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VIRGO commissioning plan

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Introduction

The VIRGO commissioning started in fall 2003. After two years all the main components of the detector are in action and the noise has been decreased by orders of magnitude since the first engineering data taking. The detector operated continuously for several days and its robustness against long term drifts, failures, earthquakes and weather changing conditions have been tested. Thanks to a large effort concerning automation and diagnostics it is presently possible to operate the detector for a long time with a reduced crew of people.

The main goal of this document is to describe all the steps necessary to conclude the VIRGO interferometer commissioning (that means to reach the design sensitivity with a good duty cycle). This roadmap is based on the experience cumulated in the last two years. Several noise sources was measured, modelled and simulated. Actions are planned to reduce their amplitudes and/or their coupling with the interferometer output. The attempt to make an ultimate planning for the VIRGO commissioning faces with the problem to predict the influence of noise sources whose modelling is difficult (diffused light, environmental disturbances, clipping, etc.). This is particularly true for the low frequency region (i.e. below 50 Hz), where many technical noises show up and no data or experience is available in the international community.

Section 1 provides a description of the main goals of the commissioning and an overview of the detector activities. *Section 2* concerns the commissioning organization. The breakdown structure, the relationship between the commissioning activities and the VIRGO sub-systems, the decision chain and the organization of the work on different timescales (daily, weekly, monthly) are here illustrated. In *Section 3* a detailed description of the status and plans for each commissioning sub-topic is provided. In *Section 4* the commissioning planning is presented.

1. Overview

1.1 Commissioning Goals

The goal of the commissioning can be summarized in the following three conditions:

1. Reach the VIRGO sensitivity;
2. Have a sufficiently high duty cycle over several months;
3. Put the operators team in condition to run the detector routinely for long periods.

The VIRGO design sensitivity is shown in Fig1.1 together with the *fundamental* limiting noise sources. Before to reach these *fundamental* limits, several number of technical noise should be decreased (laser noises, control noises, etc..).

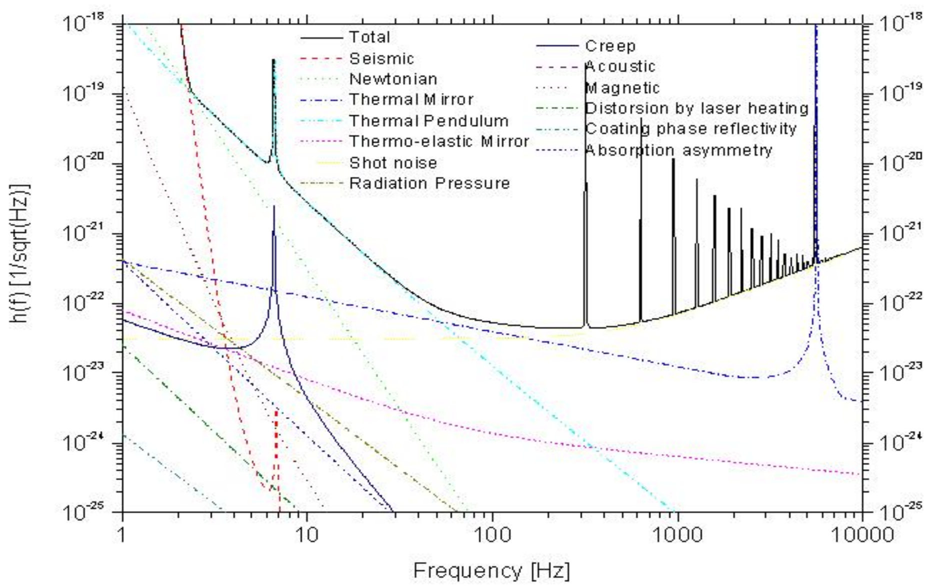

Fig 1.1 VIRGO design sensitivity

In order to reach a sufficient high duty cycle (around 70-80%) several factors are important:

- the control systems should be robust enough to deal with environmental disturbances or drifts in the interferometer parameters.
- in case of loss of lock of the detector, the recovery procedure should be fast enough.
- the detector operation crew should be able to perform a fast diagnostic of failures and to restore the situation quickly.

It is important to stress that the duty cycle of the detector is not a priori connected with its sensitivity. However, in order to reduce as much as possible the technical noise sources, sometimes it is necessary to reduce the gain of the control systems (which are intrinsically noisy), diminishing the robustness of the interferometer.

In order to run the detector over several months several factors are important:

- An ensemble of automatic procedures have to developed. Periodically tunings of the interferometer control systems and of all sub-system have to be done even in absence of the experts.
- The operator team has to be trained in order to perform fast diagnostics and to deal with sub-system failures.

1.2 Commissioning global strategy

The commissioning of such a kind of detector is done in the following way. The first step is to implement and operate all the control systems required to run the interferometer. Then the control systems and the various interferometer parameters are tuned in order to reduce the noise and thus improve the detector sensitivity. In practice these two objectives are pursued in parallel; while the control system is implemented and tuned the noise performances of the detector are continuously monitored and studied.

The control system was implemented on sub-ensembles of the interferometer of increasing complexity. First of all it was implemented and deeply studied on the 3 km long Fabry-Perot placed along the north arm. Sub-systems like the injection system, the global control, the detection system and the two suspensions supporting the mirrors composing the cavity were tested and debugged. The work was performed also on the West Fabry-Perot. This second step (essentially a repetition of the work done on the North arm) allowed to tune the control of the suspension of the beam splitter and of the two mirrors composing the West Fabry-Perot. In both cases the noise performances obtained with a single Fabry-Perot are studied and monitored. Due to the excellent frequency resolution of the 3 km long Fabry-Perot these noise studies allowed to understand in detail the laser frequency noise and thus to tune the injection system control.

The second step consists in recombining the light reflected by the two arms and run the interferometer in the so-called ‘recombined’ configuration. At this stage all the components of the interferometer are used with the only exception of the power recycling mirror which is kept misaligned. The main differences with respect to the operation of a single arm consists in the locking of the interferometer which have to deal with three degrees of freedom instead of a single one: the length of each Fabry-Perot cavity and the phase difference between the two beams reflected by the arm cavities. This phase allowed to test the performance of the longitudinal control of the beam-splitter in order to keep the interferometer output locked on the dark fringe. In addition it allows to shake all the hardware and software needed for the locking of the interferometer (i.e. the global control sub-system). The implementation of remaining parts of the control system (non-linear alignment, automatic alignment and suspension hierarchical control – see next sections) take advantage of the work done with a single cavity since they can be run in a very similar configuration. Moreover by keeping the interference between the two beams locked on the dark fringe the sensitivity of the interferometer output to all common mode noises linked with the laser source is considerably reduced and, as a consequence, the sensitivity considerably improved. As a consequence in this configuration more noise sources becomes relevant and can be investigated.

The third step consists in running the interferometer in the recycled mode, that is the VIRGO final configuration. Several difficulties are linked with this phase. The interferometer locking requires the simultaneous control of four degrees of freedom (the two Fabry-Perot cavity lengths, the recycling cavity length and the phase difference between the two beams reflected by the arm cavities) by means of a set of error signals having a considerable smaller linear range compared to the case of the recombined interferometer. In addition the automatic alignment strategy needs to be completely redefined since the presence of the recycling cavity introduces large coupling between the arm cavities and, as a consequence, the strategy developed for the recombined interferometer is not usable anymore. Finally during this phase the amount of power stored in the interferometer increases considerably and so only at this stage all the potential problems connected with the heating of the mirrors or the resistance of the photo-detectors become relevant. The implementation of the other parts of the control system (suspension hierarchical control and second stage of laser frequency stabilization – see next sections) need to be retuned. Nevertheless they can largely rely on what developed during the commissioning of the recombined interferometer.

The final step of the VIRGO commissioning is the so-called noise hunting phase, although noise investigations can already start during the previous steps of the commissioning. They becomes a continuous and systematic activity only when all the parts of the control systems are running with the interferometer in the recycled mode. Several technical noises couple into the interferometer output via not very well known coupling mechanisms and they becomes observable only at this final stage. For instance, small but relevant effects due to diffused light depends on the exact final alignment of the interferometer and of the monitoring beams on the several photo-detectors used for the interferometer control. During the noise hunting phase all the possible noise sources are investigated and the control system has to be retuned on the basis of the results of these investigations. Depending on the noise hunting results some parts of the interferometer may have to be improved of substituted.

During this phase commissioning is interleaved with longer and longer data taking periods that will carry the VIRGO interferometer from a commissioning mode into the science mode. Moreover as soon as the interferometer reaches a sufficient level of reliability and sensitivity the detector is run in data taking mode during the night and the weekends while the noise hunting goes on during the day.

In summary, the commissioning of VIRGO consists of the implementation of the control system and the understanding of the noise performances. This two main operations was planned in four main steps:

A. The commissioning of the two interferometer arms;
B. The commissioning of the recombined interferometer;
C. The commissioning of the recycled interferometer;
D. The noise hunting.

For the first three steps the implementation of the control system consists always of the same sequence of operation (independently of the optical configuration):

1. Implementation of the non-linear automatic alignment;
2. Implementation of the locking system;

3. Implementation of the automatic alignment;
4. Implementation of the second stage of frequency stabilization;
5. Implementation of the suspensions hierarchical control;
6. Investigation of the noise performances.

It is clear that as the commissioning progresses the sub-systems performances will be subject to more and more detailed analysis that can put in evidence the necessity of improvements. For this reason the commissioning of the interferometer is often interrupted in order to allow the sub-system improvements.

