Advanced Virgo Squeezed Light Source Project Overview

S. S. Y. Chua

7 October 2014

Chapter 1

Project Overview

1.1 Context

The Advanced Virgo detector [1] will employ 100 W class lasers and light recycling techniques. The nominal sensitivity curve of the instrument will be reached after three successive configuration stages, namely:

- Configuration 1: 25 W Power Recycled Michelson
- Configuration 2: 125 W Dual Recycled Michelson with Tuned Signal Recycling
- Configuration 3: 125 W Dual Recycled Michelson with Detuned Signal Recycling

These nominal sensitivity curve for each stage is shown in Figure 1.1 [2].

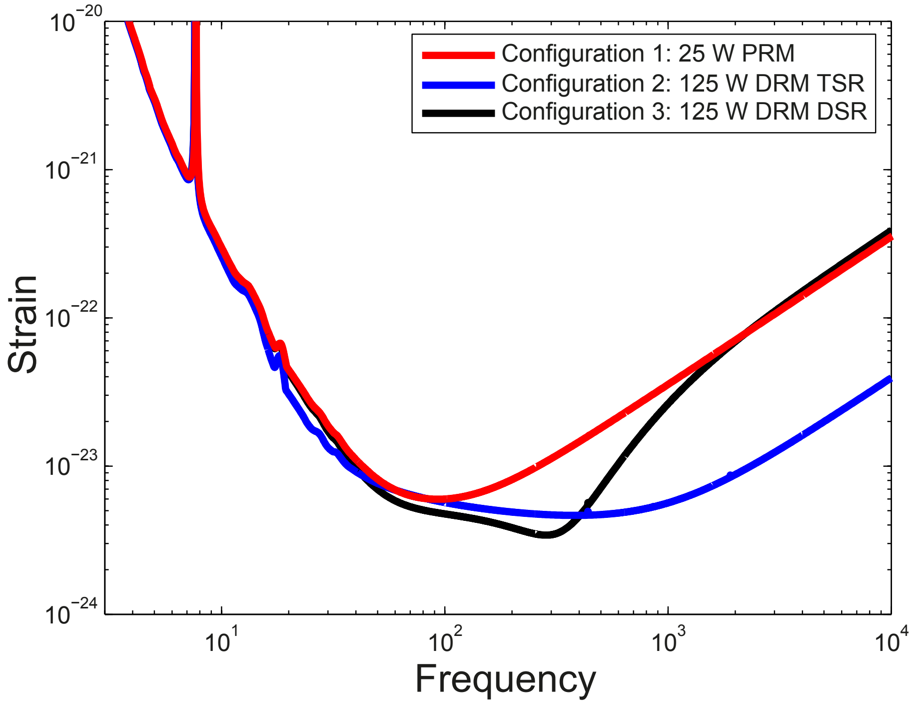

Figure 1.1: Sensitivity curves for the three configuration stages of Advanced Virgo.

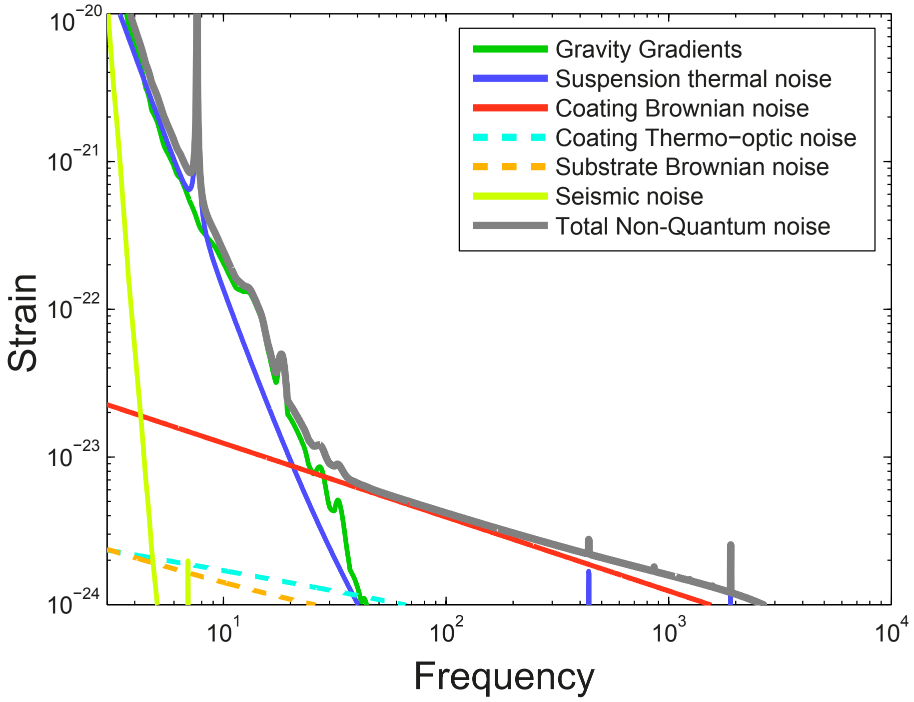

Figure 1.2: Contributions from non-Quantum noise sources to the sensitivity.

