Constructing Test Bench for Integration Tests of Components Developed for DECIGO and B-DECIGO

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Abstract

- DECIGO project and its precursor project B-DECIGO is under way for launch in a few tens of years.
- For them, many R&Ds are on going.
- We are considering the interferometer configuration and initial locking scheme.
- To demonstrate them, it is planed to construct a test bench in Lab.
- With this test bench, an integration test of components developed independently will also be performed.

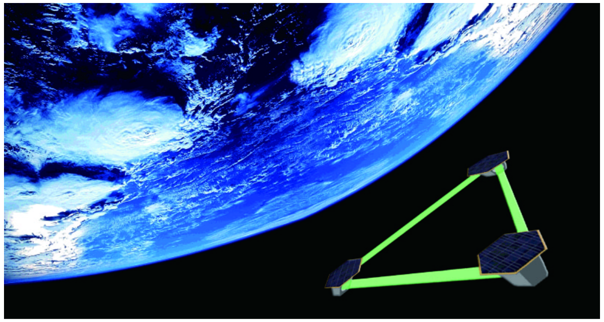


Image of B-DECIGO.
(made by S. Sato)

Outline

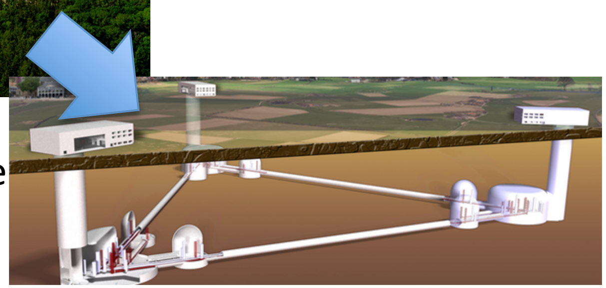
1. DECIGO Project
2. Interferometer configuration of DECIGO and B-DECIGO
3. First locking of B-DECIGO
4. Test bench for ground based demonstration

Introduction

- So far, 6 gravitational wave (GW) events have been detected by ground-based detectors.
- For further expansion of the GW physics and astronomy, we have two choices.

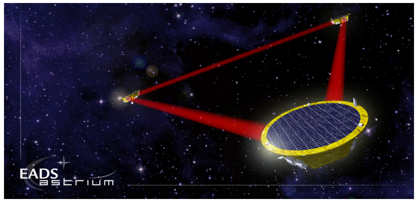
Improve ground-based detectors' sensitivity (10 Hz-1 kHz)

LIGO Livingston (Credit: Caltech/MIT/LIGO Lab)

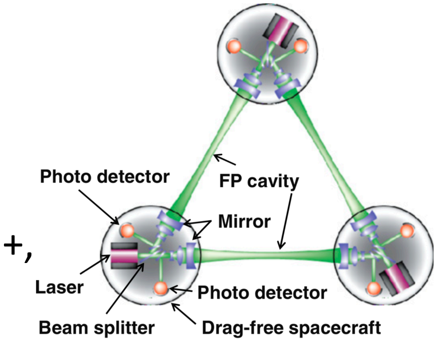


Einstein telescope (http://www.et-gw.eu)

Develop space detectors (0.1 mHz-10 Hz)



LISA (Credit: EADS Astrium)



DECIGO (S. Kawamura+, CQG, 2011)

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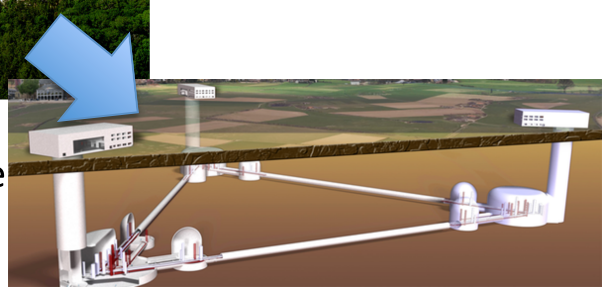

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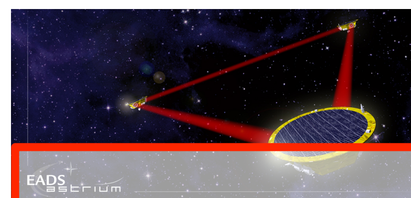

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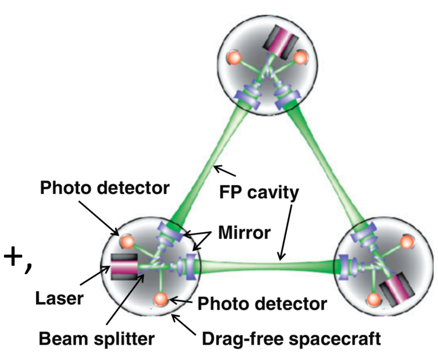
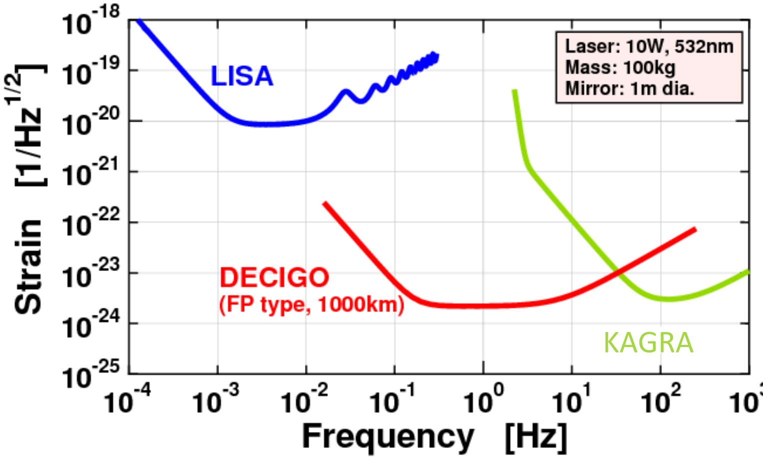


DECIGO (S. Kawamura+, CQG, 2011)

DECIGO Project

DECIGO Project

- Decihertz Interferometer Gravitational Wave Observatory = DECIGO



Sensitivity comparison with DECIGO, LISA, and KAGRA.

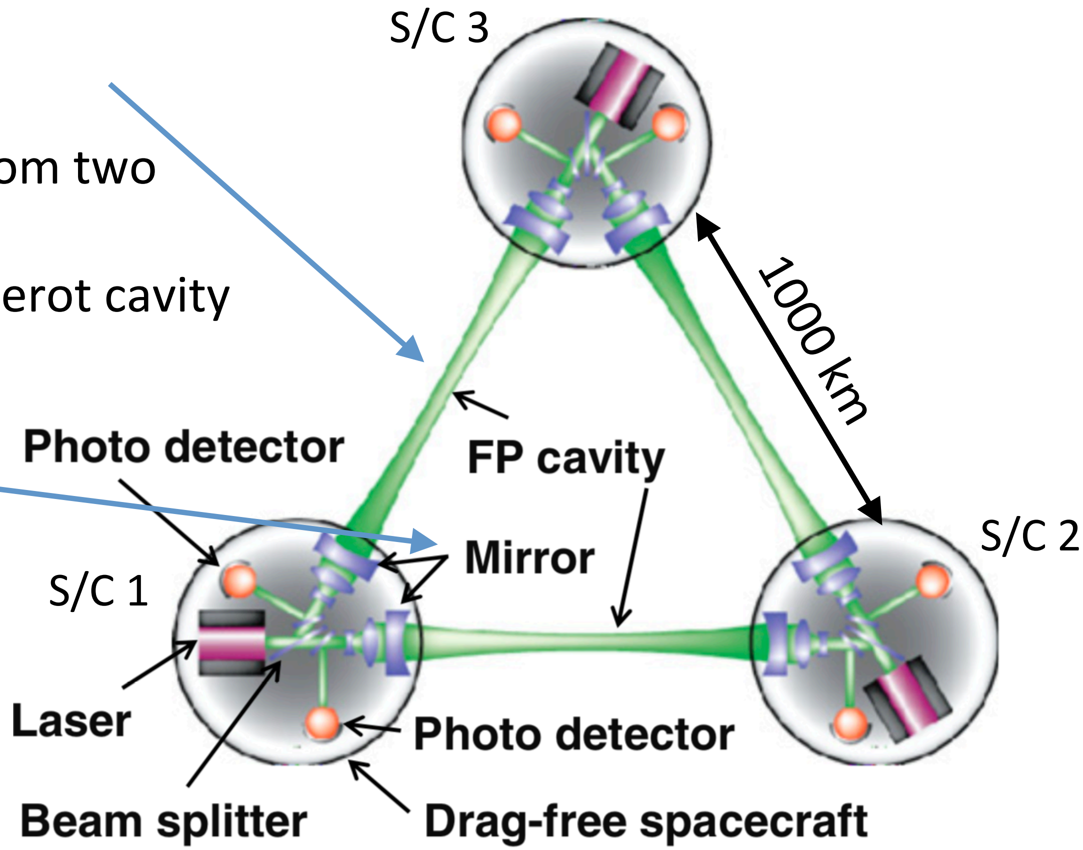
- DECIGO and its precursor detector B-DECIGO are space GW observatory project which bridge the gap between LISA and ground based detectors.
- For DECIGO and B-DECIGO, development and/or simulation of many components are on going.

DECIGO schematic

Arm (Cavity)
- Length: 1000 km
- Finesse: 10
- Shared by lights from two space crafts (S/Cs)
= Dual-path Fabry-Perot cavity

Mirror
- Mass: 100 kg
- Dia.: 450 mm

Laser
- Wave length: 515 nm
- Input power: 10 W
- Freq. fluc.: <1 Hz/rtHz @1 Hz



DECIGO schematic (S. Kawamura+, CQG, 2011)

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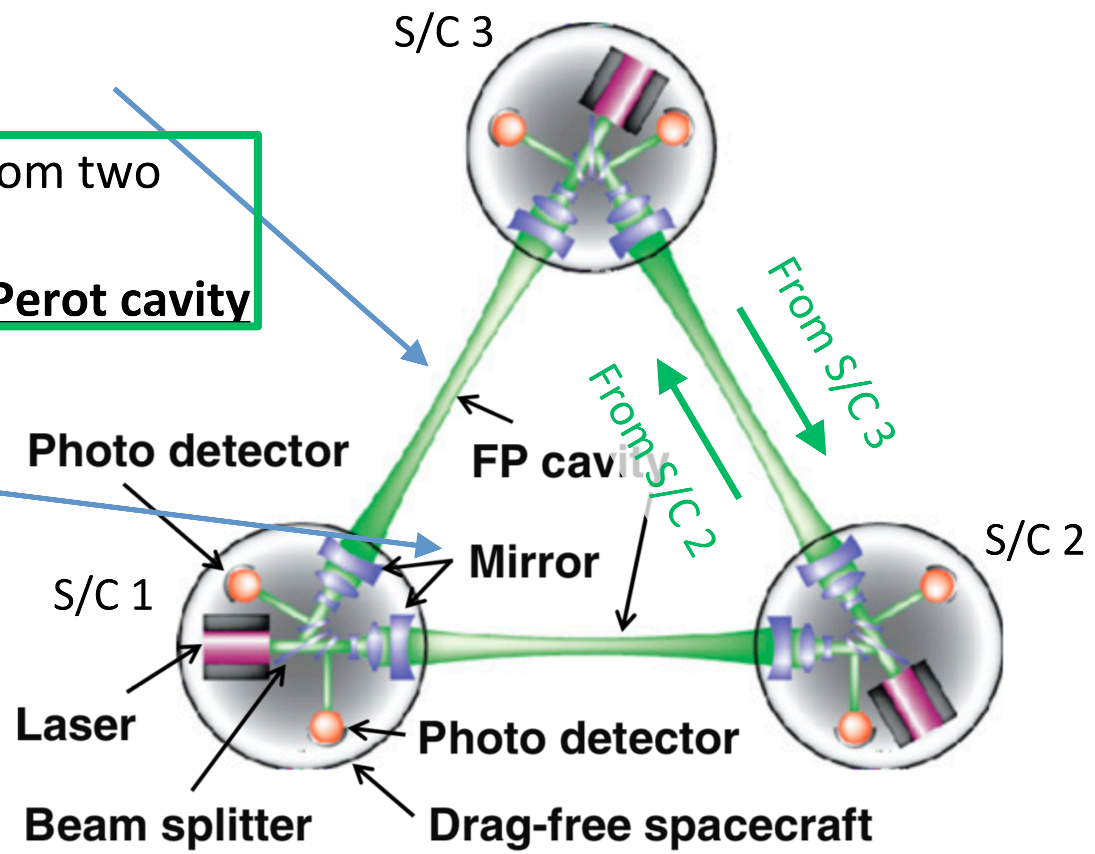


