ASC Wavefront Sensing (WFS)

Final Design Review

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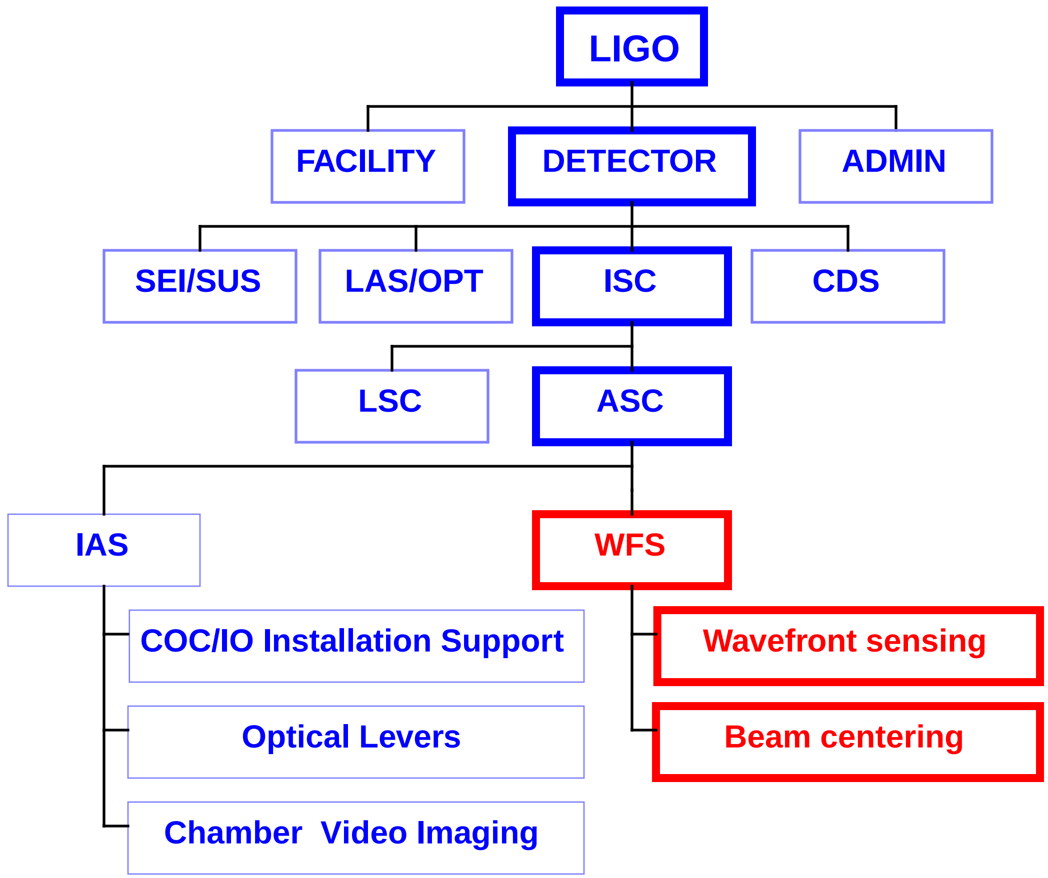
FDR Outline

- Introduction & committee charge (DHS, 15')
- WFS Scope & Requirements overview (MZ, 15')
- WFS sensing hardware (PF, 20')
- Optomechanical layout, components & features (KM, 20')
- Controls: inputs, design & performance (PF, 30')
- Implementation staff, cost, and schedule (MZ, 20')
- Discussion & action items (DHS, ?')

ASC/WFS Scope

- Wavefront sensing alignment design
  - ❑ Sensors: incl. both WFS proper and beam centering
  - ❑ Control design & algorithms for operational (‘Detection mode’) alignment
  - ❑ Bootstrap procedures to initiate operation
  - ❑ Diagnostics (internal ISC, plus external Detector-wide)
- WFS hardware includes
  - ❑ “ISC tables” are designed under ASC/WFS (LSC detector/shutter and COS telescope components are ‘subs’)
  - ❑ ETM beam centering units
- Electronics to be reviewed under ASC/CDS
- Initial alignment reviewed previously(T980019-00)
  - ❑ All “active” IO and COC chambers (1 illuminator, 1 camera per)

WFS Detector/ISC Context



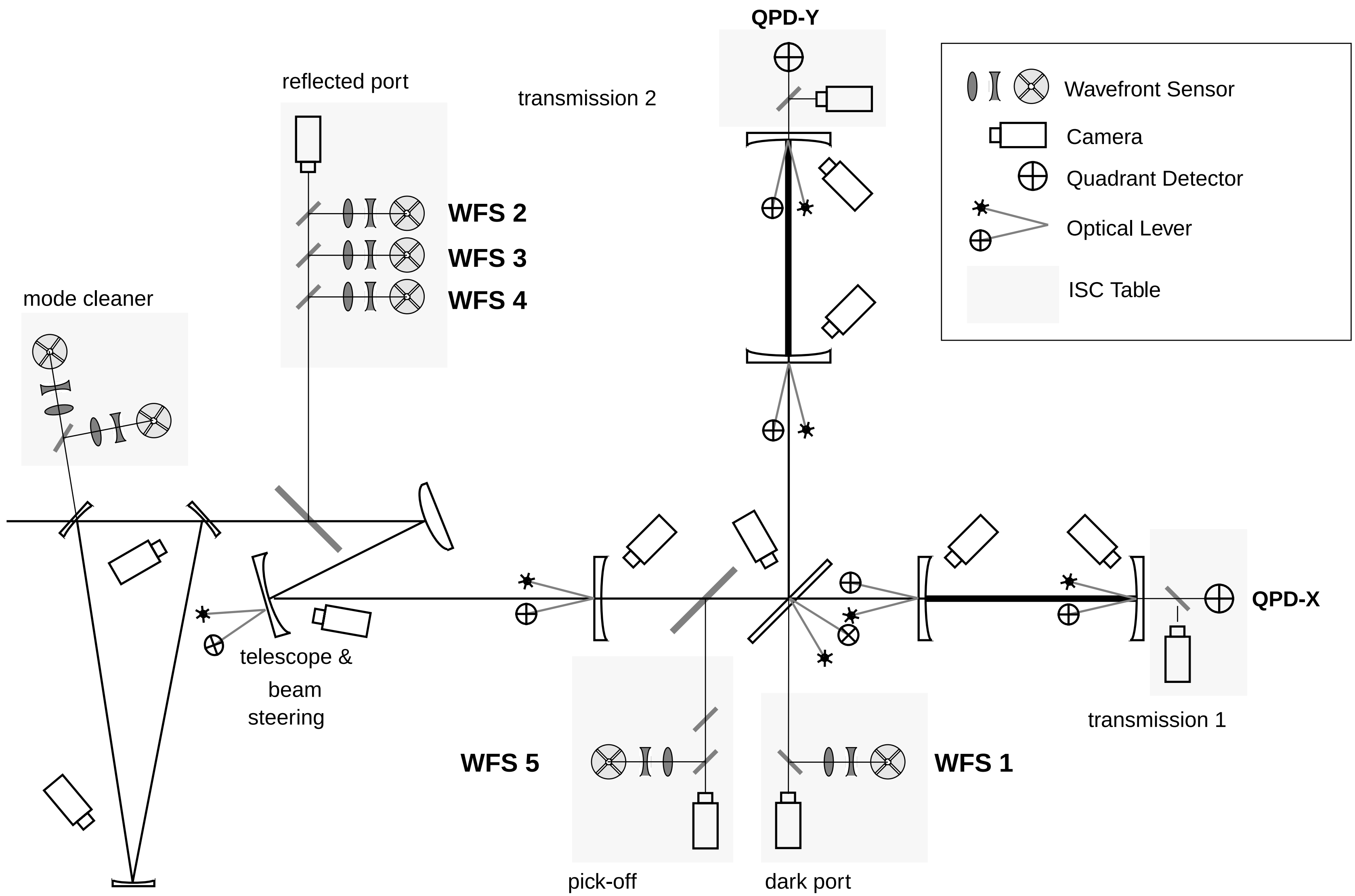
Principal WFS Interfaces

- LSC
  - ❑ LSC diodes, shutters share WFS tables
  - ❑ modulations provided by LSC (through IO)
  - ❑ acquisition procedure, diagnostics, etc. all coupled
- IO
  - ❑ alignment design & deliverables include MC alignment
- COS
  - ❑ delivers beams outside
  - ❑ second part of COS beam reducer integrated on ISC table
- SUS
  - ❑ control actuation is via SUS controllers
- COC
  - ❑ Coating & surface properties define control plant

