Optical-bench design propositions

based on proposed implementations of

1&4) Individual calibration of PM-bench relative motion;
2&3) Inter-bench laser phase-locking with no PM interface and with common polarization (no fiber twist);
5) No unnecessary heat-producing elements on the optical benches;
6) Identical, interchangeable benches to recover from arm loss;
7) Suppress thermal noise with more nearly common optical paths for local and incoming science laser beams;
8&9) Laser and USO frequency stabilization by arm-locking;
10) Stable ~1-GHz local laser-generated clock

-- Ideas proposed for scrutiny and presented graphically –

22 September 2003

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Filename: OB-22Oct03

The baseline optical-bench design is summarized. (Slides 0.1—0.6)
The following optical-bench design proposals are then considered:

1. Independent measurements are made on each bench of the relative motion (along the science-sensitive axis) between the bench and the proof mass (PM), with a backside Michelson interferometer, to provide info required for laser arm-locking. (Slides 1.1--3)

2. Phase-lock the lasers on the two benches in each spacecraft (SC) without bouncing laser light off either of the two PMs. (Slides 2.1—3)

3. Phase-lock the lasers on the two benches in each SC in a way that propagates identical polarizations and requires no fiber twist (or other means) to change polarizations. (Slides 3.1—3)

4. Improvement to the individual PM-bench relation motion measurements in Slides 1.1—3 is achieved by using a common-path pair of laser beams and beating these (instead of the USO) against the pair that interrogates the PM. This removes (common-mode) laser noise from the PM-bench measurement and helps ensure that the PM-bench measurement is as precise as the science measurement. (Slide 4.1)

5. Heat-producing elements (except for the science photodetector) are placed off the bench. (Slide 5.1)

6. Benches within a SC can be made identical and interchangeable to recover from loss of one arm, a failure from which the baseline design cannot recover. (Slides 6.1—5)

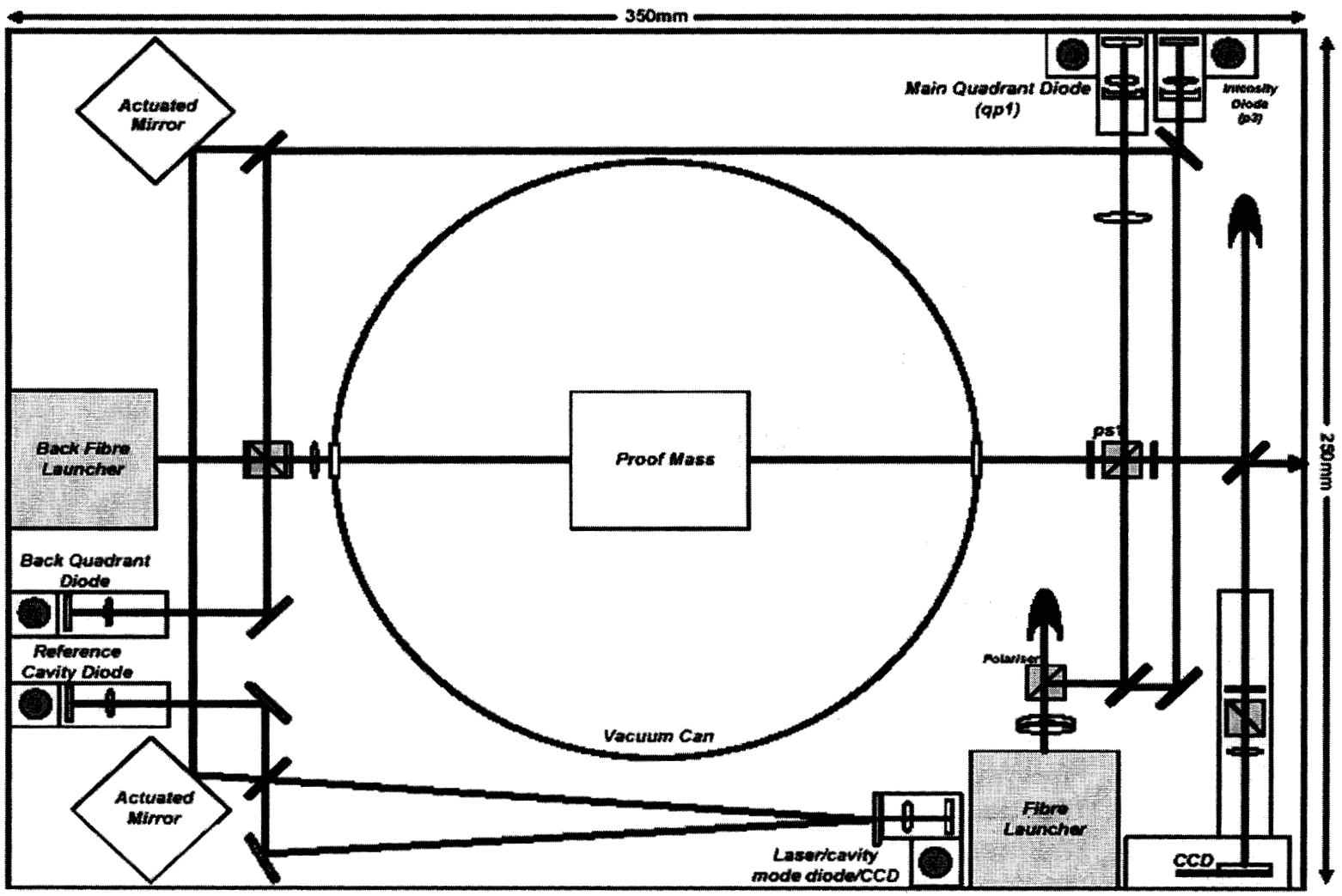
7. Wave Plates can be removed from the science-beam paths to suppress thermal effects and achieve nearly-common path and equivalent kinds and numbers of optics for local and incoming laser beams. (Slide 7.1)

8,9. Stabilize lasers by arm-locking; add USO-generated sidebands; arm-lock the USO. (Slides 8&9.1—3)

10. Generate a ~1-GHz local clock by combining with a second laser locked to another mode of a second, high-finesse "clock" cavity whose length is adjusted by the arm-locking controller (Slides 10.1—4)

0.1: The "baseline" optical bench configuration,
as adapted from FTR Fig 7.1-14 by P. McNamara, Hannover, Sept 03, to show actual footprints

1st variation with Trento Vacuum Can



0.2: The "baseline" optical bench configuration

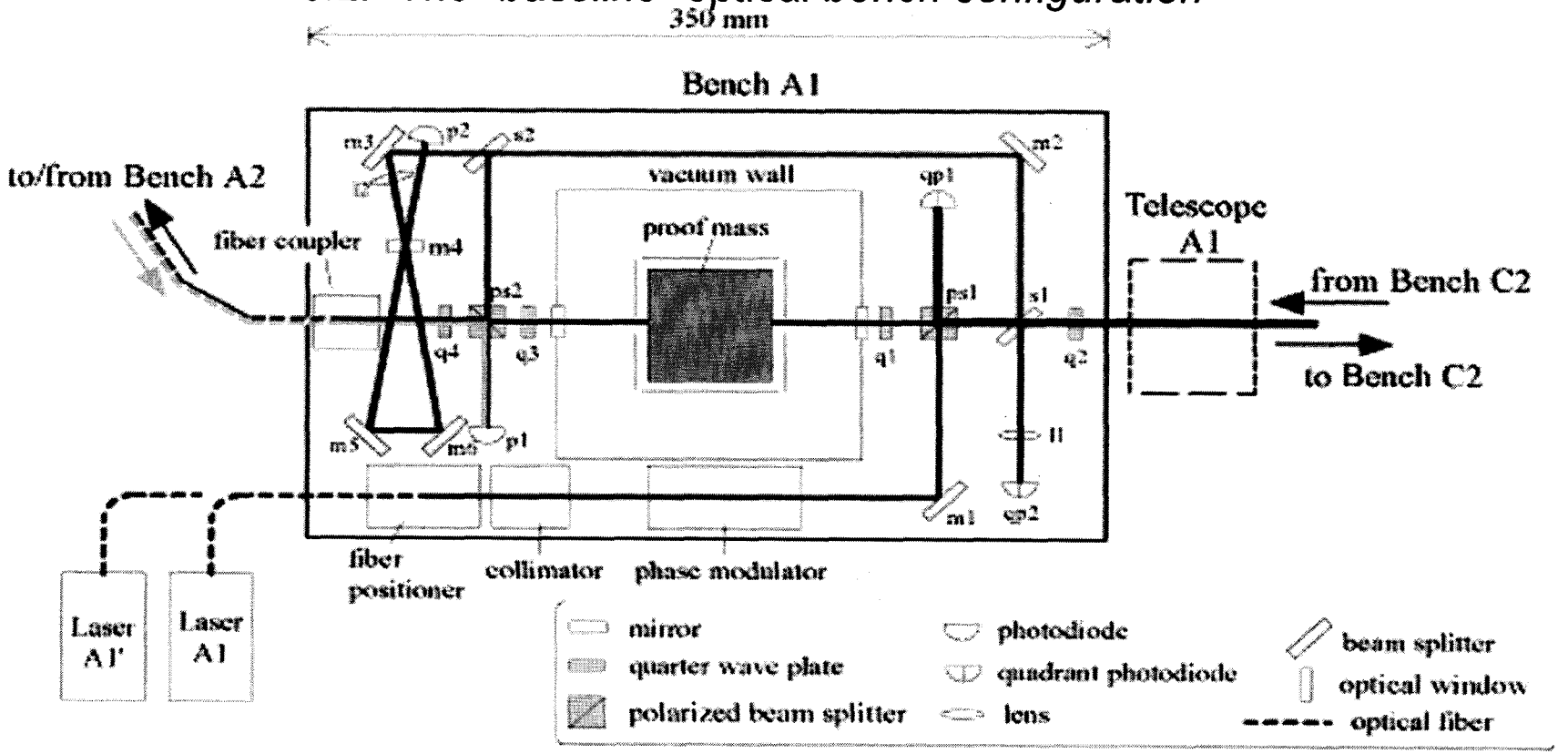
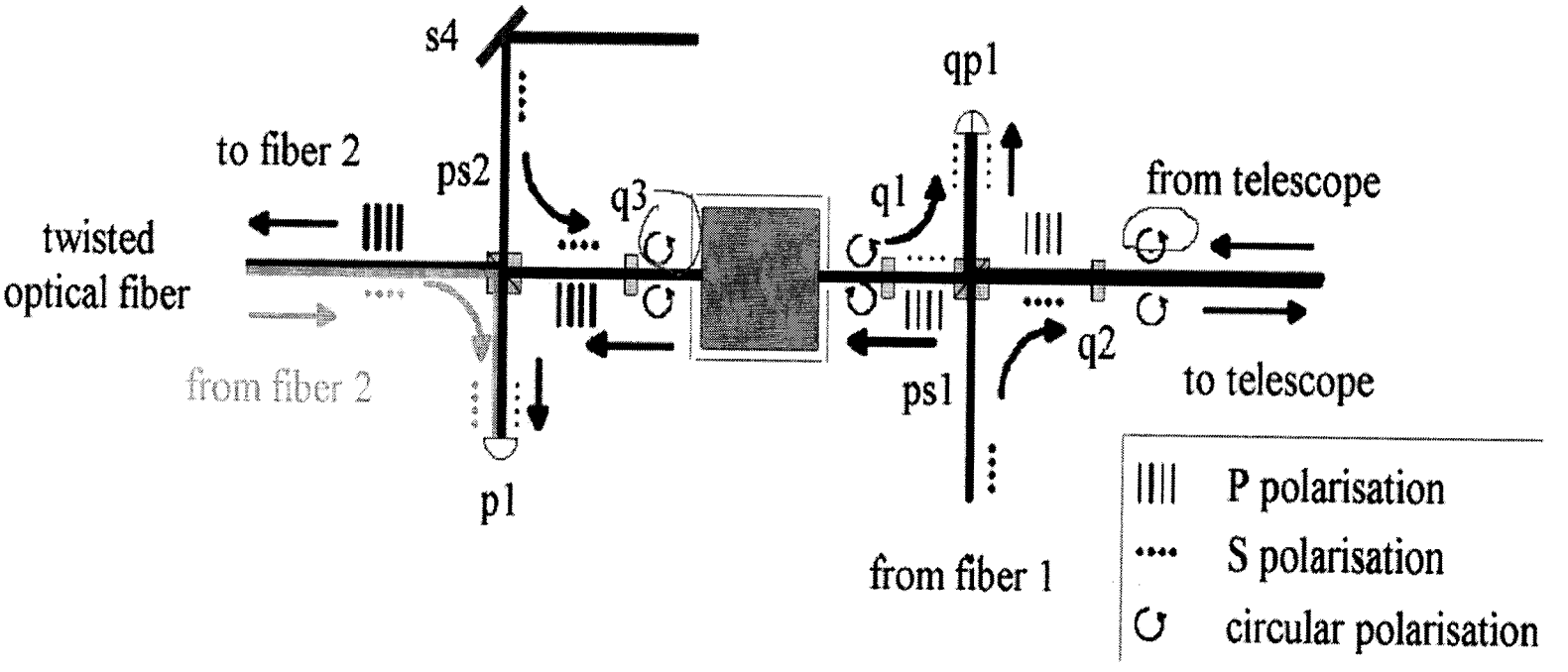


Figure 5.3 *Diagram of the optical bench. The chosen light path renders the measurement insensitive to movement on the spacecraft. The light from the local laser passes through a collimator, a phase modulator and a polarizing beamsplitter to the expanding telescope. The light beam received by the telescope from the distant spacecraft first gets reflected at the proof mass and then interferes with a small fraction of the local laser light at a (quadrant) photodiode (upper right). The diode in the lower left senses the signal for the phase locking between the two lasers at the same spacecraft. The diode in the upper left locks the laser to the reference cavity and the quadrant diode in the lower right is used in pointing the spacecraft.*

Excerpted from *LISA System & Technology Study Report*, July 2000; Identical to Fig.3.3 of the *Pre-PhaseA Report* (1999) and Fig. 4.3-4 of the *Final Technical Report* (Astrium)

0.3: The "baseline" optical bench configuration



Beam separation through polarization.

