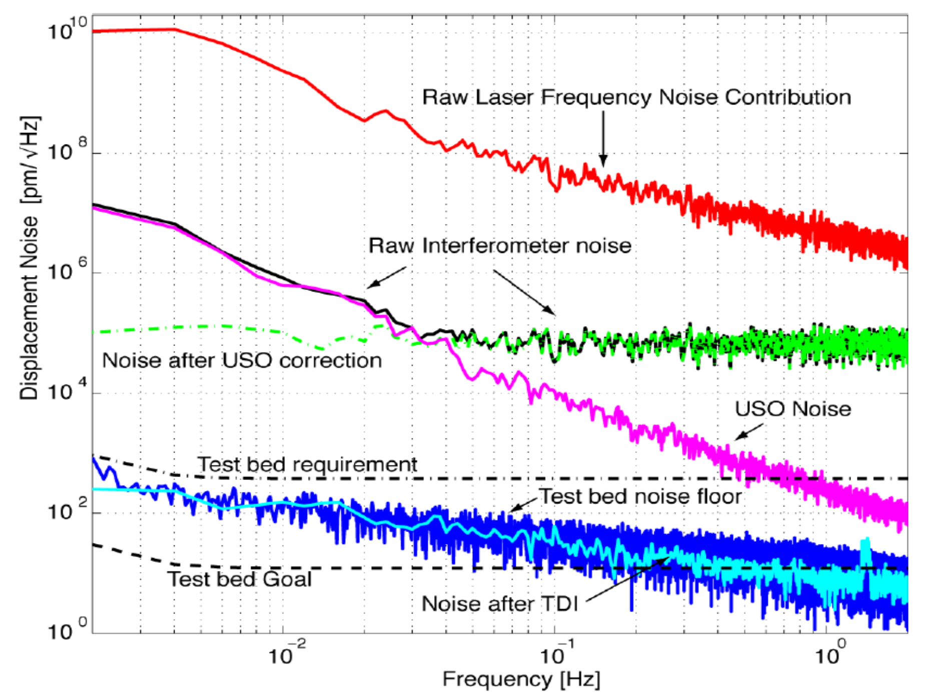
Ongoing R&D at JPL, AEI, GSFC, UF, …

LISA Interferometry



JPL-Testbed

- Sagnac Configuration
- Laser Transponders
- Multiple Photo detectors
- …



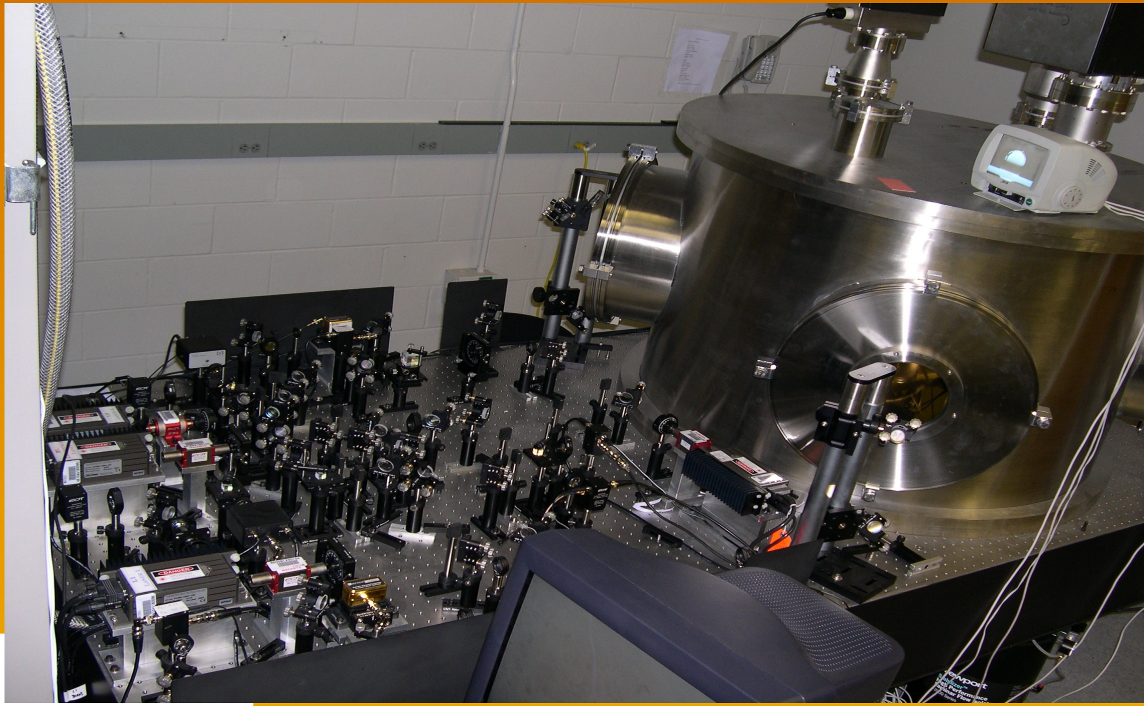
<u>Critical areas:</u>

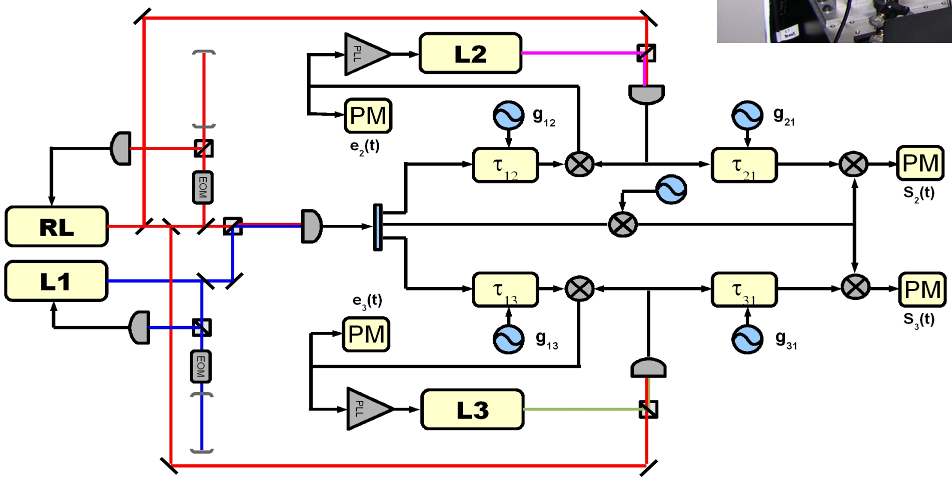
- Dispersion in PDs
- Timing noise in ADCs
  - Pilot tone (JPL)
  - Adding the pilot tone
- …

LISA Interferometry

UF-Testbed with:

