ALIGNMENT SENSING/CONTROL DESIGN REQUIREMENTS REVIEW

29 August 1996

I. Introduction (P Fritschel)
II. Requirements: Initial and Acquisition Modes (PF)
III. Conceptual Design: Initial and Acq. Modes (M Zucker)
IV. Requirements: Detection and Diagnostic Modes (PF)
V. Conceptual Design: Detection Mode (D Sigg)
VI. Alignment & Servo Modeling (G González)
VII. Diagnostics, Interfaces & Open Issues (M Zucker)

DCC

ASC: SCOPE AND RESPONSIBILITIES

- Installation Support:
  - ›› determination of interferometer optical axes
  - ›› provide readout of alignment of suspended optics (IOO, COC, *COS*)
- Beam Centering:
  - ›› hardware and algorithms for sensing and controlling the beam position on the suspended optics
- Angular Alignment:
  - ›› sensors and controls for maintaining the mode cleaner and interferometer (COC) angular alignment
- Support commissioning, test and diagnostics of the Detector subsystems

ASC: MODES OF OPERATION

- Initial Alignment Mode

  ›› INSTALLATION: provide a readout (referenced to the beam axes) of the initial pitch and yaw orientation of each suspended optic

  ›› Establish input beam direction: adjust input beam direction (& beamsplitter angle) so that it is down the tubes and on the mirrors

  ›› Adjust the alignment of the COC optics such that they are within the Acquisition Alignment tolerance (degree of alignment which enables length locking - by LSC - of the interferometer)

- Acquisition Alignment Mode

  ›› Holding mode: COC optics are held within the Acquisition Alignment tolerance continuously over the lock acquisition procedure

  ›› Mode cleaner alignment is controlled

ASC: MODES OF OPERATION

- Detection Mode
  - ›› sense and control alignment of the mode cleaner
  - ›› sense and control alignment of the interferometer (COC)
  - ›› sense and control the centering of the beams on the COC optics
  - ›› provide a measure of the alignment and centering
- Diagnostic/Calibration Mode(s)
  - ›› provide diagnostic capability of ASC performance
  - ›› calibration procedures within the ASC
  - ›› provide a measure of the mode matching of the IOO beam to the intererometer
  - ›› support diagnosis of other subsystems

ORIENTATION DEGREES-OF-FREEDOM AND COORDINATES

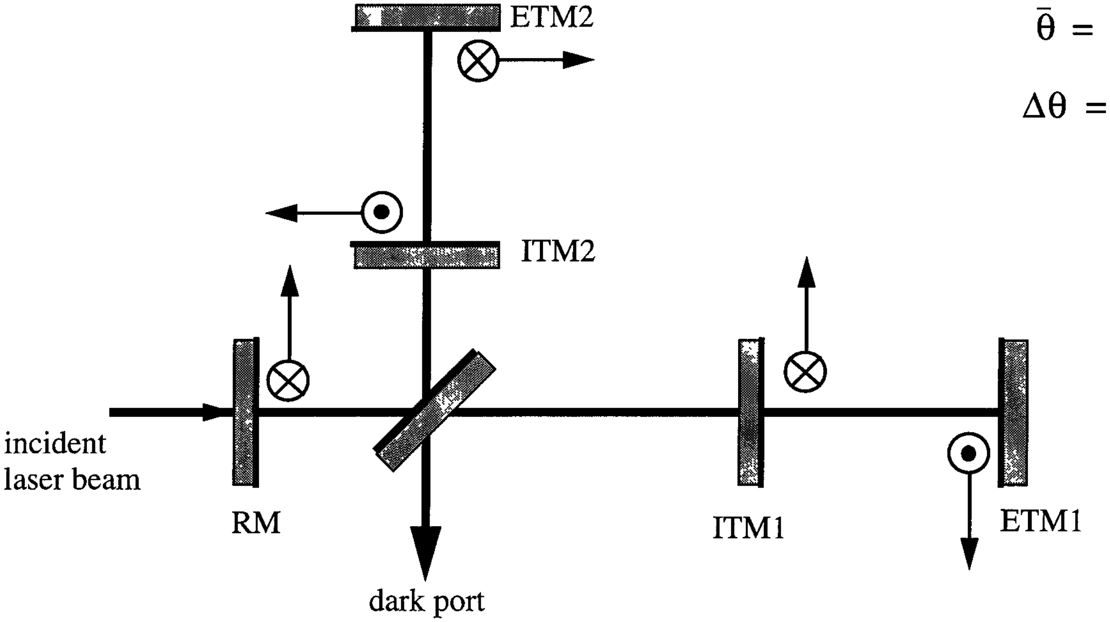
Pitch = θ (Θ normalized)
Yaw = ϕ (Φ normalized)

Div. angle = 9.65 μrad

Common/Differential Basis:

$$\bar{\theta} = (\theta_1 + \theta_2)/\sqrt{2}$$

$$\Delta\theta = (\theta_1 - \theta_2)/\sqrt{2}$$



ASSUMPTIONS & DEPENDENCIES FOR DERIVING REQUIREMENTS

- **Systems:** each noise mechanism - no more than 0.5% degradation of SRD curve
- **LSC:** alignment deviation at which length acquisition is posible: 0.5 μradian per degree-of-freedom per optic
- **IOO:** Input beam direction fluctuations - figure in determining Detection mode alignment requirement
- **SUS:**
  - angular control range
  - controller angular noise
  - thermal noise of pitch/yaw modes
- **COC:**
  - mirror radii of curvature
  - apertures of optics

ASC REQUIREMENTS

Initial and Acquisition Alignment Modes

ASC REQ'S: INITIAL ALIGNMENT - INTERFEROMETER INSTALLATION

- During installation of interferometer optics, the ASC is required to provide the following position information:
  - ›› information for locating an optical component transverse to the beam axis, within ~1 mm of the desired position
  - ›› orientation information, allowing the normal of the coated surface to be aligned with the beam axis to within 10% of the SUS actuator angular dynamic range
    - current SUS range is 2 mrad p-p in pitch and yaw
    - ASC read-out thus must be accurate to within ± 0.1 mrad of the beam axis

ASC REQ'S: IA - TRANSITION TO ACQUISITION ALIGNMENT

- Mode cleaner - attain alignment which enables length locking

  ›› to allow unambiguous locking on TEM_{00} mode, we require that the MC angles be adjusted to within (1/5 x cavity divergence angle) of ideal alignment

- IFO - adjust alignment of COC and input beam to achieve the LSC Acquisition Alignment tolerance

  ›› alignment tolerance is taken to be 0.5 μradian per angular degree-of-freedom (1/20 of the beam divergence angle in the arm cavity)

  ›› modeling work in progress will examine this issue

ASC REQ'S: ACQUISITION ALIGNMENT MODE

- Mode Cleaner is locked and aligned at its final alignment
  - ›› the MC must be aligned such that the TEM_{00} power transmission is no less than 99% of the perfectly aligned case
  - ›› this degree of alignment must be reached within 5 sec of length lock
- COC are maintained within the LSC Acquisition Alignment tolerance
  - ›› Acquisition Alignment is a holding mode for the COC
  - ›› alignment must be held for a time adequate to permit LSC acquistion

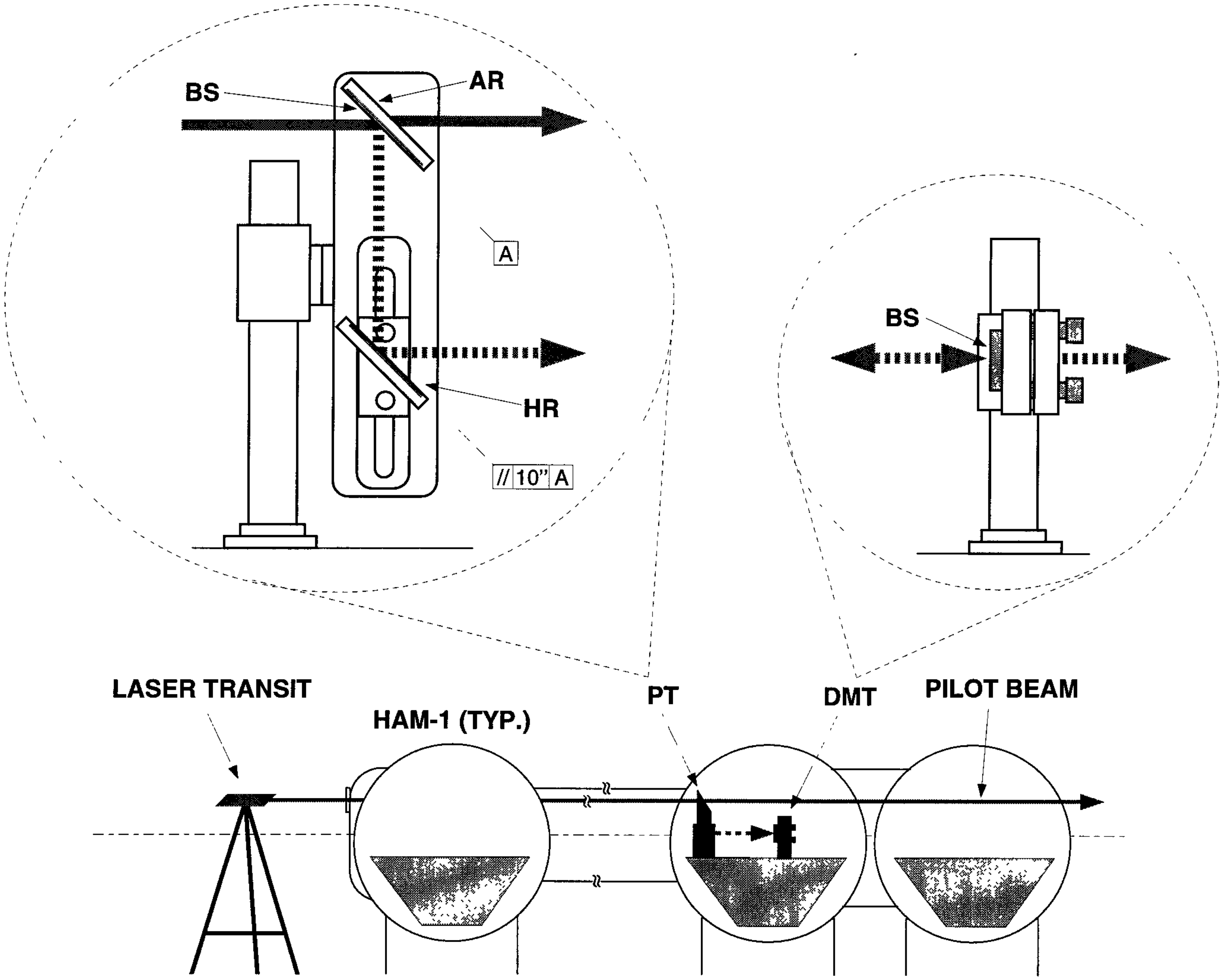
CONCEPTUAL DESIGN: INITIAL AND ACQUISITION ALIGNMENT

- Initial alignment: 3-step procedure
  - ››Support SUS installation setup to ~ 0.1 mrad before pumpdown
    - Surveying tool kit
  - ››Set up “flywheel” references to maintain this accuracy through pumpdown
    - Optical lever systems
  - ››Lock RMI subset interferometer & iterate angles to achieve 0.5 μrad
    - Beam centering video and QPD systems
- Acquisition alignment: hold for LSC to acquire
  - ››Local SUS damping adequate over relevant timescales
  - ››Backup: use optical lever readouts to hold some or all DOF

INITIAL ALIGNMENT: SUS INSTALLATION SUPPORT

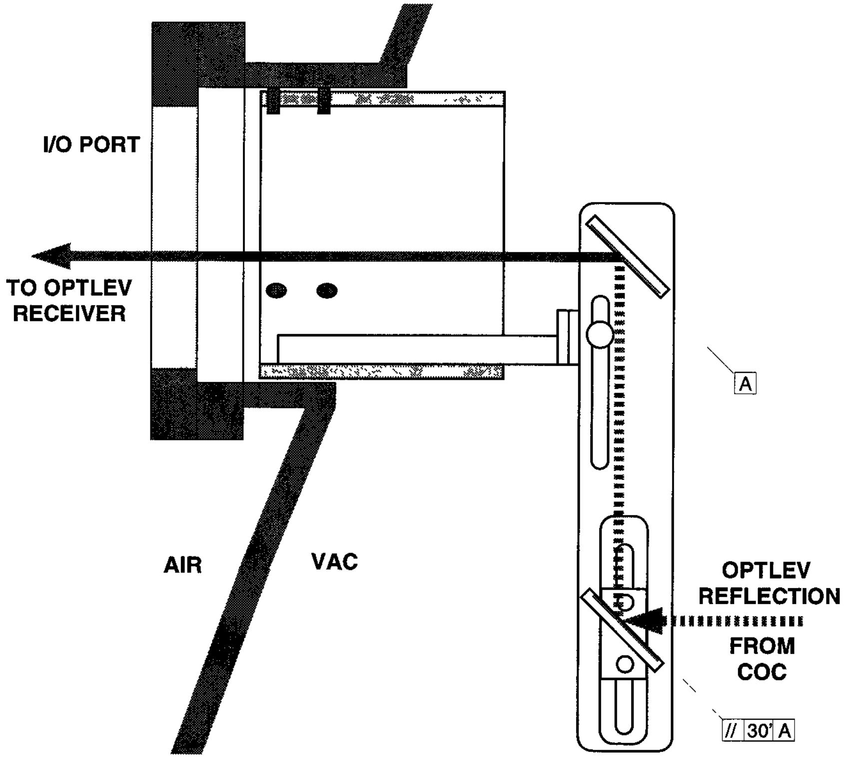
- Starting point: facility monuments (previously used by PSI)
  - ››Monument layout & specsTBD, but PSI requirements (+/- 2 mm transverse WRT BT axes) reasonably consistent with ours
- Conventional surveying to set up "Pilot Beams" || BT axes
  - ››Commercial tooling usable or readily adaptable
- Lateral transfer optics (*periscope tools*) give pilot beam samples at component locations
- Stunt-mirrors (*dummy mirror tools*) to set up & null optical levers
- Install COC using optical lever readouts
- (*check optical levers after pumpdown*)