0.4: The "baseline" optical bench configuration

Useful primer for optical diagram reading (conventions used here):

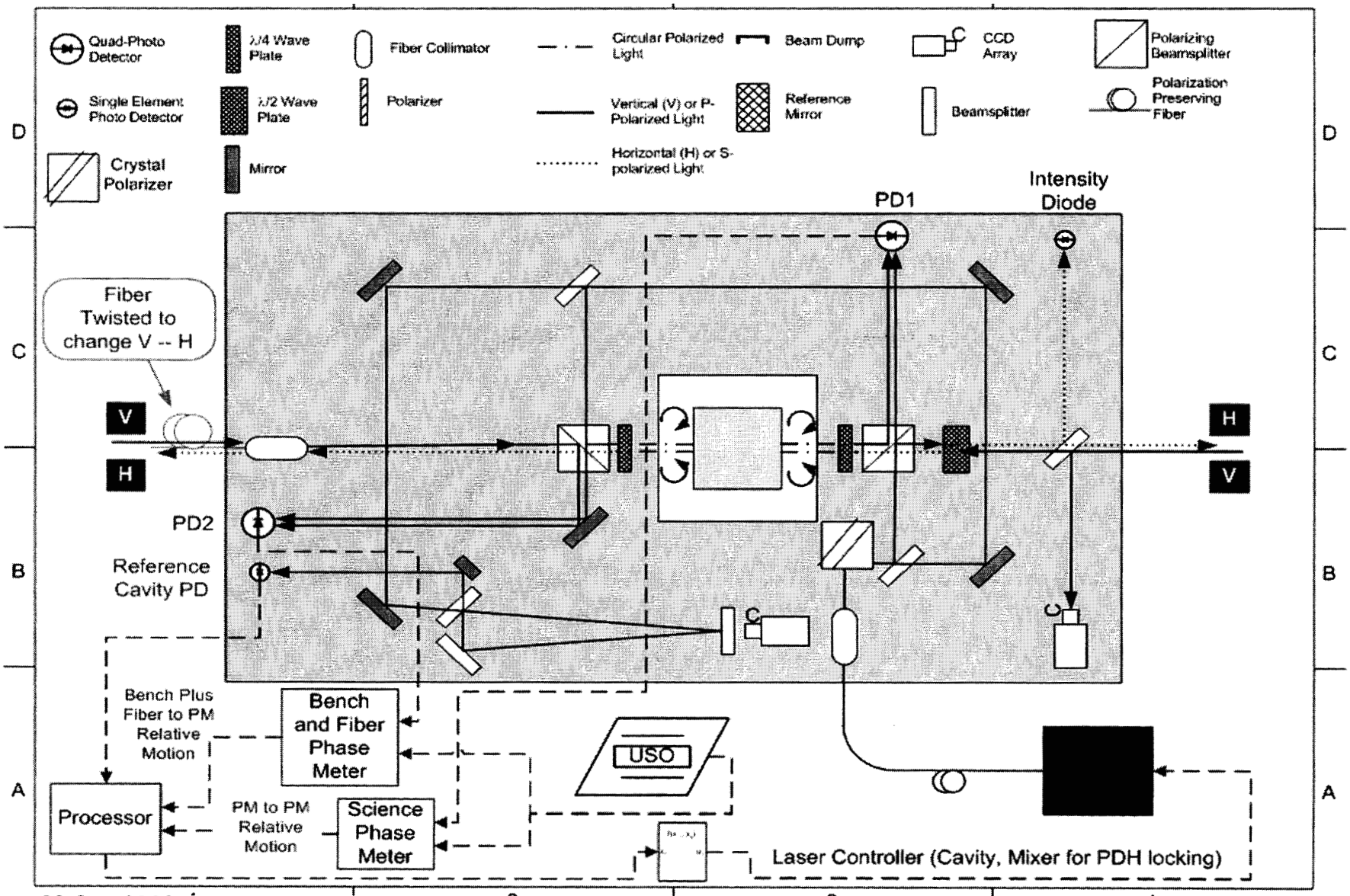
- Vertical (V, *aka* S) polarization: **V** (S) ↔ **R** (QWP)
  - denoted by solid lines: ———
  - is changed to Right Circularly Polarized (R) upon passage through a quarter-wave plate (QWP), unless noted otherwise (*e.g.*, unless the QWP is deliberately angled to make V become L);
  - is unchanged upon reflection.

- Horizontal (H, *aka* P) polarization: **H** (P) ↔ **L** (QWP)
  - denoted by dotted lines: .....
  - is changed to L upon passage through a QWP, unless noted otherwise
  - is unchanged upon reflection

- R (L) polarizations: **R** ↔ **L** (reflection)
  - denoted by dot-dash lines: ·—·—·—
  - is changed to V (H) upon passage through a QWP, unless noted otherwise;
  - is changed to L (R) upon reflection

0.5: The "baseline" optical bench configuration*

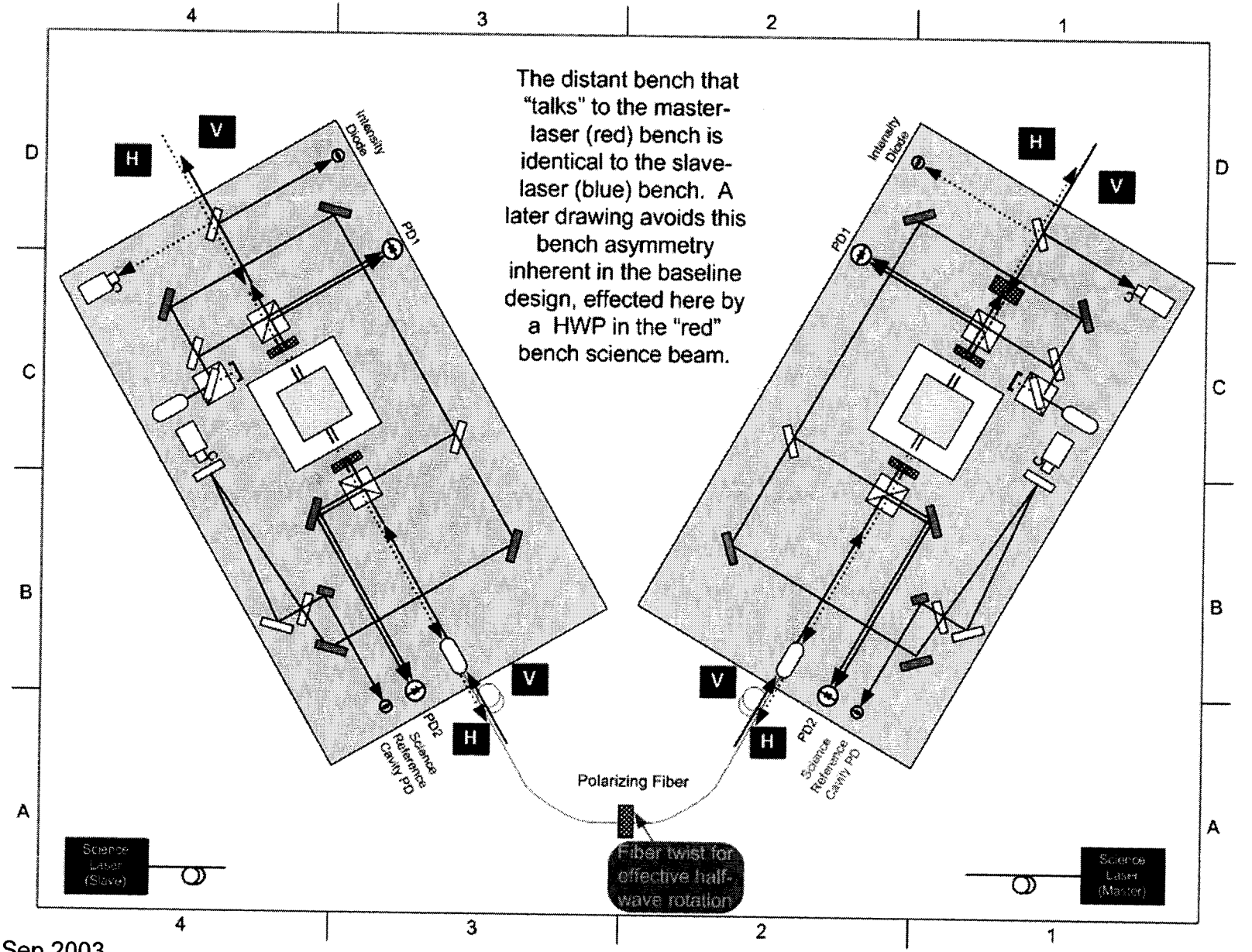
**HWP shown instead of QWP, hence H,V instead of L,R polarizations;*
this is not a proposed change and should be ignored until Consideration #6, described below



22 Sep 2003 7-BLS

Filename:A1-a.4-BaseLine

0.6: The "baseline" optical bench configuration



22 Sep 2003

Filename:A1-b.4-BaseLine

8-BLS

1. Individual PM-Bench relative motion calibration

- ***The baseline inter-bench backside measurements provide only linear combinations of the two PM-bench relative motions plus uncalibrated additive noise, unsolvable for individual bench motion (which is needed to exploit laser arm-locking fully).***
- ***Instead, measure PM-bench motion with a backside Michelson interferometer between a fixed mirror and the PM, using two pick-offs from the science laser beam, one offset by ~10 kHz via combination of an AOM (~30MHz) & post-PD electronic down-shifting.***

•Use Quadrant PD (for PD2) to monitor independently each PM position and rotation.

- *This enables the Science PD1 to give unambiguous information on SC-SC pointing.*
- *Very little power (<<1mW) needed to give a 5-pm/rtHz measurement.*
- *Optical bench stability ensures that the two path lengths in the Michelson set-up can be made equal and constant to better than is required to suppress laser noise (with the laser pre-stabilized to $10^{-13}/\sqrt{Hz}$, it would take a 10-m imbalance to produce 1pm/√Hz error)*
- *Additional pick-off prior to the Michelson can be used instead of the USO to suppress other sources of common-mode optical-path noise in the measurement (e.g., AOM drift; see #4 below)*

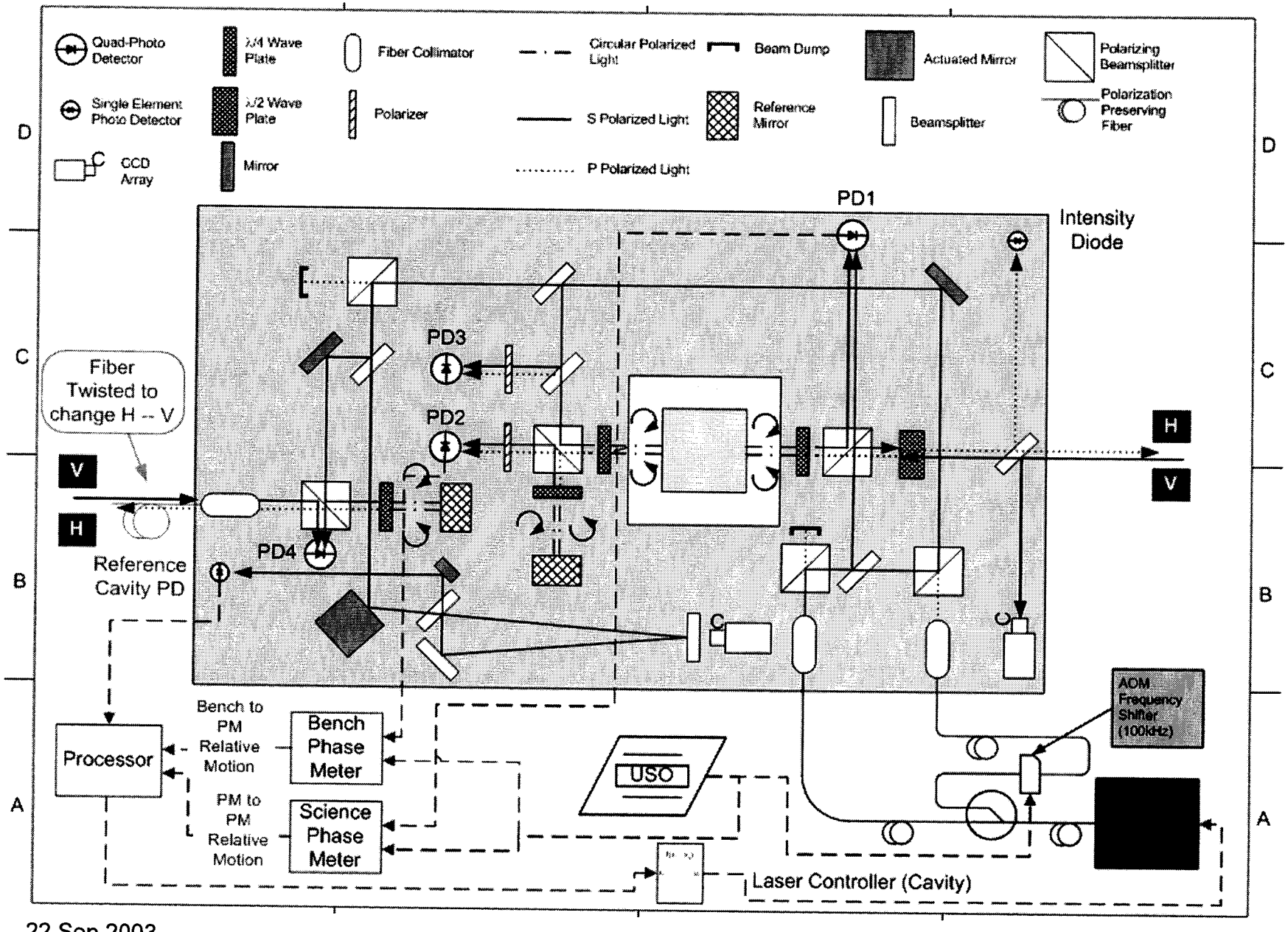
2. Use fixed reference mirror for inter-bench phase-locking, too!

