CALIFORNIA INSTITUTE OF TECHNOLOGY

Laser Interferometer Gravitational Wave Observatory (LIGO) Project

To/Mail Code: Stan Whitcomb
From/Mail Code: Kent Blackburn
Albert Lazzarini
Phone/FAX: 395-3185/8444
Refer to: LIGO-E960108-A-E
Date: July 31, 1996

Subject: Closeout of COC DRR AI#11 -- Recommendation of parameter choices in 2 km interferometer design.

Background

At the COC DRR of 23 February 1996, an action item was assigned to Systems Engineering and Integration (AI#11, LIGO-E960027-00-D) to propose the **h**[f] design sensitivity for the 2 km interferometer. Performance of the 2 km instrument was considered with regard to varying the design parameters listed in Table 1. The effect of baseline distance change between 2 km and 4 km instruments was assumed not to affect the seismic displacement noise, **x**[f], of the 2 km interferometer. Consequently, the assessment of design and performance impact was limited to considering the thermal and shot noise components of **h**[f].

Table 1: Parameters considered in specifying h[f] for 2 km interferometer

Parameter	Effect on IFO performance	Options/Advantages	Disadvantages
Reflectivities of ITM/ETM	i. Cavity storage time ii. IFO knee frequency iii. Irradiance on mirrors	A. Increase 2 km cavity finesse to keep IFO knee frequency of 2 km at same point as 4 km => frequency dependence of the shot noise identical. B. Maintain same finesse as 4 km IFO => circulating power not increased above 4 km values.	A. Beam irradiance on cavity mirrors increased because stored power increases. B. Knee frequency of 2 km machine becomes 180 Hz. => different shot noise characteristics for 2 km instrument.
Mirror radii of curvature	i. Cavity g-factor; ii. Beam spot dimensions; iii. Guoy phases of higher modes;	A. Change g-factor of 2 km IFO to increase spot size on ITM/ETM => decreases coating irradiance levels inside 2 km cavity.	A. Mode strcuture would change -- impact, although not completely assessed, appears to be too great in design to pursue further.
Mirror dimensions	i. Affects thermal noise; ii. Affects diffraction losses.	A. Overlap of mirror modes and beam spot can be tuned to minimize thermal noise for the smaller 2 km beam spot sizes.	A1. Fabrication of 2 km mirrors would become very different from 4 km mirrors; A2. Mirror blanks would become unique; A3. Improvement is minimal.

Discussion

In consultations with Bill Kells and Stan Whitcomb, it was concluded that changes of either cavity g-factor[1] or overall mirror dimensions were too extreme to warrant further consideration at this time. These parameters affect principally the thermal noise regime of the sensitivity; however, the payoffs in improvement are minimal: decreased optic size, affects internal thermal noise by competing effects with opposite signs: improved overlap between laser spot and mirror vibrational modes reduces noise but the reduced mass increases noise. In addition, decreased test mass leads to increased thermal noise contribution from pendulum and wire resonances.

The options which were assessed were to either: (i) maintain IFO knee frequency the same as in the 4 km IFO; or (ii) to maintain the reflectivities in the 2 km IFO the same as in the 4 km IFO. Figure 1 presents the best estimate of the baseline strain sensitivity for the 4 km. Figure 2 shows **x**[f] for the 2 km IFO in which the knee frequency is maintained at 90 Hz (option (i) above). Figure 3 shows **x**[f] when the reflectivities are maintained the same as in the 4 km instrument (option (ii) above). The parameters used in calculating the three sets of figures are listed in Table 2.

1. Comparison of 2 km and 4 km IFOs at low frequency (seismic-dominated regime)

Changing optical parameters does not affect displacement noise arising from seismic activity. Because of the shorter baseline, the 2 km IFO strain sensitivty will be 2x worse than the 4 km IFO in this regime.

2. Comparison in mid-range (thermal noise regime)

The beam spot sizes are 1/1.6 and 1/1.26 (for end and vertex masses, respectively) smaller relative to the optic aperture and this causes an increase in absolute displacement noise from internal thermal noise for the 2 km instrument relative to the 4 km IFO. In addition, the shorter baseline reduces strain sensitivity by a factor 2x relative to the 4 km instrument. Variation in cavity storage time does not affect this regime.

