Analysis of Technical Noises of Cosmic Explorer

This document describes technical noises of the proposed Cosmic Explorer. Sensitivity curve of this instrument is limited by shot noise and coating thermal noise above 20Hz. In the frequency range 10-20Hz sensitivity is limited by suspension thermal, gravity gradient and quantum radiation pressure noise.

The goal of the design optimization is to reduce coupling of technical noises to the gravitational wave channel. Technical noises considered in this document are angular controls, coupling from auxiliary channels, frequency noise, beam jitter, scattering, squeezed film damping and dark noise.

1 Angular motion

Coupling of angular control noise is one of the most significant technical noises in the frequency range 10-30Hz. Bandwidth of angular servos is determined by the level of the seismic motion and frequency of the soft mode. When resonating power in the arm cavities is high enough, soft mode becomes unstable.

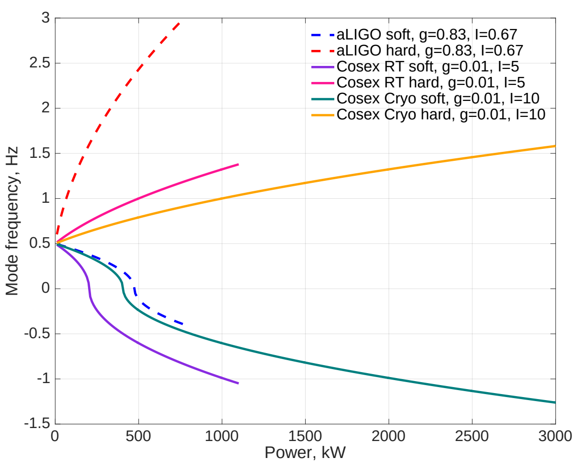

Figure 1: Dependence of hard and soft mode frequencies on cavity power.

Feedback control servo is required to suppress angular instability. Bandwidth of the servo depends on the soft mode frequency f_{soft}. Unity gain frequency should be a factor of 2-3 higher compared to f_{soft} and cut off frequency can be achieved at the level of $\sim 10 f_{soft}$. Example of open loop is shown in Fig 2.

In order to minimize coupling of angular controls to gravitational channel, frequency of the soft mode should be minimized. This can be achieved by increasing g-factor of the cavity. However, in this case beam sizes on test masses also increase as well as coupling of angular motion of the mirror to intracavity power fluctuation. Table 2 summarizes

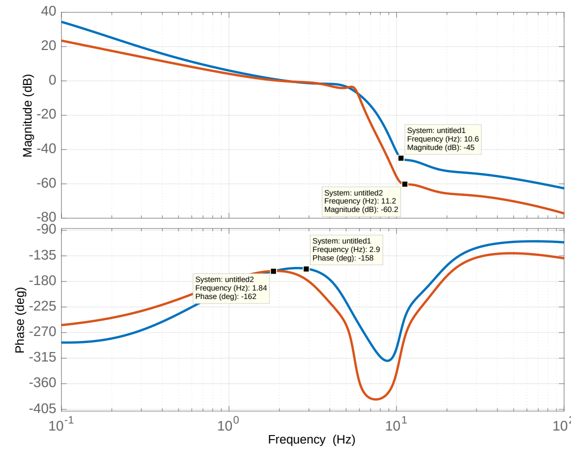

Figure 2: Open loop of the angular servo used to stabilize soft mode at -0.8Hz.

these parameters for different g-factors. Misalignment angle $\triangle\alpha_{FP}$ indicates by how much should the mirror be moved to reduce resonating power to zero. Index FP means in Fabry-Perot configuration. In full lock with coupled cavities, this angle is smaller.

	RoC, km	f_{soft}, Hz	Beam size, cm	$\triangle\alpha_{FP}$, urad	f_{HOM}, kHz
aLIGO, 750kW	1.934, 2.245	-0.4	6	3.2	5.07
CosEx, RT, 1.1MW, $5kgm^2$	39	-1.09	11.64	4.1	1.84
	32	-0.97	11.83	3.9	1.57
	28	-0.89	12.24	3.5	1.35
	25	-0.82	13.01	3.0	1.11
	22	-0.75	15.35	1.8	0.73
	20.5	-0.72	20.96	0.7	0.37
CosEx, Cryo, 3MW, $10kgm^2$	39	-1.31	14.05	4.9	1.84
	32	-1.17	14.27	4.7	1.57
	28	-1.08	14.73	4.3	1.35
	25	-1.00	15.71	3.6	1.1
	22	-0.93	18.53	2.2	0.73
	20.5	-0.89	25.29	0.9	0.37

Table 1: Frequency of the soft mode, beam size on test masses, misalignment angle and transverse mode spacing for different radii of curvature of test masses.

