Advanced Virgo+ Optics Update

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October 11$^{\text{th}}$, 2019

Introduction

Cavity Configurations

Mirror Tilt Tolerance

RoC Perturbation Tolerance

Optomechanical Modes

Conclusion

References

Advanced Virgo Interferometer

- Michelson interferometer with Fabry-Perot arm cavities and power recycling chamber
- System lock, calibrations and tuning using a combination of these sub-systems
- Near perfect mirrors with reflective substrates

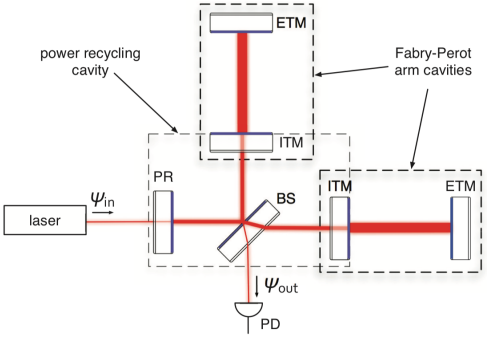
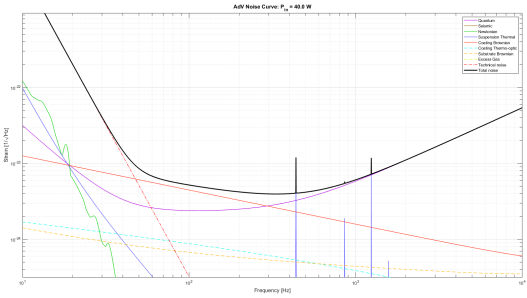


Figure: Figure 1.4 in [1]

Current AdV Noise



- Mid-frequency range dominated by coating Brownian noise
- Increase beam width on mirrors, better averaging out of coating Brownian noise

Project goals

- Keep input mirror spot size as in AdV, increase end spot by 60%
- 'ABCD' matrix method [2] to find cavity properties
- Analytic and numerical investigations into cavity RoC and tilt tolerance (FINESSE and OSCAR)
- Analytic and numerical investigations into optomechanical modes (FINESSE and OSCAR)
- numerical investigations to quantify improved sensitivity (GWINC)

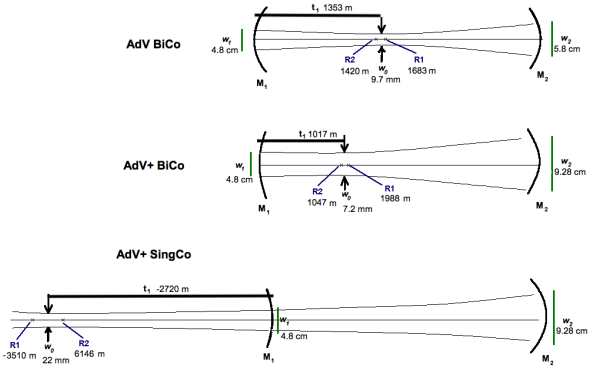
Allowed RoCs

- Solve two equations $w_{1,2}^4 = (\frac{\lambda R_{1,2}}{\pi})^2 \frac{R_{2,1}-d}{R_{1,2}-d} \frac{d}{R_1+R_2-d}$ for R_1 and R_2
- Waist w_0:

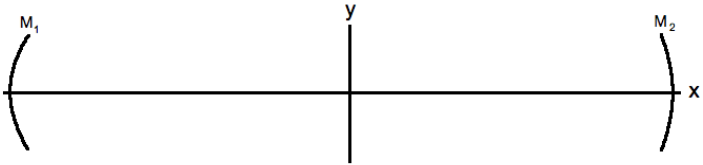
$$w_0^4 = \left(\frac{\lambda}{\pi}\right)^2 \frac{d(R_1-d)(R_2-d)(R_1+R_2-d)}{(R_1+R_2-2d)^2}$$

- Distance from M1:

$$t_1 = \frac{d(R_2-d)}{R_1+R_2-2d}$$



Cavity Tilt and shift



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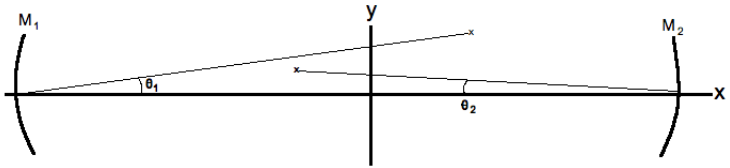
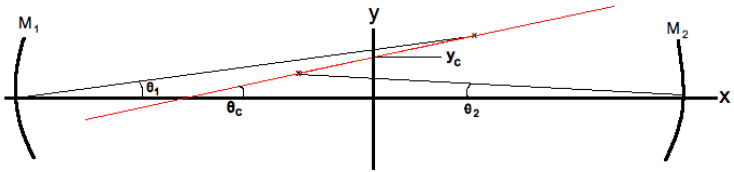


- Asymmetric mirror tilts θ_1 and θ_2 cause cavity shift y_c and tilt θ_c

Cavity Tilt and shift



- Asymmetric mirror tilts θ_1 and θ_2 cause cavity shift y_c and tilt θ_c
- For small tilts, can approximate