- Laser Transponders
- Signal travel times
- Doppler shifts
- UF-Phasemeter

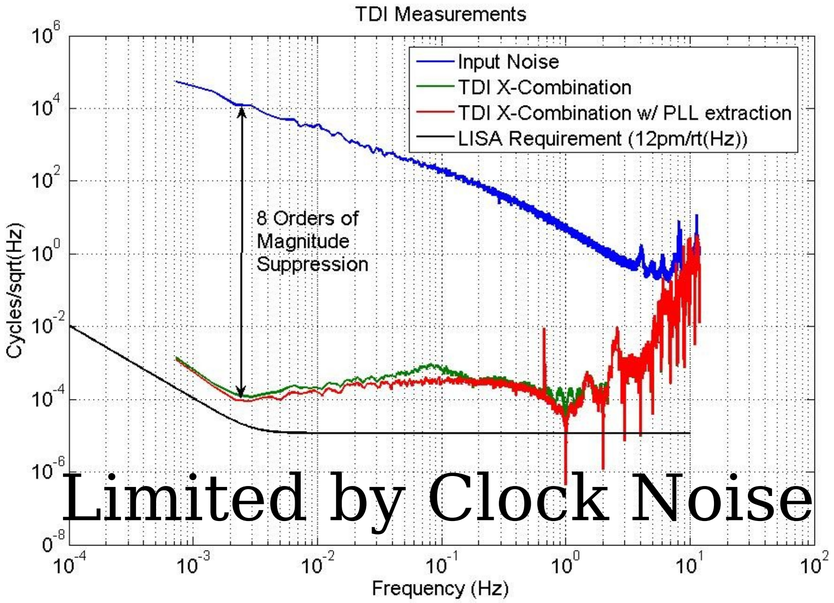




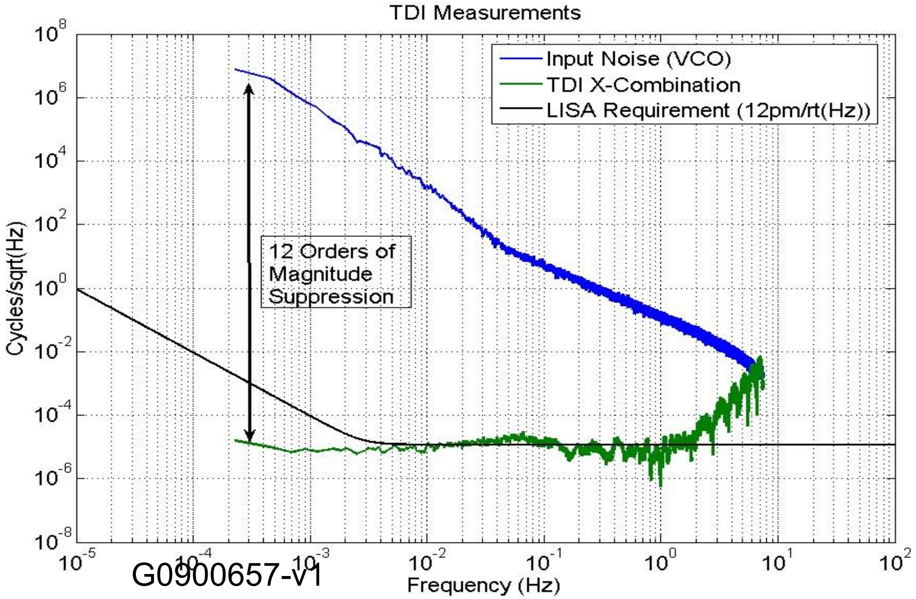
LISA Interferometry

UF-Test with:

- Laser Transponders
- Signal travel times
- Doppler shifts
- UF-Phasemeter



Limited by Clock Noise



Component test
w/o clock noise
but larger input noise

LISA Interferometry

What do we need to make this work?

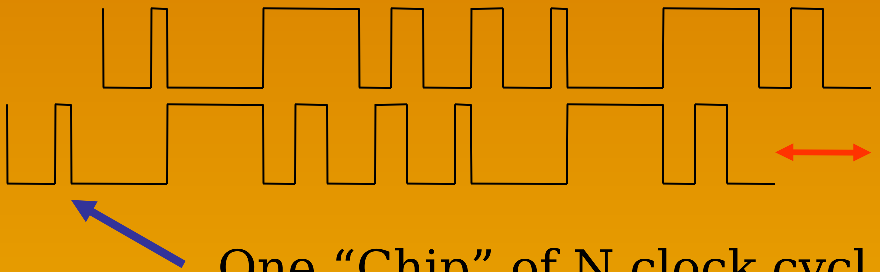
- We need to be able to measure $\phi(t)$ in each signal with the necessary accuracy
  - Phasemeter

- The time stamps on each $\phi(t)$ have to be accurate.
  - Ranging: $\Delta L/c = \Delta\tau$
  - Laser frequency stabilization $\delta\nu$ (to reduce the required ranging accuracy)
    - Requirement: $\delta\nu\, \Delta L/c = \delta\nu\, \Delta\tau < 10^{-6}$cycl./rtHz

LISA Ranging

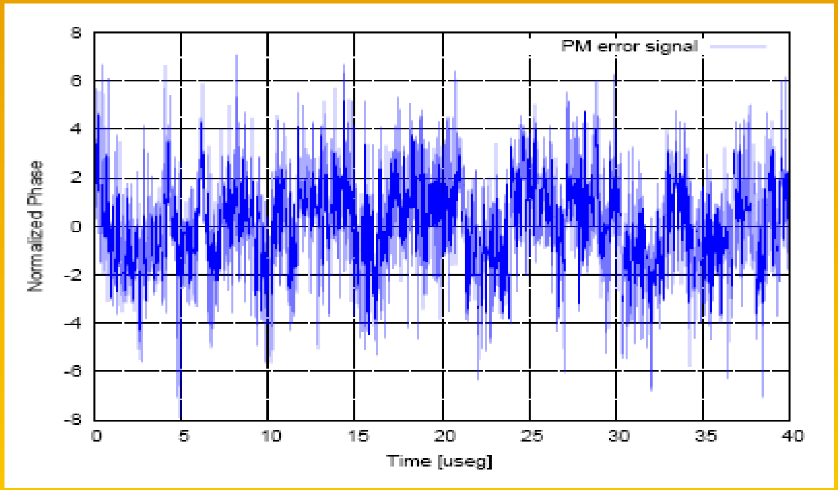
Δτ: Uncertainty in Signal Travel time ~ Ranging

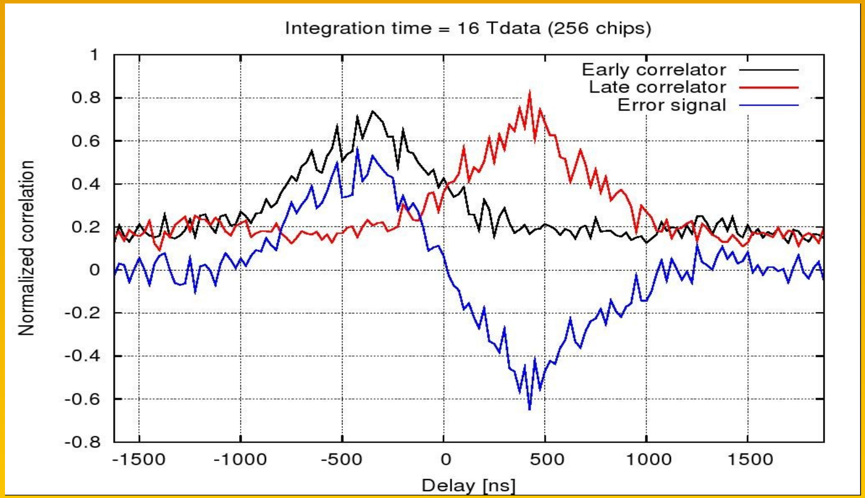
- Modulate Laser field with PRN code
- Current Best Estimate: ΔL < 1m



Accuracy <
Clock cycle using interpolation

One “Chip” of N clock cycl.