If Cosmic Explorer runs with test mass radii of curvature $R_c \approx 32km$, then coupling of angular motion to test mass fluctuations is less compared to aLIGO case by a factor of 1.5. If suspension is not controlled then RMS of angular motion is $0.1-0.2urad$ and beams on test masses move by $1cm$. At the same time frequency of the soft mode is $f_{soft} \approx 1Hz$ and cut off of the angular controls noise becomes possible at 10Hz.

Angular controls noise couples to arm differential signal through beam off centering. DC coupling is cancelled using feedforward controls and residual noise is dominated by RMS motion. Arm transmission QPDs are limited by shot noise above 10Hz.

$$N_{pos,etm} = \sqrt{\frac{2h\nu}{P_{qpd}}} W_{etm} \frac{R_{itm} + R_{etm} - L}{R_{etm}(R_{itm} - L)} \frac{rad}{\sqrt{Hz}}$$

$$N_{pos,itm} = \sqrt{\frac{2h\nu}{P_{qpd}}} W_{etm} \frac{R_{itm} + R_{etm} - L}{R_{etm} R_{itm}} \frac{rad}{\sqrt{Hz}}$$

$$N_{ang,etm} = \sqrt{\frac{2h\nu}{P_{qpd}}} W_{etm} \frac{R_{itm} + R_{etm} - L}{R_{etm} R_{ang}} \frac{rad}{\sqrt{Hz}}$$

$$N_{ang,itm} = \sqrt{\frac{2h\nu}{P_{qpd}}} W_{etm} \frac{R_{itm} + R_{etm} - L}{R_{itm} R_{ang}} \frac{rad}{\sqrt{Hz}}$$

$$R_{ang} = 1/\sqrt{1/R_{etm}^2 + (\lambda/\pi W_{etm}^2)^2}$$

where N_{pos} and N_{ang} is angular noise measured by position and angle QPDs. When g-factor approaches 0, it is beneficial to use near-field QPD for ETM and far-field for ITM. For power on QPD $P_{qpd} = 20mW$ we get shot noise $10^{-14} rad/\sqrt{Hz}$ for $R_c = 32km$.

Using 2-3Hz bandwidth angular loops, RMS of residual angular motion for aLIGO is 2nrad. Assuming similar angular motion for CosEx, RMS motion of beam on the mirrors is $dW_{itm} = dW_{etm} \approx 0.1mm$. Corresponding longitudinal noise is $\approx 3 \cdot 10^{-18} m/\sqrt{Hz}$. Low pass filter at 5Hz rolls off this control noise at 10Hz by 40-60dB and total contribution to gravitational channel is $\sim 10^{-20} m/\sqrt{Hz}$.

2 Auxiliary channels

Residual fluctuations in DRMI longitudinal degrees of freedom above 10Hz are due to sensing noises. Since bandwidth of DRMI loops is in the range 10-100Hz, control servos engage sensing noise into the cavities.

Any residual MICH motion couples to the OMC transmitted signal in the same way as DARM motion, but without the amplification factor G_{arm} provided by the arm cavity build-up. This coupling coefficient weakly depends on the DARM offset and alignment, unless the power build-up in the arm cavities is significantly changed

$$DARM = \frac{1}{G_{arm}} MICH$$

Increasing G_{arm} reduces MICH coupling to DARM but increases coupling of the frequency noise and input beam jitter. For aLIGO $G_{arm} = 260$ and frequency noise is a factor of 100 below sensitivity curve. However, jitter noise in the frequency range 100-300Hz is only factor of 3-10 below sensitivity curve. This jitter comes from resonances of mirror mounts on the PSL table. Jitter is filtered by a factor of 200 by the input mode cleaner but still produces significant power fluctuations at AS port.

If we choose $G_{arm} = 500$, coupling of MICH noise to DARM at 10Hz is $10^{-19} m/\sqrt{Hz}$. Using feedforward cancellation technique, it is possible to reduce this noise by a factor 100. In this case, DARM noise is $10^{-21} m/\sqrt{Hz}$ due to MICH noise. Schnupp asymmetry is chosen to optimize MICH and SRCL sensitivity. Since SRM power transmission is 0.1, imbalance in Michelson length, should be $1.5cm$.