- *Eliminate unnecessary additional disturbance to PM.*
- *Remove the disturbance constraint on amount of power for phase-locking*
  - 1 mW produces a dc differential acceleration of ~5 pm/s^2 (~ 2I/mc).
  - 20 nW/rtHz laser intensity noise produces 10^{-16} m/s^2-rtHz acceleration noise on the PM).

Filename:A2.4-RefMir&USOBench

*Note: Per suggestion #5 below (but not yet incorporated in these first drawings), all power-dissipating elements can and should be placed **off** the OB. This includes all CCDs, PDs, QPDs (except for the science PD1), AOMs, and possibly also the laser reference cavity, if it requires special thermal control.*

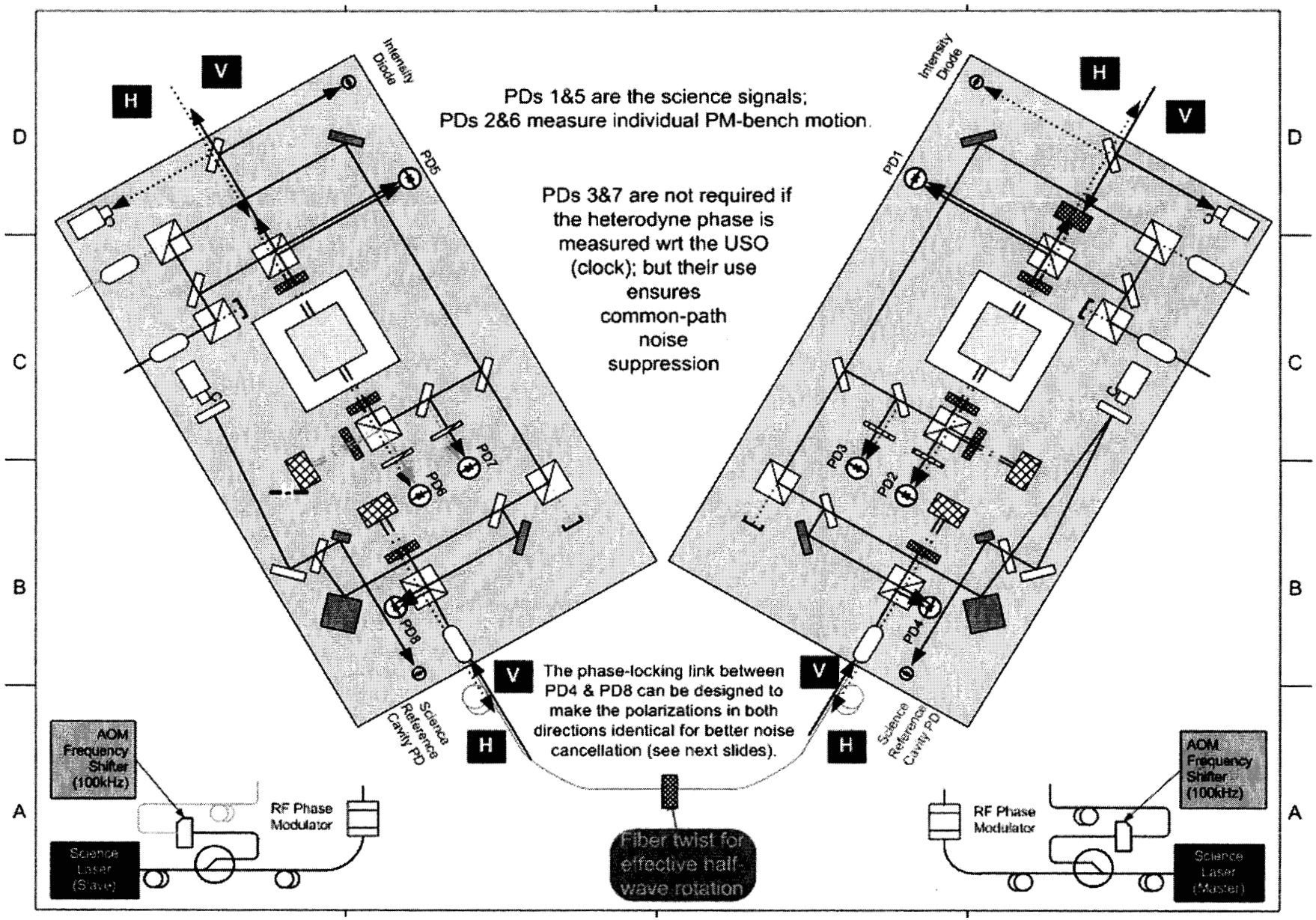
1.2, 2.2



22 Sep 2003

Filename:A2.4-RefMir&USOBench

10-BLS


PDs 1&5 are the science signals;
PDs 2&6 measure individual PM-bench motion.
PDs 3&7 are not required if the heterodyne phase is measured wrt the USO (clock); but their use ensures common-path noise suppression
The phase-locking link between PD4 & PD8 can be designed to make the polarizations in both directions identical for better noise cancellation (see next slides).
Fiber twist for effective half-wave rotation
Intensity Diode
Science Reference Cavity PD
AOM Frequency Shifter (100kHz)
RF Phase Modulator
Science Laser (Slave)
Science Laser (Master)
PD1
PD2
PD3
PD4
PD5
PD6
PD7
PD8
H
V
A
B
C
D

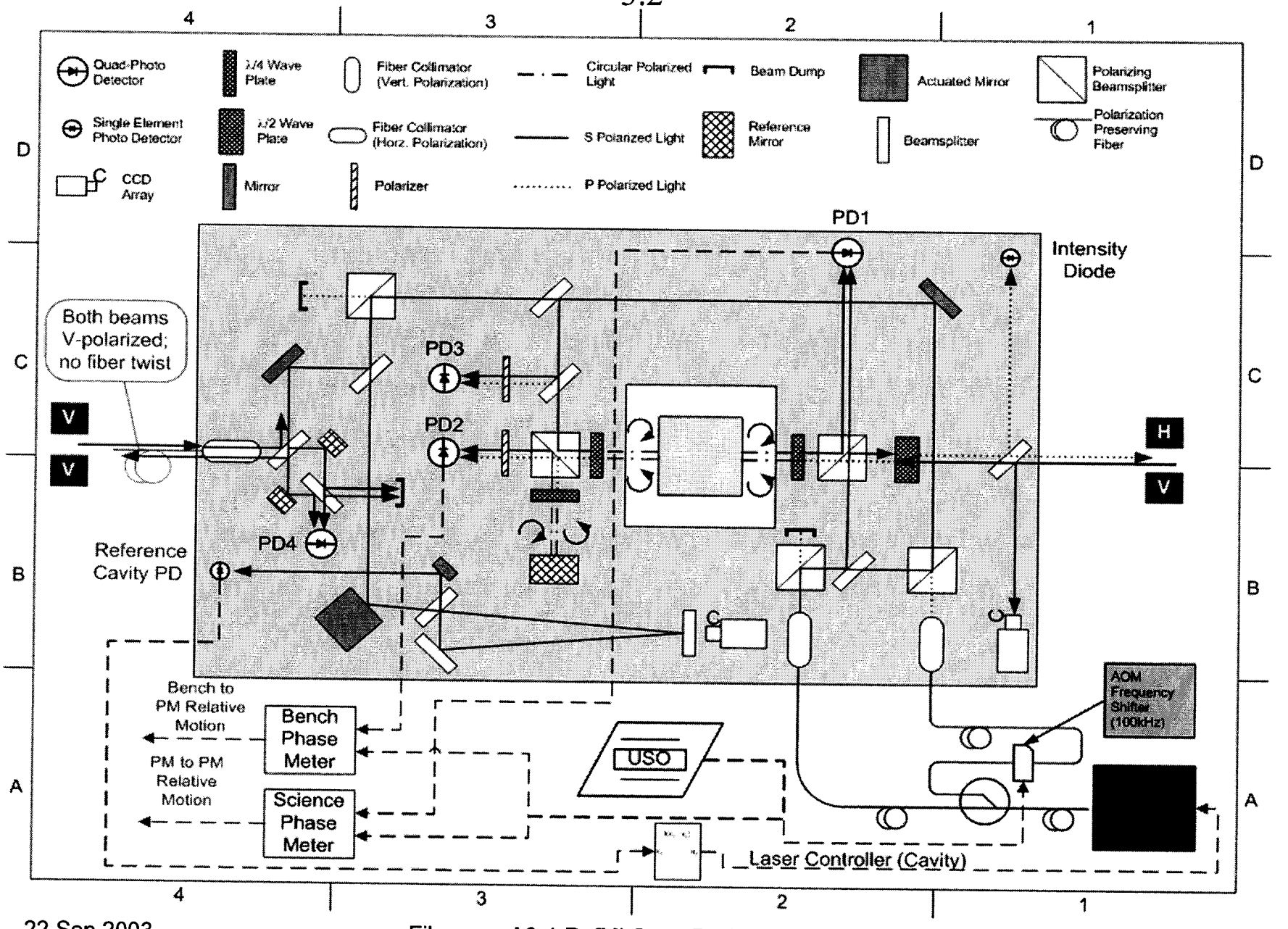
3. Make the inter-bench fiber modes propagate with identical polarizations:

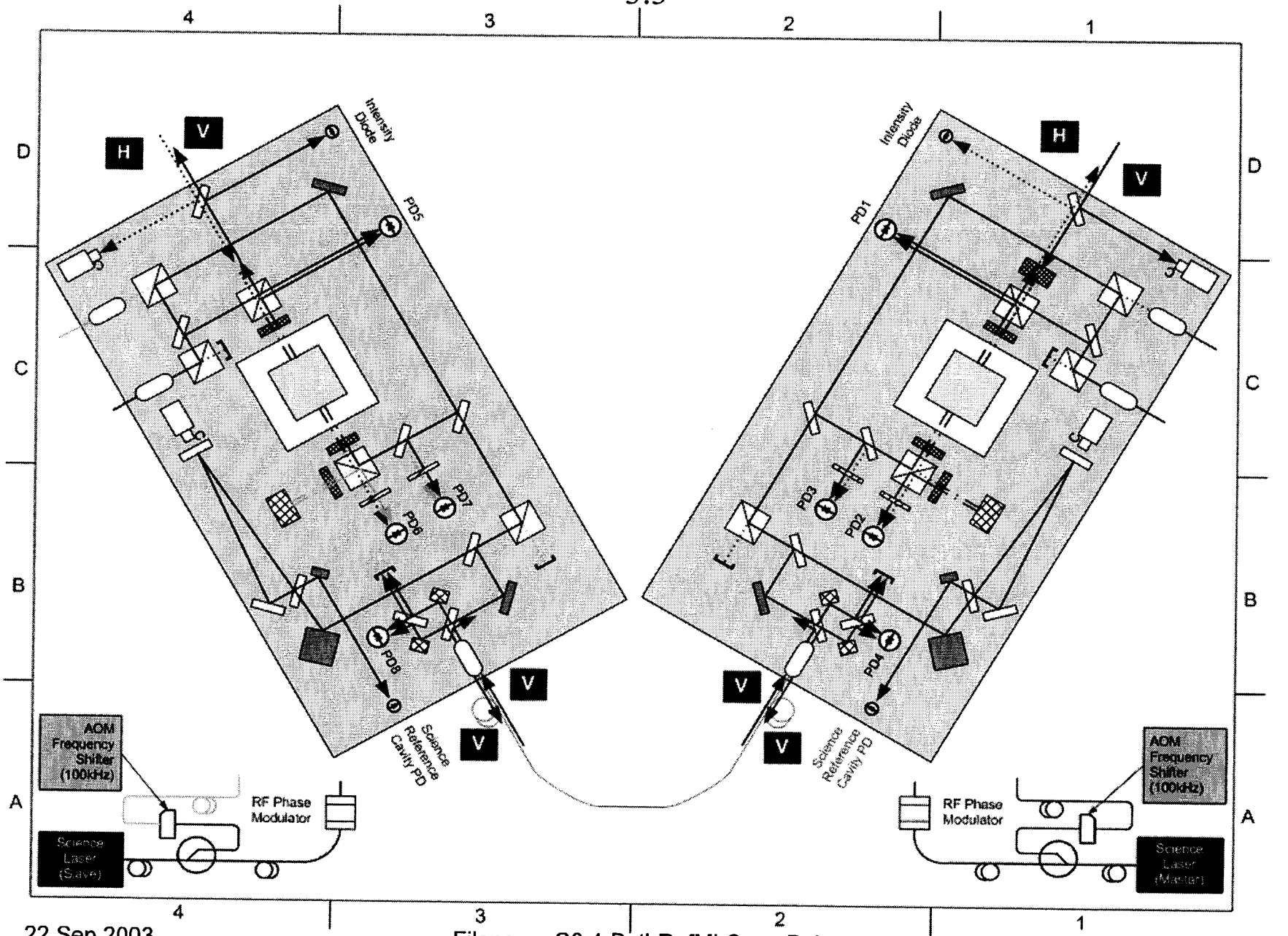
- *The baseline inter-bench measurement scheme requires sending oppositely polarized light to/from the benches; and it requires changing the polarizations enroute by twisting the (polarizing) fiber, due to the design in which each beam touches only one PM.*

- *Use of backside Mach-Zehnder-like interferometers with fixed reference mirrors instead of the PMs will symmetrize the backside optics and polarizations.*

Thus, identical polarization modes propagate in both directions in the fiber, making this noise source common-mode.