AEI-Results

LISA Interferometry

LIGO: $\Delta L \sim 50\,000$ km would require $\delta\nu < 60\mu$Hz/rtHz

- Phasemeter
- <u>Timing System for Constellation</u>

Requirement from $2\pi\,\delta\nu\,\Delta L/c = 2\pi\,\delta\nu\,\Delta\tau$

$\Delta L = 1$m → $\delta\nu = 300$Hz/rtHz above 3mHz

- Goal: $\delta\nu = 30\text{Hz/rtHz}\,(1+(2.8\text{mHz}/f)^4)^{1/2}$

<u>Multiple Options:</u>

- Local stabilization on fixed cavity or iodine line
- Stabilization on LISA arms (~LIGO-like)
- Or a combination of both

Cavity Stabilization

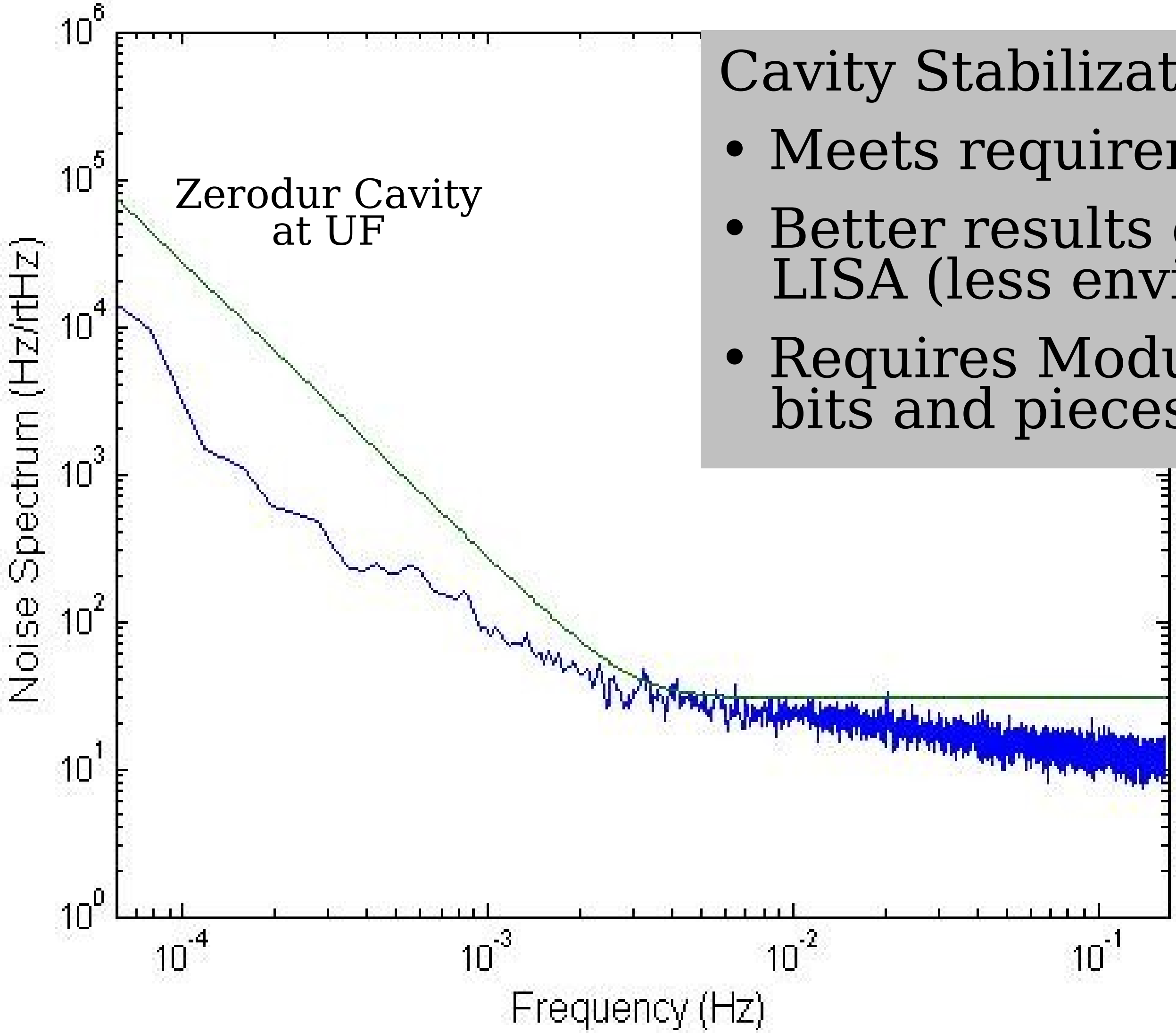
Fixed:

- Pound Drever Hall technique
- Heterodyne Interferometer (LTP-style IFO)

Tunable (to combine with Arm locking):

- PZT-cavity
- Offset phase lock
- Sideband locking

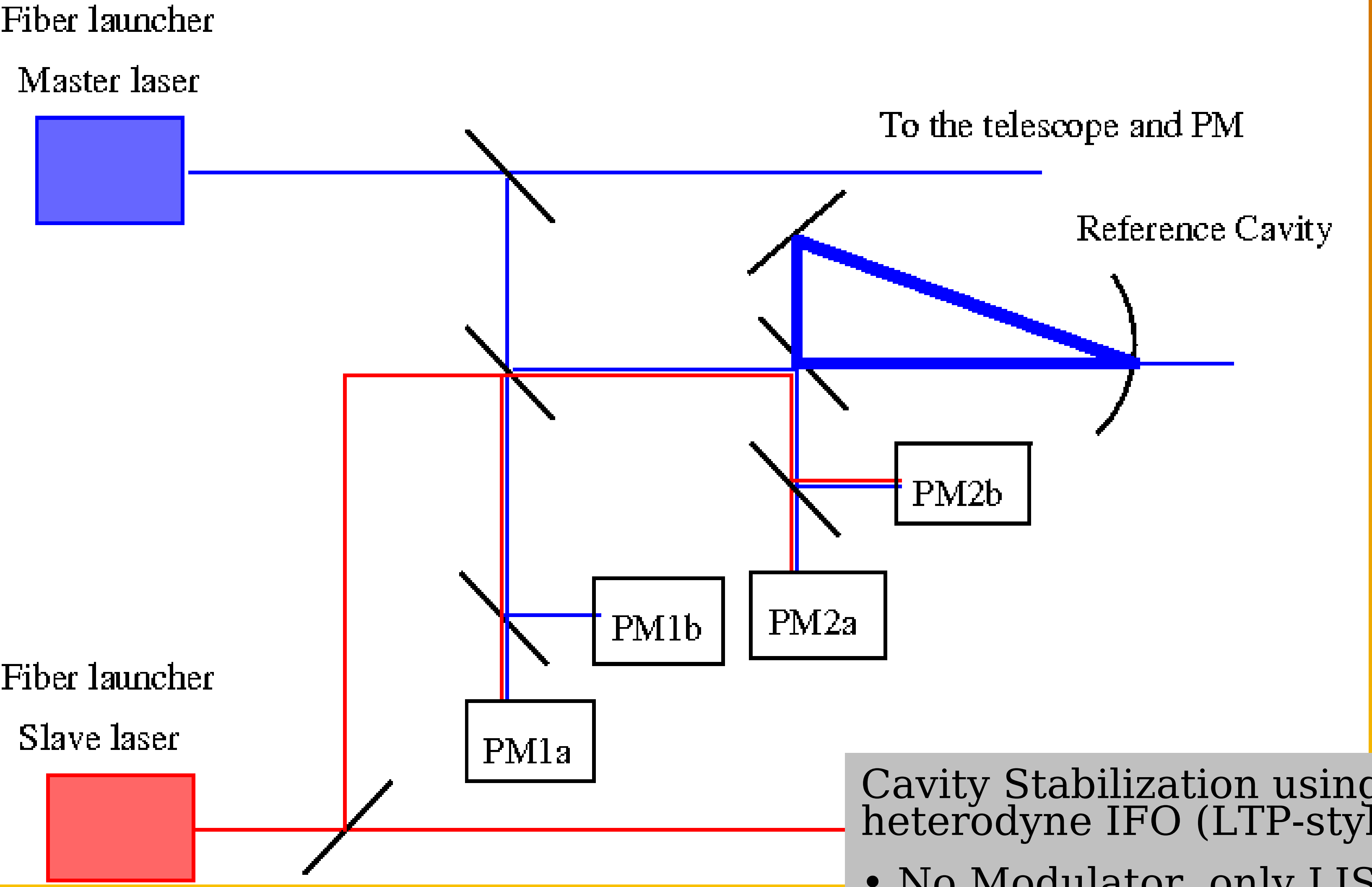
Cavity Stabilization



Cavity Stabilization with PDH

- Meets requirements
- Better results expected in LISA (less environmental noise)
- Requires Modulator and other bits and pieces.

