Disturbance Reduction System
A Proposed Space Demonstration of Drag-Free Technology[1]

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October 19, 2001

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[1] The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Web posted at http://www.cco.caltech.edu/~cajagwr

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Disturbance Reduction System

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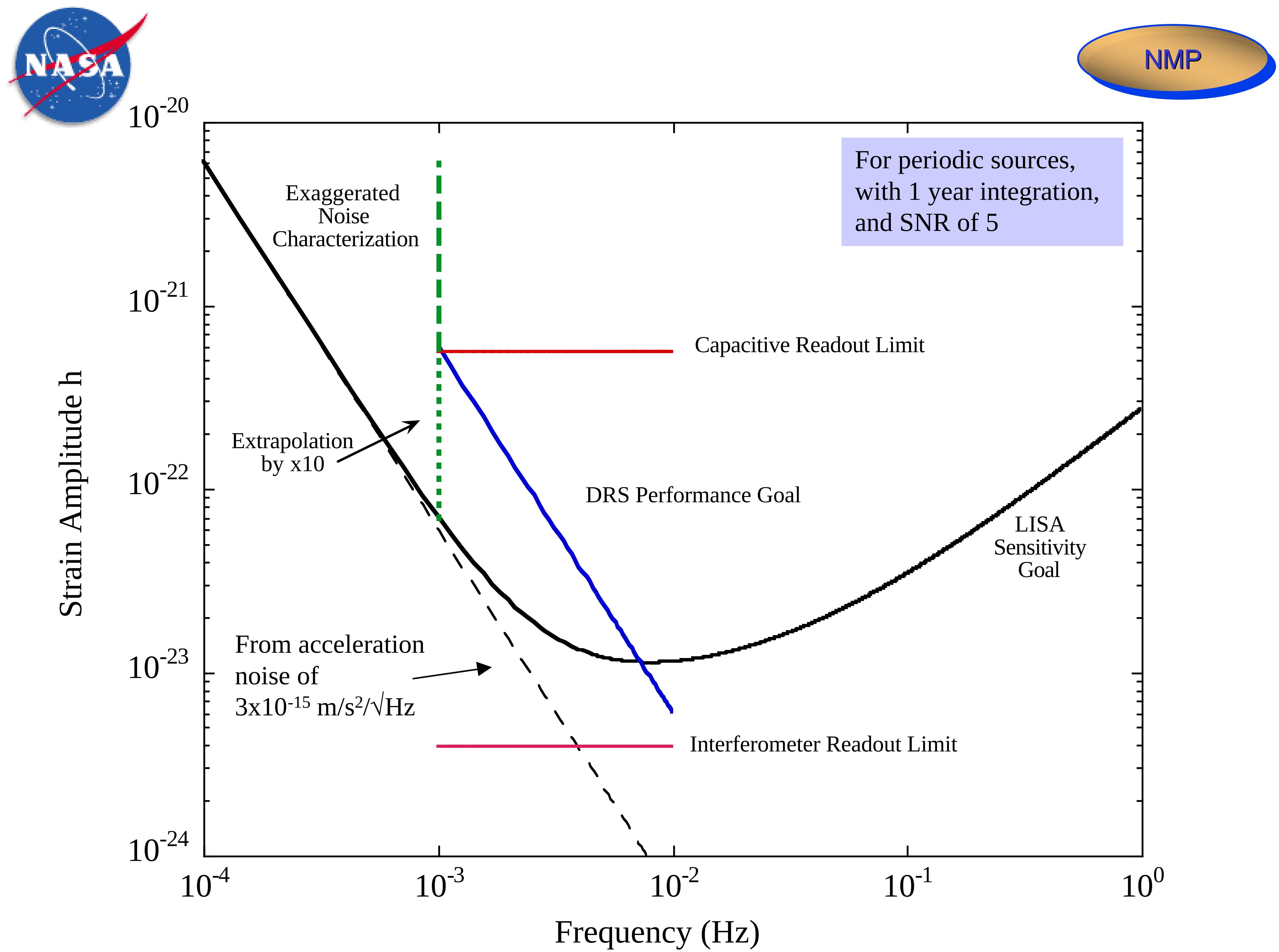
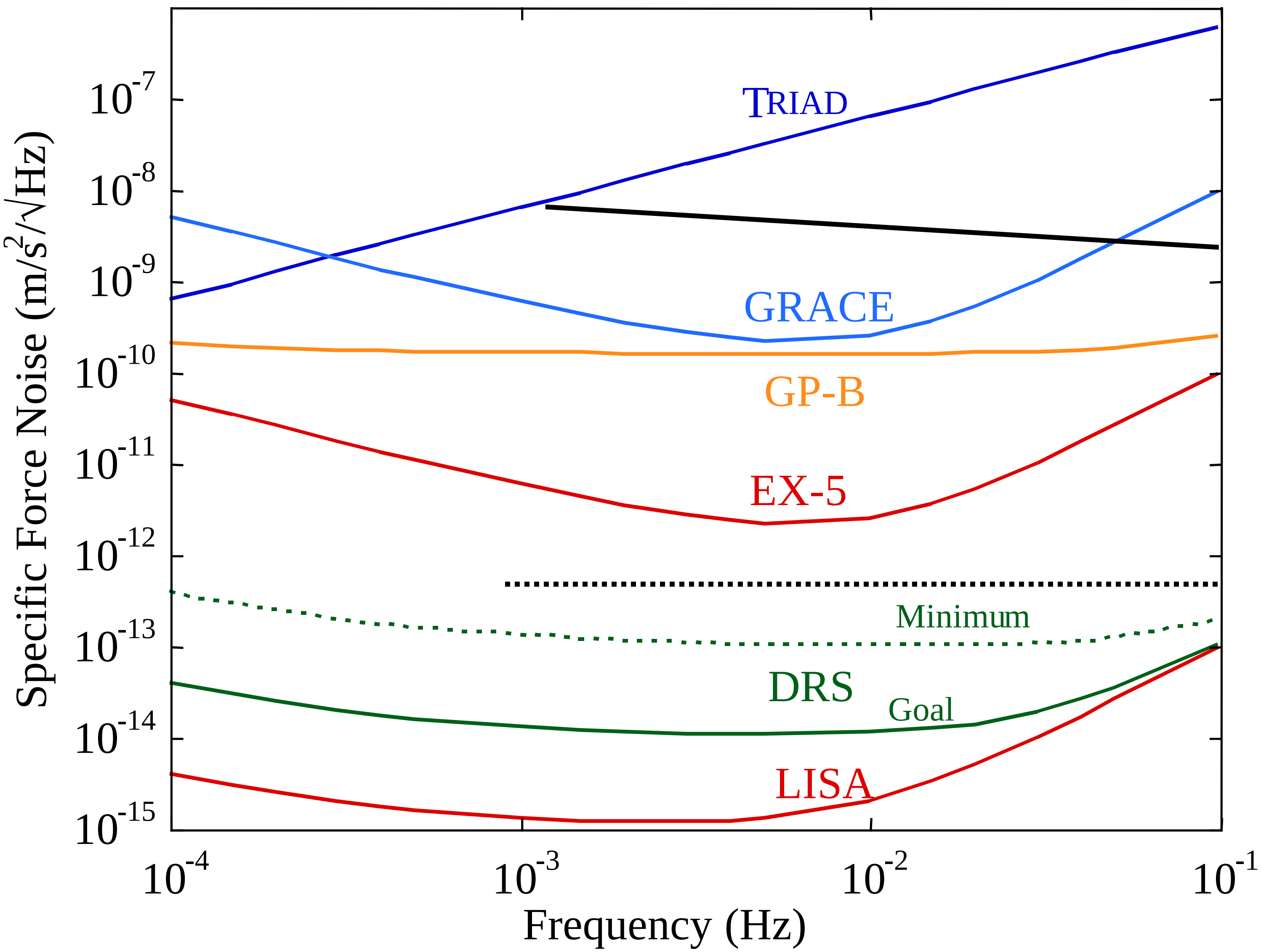
California Institute of Technology

19 October 2001

- **LISA measures changes of distance between test masses separated by 5 million km**
- **Displacement noise on test masses limits sensitivity at low frequency**
- **Displacement noise is caused by forces (not vibration)**
  - Magnetic
  - Electrostatic
  - Thermal
  - Gas Pressure
  - Gravity (from spacecraft)
- **LISA goal is about one million times better than so far demonstrated**
- **DRS will demonstrate performance within x10 of LISA goal**


NASA
NMP
For periodic sources, with 1 year integration, and SNR of 5
Exaggerated Noise Characterization
Capacitive Readout Limit
Extrapolation by x10
DRS Performance Goal
LISA Sensitivity Goal
From acceleration noise of $3x10^{-15}$ $m/s^2/\sqrt{Hz}$
Interferometer Readout Limit
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Strain Amplitude h
Frequency (Hz)


TRIAD
GRACE
GP-B
EX-5
Minimum
DRS
Goal
LISA
Specific Force Noise (m/s^2/√Hz)
Frequency (Hz)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

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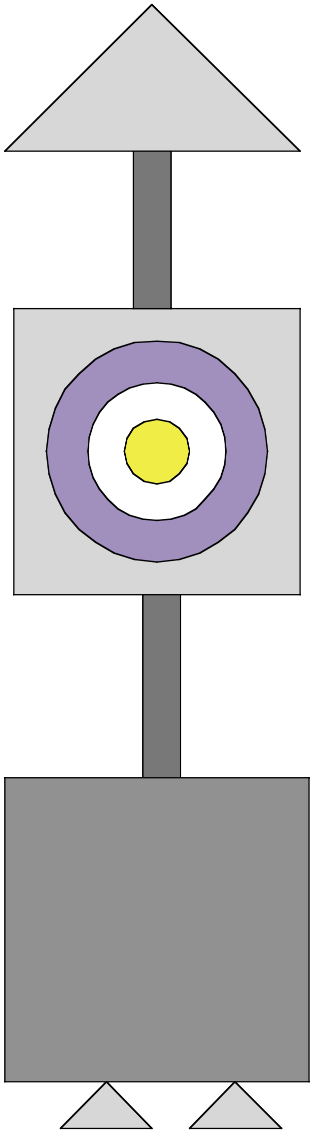
- **TRIAD was launched in 1972 by US Navy as a navigation beacon demonstration**
  - Reference sensor built at Stanford
- **Spherical test mass**
  - Gold-Platinum - nonmagnetic
- **Position of mass sensed optically**
- **1 cm gap between mass and cavity wall**
- **Thrusters fired to keep spacecraft centered on test mass**
- **Drag-free performance demonstation limited by spacecraft tracking accuray, Earth gravity field uncertainty**



