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Initial Set of Optical Parameters for Numerical Simulations towards Advanced VIRGO

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1 Introduction

This note describes a basic parameter set for analytic computations or numerical simulations towards an optical layout for Advanced VIRGO. This data is meant as a reference and as a starting point for a more in-depth analysis. Thus, the numbers given below will *not* represent a working interferometer model.

2 Nomenclature

In the following, we are using a new nomenclature for optical components, lengths and output ports. We propose to use this set of names during the design of an optical layout, especially when employing numerical simulations. An extension of the historic name system to include additional output ports would probably be confusing. A new, clear set of names will avoid confusion between the current layout and the various layouts proposed for Advanced VIRGO. At the same time, it will make it easier for new or external members of the VIRGO working groups to become familiar with the subject.

The names proposed here were chosen with the aim of balancing internal consistency with an intuitive approach. The following paragraphs will describe the new nomenclature and provide look-up tables for translating between the historic VIRGO names and those used in this document.

2.1 Mirrors and Lengths

The interferometer arms will be identified by the letters 'X' and 'Y', with the North arm, in-line with the input beam, being the X-arm. Cavity mirrors are called *input mirror* (IM) or *end mirror* (EM). Thus the North arm cavity (X arm) is formed by IMX and EMX. The recycling mirrors are called *power recycling mirror* (PRM) and *signal recycling mirror* (SRM).

The optical path lengths between primary optical surfaces are commonly referred to as *lengths*. In the central area these lengths are denominated with the small letter 'l', e.g. the distance between the primary surface of the beam splitter (BS) to the signal recycling mirror (SRM) is stated as 'lsrm' (note: the 'm' helps to distinguish this from the length of the signal recycling cavity), the distance between the BS to the West input mirror (IMY) is given as 'ly'. The arm cavity lengths are stated using a capital 'L'. E.g. the length of the West arm cavity (Y arm) will be given by 'Ly'.