INITIAL ALIGNMENT: SETUP AND TOOLING

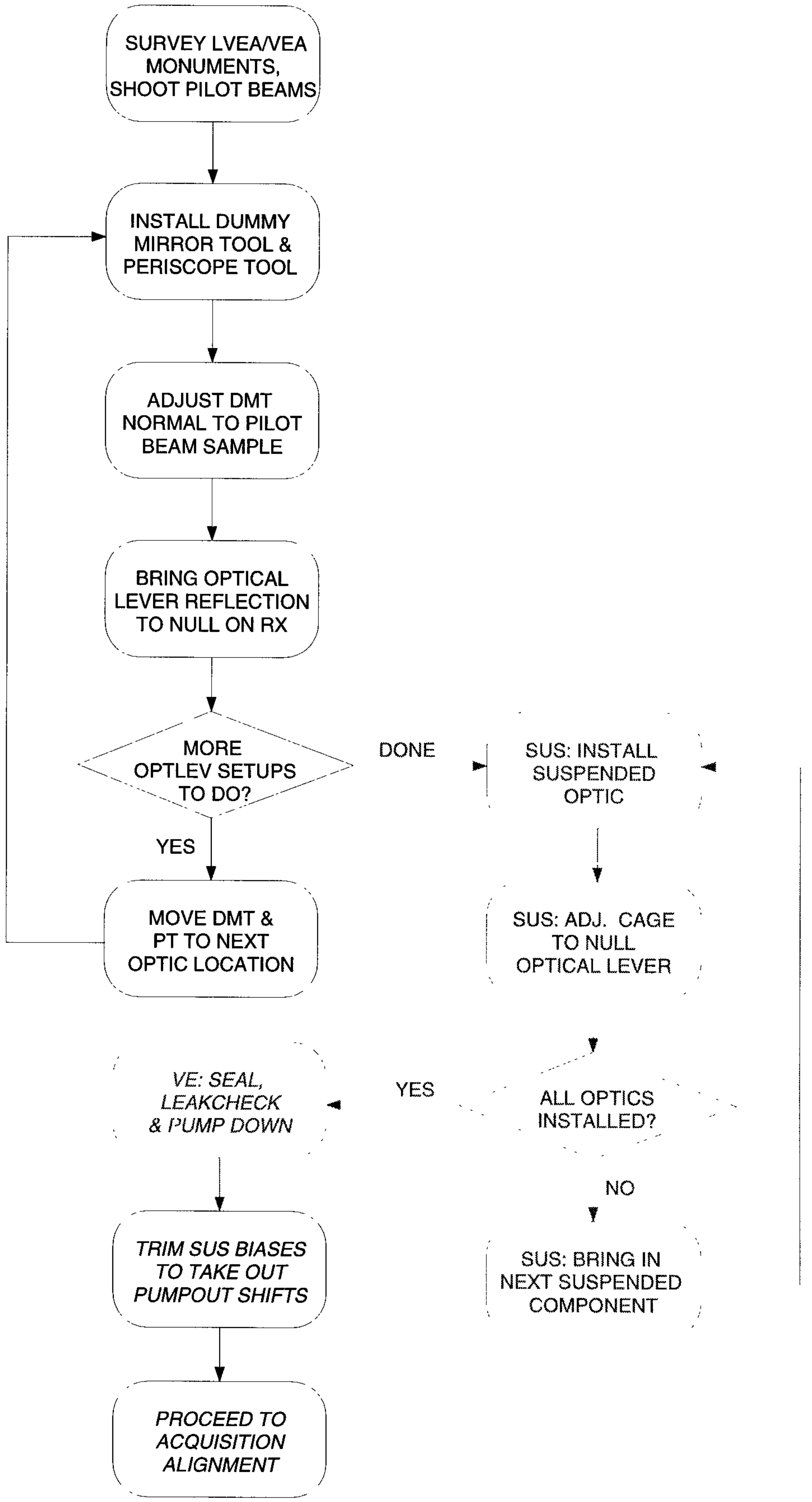


INITIAL ALIGNMENT: OPTICAL LEVERS

- Short-arm (~ 2-4 m) “local” systems; fiber-coupled LD Tx, QPD Rx, mounted to external demountable pedestals
- Port-mounted internal “reach” periscopes grab output beams where req’d.



INITIAL ALIGNMENT: INSTALLATION PROCEDURE



SURVEY LVEA/VEA MONUMENTS, SHOOT PILOT BEAMS

INSTALL DUMMY MIRROR TOOL & PERISCOPE TOOL

ADJUST DMT NORMAL TO PILOT BEAM SAMPLE

BRING OPTICAL LEVER REFLECTION TO NULL ON RX

MORE OPTLEV SETUPS TO DO?

YES

MOVE DMT & PT TO NEXT OPTIC LOCATION

DONE

SUS: INSTALL SUSPENDED OPTIC

SUS: ADJ. CAGE TO NULL OPTICAL LEVER

ALL OPTICS INSTALLED?

NO

SUS: BRING IN NEXT SUSPENDED COMPONENT

YES

VE: SEAL, LEAKCHECK & PUMP DOWN

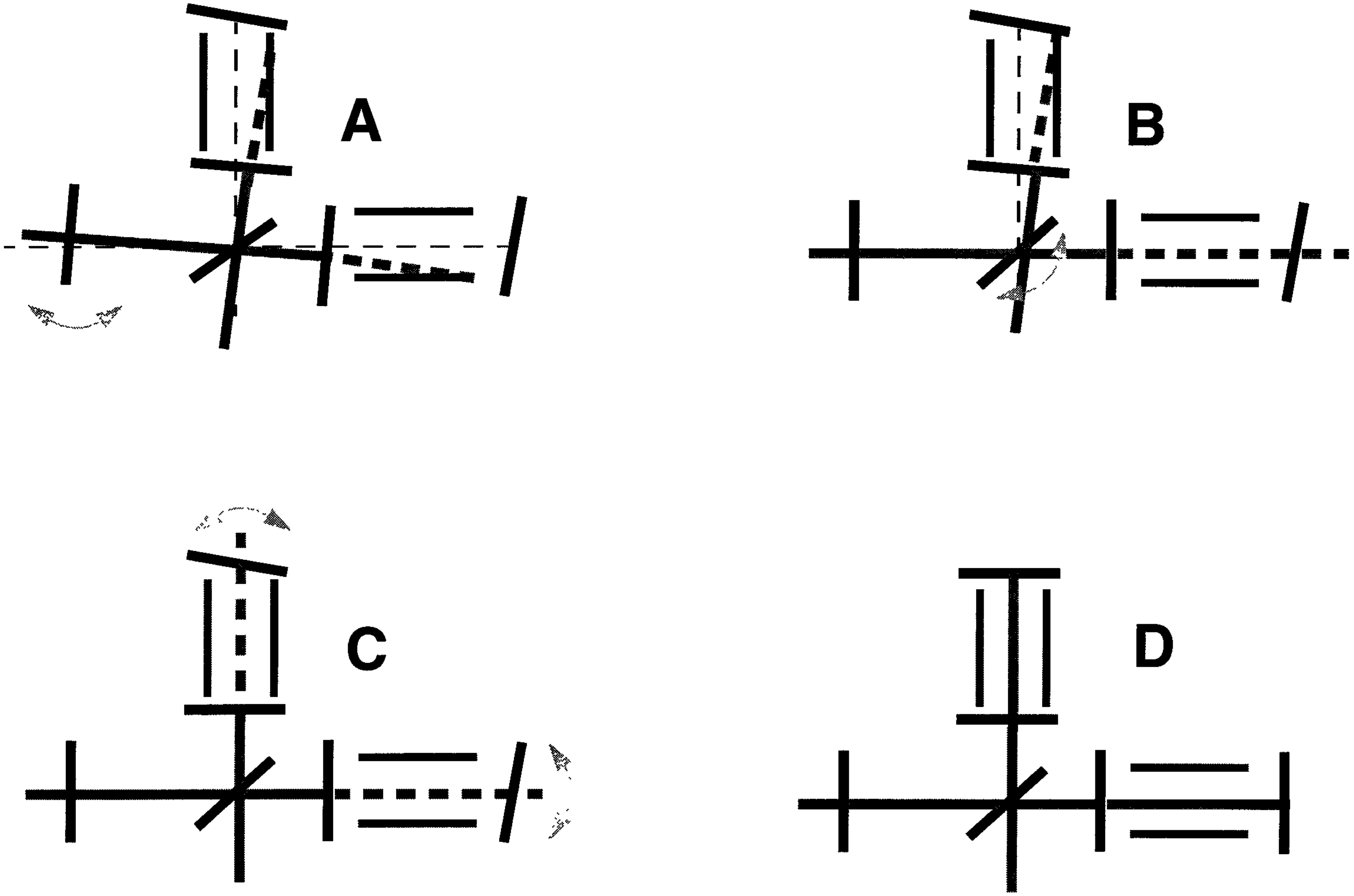
TRIM SUS BIASES TO TAKE OUT PUMPOUT SHIFTS

PROCEED TO ACQUISITION ALIGNMENT

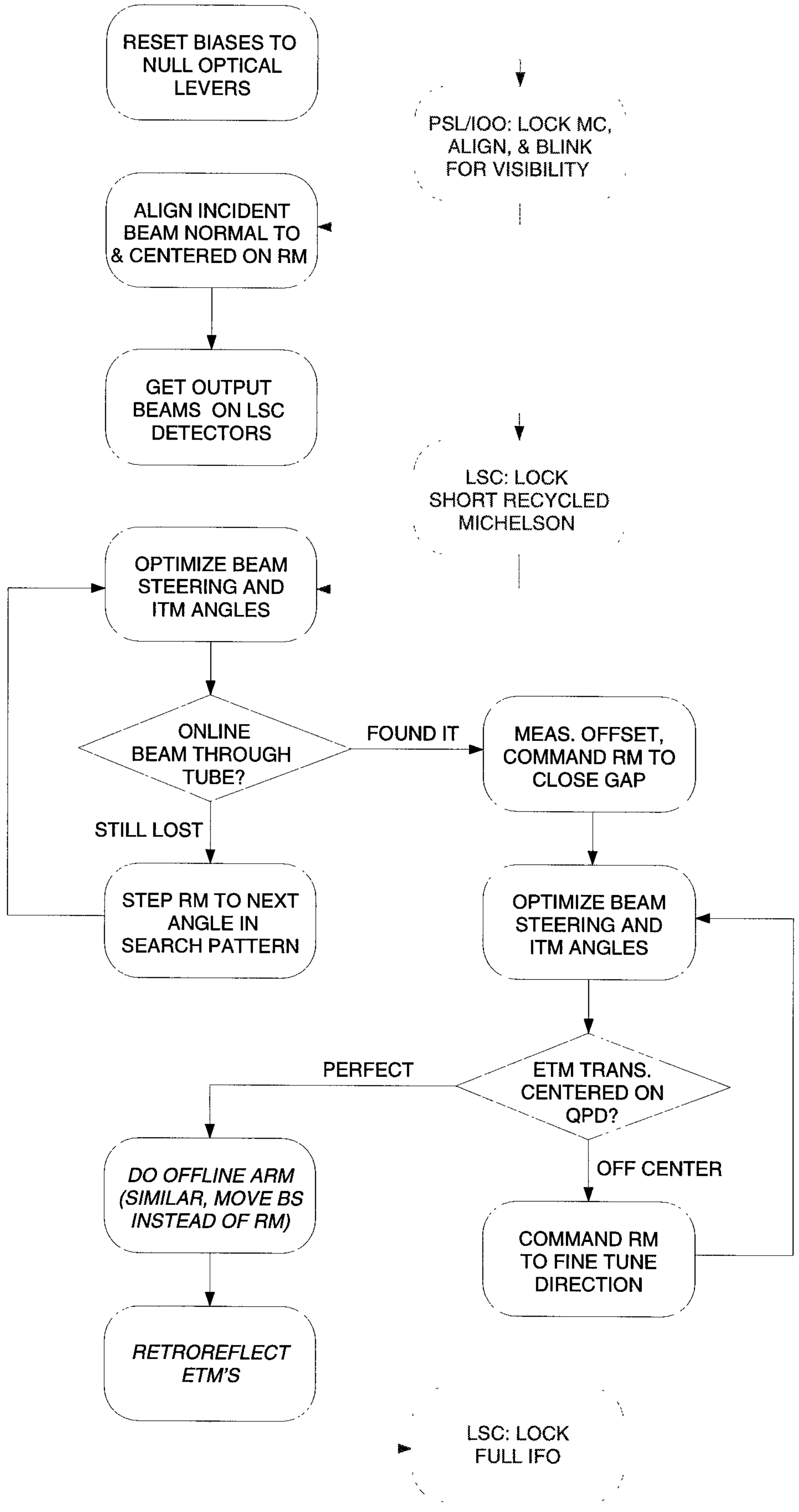
INITIAL ALIGNMENT: THREADING THE BEAM TUBES

- Lock up the recycled short Michelson (like the PNI)
  - Engage WFS control on short RMI after locking to hold relative alignment
- Seek transmitted/scattered light (watts!) at ETM locations
  - Video cameras monitor interior wall of ETM chamber
- Iterate whole RMI to repoint beams (search pattern if req'd)
  - tube clear aperture dia. = 0.25 mrad, odds not bad for hole-in-one
- When through beams detected, measure positions & reckon/goto ETM center
  - Bring to null on ETM transmission QPD
- Rotate ETM's to retroreflection
- Engage LSC...