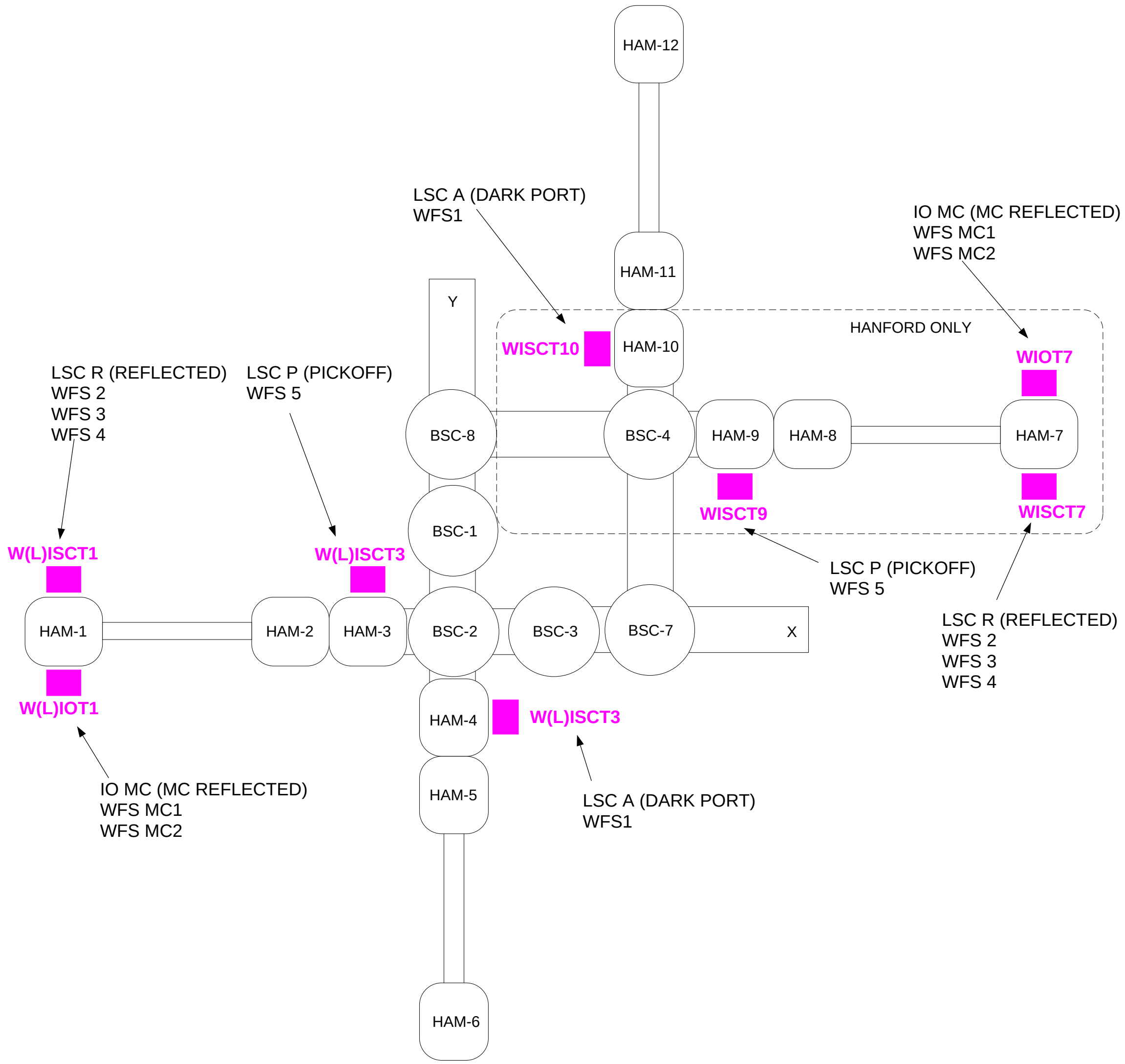
Primary WFS Requirements

- “Detection” mode alignment: 10^{-8} rad rms (most sensitive DOF of core optics)
  - ❑ driven by shot noise SNR
- Beam centering: 1 mm RMS (w.r.t. true C of R for COC)
  - ❑ thermal pitch/yaw excitation X decentering lever arm --> strain
- Availability
  - ❑ These criteria apply during “noisy Louisiana” conditions