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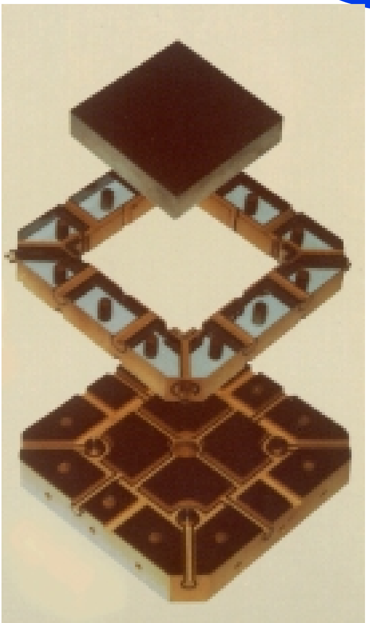
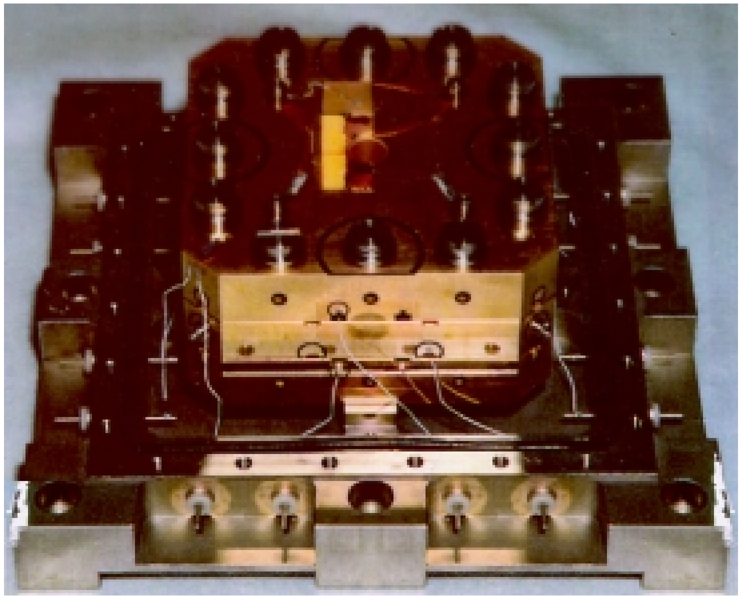
- **GRACE will have 2 spacecraft carrying accelerometers from ONERA**
  - Similar to accelerometer on CHAMP mission
  - Should perform to 10^{-10} m/s^2/$\sqrt{\text{Hz}}$
- **CHAMP launch July 2001**
  - Single spacecraft (similar to GRACE s/c)
  - Some problems with accelerometer
- **GRACE launch February 2002**





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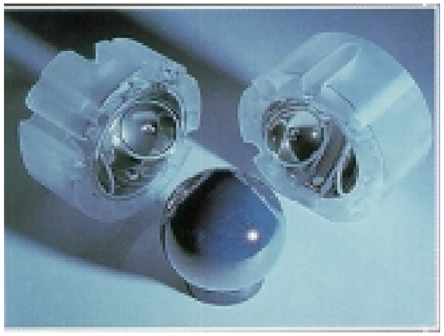
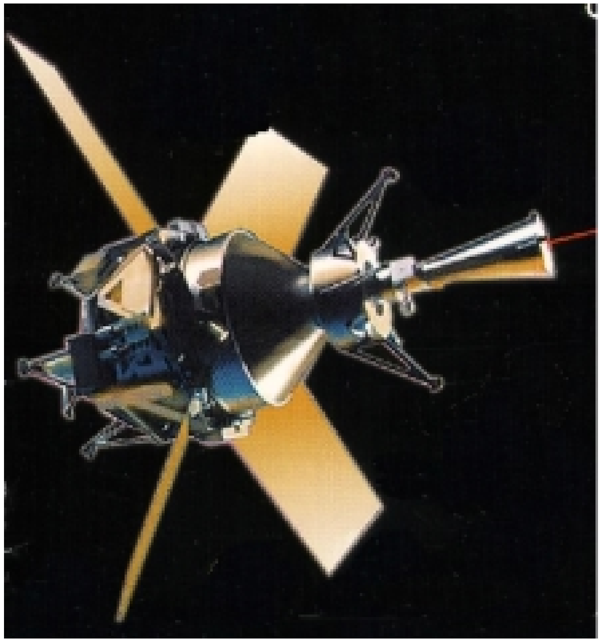
- **GP-B Gyroscope**
  - Spherical quartz test mass coated with nibium
  - Capacitive position measurement of the test mass w.r.t. housing for drag-free control
  - Ultraviolet light used to control charge on test mass

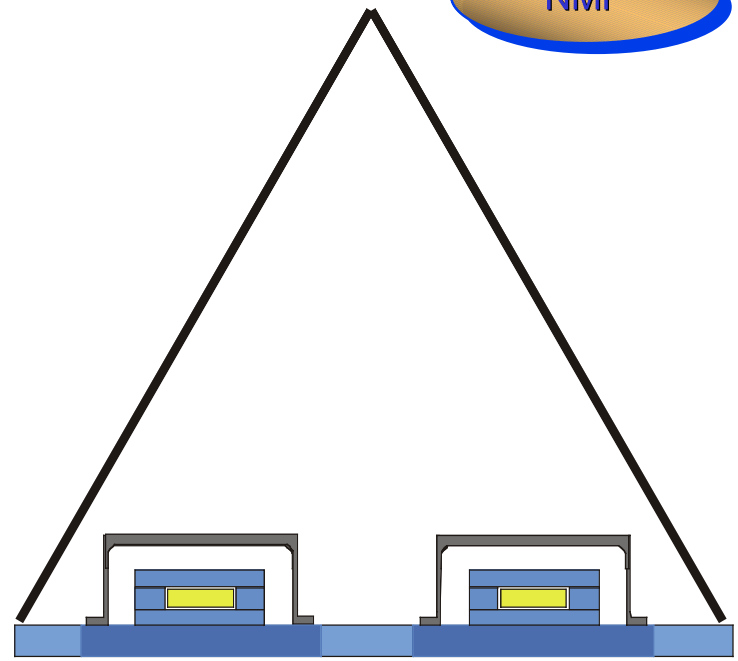


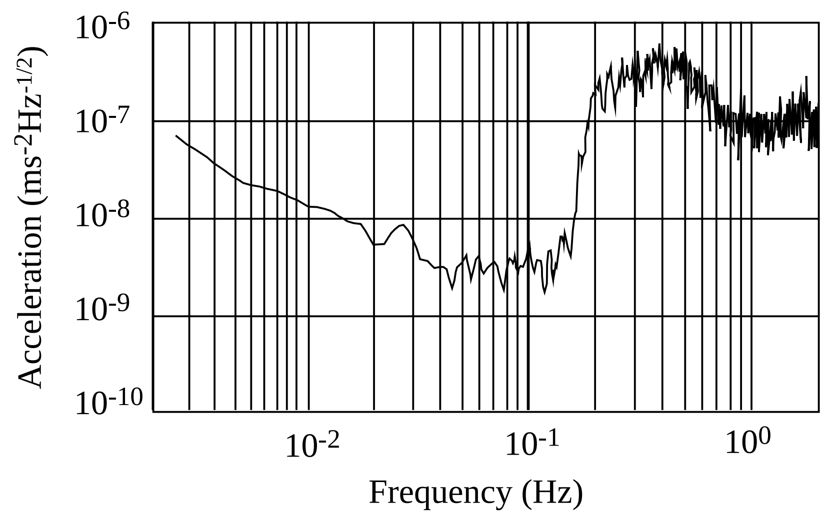
- **Acceleration performance can be measured by comparing two gyroscopes**
  - Accuracy is limited by A/D converter



- **Launch October 2002?**

- **Two accelerometers compared in ground tests at ONERA**
  - Accelerometers mounted on pendulum platform
  - One accelerometer used to control position and orientation of platform
  - Second accelerometer transverse noise measured
  - Noise limited by ability to keep accelerometer vertical
    - Twisting of platform, etc.