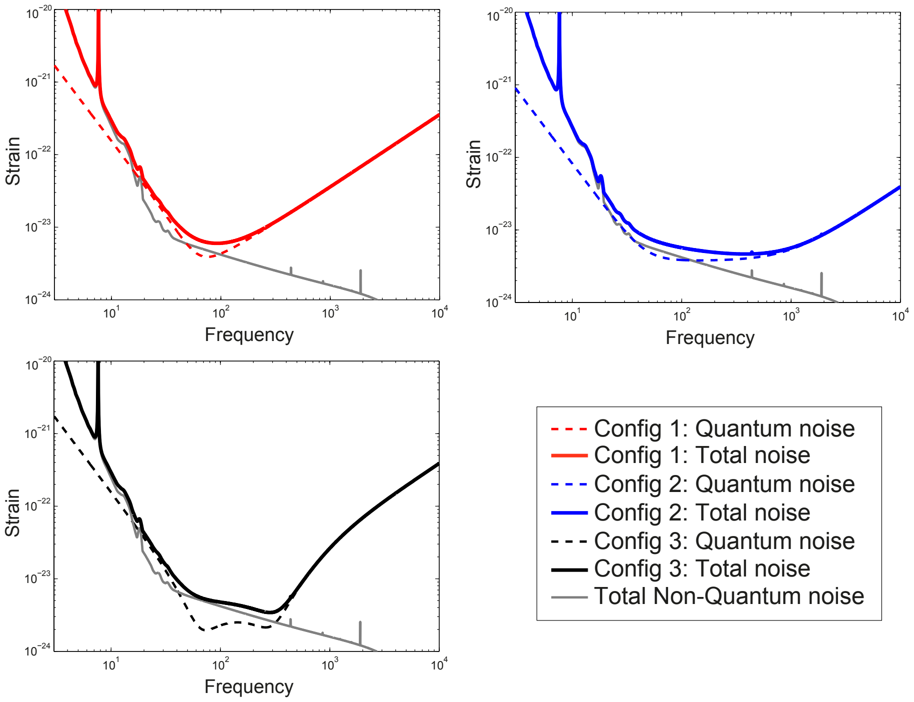

Figure 1.3: The sensitivity curves for the three configuration stages, and the contributions from Quantum noise and non-Quantum noise sources.

Quantum noise, arising from the quantum nature of light, will be a limiting noise source over most of the GW signal frequency band, with Quantum Radiation Pressure Noise (QRPN) at low frequencies, and Quantum Shot Noise (or shot noise) at frequencies above ~100 Hz. Figure 1.2 shows the contributions from noise sources other than quantum noise, while Figure 1.3 shows the sensitivity curves with the Quantum and non-Quantum noise contributions.

The step-wise configuration plan puts time-pressure on the goal of sensitivity-matching the Advanced LIGO detectors [3] that are being concurrently built in the US. Moreover, high power operation in Advanced Virgo is a riskier prospect due to Advanced Virgo having marginally stable recycling cavities, as compared with Advanced LIGO's stable cavities. Therefore, a technique needs to be on stand-by that can help achieve higher sensitivities through reducing quantum noise without increasing optical power. The injection of squeezed vacuum states provides such a technique.

The LIGO Scientific Collaboration and GEO Collaboration have developed and demonstrated squeezed light technologies and squeezed-light-enhancement of interferometric measurements. Of important note:

- Squeezing magnitudes of up to a record of 12.7 dB at 5.5 MHz [4] and up to 11.6 dB across audio gravitational-wave detection band [5] being **measured**.
- Squeezing magnitudes of greater than 14 dB squeezing being **produced** from Optical Parametric Oscillators (before measurement losses) [6].
- The successful experimental demonstration of squeezed light sensitivity-enhancement and broadband quantum noise reduction on the 4km Enhanced LIGO interferometer at Hanford. This demonstration achieved a strain sensitivity greater than the S6 Joint Science Run [7].
- The current, routine operation of squeezed light enhancement with the GEO600 interferometer. Squeezed-light integration techniques and system controls have been refined, and very high duty cycles of >99% over weeks have been achieved [8].
- Coherent Sideband Locking technique for squeezed light ellipse control [9], the standard technique used for both the LIGO Squeezed Light experiment and GEO600 operations.
- Extensive theoretical work and increasing technical development of optical cavities for squeezed light rotation [10].

