THE FMI ALIGNMENT EFFORT

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- **Goal**
  Establishing a wavefront sensing scheme for the LIGO alignment sensing and control (ASC).

- **Scope**
  - **Modal Model**
    Mathematical tool for describing angular misalignments in gravitational-wave interferometers.
  - **FMI Experiment**
    Verify the wavefront alignment scheme
    Develop and characterize the wavefront sensing hardware

LIGO-G960172-00-D

MODAL MODEL

Angular misalignments excite higher-order transverse modes

❑ Modal Space

Fields	Vector
Free space propagation	Operator
Mirror Distortions	Operator
Optical Train	Operator1 ∘ Operator2 ∘...

❑ Detection Scheme

- ❍ Based on Pound-Drever-Hall and Schnupp locking techniques.
- ❍ Beating of a higher-order mode against the TEM_{00}
  ➪ spatial map of this higher-order mode.
- ❍ Segmented photodetector

Rules of Thumb for Angular Misalignment

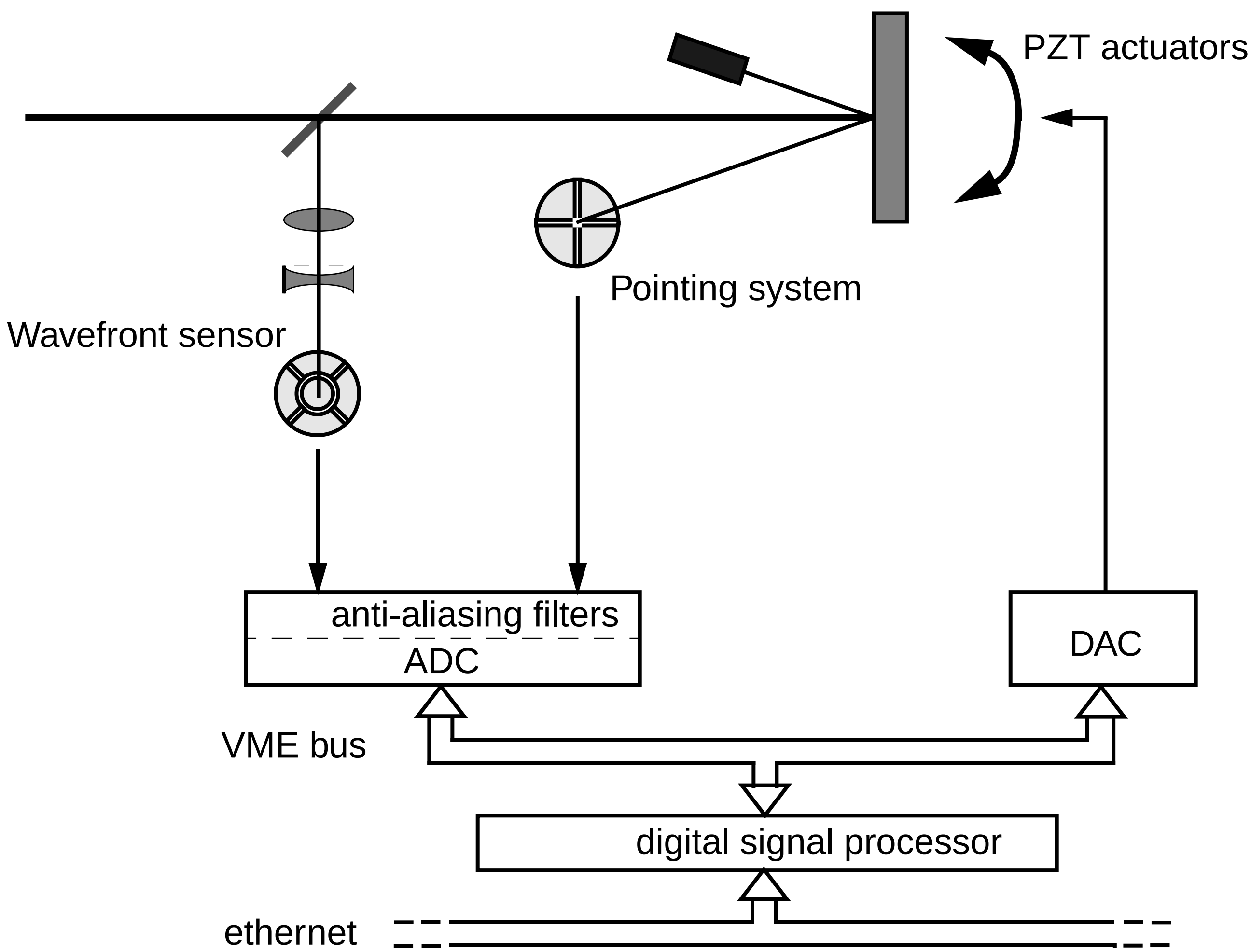
- TEM_{10} amplitude $\propto$ Misalignment angle.
- Wavefront sensor measures TEM_{10} amplitude.
- Distinguishing cavity input and rear mirrors
  - Additional Guoy phase shift for TEM_{10} excited in the cavity.
  - TEM_{10} generated by a resonant field shows no distinction between input and rear mirrors.
  - Non-resonant fields see the input mirror only.
  - need TEM_{00} of resonant field at detection port.
  - no distinction for highly degenerate cavity!
- Double cavity: special case.