1.3 Present status of the detector

Presently the commissioning of VIRGO is approaching the end of phase C. Most of the control system of the recycled interferometer were put in operation (even if with the input power decreased by a factor of ten - see below). A pretty detailed understanding of the noise performance in the present conditions was achieved. The following paragraphs give an overview of the control systems, data taking and noise hunting. Then the motivations for injection bench and PR mirror replacement are illustrated.

1.3.1 Status of the control systems

The detector is running in the recycled configuration with an input power of about 0.8 W. The lock of the interferometer is routinely acquired with the *variable finesse* technique and it is stable for hours.

The automatic alignment of the interferometer was achieved. Ten degrees of freedom (2 angular degrees of freedom for 5 mirrors) were controlled using quadrant photodiodes (or *wavefront sensors)* placed in different ports of the detector.

The hierarchical control of the suspension system has been achieved: the low frequency forces are re-allocated to the inverted pendulum, and the force in the Hz region in the marionetta. Once the marionetta control is active, the dynamic of the force sent directly to the mirror can be reduced, then reducing the actuators noise.

A general automation of the locking procedure has been also achieved, including switching to low noise states and calibration processes. With only one script is possible to bring the interferometer from the unlocked state to science mode, in about 5 minutes.

1.3.2 Results of data takings C6 and C7

Fig.1.1 shows the evolution of the VIRGO sensitivity for all the commissioning runs. The different configurations are explained here below.

C1 – North cavity locked at resonance (14-17 Nov. 03).

C2 – North cavity locked at resonance and automatically aligned (20-23 Feb. 04).

C3 – As C2, with second stage frequency stabilization (23-26 Apr.04). Recombined interferometer (26-27 Apr.04). The sensitivity in Fig.1.2 refers to the recombined configuration.

C4 – Recombined interferometer with automatic alignment, second stage frequency stabilization and tidal control (24-29 June 04).

C5 – As C4, with suspension hierarchical control (2-6 Dec.04). First data taking with the recycled interferometer (6-7 Dec.04) with the reduced power (0.8 W). The sensitivity curve in Fig.2 refers to the recycled configuration.

The runs C6 and C7 were also performed with the recycled configuration and with the reduced power. The run C6 (29th July, 12th august) was a 14 days-long run, aimed to collect data for detector the characterization and data analysis purposes. The main differences with respect to the C5 run was the presence of a partial automatic alignment: 2 angular degrees of freedom were controlled with a full bandwidth (few Hz), and the remaining 8 were controlled with a reduced bandwidth (few tens of mHz). We refers at the latter as a *drift control.*. This partial automatic alignment guaranteed to have both short term and long term stability. During C6 the interferometer was locked for about 90% of the time, and the duty cycle for science mode was about 85%, and the longest continuous locking stretch was 40 hours. Some noise hunting activities were carried on during the run, with consequent sensitivity improvements in the central and high frequency regions. The best horizon for optimum oriented 1.4-1.4 NS-NS inspirals was 0.56 kpc (SNR = 8).

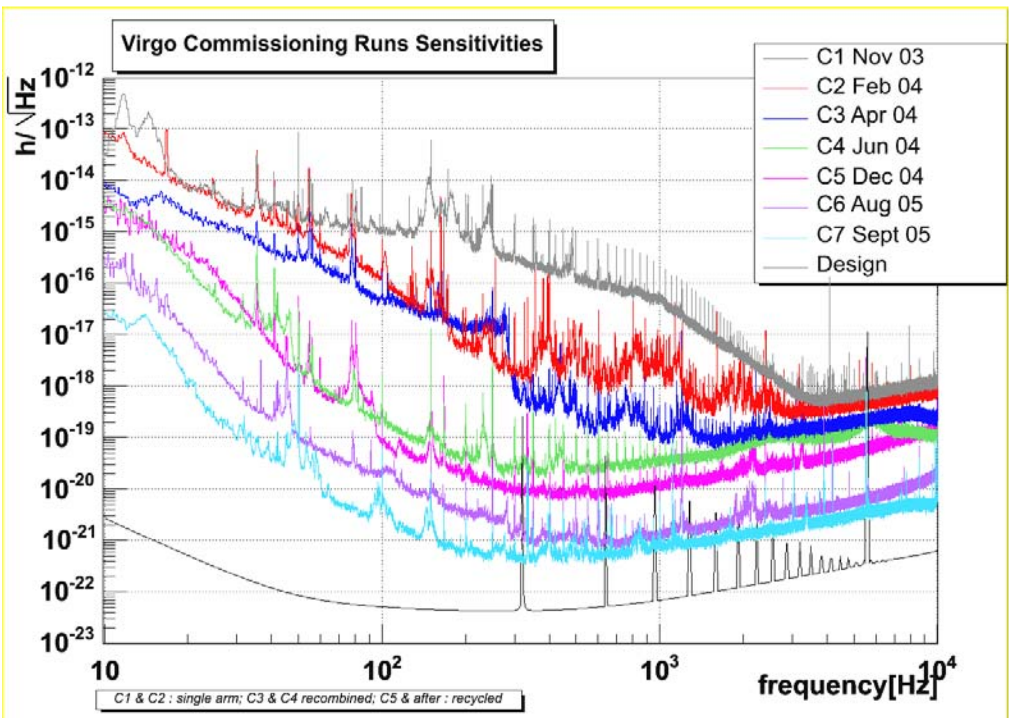

Fig 1.2 - Strain sensitivities for the 7 commissioning runs
The different configurations are explained in the text.

For the first time a complete automation of the locking procedure was present. A single script is enough to bring the interferometer in science mode, through all the sequence of locking states.

Fig. 1.3 shows the noise budged for C6. We observe that the incoherent sum of the different noise contributions almost reproduce the sensitivity curve, showing that the interferometer noise has been essentially understood.

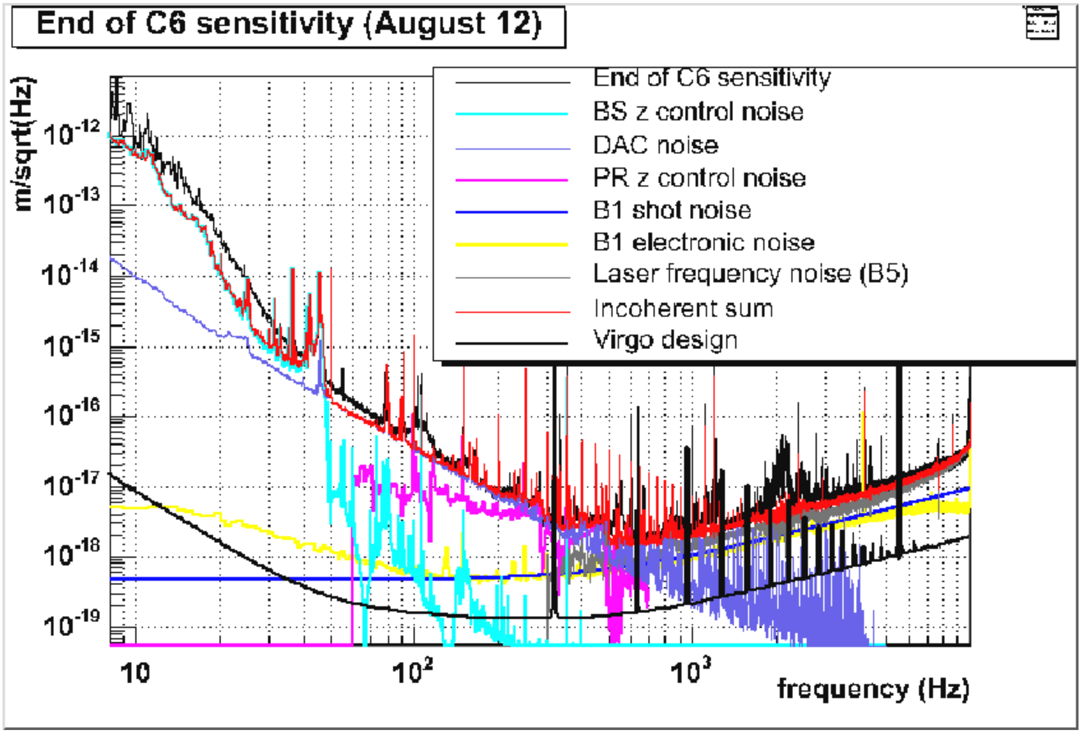

Fig 1.3 - Noise budget for C6 run

The run C7 (14th September, 19th September) was a 5 days-long run, whose duration was limited by the planned interferometer shutdown.

With respect to C6, the complete automatic alignment and the full hierarchical control were operating. During C7 almost all the control systems of the interferometer were then working. The duty cycle in science mode was around 65%. The duty cycle decreasing with respect to C6 was due to a not perfect tuning of the control system (because of time constraints, since the shutdown was approaching), to worst weather conditions and problems with mode-cleaner locking.