Filename:A3.4-RefMirSamePol&USOBench


Quad-Photo Detector
λ/4 Wave Plate
Fiber Collimator (Vert. Polarization)
Circular Polarized Light
Beam Dump
Actuated Mirror
Polarizing Beamsplitter
Single Element Photo Detector
λ/2 Wave Plate
Fiber Collimator (Horz. Polarization)
S Polarized Light
Reference Mirror
Beamsplitter
Polarization Preserving Fiber
CCD Array
Mirror
Polarizer
P Polarized Light
PD1
Intensity Diode
Both beams V-polarized; no fiber twist
PD3
PD2
PD4
V
V
H
V
Reference Cavity PD
Bench to PM Relative Motion
PM to PM Relative Motion
Bench Phase Meter
Science Phase Meter
USO
AOM Frequency Shifter (100kHz)
Laser Controller (Cavity)

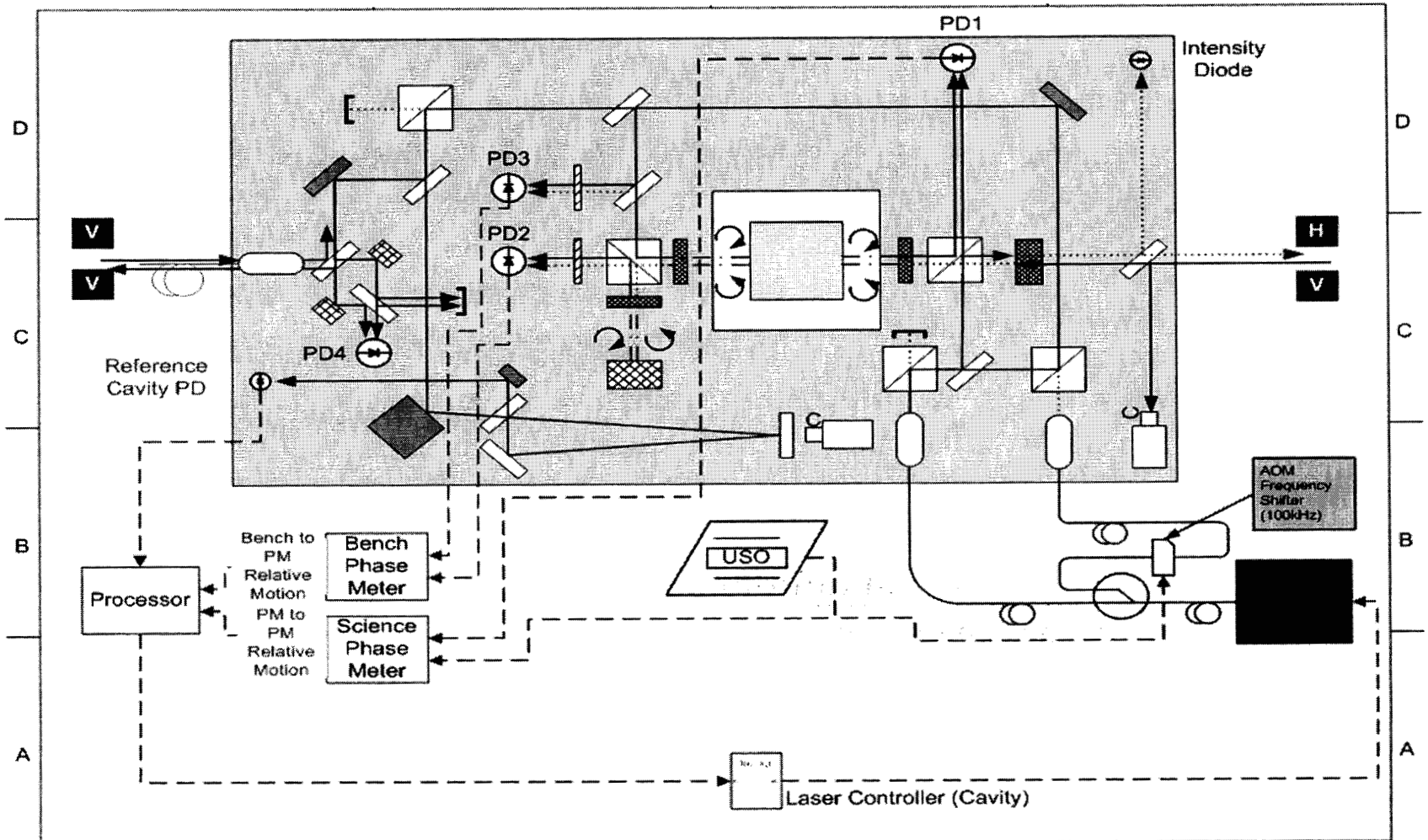

4
3
2
1
D
C
B
A
H
V
Intensity Diode
PD5
PD7
PD6
PD8
Science Reference Cavity PD
AOM Frequency Shifter (100kHz)
RF Phase Modulator
Science Laser (Slave)
PD1
PD3
PD2
PD4
Science Laser (Master)

4. Laser-noise-insensitive bench-motion measurement

- ***Use two common-path pairs of laser beams for the bench-motion measurement (instead of one pair and the USO)***

➔ Individual PM-bench motion measurement is insensitive to laser noise.

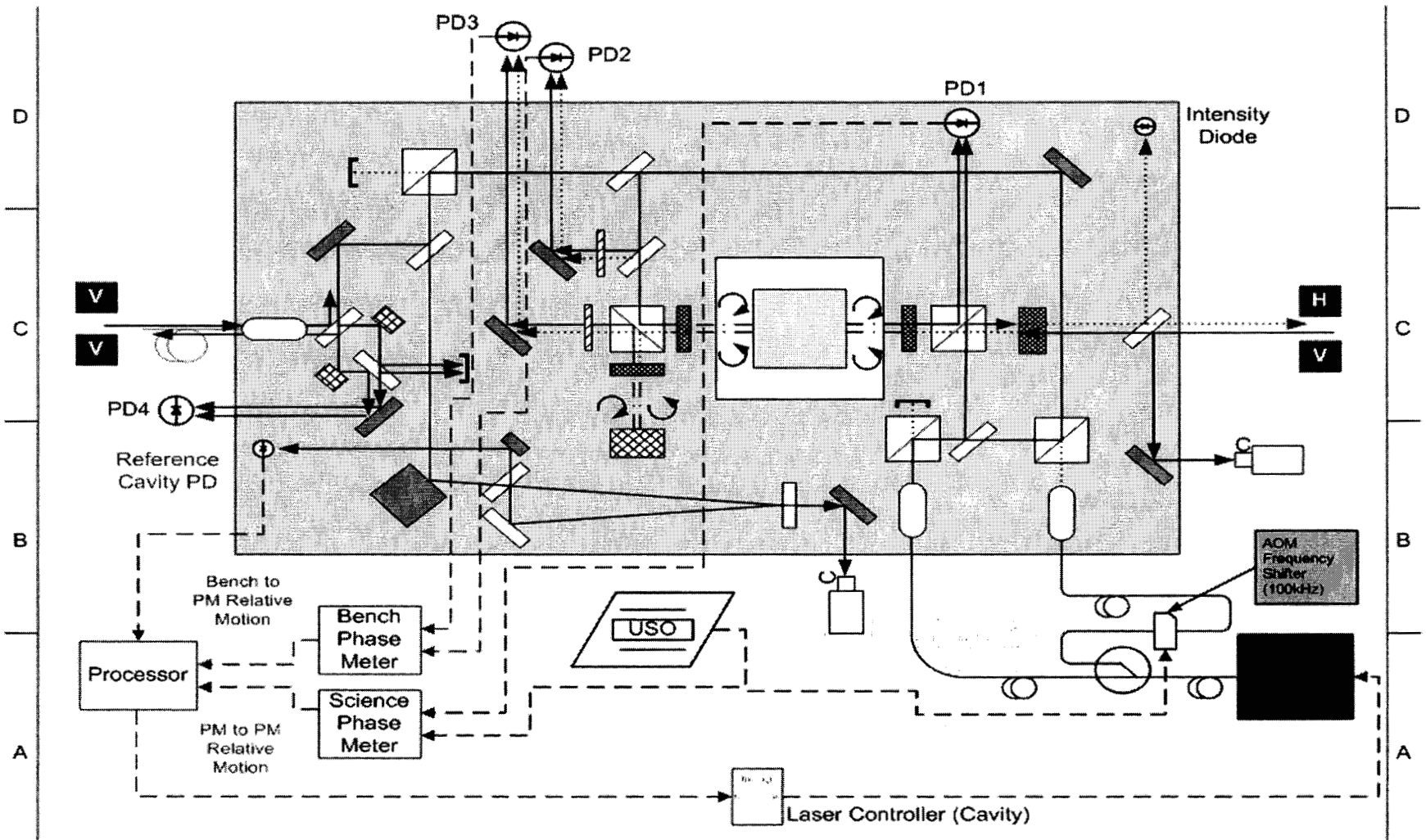
n.b.: Care must be taken with alignment to avoid parasitic reflections.



Filename:A4.4-RefMirSamePol&CMBench

5. Heat-producing elements should be off the OB (QPD, PDs, CCDs,AOMs, etc.)

- *Only PD1 (science) must be on the OB (it is small, wideband, sensitive to alignment).*
- *Laser reference cavity can also be moved, e.g., to give it additional thermal control.*



6. *Should OBs be identical and interchangeable?*

(e.g., to simplify production; to provide redundancy in case of arm loss; etc.?)

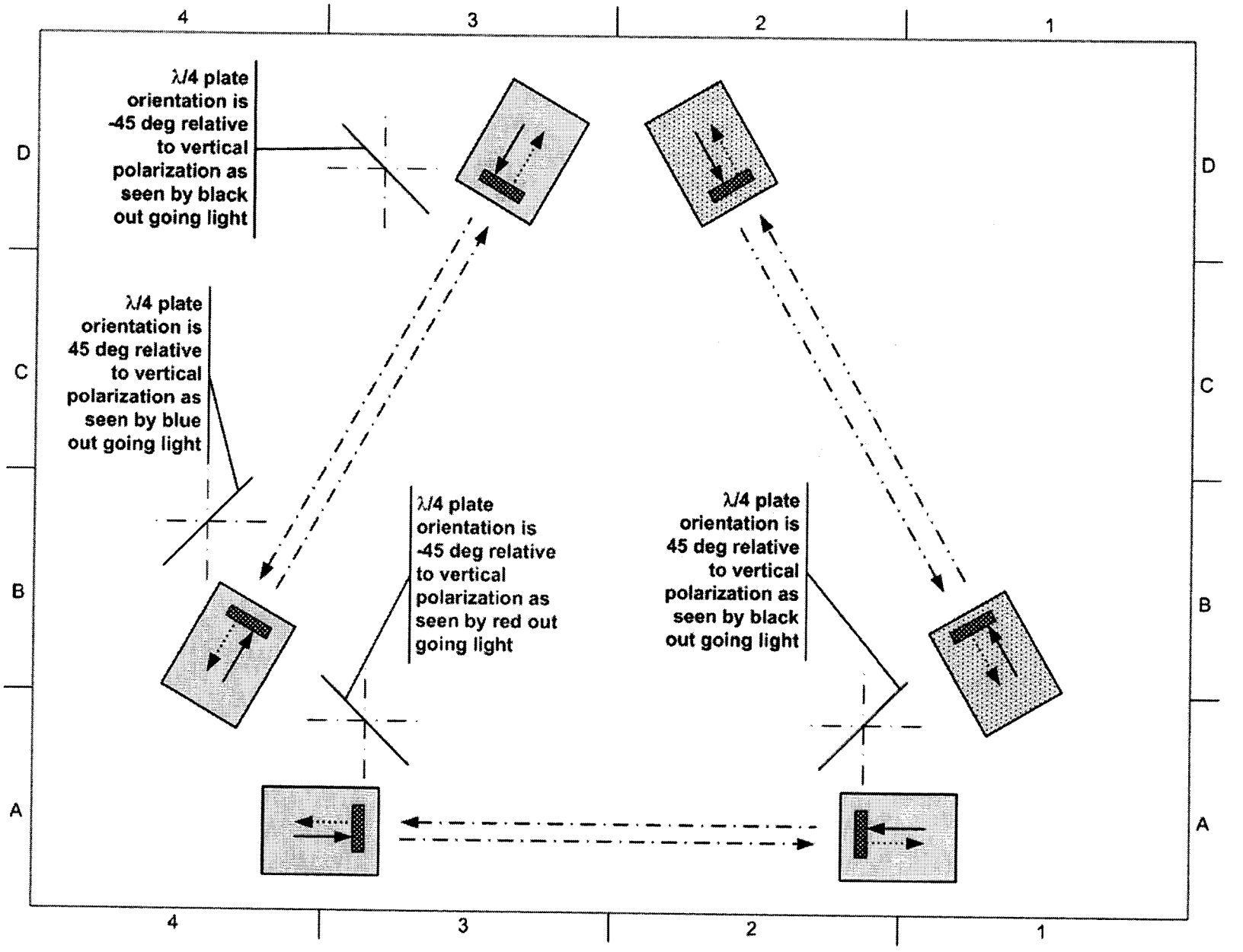
There is an inherent inter-SC "asymmetry" in that the outgoing (science) beam must be oppositely polarized from the incoming science beam.