3. Comparison at high frequencies (shot noise regime)

The shot noise for the 2 km IFO is affected by choice of cavity storage time. At frequencies beyond the cavity pole, performance is indepedent of storage time and both 90 Hz and 180 Hz designs achieve identical performance. Below the pole, the increased power associated with the greater finesse of an instrument with a 90 Hz cavity pole reduces the shot noise below the level attainable with a 180 Hz pole. However, in this transition regime where cavity pole affects shot noise, instrument sensitivity is dominated by thermal noise (#2 above).

Conclusions

Comparison between Figures 2 and 3 indicates that while the shot noise component of **h**[f] @100 Hz for option (ii) is almost 2x greater than it is for option (i), this effect is masked for both options (i) and (ii) by the fact that the internal thermal noise is greater than shot noise by factors 3.3x and 2.5x for options (i) and (ii) respectively. This arises from the smaller beam spot dimensions for a 2

1. This issue may be reopened pending lessons learned in Pathfinder regarding the desirability to fabricate ITM/ETM optic pairs with identical radii of curvature for both 2 km and 4 km IFOs (and thus differing g-factors).

km instrument having the same mirror dimensions and g-factor as the 4 km IFO. Given the constraints that mirror dimensions and g-factors are not parameters which can be varied, the net performance difference between options (i) and (ii) is insignificant. However the greater finesse associated with option (i) means that the circulating power within the cavities will be greater for this design option.

Recommendation

The recommendation is to maintain the same mirror reflectivities in the 2 km IFO as in the 4 km IFO, thereby leading to (a) mirror irradiances in the 2 km system that are 2.5x and 1.6x greater (for end and vertex masses, respectively) than in the 4 km IFO and (b) a knee frequency of approximately 180 Hz.

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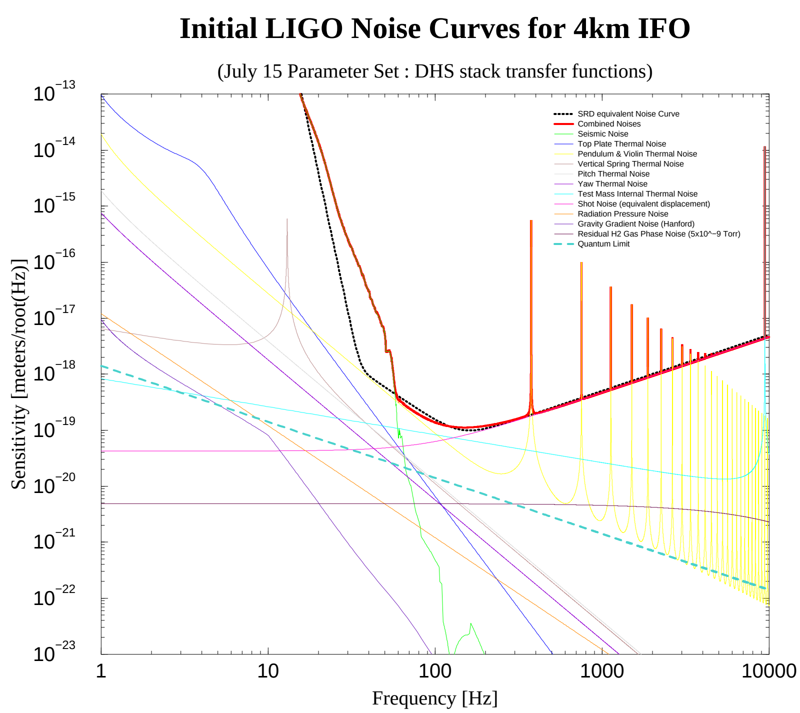

