THE FMI ALIGNMENT EXPERIMENT

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❑ Effects of misalignment

- ❍ Degradation of GW sensitivity $\Rightarrow$ $\theta_i \sim 10^{-8}$ rad
- ❍ Misalignment-beam jitter coupling $\Leftrightarrow$ $\theta_i \sim 10^{-8}$ rad

❑ Need for wavefront sensing

- ❍ drifts of the local frame $\Rightarrow$ $\theta_i \sim 10^{-7}$ rad
- ❍ interferometric sensing using existing modulated light

❑ Goals of the FMI experiment

- ❍ Establish and verify a wavefront sensing scheme for LIGO
- ❍ Validate the modal model
- ❍ Develop and characterize the wavefront sensing hardware

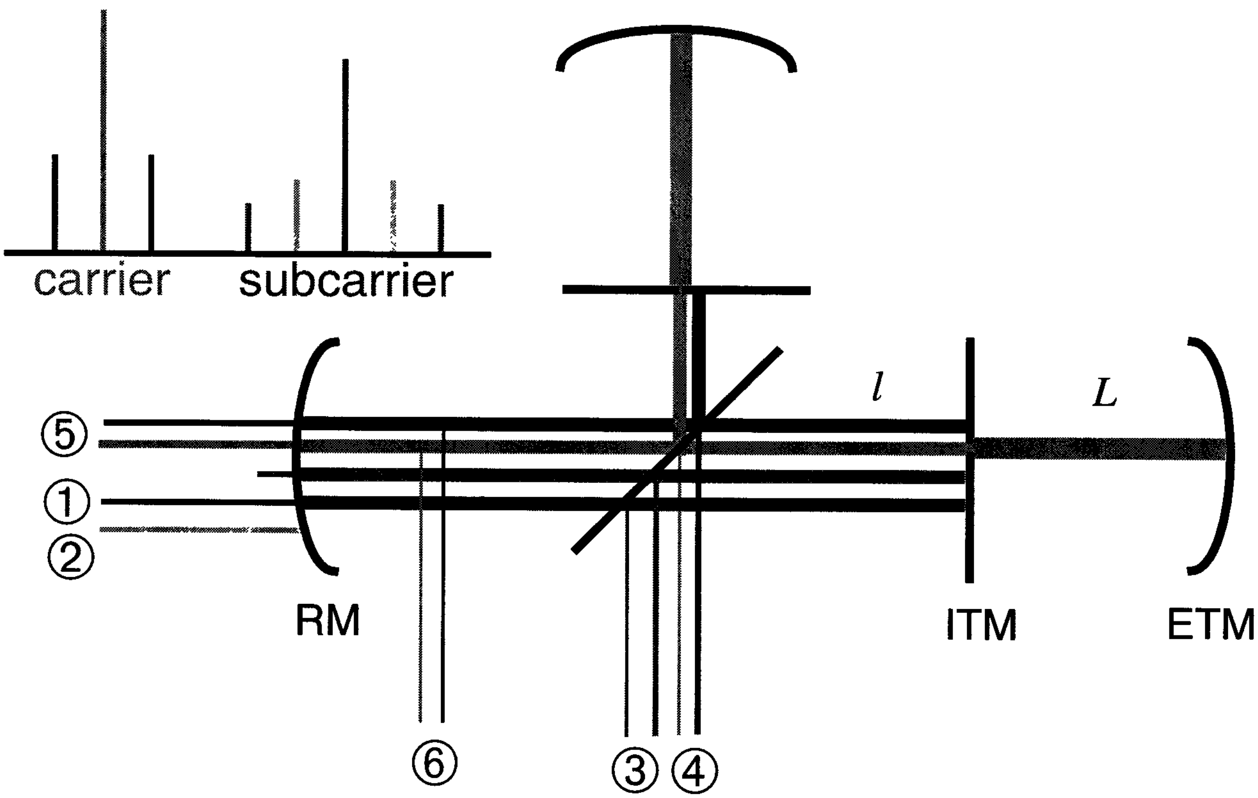
LIGO-G960269-00-D

Principles of Wavefront Sensing

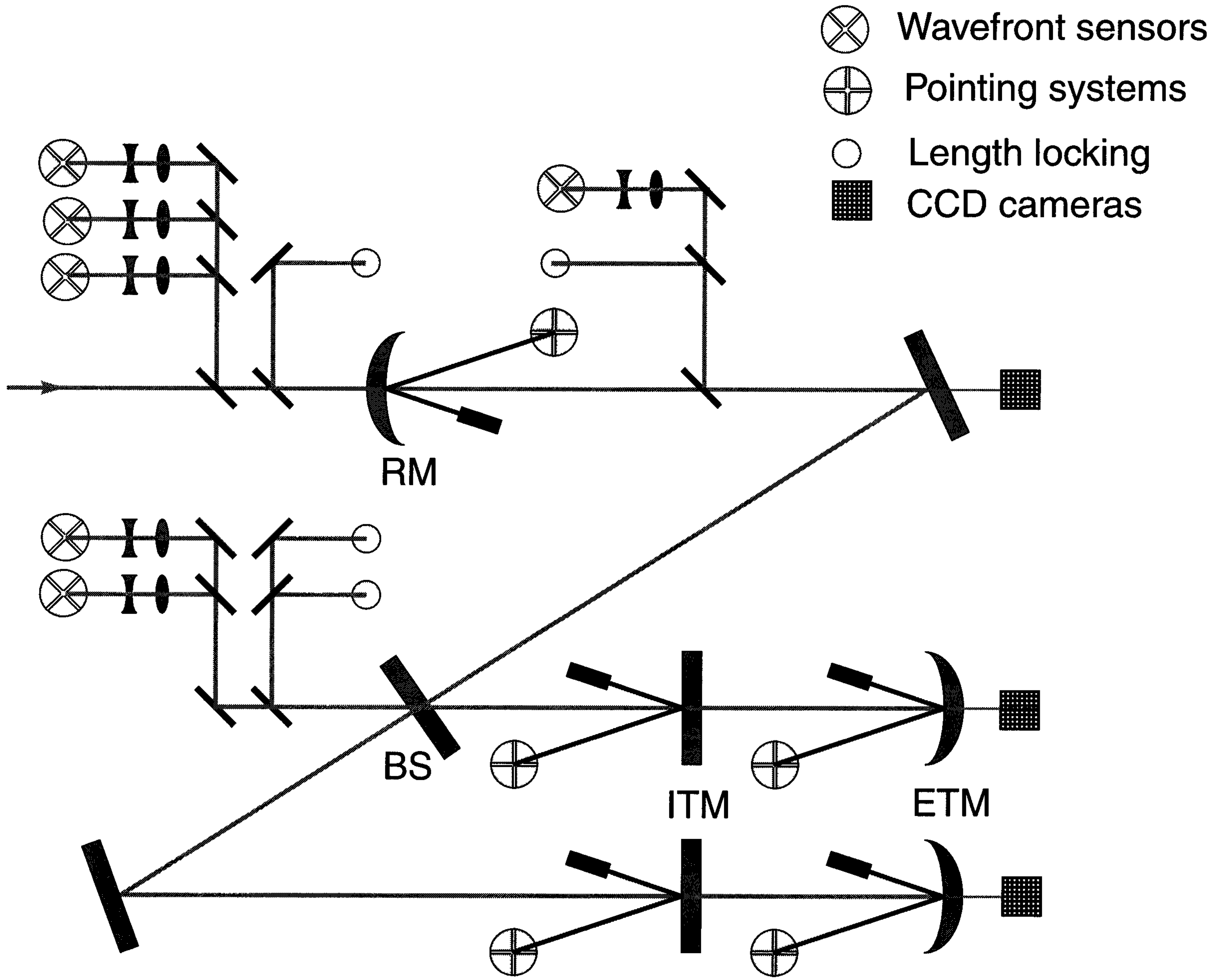
Angular misalignments excite higher-order transverse modes