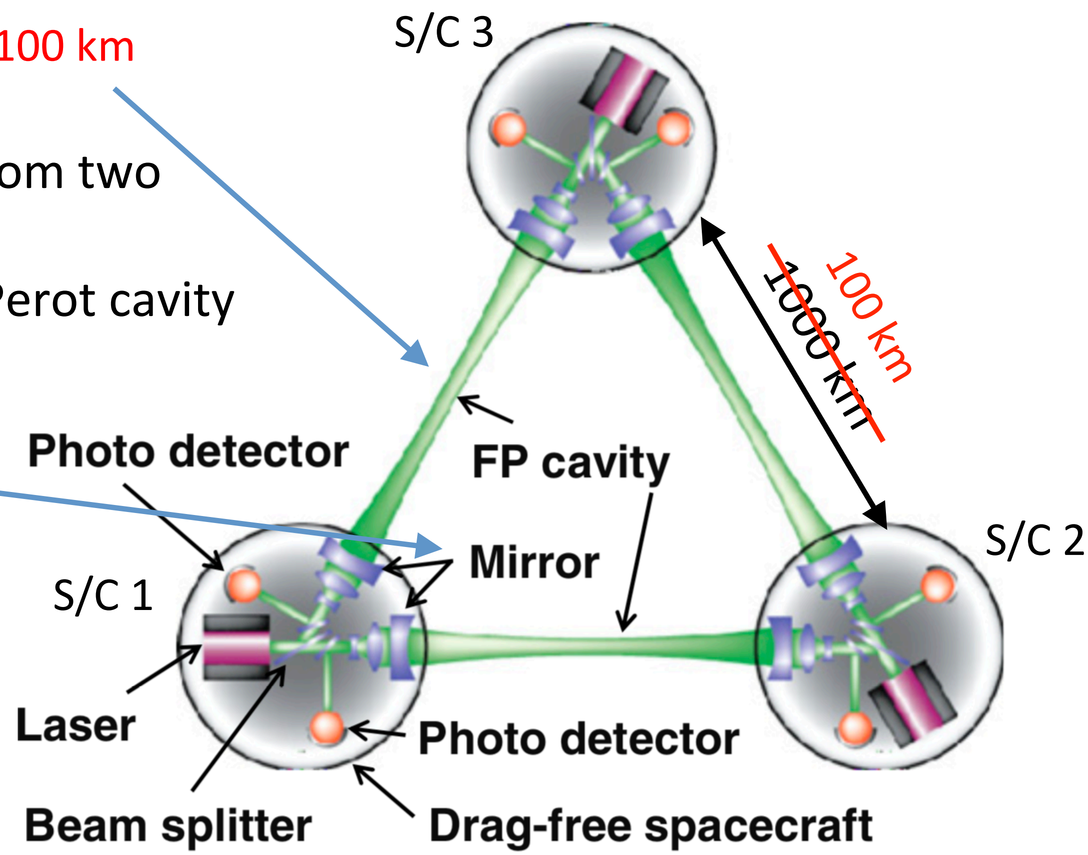
DECIGO schematic (S. Kawamura+, CQG, 2011)

B-DECIGO schematic

Arm (Cavity)
- Length: ~~1000 km~~ 100 km
- Finesse: ~~10~~ 100
- Shared by lights from two space crafts (S/Cs)
= Dual-path Fabry-Perot cavity

Mirror
- Mass: ~~100 kg~~ 30 kg
- Dia.: ~~450 mm~~ 300 mm

Laser
- Wave length: 515 nm
- Input power: ~~10 W~~ 1 W
- Freq. fluc.: <1 Hz/rtHz @1 Hz

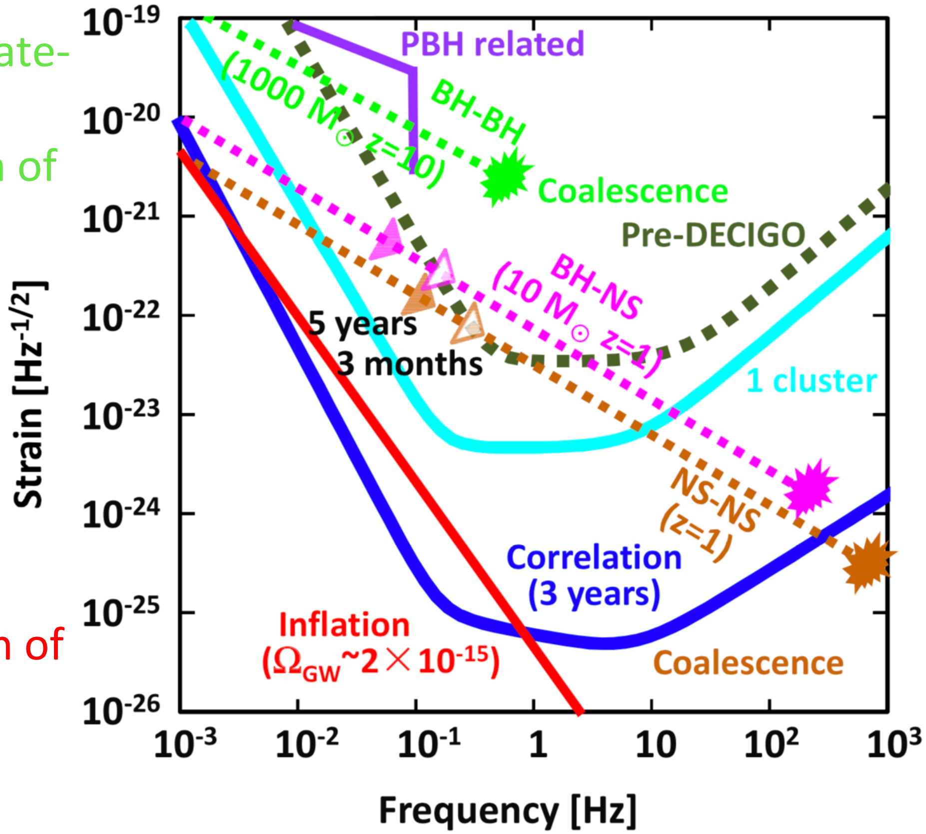


DECIGO schematic (S. Kawamura+, CQG, 2011)

Sensitivity and science

- Observe intermediate-mass black holes
->Reveal mechanism of formulation of supermassive black holes

- Verify inflation
-> Direct observation of the beginning of the universe



DECIGO and B-DECIGO sensitivity. B-DECIGO was called Pre-DECIGO formerly.
(S. Kawamura+, CQG, 2011)

- Dark-matter (candidate) search [1]

Test gravity theories [2]

- Study neutron physics
- Measure accelerated universe directly [3]
  -> Dark-energy search

[1] R. Saito+, *PTP*, 2009
[2] K. Yagi+, *PTP*, 2010
[3] N. Seto+, *PRL*, 2001

Challenges for mission

- Low force noise requirement ($<1\times10^{-16}$ N/rtHz)
  - LISA Path Finder result @0.01 Hz: 4×10^{-15} N/rtHz
- Low S/C displacement noise requirement ($<1\times10^{-19}$ m/rtHz @0.1 Hz)
  - Low noise, high dynamic range, continuously variable thrustor is required.
  - S/C alignment and drag-free control scheme (signal processing scheme) is necessary.
- First locking after initial S/C tracking.
- Interferometer configuration
  - Dual-path Fabry-Perot cavity is most promising though.
  - Configuration itself should be demonstrated.
  - In any choice, practical problem should be investigated.
- Integration test
  - Thruster, S/C tracking with Acousto-Optic Deflector (AOD), and so on.

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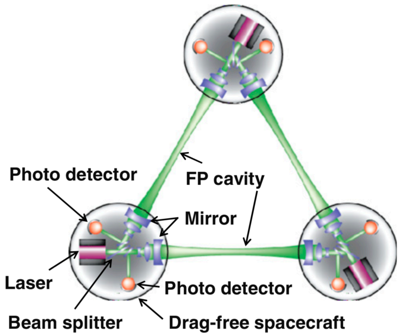
Currently, we are considering these points theoretically and/or experimentally.

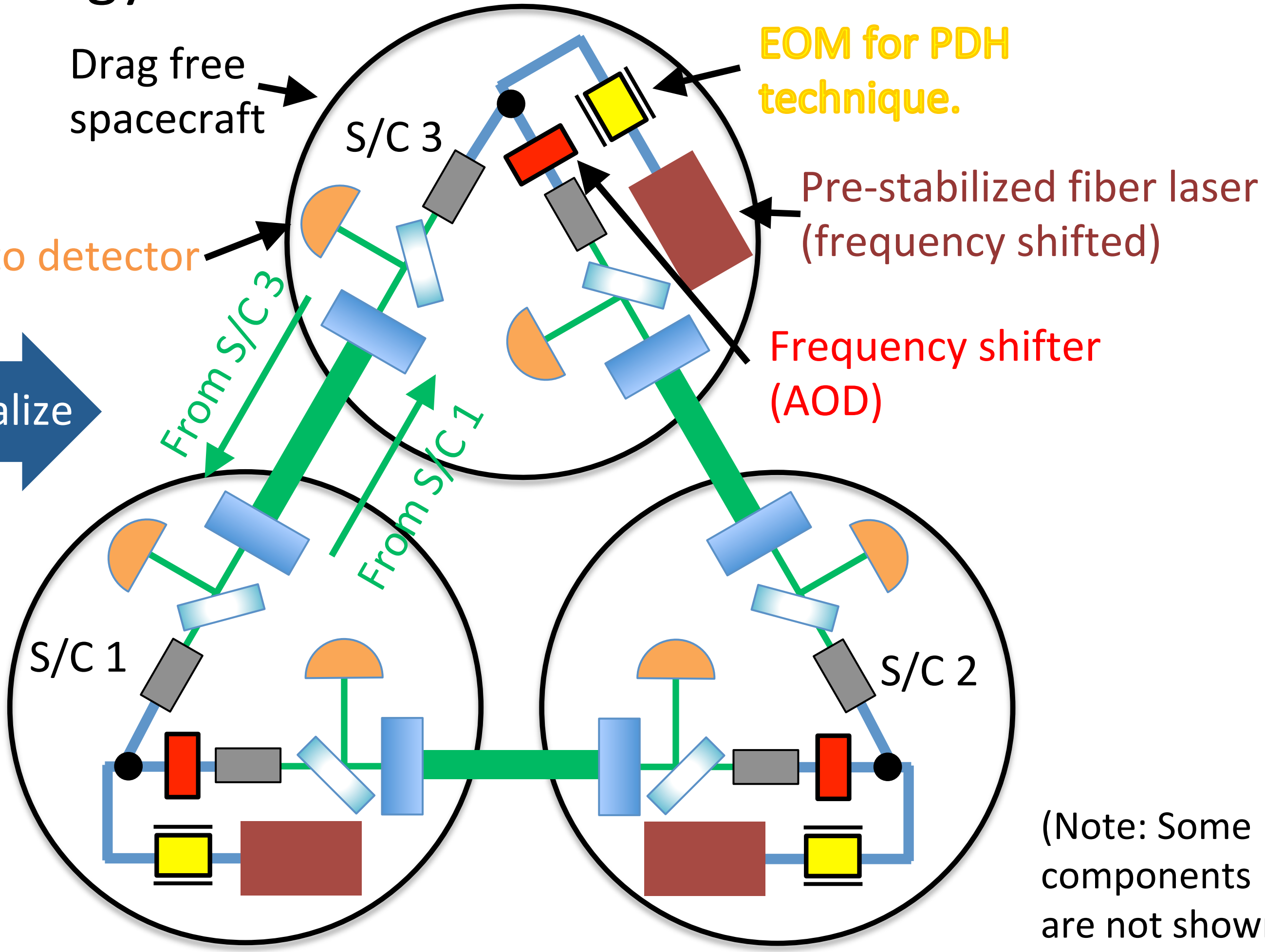
Interferometer configuration

- How to realize interferometer operation?
  - Control topology should be considered.