Cavity Stabilization



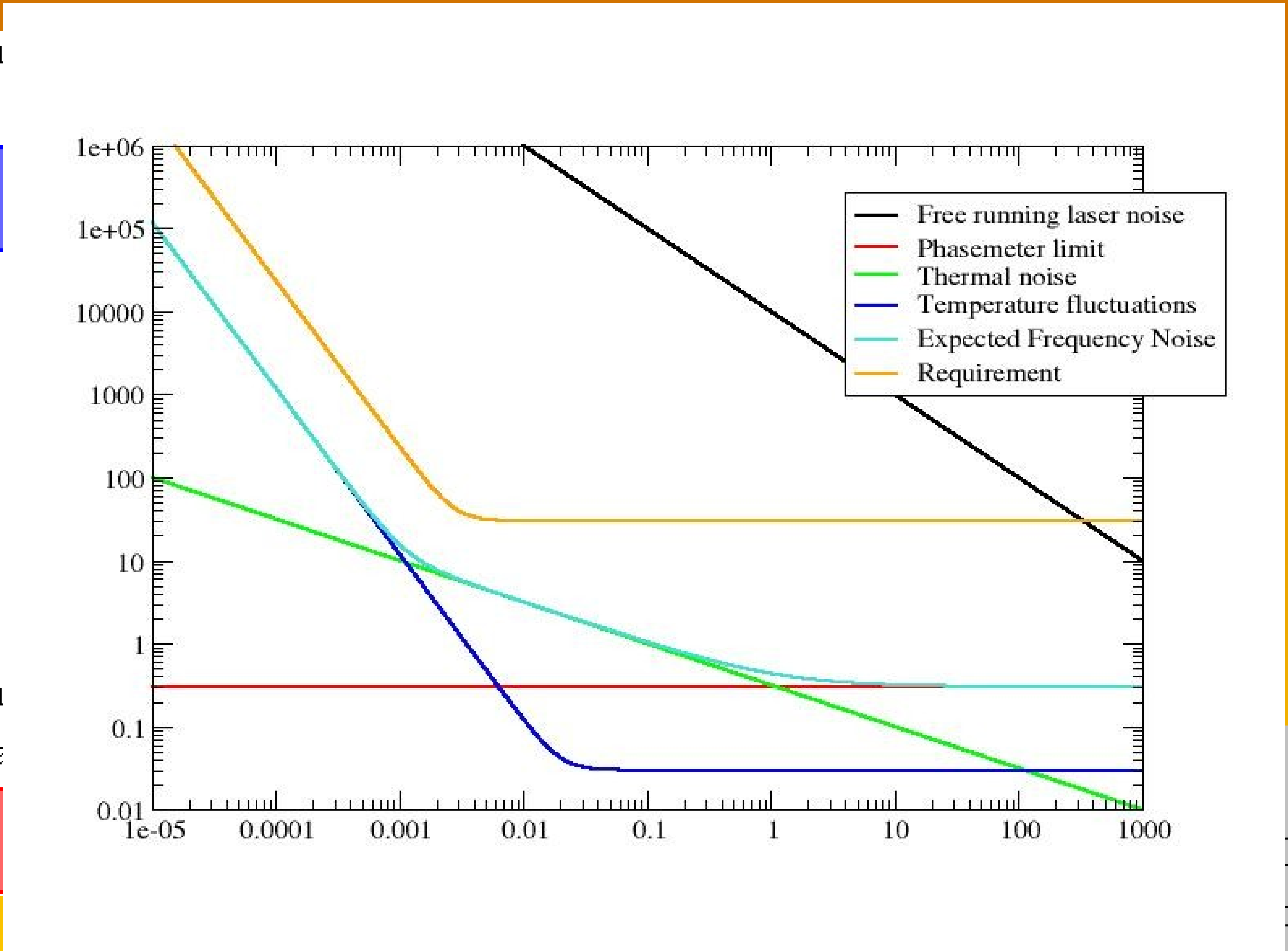
Cavity Stabilization using heterodyne IFO (LTP-style)

- No Modulator, only LISA PM
- Should easily meet requirements with stable cavity.

Cavity Stabilization

Fiber lau

Master



Fiber lau

Slave la

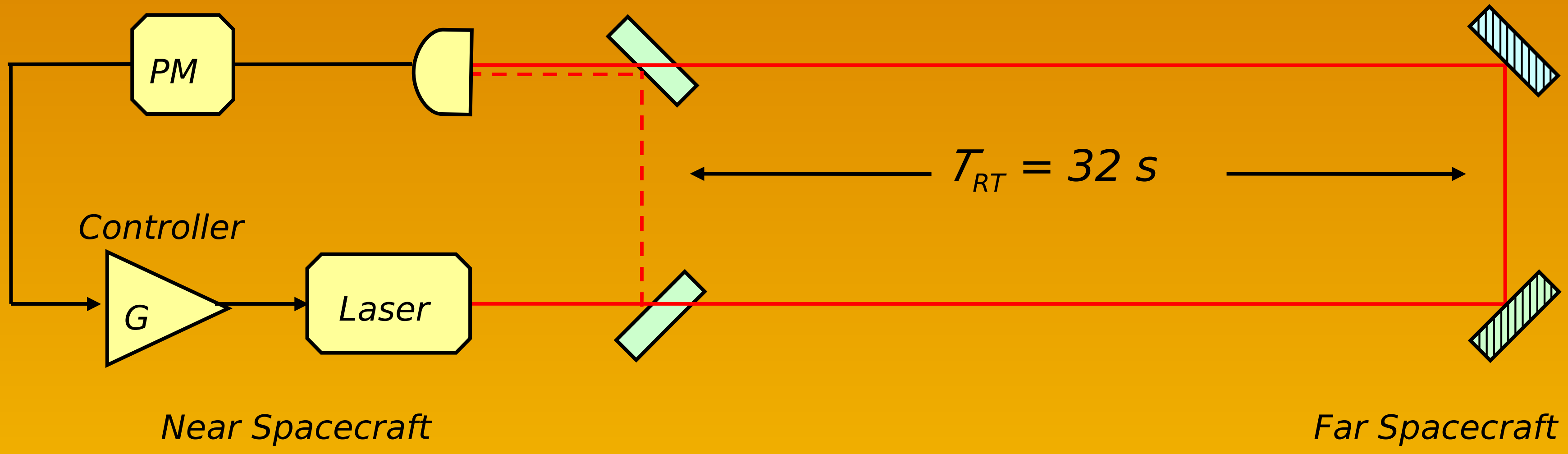
M

ments

with stable cavity.