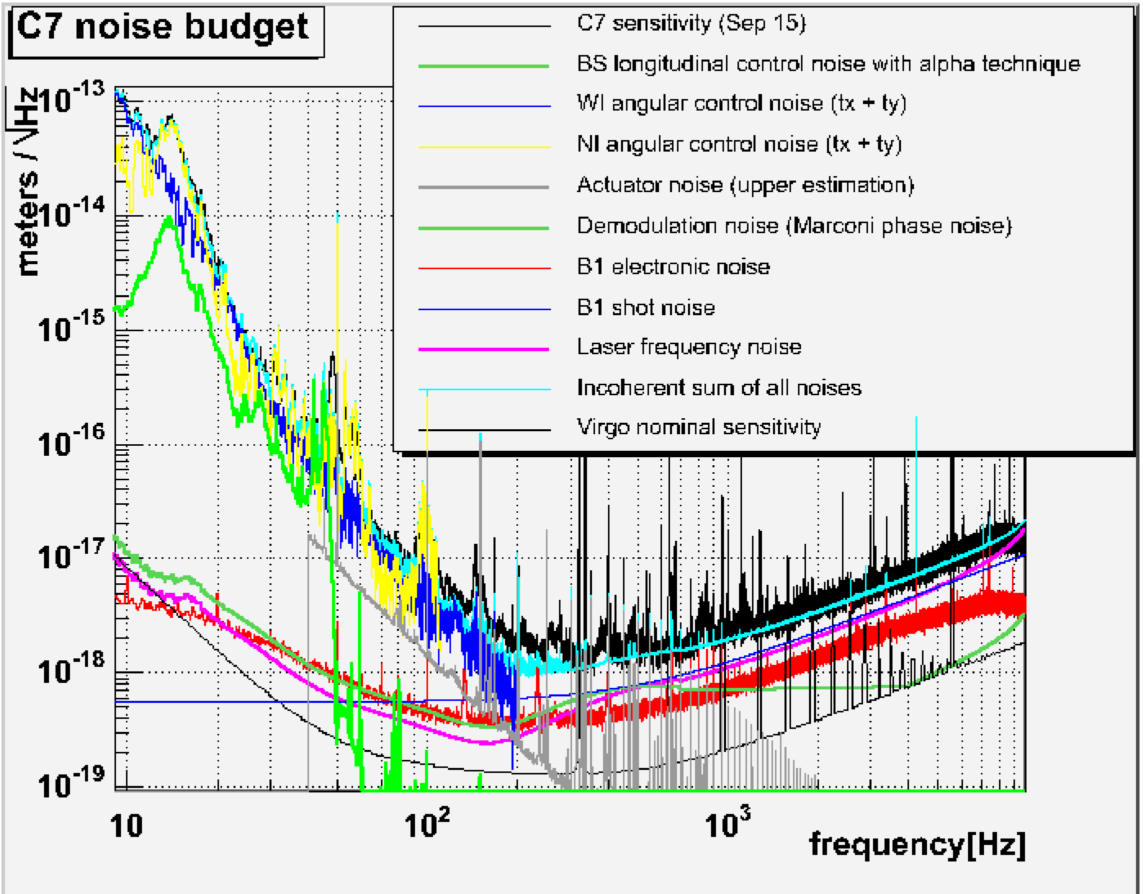

Fig. 1.4 - Noise budget for the run C7

A few changes in the set-up were also performed in order to increase the sensitivity, following the noise budget computed for C6. The peak horizon for NS-NS inspiral (same conventions as before) for C6 was around 1.65 Mpc, the mean horizon was around 1.4 Mpc.

Fig.1.4 shows the noise budget for C7. The noise floor was roughly understood in all the spectrum. Above 200-300 Hz the sensitivity is limited by the shot noise of B1 photodiode and B5 photodiode translated in frequency noise (see also section “noise reductions at high frequency). Below 200 Hz the sensitivity is limited by angular control noises and beam splitter longitudinal control noise.

The high frequency part being limited by the shot noise, this is a clear motivation to increase the power of the interferometer, that, as shown in the following, implies the replacement of the injection bench.

1.3.3 Motivation for a design of a new IB

After the first unsuccessful attempts to lock the recycling cavity (July 2004) it turned out clearly that the light reflected back from the interferometer into the IMC was causing interference fringes and a feedback preventing the locking of the interferometer. The problem was caused by the light scattered by the MC mirror, which was re-injected in the light path going into the interferometer. The temporary solution to this problem was the replacement, in September 2004, of the M6 mirror with a 10% reflecting mirror. In this way the light coming back from the interferometer into the IMC was reduced by a factor 100 (fringes reduced by a factor 10). The obvious drawback of this solution was that the power injected into the interferometer was reduced by a factor 10. After the installation of the 10% reflecting M6 mirror and the matching of the beam into the interferometer, the induced noise in the IMC by the back reflected light was reduced by the expected amount, and the locking of the recycling cavity was acquired at the end of October 2004.

The long term solution for the backscattering problem was to install a Faraday Isolator after the IMC. With the present bench design the installation of the Faraday Isolator turns out to be impossible. In addition, the decision to replace the curved PR mirror with a plane mirror (in order to avoid misalignment noise induced in the beam direction by transversal movement of the PR mirror) was taken in November 2004. These two changes required a complete redesign of the bench: more space was needed, and a different collimation optics on the main beam was also required. The main constraints were the following:

- The largest aperture Faraday Isolator has an aperture of 20 mm; the beam coming out from the IMC has a waist of 5 mm. In VIRGO it has been decided not to have aperture smaller than 5 times the beam waist passing through it, in order to reduce losses to some ppm. For this reason, since 20 mm are only 4 times the beam waist coming out from the IMC (supposing no miscentering is present), the beam has to be reduced in size after the IMC before entering into the Faraday Isolator. It was decided to reduce the beam size to about half of that coming out from the IMC (from 5 mm to 2.65 mm), using a short telescope after the IMC output mirror.

- The PR, being plane, cannot be used any more as a lens to collimate into the interferometer.

  Thus, owing to the smaller dimension of the beam in the Faraday Isolator and to the fact that the PR is plane, the telescope to be placed after the Faraday Isolator, to collimate into the interferometer, needs a larger magnification factor than it had in the old IB. Simulations showed that using spherical mirrors, taking into account the available space which limits the telescope length, would have resulted in spherical aberrations. For this reason the possibility to use off-axis parabolic mirrors was explored.

Other problems that had to be studied were:

1) Mechanical resonances of the Injection Bench (wires, components, dihedron, ….)
2) Stray light on the bench
3) Beam monitoring on the bench
4) Actuators
5) New alignment system of the whole ISYS: the IB should be kept completely under automatic alignment (instead of being controlled with the local controls, as it used

to be): this was decided in order to completely remove ground based controls and to be constrained to rely on the alignment on the RFC for the IMC-beam alignment

All these items required a complete redesign of the bench. It was not possible to take care of all these problems with the old IB.

1.3.4 Motivations for a design of a new PR mirror

The present power recycling mirror is a composite structure, exhibiting several mechanical resonances in the frequency range between 100 Hz and 1 kHz. These resonance, being almost in the locking bandwidth (100 Hz), makes the control of this mirror very difficult (see section 3.1). For these reasons it has been decided to have a monolithic mirror, with the first internal resonances at frequencies similar to the test masses resonances (>3 kHz). In order to increase the recycling factor, and then the power circulating inside the interferometer, it has been decided to increase the reflectivity of this new power recycling mirror from 0.92 to 0.95. For the reasons explained before, the new power recycling mirror will not act also as the 3rd mirror of the input telescope, but it will be flat.

2. Commissioning Organization

2.1 Work organization

The experimental work is structured on 3 different timescales:

- *Daily activity*. The working time is divided in two shift (8am-4pm, 4pm-11pm). A shift is associated with a commissioning task (i.e. marionetta control of the west end suspension). The commissioning task is carried out by a crew of about 2 people. During the shift an operator checks the correct working of the interferometer, and – through dedicated procedures – put the interferometer in the configurations required by the commissioning crew. At 3 pm a daily meeting takes place in the control room, with the purpose to discuss the daily planning and results. The daily meeting is chaired by the shift coordinator, appointed each week. The goal of the shift coordinator is to follow the experimental activities of the week, to track the problems and to improve the communication between the different commissioning crew and the sub-system experts.

- *Weekly activity*. The results and the planning of the week is discussed at the commissioning weekly meeting, which take place each Tuesday at 2h30 pm, in the meeting room, and which is chaired by the commissioning coordinator. The weekly meeting is done through teleconference or videoconference with all the VIRGO labs that want to joint.

- *Monthly activity*. The results and planning of the month is discussed at the commissioning meeting, which take place each first Monday of the month, in the framework of the VIRGO collaboration meeting. The meeting is chaired by the commissioning coordinator. Problems which need major changes in the detector set-up are transmitted to the VIRGO detector coordinator, who ask for a discussion in the framework of the detector meeting (occurring the day after the commissioning meeting). If needed, the commissioning and detector coordinator report to the VSC about topics requiring formal decisions from this committee.

2.2 Work breakdown structure

Since its beginning, the commissioning was divided in the following activities, transversal with respect to the various VIRGO sub-systems.

a) *Length Sensing and Control (LSC)*
It includes tasks such as photodiodes tuning, lock acquisition, output mode-cleaner locking, laser frequency stabilization and linear locking.

b) *Alignment Sensing and Control (ASC)*

It includes tasks such as pre-alignment, non-linear alignment, quadrants tuning and linear alignment.

c) *Mirror Suspensions Control (MSC*)
It includes tasks such as inertial damping tuning, local controls tuning, repartition of global feedback forces on the various stages of the suspensions and design of feedbacks for the mirror position control (suspension dependent).

d) *Optical Characterization (OPC)*
It includes tasks such as large mirrors commissioning, input/output optics characterization (on injection, detection and end benches) and modulation frequency tuning.

e) *Electronics & Software (E&S)*
It includes tasks such as commissioning of control digital electronics and the commissioning of software used in interferometer control and monitoring.

f) *Detector Operation (DO)*
It includes tasks such as the organization of commissioning shifts, the definition and the collection of the procedures required to run the interferometer and the organization of the engineering runs.