INITIAL ALIGNMENT: THREADING THE BEAM TUBES (CONT'D)



INITIAL ALIGNMENT: ACQUISITION PROCEDURE



RESET BIASES TO NULL OPTICAL LEVERS

PSL/IOO: LOCK MC, ALIGN, & BLINK FOR VISIBILITY

ALIGN INCIDENT BEAM NORMAL TO & CENTERED ON RM

GET OUTPUT BEAMS ON LSC DETECTORS

LSC: LOCK SHORT RECYCLED MICHELSON

OPTIMIZE BEAM STEERING AND ITM ANGLES

ONLINE BEAM THROUGH TUBE?

FOUND IT

MEAS. OFFSET, COMMAND RM TO CLOSE GAP

STILL LOST

STEP RM TO NEXT ANGLE IN SEARCH PATTERN

OPTIMIZE BEAM STEERING AND ITM ANGLES

ETM TRANS. CENTERED ON QPD?

PERFECT

OFF CENTER

DO OFFLINE ARM (SIMILAR, MOVE BS INSTEAD OF RM)

COMMAND RM TO FINE TUNE DIRECTION

RETROREFLECT ETM'S

LSC: LOCK FULL IFO

ASC REQUIREMENTS

Detection & Diagnostic Mode Requirements

NOISE BUDGET ALLOCATION
SUMMARY OF 0.5% DEGRADATION MECHANISMS

- **ASC.** Mode cleaner misalignment ⇒ power loss
- **ASC.** COC misalignment ⇒ power loss
- **ASC.** Allotment of anti-symmtric port light for ASC detection ⇒ power loss in GW detection
- **ASC & IOO.** COC misalignment + input beam direction fluctuations ⇒ phase noise
- **ASC & SUS.** Beam de-centering + angular noise ⇒ displacement noise
- **ASC & SUS.** ASC control system noise + SUS controller cross-coupling ⇒ displacement noise

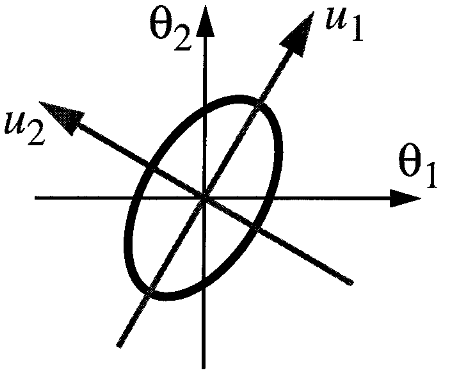
ASC REQ'S: DETECTION MODE ALIGNMENT REQUIREMENTS

- **Mode Cleaner** - no more than 1% power transmission loss due to misalignment (div. angle ≈ 180 μrad ⇒ req. ~ 10 μrad/d.o.f.)

- **Core Optics Components** - two main effects:

›› *Beam pointing sensitivity.* Misalignments create a first order sensitivity to fluctuations of the input beam direction.

›› *Shot noise limited sensitivity.* Misalignments reduce the power in the cavities, quadratically with each d.o.f.



u_i, basis of ellipsoid axes

Ψ_i ,angles in u_i basis

σ_i, lengths (variances) of ellipsoid axes, norm. units

$$\frac{SNR_{\text{misaligned}}}{SNR_{\text{aligned}}} = 1 - 2\sum_{i=1}^{5}\left(\frac{\Psi_i}{\sigma_i}\right)^2$$

COC ALIGNMENT REQ. – VARIANCE ELLIPSOID

	variance σ_i^2	ellipsoid axis					u_i
		$\Delta\theta_{ETM}$	$\Delta\theta_{ITM}$	$\overline{\theta}_{ETM}$	$\overline{\theta}_{ITM}$	RM	
signal-to-noise	6.34	0	0	**0.39**	**– 0.74**	**– 0.54**	u_5
	0.790	0.014	– 0.030	**0.92**	**0.32**	**0.23**	u_4
	0.160	**0.41**	**– 0.91**	– 0.03	0	– 0.01	u_3
	0.00107	**0.91**	**0.41**	0	0	0	u_2
	0.00074	0	0	0	**– 0.59**	**0.81**	u_1

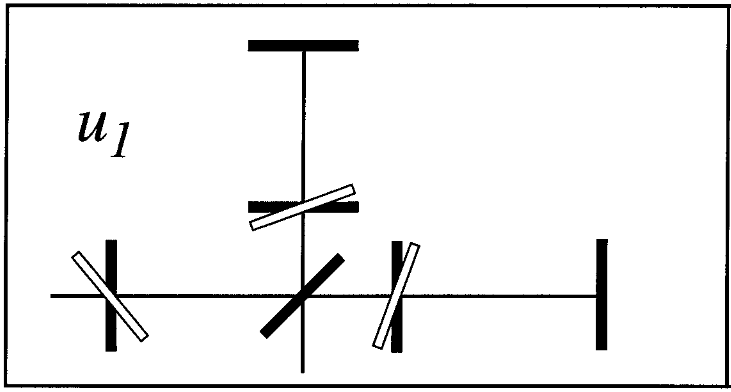
Requirement:

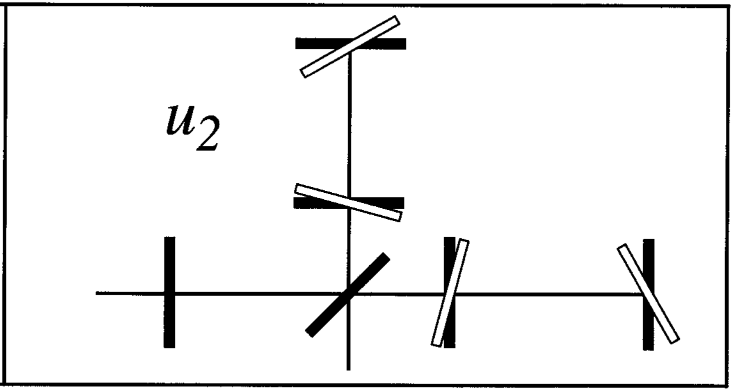
$$2\sum_{i=1}^{5}\left(\frac{\psi_i}{\sigma_i}\right)^2 \le 0.5\%$$

if all angles have same rms misalignment,

$$\Delta\theta \le \sqrt{\frac{0.005}{2\sum(1/\sigma_i^2)}}$$

or can distribute pain according to variance





ALIGNMENT REQUIREMENT – BEAM JITTER COUPLING

- Misalignment + beam jitter = phase noise < SRD/10
- Effect has been computed with modal model, including an audio sideband model of the input beam jitter
- Result is expressed as the equivalent displacement signal:

$$\delta L_{-} \approx 7.1\times10^{-21}\left(\frac{\Psi_2}{10^{-8}\ \mathrm{rad}}\right)\left(\frac{\alpha + 0.16x}{4\times10^{-9}/\sqrt{\mathrm{Hz}}}\right)\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

α = input beam tilt, units of beam divergence angle
x = input beam translation, units of waist size

- Approach is to keep ψ_2 at the level driven by shot noise (10^{-8} rad), and require beam jitter to satisfy above

SUMMARY OF ALIGNMENT REQUIREMENTS

Degree of freedom	***Allowed misalignment, rms***	***Degradation of shot noise sensitivity***	***Beam jitter - Misalignment noise at 150 Hz***
$\Delta\theta_{ETM}$, $\Delta\phi_{ETM}$	**1.0×10^{-8} rad (each d.o.f.)**	0.5% (sum over all d.o.f.)	$\delta L_{-} = 1 \times 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
$\bar{\theta}_{ETM}$, $\bar{\phi}_{ETM}$			—
$\Delta\theta_{ITM}$, $\Delta\phi_{ITM}$			$\delta L_{-} = 1.6 \times 10^{-21}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
$\bar{\theta}_{ITM}$, $\bar{\phi}_{ITM}$			—
θ_{RM} , ϕ_{RM}			—
u_1	**1.0×10^{-8} rad**	0.14%	—
u_2	**1.0×10^{-8} rad**	0.1%	$\delta L_{-} = 1 \times 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
u_3	3.0×10^{-8} rad	0.007%	—
u_4	5.0×10^{-8} rad	0.003%	—
u_5	1.0×10^{-7} rad	0.002%	—

BEAM CENTERING REQUIREMENTS

- *Lever arm effect:* angle noise + beam offset from c.o.r. = displacement noise < SRD/10
  - ›› Thermal noise of pitch and yaw modes
  - ›› Coil driver noise
  - ›› Seismic noise
- *Diffraction:* increased diffraction loss for a de-centered beam
- **COC: Test Masses.** Lever arm effect is the driver –
  - ›› at 40 Hz: thermal noise + coil driver = $3.6\times10^{-17}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$ (SUS DRD)
  - ›› angle noise x offset < $5\times10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
  - ›› offset from center of rotation (d) < 1.4 mm

⇒ **take requirement to be $d \leq$ 1.0 mm for test masses**

CENTERING REQUIREMENTS CONT'D

- **Beamsplitter & Recycling mirror.** Diffraction is the driver (displacement noise can be much higher than for TMs).

  ›› BS aperture loss is below 100 ppm (COC req) for offset up to 1 cm from minimum loss position (COC DRD)

  ›› FFT tests of aperture shifts – no significant effects seen for an offset of 1cm

⇒ **take requirement to be $d \leq 5.0$ mm for the BS and RM**

- **Mode Cleaner mirrors.** Lever arm effect.

  ›› ASC/SUS lever arm noise is alloted 20% for pitch and 10% for yaw of the displacement noise leading to $10^{-4}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ stability requirement

  ›› given the SUS thermal noise reqs. for the MC mirrors:

⇒ **requirement is $d \leq 3.0$ mm for mode cleaner mirrors**

CONTROL SYSTEM NOISE ALLOCATION

- Displacement noise in GW band
  - ›› **test masses & BS:** (ASC angle noise + SUS x-coupling) – no greater than SRD/10
  - ›› **recycling mirror & steering mirrors:** no greater than thermal noise req.
- Angular noise in GW band
  - ›› small enough that centering tolerance is not affected
  - ›› < 50% of thermal/coil driver/seismic angle noise
- Analogous requirements for mode cleaner control signals
- Power allocation
  - ›› ASC can take no more than 1% of the anti-symmetric port power

DIAGNOSTIC & COMMISSIONING REQUIREMENTS

- Provide a measure of the mode matching of the input beam to the interferometer
- Determine offsets from lock-points from optimal alignment
- Determine GW band noise produced by control systems
- Monitor applied feedback torques
- Determine closed loop control loop transfer functions
- Capability to produce controlled misalignments of all degrees-of-freedom

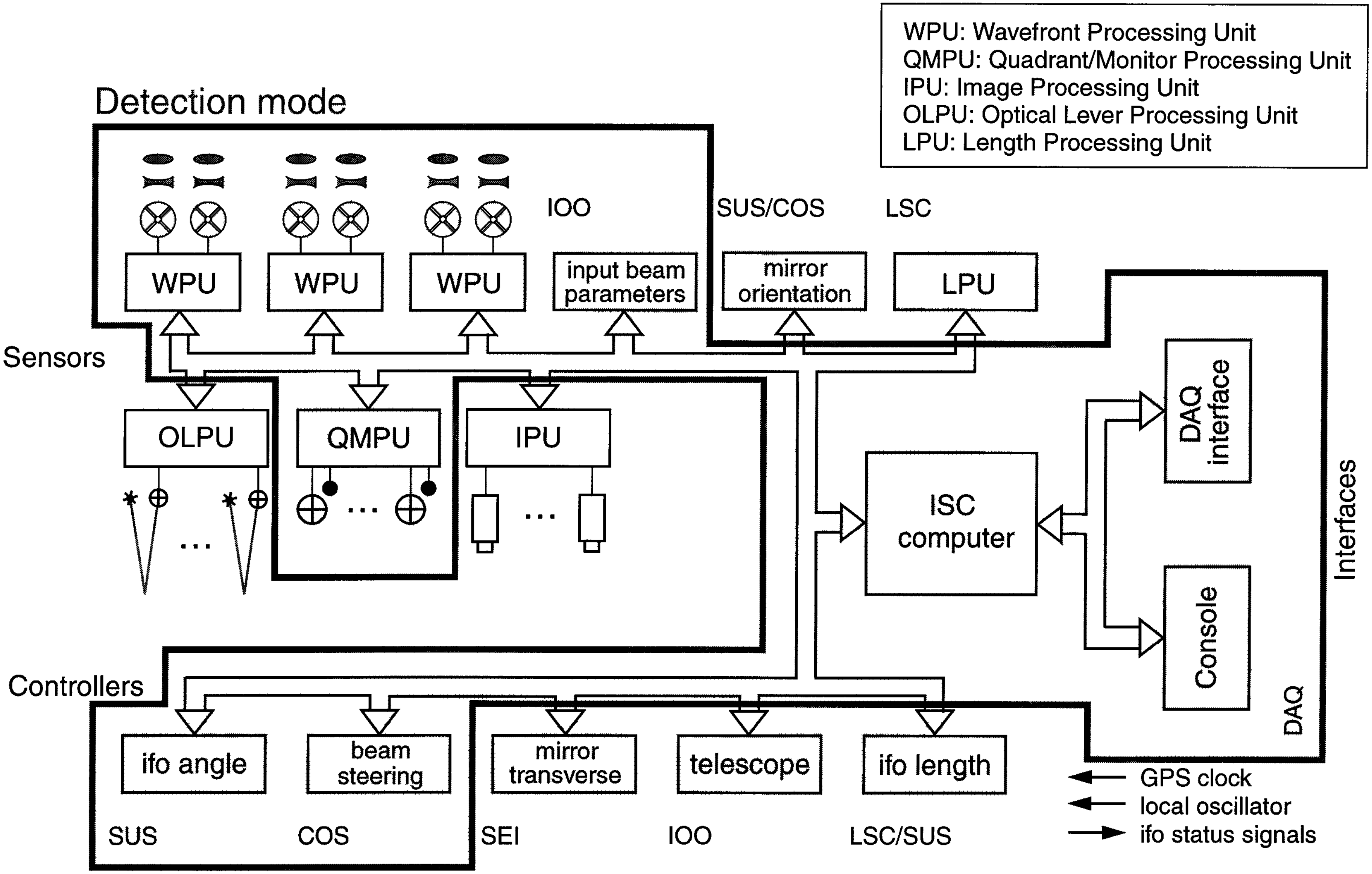
ASC CONCEPTUAL DESIGN DETECTION MODE

ASC DRD II — August 29, 1996

Daniel Sigg

- ☐ Part 1: Design Overview
  - ○ Description/features of the ASC detection mode
  - ○ Detectors (sensors), data links and data processing
- ☐ Part 2: Modeling
  - ○ Alignment matrix
  - ○ Beam direction