Conceptual design.

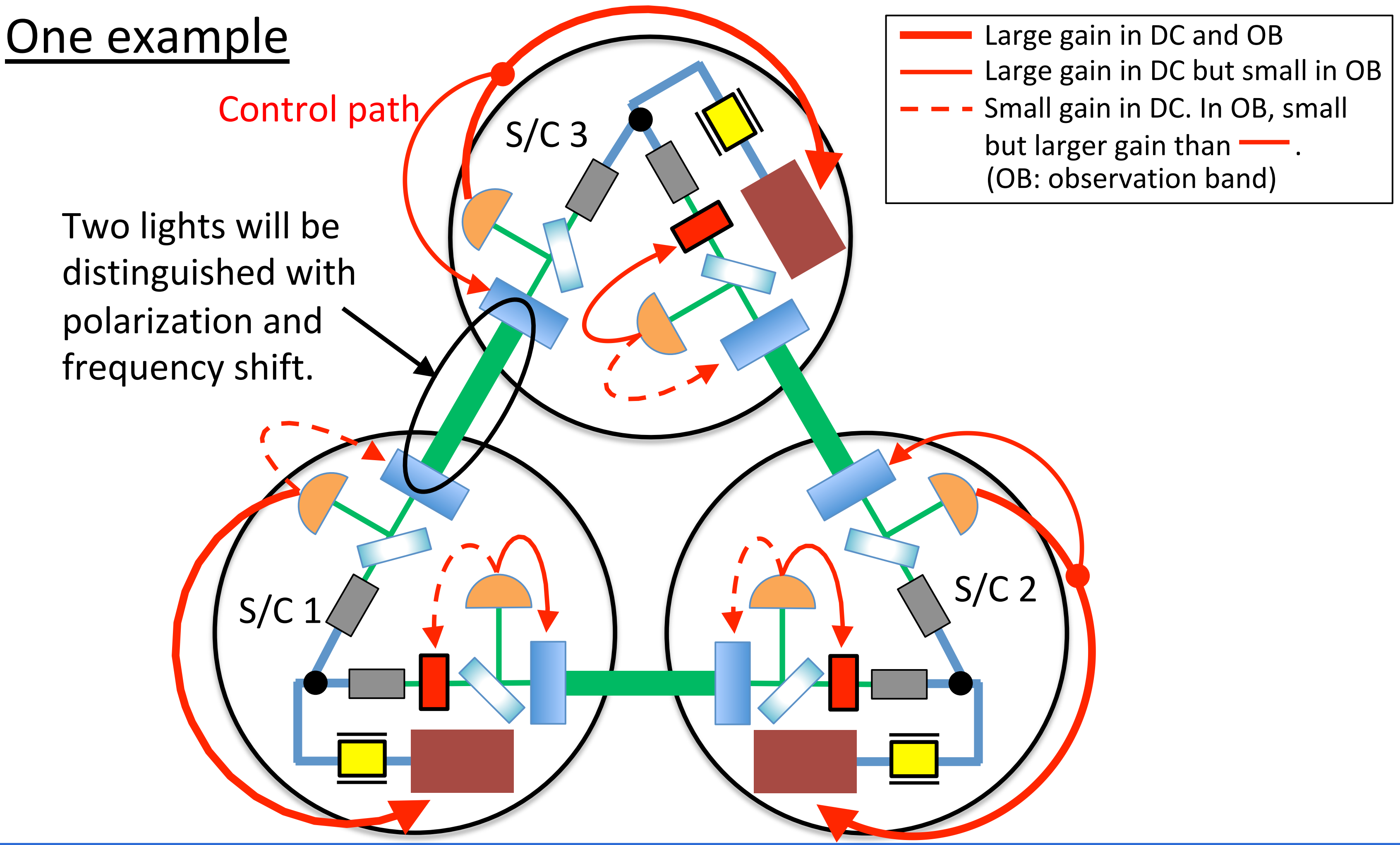
Realize



(Note: Some components are not shown.)

Interferometer configuration

- Several possibilities are considered.



Interferometer configuration

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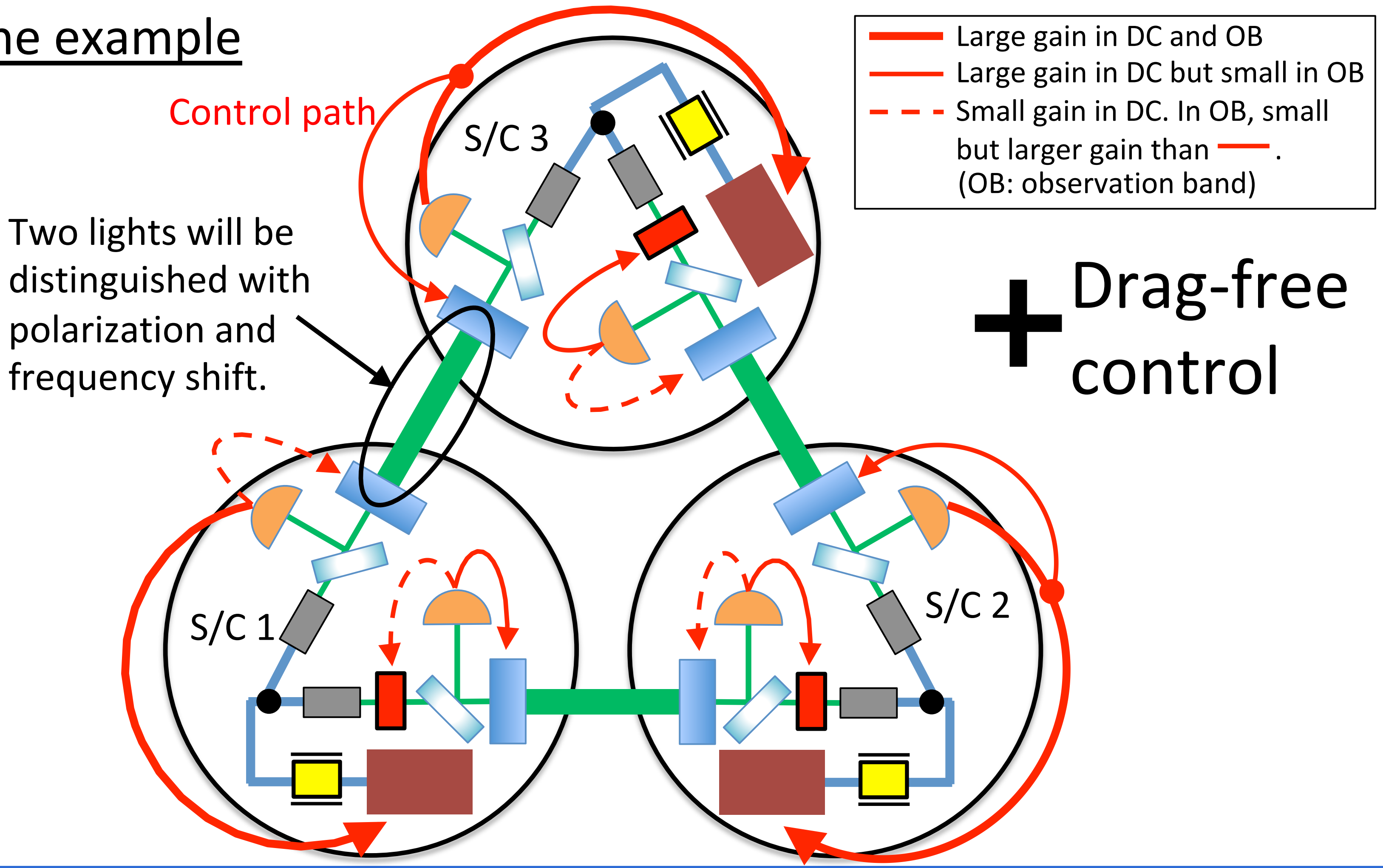
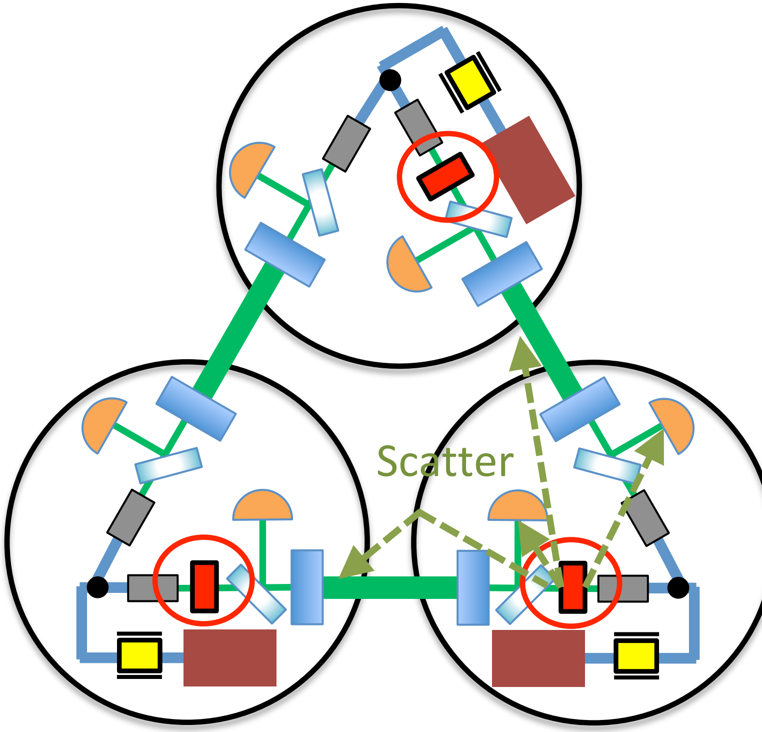
One example



+ Drag-free control

Interferometer configuration

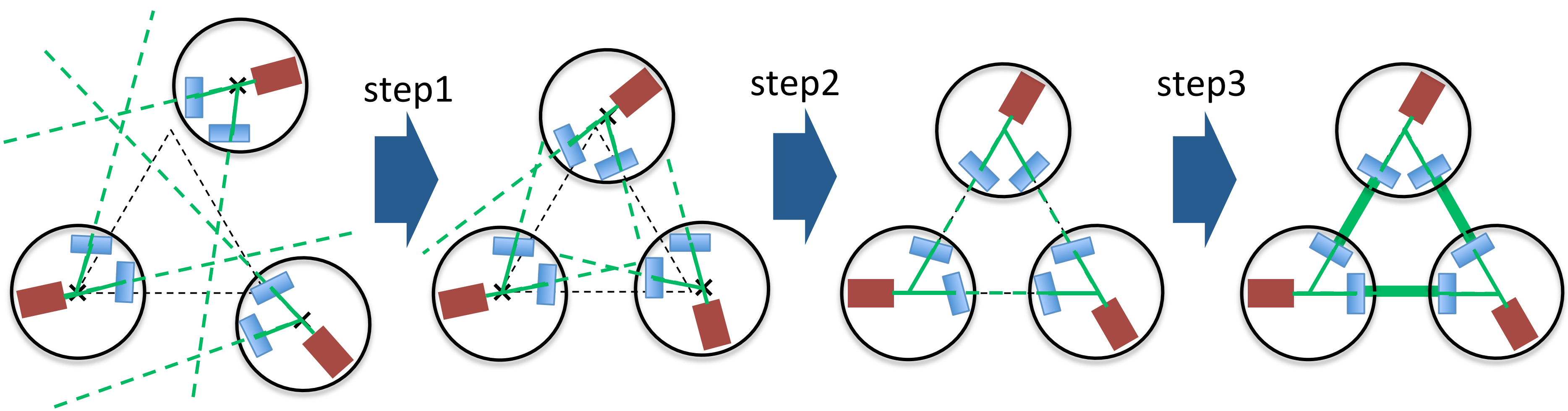
- Even if it works well theoretically, we cannot avoid practical problems.
  - Signal decoupling including drag-free control.
  - AODs scattering which is correlated with two arms and cannot be distinguished from GW signal.
- Before launch, all problems must be resolved experimentally.