Each transversal activity has a coordinator, who provides a planning for the activity, leads the experimental work and manages the interactions with the various VIRGO sub-systems. The planning of each activity is discussed with the commissioning coordinator and compose the commissioning plan. Each coordinators leads also the noise studies related with the correspondent transversal activity.

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3. Commissioning Activities: Status and Plan

3.1 Length sensing and control

3.1.1 Introduction

Lock the interferometer means to put it on its working position, starting from an uncontrolled condition, where the mirrors are freely swinging driven by seismic noise. For VIRGO the operating point corresponds to have the laser carrier resonating in the Fabry-Perot cavities (with the sidebands at the anti-resonance), the carrier and the sidebands resonating in the recycling cavity and the carrier on the dark fringe. These conditions translate into fixed relationships between the laser wavelength and four independent lengths of the interferometer:

- the common (CARM)and the differential (DARM) length of the long arms, defined respectively as $L_{CARM} = L_N + L_W$ and $L_{DARM} = L_N - L_W$;
- the differential length of the short Michelson arms (MICH), $l_{MICH} = l_N - l_W$;
- the length of the recycling cavity (PRCL), $l_{PRCL} = l_0 + \frac{l_N + l_W}{2}$.

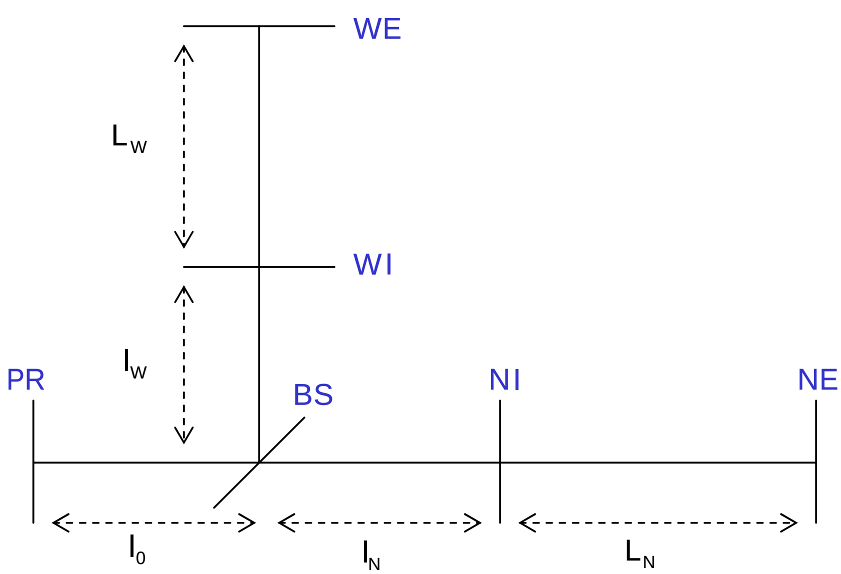


Fig.3.1 – The interferometer longitudinal degrees of freedom.

These four lengths have to be controlled with a very high accuracy (typical rms of 10^{-12} - 10^{-10} m). The swinging mirrors are locked in the right longitudinal position by using Pound-

Drever-Hall like signals and acting on the mirrors by the reference mass coil-magnet actuators. All the lengths are reconstructed by mixing the signals extracted from photodiodes placed at different output ports of the interferometer. These signals are sent to the global control system that computes the correction signals to be sent to the mirrors at a 10 kHz sampling rate.

3.1.2 Status of the Locking Activities

As mentioned above, the VIRGO commissioning has been organized in steps of increasing complexity, starting from fall 2003: a single Fabry-Perot arm, the recombined interferometer, and the recycled interferometer.

a) The variable finesse locking technique

For the full locking of VIRGO a completely original locking technique was found. The main idea is to lock the interferometer far from the dark fringe. In this way a good fraction of light escapes through the anti-symmetric port and the power build-up inside the recycling cavity is extremely low. All the lengths of the interferometer are almost decoupled and the line-width of the recycling cavity is large, making the control design easier. From this stable and controlled state, the interferometer is adiabatically brought onto the dark fringe. This technique has been called *variable finesse lock acquisition*, because the finesse of the recycling cavity changes during the lock acquisition path, increasing the detuning with respect to the dark fringe decreases.

The locking procedure starts having the PR mirror slightly misaligned, in order to further decrease the power stored inside the recycling cavity. The simple Michelson is kept at mid-fringe (50% reflected, 50% transmitted), adding an offset in the dark port DC signal and applying the correction to the BS mirror. During this phase, since all the degrees of freedom are almost decoupled, the two arms can be independently locked using the end photodiodes. The small quantity of light reflected by the interferometer is used to control the recycling cavity power length, using the reflected beam demodulated at the third harmonic of the modulation frequency. This stable configuration can usually be reached in few seconds, preventing mirror excitations. From this condition the PR is realigned, always while maintaining the Michelson at mid-fringe, giving a very low recycling gain.

In order to increase the recycling gain, the Michelson has to be brought on to the dark fringe: this is done adiabatically, decreasing the offset in the Michelson error signal. At the same time the control scheme evolves to take into account the increasing coupling between the different degrees of freedom:

- the frequency stabilization servo (the so-called *Second Stage of Frequency stabilization, or SSFS*) is engaged, in order to significantly reduce the contamination of the CARM degrees of freedom on all the photodiodes ;
- DARM is kept in a locked state by one of the end photodiode signals.

The final step of the lock acquisition sequence consists of switching from the DC signal to a demodulated one to control the small Michelson length: the offset in the Michelson error signal is removed, the interferometer goes on to the dark fringe and the recycling cavity gain increases up to the maximum value.

The PRCL length remains stably controlled by the reflected 3f-demodulated signal during the entire lock acquisition sequence. This is in fact the main advantage in using the 3f-demodulation scheme with respect to the standard f scheme for the PRCL control: the stability of the transfer function and sign of the PRCL reconstructed length even during lock acquisition, which allows us to keep this degree of freedom locked without changing the control scheme.

Once the ITF is locked onto the dark fringe, the DARM control is moved from the end photodiode signal to the dark port signal.

The locking of the full interferometer by the variable finesse technique was achieved for the first time in October 2005, with typical locking period of one hour, limited by the misalignments of the interferometer due to fluctuations and drifts in the mirrors locally controlled.

b) The interferometer instabilities

After the two week-long shutdown occurred after C5 (when a full realignment of the injection system occurred) bi-stabilities (or “jumps”) in the recycling cavity power were observed during the locking period. These fast (a few tens of ms) transitions to a lower power level occurred each a few seconds (or a few minutes), depending on the observation period. The evidence was that the power in the recycling cavity, after a jump, stays in the low level state (around half of the standard recycling power level) for a variable period of a few tenths of seconds, then coming back to the original value.

Even if the reason of this spurious effect was not fully understood, several tests were performed in order to exclude problems due to electronics, environmental noise, etc.., leading to the conclusion that the mechanism has to be searched in the interferometer optics.

Bi-stabilities made the locking less robust, slowing down the activities in the first five months of the year.

Around the half of May the photodiode B5 was found not correctly centered. After a careful centering of the photodiode the bi-stabilities disappeared.

After one week of unperturbed operations (May 19th – May 26th), we were obliged to re-alignm the injection bench due to a problem of laser used in the local controls. After this operation the bi-stabilities appeared again, despite the fact that the B5 photodiode was correctly centered.

In early July we found how to orientate again the injection bench in the position of the week May19th-May 26th). After this operation the bi-stabilities completely disappeared. It’s not clear why special alignment positions of the injection bench can generate such a kind of bi-stabilities, some hypothesis are: beam clipping on injection bench mounting (observed), spurious light (observed) and secondary beam coming from the interferometer and not correctly managed at the injection bench level (problem know).

This “extra-light” (spurious beam, stray light) or this “lack of light”(clipping) at the injection bench level can enter in the photodiodes used to control in the interferometer and perturb the working position of the interferometer itself. The same mechanism can explain the raison why we have observed bi-stabilities when the B5 photodiode was not correctly centered.

We should mention that all these optical problems of the injection bench (secondary beams coming from the interferometer, beam clipping, …)have been taken in account in the design of the new IB.

A second type of instabilities which seems to have a different mechanism have also been observed. Even if they have a different shape with respect to the bi-stabilities already mentioned, this second type of instabilities were confused often with the first ones, and this probably slowed down the diagnostics.

This second type of instabilities seems to be not associated with a second state stable of the interferometer. The problem has been removed by detuning the optimal demodulation phases of the B2_3f signal (used for the power recycling length control) by about 75 degrees.

By locking the interferometer on another reflected signal (the one demodulated at f) we have observed that when the correct phase of B2_3f is set, this signals shows a large optical offsets, which is not present in the theory. The same offset is present, since the beginning of the recycled interferometer commissioning, in the B2 signal. Both are not understood, but they can have the some origin of the bi-stabilities (beam clipping, secondary beams, …).

c) The Control Noise Reduction

A robust locking of the interferometer was thus achieved at the beginning of this Summer. All the accuracies are within the specifications. Locking periods of several hours took place thanks to the angular drift control, making the interferometer much stable on the long period. In the last months the locking activities were also focused on the reduction of the noise induced by the control of the additional degrees of freedom (small Michelson and power recycling cavity length). This was done mainly by optimizing the control filters and by starting to apply noise subtraction techniques, as it will be discussed in the noise hunting session.