The injection of a squeezed state reduces quantum noise for a given operating laser power. The technique thus not only has the capability to reach high-power sensitivity with lower input power, but can improve high-power sensitivities without needing even higher optical power. It will provide a pathway to further increase the sensitivity of Advanced Virgo after the last configuration step. This is further exemplified by the inclusion of squeezed light into baseline designs for next-generation gravitational detectors, for example the Einstein Telescope [11] and Third Generation LIGO [12].

Given the motivations of risk mitigation of operating with high power, sensitivity-matching timeliness with Advanced LIGO, and potential further sensitivity enhancement with full power Advanced Virgo, this document presents the Technical Design for a Squeezed Light Source for Advanced Virgo.

1.2 Outlook

The above developments in squeezed light were only recently reached, and well after the design approval of the Advanced interferometer upgrades being completed now. Hence squeezed light was not a consideration in the design of these advanced detectors. For the majority of this Design document, this implies that:

- The predicted parameters and characteristics of Advanced Virgo will be taken as given.
- No major structural changes are proposed to the core Advanced Virgo interferometer.
- This system will be prepared in parallel and with no impact on the Advanced Virgo installation and commissioning schedule.

However, later modifications to the interferometer (post Advanced Virgo commissioning) for improving squeezed light enhancement will considered as part of this Design Report [**maybe?**].

1.3 Squeezed Light Source Production Targets

Given the current stage of squeezed light production technology, and the parameters of the Advanced Virgo interferometer, we set the following targets for this system:

- Target of at least 14 dB of squeezing produced from the OPO, commensurate with the levels being produced from current technology.
- A maximum of 22% optical losses for the squeezed light (between OPO and interferometer readout PD), as outlined in the Proposal Document [13].
- A maximum of 20 mrad rms of squeezing ellipse phase noise, commensurate with what is being achieved at GEO600 [14].

Combining these requirements and efficiencies, the squeezed light source should make available **up to** 6 dB squeezing and 14 dB antisqueezing of the quantum noise at the interferometer readout.

1.4 Sensitivity Projections

To make sensitivity projections for Advanced Virgo with squeezed light, the code platform used is GWINC, and the code is the combination of two code sets with modifications. The first code set, and the dominant portion of the model, is the Advanced Virgo GWINC code, as of July 2014. The quantum noise subroutine of the Advanced Virgo GWINC code is replaced by the second code set, the LIGO GWINC Developer quantum noise subroutine code. This second code is not yet part of the official LIGO GWINC module, but has been used in the development of LIGO Third Generation design curves [12]. This second code implements the full two-photon matrix description of quantum noise [15]. Additional modifications towards functionality and capability have also been made, such as modifications to include squeezing ellipse phase noise.

1.4.1 Recovery of Sensitivity at lower interferometer input optical powers

We firstly consider a squeezing/antisqueezing injection that results in an anti-squeezed magnitude (after losses and phase jitter) of 7 dB. This is to match an equivalent QRPN increase as if it were from high power operation. The squeezing/antisqueezing level of 7.9 dB gives such a result. Figure 1.4 shows the sensitivity curves for the Low Power Dual Recycled Michelson with tuned Signal Recycling and squeezing, compared to the High Power Dual Recycled Michelson (Advanced Virgo second configuration). [**Include other configurations**]

The squeezed quantum shot noise at higher frequencies does not fall to the High Power level. This is explained by the 4.5 dB improvement being an equivalent factor of 3 increase in optical power, while the High Power level of 125 W is a factor of 5 greater. However, the injection of squeezing gives a **partial recovery** of sensitivity at lower optical powers. This is further shown by the GW-source ranges for both Neutron Stars and Black Holes.