ASC SYSTEM OVERVIEW



WPU: Wavefront Processing Unit
QMPU: Quadrant/Monitor Processing Unit
IPU: Image Processing Unit
OLPU: Optical Lever Processing Unit
LPU: Length Processing Unit

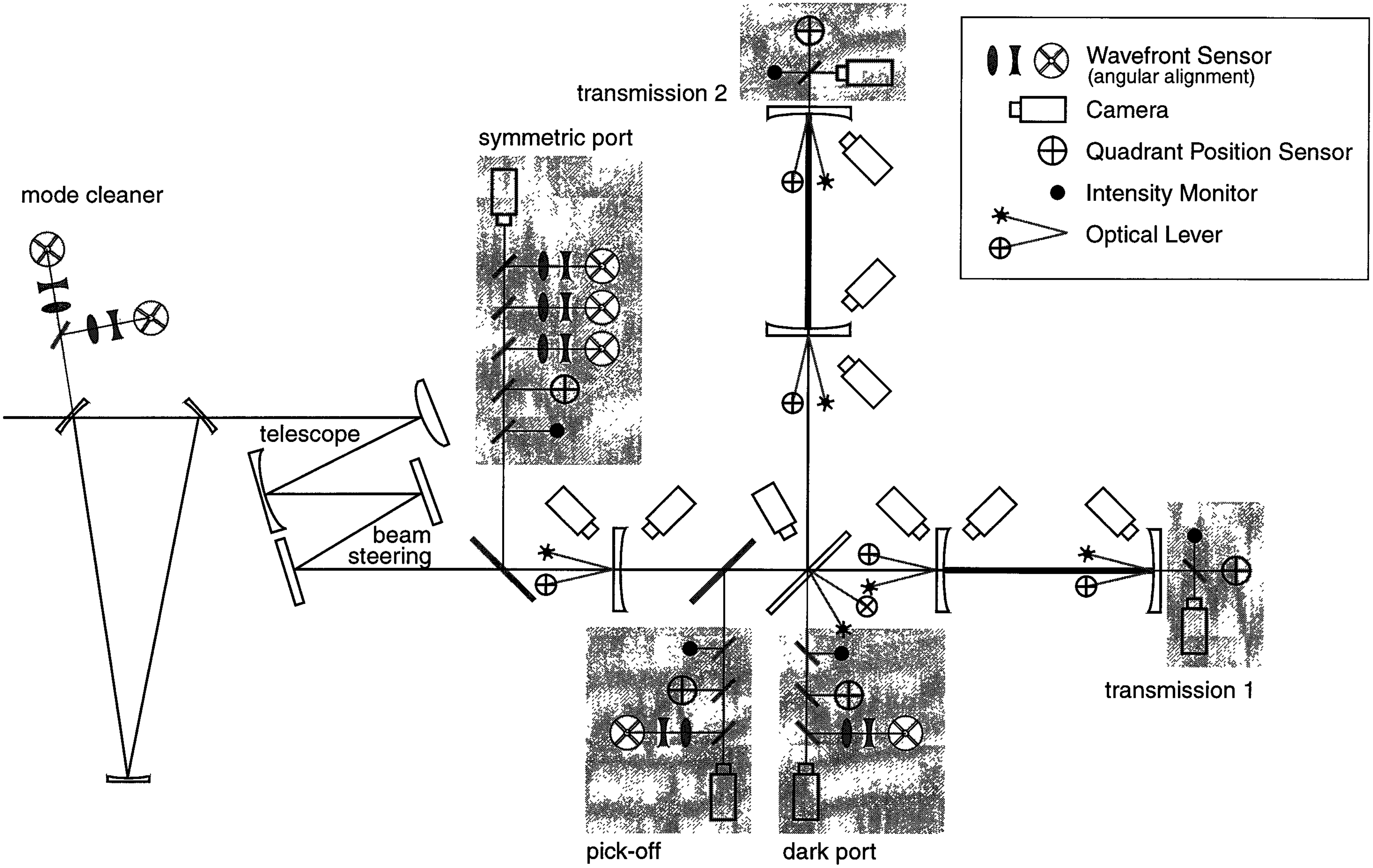
DESCRIPTION/FEATURES OF ASC DETECTION MODE

- ❑ Angular (mis)alignment
  - ❍ Wavefront sensing: measuring TEM_{10}/TEM_{01} excitation in the ifo
  - ❍ Adjust RM, ITM and ETM relative to the input beam direction
- ❑ Beam direction
  - ❍ Quadrant sensors at arm cavity transmission and ifo reflection
  - ❍ Adjust input beam direction and beamsplitter orientation.
- ❑ Not used for control during detection mode
  - ❍ Optical lever data / local suspension sensors
  - ❍ Beam centering on ITM and BS
  - ❍ Mode matching of the input beam

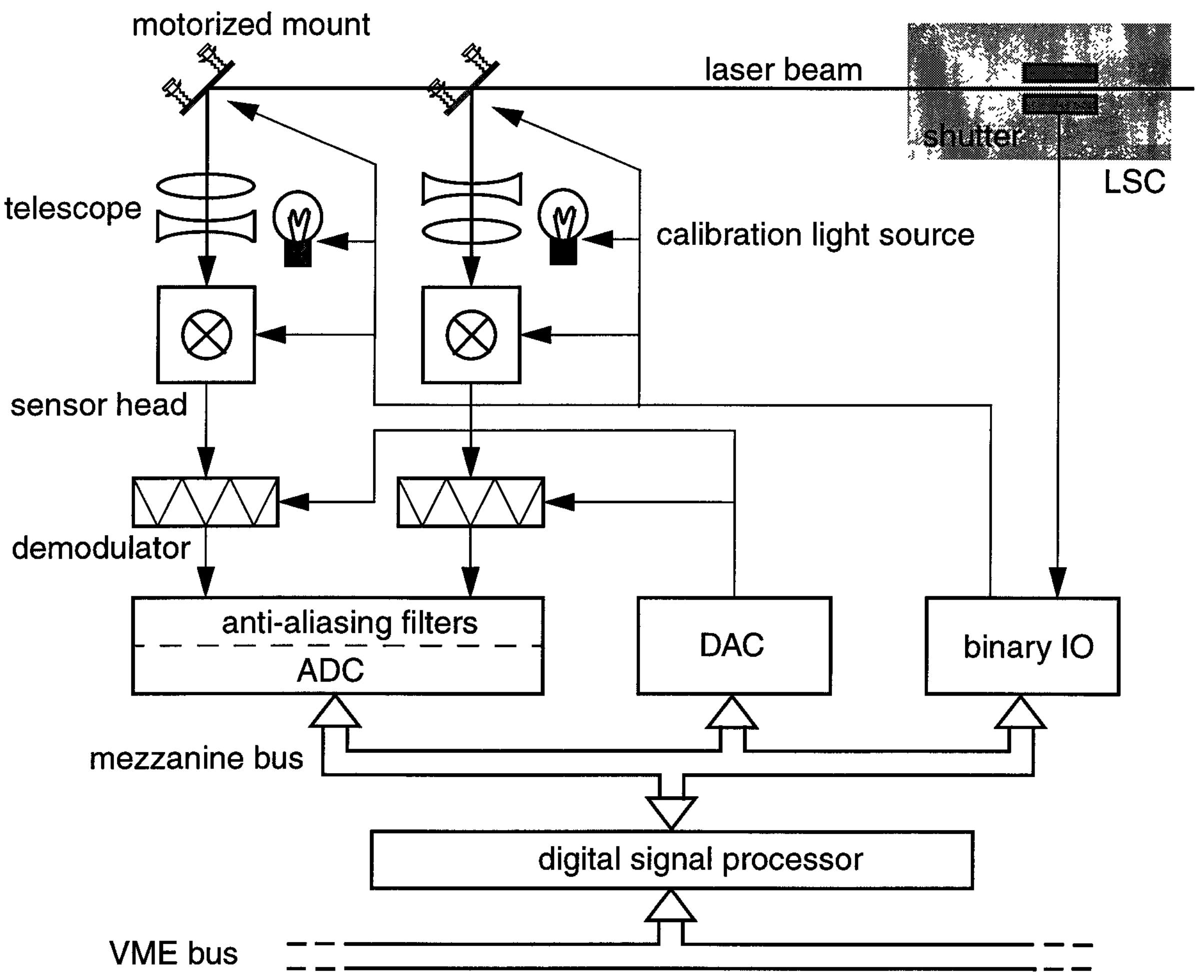
DESCRIPTION/FEATURES OF ASC DETECTION MODE (CONTINUED)

- ☐ Ifo layout and optical configuration
  - ○ Ifo lengths must be locked for wavefront sensing
  - ○ needs non-resonant sidebands to separate RM and common ITM
  - ○ uses existing ports
- ☐ Digital servo system
  - ○ Complicated enough to make a digital implementation highly desirable
  - ○ Data acquisition for alignment is then part of the ASC subsystem

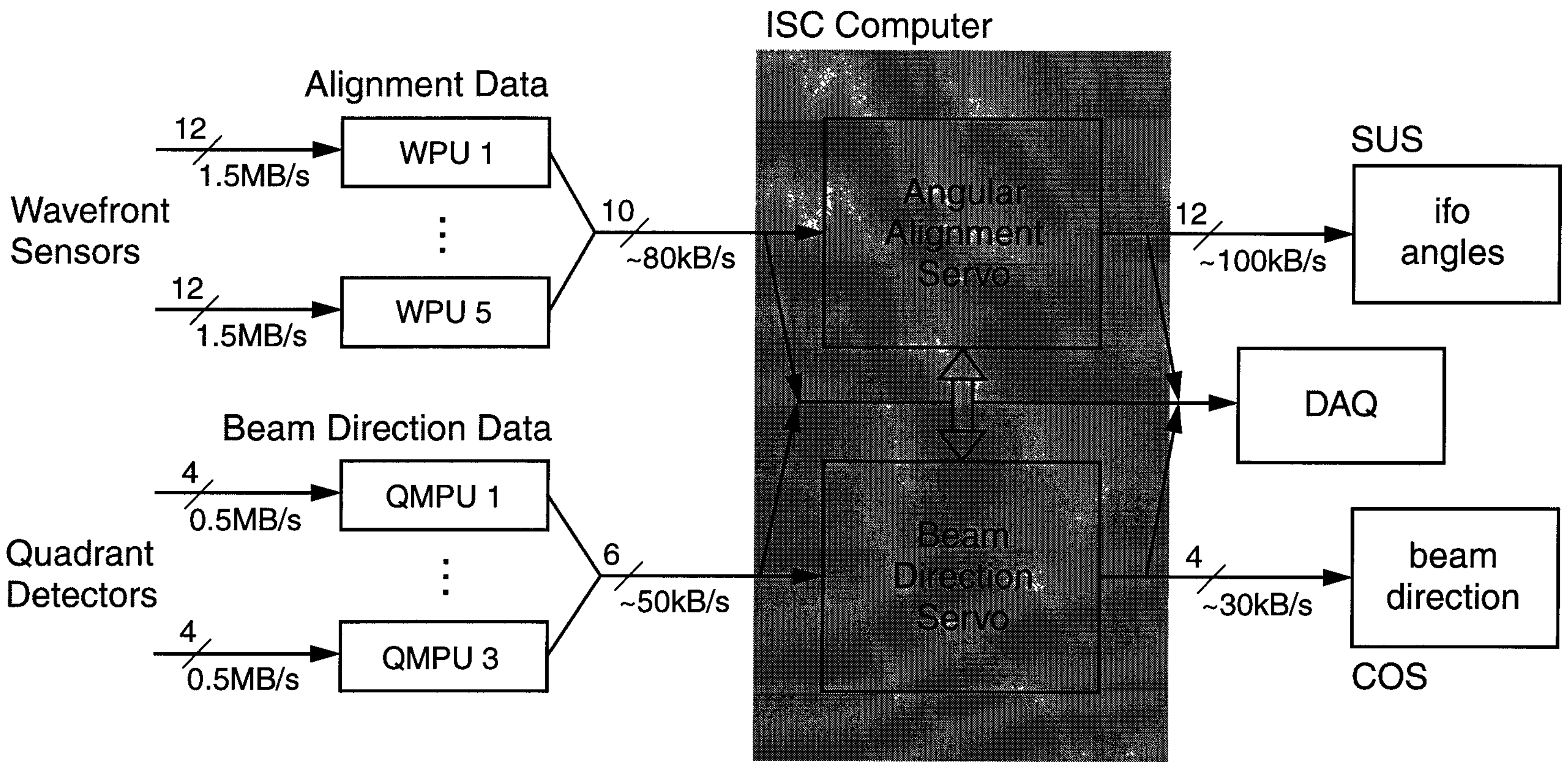
DETECTORS AND SENSORS FOR THE ASC



WAVEFRONT SENSOR SCHEMATICS



DATA LINKS AND PROCESSING



ALIGNMENT MATRIX

		Power split	*Angular Degree-of-Freedom*				
port			***ΔETM***	***ΔITM***	***ETM***	***ITM***	***RM***
1	dark port	1%	**–0.33**	**–0.15**	0	0	0
2	reflection	1%	5.7×10^{-4}	**–0.034**	0	0.0034	–0.0048
3		1%	0	0	0	**0.19**	**–0.27**
4	non-resonant sideband	2%	0	0	-5.8×10^{-4}	-2.6×10^{-4}	$\mathbf{6.1 \times 10^{-3}}$
5		2%	0	0	$\mathbf{-6.6 \times 10^{-3}}$	$\mathbf{-3.0 \times 10^{-3}}$	5.3×10^{-4}
6	pick-off	30%	-5.0×10^{-5}	$\mathbf{-2.9 \times 10^{-3}}$	0	2.9×10^{-4}	-4.0×10^{-4}

Units are Watts per normalized angle.