3.1.3 The Remaining Steps

The steps needed in order to complete the commissioning of the locking of the recycled interferometer are the following ones:

a) Re-shuffling of the locking algorithm:

This activity will allow us to increase the available computational time of the locking process and thus the implementation of more aggressive filters necessary to reduce the noise in the interferometer.

b) *Switch from the reflected 3f-demdoulated signal to the f-demodulated one*

Once the power stored in the interferometer will be the nominal one, the switch from the 3f to the f-demodulated signal for the controlling of the recycling cavity length will be mandatory for noise hunting purposes (see 4.1 section).

c) *Automation, detector monitoring and operator training*

It is necessary to implement new functionalities in the automation and in the detector monitoring. The goal is also to make not expert people able to perform all the actions necessary to tune the locking parameters, to monitor the locking performance and to perform a full diagnostic in case of failures;

d) *Analysis and improvement of the locking robustness*

The robustness of the locking has to be studied and improved as a function of mirror misalignments, seismic not stationary events, etc. both by dedicated tests and by monitoring the interferometer for long periods;

e) *Locking characterization*

Characterization measurements of the locking will be necessary for a better understanding of the system. In particular it will be important to perform accurate measurement of the sensing matrix (connecting photodiode signals to mirror longitudinal displacements) and of the driving matrix (connecting the force applied to the mirror with the displacements of the different locking degrees of freedom).

f) *Frequency servo tuning and characterization*

A calibration of the SSFS signals and a permanent measurement of the SSFS unitary gain frequency will be implemented (by injecting a calibration line in the laser correction signal). A permanent measurement of the interferometer arm asymmetry will be also performed via line injections.

3.2 Alignment sensing and control

3.2.1 Status Report

Before the shutdown, two important milestones had been reached:

1. The drift control system, which uses the linear alignment error signals as offsets for the local control error signals. In this way, the mirrors were kept under local control, avoiding the complications on loop stability due to couplings and imperfect mirror angle reconstruction; the slow drifts were corrected by shifting the local control set-point, keeping the interferometer well aligned for up to 40 hours during C6.

2. The full linear alignment, where 5 mirrors (10 degrees of freedom) were controlled with high bandwidth (3 Hz), using only the linear alignment error signals. This configuration has worked up to 30 hours continuously, and was used during C7.

3.2.2 Points to be improved

a) Linear alignment robustness

In the full configuration, more experience is required in order to understand whether the linear alignment system will work with a given set of parameters under all circumstances; we must understand whether a tuning of gains, offsets etc. must be regularly performed, in which case the system must be made more robust against these changes.

b) Finding the final linear alignment configuration

The configuration used during C7 is the result of a first trial, and it is not yet optimized for decoupling, noise or robustness. Different methods are foreseen for improving the configuration; these include redistributing the quadrant signals used for error signal reconstruction (change of the reconstruction matrix), and finding new signals for linear alignment (like placing quadrant diodes in new positions). Out of the 6 mirrors, one will be controlled by a slow beam pointing stabilization system. The choice of this mirror (initially the beam splitter, in the most recent configuration rather the West input mirror) is not yet frozen.

c) Error signal reconstruction

When exciting each mirror at a specific frequency, the reconstruction matrix, used for obtaining the error signals for each mirror from the quadrant diode signals, does not yield satisfactorily decoupled signals. Due to the inherent tolerance of a multi-input, multi-output system, the full linear alignment system works even in this condition, but a good reconstruction is a key element for a stable and robust system, independent from eventual changes of external parameters. The correct way of forming auto-alignment error signals from the quadrant diode signals (matrix inversion, hand selection of signals, . . .) needs to be understood, and more reconstruction measurements need to be performed. Retuning of the optical set-up may be useful for obtaining a better decoupling.

d) Alignment offsets

Presently, the reconstructed auto-alignment error signals are not zero when the interferometer is perfectly aligned; these offsets, which must be artificially subtracted, are not constant, and seem to require occasional readjustments for keeping an optimal power. The causes of the offsets are not yet understood. Simulations have shown, that one possible cause might be ghost beams, created by beam splitters used in front of the quadrant diodes. Therefore the replacement of these beam splitters is foreseen.

e) Linear alignment noise

Switching on the full linear alignment in the present configuration still causes some worsening of the interferometer sensitivity. This should improve once the linear alignment system converges towards the final configuration; moreover, an effort must be done for optimizing the correction filters for injecting as little control noise as possible (steep roll-offs etc.). More details are given in the section 4.

f) Beam/mirror centering

If the beam incident on a mirror is not centered, then any angular motion of the mirror introduces a change in cavity length. This introduces angular noise into the dark fringe. The experience of other gravitational wave detectors suggests a centering need of the order of a millimeter.

g) Automation of PR mirror alignment

Currently, the power recycling mirror pre-alignment is the only step of the locking/alignment sequence which is still manually performed. Some effort towards automation had been made in the past, but the automatic procedure worked well only for an the initial period after implementation. After a few weeks, some gains and offsets, empirically determined, started to drift, thus spoiling the procedure's performance. The plan is to determine a new procedure, and then to automate it.

3.2.3 Controls remaining to be implemented

a) Beam drift control

The linear alignment loops act on 5 out of 6 mirrors. The remaining degrees of freedom of misalignment are slow drifts of the beam pointing in the North and West arms. It is foreseen to act on the input beam (via piezo-mounted mirrors) for correcting the drift of the North beam, and on the beam splitter (or, in the most recent configuration, the West input mirror), for West beam. These slow loops might require fast contributions for damping eventual mirror oscillations.

b) New mode cleaner auto-alignment scheme

A new auto-alignment scheme is foreseen for the mode cleaner, which acts on the mode cleaner curved mirror and on the injection bench; at the same time, the input beam will be aligned with respect to quadrant diodes on the external injection bench. This last step has already been achieved. A new auto-alignment system is also foreseen for the reference cavity, which uses the new piezo-mounted mirrors on the suspended injection bench.

3.3 Mirror suspension control

3.3.1 Description

The main commissioning goals of the Mirror Suspension Control (MSC) activity are:

- the reduction of the residual motion of the suspended mirrors, mostly associated to the normal modes of the SA, to ease the acquisition and maintain of the lock. This is achieved with:
  - the *inertial damping,* a three d.o.f. control performed at the level of the soft inverted pendulum;
  - the *local control,* three d.o.f. control performed at the level of the steering filter-marionette and recoil mass-mirror;

- the realization of the full hierarchical control of the Superattenuator (SA), that is the splitting of the locking effort over the three actuation points (inverted pendulum (IP), marionette and recoil mass (RM). Such a splitting allows to reduce the maximum force required on the RM actuators and, consequently, the electronic noise re-injected in the detection bandwidth. According to the present design the control bandwidth are:

- DC-0.01 Hz, IP: this control compensates for slow and large strains of tidal or thermal origin. We will refer to it as *tidal control*;
- 0.01-5 Hz, marionette: this frequency range includes all the SA resonance. The re-allocation of the locking force to the marionette allows to reduce strongly the maximum force required on the RM;
- 5 Hz-50 Hz, RM: the high frequency part of the locking force is still exerted on the mirror via RM.

3.3.2 Inertial Damping

The inertial damping is running on all the SA since years. Its performance is limited by amount of seismic noise re-injected by the position sensors (LVDT) used to control the IP at low frequency. Until C7 the blending between position and inertial sensors was set at 50 mHz. Reducing the crossover frequency would also improve the performance and make the system more robust also in stormy days, when the amplitude of the microseismic peak can be up to a factor 100 larger. Reducing the crossover frequency is not easy for several reasons:

- due to non perfect parallelism of the IP legs a translation-to-tilt coupling is present (cradle/saddle effect), that messes up the accelerometer signal at very low frequency. In fact, the tilt is proportional to the position sensor signal. Therefore, the problem was solved by implementing a more complex sensing matrix, using the LVDT signals to "subtract" the tilt;
- the accelerometers lose sensitivity at low frequency and the 1/f electronic noise of the ADC can be a limitation (the ACC noise is lower than the ADC one). We found that a

further amplification of the ACC signal allowed to reduce the crossover frequency down to 30 mHz (tested on two SA, NE and NI);
- the role of DSP arithmetic noise is being investigated. A new algorithm for filters implementation is being developed and the first results are very promising.

We planned some work for the enhancement of the ID performance, to be done during the shutdown. The amplification of the ACC has been performed on all long towers except PR. Five towers are now working with a 30 mHz crossover since a few weeks.
The new algorithm used by the DSP to calculate the filters with a lower arithmetic noise is ready to be tested.

New ideas are being studied: we plan to change the coordinate system used for the ID, passing from the basis of the IP normal modes to the Virgo reference system. This would simplify the comprehension of the SA behavior for non experts but, above all, will allow to test a new strategy: switch off the LVDT control along the beam direction using only the tidal control signals. This would be possible on 4 towers only (since 4 locking signals are available) but could anyway help to reduce the reinjected seismic noise.

3.3.3 Local controls

During the first part of the commissioning the local control system was particularly stressed because of the evolution of the machine understanding when facing different commissioning phases. Indeed, this period was quite useful to study the response of the system to a variety of conditions and its regime performance. Since the target of the first part of the commissioning was to reach a stable operation of the full interferometer, the major efforts have been spent on the following topics:

- optimization of the hardware set-up to provide better error signals;
- increase of control accuracy to facilitate locking and linear alignment studies (0.3 urad rms over 5 Hz control BW);
- management of a variety of issues related to operation transients (e.g. interferometer start-up, interferometer-recovery and automation) and particular situations (failures in error signal reconstruction or environmental matters).

The plan can be divided in two main sections: A) interferometer stop (autumn) and B) commissioning of full interferometer step-2 (or second part).