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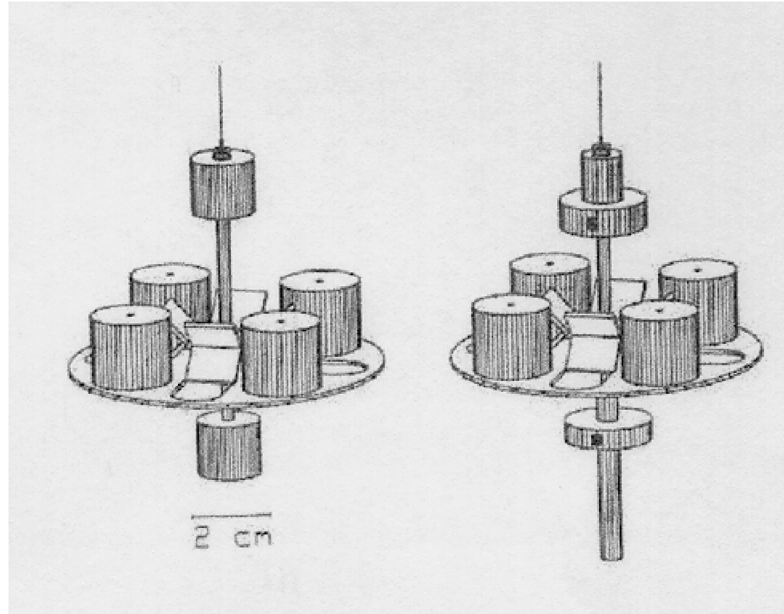
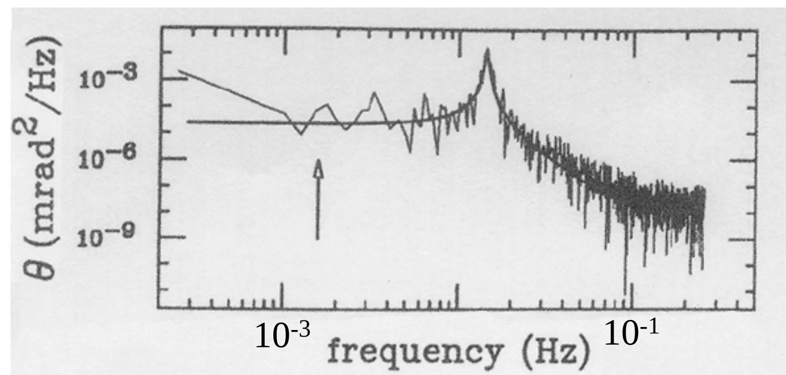
- **The Eöt-Wash torsion balance experiment measures rotational noise in the LISA measurement band**
- **The noise place an upper limit on the force noise on their masses of $5x10^{-13}$ N/√Hz**
  - This is within factor of 200 of LISA noise requirement
- **While not for LISA geometry, it does show low force noise levels can be achieved**

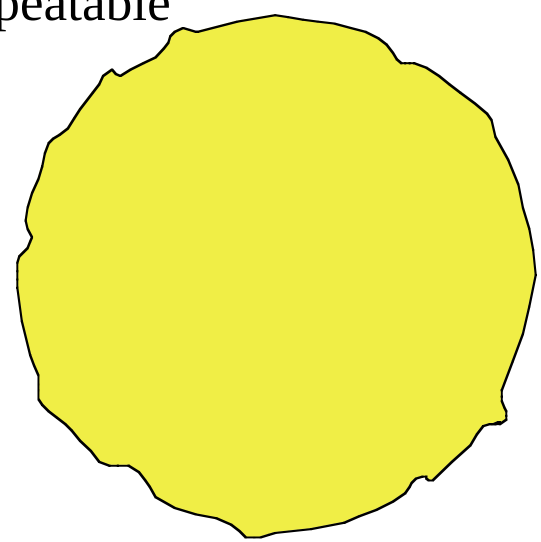




Y. Su et al. Phys Rev. D **50**, 3614

Sphere vs Cube

- **Sphere does not require angular control**
  - Simplifies control system
  - Avoids possible introduction of noise through angular control
    - Might allow larger gaps
      - Potentially lower electrostatic noise
- **Cube provides plane surface for laser reflection**
  - Imperfect at picometer level
    - But position and attitude can be controlled for repeatable measurement
  - Sphere is not round to picometer level
    - Laser beam will wander over surface
      - Rotation of sphere allows average over longitude
      - Variation in latitude not averaged
        - » Extrapolation from GP-B indicates may be okay
        - » Not easily tested (even in DRS)



Position-Dependent Noise

- **Gravity from spacecraft**
  - 1 kg mass 10 cm from test mass gives a gradient of 10^{-7} $m/s^2/m$
  - Motion of spacecraft by 10 nm/√Hz gives acceleration noise of

- **Patch Fields**
  - Voltage potential differences at crystal boundaries trap charges on test mass a surrounding surfaces
  - Relative force

$$\Delta F \approx \sum \frac{\varepsilon_0 S_i v_p}{g_i^3} \cdot \Delta x$$

    - Summed over surfaces S_i, potential v_p, gaps g_i

Magnetic Noise

- **Lorentz Force**
  - Force from charged test mass moving in variable solar magnetic field
  - $\Delta a \sim Qv/m^*\Delta B$
    - For charge Q on test mass at 0.1 of GP-B charge control, and magnetic field fluctuations ΔB in heliocentric orbit
    - Should be at LISA goal
    - Can be shielded electrostatically
- **Magnetic Couple**
  - Force from induced magnetic moment of test mass moving through solar magnetic field
  - $\Delta a \sim 6X_m V B_{sc}/(\mu_o m r_{sc})^*\Delta B$
    - Test mass magnetic moment from susceptibility X_m over volume V induced by spacecraft magnetic field B_{sc} at distance r_{sc}
    - Constrains material choice, magnetic fields on spacecraft

Temperature Noise

- **Gas pressure noise**
  - Noise from changes in gas pressure from temperature fluctuation
  - $\Delta a \sim AP/(2mT)\bullet\Delta T$
  - For cross-sectional area A at gas pressure P and temperature T
  - LISA goal met with $P \sim 10^{-8}$ Torr, $\Delta T<10^{-4}$ K/$\sqrt{\text{Hz}}$

- **Thermal photon pressure**
  - Walls facing test mass cause thermal radiation pressure
  - A change in the difference in the temperature of surrounding walls causes acceleration noise
  - $\Delta a \sim 8A\sigma T^3/(3mc)\bullet\Delta T$ (σ is Stefan-Boltzman constant, c is speed of light)
  - LISA goal met with $\Delta T<<10^{-4}$ K/$\sqrt{\text{Hz}}$

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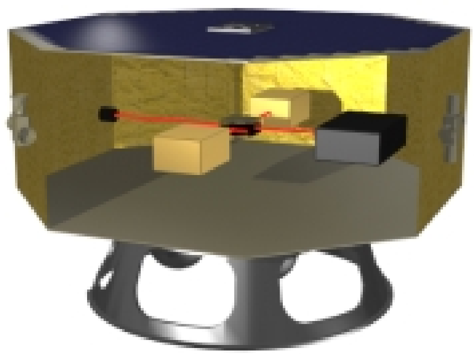
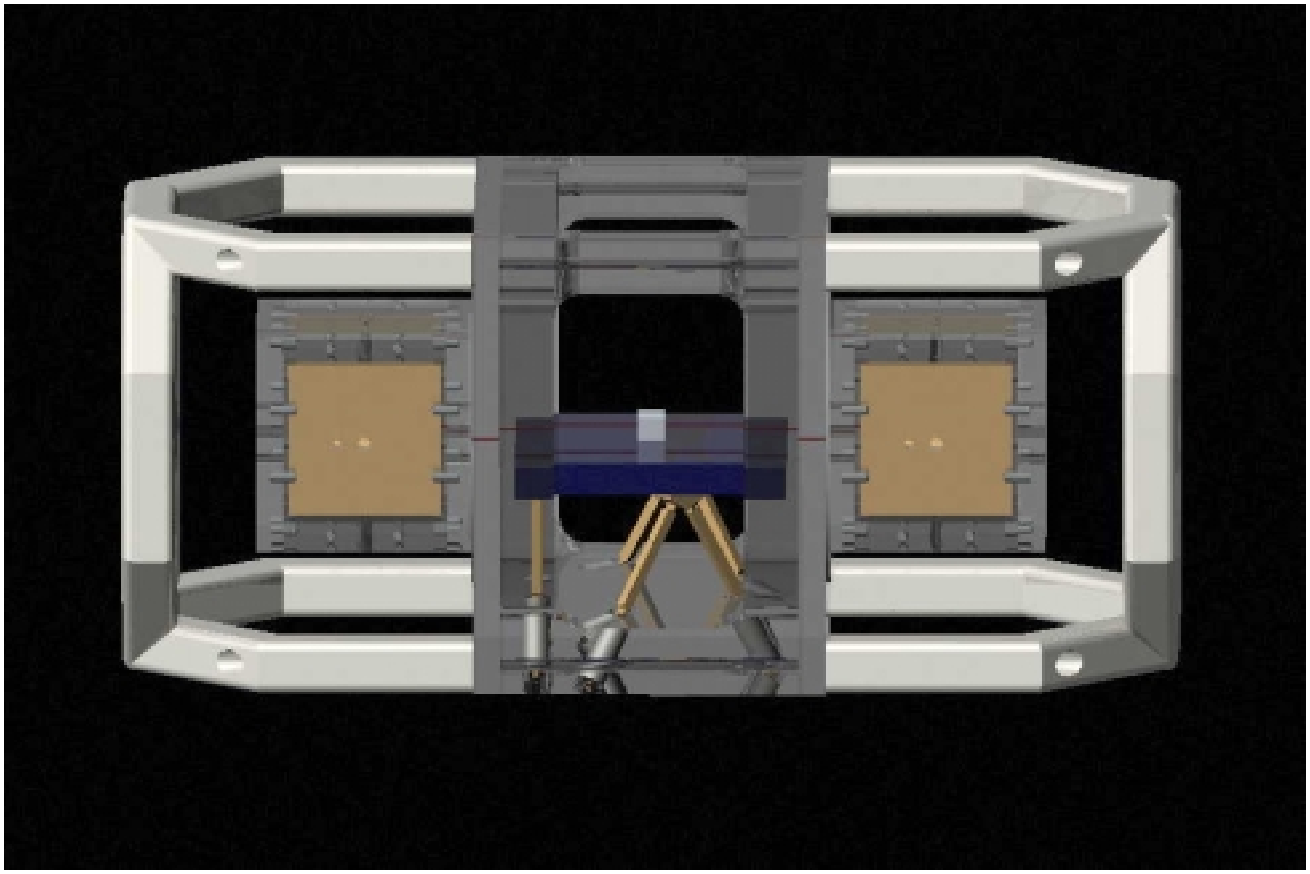
DRS Concept



- **The DRS instrument package consists of**
  - Two gravitational sensors
  - MicroNewton thrusters for spacecraft position control
  - Interferometer to measure the distance between the two test masses.
- **The instrument package will be mounted on a host spacecraft**
  - Primary option is ESA SMART-2 spacecraft
  - Backup is NASA Starlight collector spacecraft
  - Both plan launch in Summer 2006
- **Spacecraft will be launched on an Earth-escape trajectory.**
  - Having the spacecraft far from the Earth is required to reduce effects of gravitational gradients.