Possible scattering problem due to AODs.

First locking

- First locking is one of the most serious problems of DECIGO/B-DECIGO.
- "First locking" can be divided into 3 steps.
  1. S/C tracking (~10 m, 100 urad)
  2. Optical S/C alignment (~10 cm, 0.1 urad)
  3. Cavity locking (~1 um)



First locking

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This locking scheme should be demonstrated before launch.

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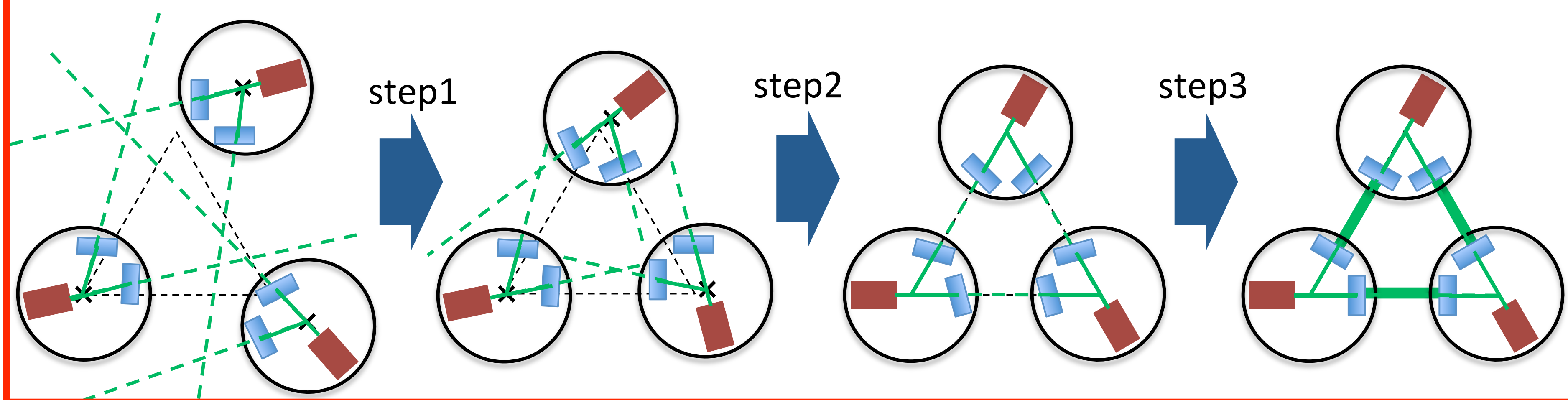
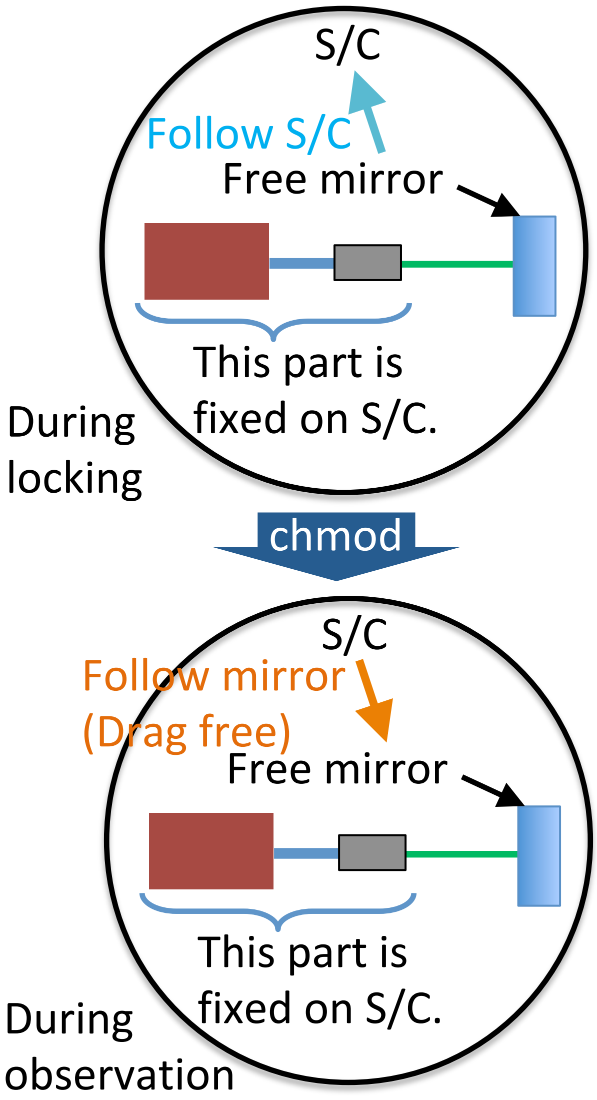


First locking

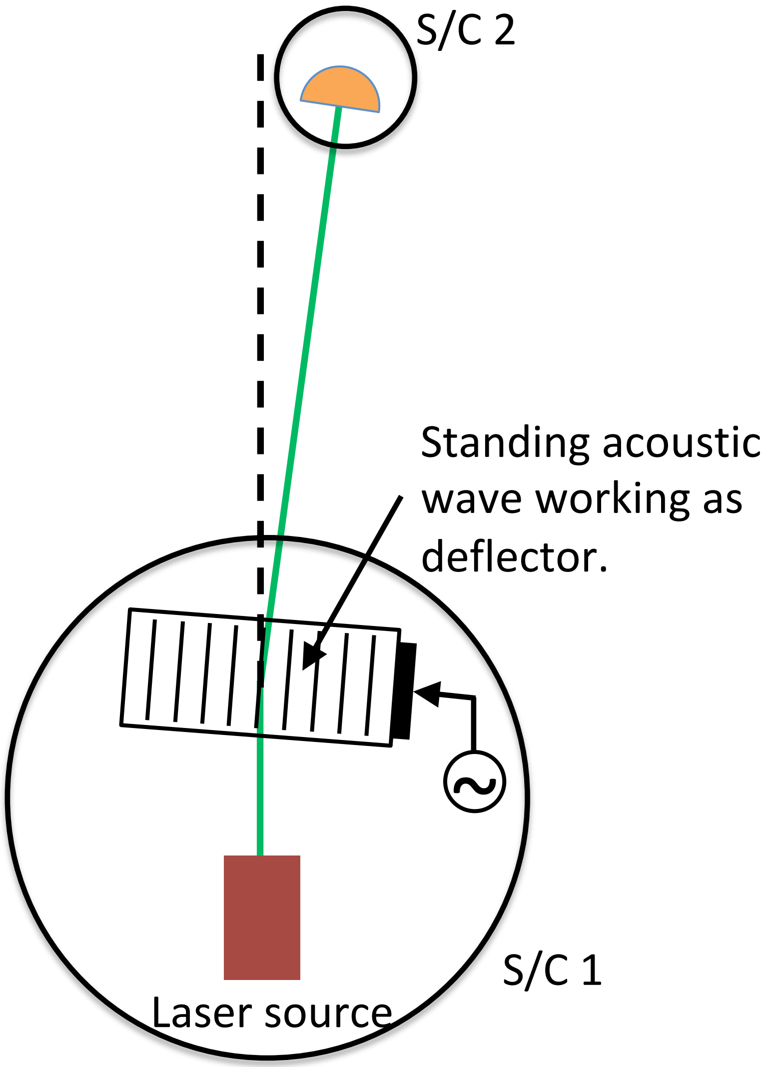
- One thing which is need to be demonstrated is control topology changing according to operation phases.
- In locking phase, the mirrors are controlled to follow S/Cs.
- In observation phase, the S/Cs are controlled to follow mirrors.

  = Drag free control



First locking

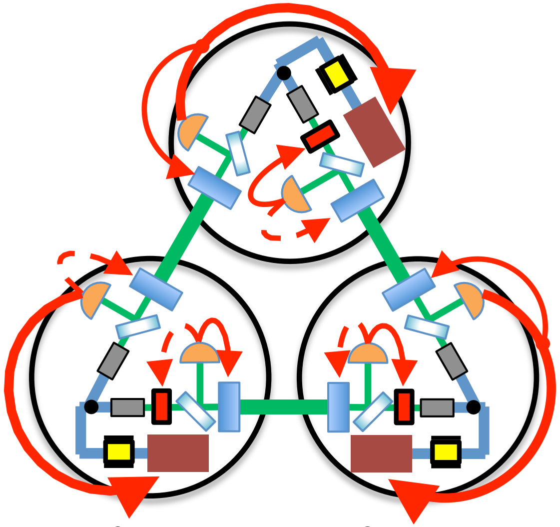
- In each phase, different techniques and schemes will be used.
- For example, AODs technique scanning optical path will be used.



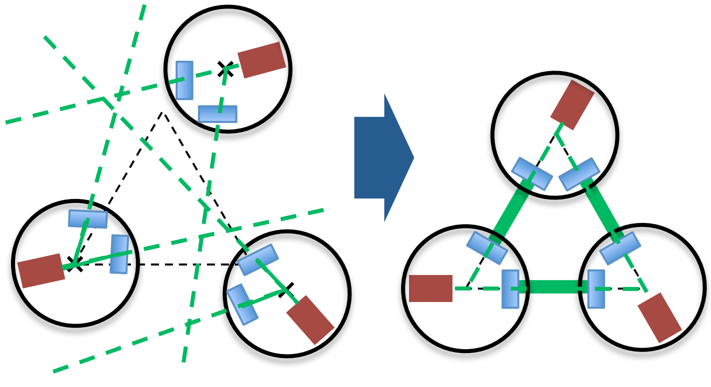
Schematic of AOD tracking technique.

Test bench

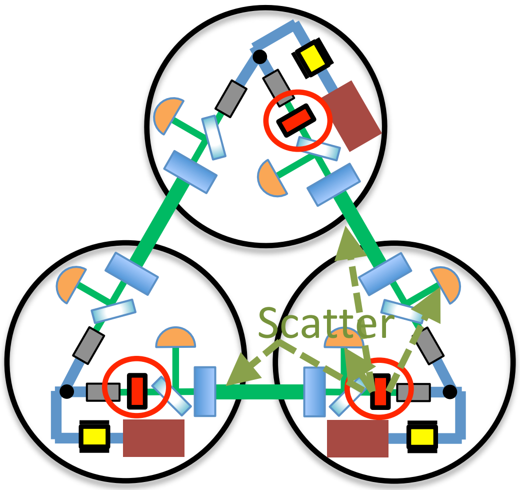
- In space project, all used techniques must be demonstrated before launch.
- We plan to construct test bench will be constructed in Lab especially for demonstrating interferometer configuration, initial locking scheme, and their practical problems.



Interferometer configuration.