FEATURES OF ALIGNMENT MATRIX

- ❑ Non-resonant sidebands separate RM and common ITM
- ❑ WFS 1 and 3 are parallel to the most sensitive degree-of-freedoms for gravitational-wave degradation
- ❑ Non-resonant sidebands improve common ETM detection
- ❑ Dark port needed for differential ETM
- ❑ Dark port has no carrier TEM_{00}
  → no separation between differential ITM and ETM
- ❑ WFS in reflection need carrier TEM_{00}
  → ifo must not be too close to critically matched!
- ❑ WFS at pick-off is insensitive to ifo matching

ALIGNMENT ERRORS

- ☐ Shot noise $\leq 10^{-14}$ rad/$\sqrt{\text{Hz}}$
  - ○ Unimportant for alignment requirements at low frequencies
  - ○ Is larger than thermal noise at 100 Hz → filter for controller signals
- ☐ Offset Errors (should be smaller than 10^{-8} rad)
  - ○ Residual length signals: $< \sim 10^{-9}$ rad (30dB CMRR)
  - ○ RF pickup: $< \sim 10^{-10}$ rad
  - ○ Electronic offsets: $< \sim 10^{-9}$ rad

BEAM DIRECTION

- ☐ Dependent degree-of-freedoms
  - ○ WFS adjusts the mirrors relative to the input beam direction
  - ○ Input beam tilt (shift) and the beam splitter orientation have to be controlled by other means
- ☐ Quadrant position sensor in transmission of the arm cavity
- ☐ Beam direction matrix

port	*BS*	IB_{tilt}	IB_{shift}
reflection	–0.033	–0.011	1.02
transmission ETM_1	0.019	–1.12	1.33
transmission ETM_2	2.46	–1.12	1.33

Units are waist size per divergence angle (for BS and IB_{tilt}) or per waist size (IB_{shift}).

Alignment Fluctuations Modeling

Goal: get a baseline for design of servos that satisfy requirements.
or: how far are we from requirements when we begin?

Tools: Flow diagram (next VG)
Matlab-Simulink dynamical modeling

Inputs to the flow diagram (borrowed from various sources)

- measured ground noise (A. Rohay)
- modeled stack transfer functions (E. Ponslet, Hytec)
- SUS DRR and PDR
- etc...

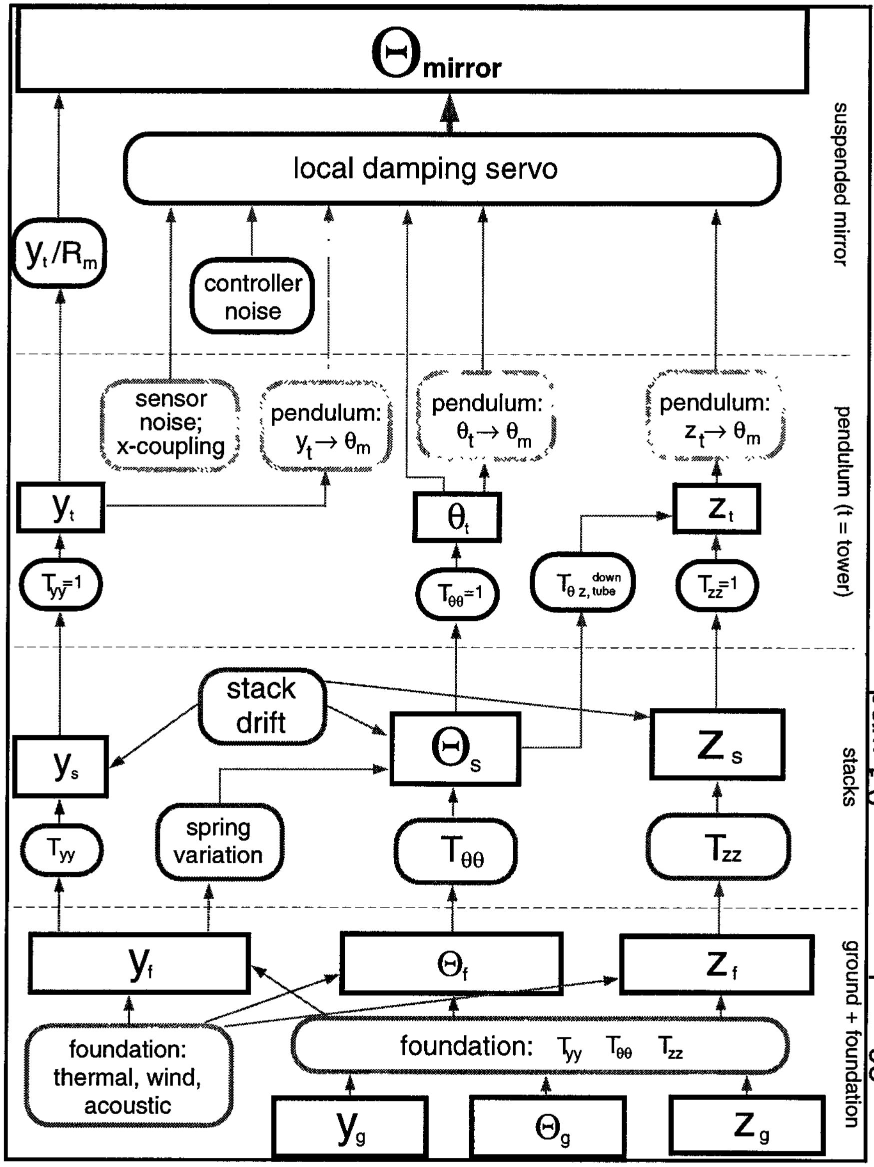
Requirements:

5 10^{-7} rad rms (A)

10^{-8} rad rms (D)

<(pend. thermal noise)/

(10*off centering distance)



Θ_{mirror}

local damping servo

y_t/R_m

controller noise

sensor noise; x-coupling

pendulum: $y_t \rightarrow \theta_m$

pendulum: $\theta_t \rightarrow \theta_m$

pendulum: $z_t \rightarrow \theta_m$

y_t

θ_t

z_t

$T_{yy}=1$

$T_{\theta\theta}=1$

$T_{\theta z, tube}^{down}$

$T_{zz}=1$

stack drift

y_s

Θ_s

Z_s

spring variation

T_{yy}

$T_{\theta\theta}$

T_{zz}

y_f

Θ_f

z_f

foundation: thermal, wind, acoustic

foundation: T_{yy} $T_{\theta\theta}$ T_{zz}

y_g

Θ_g

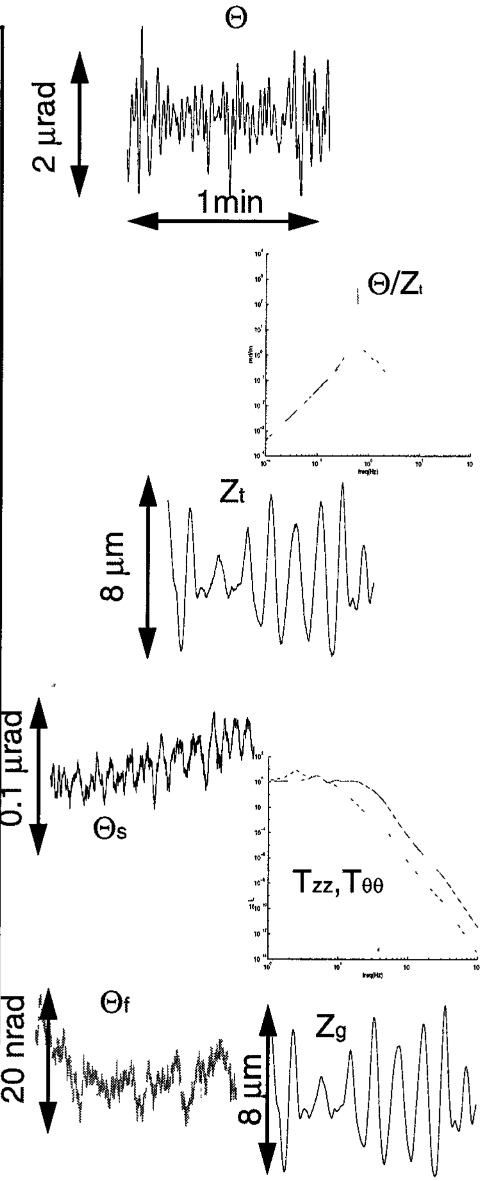
z_g

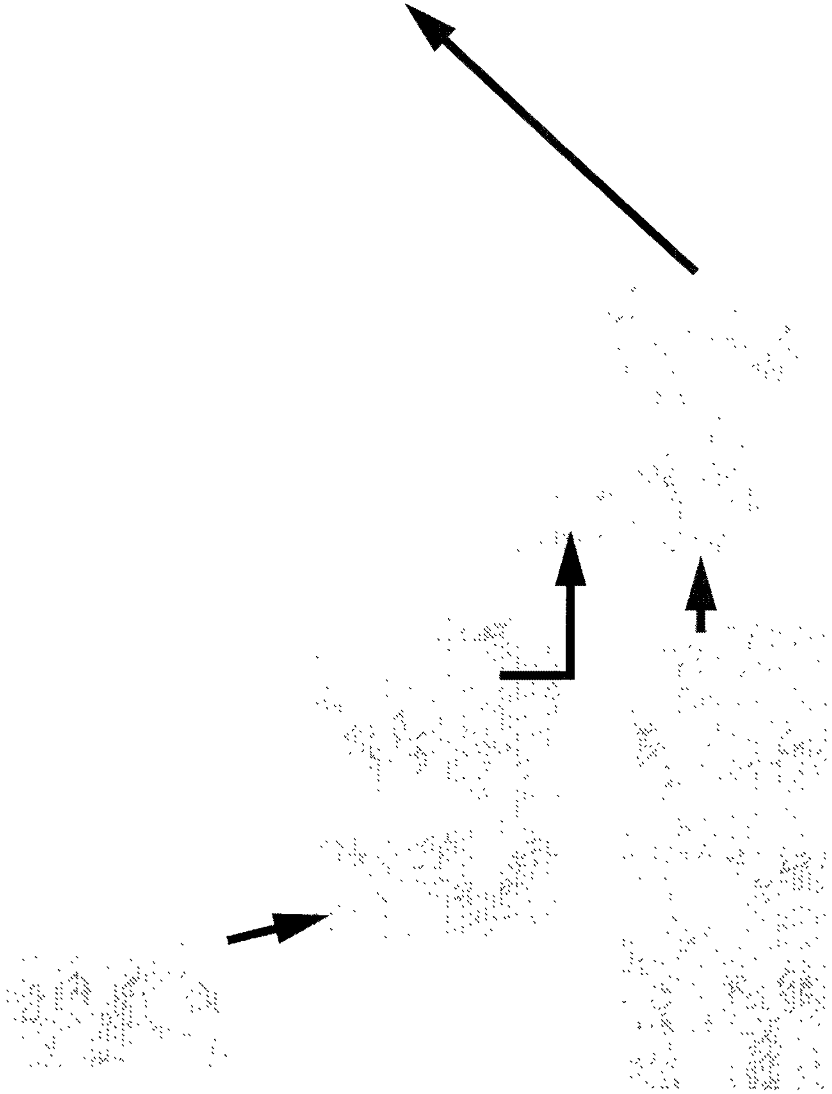
suspended mirror

pendulum (t = tower)