Instrument Configuration

- Two inertial sensors, individual vacuum housings.
- Sensors integrated with interferometer



Instrument Configuration (2)

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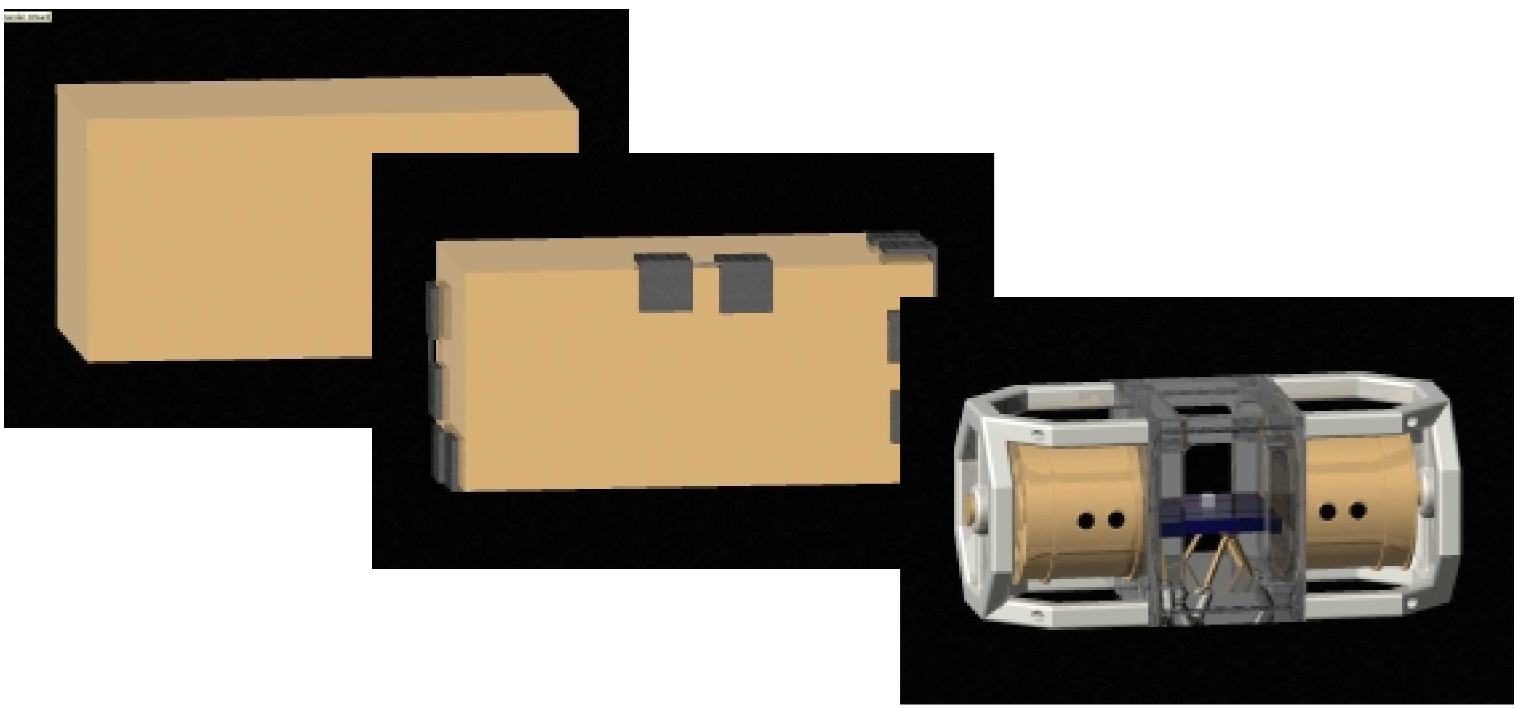
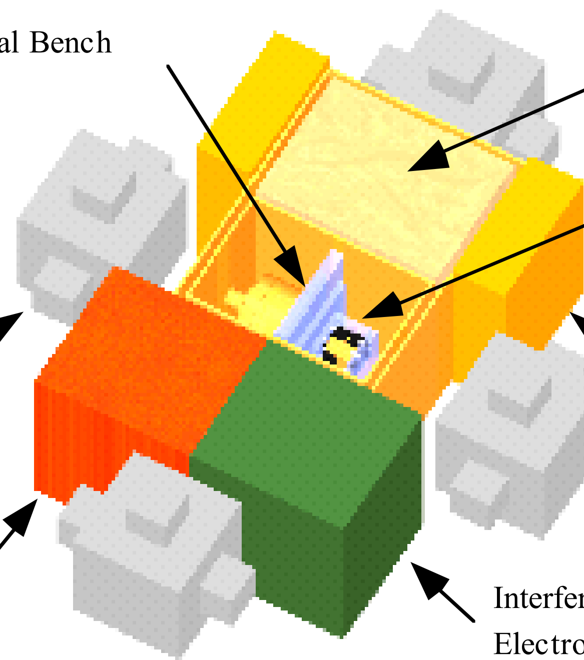
- **GRS and interferometer are in double-wall insulation box**
  - Maintain temperature constant to ~1μK over 1000 seconds
    - No active control no particular average temperature
  - Thermal requirements set by GRS thermal force noise
    - Thermal stability eases interferometer design



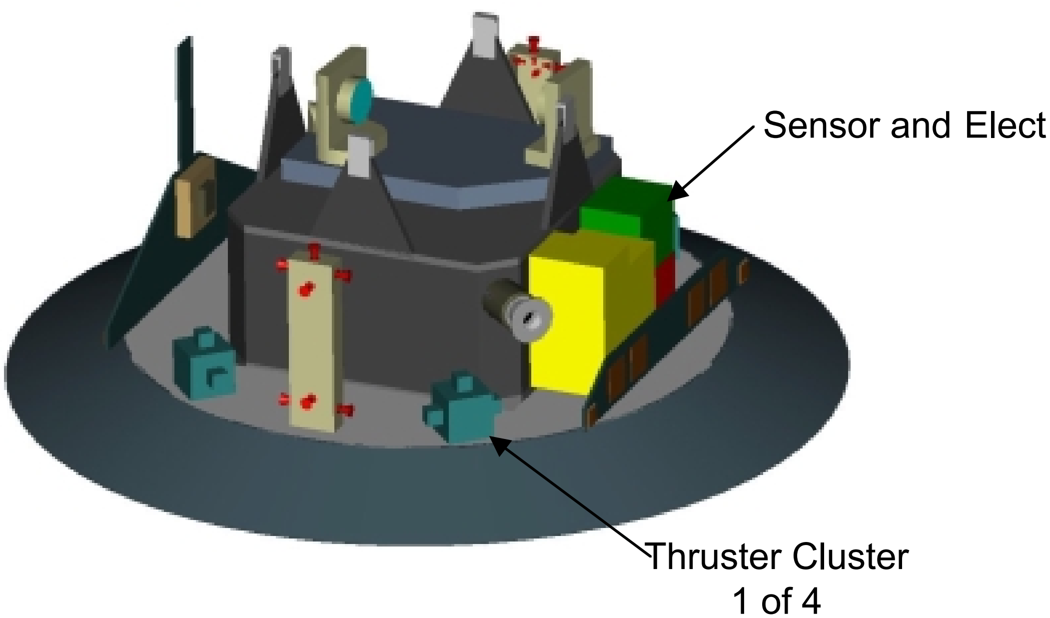
Instrument Configuration (3)

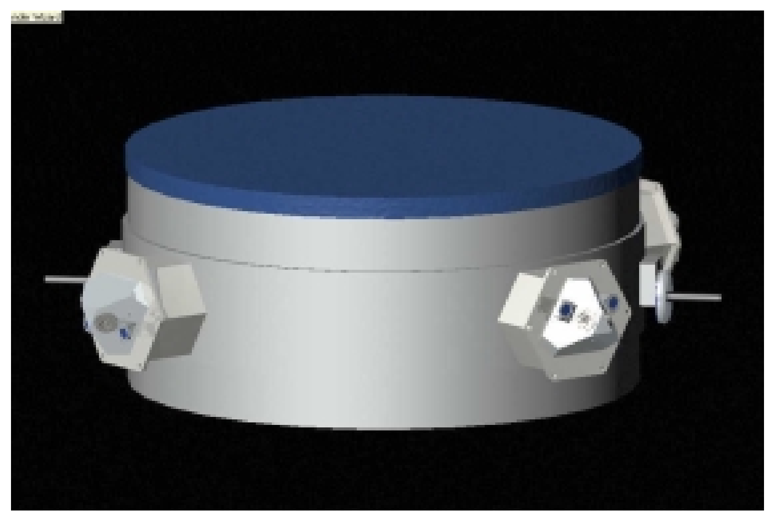
- **DRS system requirement**
  - Mass 65 kg
  - Power 130 W
  - Volume ~ 30 x 40 x 60 cm