Detection Mode Design: Sensor Types



ASC Equipment Location, Vertex Station

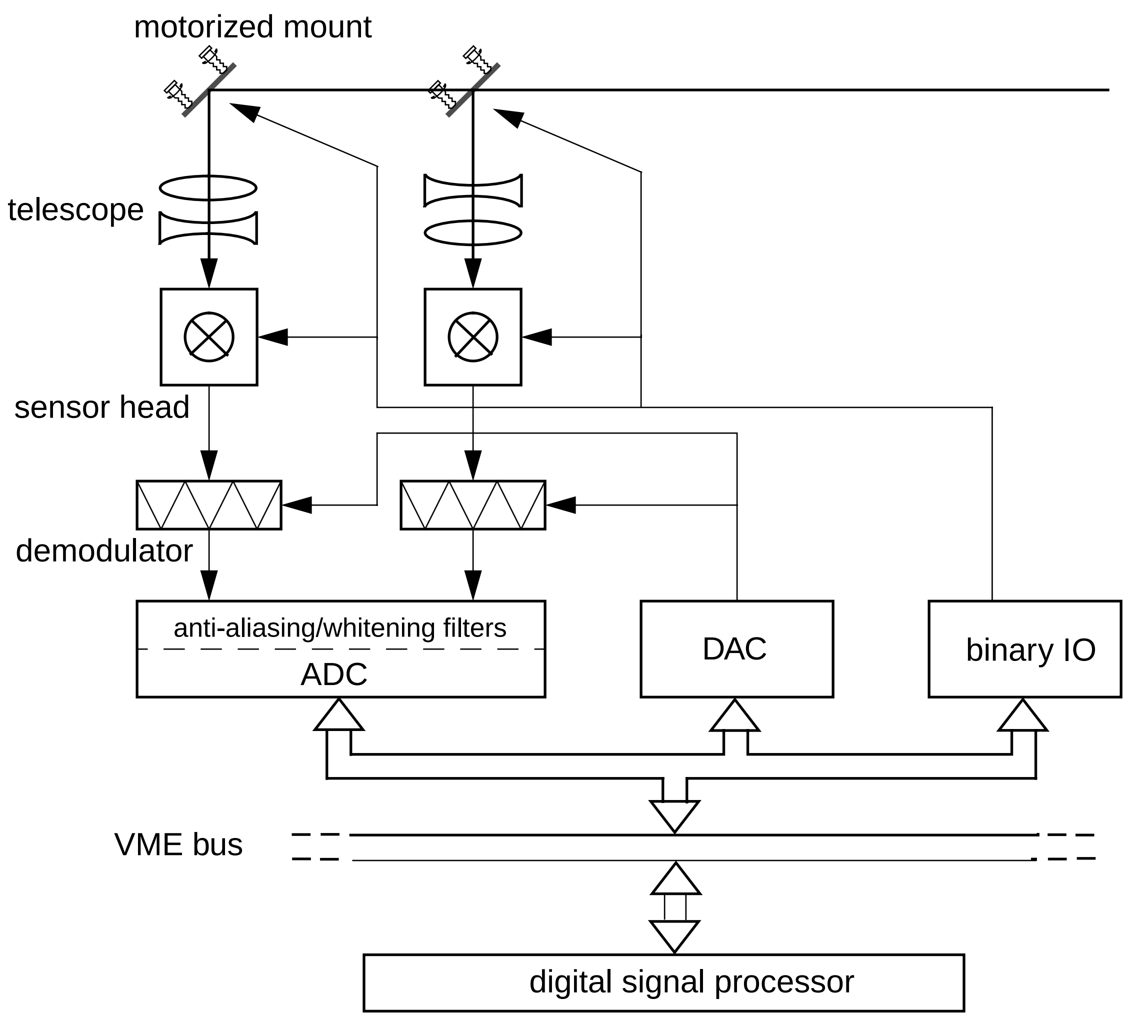


Wavefront Sensor Design

- Updated wavefront sensing matrix

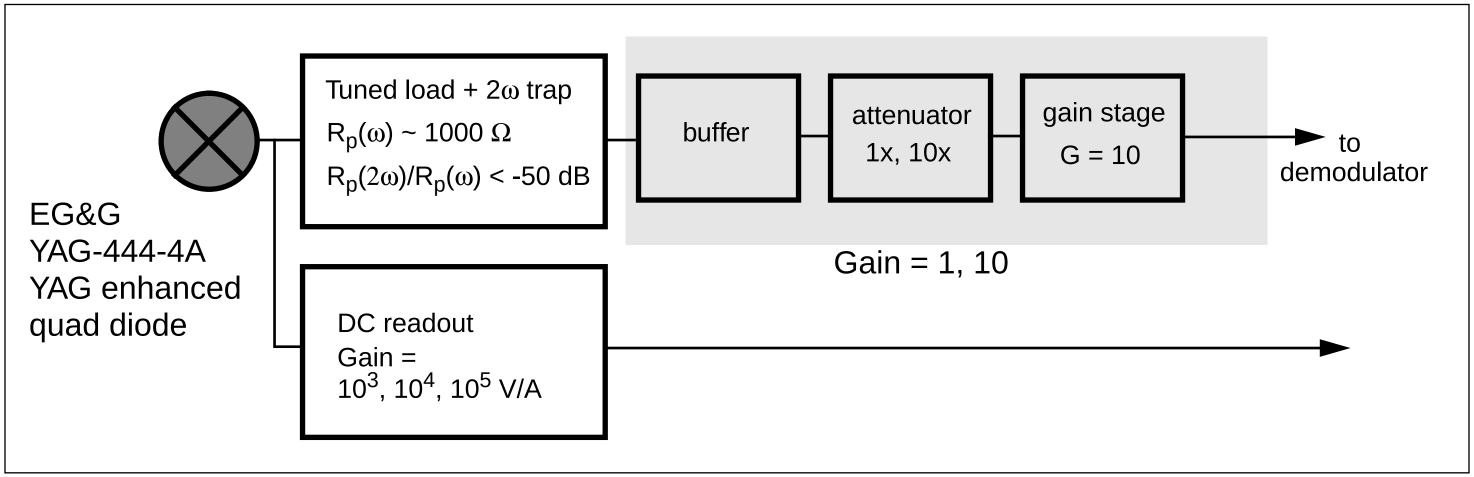
Wavefront Sensor	***Demod. Freq. R=res. SB; NR = nonres. SB***	***Splitting Factor***	***Sensing Direction***	***Gain (mW/ div angle)***
WFS 1	R	0.1%	u_2	48
WFS 2a	R	0.24%	u_1	48
WFS 2b			$-0.14\, u_1 - 0.40\, u_2 - 0.91\, u_3$	6
WFS 3	NR	2%	$0.83\, u_1 + 0.13\, u_4 - 0.54\, u_5$	7.3
WFS 4	NR	2%	$0.70\, u_1 - 0.46\, u_4 + 0.55\, u_5$	8.5
WFS 5	R	20%	$-0.14\, u_1 - 0.40\, u_2 - 0.91\, u_3$	40

WAVEFRONT SENSOR UNIT



SENSOR HEAD

- Same head design for all sensors (including MC)



Quadrant Photodiode: EG&G YAG 444-4A\

- 11.4 mm diam.
- 0.45 A/W
- 100 V reverse bias
- C = 9pF; R = 100 ohm
- Channel-channel cross-coupling:
  - -25 dB at 27 MHz (adjacent channels)
- Dark current appears stable under long term exposure to bias & bias+light (< 100 nA)

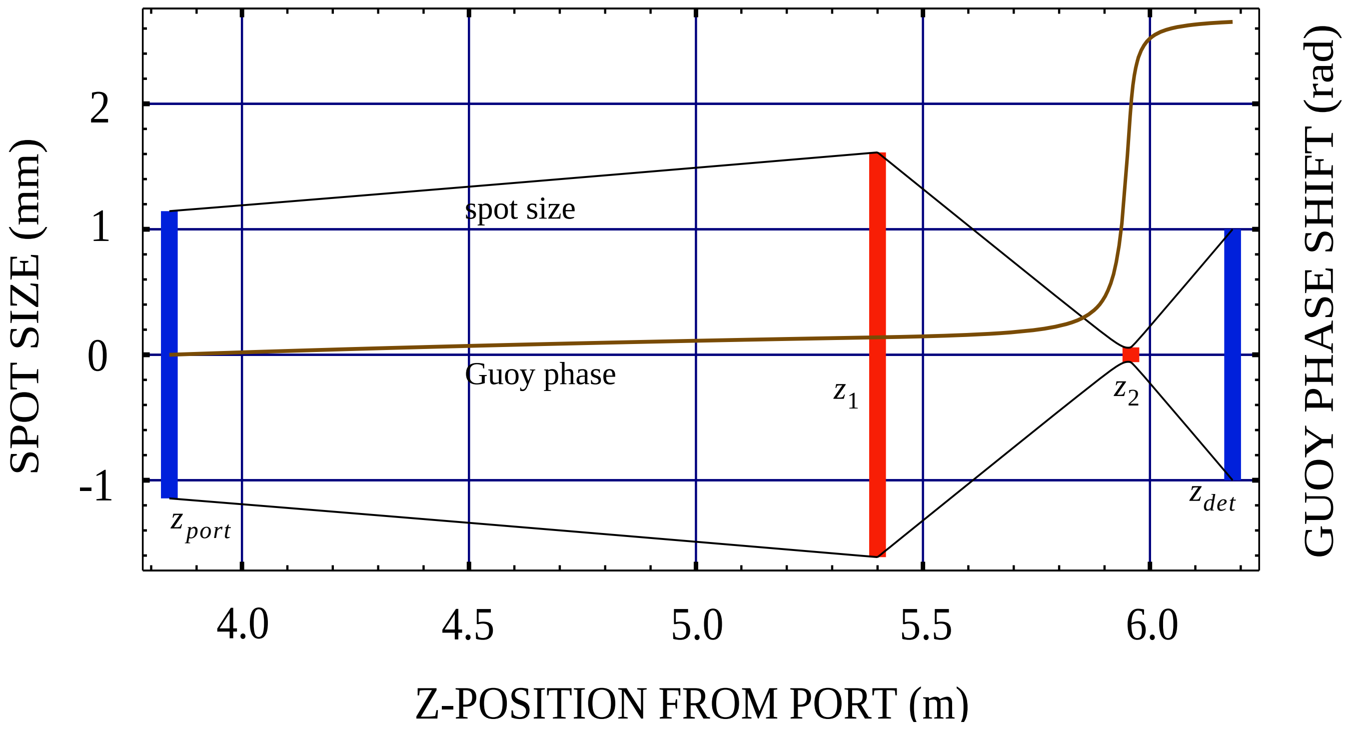
WFS Sensing Noise

WFS	*Angle Sensitivity at mixer input; per element; V/rad*	*WFS head (each channel), at the mixer input; nV/√Hz*		*Demod. input noise*	*ADC input noise[a], nV/√Hz*	S_α*, Equivalent angle sensitivity, rad/√Hz (f>40 Hz)*
		shot noise	*elect. noise*			
1	1.1×10^{7}	45	70	20	50 *(f>40 Hz)*	**9.0×10^{-15}**
2a	1.1×10^{7}	40				**8.8×10^{-15}**
2b	1.1×10^{6}	40				**8.8×10^{-14}**
3	1.6×10^{6}	115				**9.1×10^{-14}**
4	2×10^{6}	115				**7.3×10^{-14}**
5	8.7×10^{6}	250				**3.0×10^{-14}**

a. Assuming +-1V ADC range, and referred to input of the pre-ADC whitening filter.

