Ando-Michimura Lab Seminar

Recent Thoughts on Interferometer Configurations of (B-)DECIGO

2025/10/24

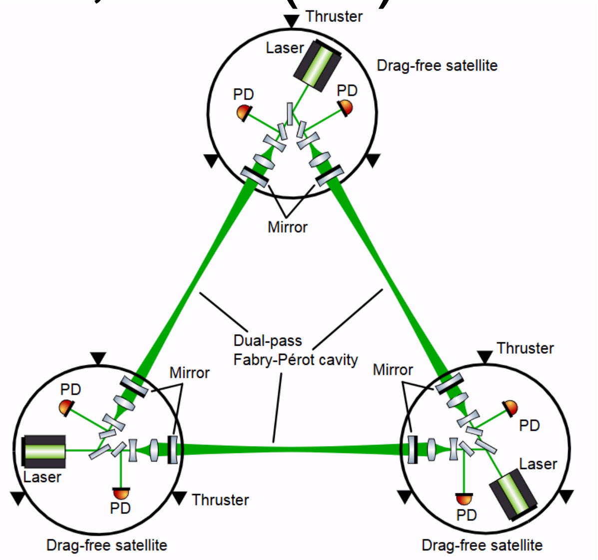
ISAS/JAXA, Yutaro Enomoto

Yutaro Enomoto

- 2014: B4 at Ando Lab.
  - Optical levitation
- 2015-2017: Master course at ICRR (Kawamura Lab.)
  - Quantum noise and optomechanical interactions
- 2017-2020: Ph.D. course at Ando Lab. (mainly at KAGRA)
  - Green locking and IFO commissioning
- 2020-2022: Takeda Lab. (東大物工)
  - Photonic quantum computing and sensing
- 2023-2025: Fujitsu Ltd.
  - Coherent optical communication
- 2025-: ISAS/JAXA
  - Space-borne GW detector and related topics

Current Interest/Concern

- What is the BEST realization/implementation of (B-)DECIGO in terms of technical feasibility?
  - To reach the BEST, study new (or old) ideas that improves the feasibility
- I want to convince myself (and others) that some specific configuration is the BEST with explicit reasons
- …and, with confidence, that (B-)DECIGO is really feasible.



From K.Nagano's Ph.D thesis

Current Interest/Concern

- Biggest concern of mine: test mass module
- Why?
  - Many challenges are pushed onto the test mass module.
    - Precise length & angle control with low-noise actuators
      - Dynamic range of $10^{-10\text{-}11}$ /sqrt(Hz)
      - Stringent requirement on alignment control
        → Global control test with IFO in space is probably necessary
        (LSC/ASC with weak actuators is the toughest part in the commissioning)
    - Requires low force noise but opens toward free space
    - High quality as a mirror with RoC~100-1000km

- How can we relax the challenges?
  - I have brought two items to be discussed

Approach 1: Back-Linked Fabry-Perot

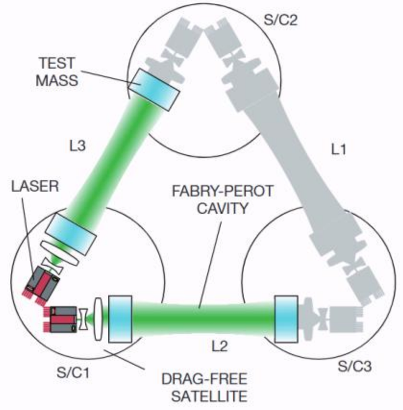


Fig. 1. A schematic view of the constellation for the BLFP interferometer. One of the three interferometers, formed by Spacecraft 1 with Fabry–Pérot cavities L_2 and L_3, is highlighted in color while the other two are shaded in gray for illustrative purposes. S/C stands for spacecraft.

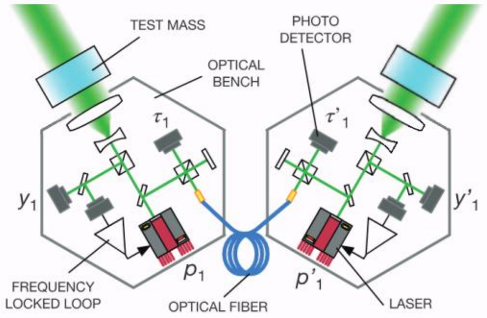


Fig. 2. A schematic view of the optical setup in Spacecraft 1.

K.Izumi+, PTEP **2021**, 073F01(2021).