DRS Installation on Spacecraft

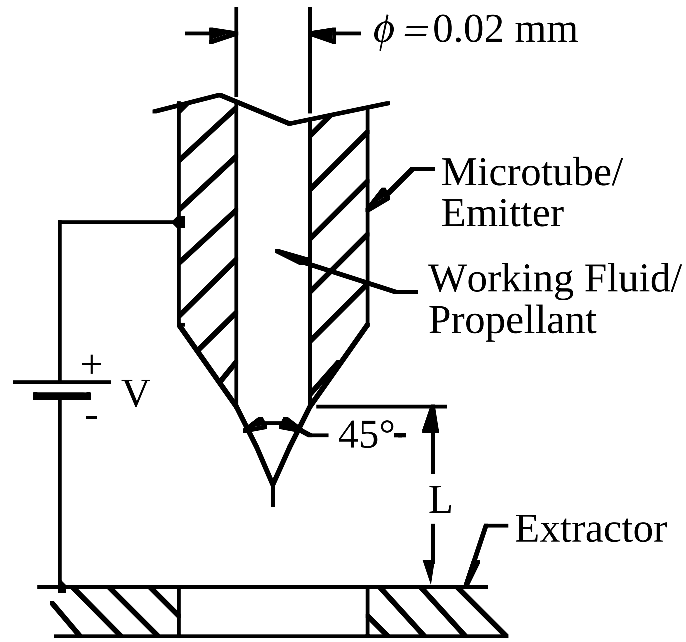
- **Starlight Collector spacecraft can accommodate the DRS instrument and thrusters as shown**
- **Other thruster configurations are being investigated**
  - 4 clusters of 3 thrusters each
  - 4 clusters of 2 thrusters

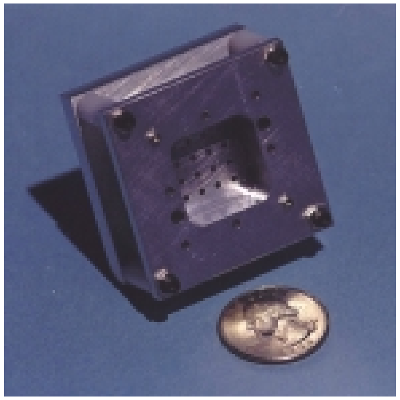


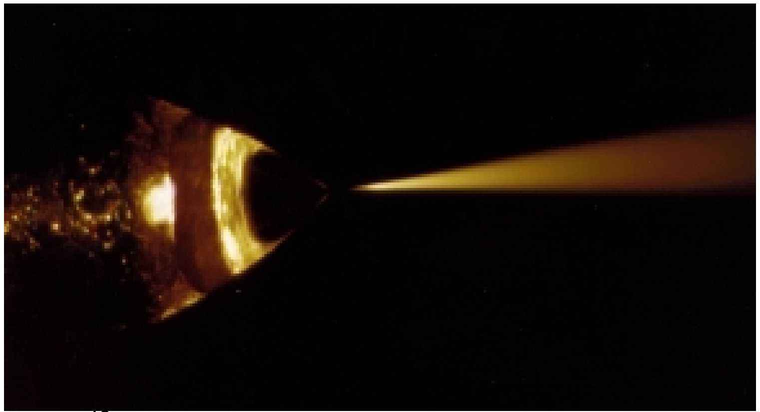


Micro-Newton Thrusters

- **Colloidal thrusters**
  - Fluid fed through fine needle
  - High voltage ionizes droplets
  - Droplets accelerated by high voltage
  - Thrust control of 0.1 μN
    - Through change of voltage
  - Many needles can be combined
    - For necessary maximum thrust
  - Control through proportional thrust
    - Allows precision position control







BUSEK

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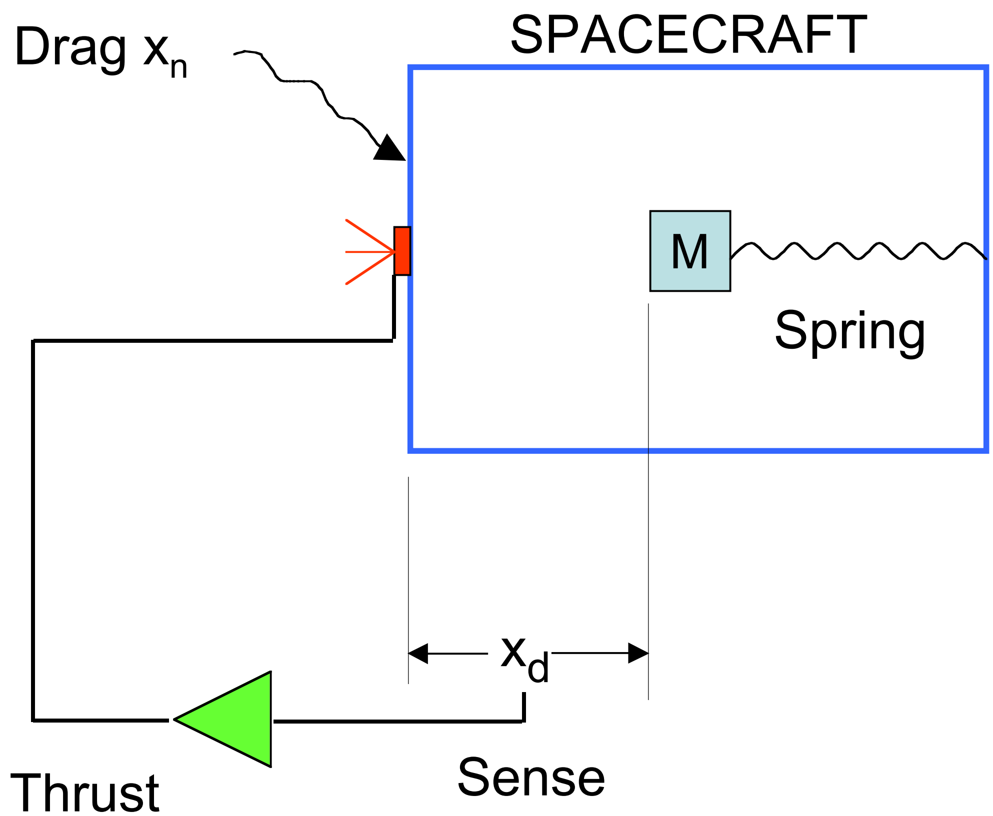
Status

- **DRS being studied for possible selection for Space-Technology 7 project**

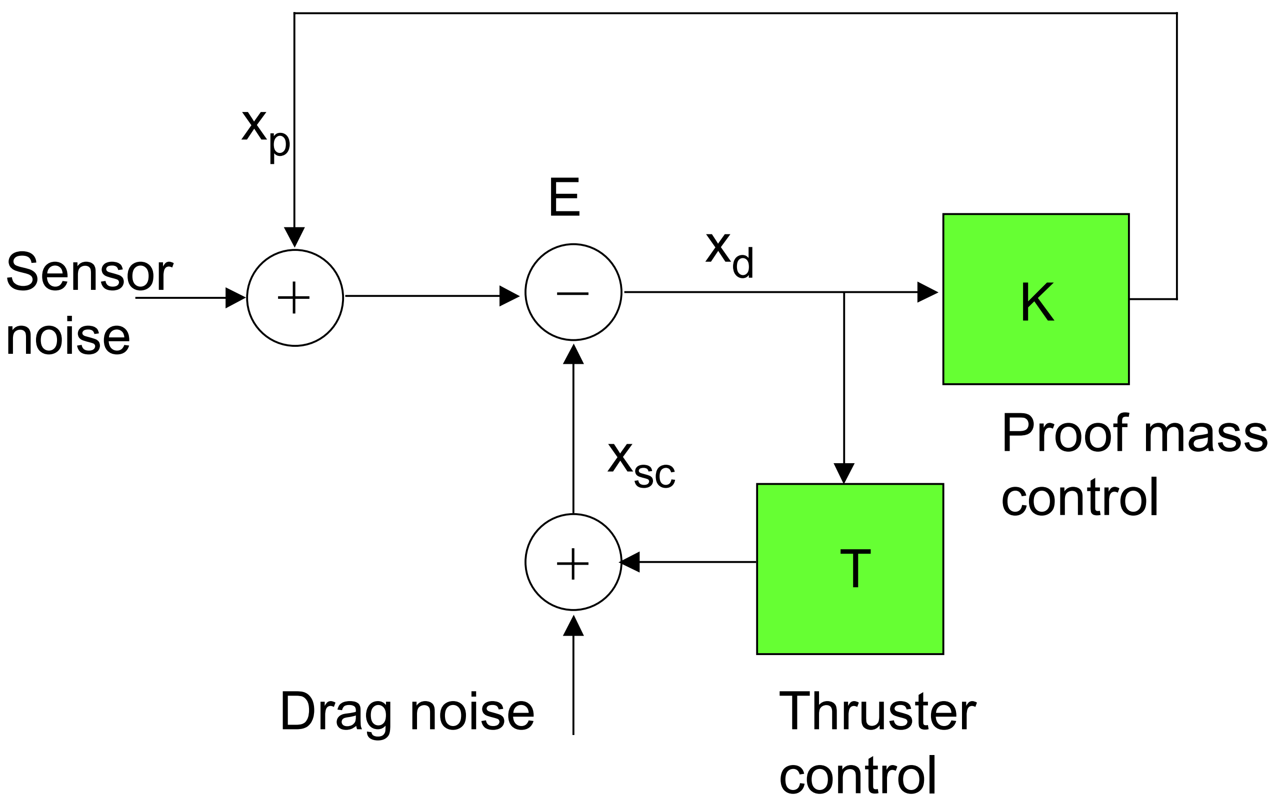
- **Other concepts being studies are**
  - Aerocapture (to save mass for missions going into orbit about planets)
  - Autonomy (to reduce mission operations cost)
  - Solar sail (for lower-mass propulsion)
- **Study report due December 2001**
- **Selection in January 2002**

Drag-Free Control



- Spring is undesirable, but necessary for stability
- Isolation short-circuited by thermal, electrostatic, gravitational forces
- At frequencies where gain is high, spacecraft moves with sensor noise

Noise Model



- E: Electrostatic sensor subtracts spacecraft position x_{sc} from proof mass position x_p
- T: Thruster controller; drives error signal x_d to 0.