Figure 1: Best estimate h[f] for initial 4 km LIGO interferometers

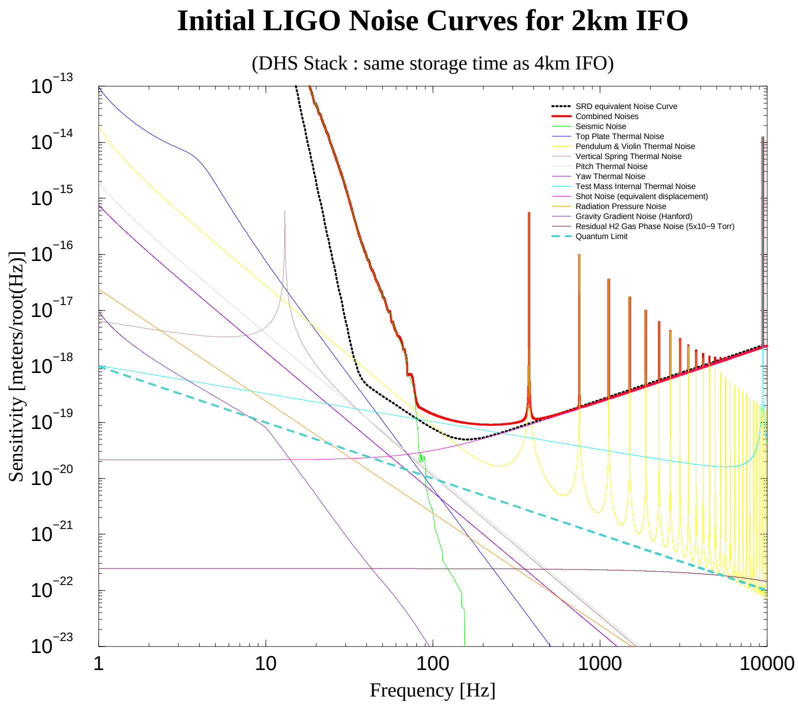

Figure 2: Estimated h[f] for initial 2 km LIGO interferometer with same storage time as 4 km.

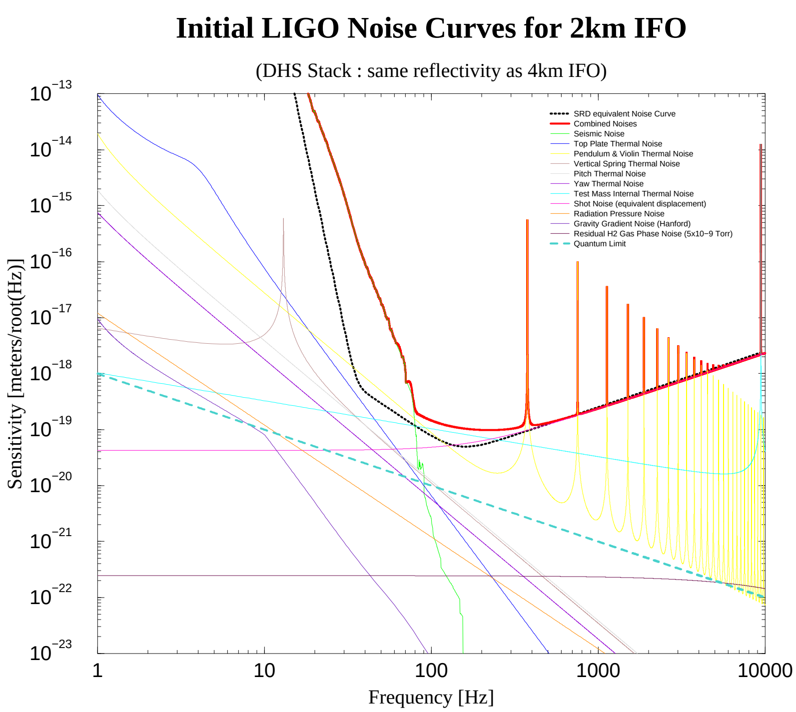

Figure 3: Estimated h[f] for initial 2 km LIGO interferometer with same mirror reflectivities as 4 km

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
pi	3.141592654			none
speed of light	299792458			m/s
permeability	1.26E-06			N/A^2
permittivity	8.85E-12			N/m
Newton const	6.67E-11			m^3/kg/s^2
Planck const	6.63E-34			Js
hbar	1.05457266E-34			Js
electron charge	1.60E-19			C
Bohr magneton	9.27E-24			J/T
nucl magneton	5.05E-27			J/T
fine-struct const	7.30E-03			none
Rydberg const	10973731.53			m^-1
Bohr radius	5.29E-11			m
electron mass	9.11E-31			kg
elec magn moment	9.28E-24			J/T
electon g-factor	2.002319304			none
muon mass	1.88E-28			kg
muon magn moment	4.49E-26			J/T
muon g-factor	2.002331846			none
proton mass	1.67E-27			kg
neuton mass	1.67E-27			kg
Avogadro const	6.02E+23			mol^-1
Faraday const	96485.309			C/mol
molar gas const	8.31451			J/mol/K
Boltzmann const	1.38E-23			J/K
Stefan-Boltzmann	5.67E-08			W/m^2/K^4
atomic mass unit	1.66E-27			kg
room temperature	295.37			K
mirror IE mass	10.8			kg
mirror IV mass	10.8			kg
mirror PE mass	10.8			kg
mirror PV mass	10.8			kg
mirror IE loss	4.00E-07			none
mirror IV loss	4.00E-07			none
mirror PE loss	4.00E-07			none
mirror PV loss	4.00E-07			none
mirror radius	12.5			cm
mirror length	10			cm
mirror Young Modulus	7.17E+11			cgs units
mirror Poisson Ratio	0.16			cgs units
mirror density	2.2			g/cm^3

