Interferometer Sensing and Control
Design Requirement Document (DRD)

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This document identifies the main elements and possible difficulties and showstoppers in the design for the interferometer sensing and control. When available, the conceptual design solution is briefly addressed.

1. Lock Acquisition

Here we describe the requirements on the interferometer functionalities to be able to bring the interferometer up to the steady state. In these requirements the noise performances are generally not considered; rather the robustness and reliability are the criteria for choosing the solutions.

1.1 Requirement from arm cavity linewidth

The OSD subsystem specifies an arm cavity finesse of F=888. The arm cavity linewidth is thus LW=56 Hz.

1.1.1 on arm cavity lock acquisition

The displacement of the arm cavity mirrors with a unity gain frequency ~ 100 Hz will lock the arm cavities on the auxiliary lasers on end benches or on the main laser. The requirement for the lock acquisition being possible is that the feedback loop response time (~10 ms) is smaller than the average duration of the resonance when the mirror is freely swinging. This time T_{res} is

$$T_{\mathrm{res}} = \frac{\lambda/2}{\mathrm{v}\,F}$$

so that would require a mirror speed smaller in average than 60 nm/s, more than one order of magnitude smaller than the one observed in initial Virgo.
The baseline solution foresees an increase of T_{res} using an auxiliary laser, with a different wavelength, located on end towers, for which the finesse in only a few units, thus allowing a mirror mean speed of ~5 μm/s.
The mirror speed distorts the shape of the Pound-Drever-Hall signal, when the time through resonance is smaller than the mean lifetime of a photon in the cavity [1]. This distortion, when present, prevents the use of the linearization technique used for the lock acquisition in the initial Virgo interferometer (digital division of the error signal by the transmitted power) that improved the lock acquisition range by a decade. The mean lifetime of a photon in the cavity is [2]

$$T_{\mathrm{cav}} = \frac{1}{2\pi\,\mathrm{LW}} = 2.8\ \mathrm{ms}.$$

The requirement for not distorting the error signal is that $T_{res} > T_{cav}$.
An alternative solution would be to ensure an average mirror speed lower than 0.2 µm/s, for example with an improved control of super-attenuator, and then use the linearization technique, having then a time ~30 ms available for lock acquisition.
Another possible solution could be the "cooling" of the mirrors: the mirror speed is reconstructed and impulses are sent to remove the mirror apparent speed.

1.1.2 on laser frequency noise - rms

The action on the arm cavity mirrors locks the cavity. For the cavity to stay around the resonance the laser linewidth should be < 50 Hz p-p on a 100 ms integration time, taking into account the limited gain around the unity gain frequency. With a margin, the specification on laser frequency noise is defined as 5 Hz RMS on a 100 ms integration time.
A Nd:YAG free running laser frequency noise is modelled with a linear spectral density of (10 kHz/f) /√Hz, corresponding to an RMS of 1 kHz on 100 ms: a laser frequency stabilization is required before engaging the laser frequency stabilization on the interferometer.
For INJ/PSL, the current design (laser frequency stabilized on IMC and IMC locked to RFC) provides 2.5 Hz rms, good enough. Any alternative design, especially with RFC not suspended on IB, should consider closely this requirement, as our RFC cavity is not designed for low sensitivity to acceleration noise.
For the auxiliary laser, the design will consider the stabilization on the main laser carried out on a 3 km fiber to end towers, the stabilization on a rigid cavity and the stabilization on a fiber reference; the final design must comply the RMS specification.

1.2 Mitigation of longitudinal and angular optical springs

The light exerts a pressure on the mirror that changes significantly the response of the arm cavity mirror suspension, both for the angular and longitudinal degrees of freedom.
For the angular degrees a freedom, the main effect is an addition of an optical rotational stiffness on the last stage of suspension; it can be either negative or positive. The arm cavities are detuned, and an optical stiffness adds to the mirror suspension stiffness. We give here simple equations for evaluation of orders of magnitude, not taking into account the possible frequency-dependent behavior of the optical spring and not modeling the suspension coupling via the optical spring.
The optical longitudinal stiffness writes

$$K_{opt,long} = \frac{P_{res}}{1 + \frac{x_{\det}^2}{x_p^2}} \frac{(4/c)x_{\det}}{x_{\det}^2 + x_p^2}$$

where P_{res} is the power in the cavity when no detuning is present, x_{det} is the detuning (in m) and x_p the length cavity pole $\lambda/(2F)$. The spring is negative when the cavity is shorter that in the resonant situation (anti-spring). For DC detection, one of the arm cavities needs to be shortened while the other one is lengthened.
The optical rotational stiffness is