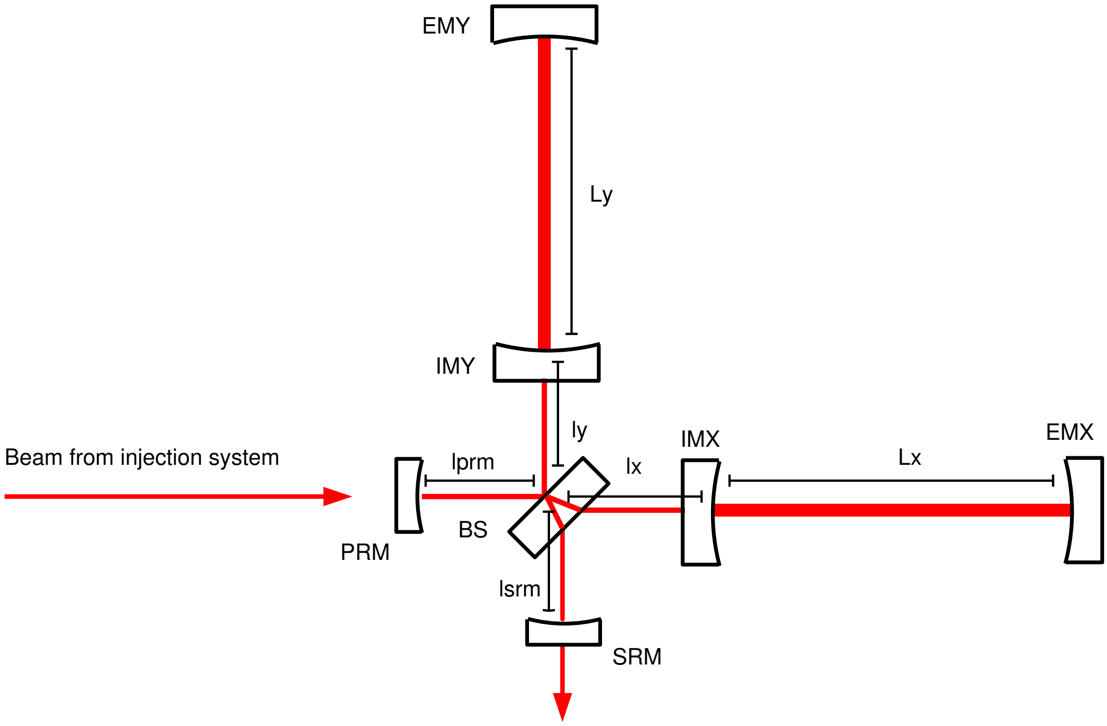

Figure 1: Names of the main optical components and of the optical path lengths ('lengths' for short) between primary optical surfaces. Note that in practice the optical path length has to be compiled from various paths inside and outside optical substrates. However, many simulations are or can be performed using optical surfaces instead of more complex and realistic models of optical elements. Thus, when comparing parameter sets, any implementation in numeric simulations should be presented using such simplified optical path lengths.

Figure 1 shows the names for the main optical components and the lengths (i. e. optical path lengths in between primary optical surfaces), in Table 2 the new names are described and compared to historically used names.

Name	Description
lx	distance from the BS to IMX
ly	distance from the BS to IMY
lprm	distance from the BS to the power recycling mirror (PRM)
lsrm	distance from the BS to the signal recycling mirror (SRM)
Lx	length of the X arm cavity (North)
Ly	length of the Y arm cavity (West)

Table 1: Names of optical path lengths between primary optical surfaces in the main interferometer layout

2.2 Readout Ports

For the name of the main output ports of the Michelson interferometer we will make use of the commonly accepted terms 'asymmetric port' (AP) for the dark fringe output in-line with the Y-Arm and 'symmetric port' (SP) for the output in-line with the X-Arm.

The names for the other readout ports are derived from the optical component providing the beam. I.e. the light transmitted by the X-Arm cavity is detected in the X port (XP).

A large number of so-called 'pick-off' beams might be used in addition to these main output ports. Such outputs

New Name	Old Name	Description
BS	BS	main beam splitter
IMX	NI	input mirror of North (X) arm cavity
EMX	NE	end mirror of North (X) arm cavity
IMY	WI	input mirror of West (Y) arm cavity
EMY	WE	end mirror of West (Y) arm cavity
PRM	PR	power recycling mirror
SRM		signal recycling mirror

Table 2: New names for optical components and lengths of interferometer arms

will be labelled with 'PO', i.e. the reflection from the anti-reflective coating of the beam splitter will be detected in POBS. Input mirrors with wedges create pick-off beams which will be detected in POX and POY for the mirrors IMX and IMY respectively.