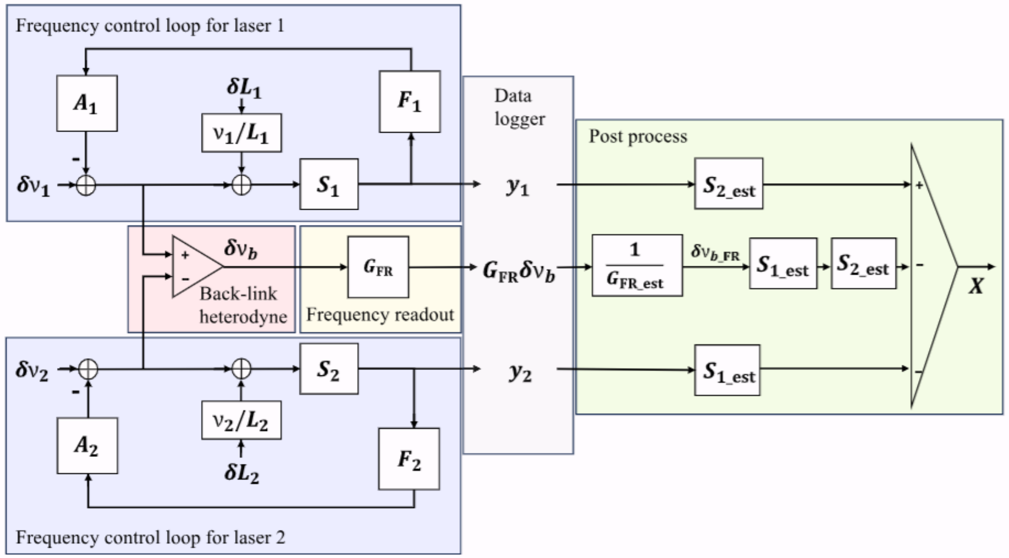
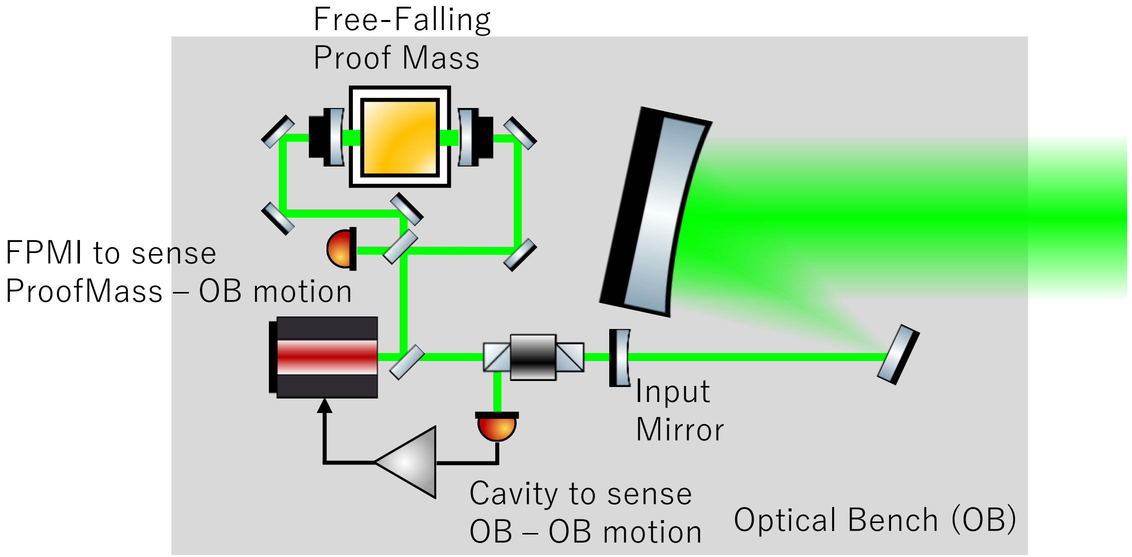


FIG. 2. Block diagram of the control system and post process for the BLFPI. The system consists of the experimental system for signal acquisition and the postprocess system to subtract laser frequency noises. The experimental system is further divided into the control system to lock the lasers to a cavity resonance, the back-link part to monitor the heterodyne beat signals, and the frequency readout part to monitor the time evolution of the beatnote frequency.

R.Sugimoto+, PRD **109**, 022003(2024).