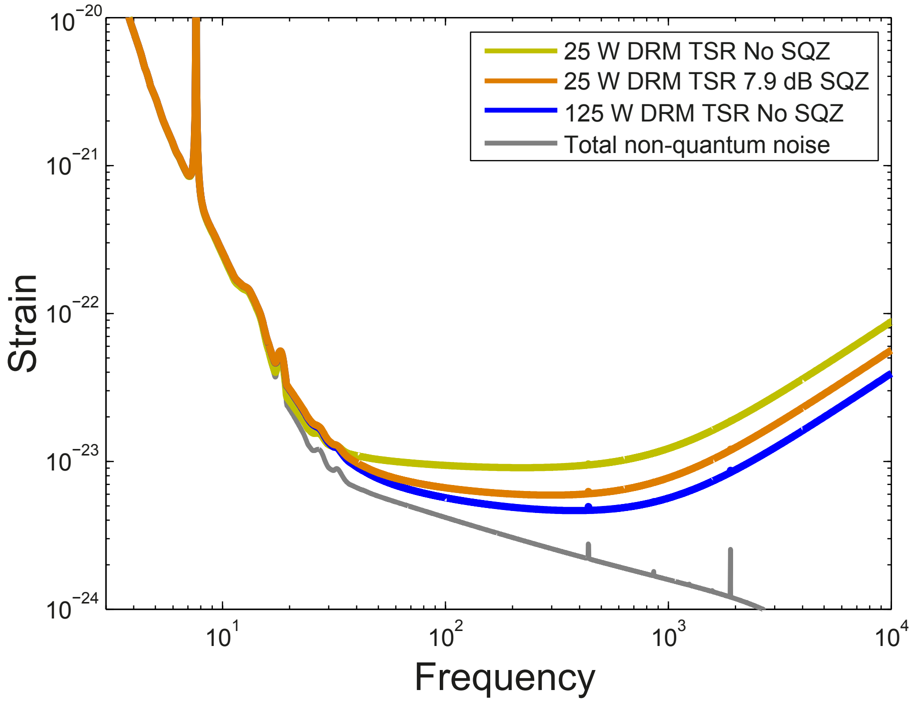

Figure 1.4: 25 W DRM tuned Signal Recyling Sensitivity Curves with and without 7.9 dB squeezing, and comparing it to an unsqueezed 125 W Sensitivity Curve

	PRM		DRM-Tuned SR		DRM-Detuned SR	
	NS	BH	NS	BH	NS	BH
25 W No Squeezing	**111.4**	**1029.2**	99.4	1063.6	121.8	1303.4
25 W Squeezing 7.7dB	103.4	629.8	118.9	1118.94	131.0	1319.5
125 W No Squeezing	112.2	649.0	**134.3**	**1197.3**	**146.4**	**1164.6**

Table 1.1: Comparison of the Mpc-ranges with and without injected squeezed light. The three expected Advanced Virgo configuration stages are highlighted.

1.5 Technical Design Document Overview

- Chapter 2 will
- Chapter 3 will etc.

1.6 Extra (Possible) Sections

1.6.1 Changing the optical loss parameter to increase recovered sensitivity

For the consideration of the Working Group

Let us consider the **total** optical loss parameter, and the potential squeezing magnitudes with improved optical loss. Some points to note:

Scenario	A	B	C	D	E	F
Input Sqz/ Asqz [dB]	7.9	7.9	7.9	7.9	14	14
Ellipse Phase Noise [mrad]	20	20	20	20	20	14
Optical Loss [%]	22	18.2	10.4	4.2	22	15.7
Output ASqz [dB]	7	7	7	7	13.6	13.3
Output Sqz [dB]	4.5	5	6	7	6	7

Table 1.2: Scenarios with different parameters.

- Scenario A represents the parameters for the 'Recovery of Sensitivity' section.
- Scenario B would be achievable for Advanced Virgo.
- Scenario C and D would not be possible for Advanced Virgo.
- Scenario D would the be the ideal choice.
- Scenario E represents the parameters of the Proposal Document.
- Scenario F could be achievable for Advanced Virgo, with considerable effort. However, there is still a (13.3 - 7) = 6.3 dB greater QRPN increase, which will reduce the sensitivity.

1.6.2 Increasing Sensitivity beyond 125 W

For the consideration of the Working Group

- 125 W DRM with tuned SR curve, and full 6dB/14dB squeezing curve
- Highlight increase in low frequency QRPN
- Highlight the need for filter cavities moving forward

Bibliography

[1] The Virgo Collaboration, arXiv:1408.3978 (2014) 3

[2] The Virgo Collaboration, VIR027A09 (2009) 3

[3] G. M. Harry for the LIGO Scientific Collaboration, Class. Quantum Grav., 27 084006, (2010) 5

[4] T. Eberle et al., Phys. Rev. Lett.,104 251102, (2010) 5

[5] M. Stefszky et al., Class. Quantum Grav., 29 145015, (2012) 5

[6] S. S. Y. Chua et al., Class. Quantum Grav., 31 035017, (2014) 5

[7] The LIGO Scientific Collaboration, Nature Photonics 7, 613-619 (2013) 5

[8] H. Grote et al., Phys. Rev. Lett 110, 181101 (2013) 5

[9] H. Vahlbruch et al., Phys. Rev. Lett., 97 011101, (2006) 5

[10] For examples Khalili, M. Evans et. al, Phys. Rev. D 88, 022002 (2013), Isogai, Oelker 5

[11] S. Hild et al., Class. Quantum Grav., 27 015003, (2010) 5

[12] R. Adhikari et al., LIGO-T1200031-v3 (2012) 5, 6

[13] Virgo Document VIR-0277A-14 (2014) 6

[14] K. Dooley for GEO 600 collaboration, G1400236-v2 (2014) 6

[15] A. Buonanno and Y. Chen, Phys. Rev. D 64, 042006 (2001) 6