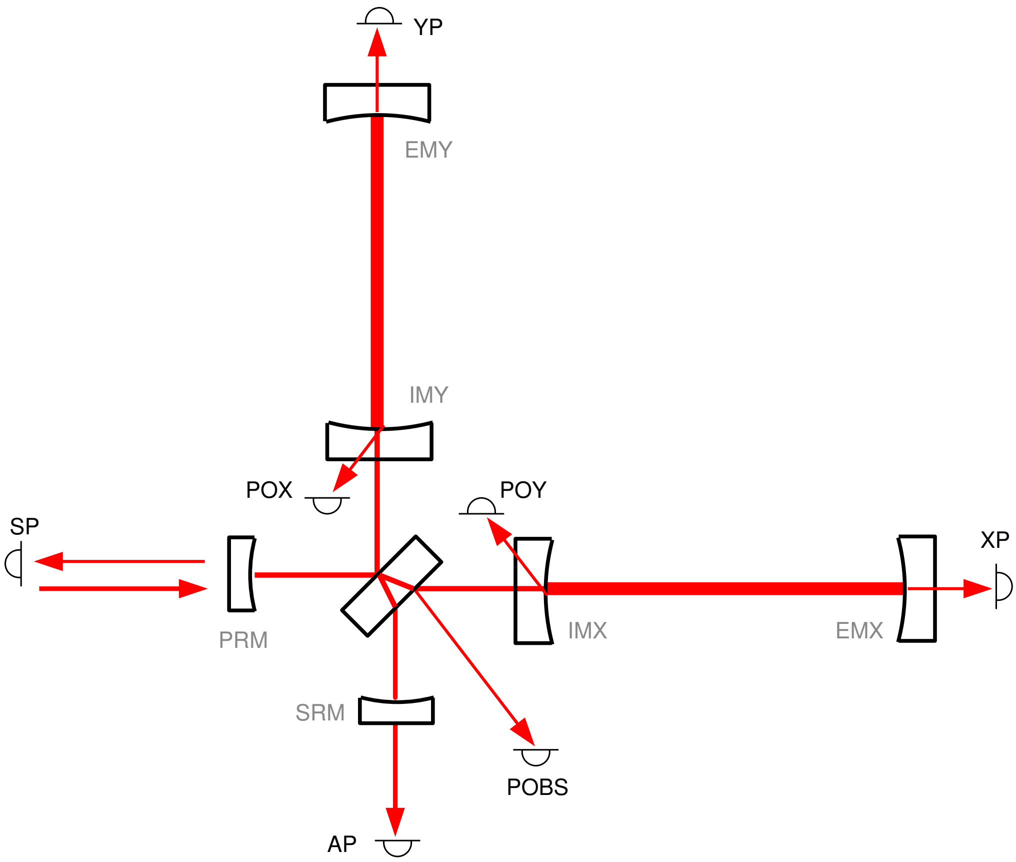

Figure 2: Names of possible output ports for optical signals derived from the main interferometer beams.

Figure 2 shows the names for possible optical readout ports, Table 3, compares them to names used before. Please note that the listed names do not include all possible ports. For example, there can be more than one output port detecting auxiliary beams reflected by the beam splitter. Such beams can be named POBS1, POBS2 or similarly following the naming convention described here.

New Name	Old Name	Description
AP	B1 (or B1p)	main dark fringe output port
SP	B2	light reflected by the power recycling mirror
XP	B7	light transmitted by the North arm (X arm) cavity
YP	B8	light transmitted by the West arm (Y arm) cavity
POBS	B5	light reflected at the AR coating of the beam splitter
POX		light reflected at the AR coating of the IMX (North input) mirror
POY		light reflected at the AR coating of the IMY (West input) mirror

Table 3: New names for possible optical readout ports

3 Optical Path Lengths

This section provides a set of optical path lengths between optical components. These are very similar to those of initial VIRGO, in fact, the aim is to find a working layout in the current vacuum enclosure. Because of the design of the vacuum tanks and the super-attenuator mirror suspensions the distances between the main optical components are mostly given by the position of the vacuum tanks.

What is not given by the layout of the vacuum system is the fine positioning of optics in the central area. The exact lengths and length differences of the optics around the beam splitter usually have a direct influence on the response function of the interferometer.

Table 3 shows the parameter set which could be used with the current vacuum system. The small length differences have been chosen arbitrarily. Their values should be optimised during the design of the interferometer control system.

value [m]	Name	Description
3000	Lx	cavity length (X arm)
3000	Ly	cavity length (X arm)
6.5	lx	distance between BS and IMX
5.7	ly	distance between BS and IMY
6	lprm	distance between BS and PRM
6.2	lsrm	distance between BS and SRM

Table 4: Optical path lengths between primary optical surfaces

3.1 To Do List

- setting these lengths requires a knowledge of all modulation frequencies for control purposes
- cavity length difference (i.e. $l_{\mathrm{srm}} - l_{\mathrm{prm}}$) must be checked. Certain control scheme might need very different values which would feedback to the rest of the layout design
- if frequencies are known, length tolerances can be computed (again, requires detailed knowledge of control system design)
- the Michelson asymmetry $l- = lx - ly$ can be optimised with respect to modulation depth, mode healing, etc.
- regularly the numerical simulations should be adding slight deviations to these lengths to check for robustness against unavoidable deviations from specifications

4 Beam Parameters

The beam can be characterised by stating the power and the beam waist size and position inside the interferometer. Later on the limits for deviations from these specifications can be computed using, for example, the optical losses, the contrast at the beam splitter or the recycling gains as a figure of merit.