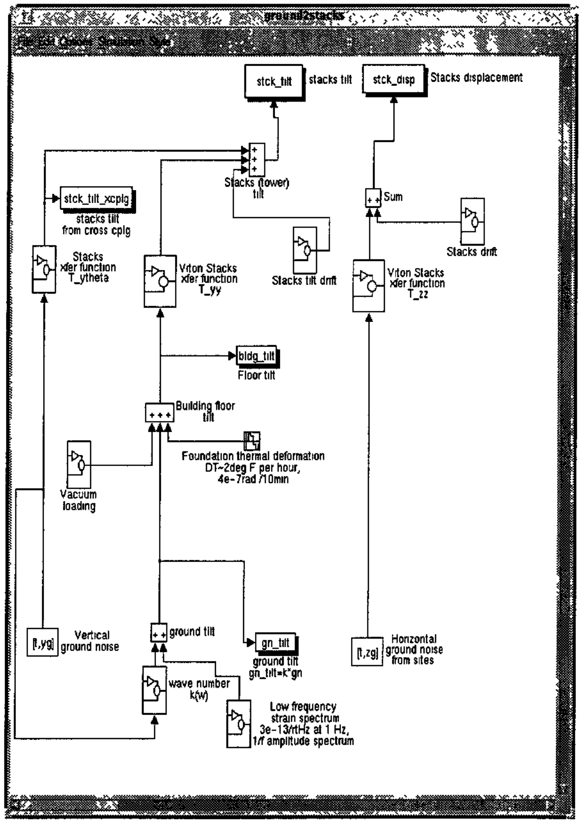
stacks

ground + foundation

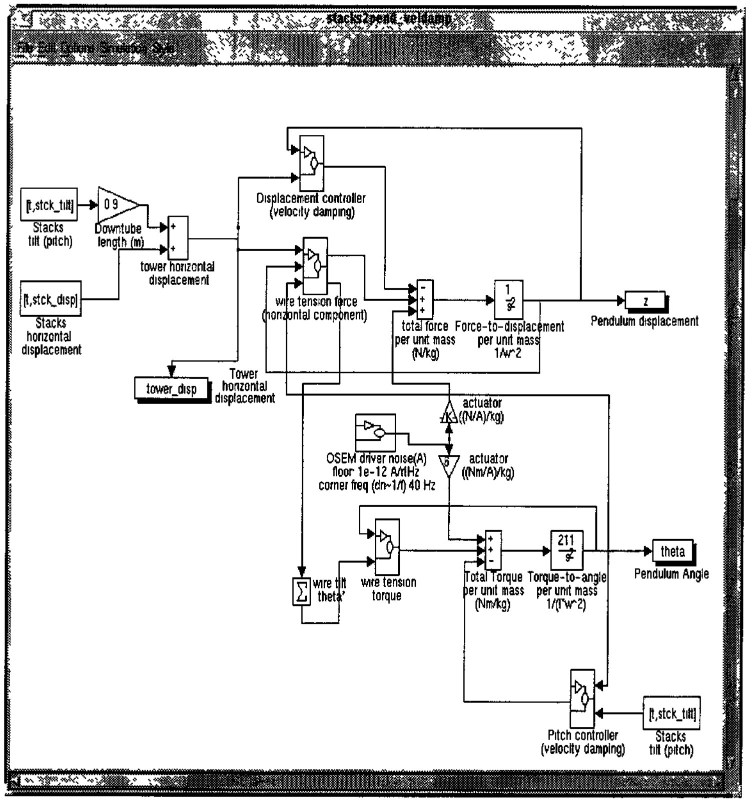




Matlab-Simulink model



ground to stacks

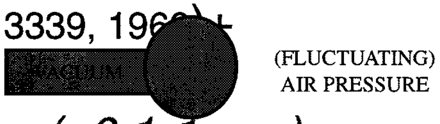


stacks to pendulum

Matlab model: relevant inputs

››ground noise: A. Rohay measurements at the sites.
rms noise: ~2 microns at LA, ~0.5 micron at WA
rms due to microseismic peak

››building tilts: air pressure fluctuations (*J.Geophys.Res.* **85** 3339, 196[illegible]) +
vacuum loading
typical air pressure-induced rms tilts ~5 nanoradians (~0.1-1 sec)

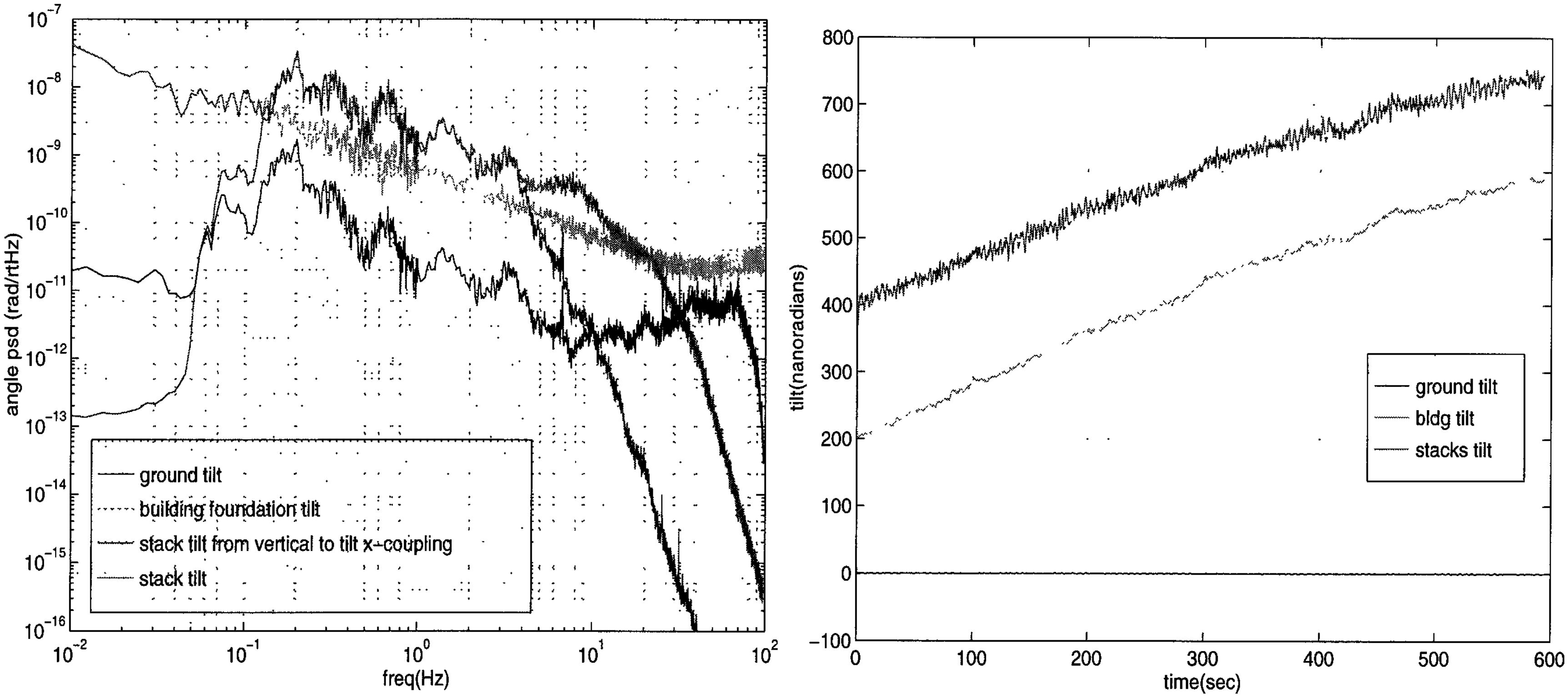


››drifts in building tilts due to temperature response of foundations (Parsons)
tilt drifts ~ 400 nanoradians in 10 minutes

›› stacks transfer functions: from E. Ponslet modeling (Hytec)
Different stack springs produce big differences, in rms and in spectra.
Stacks tilts x downtube length ~ stack displacements

››pendulum equations: based in Seiji Kawamura T960040-00-D,
Pendulum pitch is excited by displacement of suspension point.

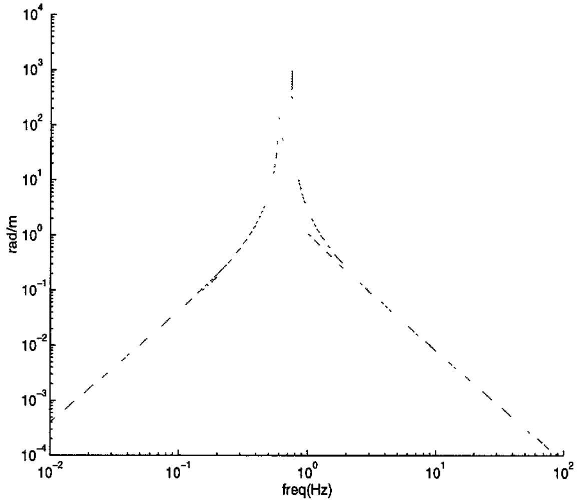
Ground to stacks: results with LA ground noise and viton spring stacks.

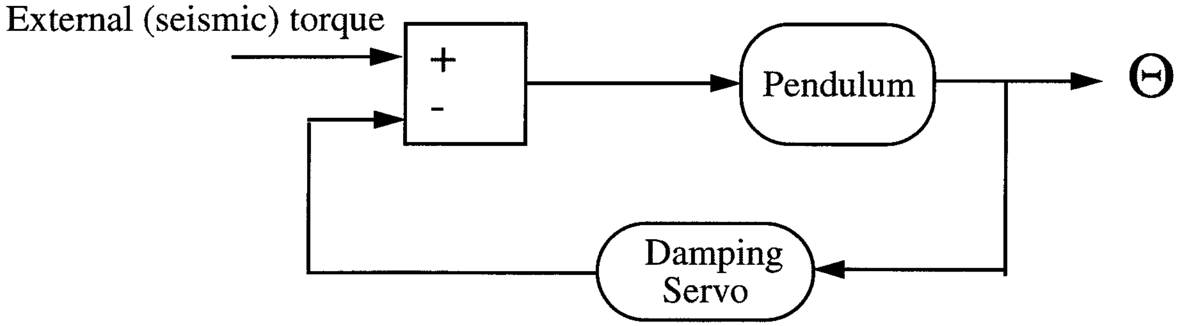


Tilts at different points between ground and top of stacks.

Stacks to pendulum: mechanical pendulum and servos.

Free and damped response to seismic input:




External (seismic) torque

\+

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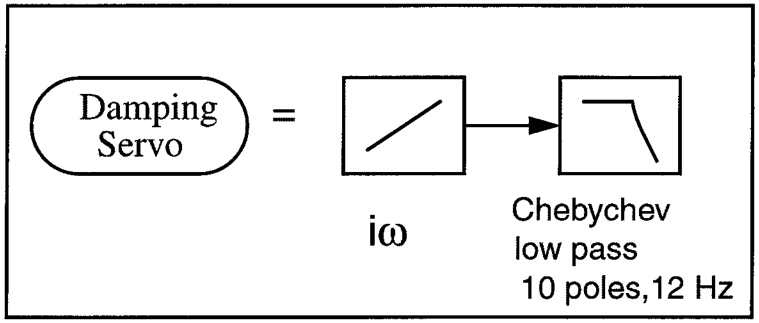
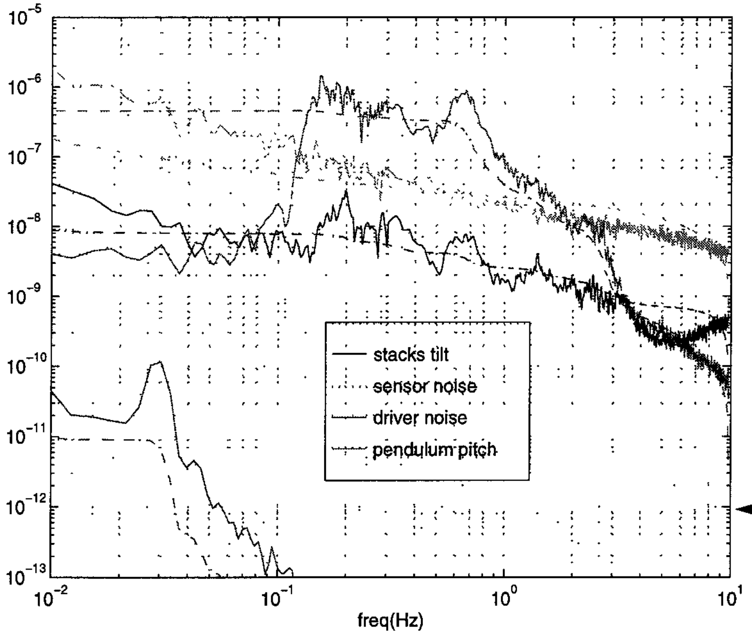
Pendulum

Θ

Damping Servo

Servos I: Velocity damping servo.