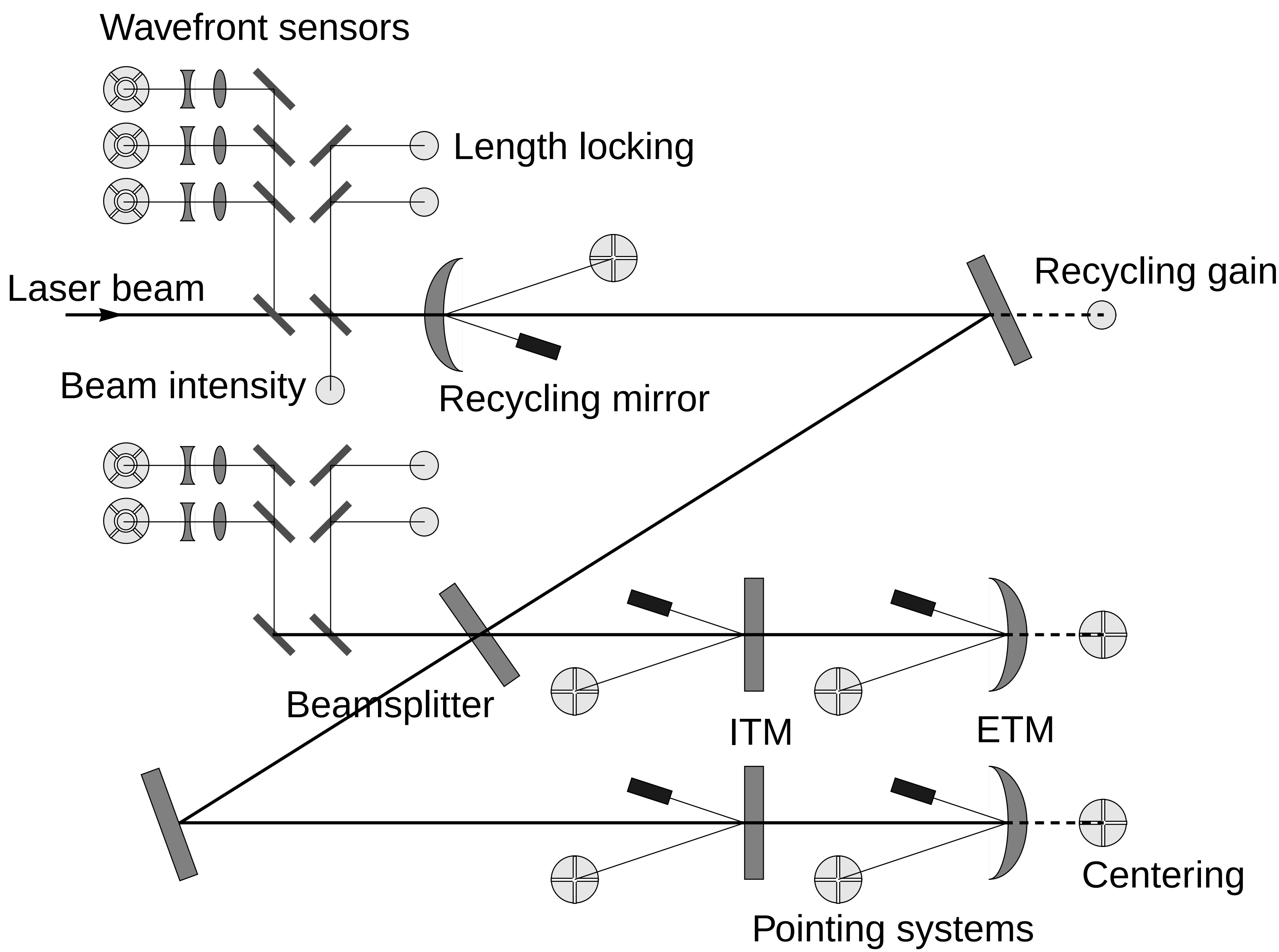
WAVEFRONT SENSOR MEASUREMENT

$$WFS_i(t, \eta, \Theta) = 2J_0(\Gamma)J_1(\Gamma)P_i$$
$$\sum_j A_{ij}\Theta_j \cos(\eta - \eta_{ij}) \cos(\omega_m t + \phi_{ij})$$

WFS_i	wavefront sensor signal at i-th port
Θ_j	misalignment angle for j-th dof
A_{ij}	alignment matrix
η	Guoy phase
η_{ij}, ϕ_{ij}	intrinsic Guoy and RF phases
P_i	power on the detector
ω_m, Γ	modulation frequency and depth

WAVEFRONT SENSOR MEASUREMENT (2)




Wavefront sensors
Length locking
Laser beam
Recycling gain
Beam intensity
Recycling mirror
Beamsplitter
ITM
ETM
Centering
Pointing systems

Possible Alignment Matrix

❑ FMI

	phases		angular degrees of freedom				
port	**rf**	**Guoy**	**ΔETM**	**ΔITM**	**$\overline{\text{ETM}}$**	**$\overline{\text{ITM}}$**	**RM**
1 dark port, CR	Q	80°	**51.9**	**50.4**	0	10	0
2 dark port, SC	Q	-12°	0	**13.5**	0	0	0
3 recycling, CR	I	87°	0	0	**105**	**219**	-31.4
4 reflection, SCNR	I	-89°	0	0	0	**2.51**	**-1.73**
5 reflection, SCNR	I	-28°	0	0	0	**-1.20**	**3.61**