Arm-Locking I

- Lasers might be pre-locked to mechanical (cavity or Mach-Zehnder) or spectroscopic reference (iodine)
- Use the arms as a stable frequency reference

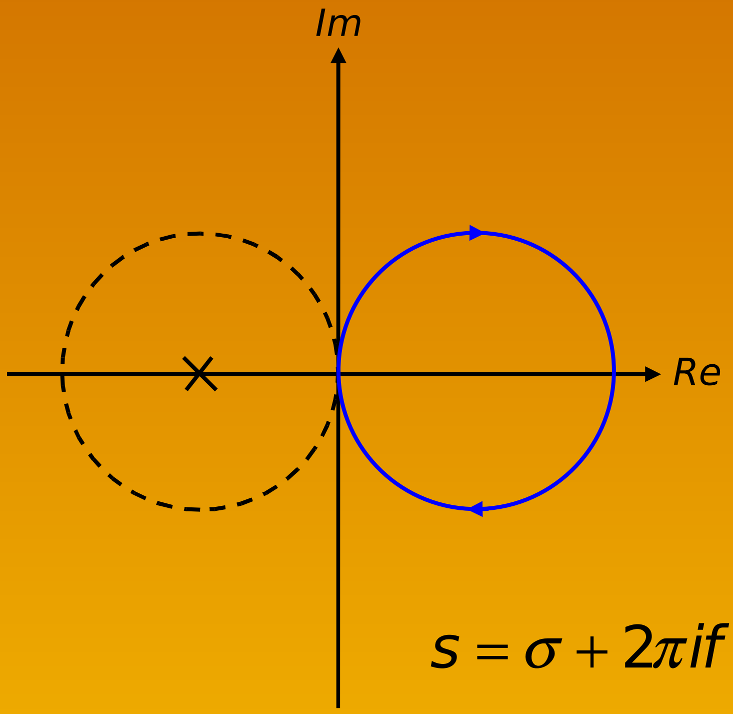


- Single-arm locking error signal: $\phi(t)-\phi\left(t-\tau_{RT}\right)$
- Insensitive to noise at frequencies: $f_n = n/\tau_{RT}$

Arm-Locking II

- General closed-loop stability

$$T_{CL}(s) = \frac{1}{1+T_{OL}(s)}$$



$$s = \sigma + 2\pi i f$$

- Laplace-domain arm-locking error signal

$$1 - \exp(-s\tau_{RT})$$

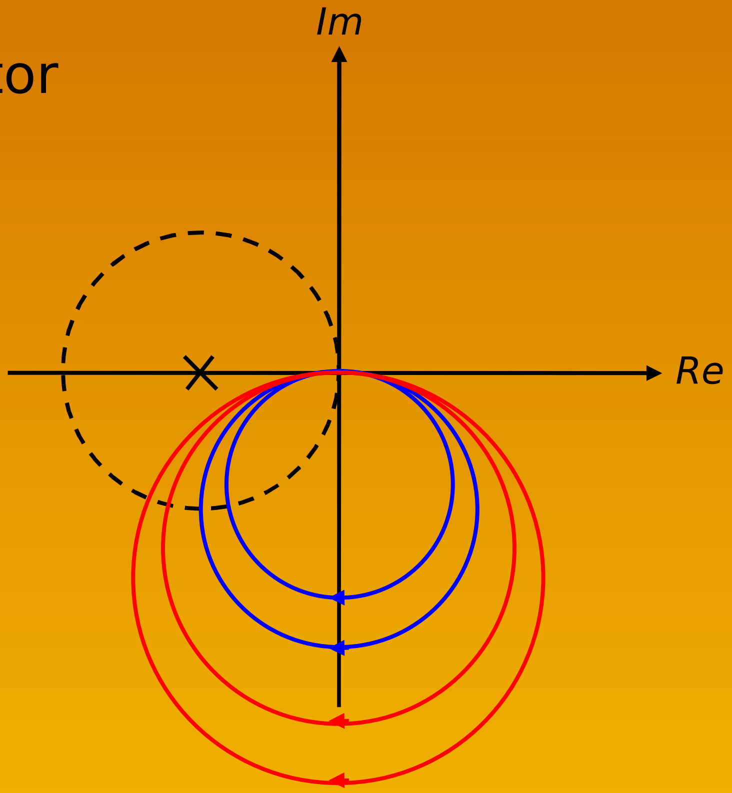
  - nulls at n/τ_{RT}
  - phase change from -90° to $+90^{\circ}$ at n/τ_{RT}

Arm-Locking II

- Frequency actuator acts as integrator

$$\frac{1}{s}\left[1-\exp(-s\tau_{RT})\right]$$

- System enters noise enhancement region
- Increased gain brings increased noise enhancement
- System is marginally stable, any phase loss (latency) could cause instability



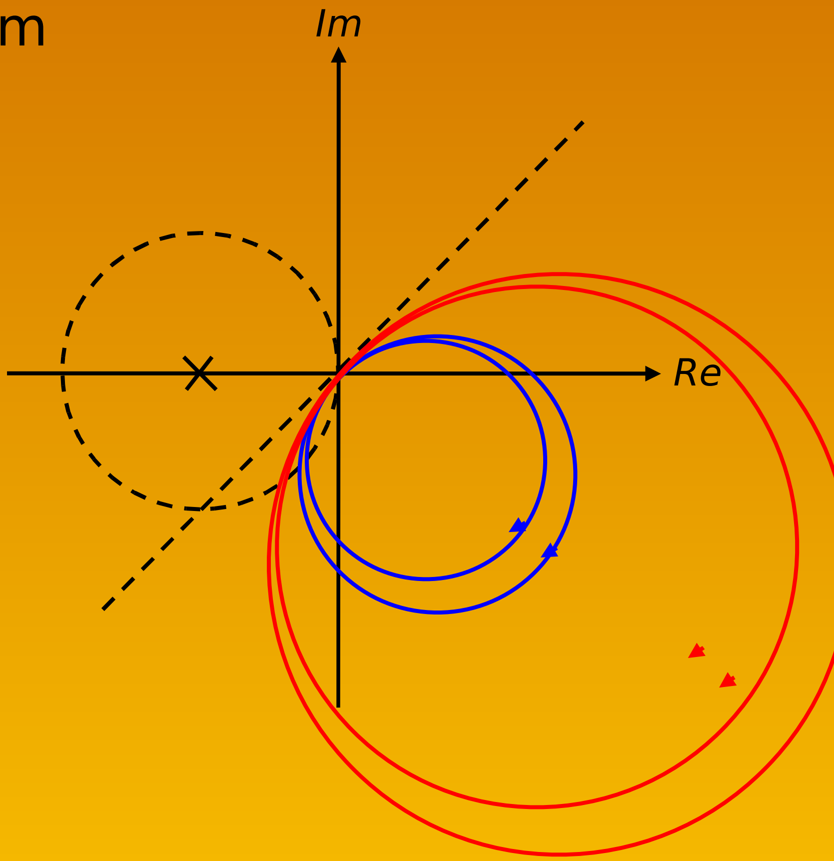
- Note: Frequency actuator as integrator can be avoided when we use frequency meter instead of phasemeter (phasemeter contains one integrator as last stage)

Arm-Locking II

- Controller with s^p slope rotates system away from (-1,0)

$$s^{p-1}\left[1-\exp(-s\tau_{RT})\right]$$

- Gain can be increased below $1/\tau_{RT}$
- Noise enhancement at n/τ_{RT} will remain finite