LA site,
viton stacks

Notice:

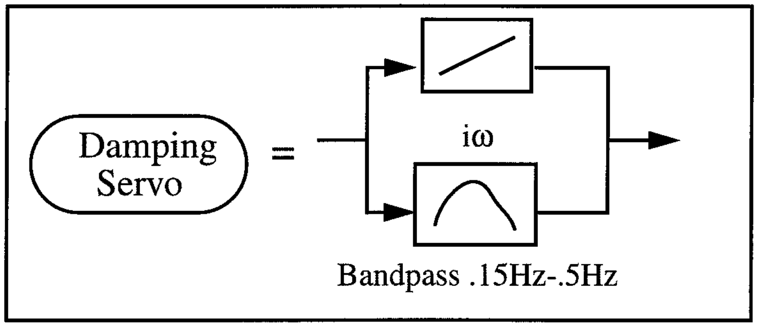
- Pendulum pitch rms is > 10^{-7} rad for t>2 sec.
- Sensor noise is larger than stack tilt.
- Summary:

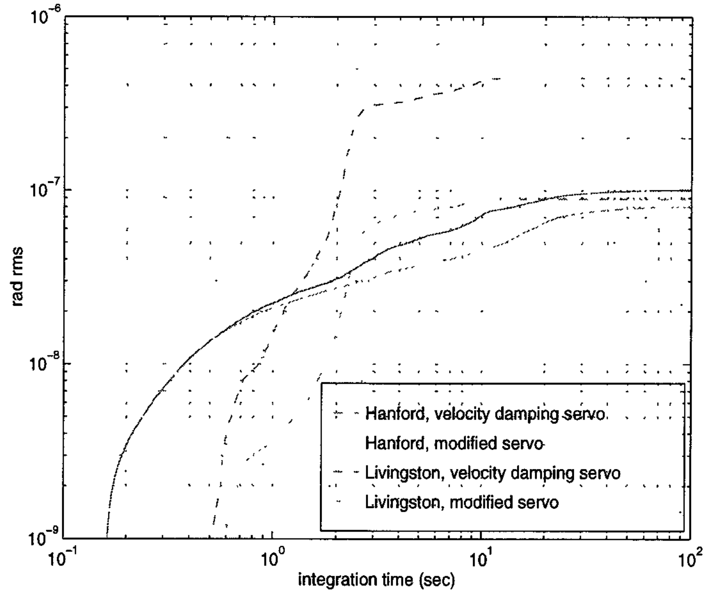
Velocity damping servo	rad rms	rad pp
viton spring stacks (LA)	$4.4\ 10^{-7}$	$3.1\ 10^{-6}$
viton spring stacks (WA)	$9.0\ 10^{-8}$	$6.4\ 10^{-7}$
leaf spring stacks (LA)	$5.9\ 10^{-7}$	$4.3\ 10^{-6}$
leaf spring stacks (WA)	$1.1\ 10^{-7}$	$8.2\ 10^{-7}$

residual rms might be too large for length lock acquisition

Servos II: “Modified” servo

- If we use the suspension towers as tilt references, we might do better than just damping the resonances.
- Since this servo is to be used in acquisition mode, we do not need low spectral density in gw band: do not use low pass filters.
- Tilt reference is dominated by *sensor noise*.
- Residual pitch rms is ~10^{-7}rad or smaller in all cases.

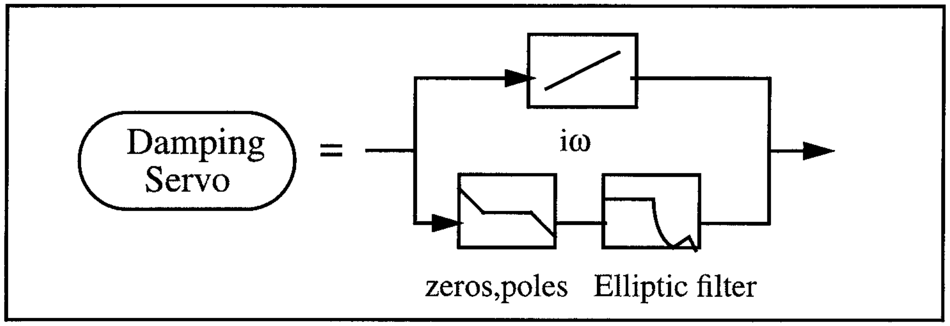




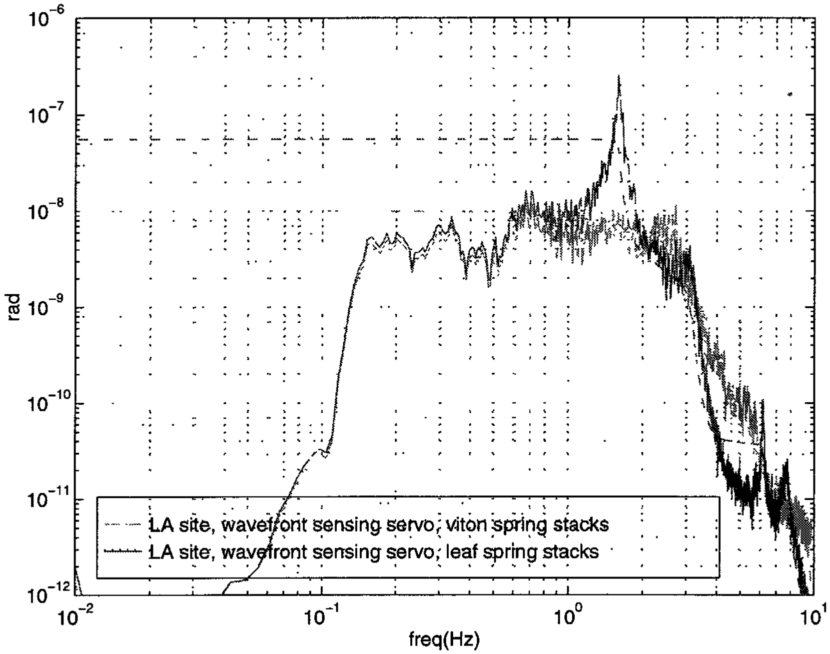
Servos III: WFS servos

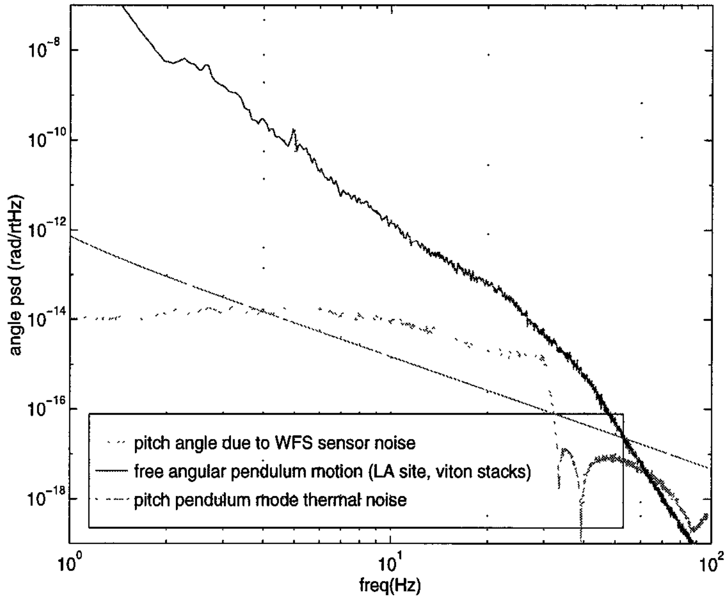
- In detection mode, we need residual rms <10^{-8}rad and low noise in gw band=> servo needs noise filtering.
- Angular reference is interferometric, from WFS (not local)=> stack tilts, OSEM sensor noise are not important.
- Servo might need customizing to the stack resonances.

Unity gain frequency	4.5 Hz
(In band) Loop response	2 poles at 0 Hz, 1 zero at 1.5 Hz
High frequency filtering	6th order elliptic, 1 dB passband ripple, 40 dB stopband attenuation, 30 Hz cut off frequency
Phase margin	45°
Gain margin	8 dB



Servos III: WFS servo (cont.)





WFS servo	rad rms	rad pp
viton spring stacks (LA)	9.8 10^{-9}	1.1 10^{-7}
viton spring stacks (WA)	2.1 10^{-9}	1.5 10^{-8}
leaf spring stacks (LA)	5.4 10^{-8}	4.0 10^{-7}
leaf spring stacks (WA)	4.2 10^{-9}	3.1 10^{-8}

Conclusions

›› **The requirements can be met (at least conceptually), both for acquisition and detection mode.**

›› We may need to “customize” servos to sites and/or stacks.

›› We need to:

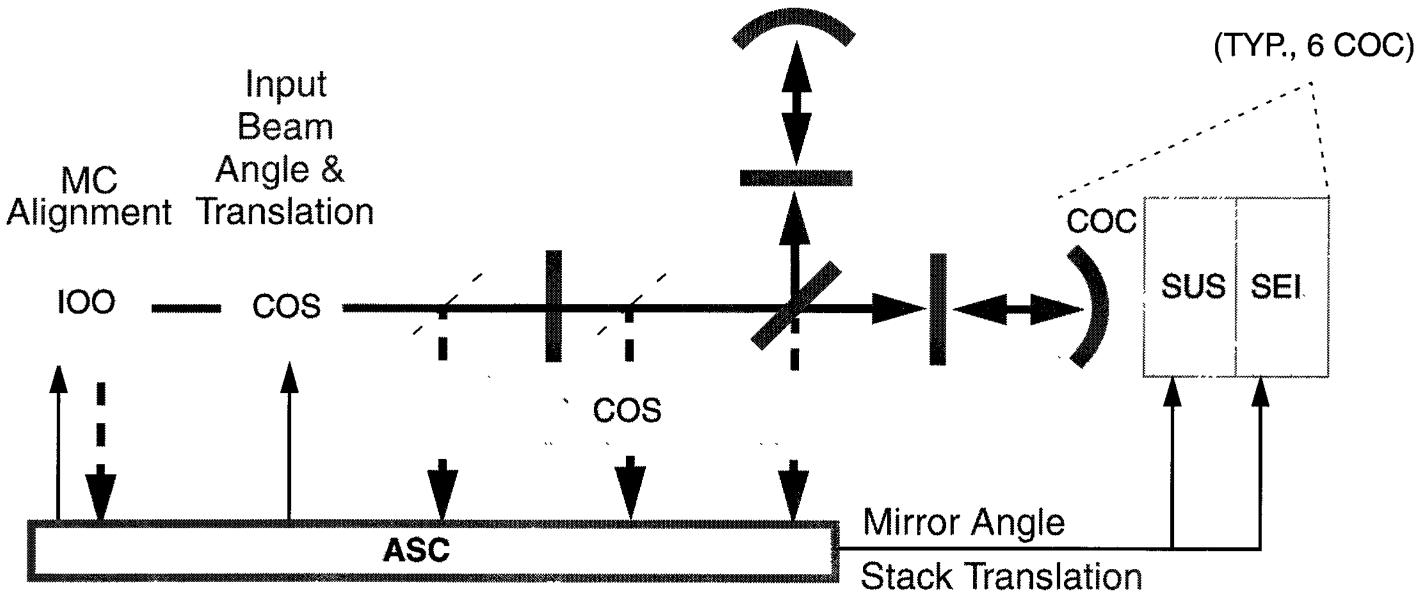
- have experimental model validation
- incorporate latest Hytec modeling results
- study remaining noise paths (mechanical and electronic cross couplings, etc.)
- have a noise model for YAW
- have a multiple input, multiple output model for WFS servo
- use length locking servos for displacement controllers

but we don’t foresee surprises (!)...

ASC DIAGNOSTICS

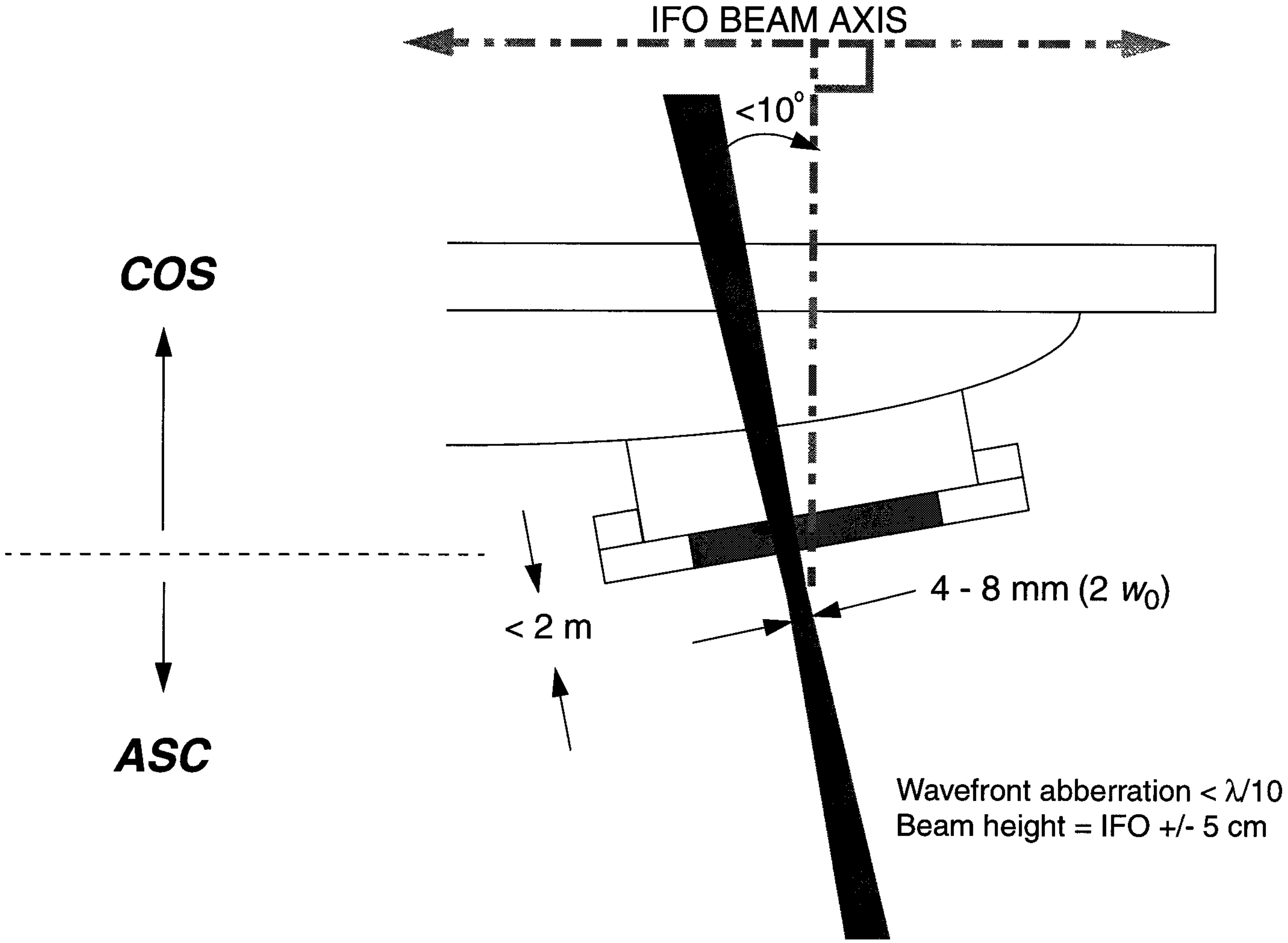
- Alternate control sensing & feedback
  - optical levers for some DOF in Detection mode
  - alternate WFS sensors/matrix elements
  - CM feedback to mirrors vs. input beam
- Nonstandard optical configurations
  - want WFS operable for short recycled Michelson (for ASC alignment procedure)
  - other variants for interferometer diagnostics (single cavity, etc.); some w/out WFS
- Mode matching readout
  - quasi-static spatial mode decomposition of reflected & dark port patterns
  - use controlled optic movements to resolve phase ambiguity
- WFS calibration & matrix diagonalization
  - similar to beam centering procedure