GUOY PHASE TELESCOPES

- Use the two lens design developed for the FMI
  - beam size on detector: 2.3 mm radius
- Design for mode cleaner WFS's complete



Quadrant Position Detectors

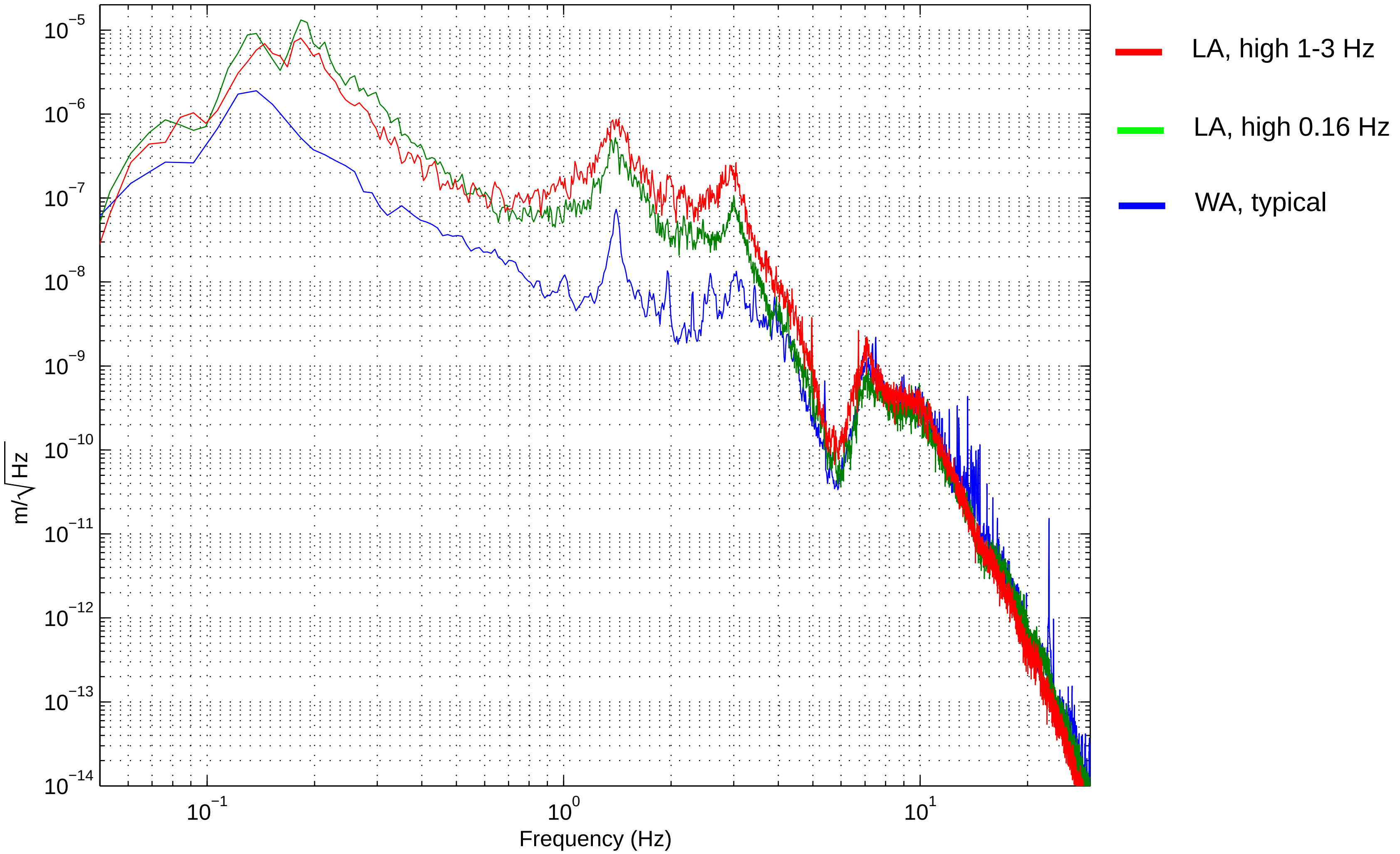
- Used for slow control of input beam and beamsplitter angles (to ~ 10^{-7} rad), to maintain 1 mm centering on ETMs
- Designed to detect transmitted beam with recycled Michel-son only (few µWs), as well as complete IFO (~.1W)
  - » operator gain control from 500 ohm - 10 Mohm

Parameter	*QPD-X*	*QPD-Y*
Spot size, radius	1.5 mm	
Photocurrent, per element	4 ma	
Position sensitivity at quad (left-right difference)	15 amp/meter	
Sensitivity to BS, IB angles	1.8×10^3 amp/rad	3.9×10^3 amp/rad
Shot noise	72 pA/√Hz	
Equivalent angle sensitivity	4×10^{-14} rad/√Hz	2×10^{-14} rad/√Hz