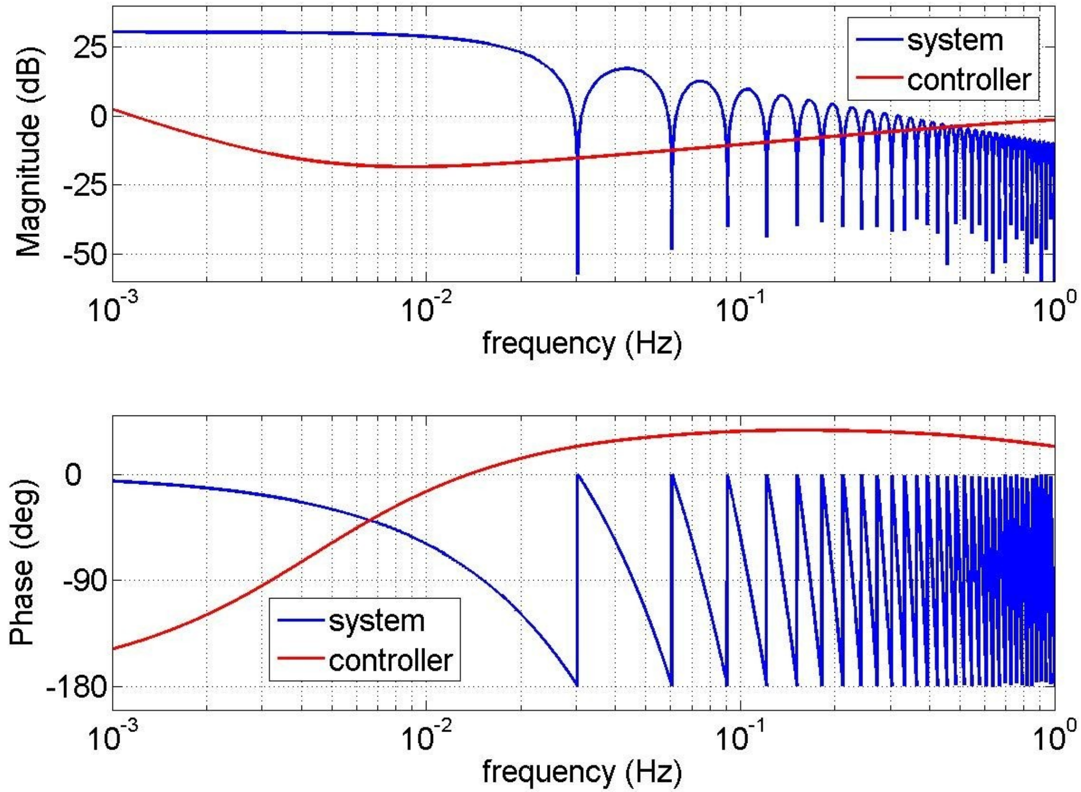
Arm-Locking II

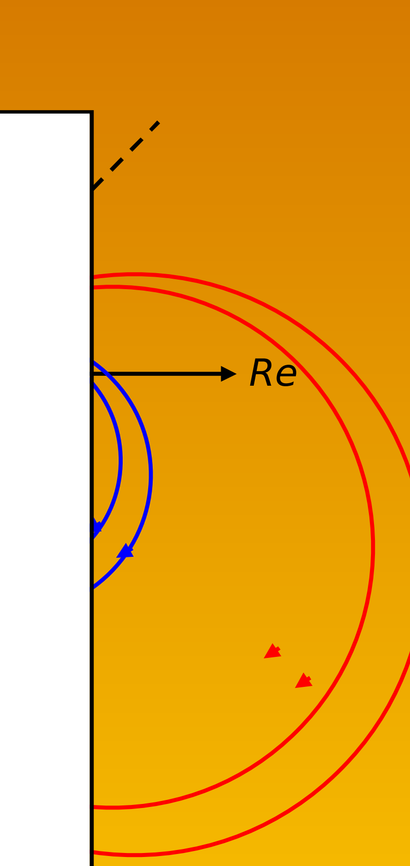
- Controller
away from (-

- Gain can b

- Noise enha
remain finite

Controller & Sensor Bode plot (incl. PM-integrator):

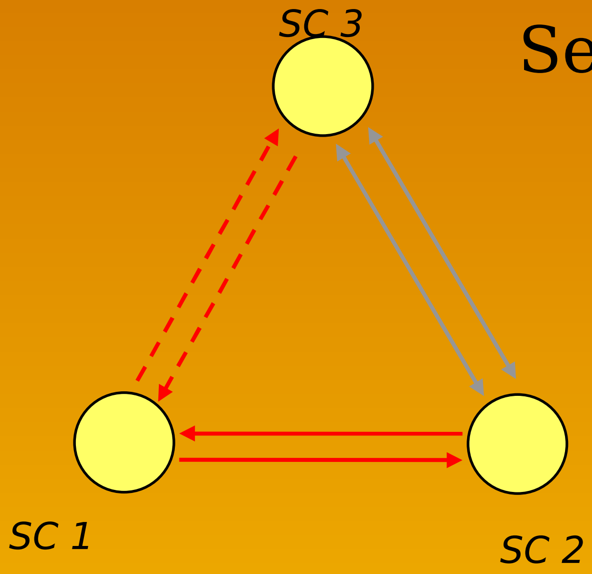




Very limited gain in the LISA band.

Dual Arm-Locking Schemes

- Use other arms to get phase noise information at nulls



dual arm-locking

- first null between 1-3 Hz
- No peaks in LISA band
- Increased noise suppression

Sensor: $S = T(f)_{com}S_{com} + T(f)_{Diff}S_{Diff}$

$$S_{com} = S_1 + S_2$$

$$\Rightarrow \phi(\omega)\,(2 - e^{-i\omega L1/c} - e^{-i\omega L2/c})$$

$$S_{Diff} = S_1 - S_2$$

$$\Rightarrow \phi(\omega)\,(e^{-i\omega L1/c} - e^{-i\omega L2/c})$$

S_{diff} has 1st zero at $1/\Delta\tau = 1\text{-}3\text{Hz}$

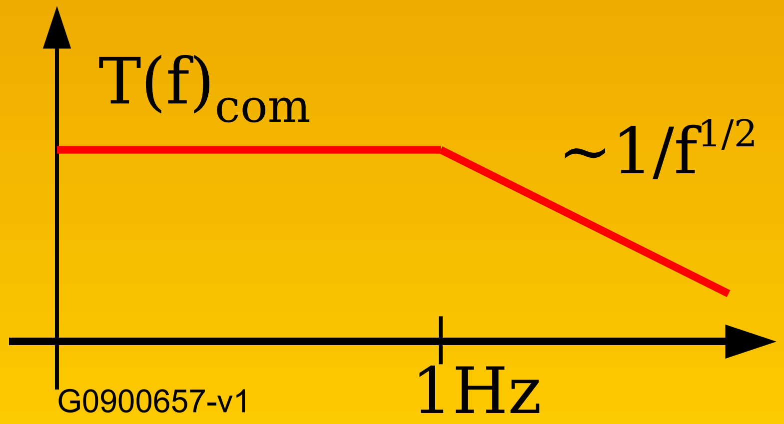
- allows to increase gain earlier
- Bad SNR at low frequencies
  (Problems with Clock noise,
  Shot Noise and S/C motion)