- **TEM_{10} amplitude $\propto$ Misalignment angle**
- **Wavefront sensor measures TEM_{10} amplitude**
- **Detection Scheme**
  - Length sensor signal:
    beating of carrier TEM_{00} field against sideband TEM_{00} field
  - Wavefront sensor signal:
    Beating of carrier TEM_{00} field against sideband TEM_{10} field
    ⇨ spatial map of this TEM_{10} mode at modulation frequency
    ⇨ segmented photodetector
  - Frequency shifted subcarrier locking technique

DETECTION SCHEME

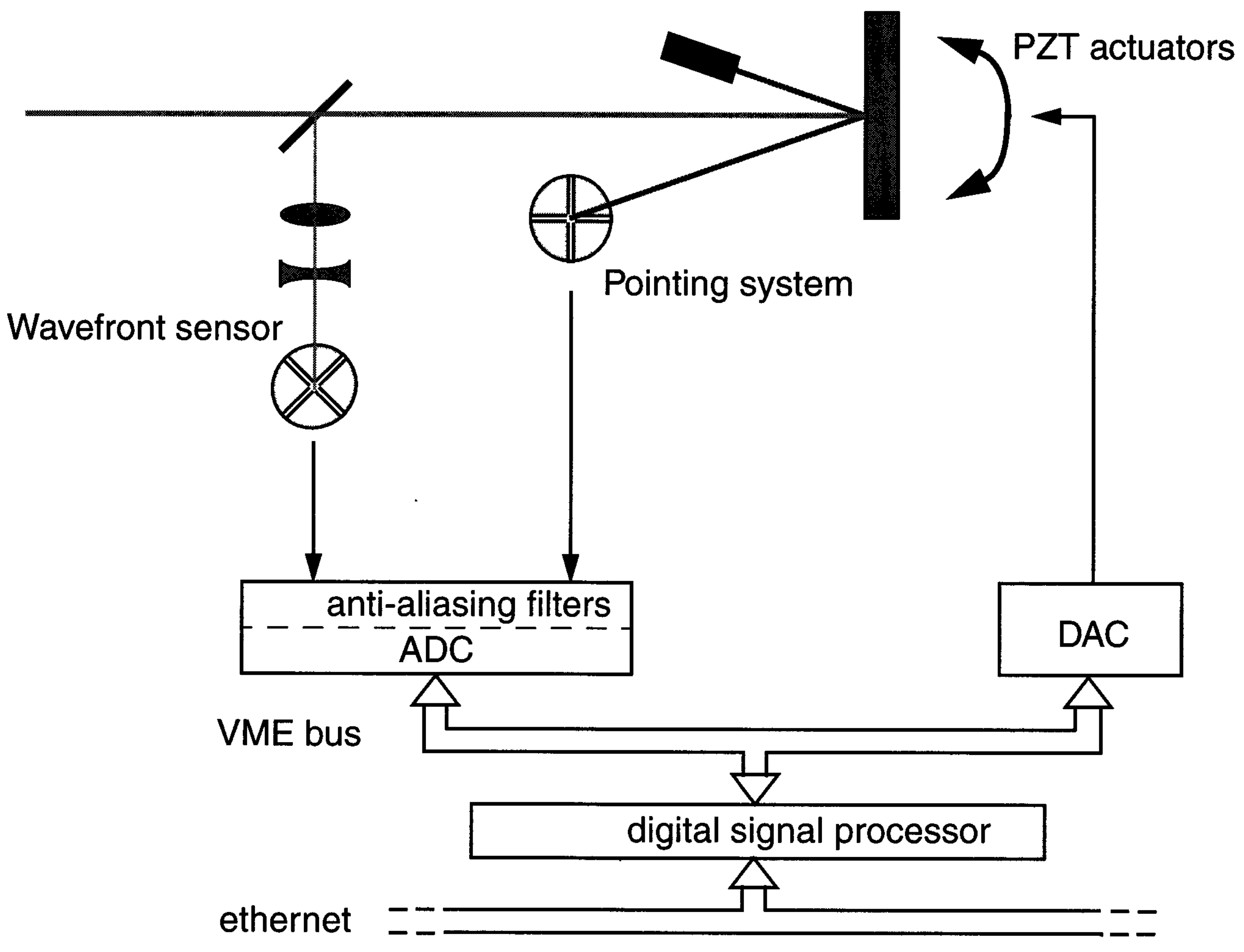


Port	①	②	③	④	⑤	⑥
LS	l_C		l_D	L_D	L_C	L_C
WFS	RM	ITM_C	ITM_D	ETM_D	ETM_C	ETM_C

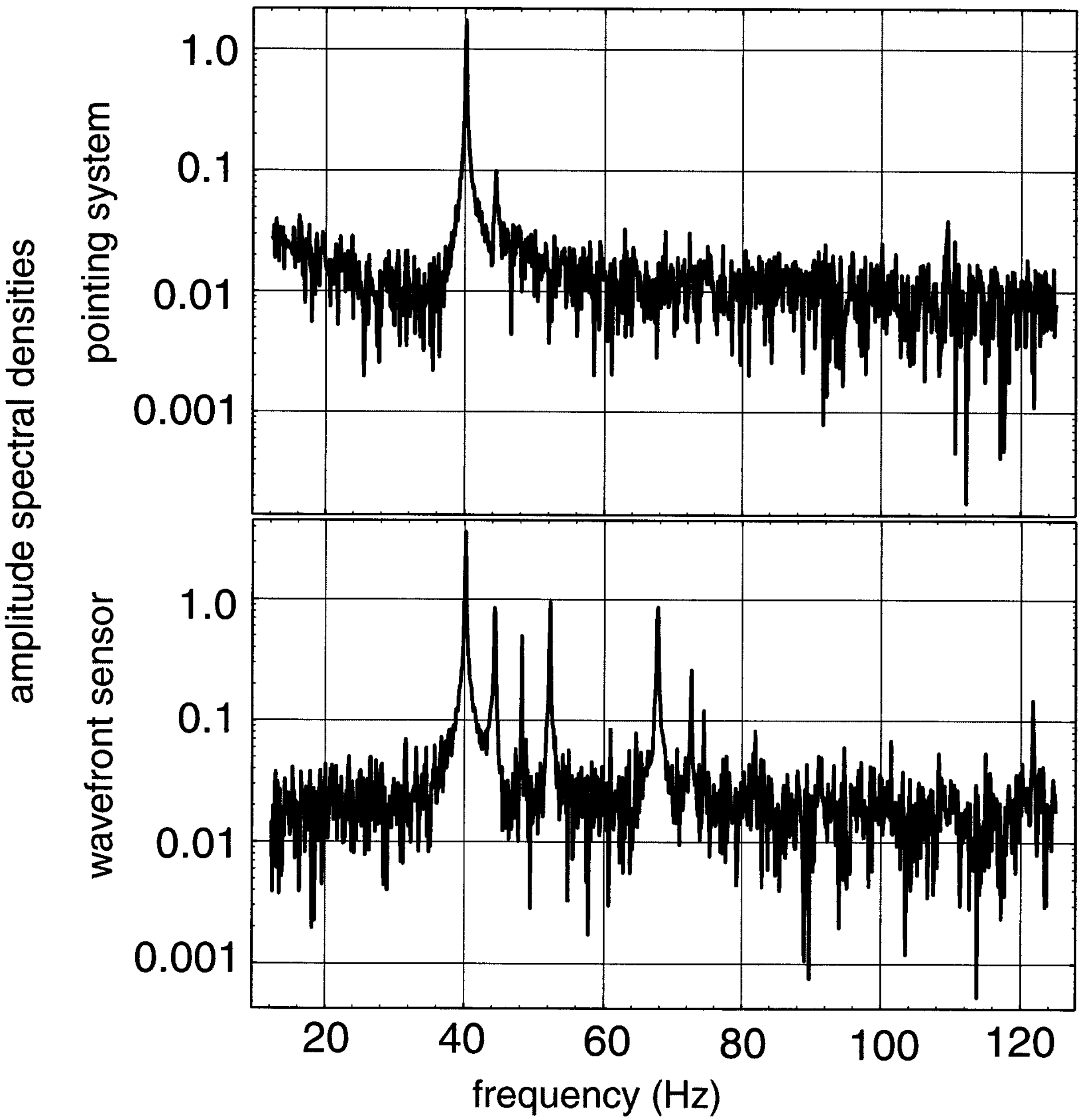


Wavefront sensors
Pointing systems
Length locking
CCD cameras
RM
BS
ITM
ETM

WAVEFRONT SENSOR MEASUREMENT



DATA



amplitude spectral densities