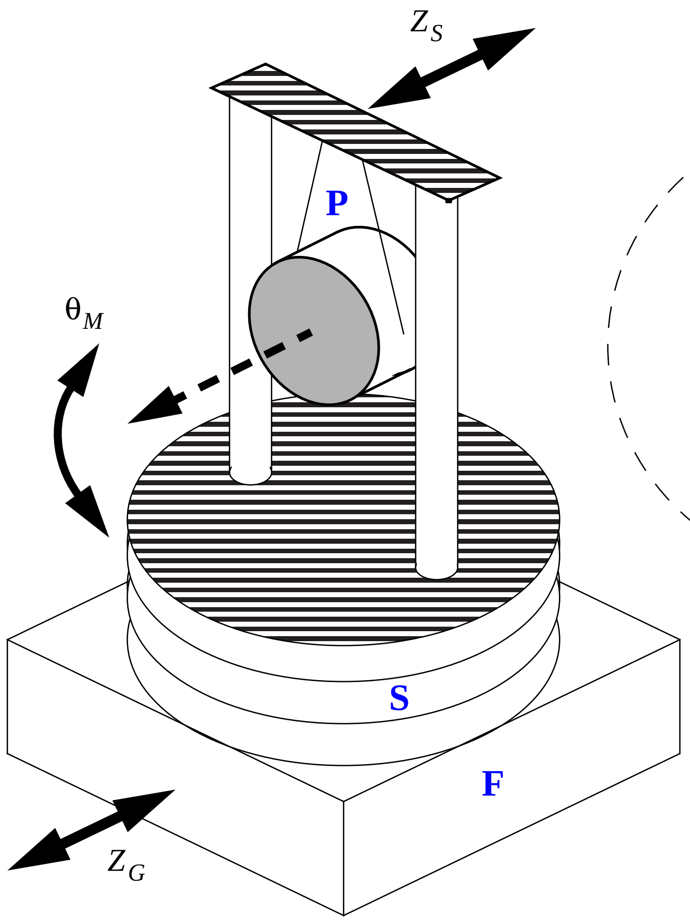
WFS Table Optomechanical Design

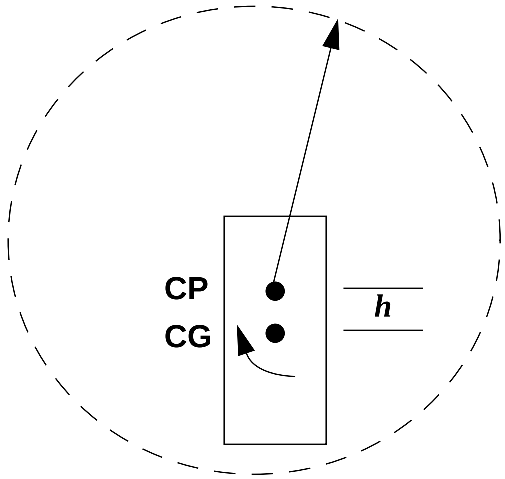
SERVO DESIGN: INPUTS TO MODEL

SUSPENSION POINT DISPLACEMENT SPECTRUM



PITCH FLUCTUATION MODEL



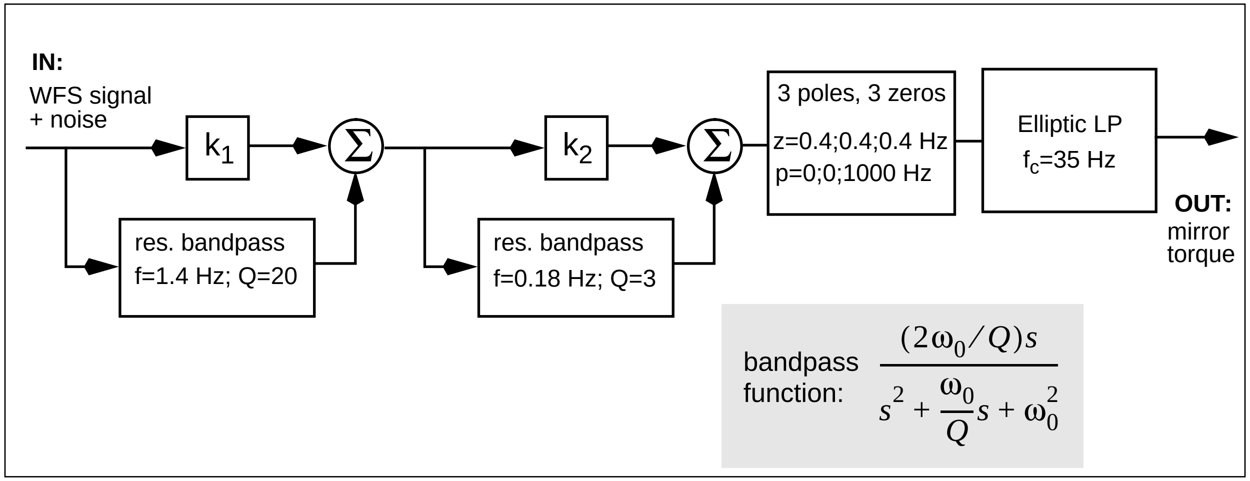


Primary effect:

Acceleration of suspension support point induces a torque about the optic's pitch axis

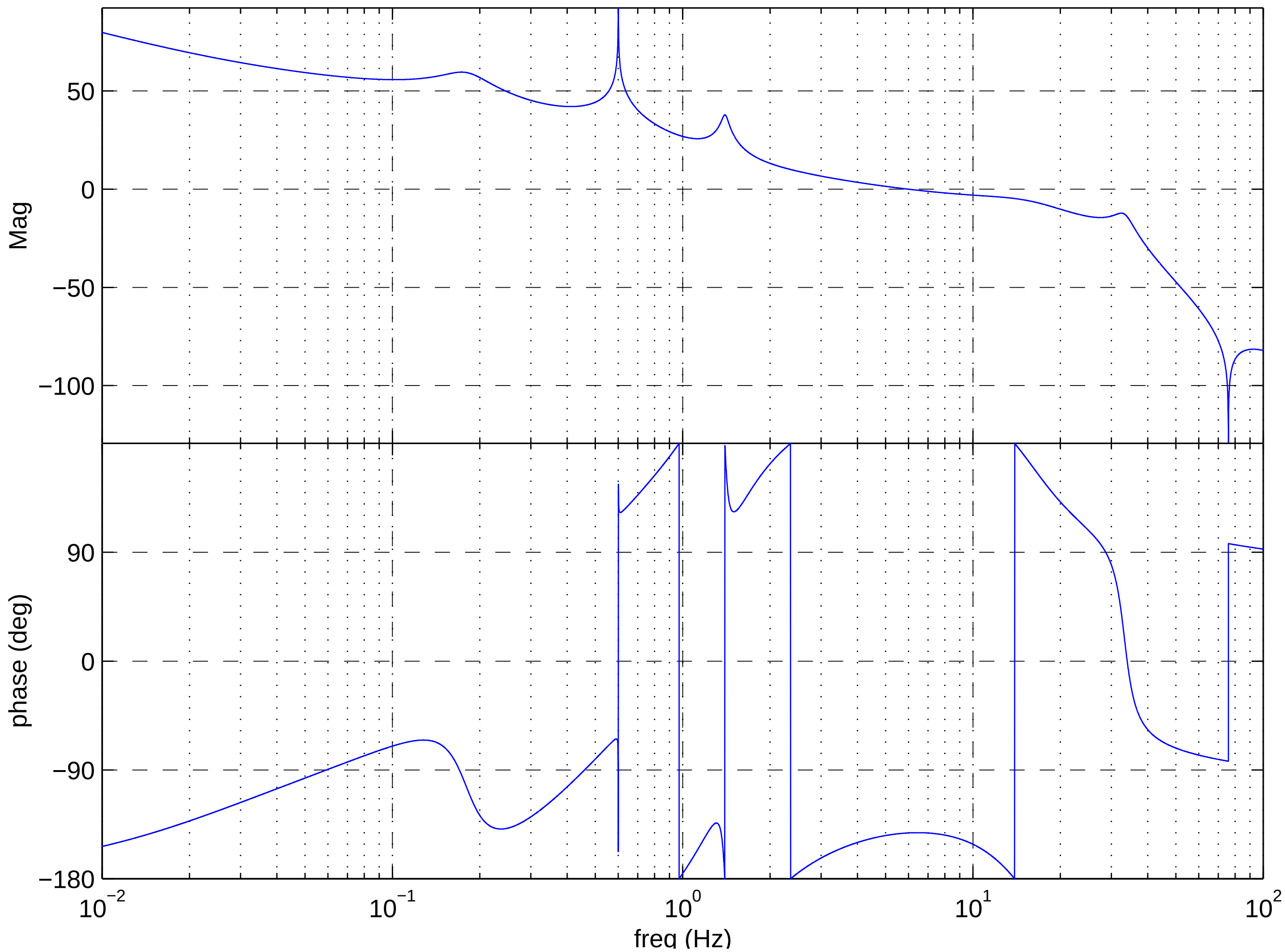
SERVO DESIGN

- Controller design for critical degrees of freedom, WFS 1&2a



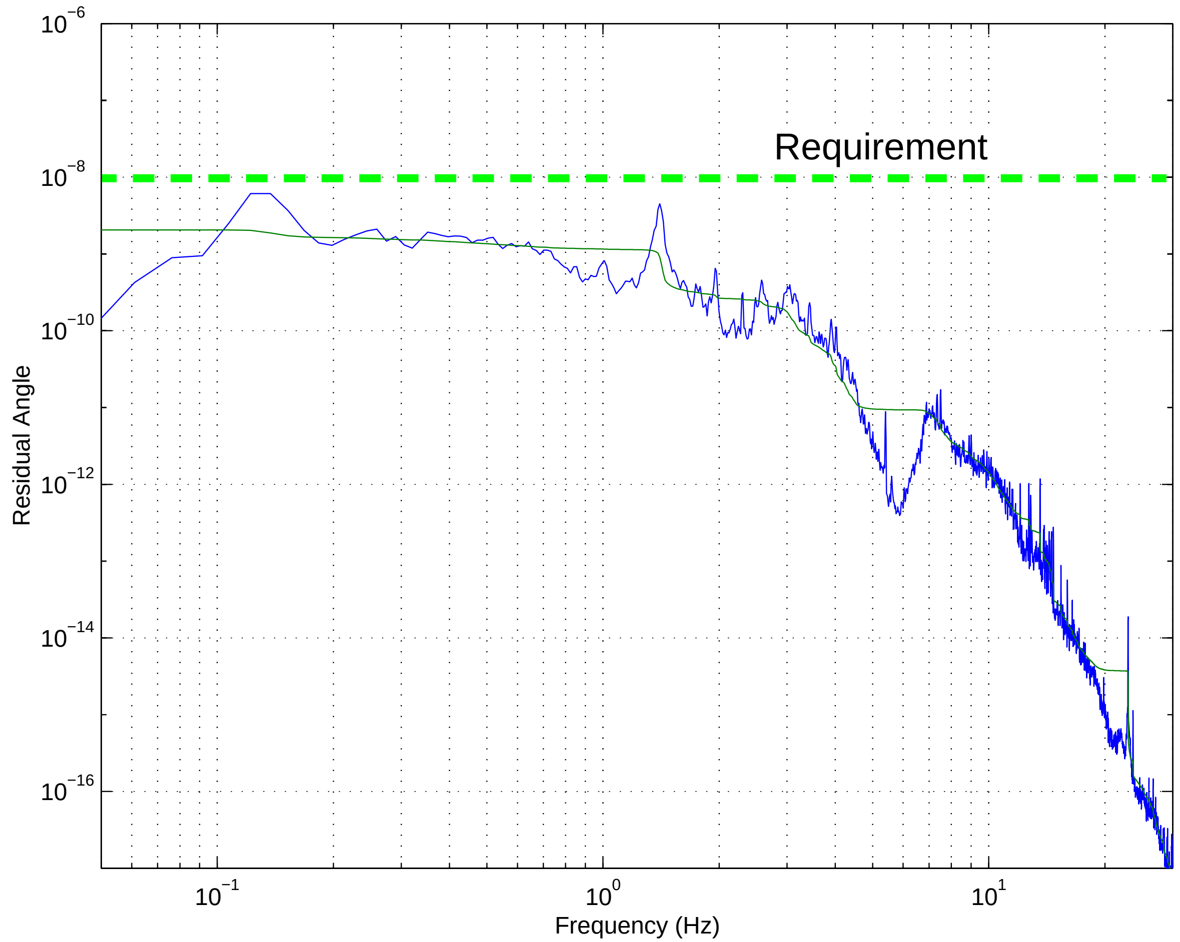
- Elliptic LPF: 4th order, 60 dB stop-band attenuation; part of SUS controller
- Unity gain frequency: 6 Hz; Phase margin 38 deg.:
  - Elliptic LPF: -22 deg.
  - 0.18 Hz BP: -12.5 deg.
  - 1.4 Hz BP: -7 deg.