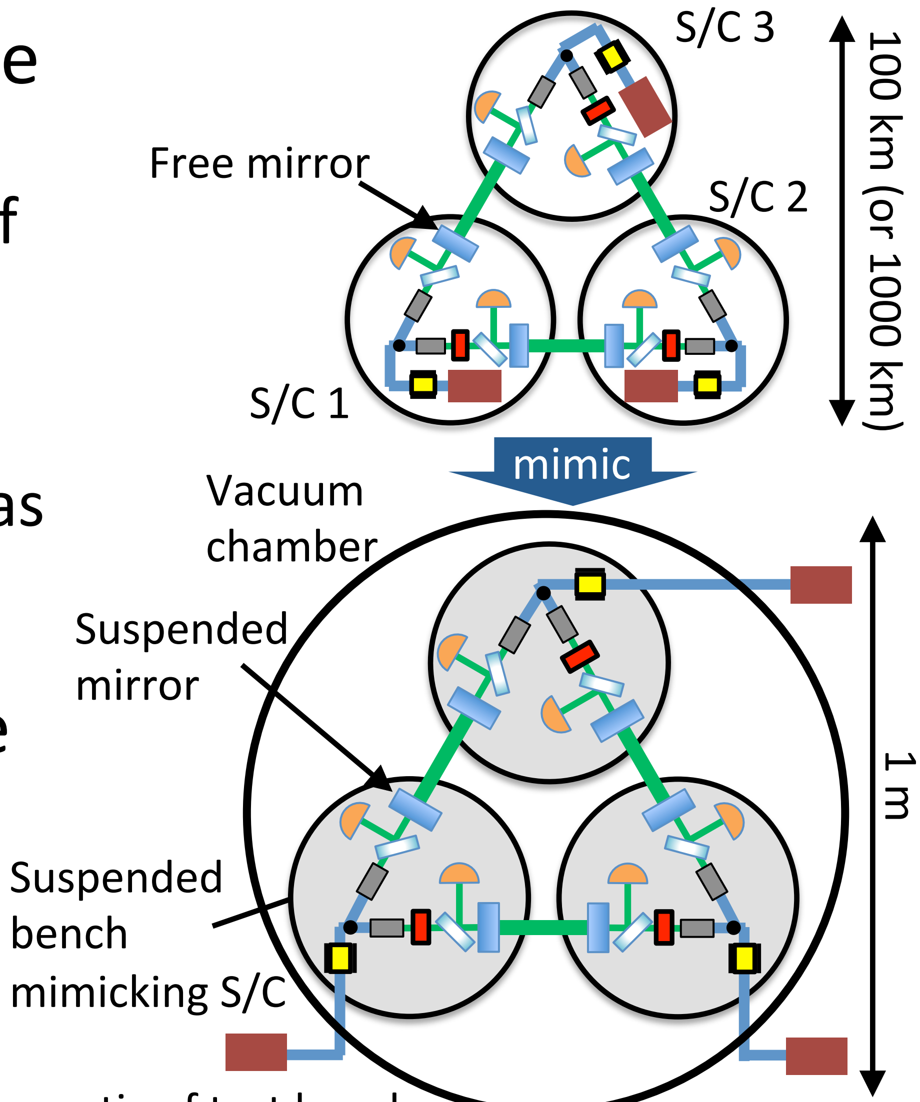
Initial locking scheme.



AOD scattering problem.

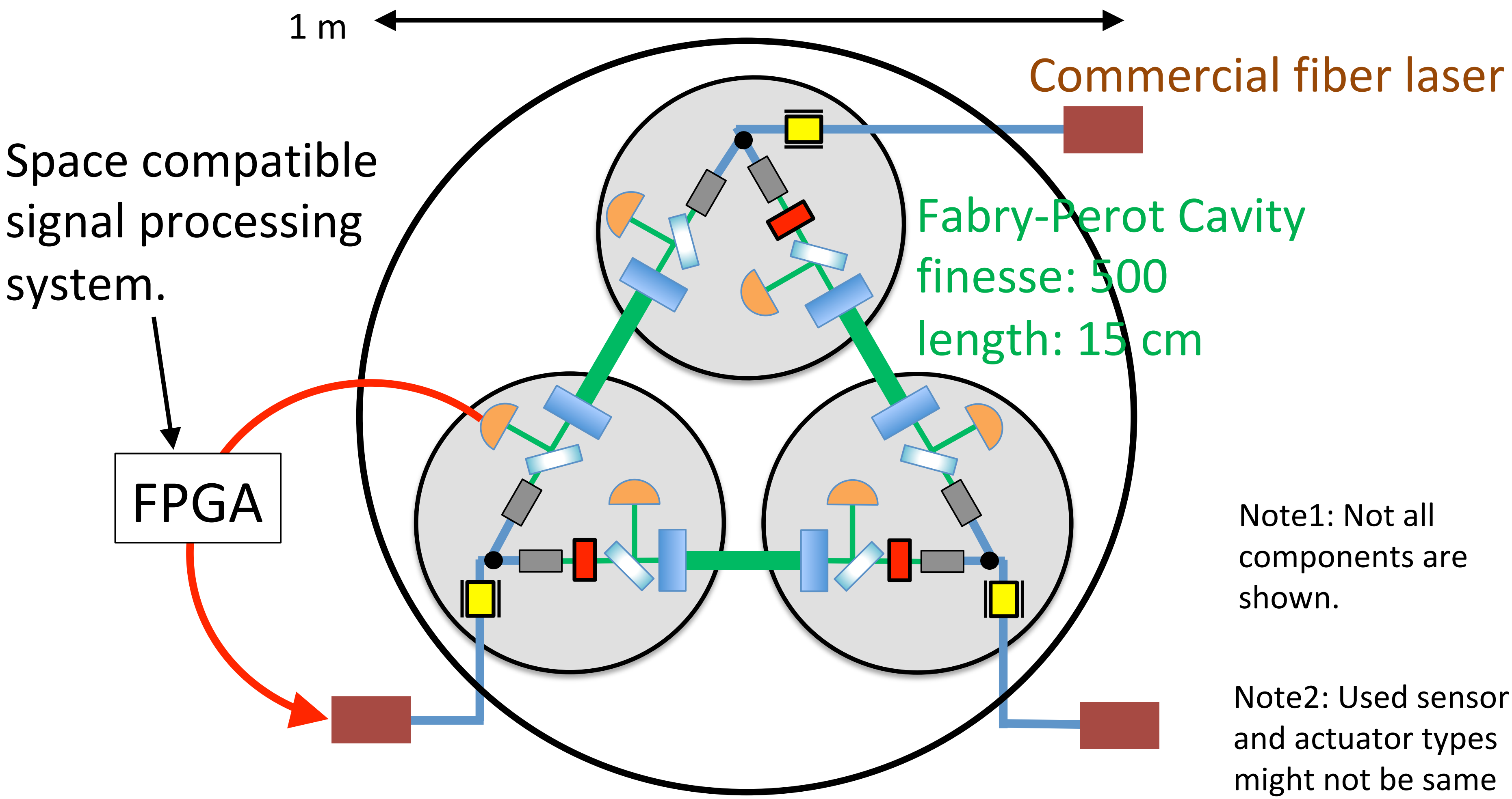
Test bench

- Test bench should have the following features.
  - Having the same topology of sensors/actuators and interferometer as the real detector.
  - Make DoFs soft as possible as we can in ground to mimic the free S/Cs.
- In addition, we plan to use this test bench for integration test for the components developed independently.



Schematic of test bench.

Test bench concept



Note1: Not all components are shown.

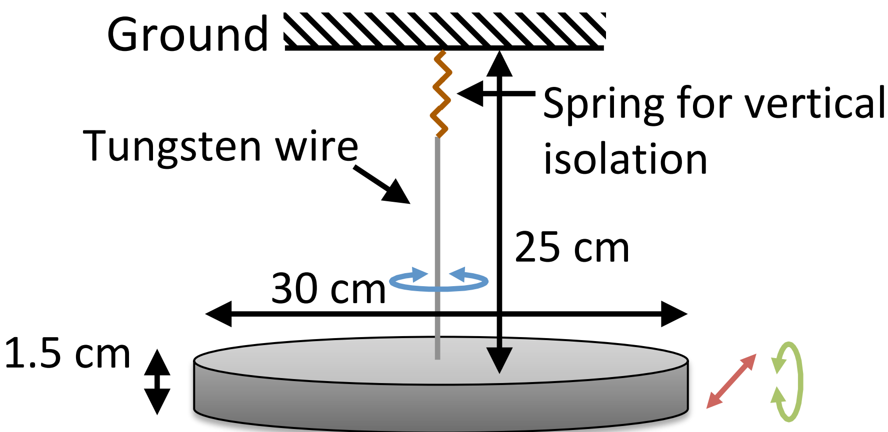
Note2: Used sensor and actuator types might not be same as the real detector.

Local sensors
- Optical levers and photo sensors

Actuators
- Coil-magnet actuators

Test bench suspension

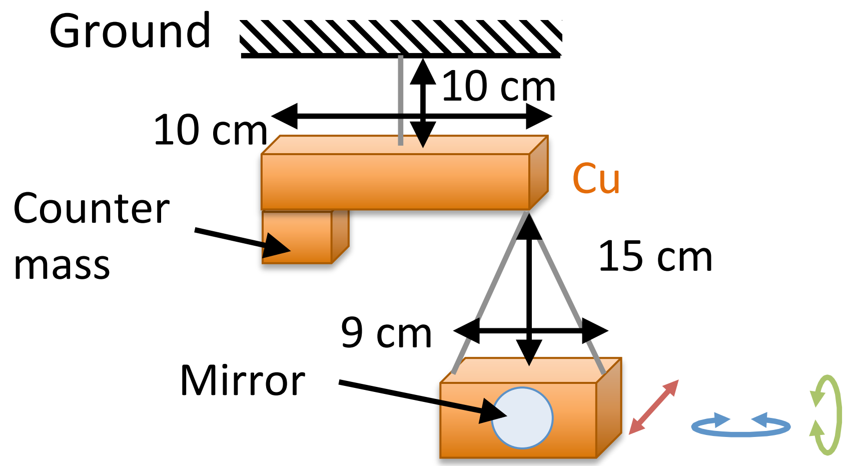
- Optical bench



Resonant frequency

- Pitch/Roll: 0.086 Hz
- Yaw: 0.012 Hz
- Transverse: 1 Hz

- Mirror



Resonant frequency

- Pitch: 0.05 Hz
- Yaw: 0.1 Hz
- Transverse: 0.02 Hz

Summary

- For DECIGO and B-DECIGO, the interferometer configuration and first locking scheme was considered.
- Dual-path Fabry-Perot configuration with AODs is most promising.
- First locking scheme has several challenges such as control topology changing according to locking phases, and so on.
- These must be demonstrated with test bench in lab.
- It can also be used for integration test of developed components.