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
obsolete #1	0			none
num mirror modes	1000			none
mirror range freq min	5000			Hz
mirror range freq max	200000			Hz
mirror range freq step	50			Hz
radial terms in mirror	20	30	30	none
axial terms in mirror	20	30	30	none
radial vol elements	40			none
axial vol elements	40			none
wire diameter	0.003			INCHES
num violin modes	32			none
wire IE freq 1	376			Hz
wire IE Q 1	9.00E+04			none
wire IE freq 2	376			Hz
wire IE Q 2	9.00E+04			none
wire IE freq 3	376			Hz
wire IE Q 3	9.00E+04			none
wire IE freq 4	376			Hz
wire IE Q 4	9.00E+04			none
wire IV freq 1	376			Hz
wire IV Q 1	9.00E+04			none
wire IV freq 2	376			Hz
wire IV Q 2	9.00E+04			none
wire IV freq 3	376			Hz
wire IV Q 3	9.00E+04			none
wire IV freq 4	376			Hz
wire IV Q 4	9.00E+04			none
wire PE freq 1	376			Hz
wire PE Q 1	9.00E+04			none
wire PE freq 2	376			Hz
wire PE Q 2	9.00E+04			none
wire PE freq 3	376			Hz
wire PE Q 3	9.00E+04			none
wire PE freq 4	376			Hz
wire PE Q 4	9.00E+04			none
wire PV freq 1	376			Hz
wire PV Q 1	9.00E+04			none
wire PV freq 2	376			Hz
wire PV Q 2	9.00E+04			none
wire PV freq 3	376			Hz
wire PV Q 3	9.00E+04			none
wire PV freq 4	376			Hz

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
wire PV Q 4	9.00E+04			none
pendulum freq IE	0.744			Hz
pendulum freq IV	0.744			Hz
pendulum freq PE	0.744			Hz
pendulum freq PV	0.744			Hz
arm 1 length	4000	2000	2000	m
arm 2 length	4000	2000	2000	m
laser wavelength	1.06E-06			m
laser incident power	6			W
photodiode efficiency	0.8			e/photon
RF modulation depth	0.45			radians
recycling power gain	30			none
IE mirror reflectivity	0.999995			amplitude
IE mirror loss	5.00E-05			ppm
IV mirror reflectivity	0.9849	0.99239		amplitude
IV mirror loss	5.00E-05			ppm
PE mirror reflectivity	0.999995			amplitude
PE mirror loss	5.00E-05			ppm
PV mirror reflectivity	0.9849	0.99239		amplitude
PV mirror loss	5.00E-05			ppm
stray power on p-diode	0.024			% Pinc
test mass inertia IE	5.12E-02			kg*m^2
test mass inertia IV	5.12E-02			kg*m^2
test mass inertia PE	5.12E-02			kg*m^2
test mass inertia PV	5.12E-02			kg*m^2
cntrl block inertia IE	4.10E-05			kg*m^2
cntrl block inertia IV	8.80E-06			kg*m^2
cntrl block inertia PE	4.10E-05			kg*m^2
cntrl block inertia PV	8.80E-06			kg*m^2
dev from center IE	1.00E-03			m
dev from center IV	1.00E-03			m
dev from center PE	1.00E-03			m
dev from center PV	1.00E-03			m
dif pitch mode freq IE	0			Hz
dif pitch mode freq IV	0			Hz
dif pitch mode freq PE	0			Hz
dif pitch mode freq PV	0			Hz
dif pitch mode Q IE	2000			none
dif pitch mode Q IV	2000			none
dif pitch mode Q PE	2000			none
dif pitch mode Q PV	2000			none
com pitch mode freq IE	0.6			Hz