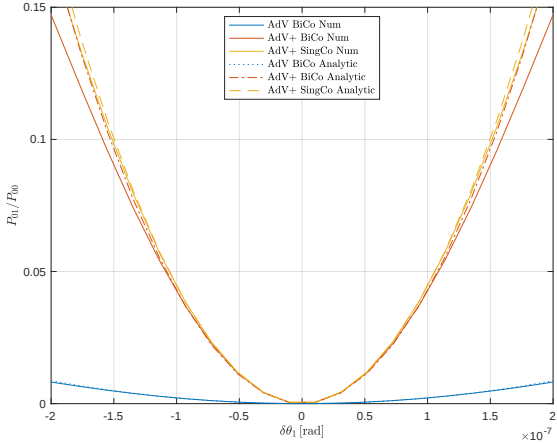
$$\begin{pmatrix} \theta_c \\ y_c \end{pmatrix} = \frac{R_1 R_2}{R_1 + R_2 - d} \begin{bmatrix} 1/R_2 & -1/R_1 \\ 1 - d/2R_2 & 1 - d/2R_1 \end{bmatrix} \begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix}$$

Mirror Tilt Example - Analytic

- Let θ_1 vary and maintain θ_2=0
- Power in HOMs: $\frac{P_{01}}{P_{00}} = \theta_1^2 R_1^2 \frac{\left(2R_2 - d\right)^2 + 4\left(\frac{w_0^2 \pi}{\lambda}\right)^2}{4w_0^2\left(R_1 + R_2 - 2d\right)^2}$
- Position of beam on end mirror: $y_{M2} = \theta_1 \frac{R_1 R_2}{R_1 + R_2 - d}$

	R_1 (m)	R_2 (m)	w_0 (m)	$\frac{P_{01}}{P_{00}}/\theta_1^2$ (μrad^{-2})	y_{M2}/θ_1 (cm μrad^{-1})
AdV BiCo	1420	1683	0.00975	0.217	2.25
AdV+ BiCo	1047	1988	0.00726	4.27	5.77
AdV+ SingCo	-3510	6146	0.0215	4.45	5.77

Mirror Tilt Example - Numerical (FINESSE)



RoC Perturbation Example - Analytic

- R_1 perturbed by $\delta R_1 << R_1$, and R_2 unchanged
- Fraction of power in 02 mode: $\frac{P_{02}}{P_{00}} = \left(\frac{\Delta w_0}{w_0}\right)^2 + \left(\frac{\Delta t_1 \lambda}{2\pi w_0^2}\right)^2$
- 'Simplifies' to: $\frac{P_{02}}{P_{00}} \Big/ \left(\frac{\delta R_1}{R_1}\right)^2 =$

$$\left(\frac{\lambda}{2\pi w_0^2}\right)^4 \frac{d^2 R_1^2 (R_2 - d)^2}{(R_1 + R_2 - 2d)^6} \left(\left((R_1 + R_2)(R_2 - 2d) + 2d^2\right)^2 + 4\left(\frac{\pi w_0^2}{\lambda}\right)^2 (R_1 + R_2 - 2d)^2 \right)$$

	R_1 (m)	R_2 (m)	w_0 (m)	$\frac{P_{02}}{P_{00}} \Big/ \left(\frac{\delta R_1}{R_1}\right)^2$
AdV BiCo	1420	1683	0.00975	16.7
AdV+ BiCo	1047	1988	0.00726	58.1
AdV+ SingCo	-3510	6146	0.0215	8.16

Optomechanical Modes

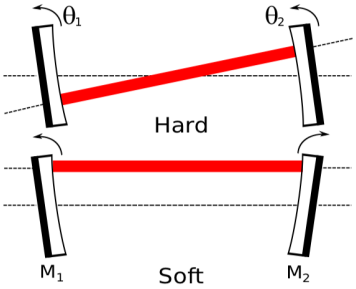


Figure: Figure 1 in [3]

- Soft and Hard optomechanical modes
- Frequecies are either real or imaginary (stable / unstable)

	Ω_s (Hz)	Ω_h (Hz)
AdV BiCo	0.0282i	0.153
AdV+ BiCo	0.600i	6.38
AdV+ SingCo	6.40i	0.601

Conclusion

- Using both analytic and numerical approaches to find resonant cavity configurations for Advanced Virgo+
- Currently comparing a bi-concave and single-concave configuration
- SingCo cavity performs better for Radius of curvature and tilt tolerancing
- BiCo cavity preforms better for optomechanical modes
- Results are important also for future detectors like Einstein Telescope where choice of cavity is still to be established

R. Bonnand.
The Advanced Virgo Gravitational wave detector : Study of the optical design and development of the mirrors.
PhD thesis, Université Claude Bernard Lyon 1, 2012.

H. Kogelnik and T. Li.
Laser beams and resonators.
Applied Optics, 5(10):1550, Oct 1966.

J. Liu, V. Bossilkov, C. Blair, C. Zhao, L. Ju, and D. G. Blair.
Angular instability in high optical power suspended cavities.
Review of Scientific Instruments, 89(12):124503, Dec 2018.