SRCL residual motion couples to the gravitational wave channel due to the DARM offset through radiation pressure force:

$$DARM = \frac{0.5}{f^2} \frac{\triangle DARM}{10pm} SRCL$$

DARM offset $\triangle DARM$ should be minimized to reduce coupling to SRCL to DARM. Lower bound is determined by carrier contrast detect, dark noise of OMC photodetectors, unsuppressed fluctuations of MICH and angular motion. aLIGO runs with offset of $11pm$. If CosEx chooses to control DARM using homodyne readout, then SRCL coupling to DARM vanishes.

T_{itm}	T_{prm}	T_{srm}	MICH, $m/\sqrt{Hz}$	SRCL, $m/\sqrt{Hz}$	$\triangle r$
0.0296	0.015	0.06	$5.4 \cdot 10^{-19}$	$3.8 \cdot 10^{-19}$	$0.7 \cdot 10^{-3}$
0.0148	0.03	0.03	$2.7 \cdot 10^{-19}$	$4.0 \cdot 10^{-19}$	$1.4 \cdot 10^{-3}$
0.0074	0.06	0.015	$1.3 \cdot 10^{-19}$	$4.0 \cdot 10^{-19}$	$2.8 \cdot 10^{-3}$

Table 2: Coupling of auxiliary degrees of freedom depending on arm finesse. Second column shows coupling of MICH to DARM, third shows SRCL to DARM without applying feedforward cancellation techniques. Power on POP PD was adjusted to keep it on the level of 32mW.

For 160kg test masses, SRCL coupling to DARM at 10Hz is $4.5 \cdot 10^{-19} m/\sqrt{Hz}$ and scales as $1/f^2$. Feedforward cancellation techniques are limited by modulation of the coupling coefficient. aLIGO suppression factor is 10 and SRCL coupling to DARM is reduced to $4.5 \cdot 10^{-20} m/\sqrt{Hz}$.

3 Frequency noise

Dominant factor of frequency noise coupling is imbalance in arm cavity optical losses:

$$\triangle r = \frac{2\triangle Z}{T_{itm}}$$

By increasing finesse of arm cavities and reducing power recycling gain, we increase coupling of the frequency noise. If we choose $T_{itm} = 0.0148/2$, then frequency noise at 100Hz is $1.5 \cdot 10^{-21} m/\sqrt{Hz}$ assuming loses in the arm cavities similar to aLIGO case $\triangle Z = 10ppm$.

4 Intensity noise

Laser amplitude fluctuations couple to gravitational wave channel though radiation pressure and as sensing noise at