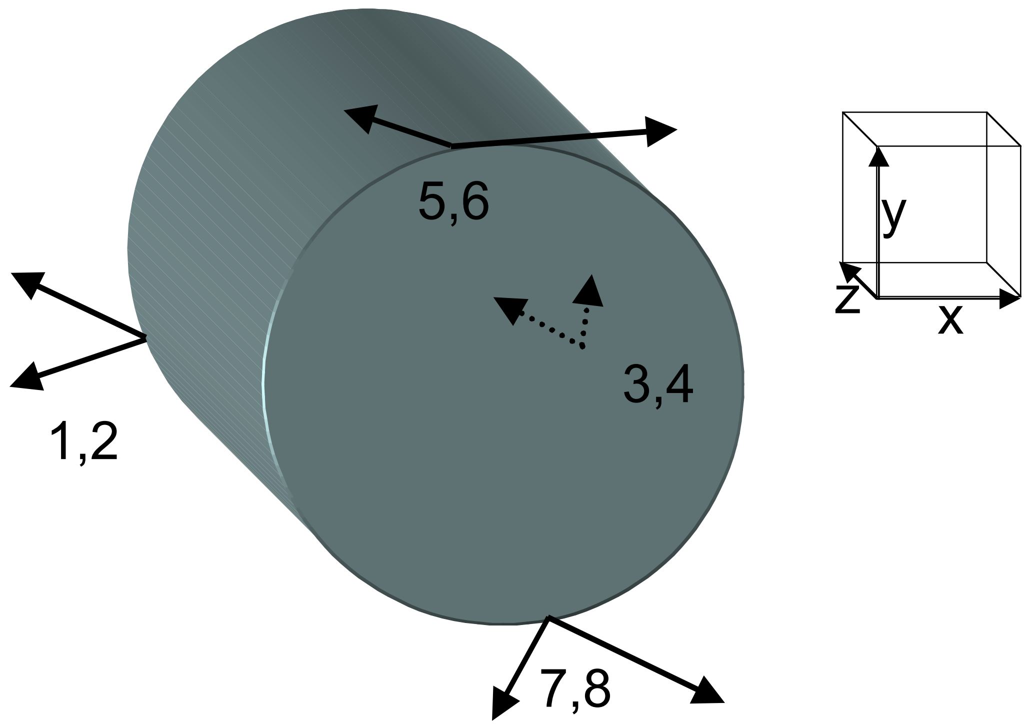
Limits to Performance

- Solar radiation pressure
  - DC Force 2_10^{-5} nt
  - Fluctuating component 2_10^{-8} nt/√Hz
- Thruster noise 1_10^{-7} nt/√Hz
  - Quantization noise requires ~ 12 bits
  - Thrust shot noise 1_10^{-10} nt/√Hz
- Allowed spacecraft motion: x_{sc} = 1_10^{-8} m/√Hz
  - Required loop gain at 1 mHz: T > 1_10^{3}
- Allowed proof mass acceleration : x_{sc} = 3_10^{-14} m/√Hz
  - Required spring softness: f_0 < 3_10^{-4} Hz (spring constant < 4_10^{-4} nt/m)

Thruster Basics

- Need to control 6 degrees of freedom simulatneously.
- Thrusters are unipolar, imposing positivity constraint on inverse of thrust matrix.
- *Conjecture*: 7 thrusters are required.
- Solutions found for 7 and 8 thrusters
- No solution yet for 8 that is tolerant of any single failure.
- Bias force from solar radiation pressure may help.

Sample Solution



	1	2	3	4	5	6	7
+x	0.48	.52	0	0.57	0.43	0	0
-x	0.38	0	1.38	0.04	0.34	0.95	0.44
…							
$+\theta_z$	1.33	1.48	2.81	0	2.81	2.46	0.35
$-\theta_z$	1.82	0.41	2.23	2.23	0	0.99	1.24