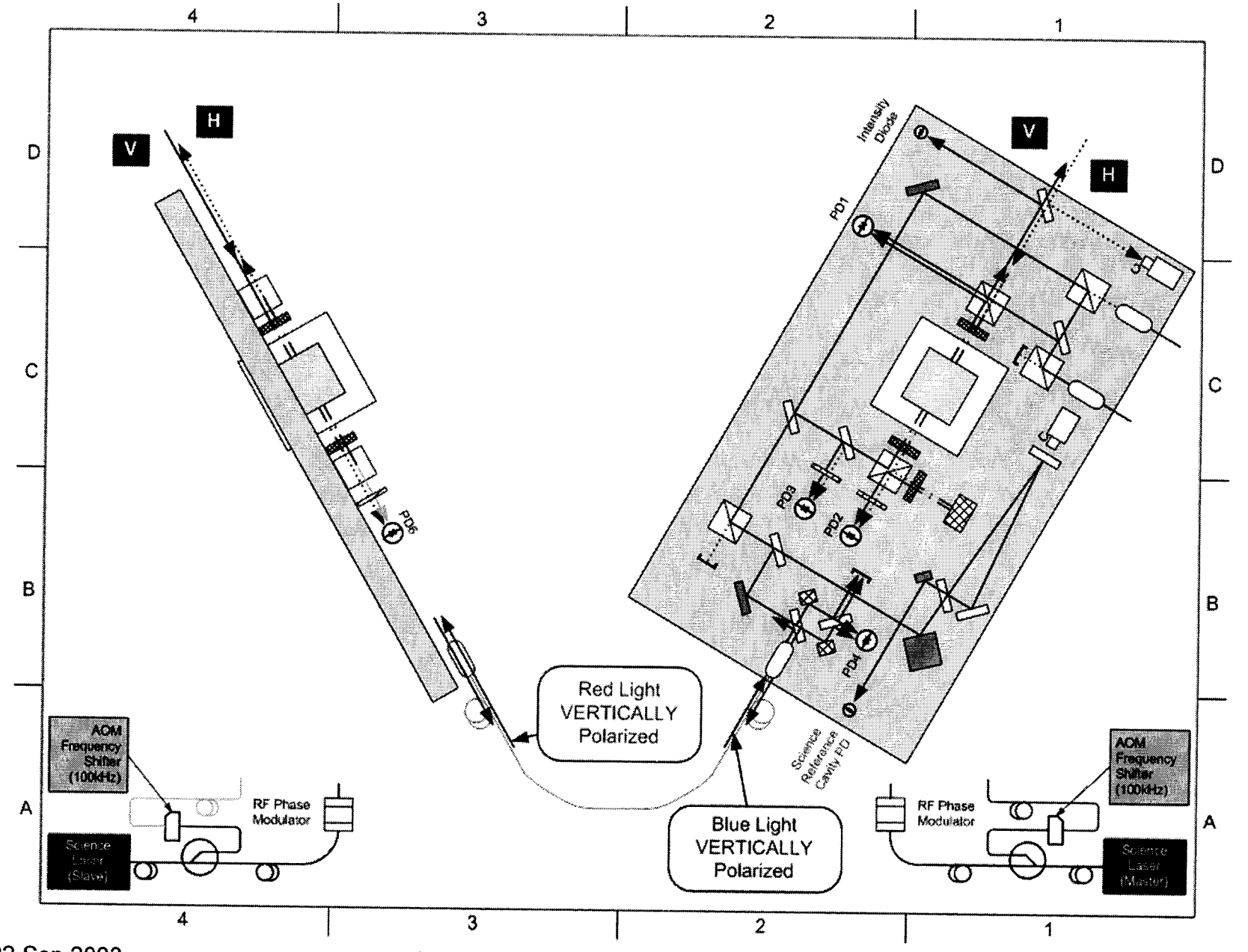
- This asymmetry results from the design requirement that the incoming, but not the outgoing, beam touch the local PM.
- Thus, the second bench must transmit light oppositely polarized from that of the first bench.

- Because the baseline design has the two OBs per SC *coplanar*, it can only achieve this asymmetry by making the two OBs ***non-interchangeable.***
  - The baseline design has QWPs in each outgoing science beam, oriented 90° to each other to transmit RCP from one bench and LCP from the other. ***Hence, if an arm is lost because of failure on one bench, it is not possible to rotate the SC to position the second bench to replace it.***

  - To show this asymmetry explicity, we've drawn a **HWP** in the outgoing path of *one* OB. The distant bench that talks to this "red" bench is identical to the "blue" bench. While the baseline design of QWPs on both benches accomplishes the same thing, it has the disadvantage of appearing to suggest a symmetry that does not in reality exist.
  - The single HWP makes the outgoing beam from one bench V-(or R-) polarized, the other H- (or L-).

- **Solutions that would restore symmetry to the OB layouts and thus provide redundancy for arm-loss risk mitigation redundancy might bring other untenable problems, such as larger dc gravitational gradients.**
  - *One solution is to rotate one OB 90° wrt the other (and build-in the ability to rotate it by 90° in emergency, to recover from loss of an arm) – see Slide 6.3.*


λ/4 plate orientation is -45 deg relative to vertical polarization as seen by black out going light
λ/4 plate orientation is 45 deg relative to vertical polarization as seen by blue out going light
λ/4 plate orientation is -45 deg relative to vertical polarization as seen by red out going light
λ/4 plate orientation is 45 deg relative to vertical polarization as seen by black out going light
4
3
2
1
D
C
B
A


V
H
V
H
Intensity Diode
PD1
PD2
PD3
PD4
PD5
Red Light VERTICALLY Polarized
Blue Light VERTICALLY Polarized
Science Reference Cavity FD
AOM Frequency Shifter (100kHz)
RF Phase Modulator
Science Laser (Slave)
AOM Frequency Shifter (100kHz)
RF Phase Modulator
Science Laser (Master)

B.3 Optical Bench Mounting Inside the Spacecraft

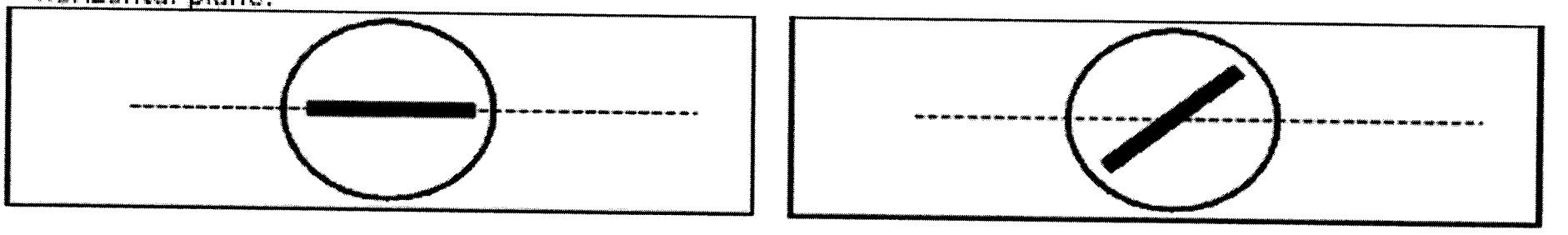
In the S/C configuration defined in the Pre-Phase A study [1] the OB is mounted horizontally (i.e. its plane is perpendicular to the S/C centreline). Nevertheless, the OB mounting with its plane rotated through an angle of 45° w.r.t. the horizontal plane (see Figure B-6) would introduce a simplification in the optical layout: the quarter waveplate that transform the linearly polarised outgoing beam in a circularly polarised beam can be removed. In this case, in fact, the light will leave one S/C in polarisation S and will be received by the other S/C in polarisation P, thanks to the relative rotation of 90° of the two, mutually faced OB's of the two S/C's. The advantages introduced by the removal of this quarter waveplate (beside have one less element to be accommodated) are:

- the possibility of working only with linear polarisation, for which it is easier to design and to predict the behaviour of the antireflection coatings of the optics;
- the removal of the main source of backreflection towards the quadrant photodiode for the detection of the beat signal between the remote laser and the local reference.

This OB mounting option has been then analysed from a mechanical point of view, to assess its viability. In particular the stress induced in the material by the launch loads have been computed using the OB FEM built for the Solutions A and B of the mechanical interfaces (see previous paragraph). The resulting map of the stress distribution for this configuration (Solution A) under the application of a 35 g's along vertical direction (45° from the normal to the OB plane) is provided in Figure B-7. The maximum equivalent stress is:

50 MPa for Solution A and **49 MPa** for Solution B.

In both cases they are considerably larger then the stresses obtained for the horizontal mounting case analysed in the previous chapter. Moreover they are very close or even larger than the ULE™ ultimate tensile stress. Thus this result advise against the adoption of the OB mounting with a 45° tilt from the horizontal plane.

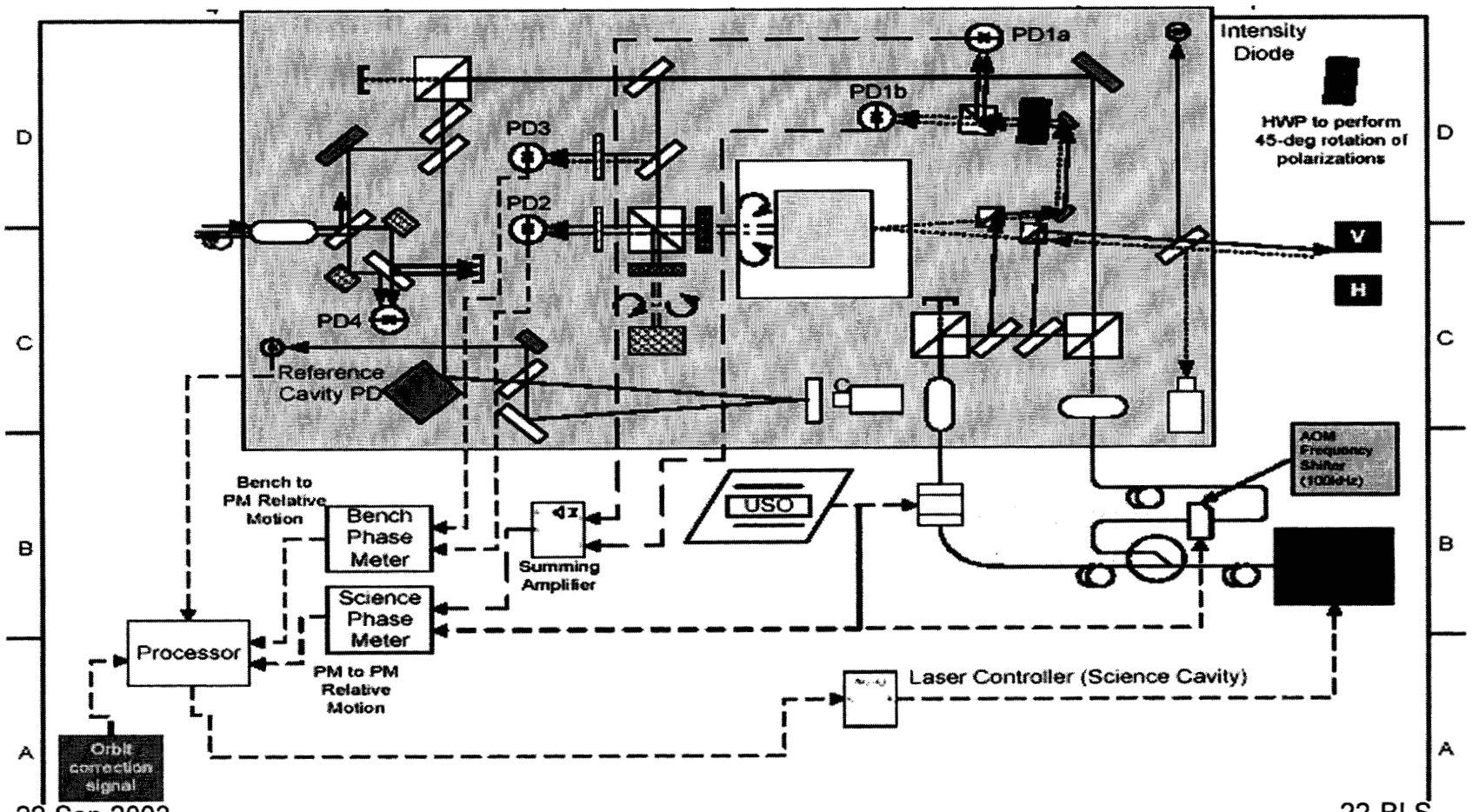


OB mounted horizontally **OB mounted rotated through an angle π/4**

Figure B-6 - Concepts for the OB mounting inside the S/C

7. Remove QWPs from science path to suppress thermal effects and make nearly-common path and (same number of) optics for local and incoming science beams.

- Why? dn/dT ~ 10^{-5}/°K, $\delta T \sim 10^{-5}$°K/√Hz, d~5mm ➔ 0.5pm/rtHz for each pass, ×8 = **4 pm/√Hz** for double passes & four QWPs between the two SC.
- Also, QWPs are different material from the bench, so bonding could add still more phase noise.
- No wave-plates in the PM-PM science measurement will reduce requirement on telescope dimensional stability.
- *n.b.* The HWP occurs after combination of local and distant science beams, so its thermal noise is common. The two remaining non-common optics are identical but in different locations, so produce small differences due to thermal gradients.