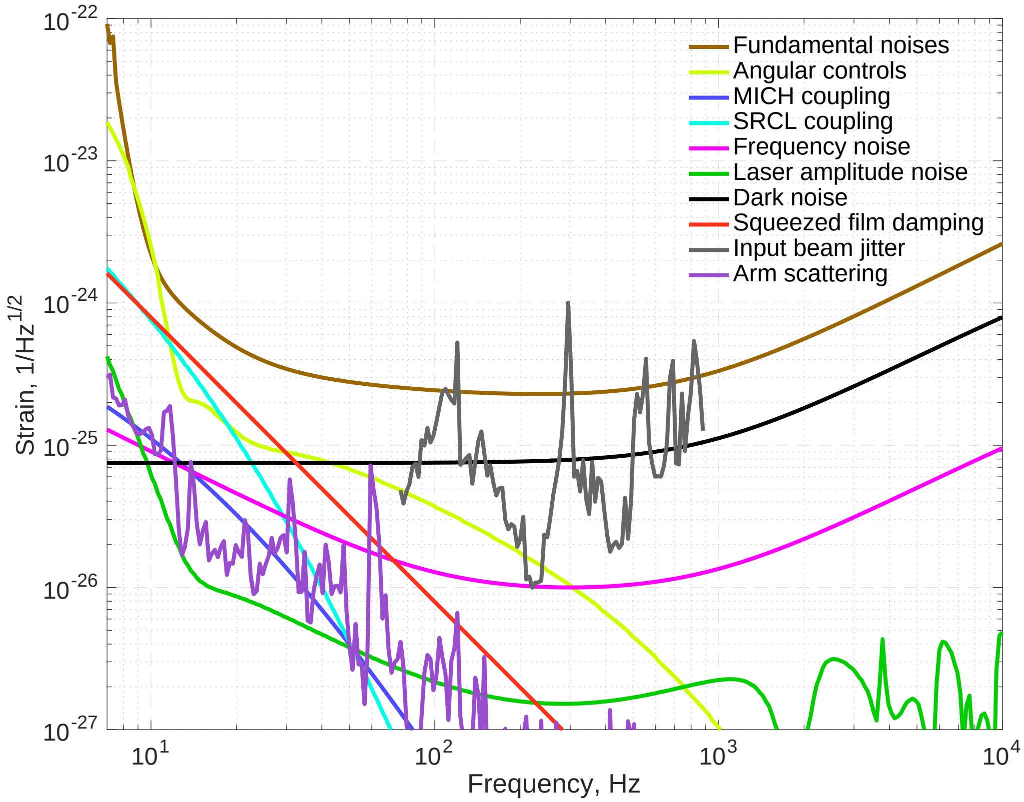

Figure 3: Noise budget for Cosmic Explorer at room temperature.

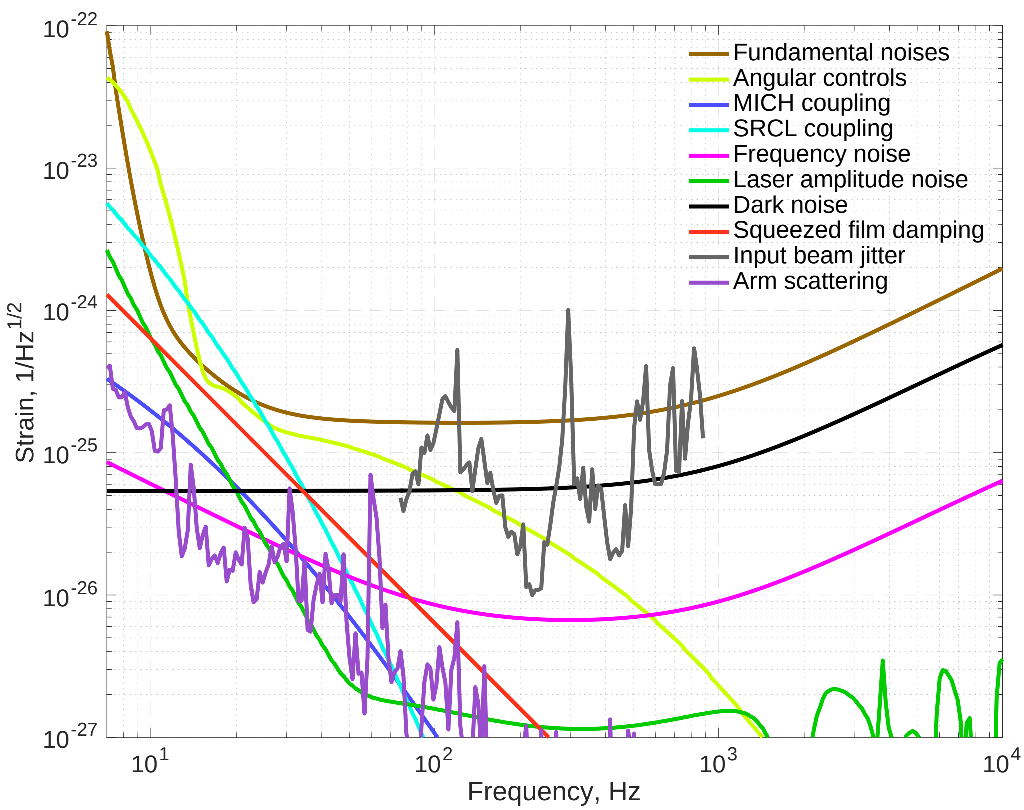

Figure 4: Noise budget for cryogenic Cosmic Explorer.

OMC transmission port. Intensity fluctuations are filtered by double cavity pole at 50mHz but are still significant source of noise.

Radiation pressure noise comes from imbalance in the two arms such as optical loss, mass of mirrors and DARM offset. For DARM offset of 10pm, coupling of intensity noise to gravitational wave channel at 10Hz is dominated by radiation pressure and at 100Hz by sensing channel.