- Merit: LSC with weak actuators is no longer required
- Drawbacks and their mitigations: today’s topic

Approach 2: Proof Mass

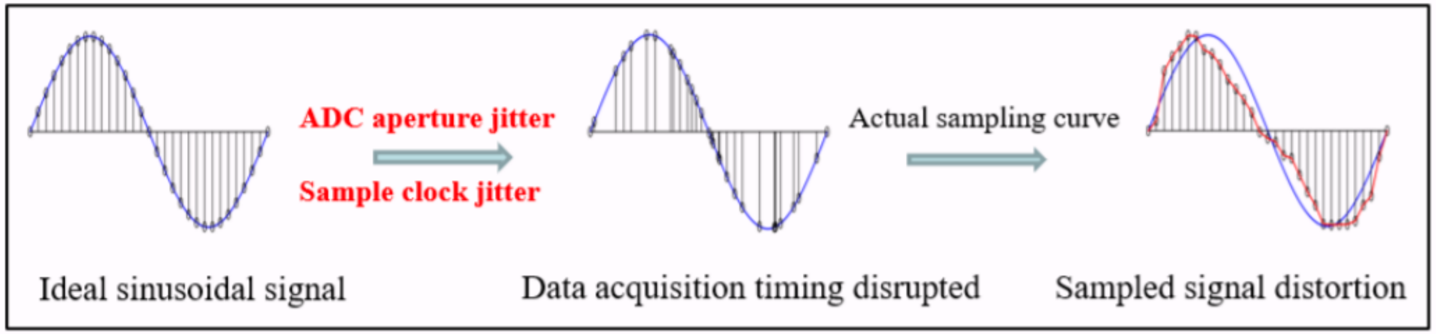


- LISA-like approach of mass-OB-OB-mass sensing
- No thorough investigations yet (at least by myself)
- Let us discuss later in more detail

Back-Linked Fabry-Perot

Back-Linked Fabry-Perot

- Drawbacks:
  - Radiation pressure noise (quantum-limited RP noise cannot be reached) → let us discuss later
  - Heterodyne beat-note detection introduces noise
    - Shot noise in the heterodyne → K.Anai+, Optics Express **32**, 19372 (2024).
    - Clock noise → **today's topic**



From Y.Xia+, Symmetry **17**, 1314 (2025).

$$\delta\tilde{\nu}(t) = \delta\nu(t) - \dot{q}(t)\nu(t)$$

Frequency recorded with jittering clock

True frequency fluctuation

q(t): clock jitter [s]

Beat-note frequency

Clock Noise in BLFP

$$\delta\tilde{\nu}(t) = \delta\nu(t) - \dot{q}(t)\nu(t)$$

Frequency recorded with jittering clock | True frequency fluctuation | $q(t)$: clock jitter [s] | Beat-note frequency

- Order estimate
  - Strain sensitivity $h \sim 10^{-22}\ /\sqrt{\mathrm{Hz}}$ with $\nu \sim 10\ \mathrm{MHz}$ and $\nu_{\mathrm{laser}} \sim 600\ \mathrm{THz}$
  - Requirement: $\dot{q}(t) < \frac{h\nu_{\mathrm{laser}}}{\nu} \sim 6 \times 10^{-15}\ /\sqrt{\mathrm{Hz}}$
    → $q(t) < 10^{-15}\ \mathrm{s}/\sqrt{\mathrm{Hz}}$ @1Hz
  - State of the art: $q(t) \sim 10^{-14}\ \mathrm{s}/\sqrt{\mathrm{Hz}}$ @1Hz (space-qualified atomic clock)