❑ LIGO

	phases		angular degrees of freedom				
port	**rf**	**Guoy**	**ΔETM**	**ΔITM**	**$\overline{\text{ETM}}$**	**$\overline{\text{ITM}}$**	**RM**
1 dark port	Q	90°	**–21.4**	**–9.77**	0	0	0
2 reflection	Q	145°	0.039	**–2.31**	0	0	0
3 reflection	I	145°	0	0	–0.04	**13.1**	**–18.4**
4 reflection, NR	I	90°	0	0	**–2.19**	**–0.98**	0
5 reflection, NR	I	0°	0	0	0	0	**2.00**

MAIN FEATURES OF THE FMI

❑ Input Optics

- ❍ Frequency shifted subcarrier modulation scheme:
  carrier sidebands at 59.5 MHz (resonant in recycling cavity)
  subcarrier at 390 MHz (dark at differential port)
  subcarrier sidebands at 39 MHz (resonant in recycl. cavity)
  subcarrier sidebands at 32 MHz (non-resonant)
- ❍ Double-passed AOM
- ❍ Fiber-coupled to interferometer

❑ Actuators

- ❍ Fast PZT using constrained layer damping
- ❍ 20 kHz servo bandwidth

❑ Pointing system

- ❍ Optical lever with a diode laser
- ❍ Sensitivity: ~ 20 V/mrad
- ❍ Noise: 1 $\mu rad/\sqrt{Hz}$ at DC, 1 $nrad/\sqrt{Hz}$ at 100 Hz

MAIN FEATURES OF THE FMI (2)