Open Loop Gain



RESIDUAL ANGLE FLUCTUATIONS

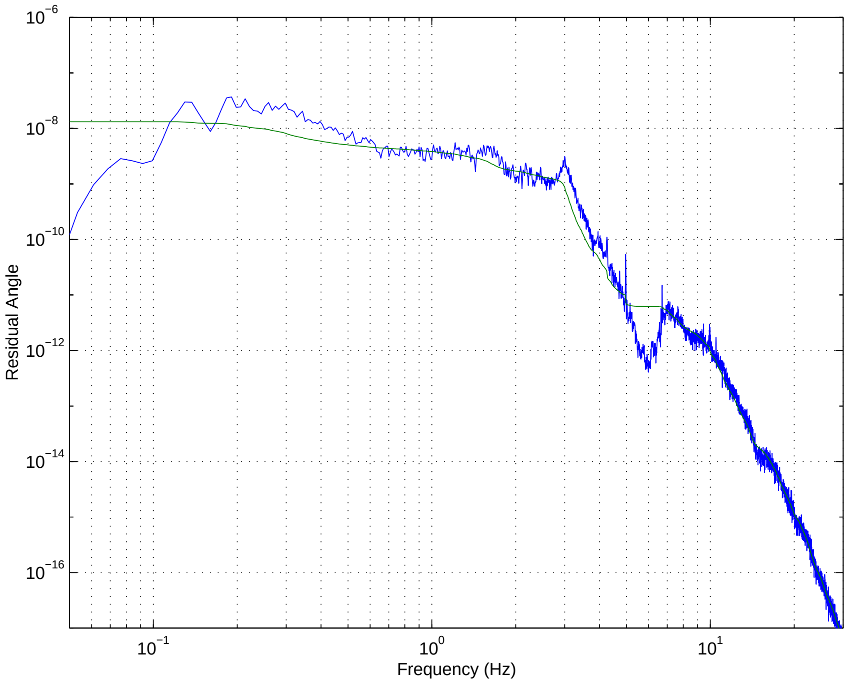
- WA input spectrum. No 1.4 Hz BP in controller.



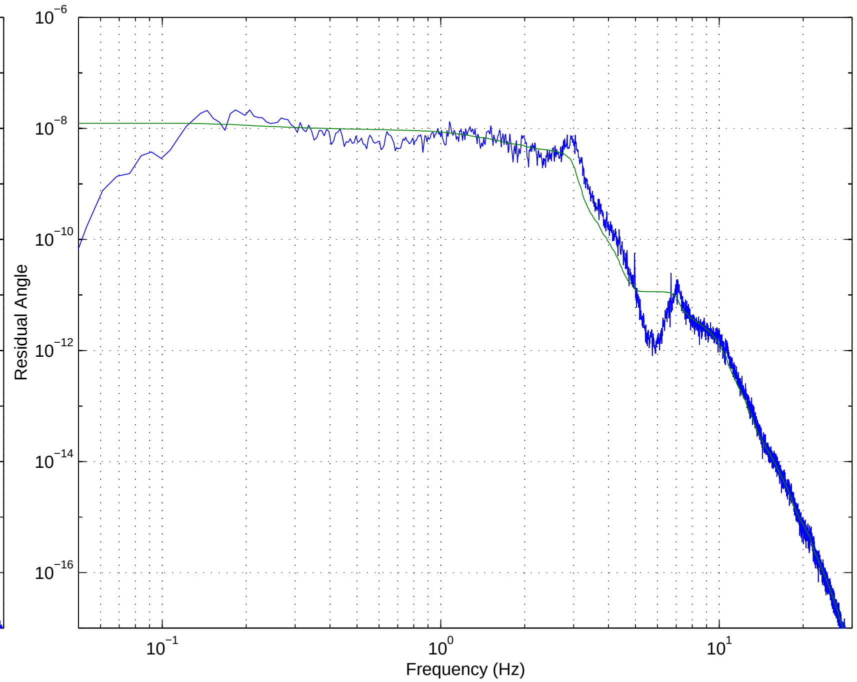
RESIDUAL ANGLE FLUCTUATIONS

- LA inputs:

high microseismic peak



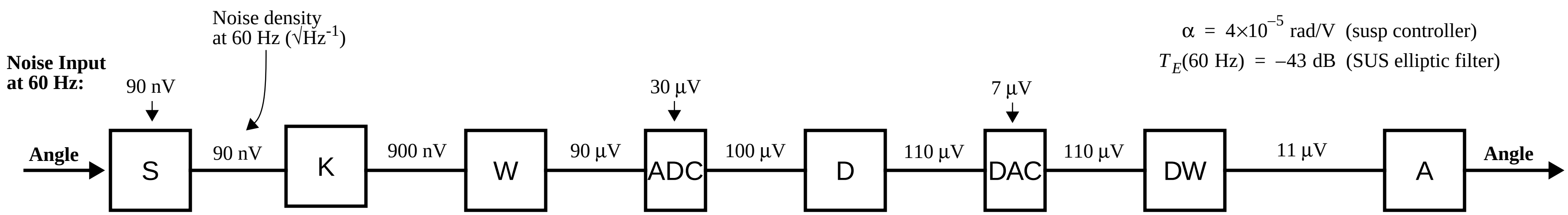
high 1-3 Hz noise



Sensing & Control Noise in GW band

$\alpha = 4\times10^{-5}$ rad/V (susp controller)

$T_E(60\ \text{Hz}) = -43$ dB (SUS elliptic filter)



Transfer function:

S	K	W	D	DW	A
10^7 V/rad	10	$100\cdot\frac{(s+2\pi4)^2}{(s+2\pi40)^2}$	$C(s)\cdot\frac{(s+2\pi1)}{(s+2\pi4)}$	$0.1\cdot\frac{(s+2\pi40)}{(s+2\pi4)}$	$\alpha\cdot\frac{0.25(s+2\pi40)}{(s+2\pi0.5)^2(s+2\pi1)}\cdot T_E(s)$

Gain at 60 Hz:

$$10^7 \times 10 \times 100 \times 4\cdot C(60\text{Hz}) \times 0.1 \times \alpha\cdot\left(\frac{0.5}{60}\right)^2\cdot\frac{1}{40}\cdot T_E(60\text{Hz})$$

$$= 0.28\cdot C(60\text{Hz})\cdot T_E(60\text{Hz})\ ,$$

which should equal: $0.08\cdot T_E(60\text{Hz})$, for a unity gain frequency of 5 Hz $\Rightarrow C(60\text{Hz}) = 0.29$