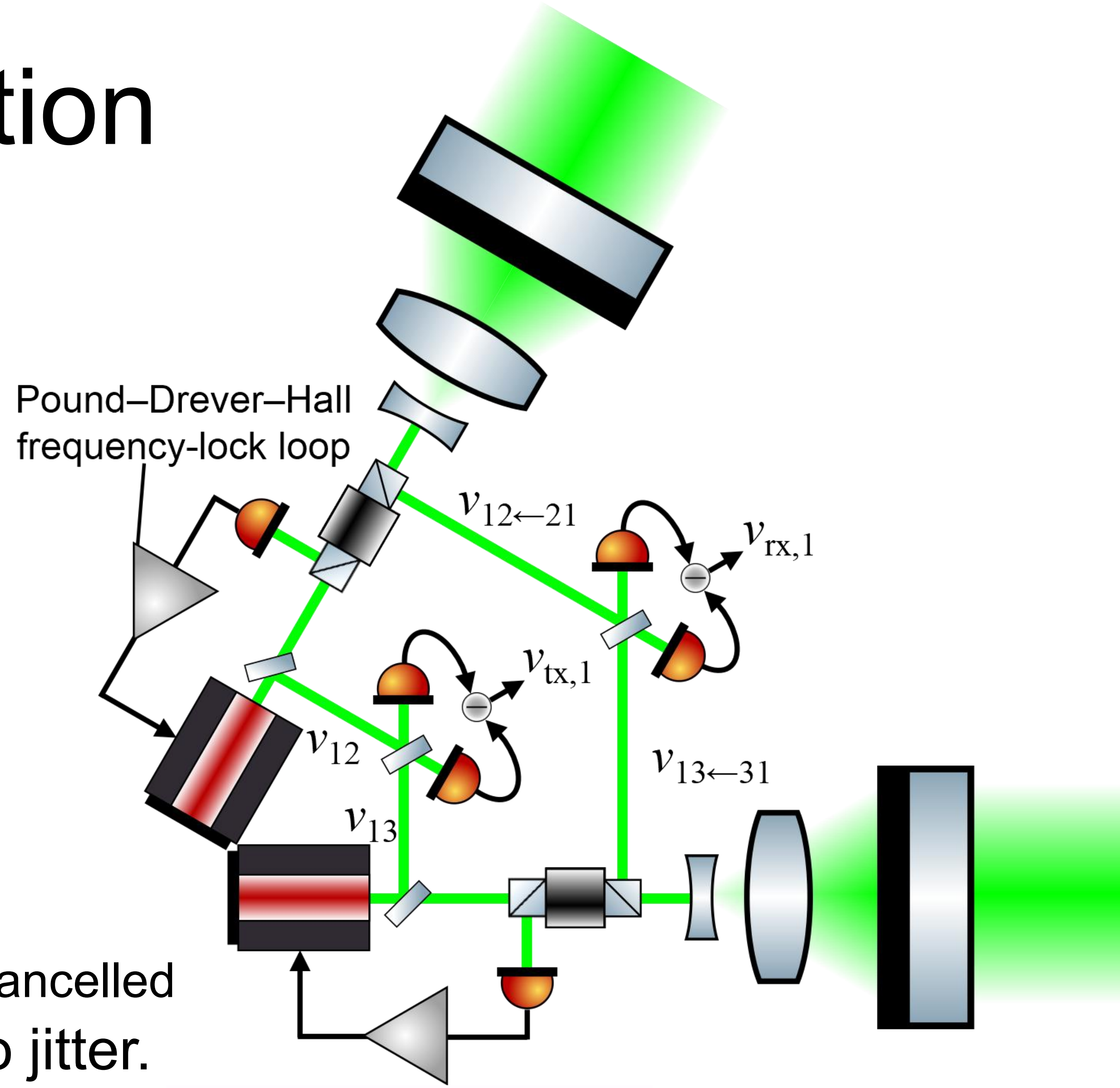
- **More than x10 reduction is necessary**

Clock Noise Cancellation

- We propose this configuration:
  - Get two beat-notes by combining
    - Two outgoing beams (original BLFP)
    - Two incoming beams

$$\tilde{\nu}^{\epsilon}_{\mathrm{tx},1}(t) = \nu^{\epsilon}_{\mathrm{tx},1}(t) - \dot{q}_1(t)\nu^{o}_{\mathrm{tx},1}(t)$$
$$\tilde{\nu}^{\epsilon}_{\mathrm{rx},1}(t) = \nu^{\epsilon}_{\mathrm{rx},1}(t) - \dot{q}_1(t)\nu^{o}_{\mathrm{rx},1}(t)$$

  - Add two signals in post-processing
    - If the beat-note frequencies are $+10$ MHz and -10 MHz for example, the clock jitter contribution would be cancelled
  - More generally, $\tilde{\nu}_{\mathrm{sum},1}$ is immune to jitter.