In the following we will assume a input power of 100 W. The corresponding intra-cavity powers will be given in Section 5.

4.1 Beam Width

The beam width should be maximised inside the arm cavities in order to minimise the influence of thermal noise. The limits for the beam size come from constraints on the optical losses. If the beam has a finite intensity at edges of the optical component (or at the edge of the HR coating), the optical losses will at some point increase above a tolerable level.

Currently the manufacturer of the high-reflective coatings can produce coatings with a homogeneous area of diameter 30 cm (of course this assumes also a free aperture of at least 30 cm diameter throughout the central interferometer and before the first lens in any output port).

Based on experience with current detectors and prototype interferometers, the beam radius should be generally no larger than one third of the mirror radius. This gives a limit of $w_{\mathrm{mirror}} = 5\,\mathrm{cm}$ for all the mirrors and $w_{\mathrm{BS}} = 3.5\,\mathrm{cm}$ for a beam splitter at 45 deg. These limits are a good starting point, even though they present a 'safe' but not optimised solution.

For minimising the coupling of thermal noise the arm cavities should be symmetric with the beam waist in their centre. In this case the beam splitter acts as the limiting optical component on the beam size. Table 5 gives the beam sizes on the optical components, designed to achieve $5/\sqrt{2}\,\mathrm{cm}$ at the beam splitter, and the corresponding radii of curvatures of the mirrors.

Please note the value of 300 km for the beam splitter is a place holder for a more accurate estimate of a residual curvature of the BS substrate. Even without thermal effects a residual curvature in the order of 100 km can be expected.

Mirror	Beam size w [cm]
cavity input mirror	3.52
cavity end mirror	3.52
beam splitter	3.54
recycling mirror	3.53

Mirror	Radius of curvature R_C [m]
cavity input mirror	1910
cavity end mirror	1910
beam splitter	300k
recycling mirror	1320

Table 5: Beam radius at the main optical components and the corresponding radii of curvature. Please note that this table shows only absolute values for the radii of curvature as the sign convention is usually different for different simulations.

4.2 To Do List

- quantify the benefits of a symmetrical arm cavity
- quantify the optical losses for a) ideal and b) realistic scenarios (including mirror maps, offsets in centring, etc)
- quantify residual radii of curvature from substrate deformation (e.g. because of thermal effects)
- check for free apertures in the vacuum tubes
- input and output optics need to be redesigned for this larger beam size

5 Mirror Specification

Table 6 gives a list of coefficients for the power transmission and power loss of the main optical components. These values have been chosen arbitrarily and are not yet matched to a specific performance or sensitivity of the Advanced VIRGO detector.

The values quoted here correspond roughly to 0.5 MW of power in the arm cavities and 1300 W of power at the beam splitter for 100 W of light impinging on the power recycling mirror (please note that the recycling cavities are impedance matched for the reflectances of the recycling mirrors stated below).

Mirror	Transmission	Losses
IMX	$5\ 10^{-3}$	$5\ 10^{-5}$
EMX	$1\ 10^{-7}$	$5\ 10^{-5}$
IMY	$5\ 10^{-3}$	$5\ 10^{-5}$
EMY	$1\ 10^{-7}$	$5\ 10^{-5}$
BS	0.5	$5\ 10^{-5}$
PRM	0.07	$5\ 10^{-5}$
SRM	0.07	$5\ 10^{-5}$

Table 6: Power transmission and losses of the main optical components.

5.1 To Do List

- quantify the light power in all parts of the interferometer and determine upper and lower limits for the power and intensity
- adjust the recycling gains (and thus the transmission of the recycling mirrors such that the quantum noise matches the thermal noise)
- we need a parametrised signal recycling model that quantifies the effect of local optical losses on the detector sensitivity
- quantify the losses with realistic interferometer models
- perform a trade-off analysis of high recycling gain versus high arm cavity gain