Appendix

Suspension for mirror in test bench

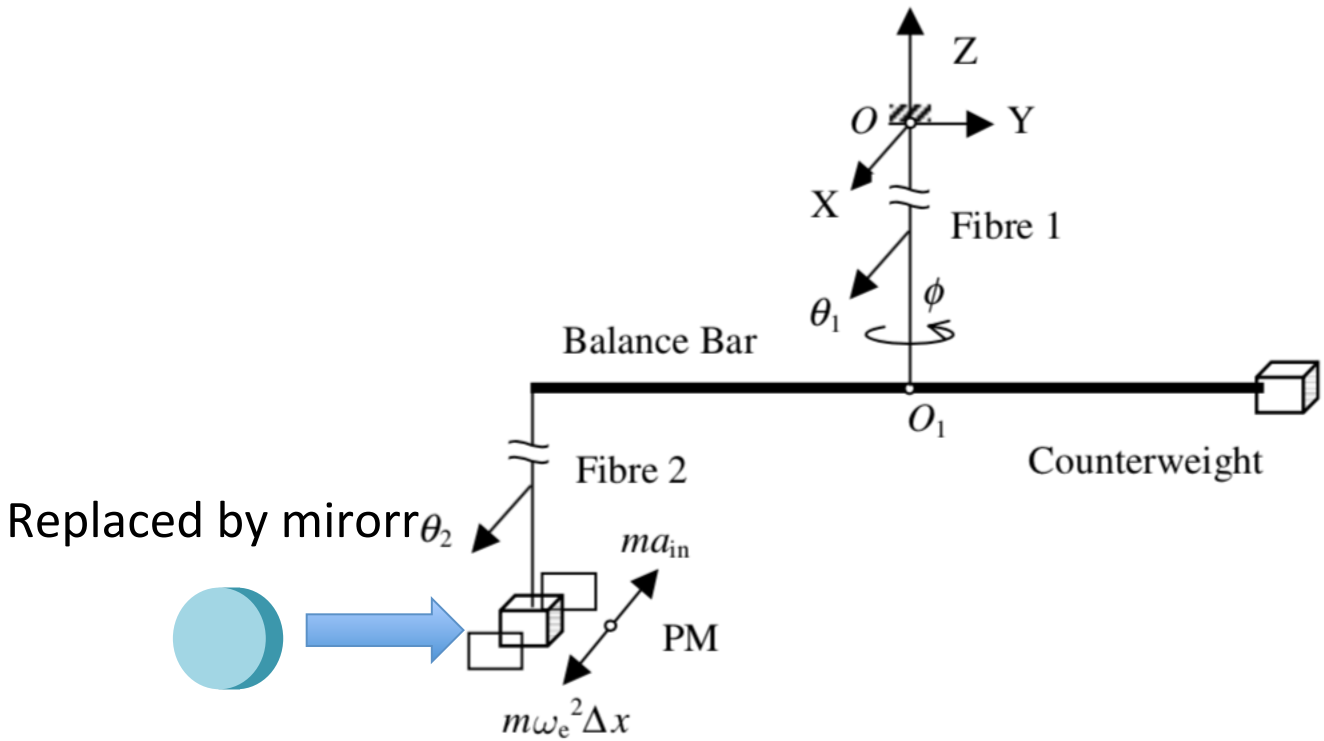
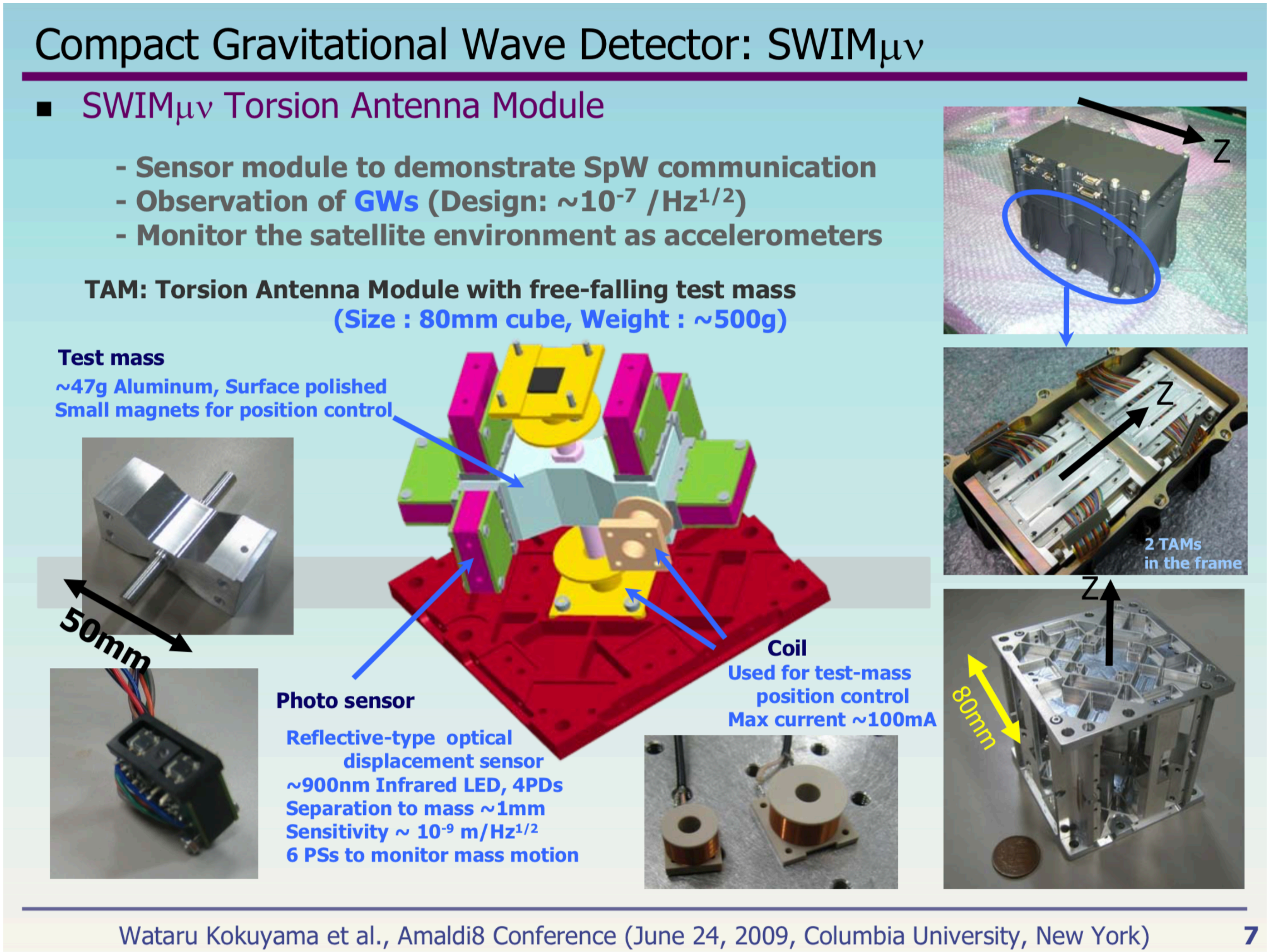


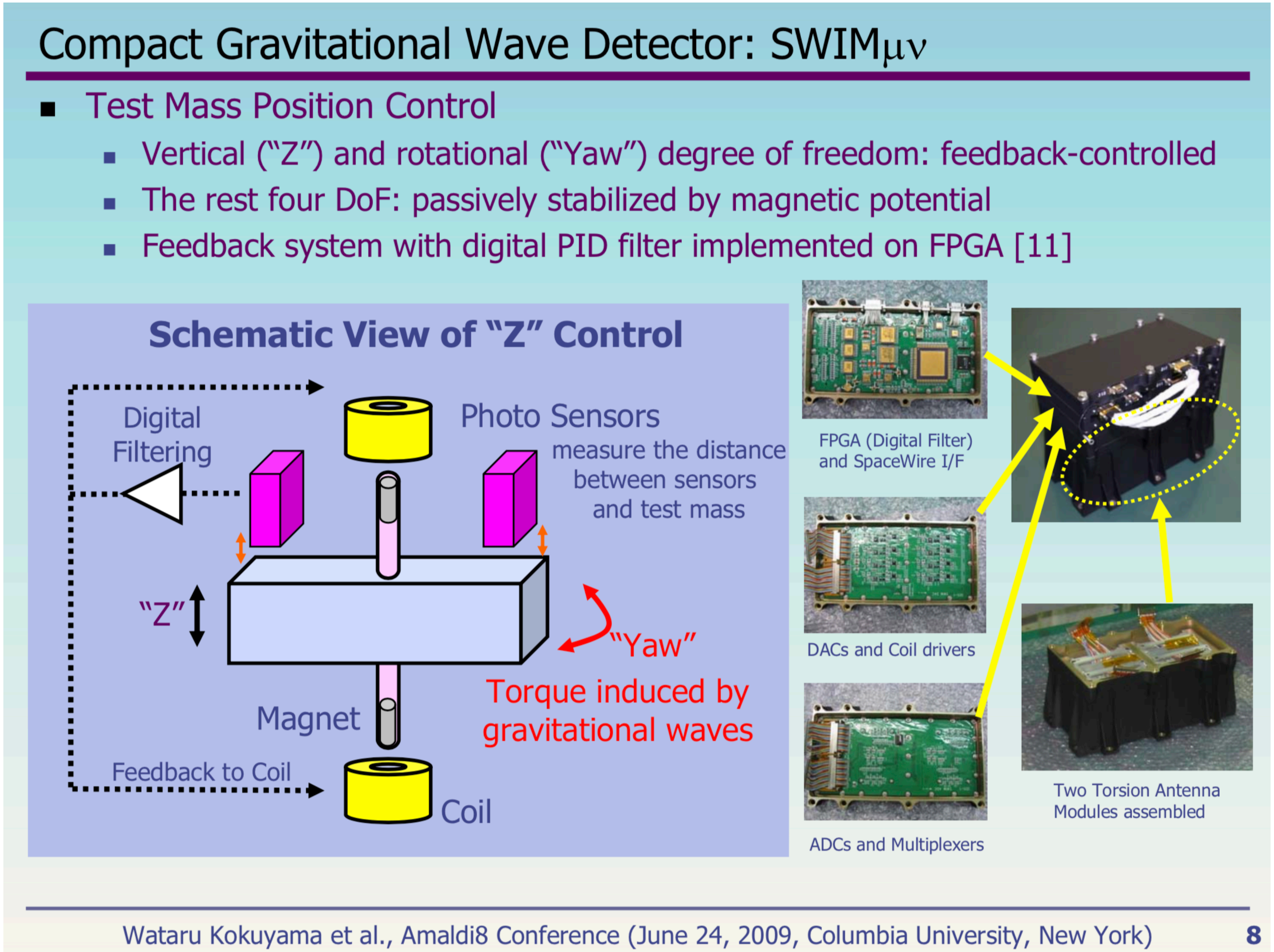
Figure 1. Simplified model of the two-stage torsion pendulum scheme.

System used for development of internal sensor of LISA. (Z B Zhou et al, *CQG* **27** (2010))

SWIM

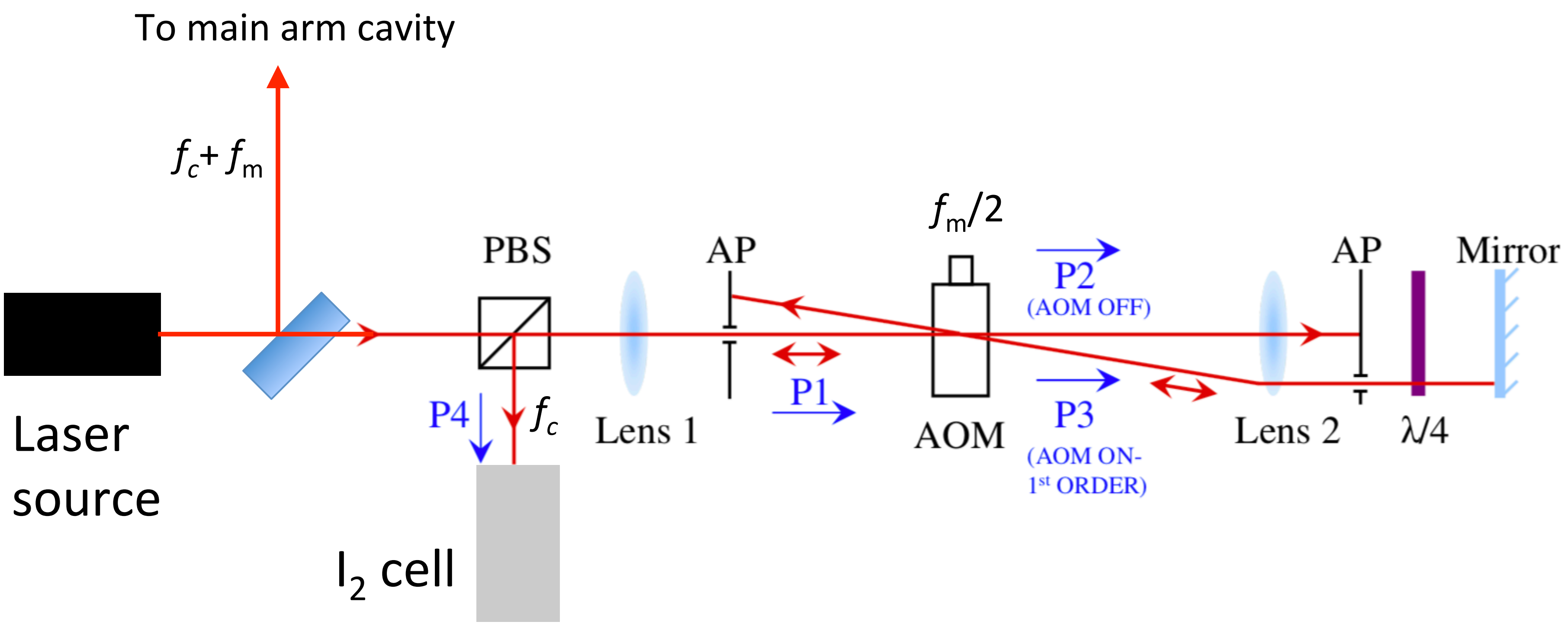

Compact Gravitational Wave Detector: SWIMμν
SWIMμν Torsion Antenna Module
- Sensor module to demonstrate SpW communication
- Observation of GWs (Design: ~10⁻⁷ /Hz^1/2)
- Monitor the satellite environment as accelerometers
TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)
Test mass
~47g Aluminum, Surface polished
Small magnets for position control
50mm
Photo sensor
Reflective-type optical displacement sensor
~900nm Infrared LED, 4PDs
Separation to mass ~1mm
Sensitivity ~ 10⁻⁹ m/Hz^1/2
6 PSs to monitor mass motion
Coil
Used for test-mass position control
Max current ~100mA
Z
2 TAMs in the frame
80mm
Wataru Kokuyama et al., Amaldi8 Conference (June 24, 2009, Columbia University, New York)
7