A-1) During the first part of the commissioning we noticed a dependence of the optical levers of the local controls on the temperature (drifts up to 1-2 urad/hour). This effect will be cured by installing new lasers equipped with thermal control. Just one laser will be tested first (October) in order to see whether the new apparatus is really more stable as expected (before completing the installation). Moreover temperature monitors will be installed at all the local control benches.

A-2) Reduction of local control noise re-injection in the VIRGO detection BW by changing the amplifier of one mirror (useful when one mirror, the BS, is left under local control).

B-1) Reduction of noise re-injection by local control and automatic alignment filters by re-shaping the common part of the digital filters (roll-off) without reducing the gain at low frequency.

3.3.4 Hierarchical control

Full hierarchical control has been successfully implemented over the Fabry-Perot end mirrors and has proved to be reliable. The interferometer has been run with full hierarchical control during C5 (in recombined mode) and C7 (in recycled mode). The reduction of the correction applied on the mirror has allowed to further reduced the DAC noise and to improve the sensitivity in the 70-120 Hz range. Tidal the control has been implemented also on the BS: getting rid of slow drifts allowed as well to reduce BS DAC noise. As the sensitivity improves, it would be necessary to further reduce the DAC noise contribution. Marionette re-allocation will be implemented also on the BS. During the shutdown BS mechanical transfer function matrix will be measured using local sensors, in order to calculate a first driving matrix for the marionette actuation. As already done with the end towers, the driving matrix will be refined once the interferometer is available using global signals.

Plans on further actuation noise reduction are presented in sec. 4.5.2.

3.4 Electronics and software

The control loops involve three important items: Photodiode readout, Global control and Suspension control (running at 10 KHz). The control algorithms are mainly distributed between the Global Control *locking* process and the DSP involved on the control of the mirror. In order to add more flexibility on the locking strategies it is needed to reduce the current elapsed time used by these two processes.

3.4.1 Global Control

Some improvements have already done before the C7 run by sending more monitoring channels to the DAQ to allow some cross correlation between channels. This activity will continue during the shutdown period.

To decrease the Global control elapsed time some parallelism will be introduced between the data transfer to the DAQ and the computing of the corrections. Thank to the *RIO* CPU architecture it is possible to perform data transfer while computation is in progress. This should allow catching up the time needed to:

- Prepare the data to be sent to the DAQ
- Anticipate the computing of the digital filter as much as possible
- Load the on-fly parameters
- Perform the algorithms initialization

Until July 2005, the elapsed time tail was up to 98us for a locking cycle of 100us. Before C6 run some real-time protections have been installed into the Locking driver part, this reduces the elapsed time tail to 82us.

Today the mean elapsed time is around 62us when the *locking* server performs only the data transfers (to read the photodiode signals, to send the error correction to the Suspensions, to send the data to the DAQ), with the interferometer locking algorithms it is 72us. With the parallelism we expect to keep the same time 62us with the current locking algorithms.

The parallelism and the elapsed time tail reduction should allow performing more complex locking algorithms.

3.4.2 Automation and Detector Monitoring Software

Automation software

Since C5 run the automation has been put in operation. A dedicated software named ALP (Automation of Locking Procedure) has been developed to this purpose. The basic ALP concept is to use the data acquired by the DAQ and to compute, on a standard workstation, the state of any sub-system by processing the collected channels related to it. According to the subsystem state, actions can be performed using the system calls or directly with messages in VIRGO inter-processes communication protocol *Cm*.

Specific Alp servers are dedicated to each task (alignment, locking,…). These servers are able to take the ITF into a well defined state (see section 3.5). The configuration file of an Alp server contains several *macro*, each *macro* being dedicated to a specific task. The *macro* concept is used to define a set of code related to an automation step. A script language has been developed to define the *macro*'s content.

As stated in section 3.5 it will be needed to perform the automatic relock of the interferometer after an unlock. Some new facilities are therefore mandatory inside the *Alp*:

- A special macro (*Guardian*) should be defined and managed as a guardian: its aim will be to identify problems and execute recovery actions.
- The detection of no data received from a server since a given time (in case of the server crash for example) should be detected and launch a sequence of pre-defined actions on the interferometer.

Detector Monitoring software

Using the channels sent to the DAQ by each server, it is now possible to monitor the state of the any subsystem according the interferometer state. This new facility has been implemented through the Detector Monitoring system (the Moni library and the QcMoni software) and put in operation for the C6 run. A dedicated QcMoni server is configured for each subsystem whose purpose is to check the status of this subsystem: it checks if the channels received from the DAQ fulfill predefined criteria which can depend on the state of the interferometer. Using this information a web page reports periodically (each 5s) the status of the subsystems and also provides some help to the operator (via a link to a dedicated Web page) to improve the subsystem state according to the reported failure.

To use QcMoni as a centralized system it should report not only the status of a subsystem but also the state of the servers involved into the subsystem. To this purpose the following developments will be needed:

- All the servers involved into the interferometer control should at least send one channel to the *DAQ* to report about their activities.
- The DAQ subsystem should be monitored. The front-end DAQ servers can directly add some channels to the stream to reports about its activities. For the back-end DAQ servers the state can be available by periodically asking the state for the servers by on front-end server.

Two other tools complementary to QcMoni had also been developed before (BigBrother for the monitoring of CPUs, disk space,…, and the ErrorLogger for the actions performed by servers). The possible improvements for these servers and their interaction with QcMoni are described in section 3.5.4.

Data streams

The figure below shows the current data flow architecture, the data sent by the front-end servers are received by the purple elements. The automation can access all the data stream and supplement it with the interferometer state. It then forwards the stream to the detector monitoring (in yellow) and for storage (in white).

Using the status of a subsystem computed by the detector monitoring facility, it is foreseen to add a failure recovering system, based on *ALP*, to complete the automation.

3.4.3 New electronic logbook

The electronic LogBook currently in use for Virgo is being considered no more fitting the users needs. The Collaboration has presented a list of requests mainly underlying the technological obsolescence of the tool. The development of the new LogBook will have improved features, taking into account all the requests, the main ones are briefly listed in the following:

1. Possibility to carry out the logbook's searches in more complex way, making use of a greater number of various parameters and granularity on the time intervals.
2. Deeply reorganization of the logbook database area, without loosing any data that is already stored in the database.
3. Possibility to open in read only mode some logbook's web pages. This imply to build some discrimination procedures which will decide which page must be visible or not;
4. Possibility to insert some graphic templates for a quicker data insert and for having a common look and feel of similar logbook's entries.
5. Possibility to specify also an author's working group and distinguish them quickly with help of colours or some symbols.
6. Capacity to support more graphical file formats in attachment.
7. The LogBook interface should include the tool made available that is used by shift coordinator to provide statistic on Interferometer down time
8. The contents of the LogBook main page (for example the number of the last entries presented) should be easily configurable and provide the potential to add new sections.
9. The tool should run seamlessly on all new generation web browsers
10. The Graphic attachment preview window should be correctly displayed;
11. The LogBook should provide the user with the potential to join email groups of their choosing. When a new entry is made in a group to which they have enlisted, they should automatically receive an email telling them so.
12. The LogBook should be accessible read-only by default, the account login should be requested only when starting a "add new entry" action
13. The LogBook interface should include the tool made available that is used to track the locking status of the interferometer, named 'Online Locking Monitor.

Decision was to be made between the FermiLab tool CLRW and a custom development. The collaboration opted to a custom development for the following reasons:

2. Some change requests were already identified for the CRLW and even if FermiLab response on joint development was positive the fear is that implementing modifications coming from the Collaboration would be difficult to manage

3. The technology on wich the custom development will be based (PHP language) is already supported in Cascina for other Virgo applications and is the one that is used for the new Virgo web pages. Converging to this techology is then convenient also on support and maintenance point of view.

4. Custom development would avoid the problem of current database porting to CRLW considered too demanding.

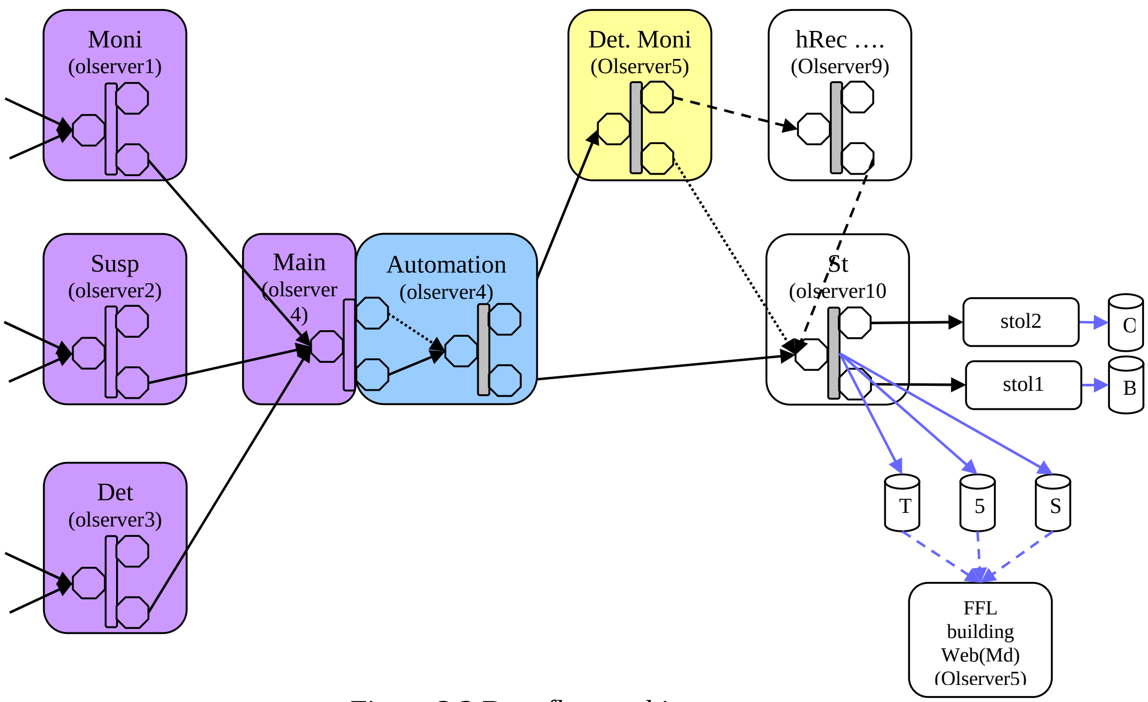


Figure 3.2 Data flow architecture

3.5 Detector operation

The Detector Operation (DO) activity covers the following items:

1 - Training of operators
2 - Organization of procedures to operate the interferometer
3 - Automation
4 - Detector Monitoring

All of these activities are performed together with the operators, when possible, and with the collaboration of the various sub-system experts. The latter two activities are pursued with a particularly close collaboration with people involved in Electronic and Software activity.
In the following, a brief description and planning of each item is provided.