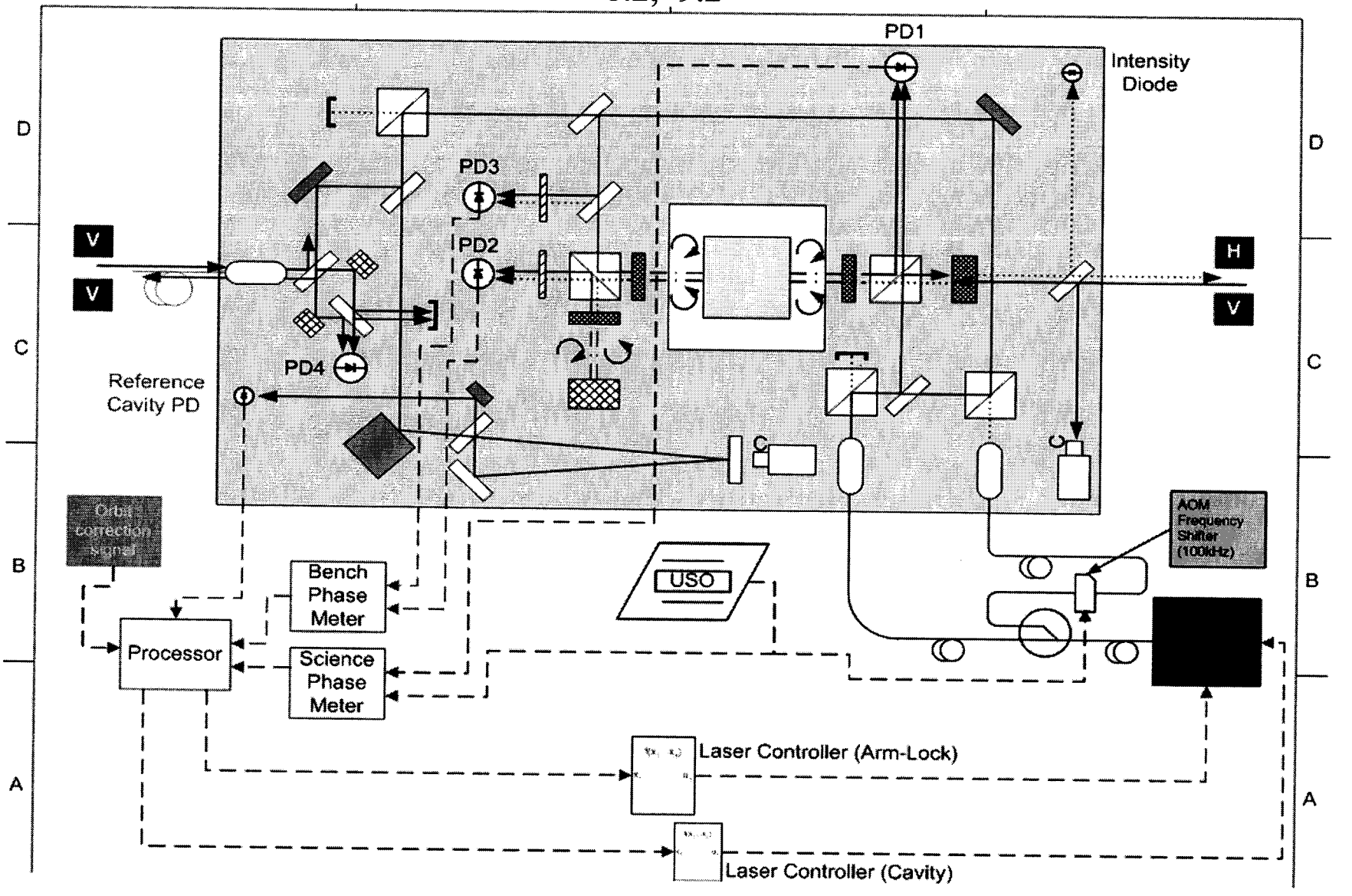
22 Sep 2003

22-BLS

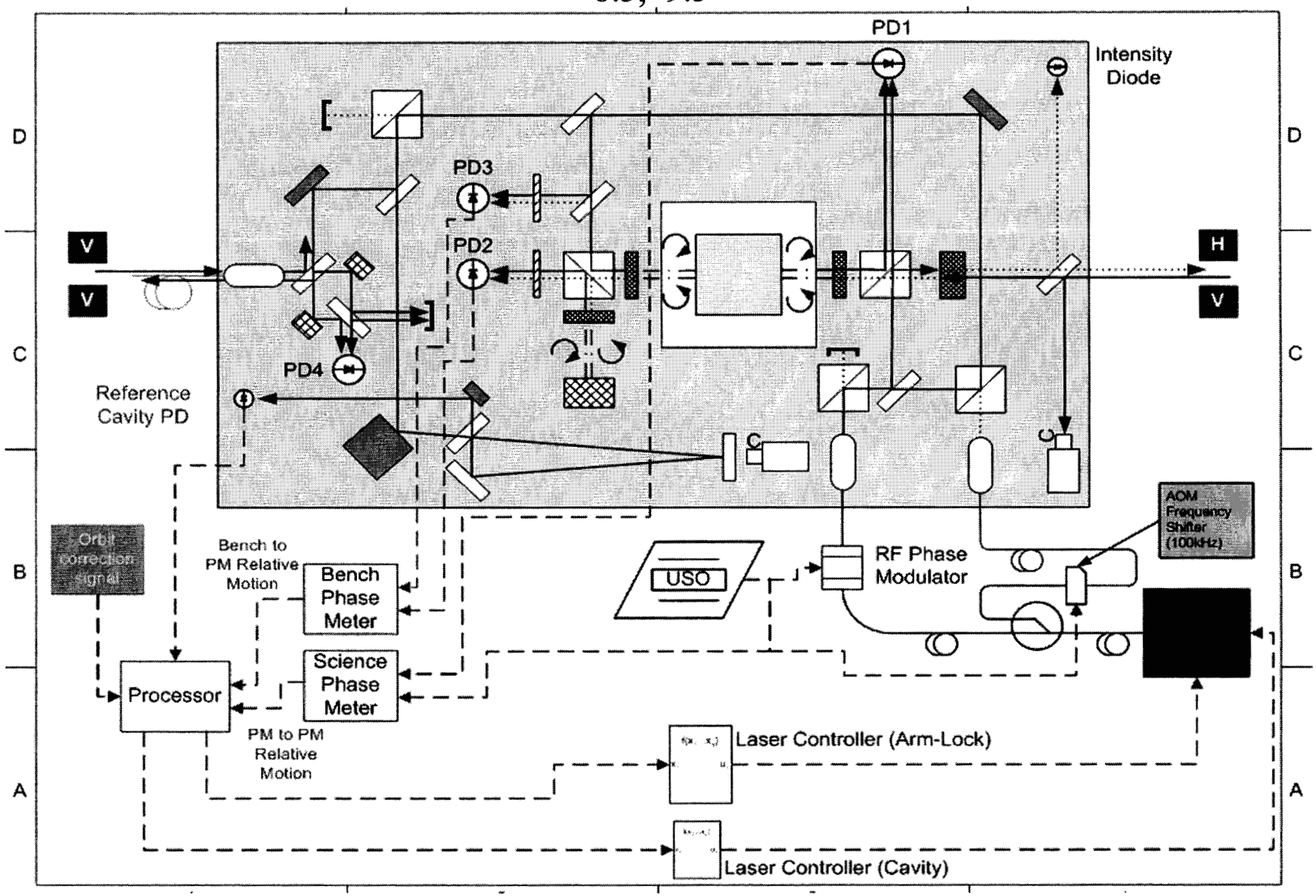
Filename: D1.4-NoWavePlate

Arm-locking to stabilize the laser(s) :

- *Requires calibration of relative PM-bench motion along the sensitive measurement (inter-SC) axis, which information is fed to the arm-locking laser-frequency control loop.*
- *This calibration must be as precise as the LISA science phase measurement across the entire LISA band, nominally 5pm/rtHz * √{1 + (2.7 mHz / f)4} (1/4 of the total budgeted error for a single phase measurement).*

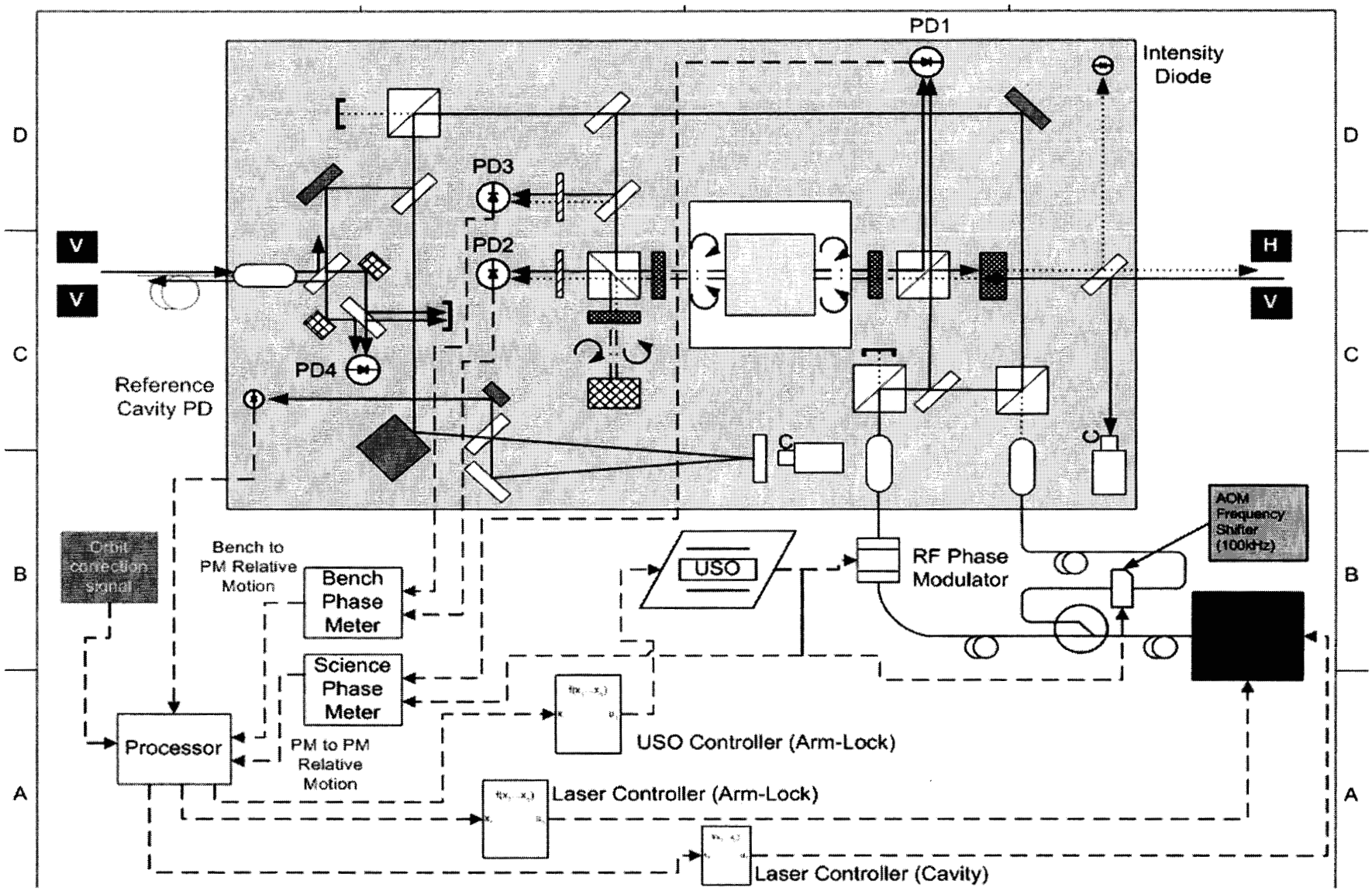


The USO generates frequencies that run the Science Phase Meter and the AOM Frequency Shifter.



The USO generates frequencies that run the Science Phase Meter and the AOM Frequency Shifter. Here, it is also used to generate RF phase-modulated sidebands (~200 MHz) on the science beam.

Filename:B2.4-ArmLockLaser,modUSO



Here the USO, as well as the science laser, is further stabilized by locking to the stable LISA arm.
The error signal is obtained from transponded clock information, *e.g.,* the sideband-sideband beat signal.