INTERFACES: CONTROL SIGNAL



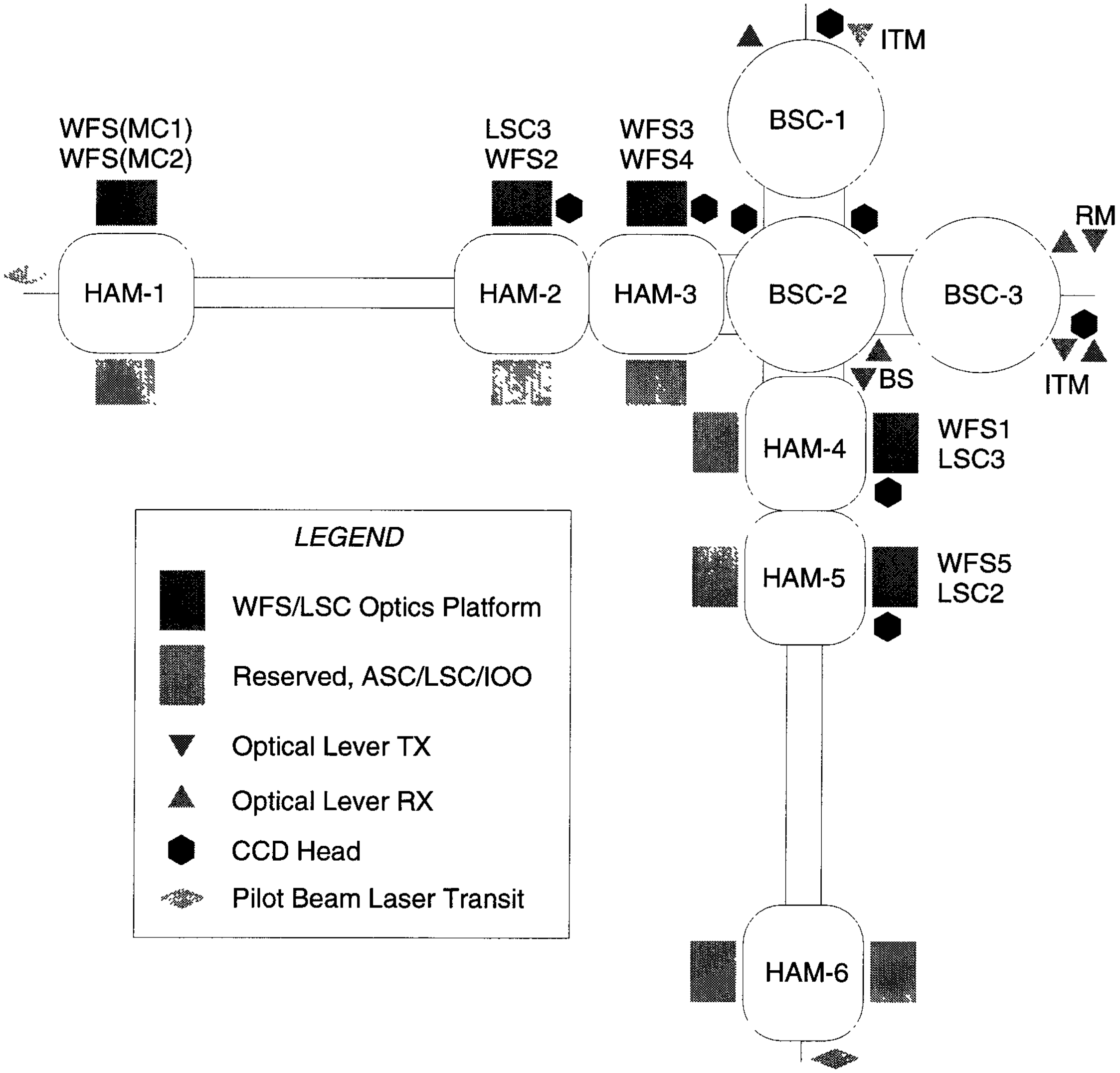
ASC SIGNAL FLOW

INTERFACES: COS OPTICAL (PROPOSED)

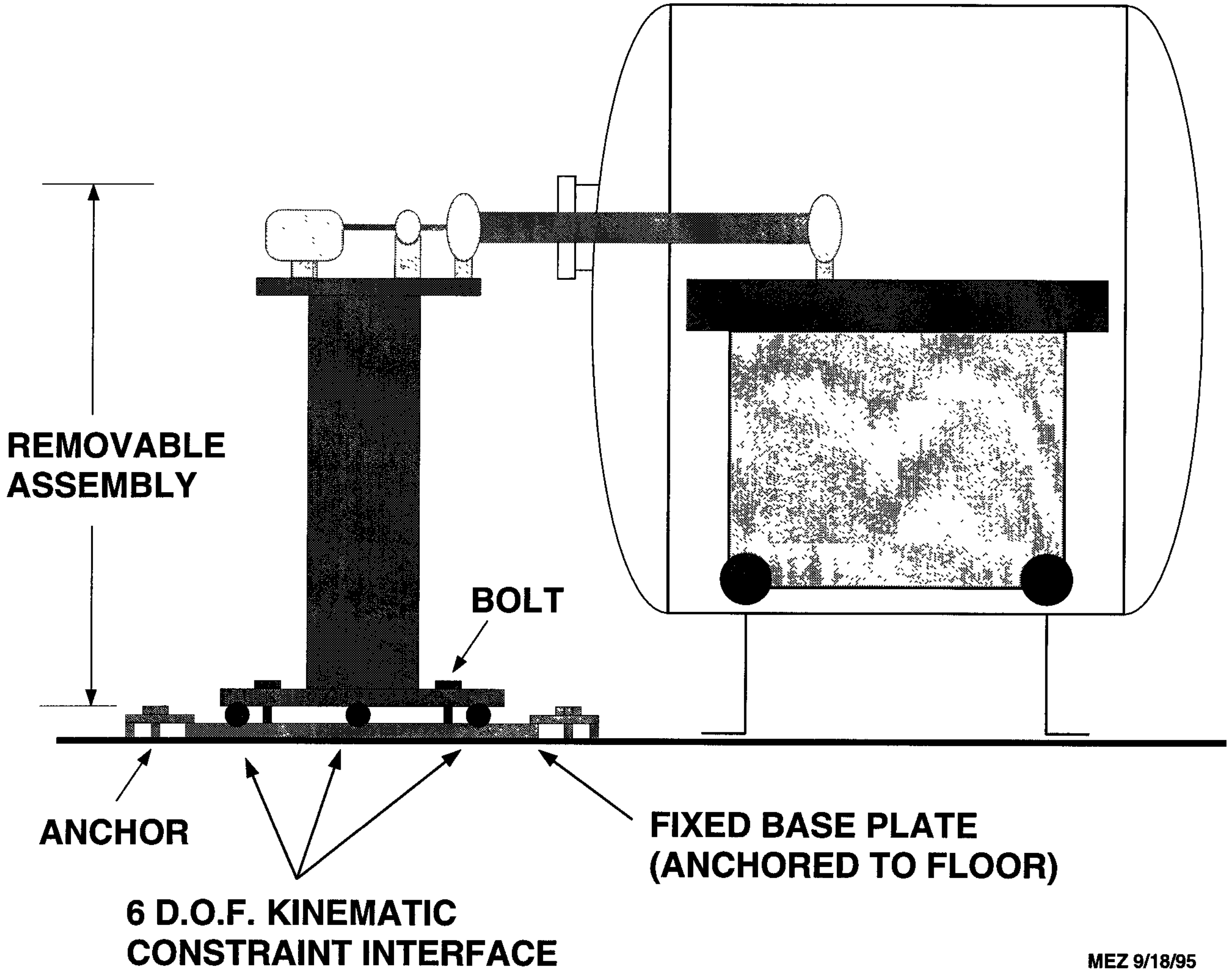


Wavefront abberration < $\lambda/10$
Beam height = IFO +/- 5 cm

INTERFACES: FACILITY/VE MECHANICAL

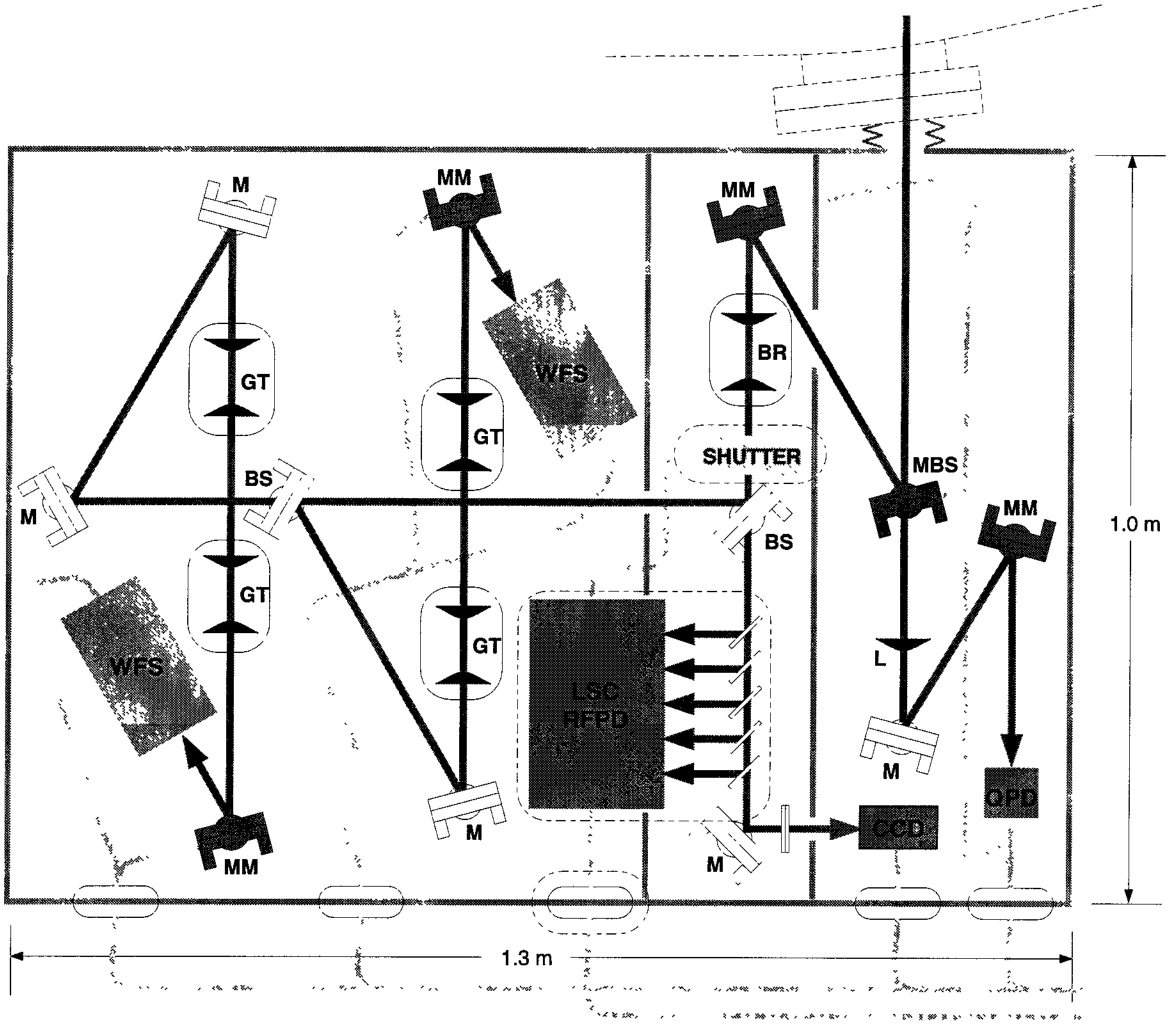


INTERFACES: FACILITY/VE MECHANICAL (CONT'D)



MEZ 9/18/95

INTERFACES: LSC OPTICAL/MECHANICAL



TOP OPEN ISSUES FOR PRELIMINARY DESIGN PHASE

- Control sensor choice for Acquisition mode
- Stack yaw ("corkscrew") drift
- WFS optical "plant" frequency response
- *Real* Acquisition Alignment tolerance for length lock