3.5.1 Training of operators

Operators are provided by the EGO interferometer Operation Department. Currently, the operators team consists of six people (including a new person that joined EGO mid September 2005). Shift activity covers 15 hours, from 8:00 AM to 11:00 PM, 8 hours each shift (one hour overlap during the daily meeting). The operators are trained by providing them with procedures to operate the detector and by organizing training events. These events consist of training sessions and demonstrations. A series of training sessions, in addition to the ones held before each run are periodically performed and held by the experts of the related fields. The demonstrations are performed in case of new procedures and take place in the control room and also in the related labs, when there are instructions concerning the hardware. In the case of new operators, a dedicated training program is organized. A new series of training sessions is foreseen for the next months, starting before the interferometer restart, particularly because as the operators are free from shifts, all of them can attend the session at the same time.

Since the new organization of the commissioning/operation foresees, during the runs, a shift team consisting only of an operator and an interferometer expert or science monitor, the role of the operator requires increased competencies. The operator will be expected to provide a first level intervention in case of problems with the detector operation, while, in case of the more complex problems, it will remain necessary to contact the on-call expert. Additionally, the operator will be required to undertake a series of characterization measurements on request (i.e. transfer functions, demodulation phase, etc.), up to now routinely performed by experts. To this end the operators training program will be at a higher technical level and will also illustrate the basic physical concepts of the system. The structure of the shift schedule will remain the same.

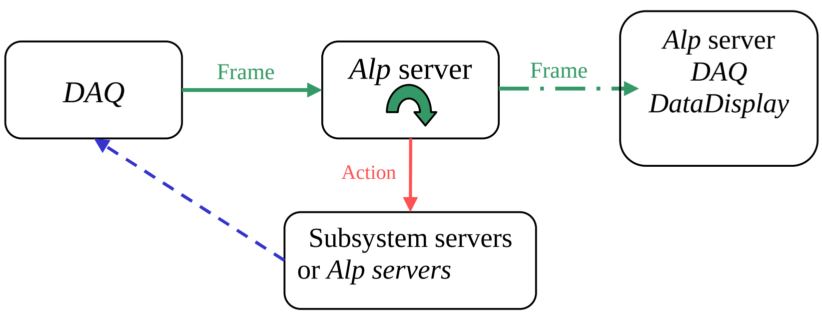
3.5.2 Procedures

The procedures to operate the various sub-systems are provided by the sub-system managers, while the general procedure to operate the whole interferometer and the procedure for the runs are provided by the DO, with the collaboration of the various experts. From time to time the authors of the procedures are invited to update the procedures and to adopt the provided HTML template. Comments and observations are sent to the authors, when needed. The updating process is usually boosted before each commissioning run. Additionally, a new log-book task, titled ‘Procedures Update’, has been introduced to allow authors and experts to enter procedure news that is not yet inserted in the periodic update.

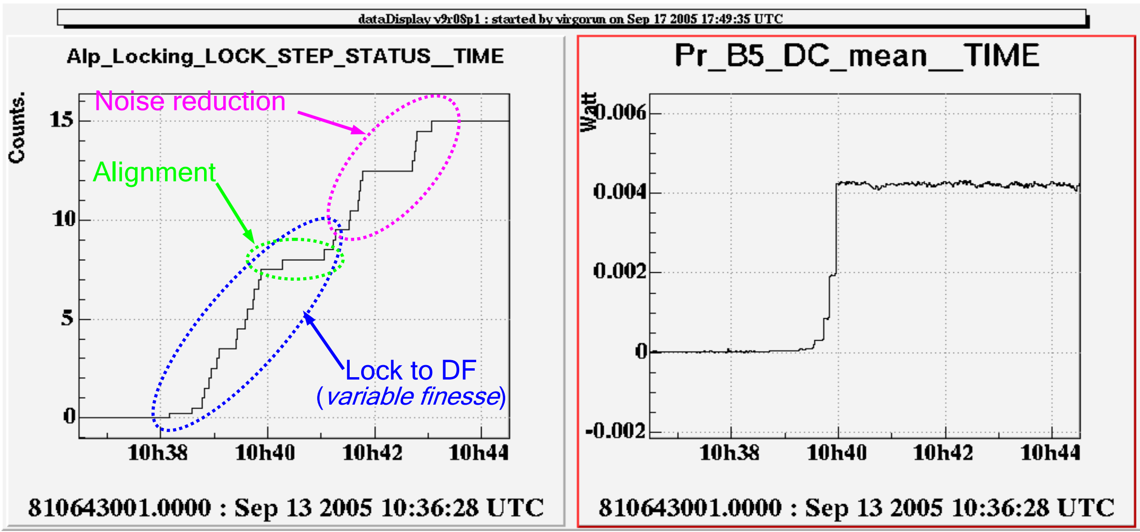
It is planned to enhance the procedure content by including also sections for troubleshooting and for routine measurements. At present the procedures information appears to be under-utilized, probably because of the current updating and consultation mechanisms. Consequently, an overhaul of the means to consult and update the procedures is intended. A possibility is a web based-system involving the transition of procedures into a database, to improve the functionality of the system.

3.5.3 Automation

The interferometer is brought to the working conditions by steering the mirrors into position and orientation by following a complex procedure. This procedure, relying on hundreds of commands sent to several real-time processors and on many checks, has been automated by using a purposely-developed software: ALP (Automation of Locking Procedure). The basic ALP concept (a simplified architecture scheme is shown in the figure below) is to use the data acquired by the DAQ and to compute, on a standard workstation, the state of any sub-system by processing the collected channels related to it. According to the subsystem state, actions can be performed using the system calls or directly with messages in VIRGO inter-processes communication protocol *Cm*.



The *macro* concept is used to define a set of code related to the same automation step and a script language to define the macro's content. Several macros have been implemented to perform the Pre-alignment and the Alignment/Locking sequences. This has eliminated the risk of human error and allowed for a short recovery time following an unlock, thus simplifying considerably the daily commissioning activities, where unlocking/relocking the ITF is often required. Automation has also been an important element in achieving the very high duty-cycle during the last two commissioning runs (C6 and C7). The typical time required for procedure execution has been in the range of 3-10 minutes (an example of which can be seen in figure below). The performance obtained by the automation during the last months of commissioning and, in particular, during C6 and C7 runs has been very satisfactory.



The next planned improvements are:

- *ALP fast*: the aim is to reduce as much as possible the overall execution time of the pre-alignment and alignment/locking sequences. The achievement of this is based on the optimization of the procedure (sleep time and sequence) and on the possibility to execute, where possible, actions in parallel, relying on the several available Alp servers. A deeper analysis, undertaken in close collaboration with the relevant experts, is needed to assess which parts of the sequence could be shrunk and/or executed in parallel. The reduction in execution time, expected to be of about a factor of two, will further decrease downtime during the commissioning and noise hunting phases.

- *Automated re-locking* (failure identification, safety actions and recovery included): this feature is essential to fulfill the requirement, detailed in the general plan (§ 1.2), of maintaining the detector in locked state, also outside normal shift times. In this way, data taking during the night and the weekend is enabled, while the commissioning goes on during the day. It is already possible to leave the ITF locked without any operator in the control room: when the ITF unlocks AlpRecycled performs a set of safety/initialization actions but does not try to relock the ITF.

Once left locked at the end of the shift, in the case of an unlock during the night or the weekend, ALP should manage the situation by acting in the following ways:

i) attempt to perform a set of pre-defined safety actions, mainly aimed at preventing further excitation or misalignment of the mirrors;
ii) identify whether the source of the unlock is due to a problem related to a particular sub-system process - typically a server crash or a server not responding. In this case, ALP attempts to restore the process;
iii) complete the safety actions of phase i) in case the completion of phase ii) was impossible due to a process problem;
iv) try to relock the interferometer, performing the pre-alignment and alignment/locking sequences.

Currently, in the case of a server crashing while the ALP process is being performed, ALP continues to try to send commands to the server, as the ALP commands do not include the possibility to know if a server has crashed. Consequently, execution of the ALP macro is blocked, leaving the detector in an intermediate state, with some intrinsic risk. Similarly, macro execution is blocked in the case of ALP trying to ask for the content of a missing channel. In addition, it is not always possible to have an acknowledgement of a command sent by the AlpRecycled server (acting as master) to other sub-system servers (including also other Alp servers, acting as slaves). As a consequence, it can sometimes occur that, when a requested command is not successfully executed, AlpRecycled does not realize and erroneously continues to execute the sequence. The implementation of an AlpGuardian server has started: this guardian is able to detect some of the problems mentioned above and to execute some security actions in order to put the system in a safe state.