Filename:B3.4-ArmLockLaser&USO,modUSO

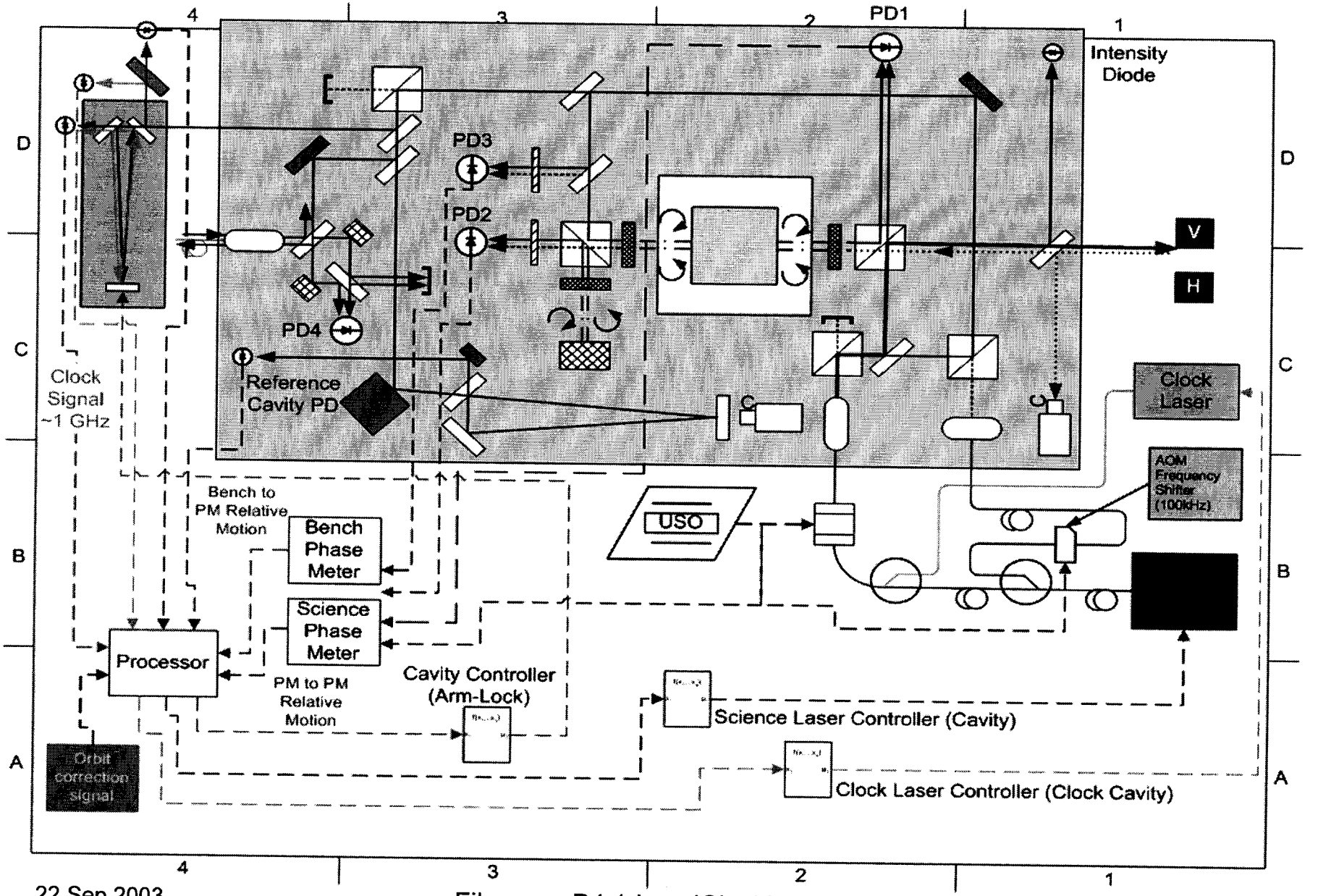
• The next slide (10.2, Filename:B4.1-LocalClockLaser) proposes generating a local "clock" at frequency ~ 1 GHz that could offer improved fractional frequency stability over USOs – *e.g.,* ~ 3×10^{-6}Hz/√Hz at 1mHz, or ~ 3×10^{-15}/√Hz fractional frequency stability at 1mHz, by using the LISA arm to stabilize the laser clock reference cavity (see Slides 10.5, 10.6 below for estimates of achievable laser stabilization with arm-locking*).

• This can be down-converted to provide a local-oscillator at 10-30 MHz whose absolute frequency noise is ~3×10^{-8}Hz/√Hz at 1mHz, which is more than 10 times quieter than can be obtained with a 5-MHz USO stable to 10^{-13}/√Hz.

• Such a clock could be generated by subtracting two adjacent modes of a high-finesse "laser clock reference cavity" that is servo-stabilized to the LISA arm.
(A 25-cm cavity has free-spectral-range c/2L~ 600MHz; hence the choice of 1-10 GHz.)

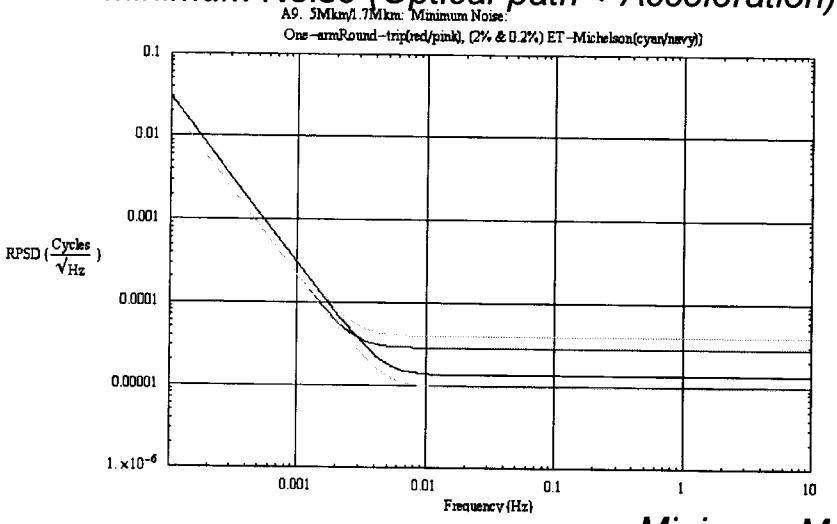
• In this scheme, the pre-stabilized science laser is further stabilized by locking it to the second "clock" cavity, which is controlled with the arm-locking information. The clock laser is locked to another mode of the clock cavity, and the beat between the two laser signals is the new "USO" signal.

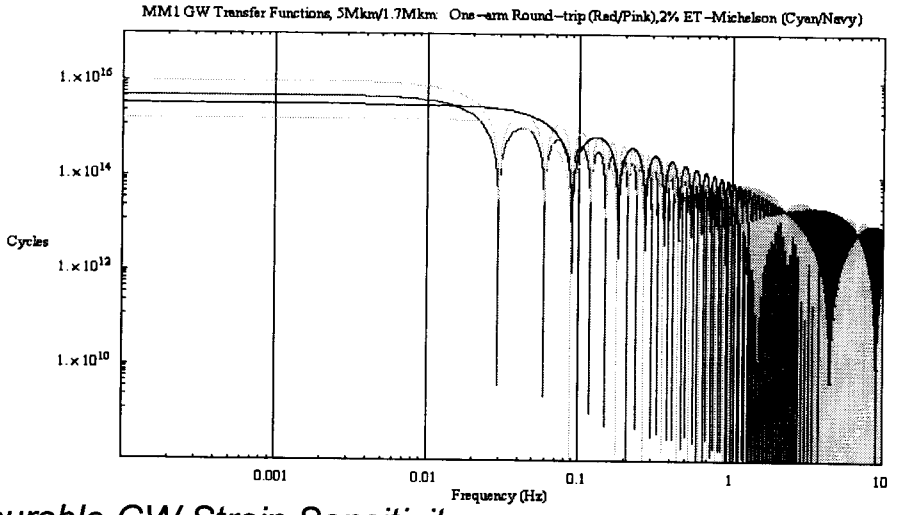
** Arm-locking was described by B. Schumaker in Hannover, December 2002, and in more detail in Pisa, July 2003 and again in Hannover, Sept 2003. Excerpts from those talks are included below as slides 10.3—10.6, with a recent improvement in gain profile. Numerical estimates cited here are inferred from the graphs given there for the obtainable level of suppression and required and achievable frequency stability.*


PD1
Intensity Diode
PD3
PD2
PD4
Reference Cavity PD
V
H
Clock Signal ~1 GHz
Clock Laser
AOM Frequency Shifter (100kHz)
USO
Bench to PM Relative Motion
Bench Phase Meter
Science Phase Meter
Processor
PM to PM Relative Motion
Cavity Controller (Arm-Lock)
Science Laser Controller (Cavity)
Clock Laser Controller (Clock Cavity)
Orbit correction signal

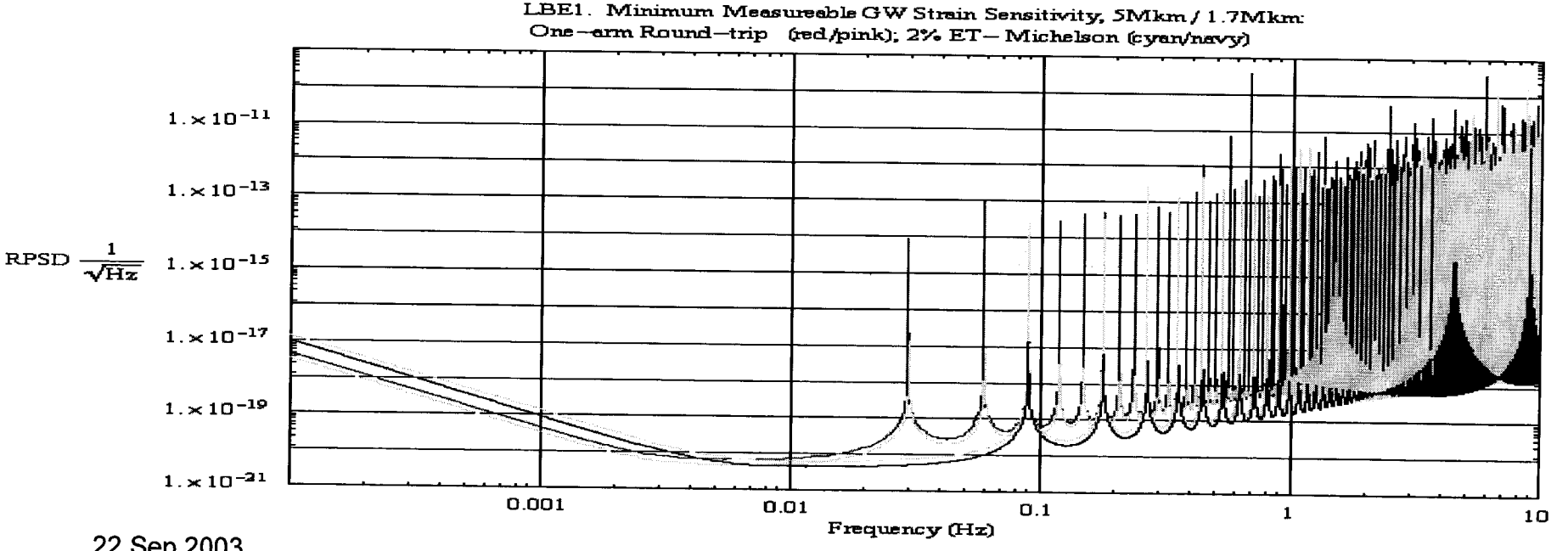
10.3: Appendix A: Excerpt from BLS, Hannover Sep03, LISA S/E Mtg

Minimum Noise (Optical-path + Acceleration) ÷ *GW Transfer Function* =





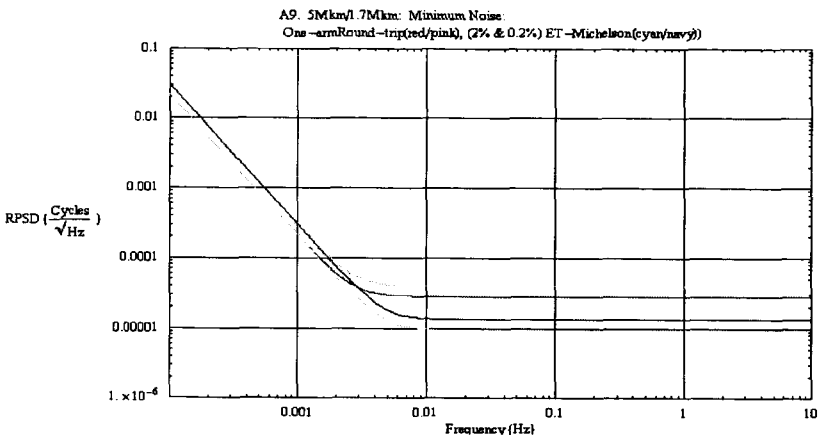
Minimum Measurable GW Strain Sensitivity

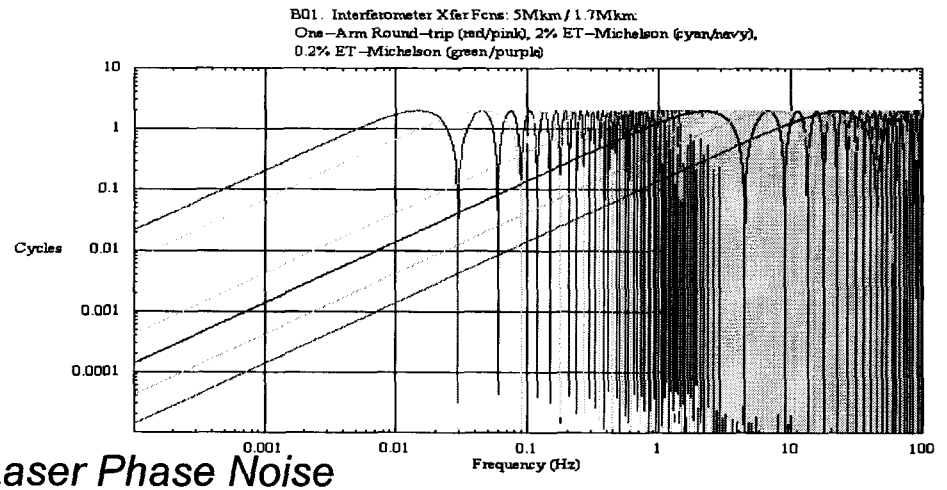


10.4: Excerpt from BLS, Hannover Sep03, LISA S/E Mtg

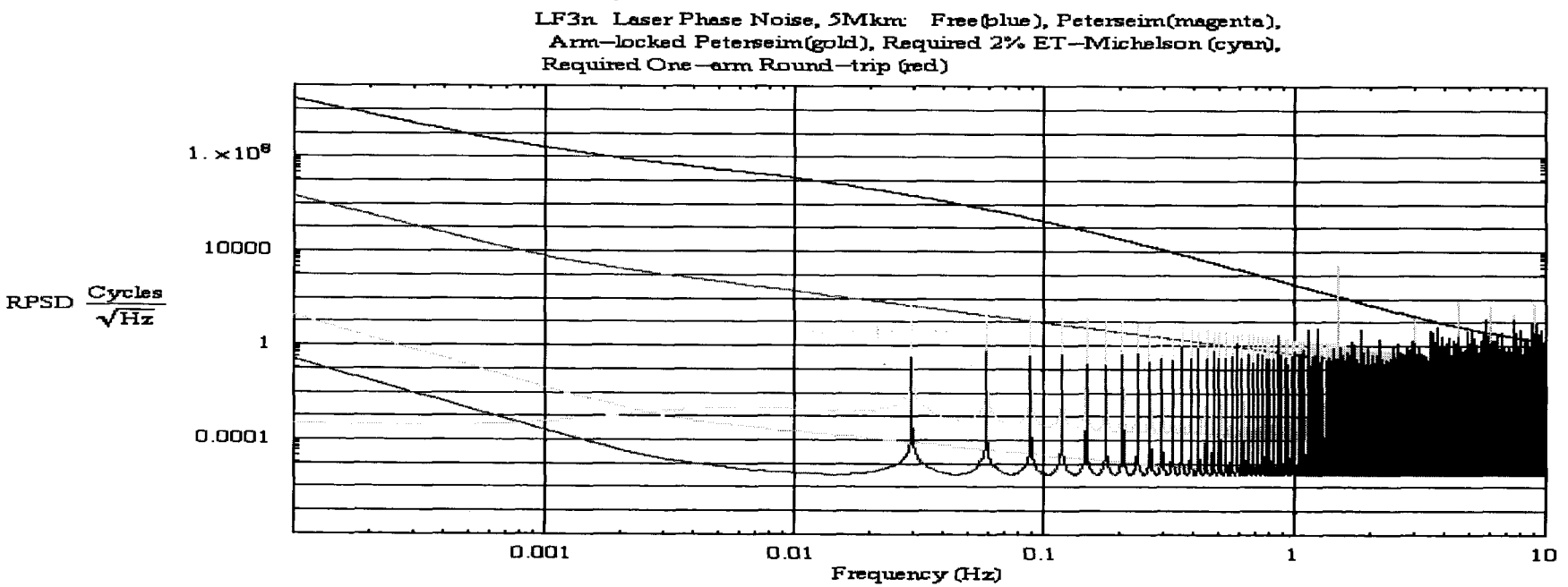
(but with improved arm-locking gain profile, shown in Slide 10.6 below)