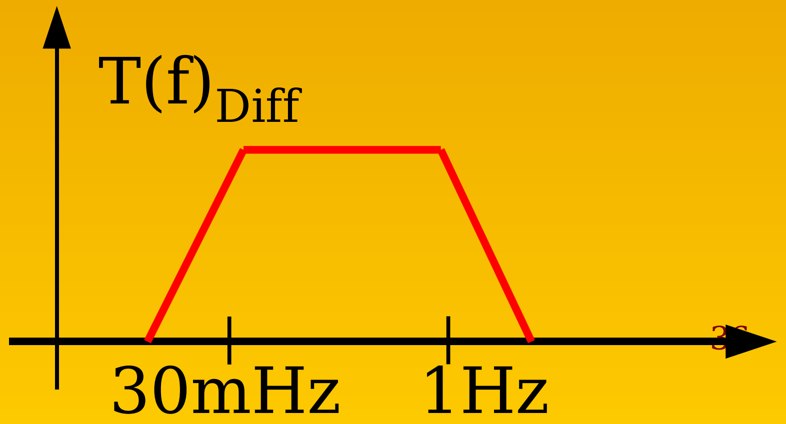
Dual Arm-Locking Schemes

Sensor: $S = T(f)_{com}S_{com} + T(f)_{Diff}S_{Diff}$

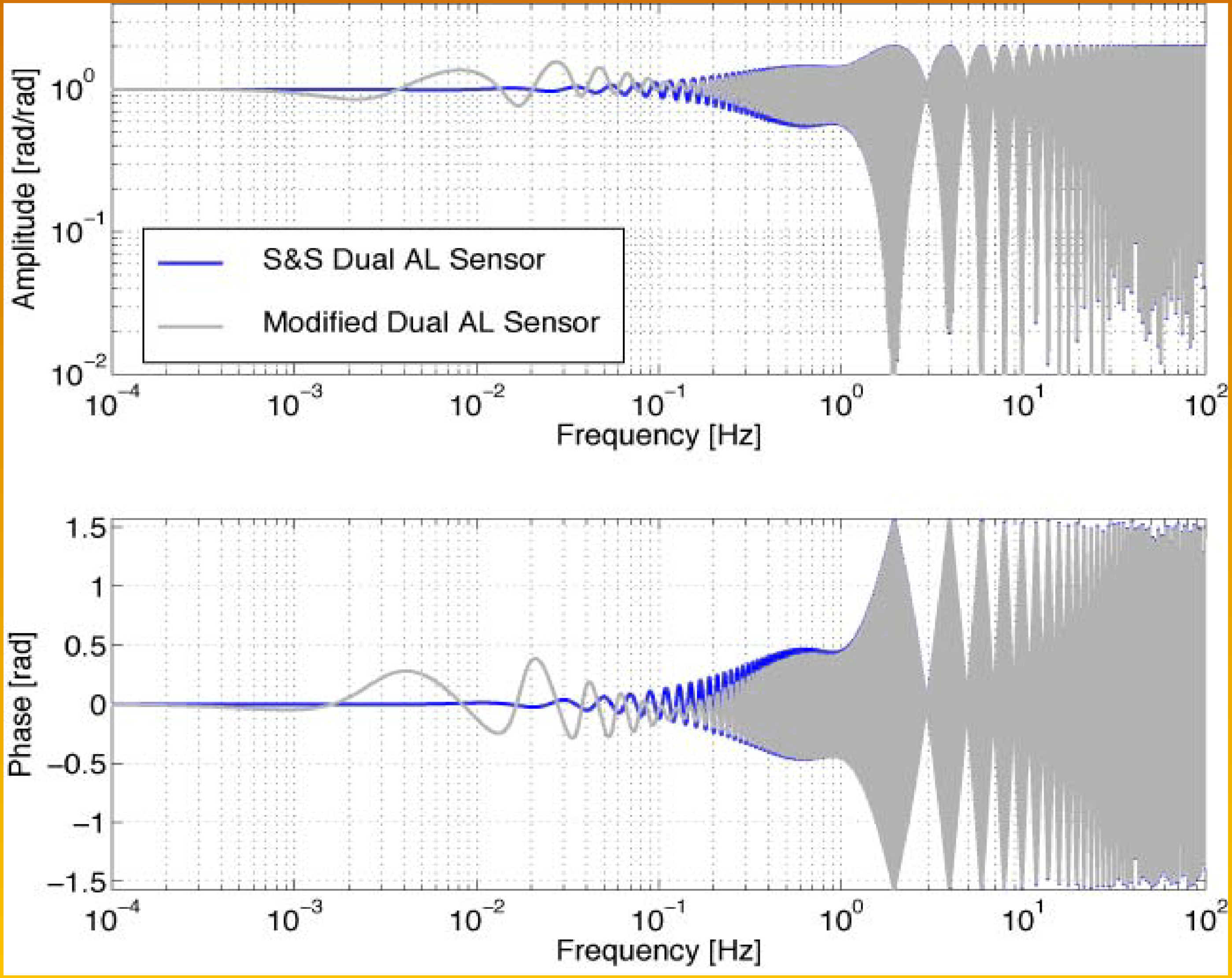
Modified Dual Arm-locking sensor:

- Common arm sensor dominates below 30mHz
  - ➢ Increase gain with multiple integrators
- Differential arm sensor modifies sensor between 30mHz and 1Hz
  - ➢ Adds signal at the sensor nulls
- Common arm signal dominates above 1Hz
  - ➢ Roll down with 1/sqrt(f)
  - ➢ Differential sensor signal is unstable above 1Hz



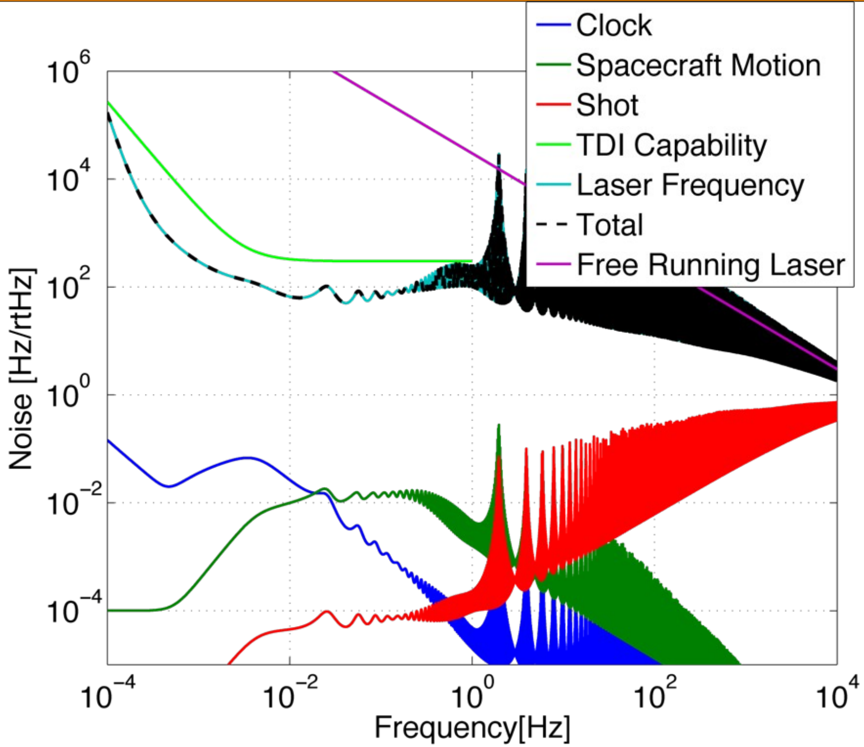


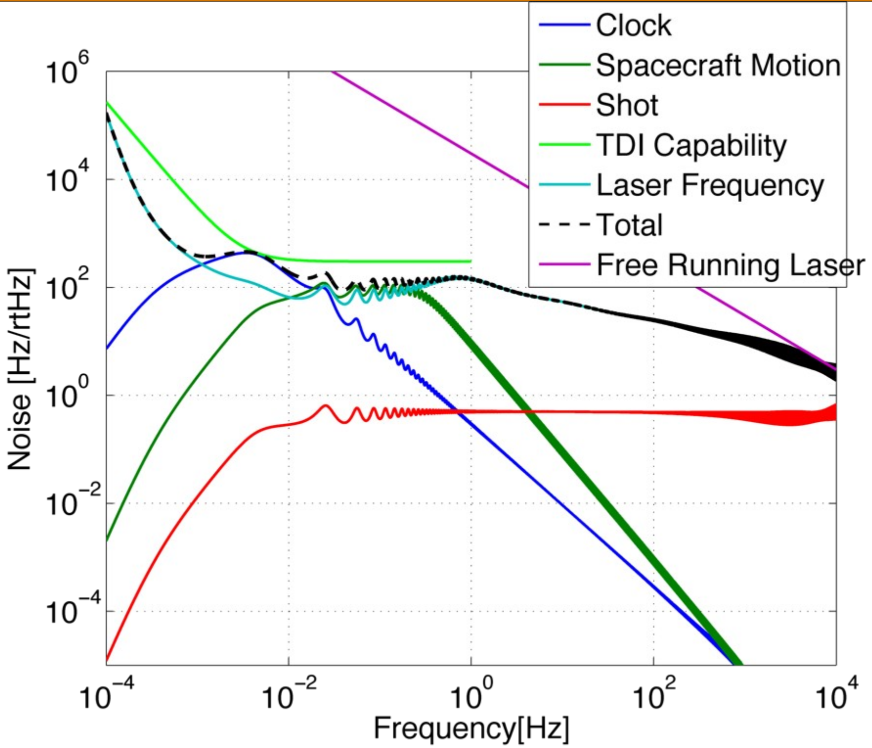
Dual Arm-Locking Schemes



Kirk McKenzie

Dual Arm-Locking Performance w/o prestabilization





Kirk McKenzie

Maximum arm length mismatch: Δtau = 0.255s, ΔL = 75,000km.