$$K_{opt,rot} = \pm \frac{2P_{res}}{c} \frac{R_x(L - R_y)}{R_x + R_y - L}$$

where R_x is the radius of curvature of the rotating mirror, R_y is the radius of curvature of the opposite mirror, and L the cavity length. A study with coupled mirrors [3] shows that the sign of the torsional stiffness depends on the two-coupled mirror mode.
When the radiation pressure is present, the suspension response D_{susp} is modified and becomes

$$D'_{susp} = \frac{D_{susp}}{1 - K_{opt} D_{susp}} .$$

where D_{susp} is the suspension response, a low pass filter, with appropriate pole for longitudinal and angular degrees of freedom, and K_{opt} the appropriate spring.
When $|K_{opt}\ D_{susp}|<1$, but non negligible, the requirement for the control system is to anticipate the transfer function change, as done in initial Virgo.
When $K_{opt}\ D_{susp}>1$, the suspension response changes its sign, with an infinite response when the two quantities are such that $K_{opt}\ D_{susp}=1$. The requirement for the control system is to mitigate this response and flip the sign; if not achieved, the system would not be controllable [4]. This requires a good estimate of the detuning, good enough for the open loop transfer functions to remain stable.
The design study will clarify the frequency dependent stiffness, with a model reflecting the coupling of the suspensions with radiation pressure in an arm cavity.

With 760 kW in arm cavities, $x_{det}= 10^{-11}$ m, $x_p=3.10^{-10}$ m, the longitudinal optical stiffness is expected to be $1,1.10^6$ N/m, much higher than the mirror suspension stiffness $M(2\pi f_{pend.})^2 =$ 570 N/m. The two quantities will be equal at P_{res} = 380 W.

1.3 Requirements on lock acquisition procedure reliability

1.3.1 Lock acquisition sequence

The requirement is to have a reliable lock acquisition sequence. A deterministic lock acquisition, with prior acquisition of the arm cavities, facilitates this requirement. The variable finesse technique avoids strong requirements on the laser linewidth (LW<fraction of Hz) when locking the power recycling cavity. The successive locking of cavities (arm cavities, power recycling cavity, signal recycling cavity) will improve the lock acquisition efficiency. This is simplified with a diagonalization of the sensing matrix. A set of 3 modulation frequencies solves this issue.

1.3.2 Mirror motion

The lock acquisition of the automatic alignment (AA) (i.e. superposition of cavity eigenmodes with laser beams) requires that the angular motion is such that the automatic alignment is within its linear range before to be switched on. We also require that when the AA is not switched on, the power fluctuations inside the cavities are within 5%.

1.3.2 Thermal effects

The lock acquisition procedure would be greatly simplified if the open loop transfer functions would not require a tuning depending on the thermal effects during the lock acquisition. This is not the case for initial Virgo and implies a long and complex lock acquisition sequence. This requires:
- a change of the recycled carrier power with thermal effects that does not exceed 20 %.
- a change of the sideband power with thermal effects that does not exceed 20 %
- a change of the coupling defect of the sidebands with the carrier that does not exceed 20 %
- a unique zero crossing for the error signals
- negligible changes in the diagonalization of the sensing matrix
- negligible offsets on error signals, thus negligible sideband unbalance.

This turns into a requirement of the power recycling cavity and signal recycling cavity to remain stable over the lock acquisition process.

2. Steady State Control

Here we describe the requirements in the steady state mode where the interferometer resolution is optimal, called “science mode” within the Virgo collaboration.

2.1 Requirements with the contrast defect

The interferometer contrast defect plays an important role in the control of the interferometer. The contrast defect may change the detuning in the long arms, thus increasing the optical spring. The contrast defect possibly introduces laser frequency noise in the dark fringe in the higher part of the detection bandwidth (TBC for DC detection), as it is the case for initial Virgo.

2.1.1 Contrast defect and DC offset

For a Michelson interferometer with Fabry-Perot in the arms, the transfer function between a length change δl of one arm cavity and the signal power fluctuation δP at the output port is:

$$F = \frac{\delta P}{\delta l} = 8\frac{L_{offset}}{l_p^2} P_{in}$$

where L_{offset} is the detuning of one arm about its resonance and $l_p = (\lambda/2)/(2F)$ is the cavity pole.

The DC output power noise is:

$$\widetilde{P}_{shot} = \sqrt{2P_{in}h\nu\left[\frac{1}{2}(1-C)+\left(\frac{2L_{offset}}{l_p}\right)^2\right]}.$$

Then the resolution (minimal detectable cavity length noise) is

$$\widetilde{l} = \frac{\widetilde{P}_{shot}}{F}$$

The resolution improvement, as stated in [5], requires that the power noise contribution from the contrast defect is negligible. The design will clarify the situation when power and signal recycling cavities are present, and the frequency dependency of the sensitivity function.