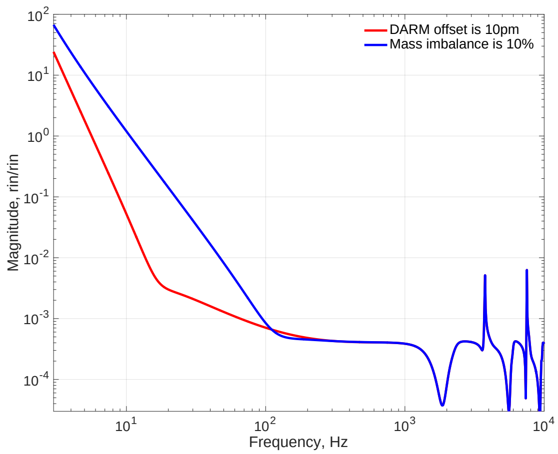

Figure 5: Transfer function from input to output intensity fluctuations.

Coupling coefficient at 10Hz is $1.5 \cdot 10^{-13} m/rin$ and at 100Hz is $3.5 \cdot 10^{-15} m/rin$. Intensity noise is stabilized using two feedback loops and residual noise level is $10^{-8}/\sqrt{Hz}$. This estimation gives DARM noise at 10Hz $1.5 \cdot 10^{-21} m/\sqrt{Hz}$.

5 Beam jitter

Angular fluctuations of the cavity axis are small above 10Hz since angular motion of core optics is less than $10^{-12} rad/\sqrt{Hz}$. At the same time input jitter coming from PSL table generates power fluctuation in the recycling cavity and propagates to the output mode cleaner.

Interferometer input jitter in the frequency range 10Hz-1kHz can be as high as $10^{-5}/\sqrt{Hz}$. Additional stabilization of input jitter is required to reduce this noise coupling to gravitational channel.

Input beam should be actively controlled with bandwidth of 1kHz. IMC axis is stable reference at these frequencies and WFS signals can be used for feedback control. Alternatively, beam jitter can be filtered passively by increasing finesse of the input mode cleaner.

6 Scattering

Scattered light noise is one of the dominant technical noises in aLIGO. Scattering from ghost beams, output mode cleaner and arm cavities are three dominant mechanisms of noise couplings.

Scattering through ghost beams can be reduced by adding baffles in the power and signal recycling cavities. Scattered light noise from the output mode cleaner can be improved by adding more Faraday isolators to the output port. Scattering in the arm cavities is more fundamental noise since all input power is burned in the cavities.

At this point it is hard to estimate scattered light noise in the arm cavities since coating parameters are still unknown. If we assume that scattering level is similar to aLIGO, we can get an order of magnitude estimate

$$DARM = \left(\left(\lambda^2 + \left(\frac{8\Gamma P}{cM\pi f^2} \right)^2 \right) \frac{dA}{d\Omega_{bs}} \sum_i K_i \right)^{1/2} TUBE$$

where P is power resonating in the arm, $\Gamma = 1.52$ is signal gain, $dA/d\Omega_{bs}$ is probability that light from baffle scatters back to the mirror, $\sum_i K_i = 4 \cdot 10^{-10} m^{-2}$ is geometric factor; summing is done over all baffles.

Beam tube moves $10^{-9} m/\sqrt{Hz}$ at 10Hz and DARM noise is $4 \cdot 10^{-21} m/\sqrt{Hz}$.

7 Squeezed film damping

Residual gas asserts damping force on test masses due to the moment exchange between molecules and mirror surfaces. A small gap of 5mm between end test masses and reaction mass increases damping noise below 100Hz by factor of 10 compared to the unconstrained case. Force coefficient depends on gas pressure and molecular mass and can be estimated using fluctuation-dissipation theorem or using Monte Carlo simulation. For aLIGO force on test masses is given by equation

$$F = 1.5 \cdot 10^{-14} \left(\frac{p}{10^{-8} Torr} \right)^{1/2} \left(\frac{m}{m_{H_2}} \right)^{1/4} [N]$$

where p is gas pressure and m_{H_2} is molecule mass.

Assuming that force coefficient stays the same and mass of test masses increases up to 160kg, we get squeezed film damping noise on the level of $3.2 \cdot 10^{-20} m/\sqrt{Hz}$ at 10Hz.

8 Dark noise

aLIGO OMC photodetectors reach shot over dark noise ratio of 10. Since Cosmic Explorer design targets for 10dB of squeezing, shot over dark ratio is reduced down to 3.

Dark noise can be improved by a factor of few if balanced homodyne readout is used instead of DC readout.