Angular noise at 60 Hz:

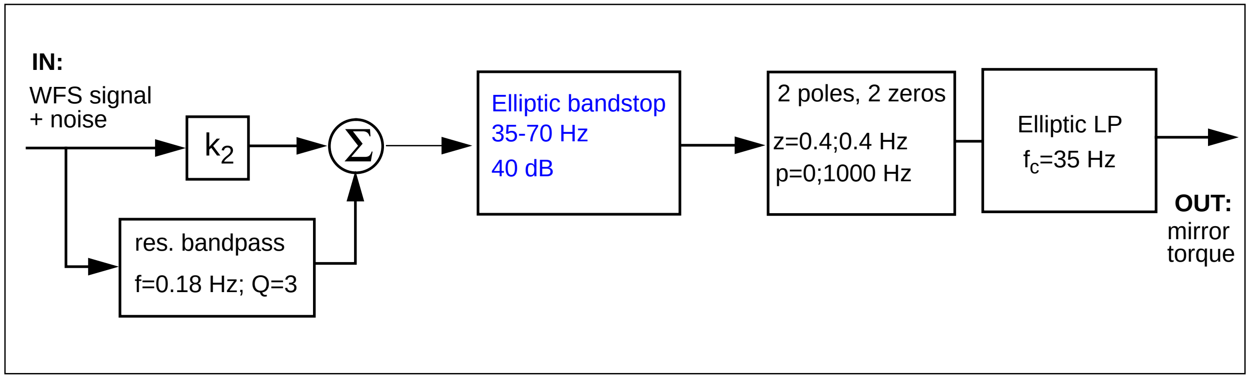
$$11\frac{\mu\text{V}}{\sqrt{\text{Hz}}}\cdot\alpha\cdot\left(\frac{0.5}{60}\right)^2\cdot\frac{1}{40}\cdot T_E(60\text{Hz}) = 5.4\times10^{-18}\ \text{rad}/\sqrt{\text{Hz}}$$

Requirement at 60 Hz: $\leq 7\times10^{-18}\ \text{rad}/\sqrt{\text{Hz}}$

Other Degrees of Freedom

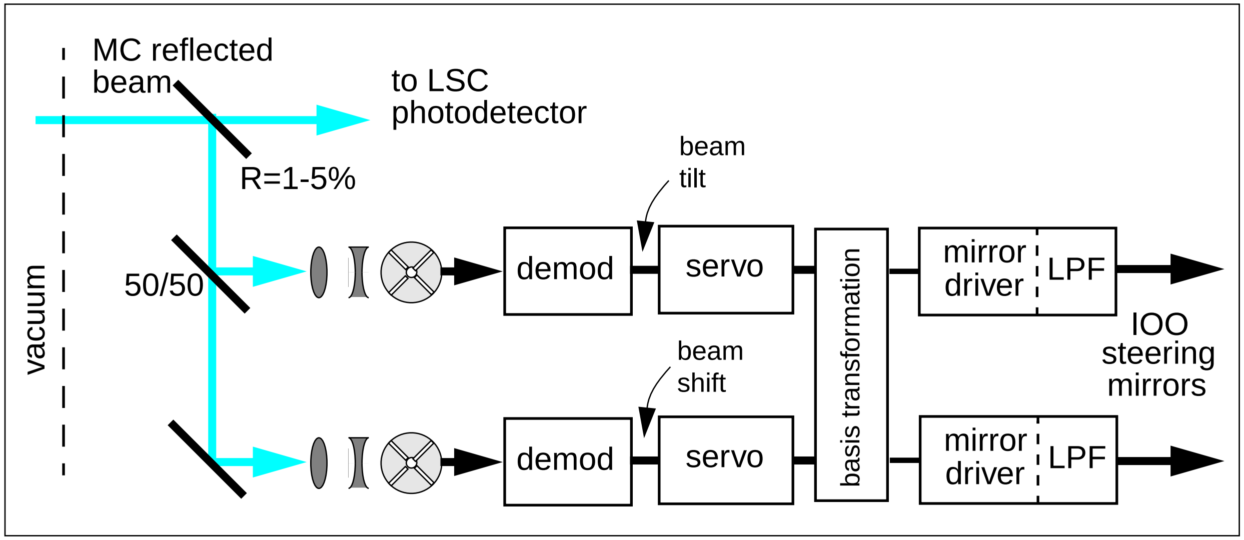
Sensor	*Sensing direction*	*S_α (rad/√Hz)*	*Filtering req.@40 Hz*	*Target servo BW, Hz*	*Target residual rms angle, rad*	*Mirrors controlled by this sensor*
WFS1	$\mathbf{u_2}$	9×10^{-15}	≥ 56 dB	6	0.8×10^{-8}	All TM's
WFS2a	$\mathbf{u_1}$	8.8×10^{-15}	≥ 56 dB	6	0.8×10^{-8}	ITM's, RM
WFS2b	$-.14\mathbf{u_1}-.4\mathbf{u_2}+.9\mathbf{u_3}$	8.8×10^{-14}	≥ 76 dB	2-3	3×10^{-8}	ITM's
WFS3	$.8\mathbf{u_1}+.13\mathbf{u_4}+.5\mathbf{u_5}$	9.1×10^{-14}	≥ 76 dB	1-2	1×10^{-7}	RM
WFS4	$.7\mathbf{u_1}-.46\mathbf{u_4}+.55\mathbf{u_5}$	7.3×10^{-14}	≥ 76 dB	1-2	1×10^{-7}	All TM's
QPD-X	**IB**	4×10^{-14}	≥ 70 dB	0.5	2×10^{-7}	IB
QPD-Y	-.9**BS**+.45**IB**	2×10^{-14}	≥ 65 dB	0.5	2×10^{-7}	BS, IB

EXAMPLE: WFS 2B



- Elliptic bandstop (6th order) implemented with a digital filter
- UGF = 3 Hz; PM = 35 deg
- Residual angle:
  - 6×10^{-8} rad-rms (LA, high 0.16Hz)
  - 1×10^{-8} rad-rms (WA)

MODE CLEANER ALIGNMENT CONTROL



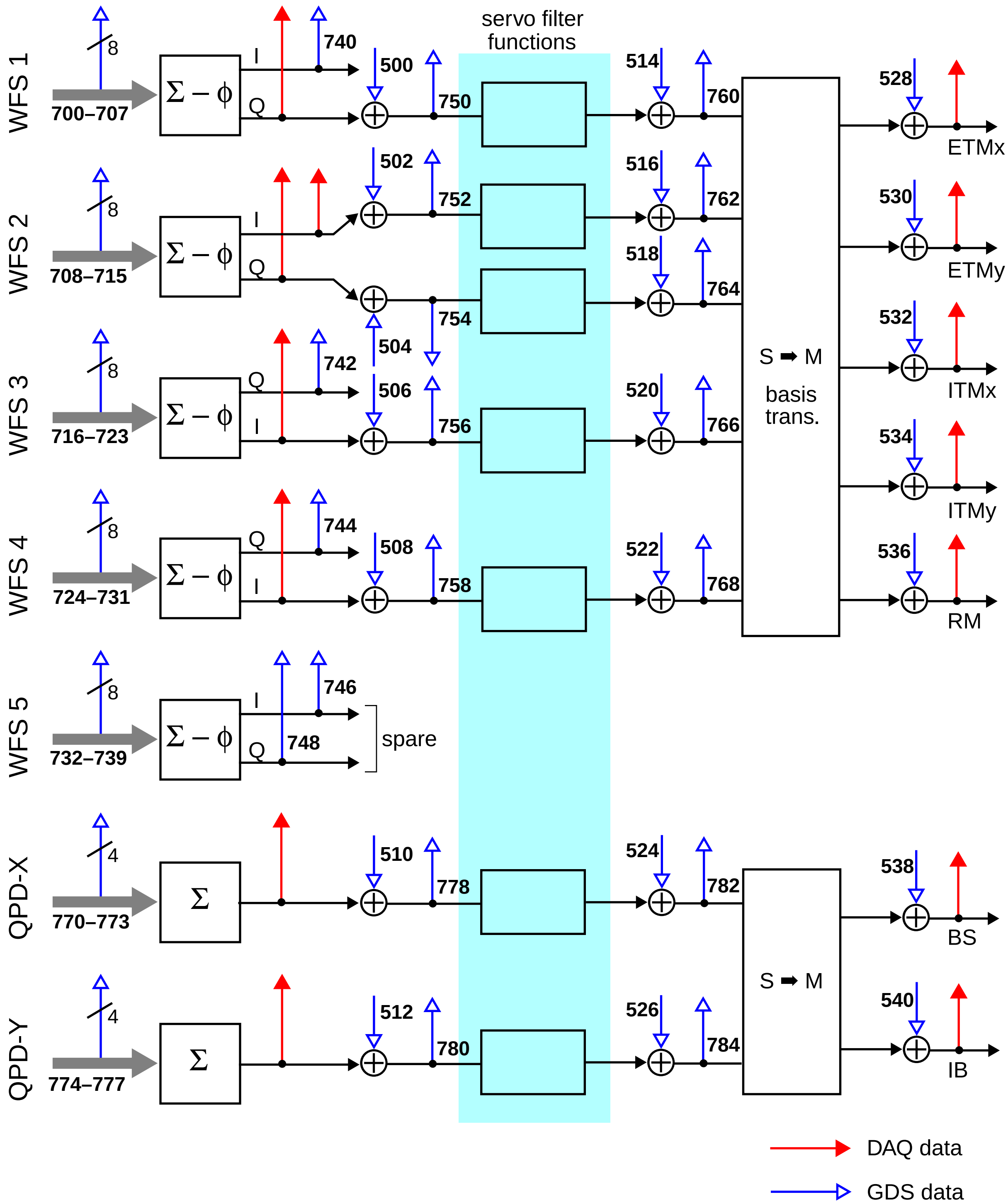
- Servo response: single pole at ≤ 0.1 Hz; UGF ~ 1 Hz.
- Residual angles of ~1 microradian or less
- Analog implementation
- LPF after mirror drivers may be needed to reduce driver noise in GW-band (beam jitter)