2.1.2 Contrast defect and shot noise on laser frequency noise

The contrast defect may re-introduce laser frequency noise on the dark fringe: either the laser not completely stabilized after the IMC, either the shot noise level of the photodiode used to measure the laser frequency noise. For initial Virgo, the laser frequency noise measurement is not shot noise limited. In that case, the shot noise can not be feed-forwarded on the dark fringe. This puts a limit on the contrast defect that has to be determined.

2.1.3 Contrast defect and thermal effects

The specification on the contrast defect may put a specification on the performance of the thermal compensation system.

2.2 Requirements with the shot noise

2.2.1 Auxiliary longitudinal loops shot noise re-introduced in the dark fringe

The preliminary design [6, fig. 1, top] shows that the shot noise of the auxiliary loops (SREC, PRCL, MICH) is re-introduced in the dark fringe. This is enhanced with the optical spring that strongly damps the DARM noise below ~50 Hz. The conceptual design envisages a feed-forward of SRCL/PRCL/MICH error signals. This requires that these degrees of freedom error signals to be shot noise limited or, at most, readout noise limited, and the shot noise should be well visible in all the subtraction band [10 Hz – 100 Hz]. The “classical” motion noise and the control noises should not contribute to the respective error signals for this technique to be possible. The design will check with a semi-classical model, probably including both amplitude and phase quadratures, that the signals are indeed correlated.

2.2.2 Quantum noises

The GWINC model establishing the “sensitivity curve” for Advanced Virgo (actually its spectral density of resolution) is using, for quantum noises (“shotrad.m” routine) a paper [7] that explicitly states that the calculations are not valid for detuned cavities. The design should check how the detuned cavities and associated optical spring change the picture.

2.3 Requirements with the control system

2.3.1 Multi inputs multi outputs system

The design of the loops usually assumes that the various degrees of freedom can be designed independently. The moderate sensing couplings of degrees of freedom can be overcome with “hierarchical gains”: more gain is put on the loop that pollutes the other ones. If one defines the sensing function elements of the two loops S_{11} and S_{22}, and the cross-coupling sensing elements S_{12} and S_{21}, then the condition for hierarchical gain to work is:

$$\left|S_{12}S_{21}\right| < \left|S_{11}S_{22}\right|.$$

For easiness of the design, we require that the degrees of freedom are independent form each other as much as possible. A conceptual design shows that a set of several modulation frequencies, together with the "double demodulation scheme", is at least partially a solution [6]. The design should check that the condition described above are always valid, including at ~50 Hz (0.6 Hz pendulum frequency detuned by the optical spring), and including at the low frequency in the dark fringe. If this is not the case, a full MIMO (multiple input multiple output system) approach is required.

2.3.2 Maintaining the system in perturbed environmental conditions

The AdV top level system may want to define a minimum duty cycle level. This can be jeopardized when bad environmental conditions (see, wind, earthquakes). If the minimum duty cycle is over the average bad environmental conditions ratio, then this puts requirements on the performance of the SUS system, in order for the ISC system to keep the lock with data taking conditions. ISC/PAY will define to SUS a maximum correction signal at the PAY level; the excess will be a specification for Inertial Damping or suspension control.

2.3.3 OMC and RFC resonance conditions

Requirements on the damping of CARM on the RFC will be determined, using OMC lock accuracy requirements and possibly stability of signals.

2.3.4 Up-conversion processes

The dark fringe will be locked with a DC signal. The design will determine the conditions to avoid non negligible up-conversion processes in the dark fringe, as well as in the other error signals.

2.3.5 Feed-forward filters

Feed-forward filters are necessary to cancel the read-out noise from auxiliary degrees of freedom, see section 2.2.1. However, these filters should not spoil the locking accuracy.

2.3.6 Modulation and demodulation techniques

Most of the error signals are obtained with a modulation/demodulation process. The study will set the specifications on the non-linearities and AM to PM conversion in the mixers. The specifications on the demodulation phases will be set to minimize the coupling of the wrong quadratures.

3. Alignment

Here we describe the requirements that are specifically related to the alignment of the cavities.

3.1 Alignment loop noises re-introduced in the dark fringe

A mis-centered positioning of the beams on the mirrors couples the alignment noises in the dark fringe. The specifications for mis-centering of the beams on the mirrors will be set.

3.2 AC and DC references for the interferometer alignment

The references for alignment will be defined such that there is a minimum use of short baselines affected by environmental noises.

4. Parametric Instabilities

Here we describe the requirements that are specific to the vibrational modes of the mirrors that are excited by the high order content of the spatial profile of the light (non-TEM00).

4.1 Forecasting the modes and frequencies possibly involved

The design will forecast how many modes are possible, what are their frequencies and what are their thresholds.

4.2 Forecasting cavity behaviour when PI develops

The design will forecast how the physical lengths and error signals are changed when a PI develops. It will predict how much optical power is transferred into a mechanical vibration.

4.3 Damping or controlling the parametric instabilities

The design will propose a solution to mitigate parametric instabilities.

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