SWIM



Compact Gravitational Wave Detector: SWIMμν
Test Mass Position Control
Vertical ("Z") and rotational ("Yaw") degree of freedom: feedback-controlled
The rest four DoF: passively stabilized by magnetic potential
Feedback system with digital PID filter implemented on FPGA [11]
Schematic View of "Z" Control
Digital Filtering
Photo Sensors
measure the distance between sensors and test mass
"Z"
"Yaw"
Magnet
Torque induced by gravitational waves
Feedback to Coil
Coil
FPGA (Digital Filter) and SpaceWire I/F
DACs and Coil drivers
ADCs and Multiplexers
Two Torsion Antenna Modules assembled
Wataru Kokuyama et al., Amaldi8 Conference (June 24, 2009, Columbia University, New York)
8

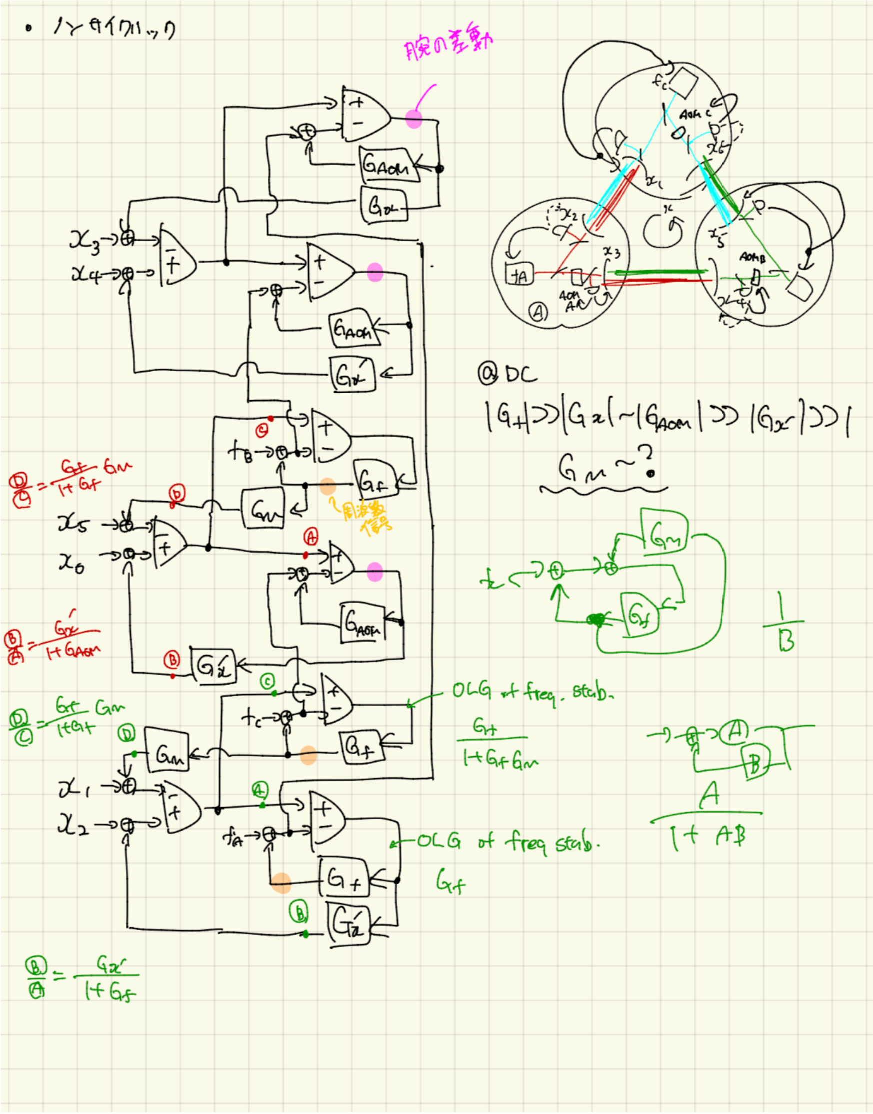
Frequency shift



Double path AOM system [1].

[1] D. J. McCarron, “A Guide to Acousto-Optic Modulators”

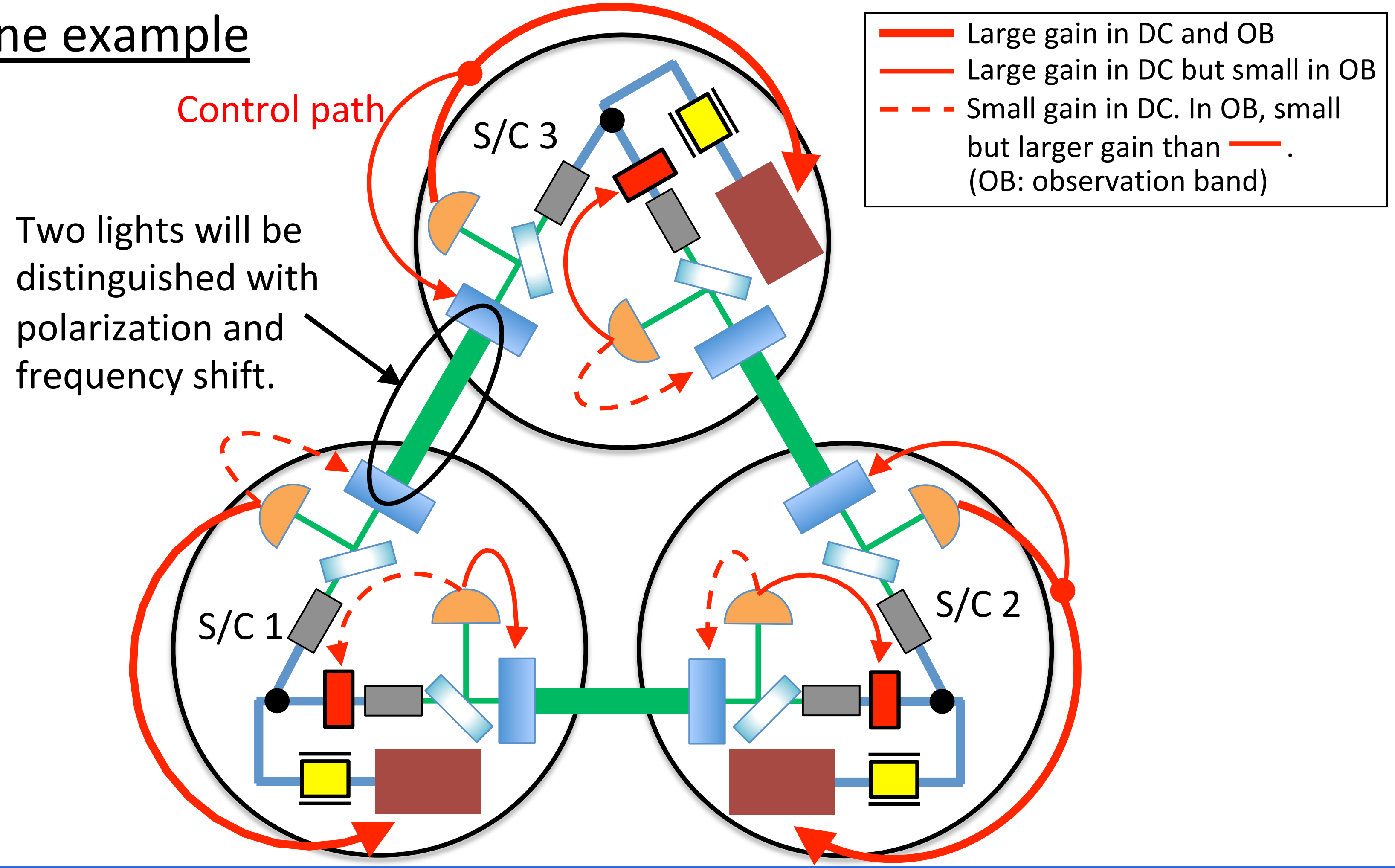
Block diagram of interferometer control



Interferometer configuration

- Several possibilities are considered.