DIAGNOSTICS

- ASC is connected to the DAQS-GDS reflective memory ring
- Diagnostic tests are performed through the GDS infrastructure
- Test points (inputs or outputs) are defined within the ASC servo, which serve as the interface to GDS-DAQS
- Up to 64 test points can be used simultaneously for ASC

RM Test Point Interface

Note: all TPs are pairs (for pitch & yaw), unless otherwise noted.



DAQ Channels

- WFS DC readout, each element of quad, 16 Hz
- WFS LO phase & RF gain settings, 1 Hz (EPICS)
- Yaw & Pitch misalignment angles for all WFS, 2048 Hz
- Yaw & Pitch misalignment angles for QPD's, 2048 Hz
- Yaw & Pitch control signals for ETMs, ITMs, RM, BS, & IB, 2048 Hz
- *Total of 27 channels at 2048 Hz*

Staff

- Engineering, procurement & mfg. supervision
  - K. Mason, lead engineer
  - M. Smith (P/T)
- CDS electronics design/fab/test/SW support
  - P. Fritschel
  - E. Daw
  - N. Mavalvala
- Assembly/test
  - M. McInnes
  - P. Fritschel
  - M. Zucker
- Schedule/budget
  - M. Zucker

Schedule

- Top-level constraints: hardware
  - ❑ IOT7 paced by IO availability (< SEI, CDS and SUS completion)
  - ❑ ISCT 7-10 paced by COC installation
  - ❑ MIT assembly work in progress (setting up assembly areas in new lab)
- 'Simultaneous' (interwoven) activity threads:
  - ❑ IAS fab/test
  - ❑ LSC fab/test
  - ❑ IO/COC installation surveys (IAS)
  - ❑ CDS electronics design/fab support
  - ❑ Site installation (WFS/LSC)

WFS table deliveries

SEQ	ID	MILESTONE	PLAN DATE
1	5	LSC Init Fab	7/15/98
2	7	LSC_1	7/31/98
3	8	LSC_2	8/31/98
4	9	LSC_3	9/30/98
5	153	LSC IOT7 ready	10/23/98
6	10	LSC_4	10/30/98
7	11	LSC_5	11/27/98
8	12	LSC_6	12/25/98
9	13	LSC_7	1/29/99
10	179	LSC ISCT7 ready	2/11/99
11	14	LSC_8	2/26/99
12	196	LSC ISCT9 ready	3/12/99
13	15	LSC_9	3/31/99
14	213	LSC ISCT10 ready	4/16/99
15	16	LSC_10	4/30/99
16	275	LSC LIOT1 ready	5/7/99
17	17	LSC_11	5/31/99
18	302	LSC LISCT1 ready	6/4/99
19	320	LSC LISCT3 ready	6/25/99
20	18	LSC_12	6/30/99
21	338	LSC LISCT4 ready	7/23/99
22	398	LSC WIOT1 ready	9/24/99
23	425	LSC WISCT1 ready	11/19/99
24	443	LSC WISCT3 ready	12/24/99
25	461	LSC WISCT4 ready	1/21/00

Est. @completion vs. budget[1] (all ISC)

Item	Budget ($k)	EAC ($k)	Δ ($k)
LSC personnel	1,076	1,778	(702)
LSC hardware	609	257	352
ASC personnel	1,385	2,757	(1,372)
ASC hardware	3,419	1,694	1,725
total	**6,489**	**6,486**	**3**

1. LIGO Construction (WBS 1.x) only; does not include installation (LIGO Ops, WBS 2.x)

EAC (WFS hardware)

ASC;WFS

							2/98 EAC				Current EAC		
ASC (5E516-5H516): Wavefront Sensing Subsystem							$713,440				$688,436		
Group	Equipment	Wa2k	Wa4k	La4k	total	Cost (ea)	Total		rev. total	rev. Cost	Current EAC	Committed	Reference
WFS	optical table	4	4	4	12	$4,800	$57,600		12	$4,800	$57,600		
WFS	table enclosure	4	4	4	12	$2,100	$25,200		12	$2,100	$25,200		
WFS	isolated table supports	4	4	4	12	$4,000	$48,000		12	$4,000	$48,000		
WFS	periscope structure	8	8	8	24	$1,600	$38,400	1	24	$1,350	$32,400	6/5/98	PP271113-75KM (partial)
WFS	beam fold/tube	8	8	8	24	$2,400	$57,600		24	$2,400	$57,600		
WFS	optical mounts	60	60	60	180	$280	$50,400		180	$280	$50,400		
WFS	mirrors	30	30	30	90	$280	$25,200		90	$280	$25,200		
WFS	beamsplitters	18	18	18	54	$260	$14,040		54	$260	$14,040		
WFS	lens & mount	24	24	24	72	$350	$25,200		72	$350	$25,200		
WFS	remote mirror mount	20	20	20	60	$1,850	$111,000		60	$1,850	$111,000		
WFS	multi-axis driver	3	3	3	9	$4,000	$36,000		9	$4,000	$36,000		
WFS	ND wheel	4	4	4	12	$350	$4,200		12	$350	$4,200		
WFS	beam camera	8	8	8	24	$800	$19,200	1	0	$800	$0	5/20/98	part of PP269918-75PF (see video)
WFS	RF PIN quads (bare)	10	10	10	30	$400	$12,000		30	$400	$12,000		
WFS	safety shutter	4	4	4	12	$550	$6,600		12	$550	$6,600		
WFS	spares	1	1	1	3	$18,000	$54,000		3	$18,000	$54,000		
WFS	alignment/test fixtures	1	0	1	2	$32,000	$64,000		2	$32,000	$64,000		
WFS	alignment laser (IR)	1	0	1	2	$3,600	$7,200	1	2	$3,698	$7,396	6/5/98	PP271435-75MZ (partial)
WFS	beamscan	1	0	1	2	$7,500	$15,000		2	$7,500	$15,000		
WFS	hardware	4	4	4	12	$550	$6,600		12	$550	$6,600		
WFS	special crates	4	2	2	8	$1,500	$12,000		8	$1,500	$12,000		
WFS	shipping	1	1	1	3	$8,000	$24,000		3	$8,000	$24,000		