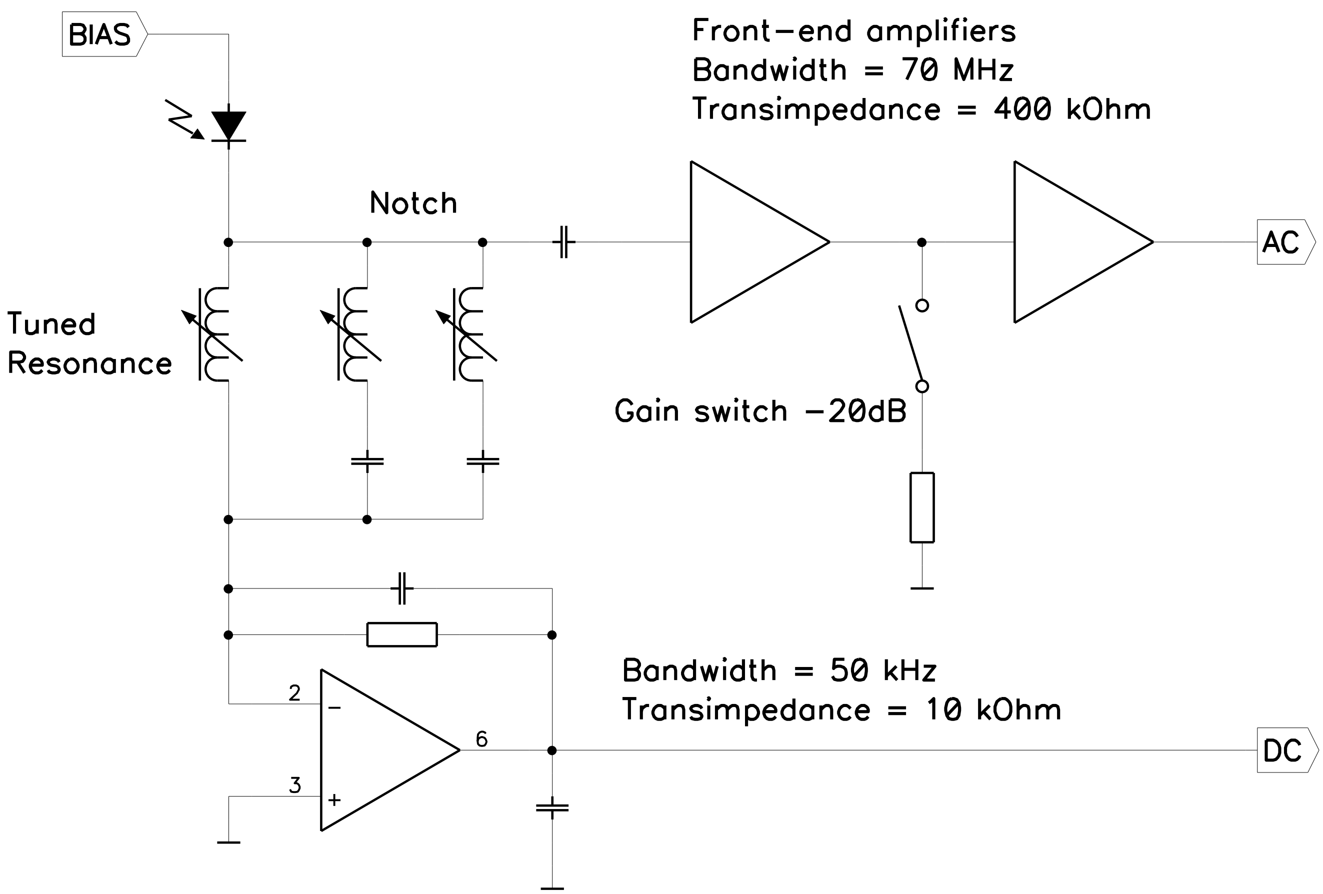
❑ Data Acquisition System

- ❍ VME based
- ❍ 128 ADC channels / 16 DAC channels
- ❍ 1 kHz sampling rate
- ❍ EPICS front-end
- ❍ Digital servo for alignment control