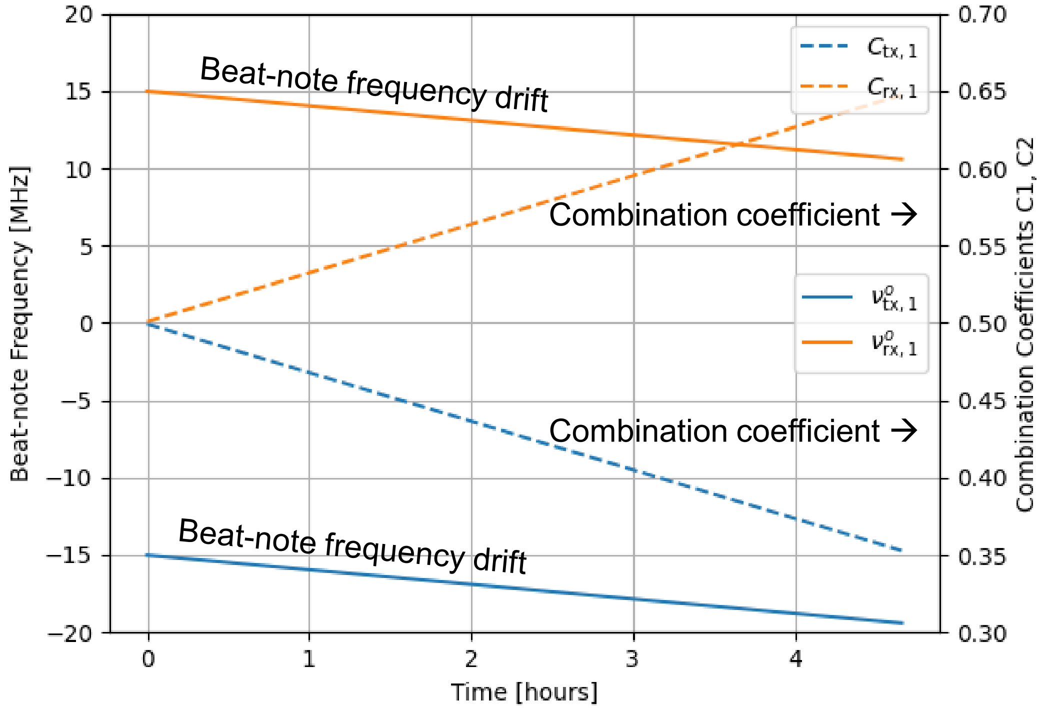


$$\tilde{\nu}^{\epsilon}_{\mathrm{sum},1}(t) = C_{\mathrm{tx},1}(t)\tilde{\nu}^{\epsilon}_{\mathrm{tx},1}(t) + C_{\mathrm{rx},1}(t)\tilde{\nu}^{\epsilon}_{\mathrm{rx},1}(t)$$

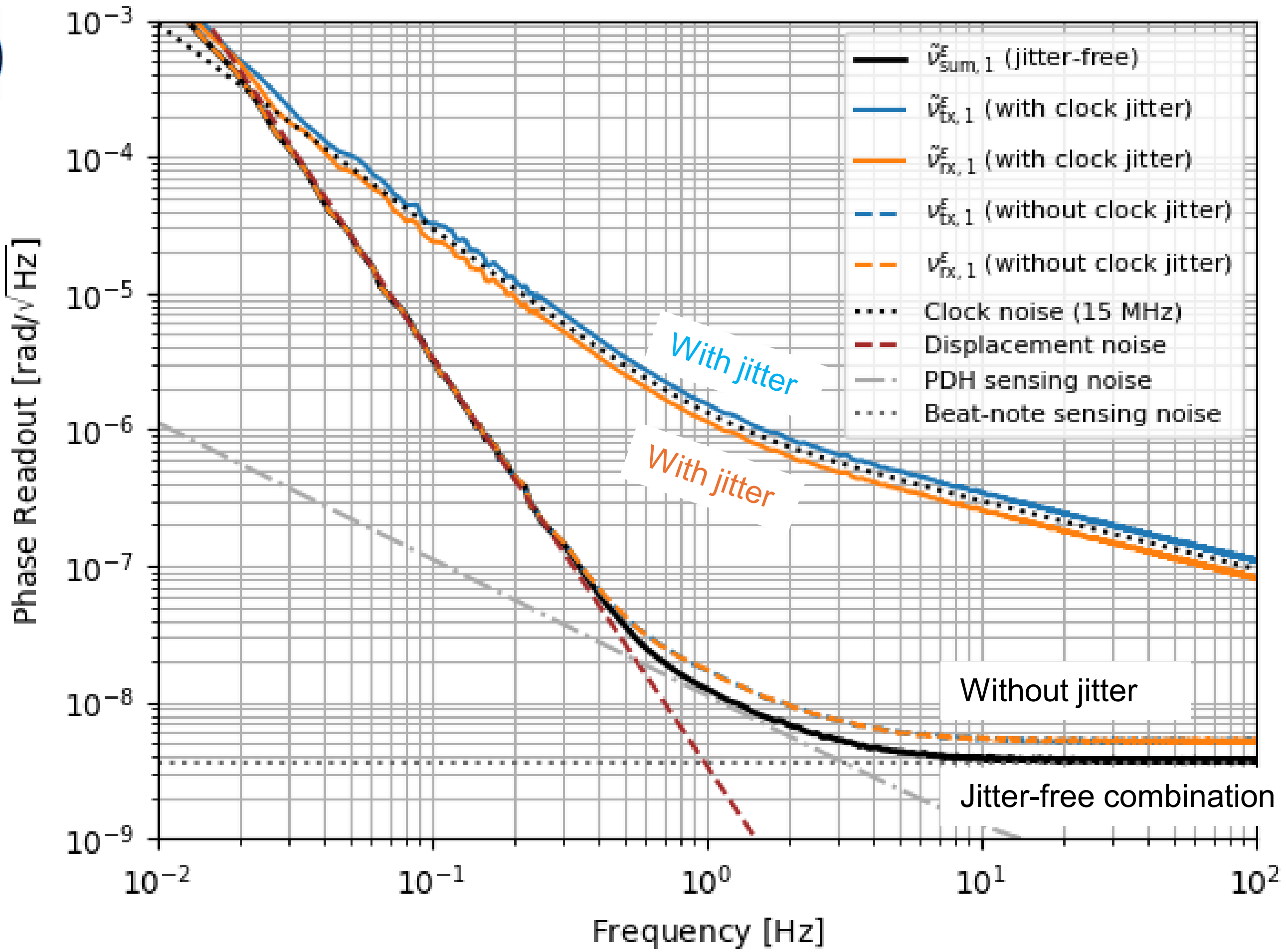
$$C_{\mathrm{tx},1}(t) = -\frac{\nu^{o}_{\mathrm{rx},1}(t)}{\nu^{o}_{\mathrm{tx},1}(t) - \nu^{o}_{\mathrm{rx},1}(t)},$$
$$C_{\mathrm{rx},1}(t) = \frac{\nu^{o}_{\mathrm{tx},1}(t)}{\nu^{o}_{\mathrm{tx},1}(t) - \nu^{o}_{\mathrm{rx},1}(t)},$$