pointing system
wavefront sensor
1.0
0.1
0.01
0.001
20
40
60
80
100
120
frequency (Hz)

Wavefront Sensor Matrix Measurement

$$V_{ij}^{ADC}(t, \eta, \Theta) = \varepsilon J_0(\Gamma_i) J_1(\Gamma_i) Z_i P_i$$

$$\boldsymbol{A}_{ij} \Theta_j \cos(\eta - \eta_{ij}) \cos(\omega_m t + \phi_{ij})$$

$\boldsymbol{A}_{ij}$	alignment sensitivity matrix element
V_{ij}	*ij*-th wavefront sensor signal
ε	quantum efficiency of detector
Z_i	gain of the detector
P_i	power on the detector
Θ_j	misalignment angle for *i*-th dof
η	Guoy phase
η_{ij}, ϕ_{ij}	intrinsic Guoy and RF phases
ω_m, Γ	modulation frequency and depth

RESULTS

❑ Alignment sensitivity matrix

	phases		angular degrees of freedom				
port	**rf**	**Guoy**	**RM**	**ITM1**	**ITM2**	**ETM1**	**ETM2**
① refl, SC NR	I	152°	**-2.59**	0.34	0.43	0	0
			-3.00	0.30	0.39	0	0
② refl, SC NR	I	92°	-1.42	**0.76**	**0.78**	0	0
			-1.75	**0.57**	**0.63**	0	0
③ dark, SC	Q	168°	-0.67	**-2.77**	**2.98**	0	0
			0.22	**-2.23**	**-2.45**	0	0
④ dark, CR	Q	80°	-1.01	14.8	-12.1	**15.5**	**-12.6**
			-0.61	9.49	-9.92	**11.3**	**-9.13**
⑤ refl, CR	I	87°	-2.05	3.65	3.67	**3.74**	**3.77**
			-2.70	2.74	2.99	**2.76**	**2.99**
⑥ rec, CR	I	140°	-20.7	32.4	32.8	**30.4**	**30.8**
			-20.9	18.4	22.4	**17.6**	**19.8**

■ matrix elements predicted by modal model

■ measured matrix elements

LIGO

Error Propagation

$$A_{ij}(\varepsilon, P_{IN}, \theta_j, f_i, \Gamma_i, Z_i, \eta_{ij}, l_{ij})$$

σ_{x_n}/x_n SAME FOR: ALL MATRIX ELEMENTS ($\varepsilon, P_{IN}, \theta_j, f_i$); EACH FREQ ($\Gamma_i, Z_i$); EACH ELEMENT ($\eta_{ij}, l_{ij}$)