<u>One example</u>



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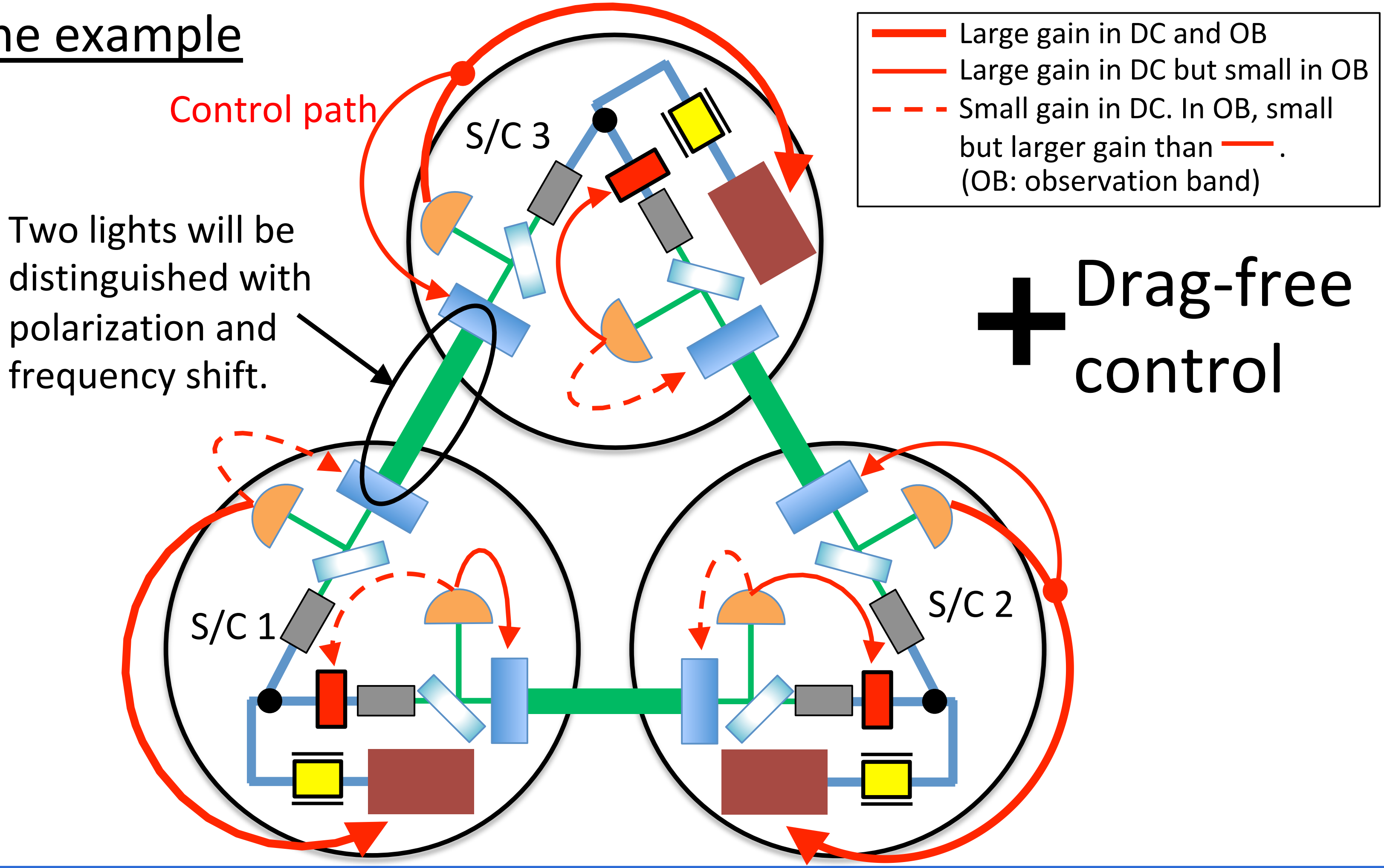
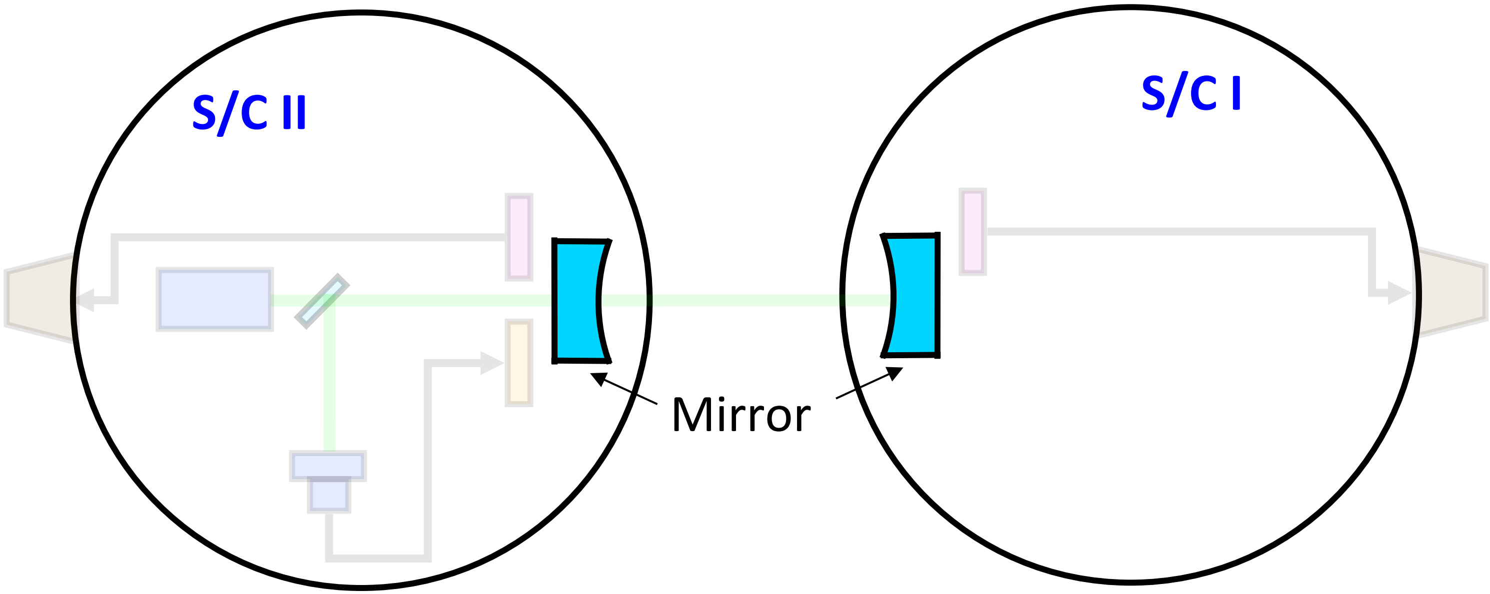


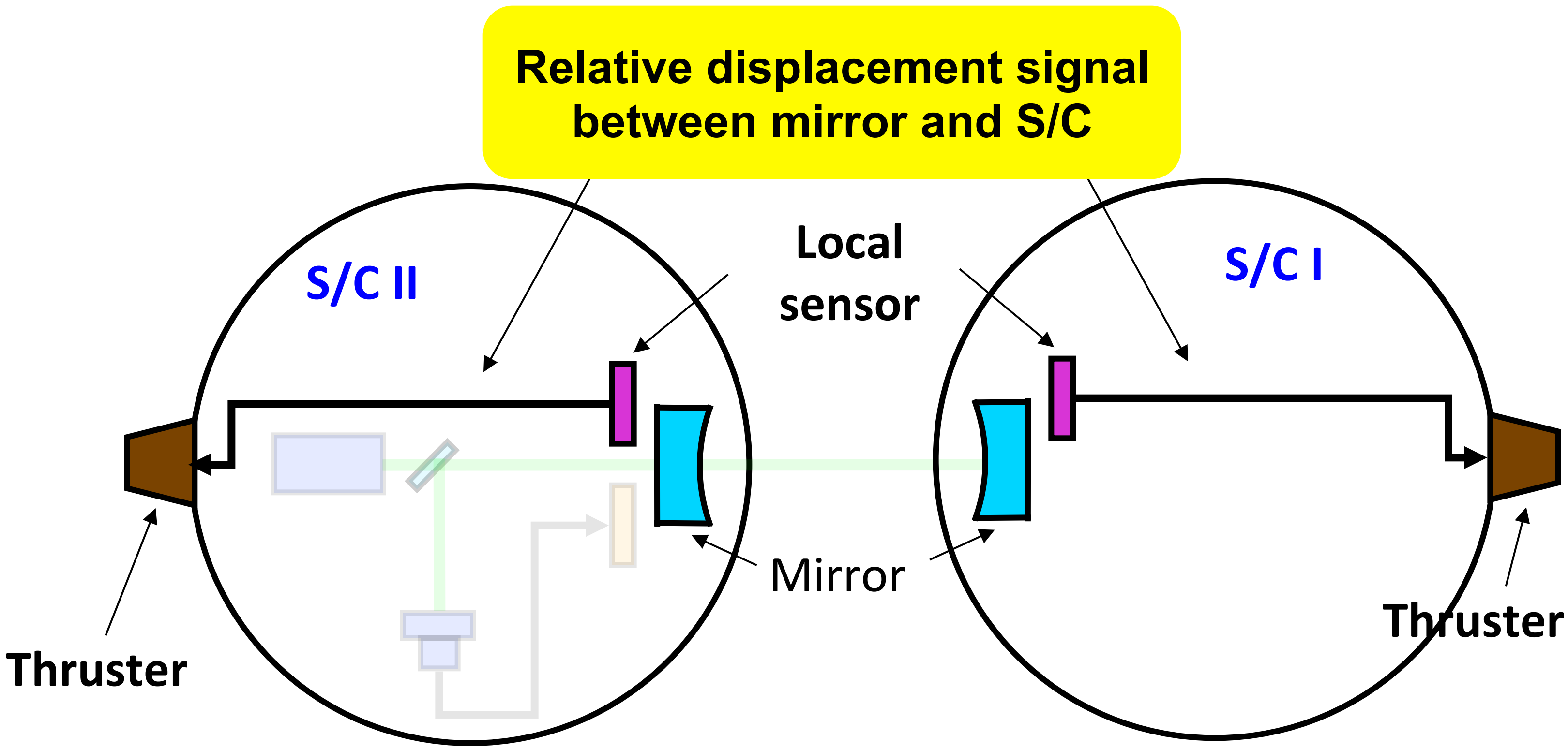
+ Drag-free control

Does a drag-free S/C consort with an optical cavity?



Made by S. Kawamura.

Does a drag-free S/C consort with an optical cavity?



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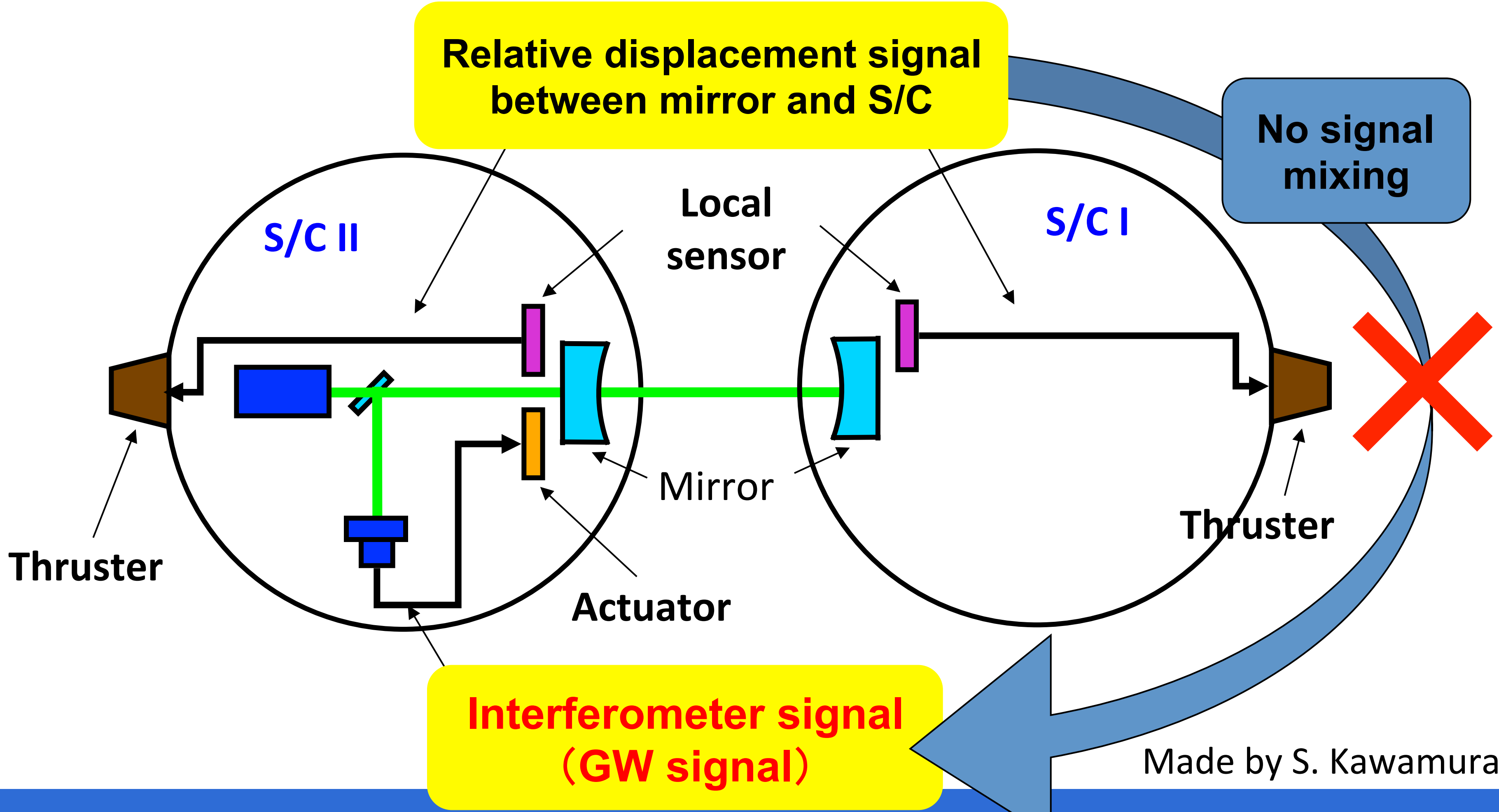

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