Clock Noise Cancellation: Simulation

$$\tilde{\nu}^{\epsilon}_{\mathrm{sum},1}(t) = C_{\mathrm{tx},1}(t)\tilde{\nu}^{\epsilon}_{\mathrm{tx},1}(t) + C_{\mathrm{rx},1}(t)\tilde{\nu}^{\epsilon}_{\mathrm{rx},1}(t)$$

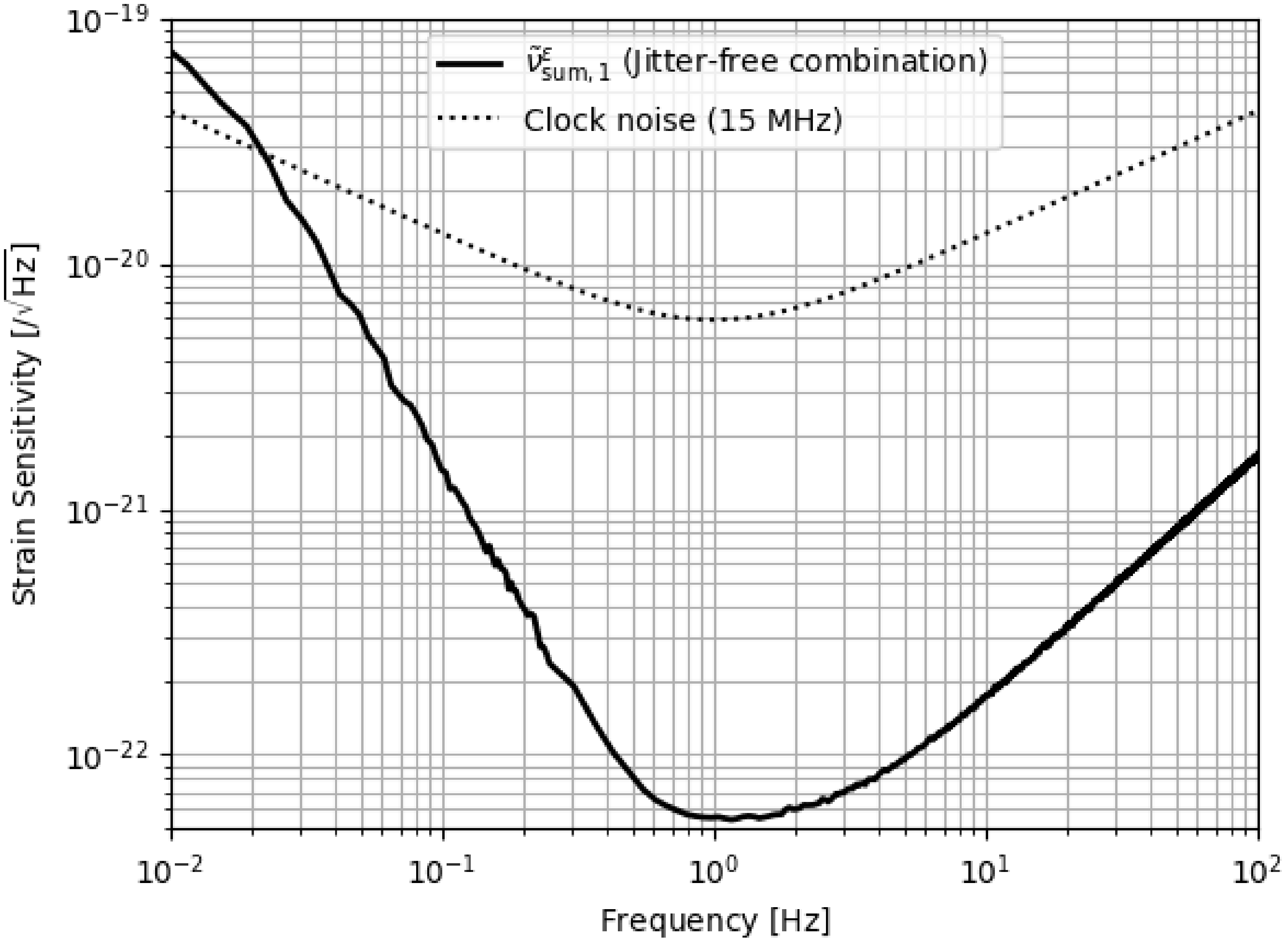


Assuming the relative velocity btw S/Cs is ~10nm/s



Cancellation is effective even with slowly drifting beat-note frequencies

Clock Noise Cancellation: Simulation



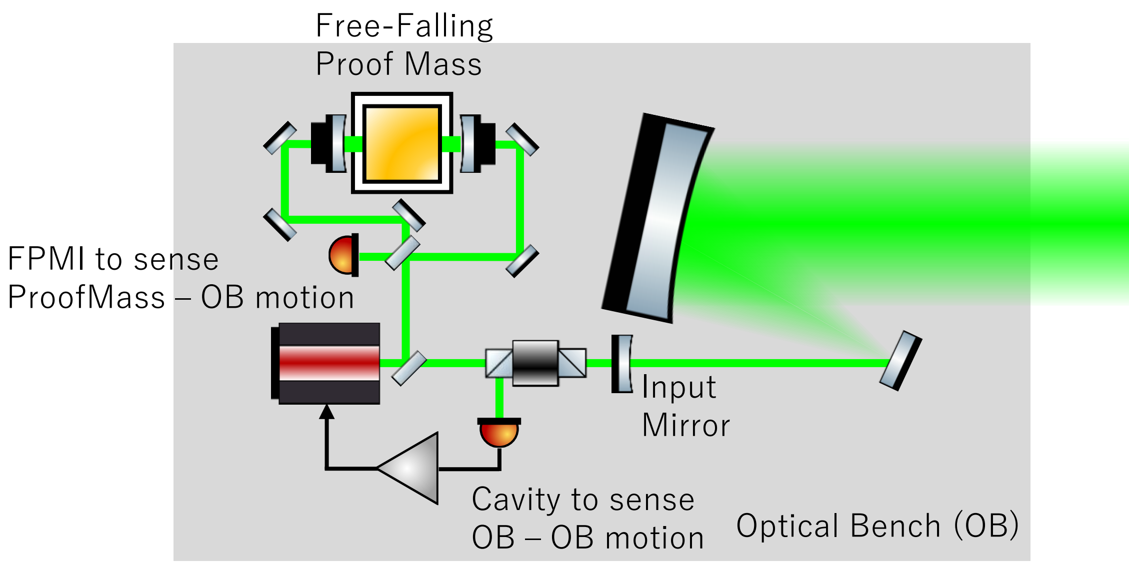
To Do's

- Currently summarizing the results so that they will be published.
  - Internal report

- Future works
  - Understand other noise sources in the phase meter
    - See if this scheme can make us reach DECIGO sensitivity
  - Necessary accuracy for the combination coefficients
  - Incomplete suppression of the frequency noise in the arm PDH loops and post-processing.