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
com pitch mode freq IV	0.6			Hz
com pitch mode freq PE	0.6			Hz
com pitch mode freq PV	0.6			Hz
com pitch mode Q IE	1250			none
com pitch mode Q IV	1250			none
com pitch mode Q PE	1250			none
com pitch mode Q PV	1250			none
dif yaw mode freq IE	0			Hz
dif yaw mode freq IV	0			Hz
dif yaw mode freq PE	0			Hz
dif yaw mode freq PV	0			Hz
dif yaw mode Q IE	4000			none
dif yaw mode Q IV	4000			none
dif yaw mode Q PE	4000			none
dif yaw mode Q PV	4000			none
com yaw mode freq IE	0.5			Hz
com yaw mode freq IV	0.5			Hz
com yaw mode freq PE	0.5			Hz
com yaw mode freq PV	0.5			hz
com yaw mode Q IE	4000			none
com yaw mode Q IV	4000			none
com yaw mode Q PE	4000			none
com yaw mode Q PV	4000			none
vert spring freq IE	13			Hz
vert spring freq IV	13			Hz
vert spring freq PE	13			Hz
vert spring freq PV	13			Hz
vert spring Q IE	333.33			none
vert spring Q IV	333.33			none
vert spring Q PE	333.33			none
vert spring Q PV	333.33			none
beam angle to horiz IE	3.10E-04			radians
beam angle to horiz IV	3.10E-04			radians
beam angle to horiz PE	3.10E-04			radians
beam angle to horiz PV	3.10E-04			radians
stack down tube length	0.9			meters
stack lever arm length	0.63			meters
horz pendulum Q IE	3.33E+05			none
horz pendulum Q IV	3.33E+05			none
horz pendulum Q PE	3.33E+05			none
horz pendulum Q PV	3.33E+05			none
topplate mass IE	250			kg

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
topplate mass IV	250			kg
topplate mass PE	250			kg
topplate mass PV	250			kg
TP vel damp freq IE	4			Hz
TP vel damp freq IV	4			Hz
TP vel damp freq PE	4			Hz
TP vel damp freq PV	4			Hz
TP vel damp Q IE	3			none
TP vel damp Q IV	3			none
TP vel damp Q PE	3			none
TP vel damp Q PV	3			none
TP int damp freq IE	6			Hz
TP int damp freq IV	6			Hz
TP int damp freq PE	6			Hz
TP int damp freq PV	6			Hz
TP int damp loss IE	0.33333			none
TP int damp loss IV	0.33333			none
TP int damp loss PE	0.33333			none
TP int damp loss PV	0.33333			none
end beamspot radius	4.565	2.88	2.88	cm
vertex beamspot radius	3.634	2.88	2.88	cm
LA ground density	2000			kg/m^3
LA Raleigh sound speed	188			m/s
LA P-wave sound speed	500			m/s
LA S-wave sound speed	200			m/s
WA upper ground density	2000			kg/m^3
WA lower ground density	2000			kg/m^3
WA Raleigh sound speed	253.8			m/s
WA upper P-wave snd spd	600			m/s
WA lower P-wave snd spd	1550			m/s
WA upper S-wave snd spd	270			m/s
WA lower S-wave snd spd	420			m/s
WA depth to lower layer	5			meters
vertex Mtest separation	4.1			meters
hydrogen mass	2			amu
water mass	18			amu
nitrogen mass	28			amu
oxygen mass	32			amu
carbon monoxide mass	28			amu
carbon dioxide mass	44			amu
methane mass	16			amu
hydrocarbon mass	41			amu

Table 2: List of parameters used in generating curves of Figures 1, 2 & 3

Parameter Name	4 km	2 km -- equal storage time[a]	2 km -- equal reflectivities[a]	Units
H2 polarizibility	7.40E-19			m^3
H2O polarizibility	1.40E-18			m^3
N2 polarizibility	1.60E-18			m^3
O2 polarizibility	1.60E-18			m^3
CO polarizibility	1.80E-18			m^3
CO2 polarizibility	2.38E-18			m^3
CH4 polarizibility	2.36E-18			m^3
H2 partial pressure	5.00E-09			torr
H2O partial pressure	1.00E-07			torr
N2 partial pressure	1.00E-07			torr
O2 partial pressure	1.00E-10			torr
CO partial pressure	1.00E-08			torr
CO2 partial pressure	1.00E-08			torr
CH4 partial pressure	1.00E-10			torr
hydrocarbon part press	1.00E-11			torr
radius vertex mirror	14558	4732	4732	meters
radius end mirror	7402	4732	4732	meters

a. empty fields indicate values used were identical as for 4 km model