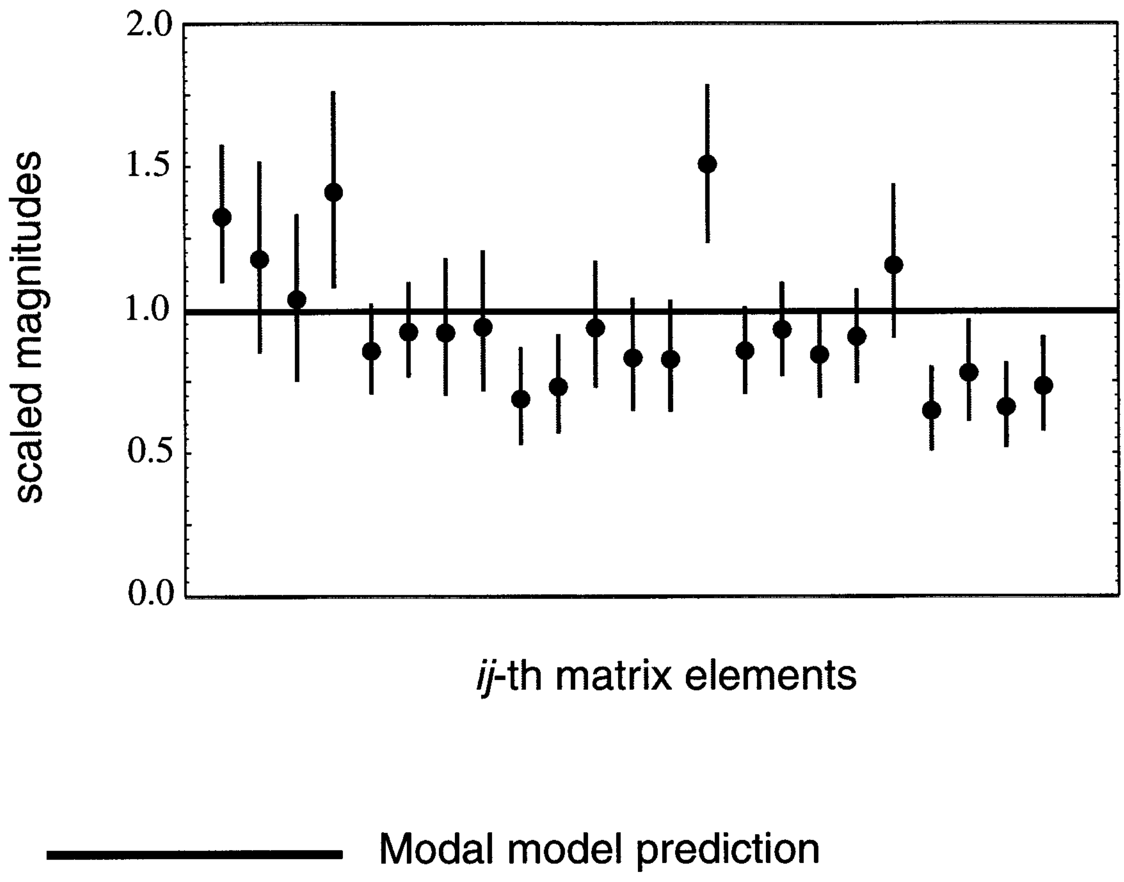
x_n	ε	P_{IN}	θ_j	f_i
σ_{x_n}/x_n	±0.05	0.15±0.05	±0.10	±0.02

x_n	Γ_{58}	Γ_{39}	Γ_{32}	Z_{58}	Z_{39}	Z_{32}
σ_{x_n}/x_n	±0.03	±0.07	±0.03	±0.10	±0.05	±0.05

x_n	η_{ij}	l_{ij}
$\frac{\partial A}{\partial x_n}\frac{\sigma_{x_n}}{A}$	±0.005 to ±0.22 diagonal off-diagonal	±0.05 to ±0.25 different ports

MATRIX ELEMENTS

❑ Non-zero matrix elements



CONCLUSIONS

- All 10 angular dofs under closed loop control ⇨ wavefront sensing works
- Measurement of matrix elements ⇨ modal model works
- Design tool for LIGO