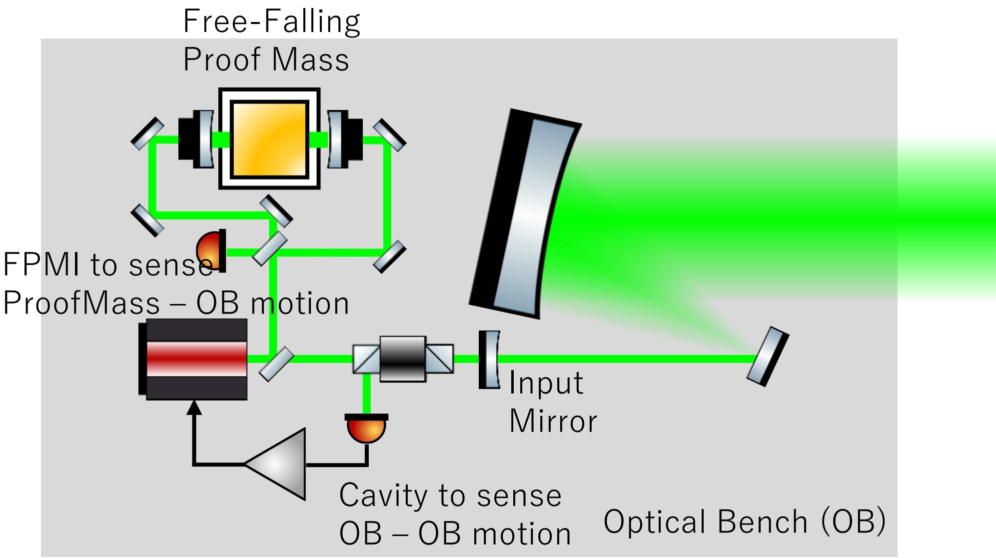
Proof Mass

Proof Mass



- Only proof mass is susceptible to force noise
- Expected benefits:
- **Major challenges are separated**
  (force noise and inter-S/C cavity)
  - No need to care actuator noise of the inter-S/C cavity control
  - The RP-noise issue in BLFP would no longer be important
- **Compound mirrors as end mirrors of the inter-S/C cavity**
  - No need to manufacture mirrors with RoC 100-1000km
  - Maybe some ASC tricks would become available (c.f. lensed cat's eye for SILVIA)
- **Proof mass module**
  - Testable as an independent module in Space
  - No diffraction loss → high finesse, quantum techniques can be employed
  - There is no DC RP force issue; RP actuator can be naturally incorporated
- <u>I believe this approach enhances the feasibility very much!</u>

Future Works



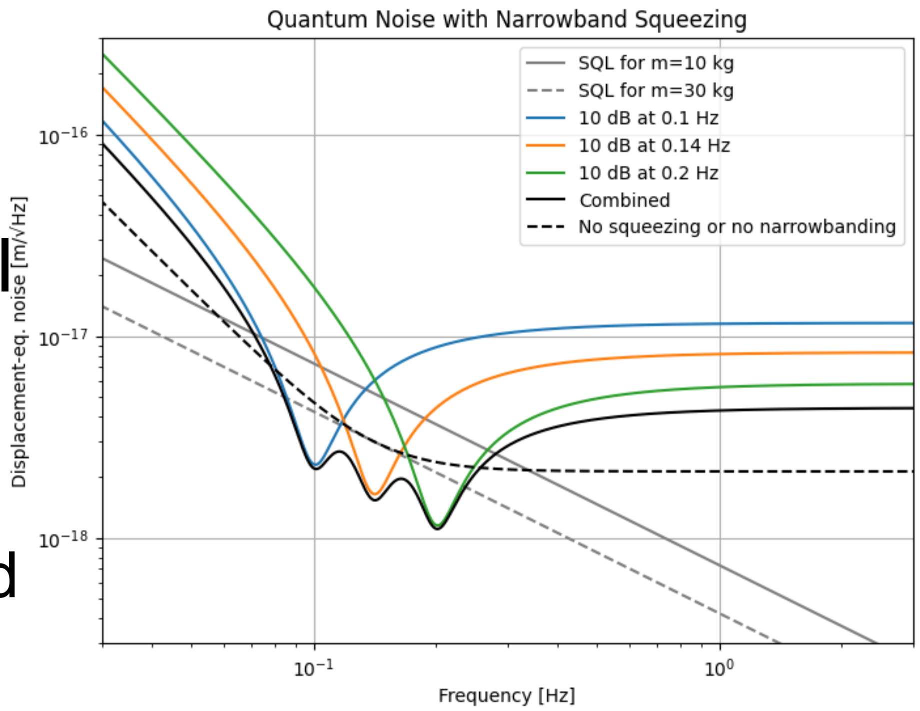
- First, real sensitivity analysis must be done
  - Should be same as quantum locking

- Required CMRR of the optical bench motion and its feasibility
  - x monitored by inter-S/C cavity
    vs
  - x monitored by local FPMI

- Alignment coupling need to be studied
  - Ideal relations between center of mass, center of curvature, proof mass, …
  - There might be some tricks to minimize alignment coupling by adjusting the relations

- And more…

Random Notes



- Having multiple proof masses might be helpful
  - To probe alignment DoFs and even elastic DoFs of the optical bench
  - Each mass beats the SQL in a narrow band, and as a whole, the SQL is beaten in a broad band

- Regardless of the IFO configurations, don't forget plasma phase noise