The DRS Interferometer

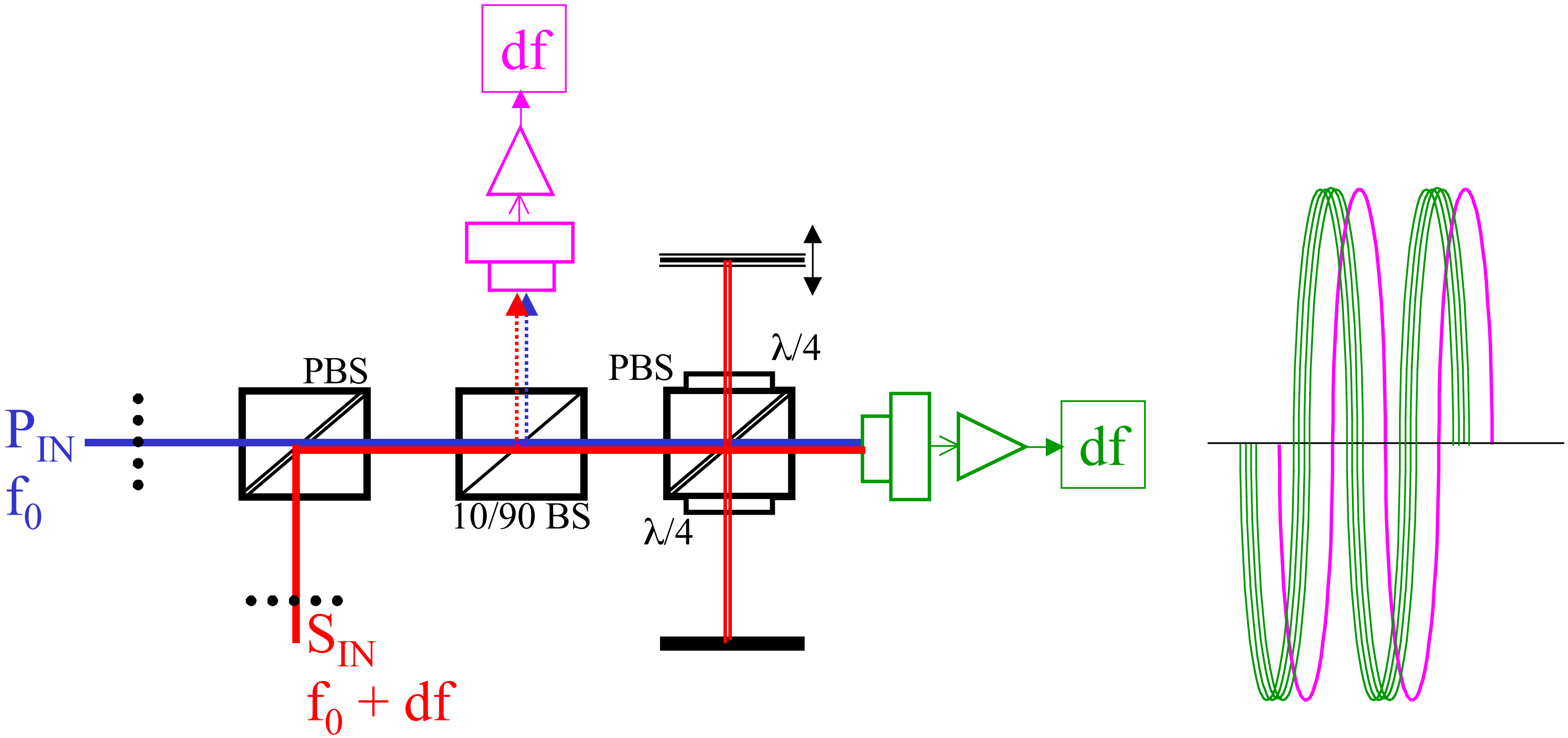
A. Kuhnert

October 19th, 2001

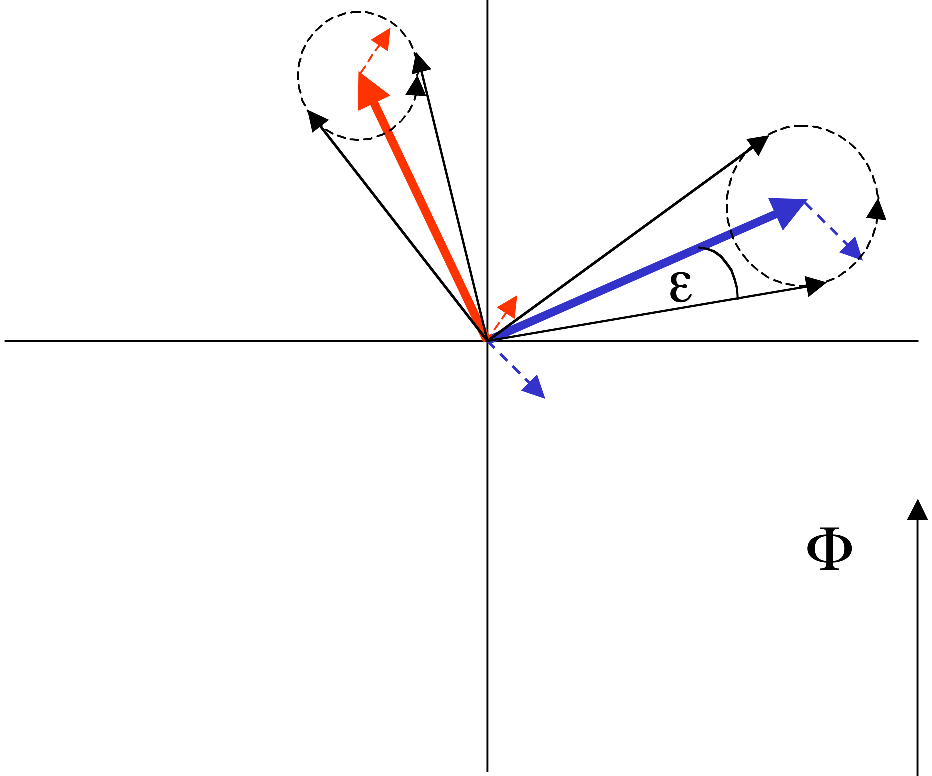
Why an interferometer

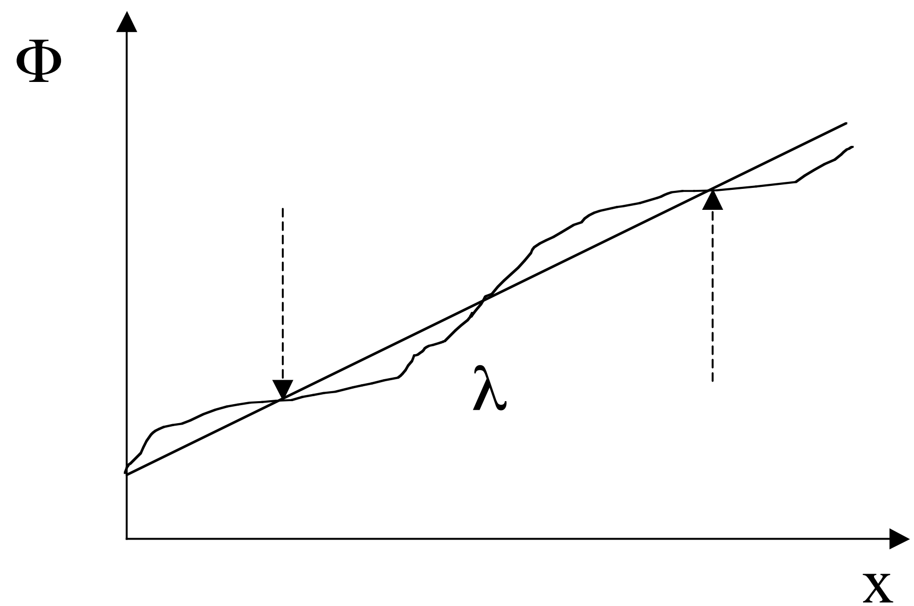
- Independent sensor for test mass separation.
- It's optical, does not interfere with test masses.
- Accelerometer sensor noise of ~1 nm/√Hz allows to measure ~$3*10^{-14}$ $m/s^2/\sqrt{Hz}$ @ 1 mHz.
- Interferometer noise/non-linearity of 10 pm/√Hz allows to measure that accelerometer performance up to 10 mHz.