Gain limited, noise sources negligible.
(Still meets capability)

Minimum arm length mismatch that meets TDI capability: Δtau =40μs, ΔL = 12km.

Noise limited for ΔL<12km.
(only see this if an interspacecraft link fails)

Dual Arm-Locking Schemes

Problem:

- Dopper shift introduces offset
  - AC-coupled sensor (corner freq.: ~μHz)
  - or estimate Doppler shift well enough

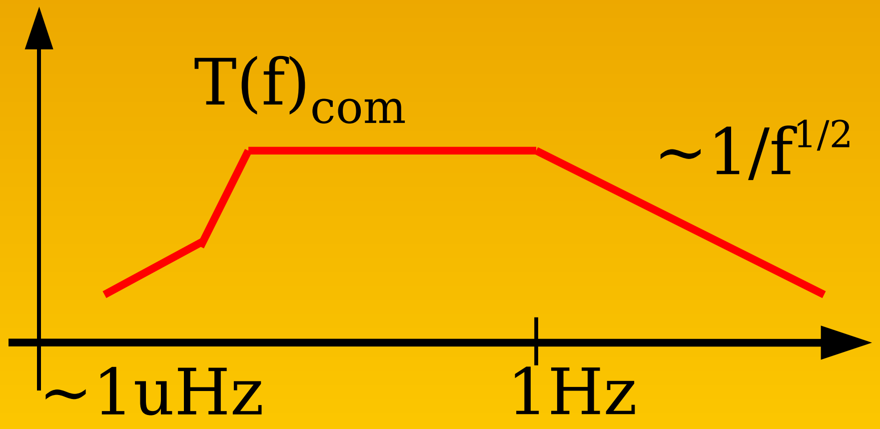
- Offset with be integrated up

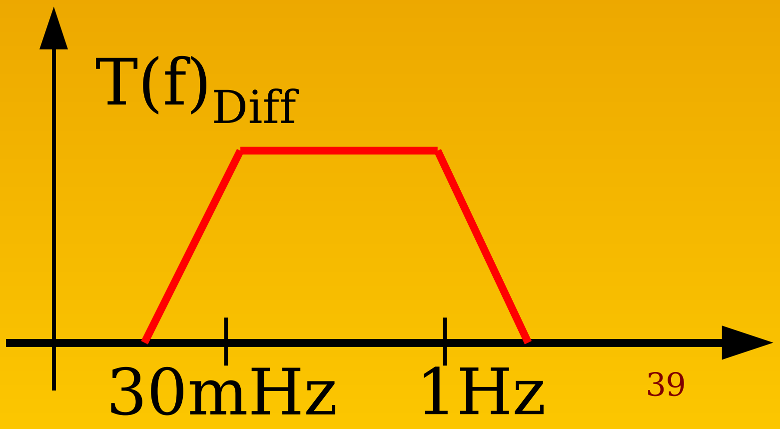
➡ linear ramp in laser frequency

Time Domain:

$\phi(t)-\phi(t-L_2/c)+\Delta\omega t$

$\Delta\omega=\omega_{\mathrm{Doppler}}-\omega_{\mathrm{PM}}$

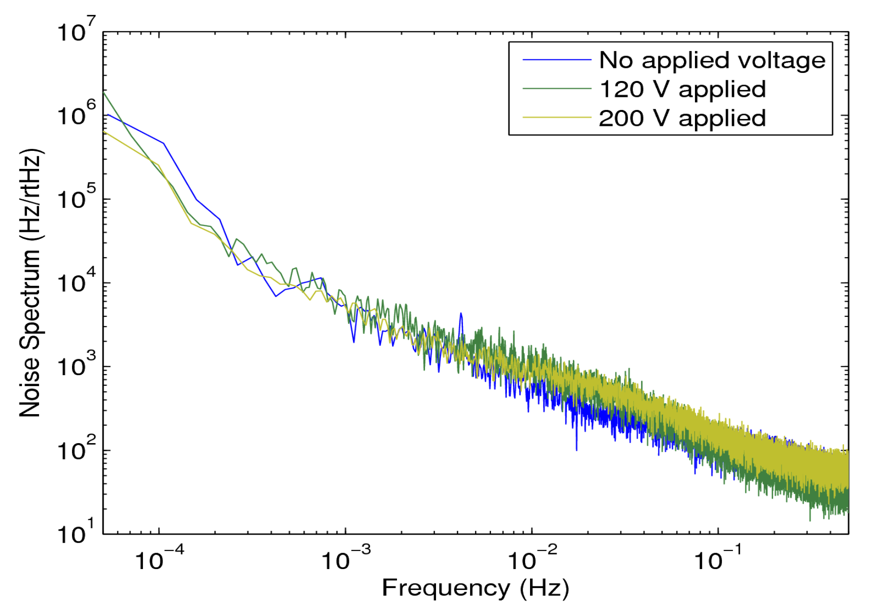




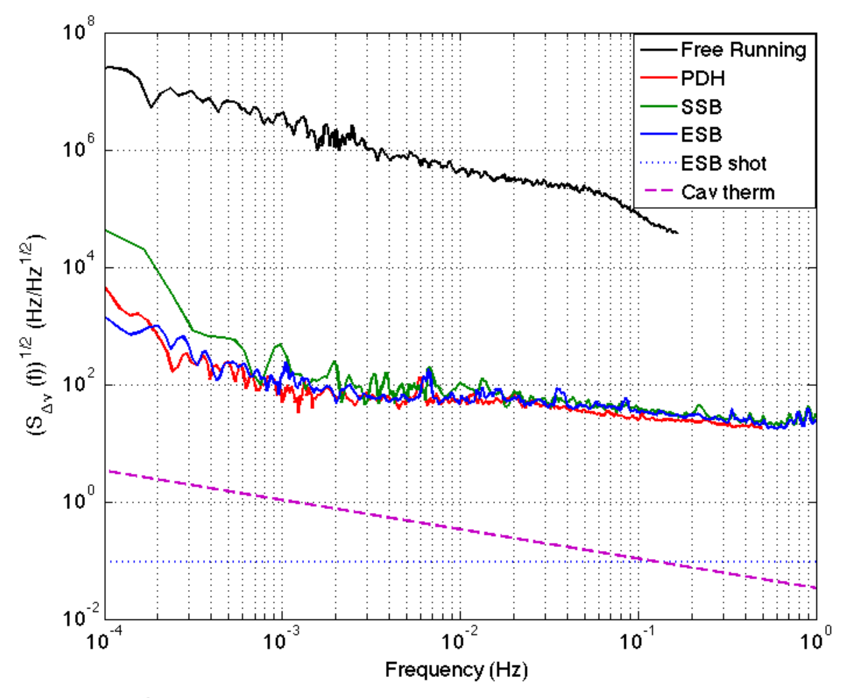
Dual Arm-Locking Schemes

with prestabilization:

- PZT Cavity
- Sideband locking
- heterodyne IFO on MZ



PZT-Cavity:
Alix Preston (UF)



Sideband locking:
GSFC results

Summary

Long baseline IFO:

- Laser frequency noise canceled in post-processing (TDI)
- Laser ranging and clock synchronization with PRN codes with <1m accuracy
- Clock noise measurements using GHz modulation tones
- Multiple options for Laser frequency stabilization:
  - Cavity
    - ➢ with heterodyne IFO (simplest)
    - ➢ PDH (most heritage)
  - Arm Locking (most elegant)
    - ➢ modified dual arm locking (MDAL)
  - Arm Locking with pre-stabilization
    - ➢ MDAL with Sideband locking
    - ➢ MDAL with PZT
    - ➢ MDAL with LTP-style Mach Zehnder