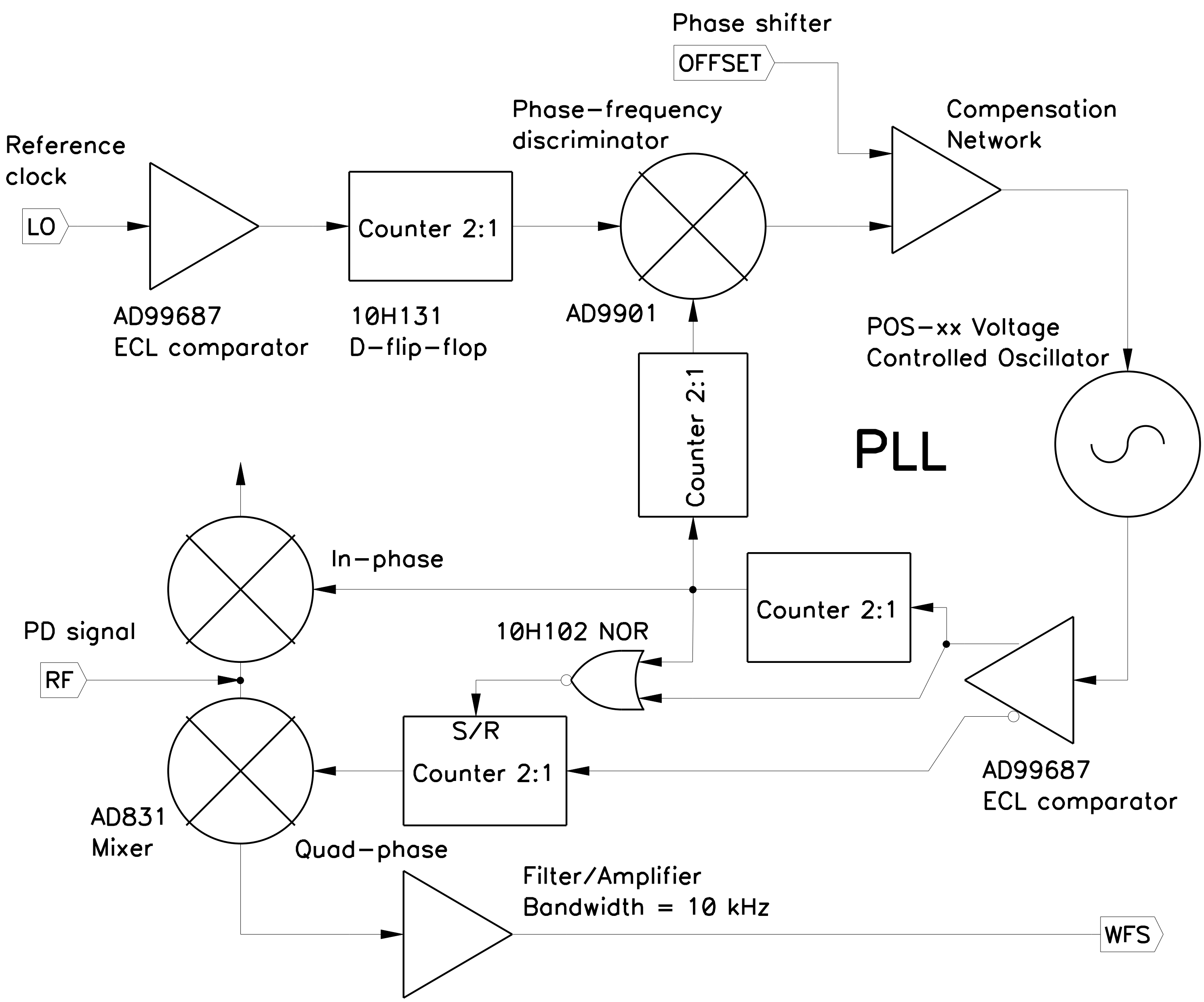
❑ Wavefront Sensor (LIGO prototype)

- ❍ Guoy phase telescope
- ❍ Sensor head:
  Quadrant photodiode
  Tuned circuit
  Shot noise limited at ~1 mW light power
- ❍ Demodulator board:
  In- and quad-phase demodulation
  Implements a voltage-controlled LO phase shifter

WAVEFRONT SENSOR HEAD



DEMODULATOR BOARD



STATUS UPDATE

❑ thus far ...

- ❍ Modal model simulations for FMI and LIGO
- ❍ Input optics and interferometer construction completed
- ❍ All length degrees-of-freedom locked and locking sequence established.
- ❍ Data acquisition system operational
- ❍ Pointing system operational
- ❍ Wavefront sensors fabricated

❑ next ...

- ❍ Wavefront sensor testing/calibration/installation
- ❍ Measurements:
  Alignment matrix for a recycled Michelson
  Alignment matrix for a complete interferometer
  Large angle limits
  Suspended interferometer wavefront tests
- ❍ Closed loop control
- ❍ Analysis