Heterodyne Interferometer

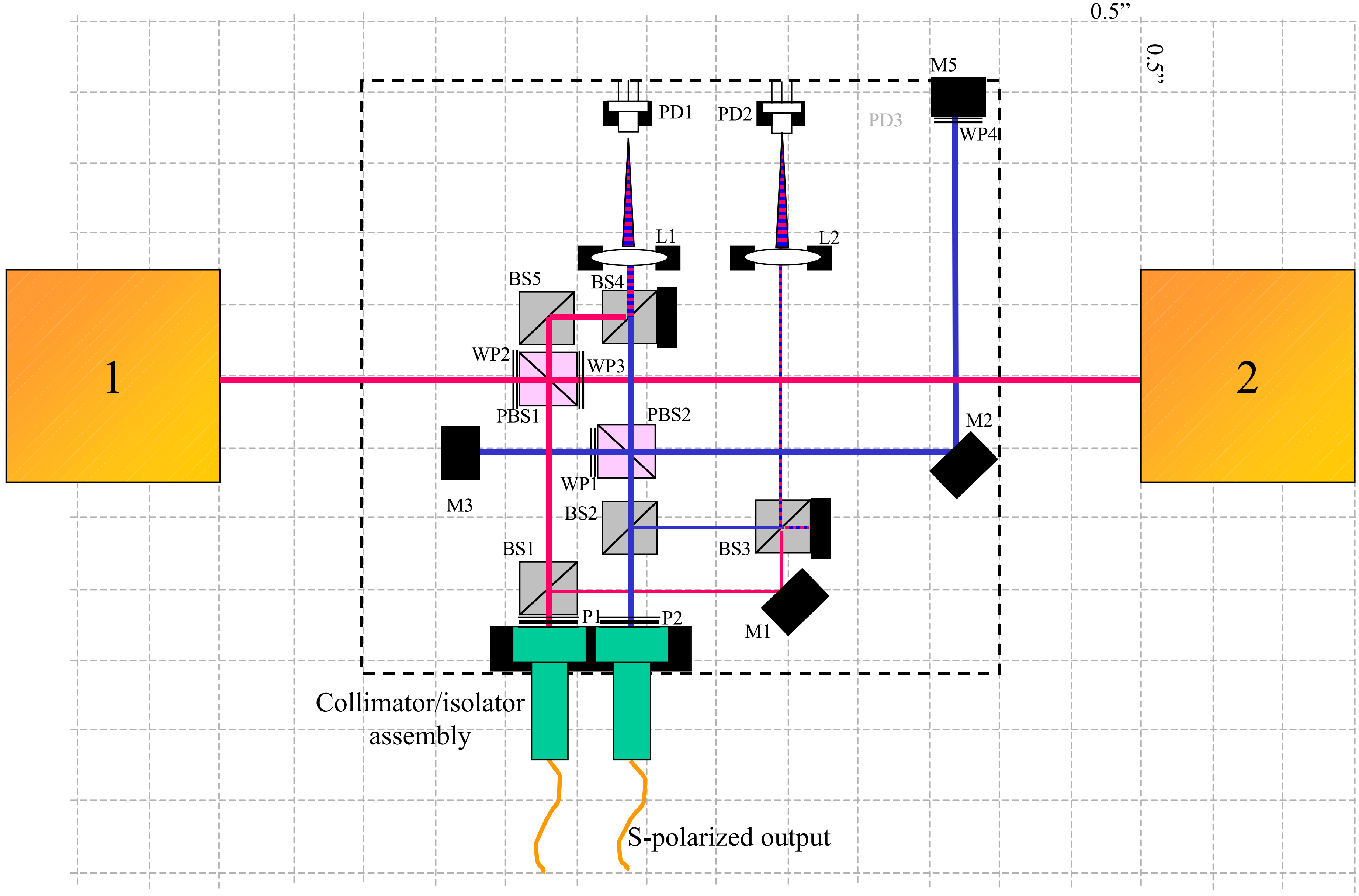


Heterodyne Interferometer Non-linearity

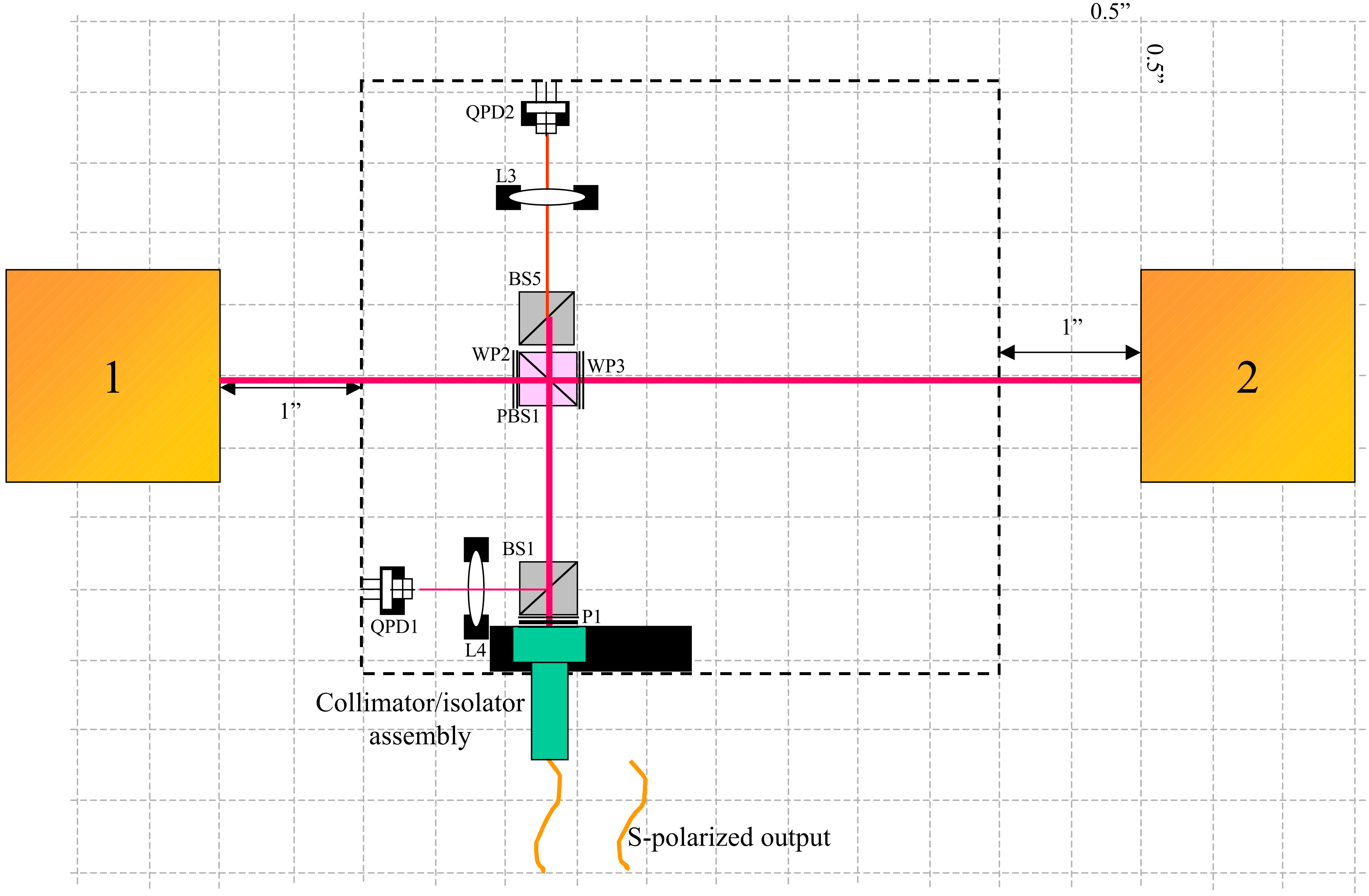




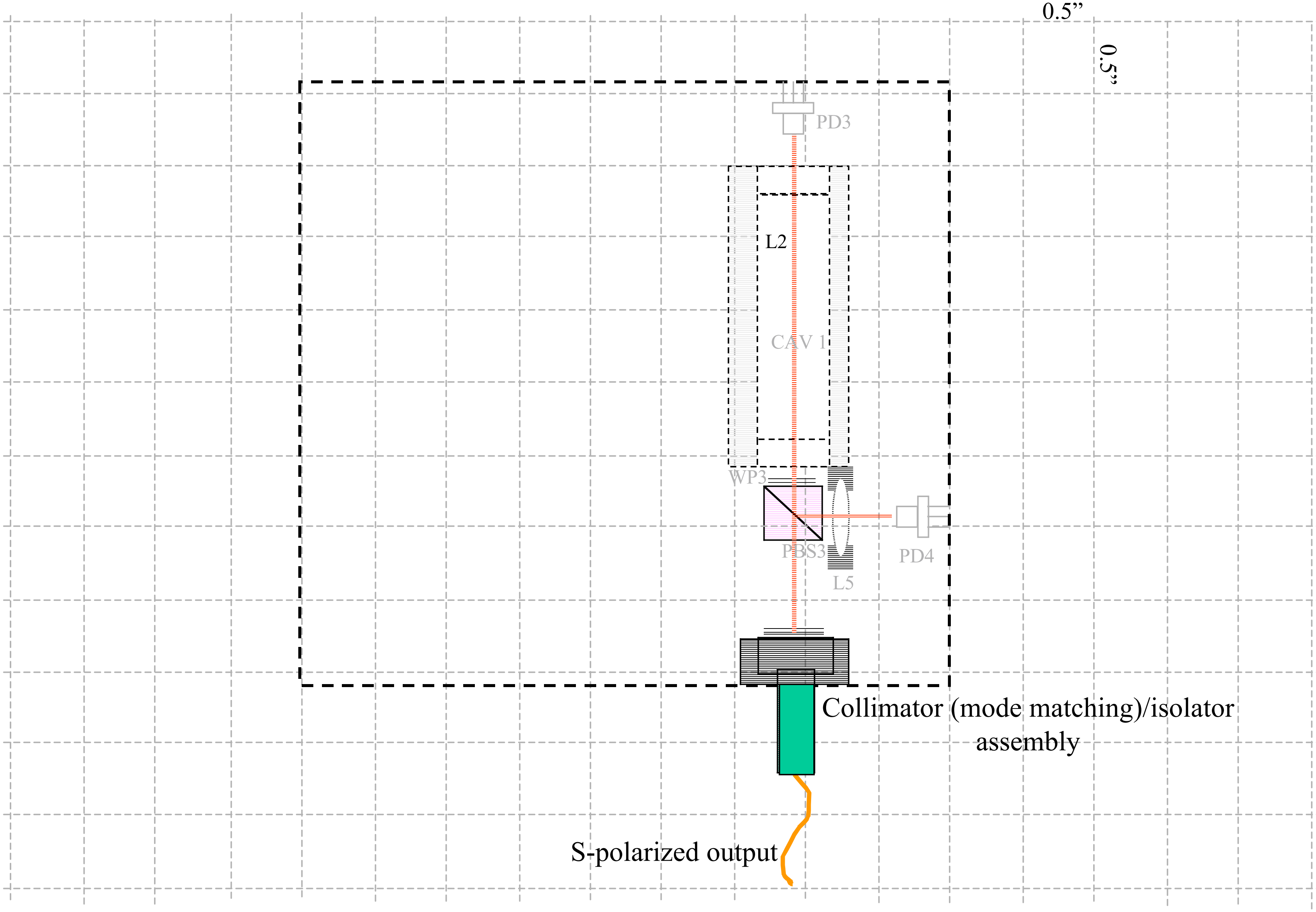
Basic Heterodyne Interferometer for DRS



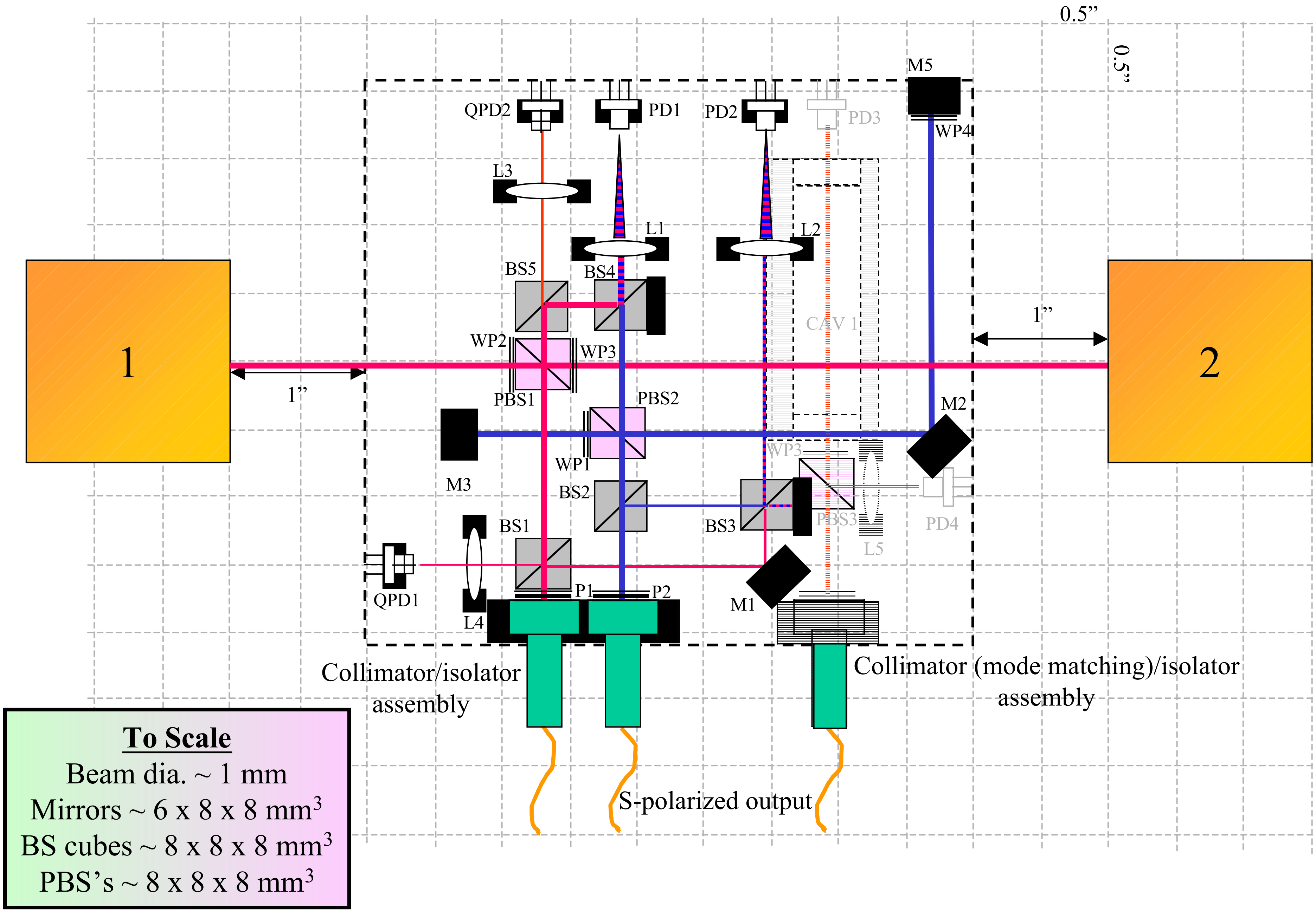
Test Mass Alignment sensors



Frequency Stabilization Reference Cavity



BASELINE DESIGN



Some numbers...

- Measurement and reference optical paths are equal within 1 mm,

  $\Phi = 2\pi/\lambda * OPD = 2\pi*\nu/c * OPD$

  $d\,\Phi = 2\pi*d\nu/c * OPD$, e.g. $d\nu$=10 GHz and OPD=1mm => $d\,\Phi \sim 3.3*10^{-2} * 2\pi$

  => $d\,\Phi \sim 7*10^{-2} * \pi$.

  We need to suppress frequency noise to <1 MHz/√Hz @ 1 mHz to achieve $7*10^{-6}$ of a fringe = 5 pm/√Hz. *(NOTE: $dL/L = d\nu/\nu$ => $dL = d\nu/\nu * L$ < 1 MHz/√Hz /227.5 THz * 1 mm < 5 pm/√Hz)*

- Reference cavity is also in 10^{-6} °K/√Hz @ 1 mHz environment, with ULE CTE ~ 10^{-8}/°K it follows that cavity is stable to 10^{-14}/√Hz, i.e. a 5 cm long cavity w/ FSR=3 GHZ is stable to ~1 Hz/√Hz @ 1 mHz.

and more numbers...

- Proof mass distance stable to ~ 1 nm (~1/600 of a fringe) => let's assume we'll have ~1 nm periodic non-linearity: => max. slope of non-linearity ~ 6 nm_{PP}/330 nm => 18 pm/ nm; worst case we'll get ~20 pm non-linearity over 1 nm motion.
  Q: Over what time scale do masses drift, i.e. is non-linearity out of signal band?

and even more…

- Measurement and reference optical paths in glass are equal within the dimensional differences of the BSs, PBSs (~100 μm), soak temperature sensitivity then is: CTE(BK7)*Δdim*ΔT ~ $10^{-5}/^{o}K*10^{-4}m*10^{-6}\ ^{o}K/\sqrt{Hz} = 10^{-15}\ m/\sqrt{Hz}$, i.e. there is room. We might use ULE for all optics since the optical bench is ULE.

Summary

- Heterodyne interferometer used as independent, non-interfering test mass separation sensor.
- Interferometer performance: ~10 pm/√Hz @ 1 mHz limited by non-linearity and pointing fluctuations (compared to 1 nm/√Hz @ 1 mHz for accelerometer noise)