Minimum Noise (Optical-path + Acceleration) ÷ *[4 × Laser Phase Noise Transfer Function]* =





Required Laser Phase Noise

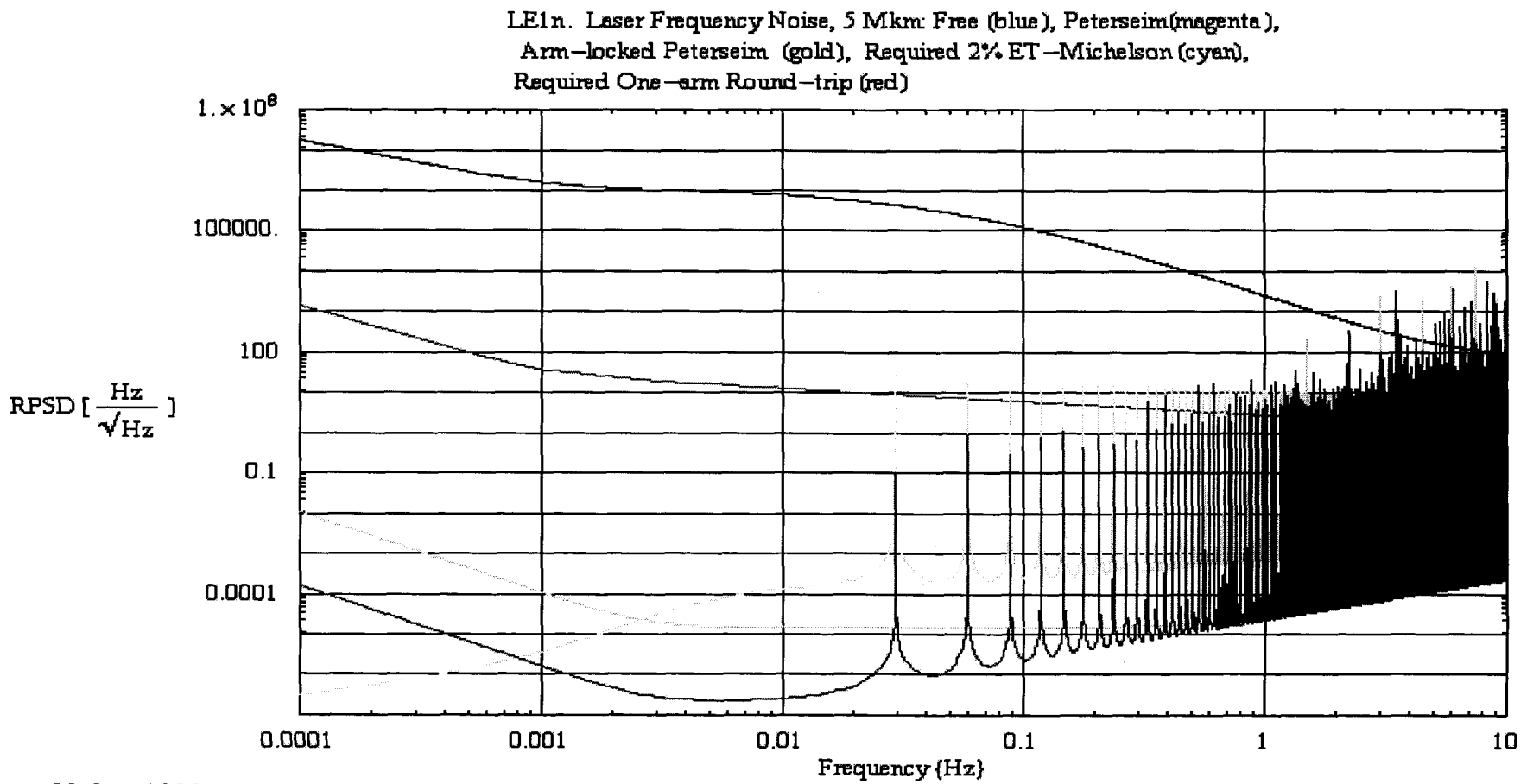


Total Noise in Science Phase Measurement
= rss of Minimum Noise with [Laser Phase Noise x Transfer Fcn]
< 1.03 x Minimum Noise if pre-stabilized Laser Phase Noise < "Req'd Laser Phase Noise"

10.5: Excerpt from BLS, Hannover Sep03, LISA S/E Mtg

(but with improved arm-locking gain profile, shown in Slide 10.6 below)

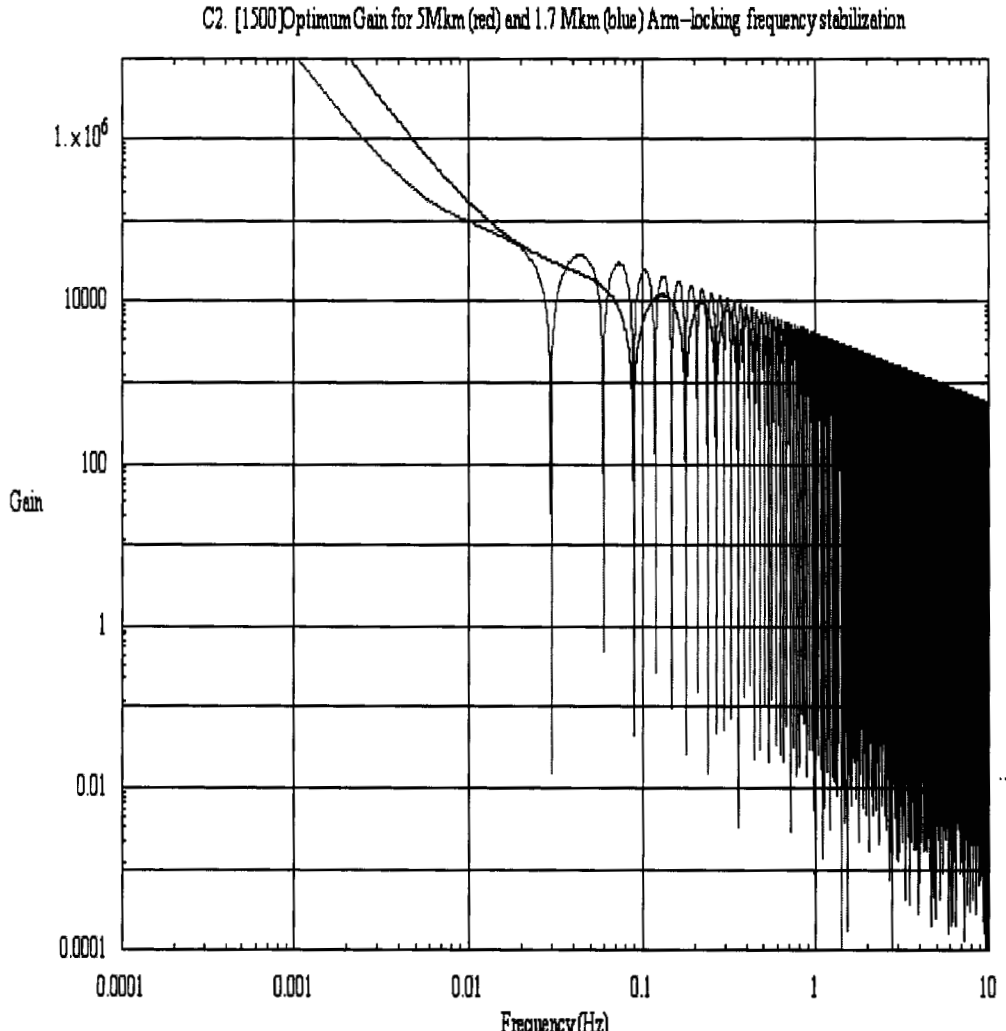
The magenta curve is a level of cavity (pre-) stabilization already achieved (Peterseim; Mueller *et al).*
The gold curve shows the improvement to the magenta curve offered by arm-locking.
The cyan curve is the laser frequency stability required by a 2%-balanced Michelson-type combination, in order to ensure that laser noise raises the total phase-measurement error by no more than 3% over that caused by the combination of irreducible optical-path, shot, and acceleration ("minimum") noise.
Thus, arm-locking surpasses the requirement below ~3mHz; above that, improvement by about a factor of 10 is needed for pre-stabilization (*e.g.,* 1Hz/√Hz at 10 mHz pre-stabilization is needed).

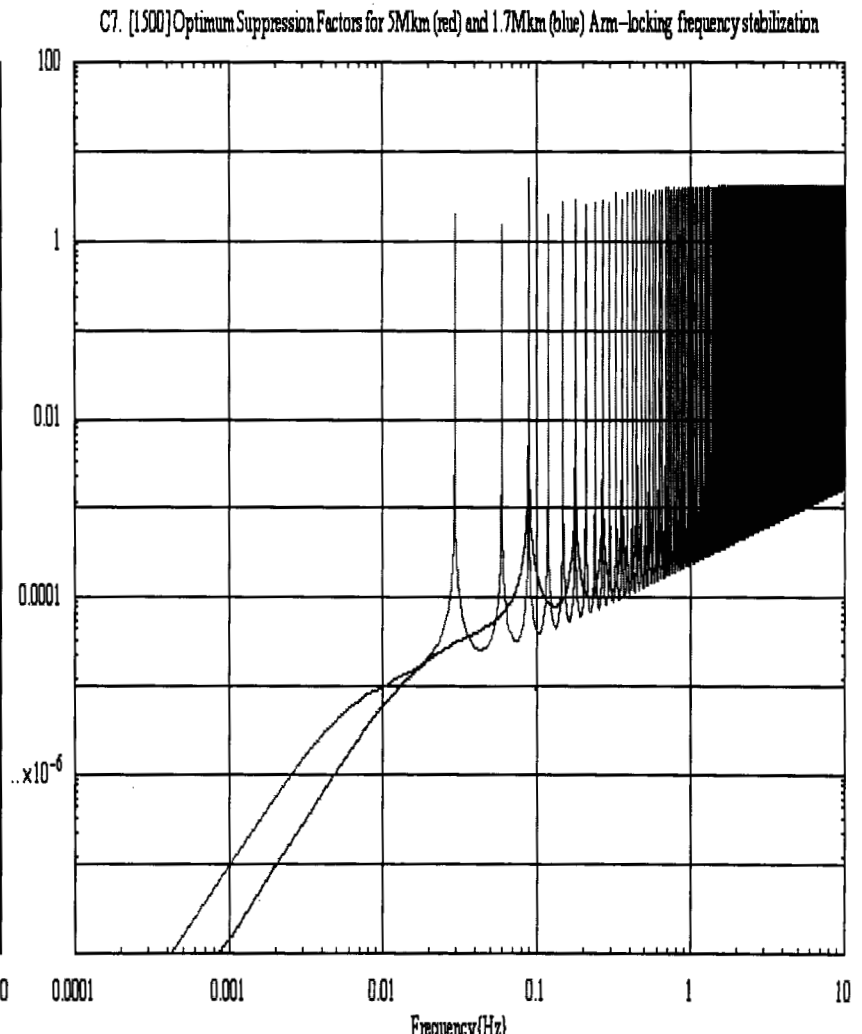


Required Laser Frequency Noise = 2 $\pi f \times$ Required Laser Phase Noise

10.6: Improved arm-locking gain profile (unity-gain at ~10kHz)

Note: This improved gain profile for arm-locking as a unity-gain frequency of ~10 kHz (versus 1kHz previously), among other modifications. It provides noise suppression of ~ 10^7 at 1mHz and ~10^5 at 10mHz





$$H_{n33}[f_] := \frac{8 * 10^{10} * 1500}{(1 + (i * f/0.0001)^{0.85})} * \frac{(1 + i*f/0.015)}{(1 + i*f/0.00001)} * \frac{(1 + i*f/0.004)}{(1 + i*f/0.00001)} * \frac{(1 + i*f/0.007)}{(1 + i*f/0.06)} * \frac{(1 + i*f/0.01)}{(1 + i*f/0.00003)}$$

$$K_{n33}[f_] := H_{n33}[f] * \frac{1 - e^{\frac{-i*2\pi*f*200*1.01}{3}}}{}$$

$$Sup_{Hn33}[f_] := Abs\left[\frac{1}{1 + K_{n33}[f]}\right]$$