To implement further improvements it will be necessary to act directly upon the ALP configuration files and also, as importantly, to add new commands (for instance: check if a server is alive, start server, etc) and features to ALP. To obtain a greater level of security there exists the potential to interface ALP with a complementary system, the EGO Global Security System to automatically contact on-call people in the case of an ALP-irresolvable problem occurring outside normal shift times.

- *Web interfaces for automatic logging of alignment/locking events* (upgrade of the existing 'Online Locking Monitor'): The Online Locking Monitor records events as they occur on the detector. This system is updated by ALP on the occurrence of any one of a series of alignment and locking events considered important for data-analysis and commissioning people (history of locking periods, related events, etc.). The information, relating to time, event type and duration, is displayed directly on a web-browsable HTML page.

The next version will be based on PHP technology, with info recorded in a MySQL database. It will provide the possibility to query over user-specified periods of time or by specific ALP events. Additionally, it will supply the means to 'sort' data in a manner determined by the user (e.g. date order, lock length etc.). The new system also removes the requirement to archive data, as is the case with the current system. The possible integration with the new logbook has to be studied.

3.5.4 Detector monitoring

In any complex and sophisticated apparatus (scientific or industrial), an online status-monitoring system is fundamental to the assessment of proper operation and the provision of alert in case of potentially dangerous malfunction. It is also a key tool for the work of operators.

The work performed during the last year on this item has focused mainly on the part least covered, that is the development and configuration of the monitoring of the interferometer via DAQ channels produced by each sub-system. To this end, a dedicated tool has been developed (the Moni library and the QcMoni software) and its configuration has been largely completed. The criteria used in QcMoni are dynamical: they can depend on the locking/alignment state if needed.

The current state of the detector monitoring system is:

i) three softwares are used for monitoring (BigBrother, ErrorLogger, QcMoni), each one focusing on specific areas of detector operation: BigBrother monitors the Daemons, the CPUs, disk space, etc..., the ErrorLogger monitors the actions performed by servers and QcMoni monitors the interferometer's status. The absence of one centralized monitor makes the following of all three softwares less straightforward and scatters the attention of the operators;
ii) the existing softwares are not completely configured: for instance not all the servers are declared to the ErrorLogger and all the subsystems are not yet fully monitored by QcMoni;
iii) a more efficient warning/alarm notification of the events should be implemented. Indeed, besides the display on the screen, it is also important to have other possibilities like a sound alarm or a message to ALP, depending on the event level and the recovering action required. The possibility to send a sms to on-call persons or an e-mail to concerned experts can also be envisaged;
iv) an hyperlink from event to recovery procedure is now available in QcMoni. This feature is not yet available in the other tools.

The proposed plan on the Detector Monitoring system concerns the following aspects:
i) implementation in BigBrother and ErrorLogger of the feature needed to export their generated information to QcMoni or development of a single tool based on the existing tools features. The first choice is currently an efficient way to provide rapidly a single monitoring interface to the operators.
ii) implementation of the missing features where necessary: event notification, hyperlink to procedures, …;
iii) completion of the configuration files containing alarms criteria for the relevant interferometer's channels, servers, processes, CPUs, etc… In the more complex cases, the criteria definition will be done with contribution of the experts. ;
ii) implementation of the missing features (event notification, hyperlink to procedures, etc.);
iii).configuration files containing quality criteria for relevant channels, servers, processes, CPUs, etc. In the more complex cases, the criteria definition will be done with the contribution of experts. For those sub-systems that have a working state depending of the step of the alignment/locking sequence, the criteria will be also dynamic, accordingly to the reached step.

3.6 Environmental noise

Although the VIRGO interferometer was designed to be in principle immune from local perturbations the effective implementation of the detector provides many ways for coupling to the dark fringe signal. One has to consider direct coupling to the test masses, coupling with the optical set up and light beams and at the electronics and read out level.

3.6.1 Coupling with test masses

Seismic isolation has been demonstrated to work effectively in the sensitivity band by performing a transfer function measurement from the top of the superattenuator to the mirror. This should be repeated with the improved sensitivity at low frequency and checking also the effect of rotations and tilts. At very low frequency the superattenuator transmits ground motion, which appears in the correction signals send to the marionetta and mirror. This motion come from Earth crust tide expansion, seism, including anthropic one, sea and wind. Upconversion, noise dependence have to be verified.
Mirrors are sensitive to magnetic field fluctuations although this can be largely reduced by proper magnet balancing during assembly. The effect of magnetic field fluctuations that may come from the power line, from local magnetic field sources or from electromagnetic perturbations (e.g. lightnings) has to be understood for the discussion of veto application to candidate events.

Finally, local gravity fluctuations are expected to be at the edge of nominal sensitivity but this has to be properly verified.

3.6.2 Coupling with the optical setup

Where light beams are not in vacuum they are exposed to local noise. Vibration, sound and slow pressure variation move benches and mirrors on them producing jitter in beam angle and phase that propagate into the interferometer. This may also induce a fluctuating response from the detection photodiodes. Sources of noise are all the motor driven mechanical devices present near the experiment: air conditioning, vacuum pumps, electronics cooling. Pressure fluctuations come from conditioned air flow and wind. Vibrations come from those same devices but also from increased seismic activity, including possible wind farms.
Temperature cause beam position drifts that show up in noise level variations. Additional effects come from spurious beams and diffused light that may interfere with the main beam, reintroducing noise.

Beam clipping is also a source of noise that must be searched for. This study has to be done in the detection lab and in the end buildings where the linear alignment benches sit.

Finally the level of coupling of the main beam tube with the interferometer by diffused light must be verified.

3.6.3 Coupling with the electronics and readout

The problem of electromagnetic interference is difficult and dedicated effort is needed. A careful verification of principles of e.m. immunity has to be completed. This includes appropriate cabling practices, ground loop avoidance, differential signal transmission where needed. The primary source is the 50 Hz power line that brings in harmonics up to the kHz. Magnetic field and radiofrequency electromagnetic field may also enter the analog sections of the readout and another source are the low voltage switching power supplies used for auxiliary purposes. Sensitive portions of the electronics should be checked for crosstalk and microphony effects. Finally the effect of ambient temperature on circuits has to be monitored.

3.6.4 Items to be studied to characterize couplings to the test masses

This is the current list of test mass couplings, either direct or through their suspension. For each of these effects a dedicated study of the influence of the dark fringe. This may take a long period of time as several effects are at low frequency and sometimes the noise source is not under control. Although a significant amount of work has already been performed this has to be continued with the interferometer gaining in sensitivity and stability. A rough estimate for this analysis is one man-year, not including the support software for data analysis and information storage, like data base access. Here is a list of items, in rough priority order:

1. Wind: data in presence and absence of wind are available and influence on the noise level has been studied. This results in further improvements in superattenuator control, in particular increasing the gain at low frequency of the top stage feedback loops.
2. Seism: the effect ground vibration have been studied showing that they appear at low frequency, well below the sensitivity band of Virgo.
3. Thunder: events with nearby thunders are available and need to be further studied
4. Lightning: there are many lighting events seen by the magnetometers and by a lightning detector placed on the roof of the central building. Only a preliminary analysis has been performed.
5. 50 Hz: the mains line is present in many channels, including the dark fringe. There is a variety of paths through which this noise can enter and they need to be investigated in a common noise reduction effort that includes not only coupling to the test masses but also electronics, optical setup.
6. Magnetic field: a detailed test has been performed in these months by generating a magnetic field near a test mass. A transfer function form the field to the test mass has been estimated and the effect of ambient magnetic field computed. This was done on a mirror that has magnets mounted in a way to be particularly sensitive to magnetic field. Tests will be repeated for other mirrors that were built in a way to be more immune to this effect.
7. Tide: a careful study of tide is going on, the last effects seen are the necessity for tide correction in the BS tower and in the mode cleaner.
8. Newtonian: this is in principle a well known noise but it can be detected only when Virgo achieves the design sensitivity at low frequency. The priority of this study is obviously rather low. Correlation of seismometers with the dark fringe will be used as a signature. Further measurements of ground motion outside the buildings should also show correlation with the dark fringe.

3.6.5 Items to be studied to characterize coupling to the optical benches

A dominant path for environmental effects to enter the interferometer is through the optical benches. There again work has been done but increased sensitivity and stability will uncover new effects. The following main sources are being investigated:

1. Pressure
    a. Air conditioning
    b. Wind
2. Sound
    a. Pumps
    b. Electronic racks
3. Vibration
    a. Pumps

b. Machinery

These have already been studied in some detail through dedicated runs where acoustic noise has been injected. As the interferometer performance improved these tests were repeated and for instance the effect of power stabilization downstream the mode cleaner were clearly seen. Also the action of acoustic noise on the detection bench was clearly seen in tests where the vacuum turbomolecular pumps were switched off. It is foreseen to have dedicated shakers on the benches to be able to introduce vibration artificially and measure interferometer immunity to these effects. Acoustic coupling was also found on the end benches, and was tracked to the presence of stray light hitting some bench cover. Stepping motors for quadrant centering were also found to introduce noise when in action.

Temperature and humidity have been found to have an influence on the long term behaviour of the injection system. This could be due to drifts in laser lab bench position. It is expected that after the changes in the laser laboratory an improvement is seen but this will have to be verified with long term data.

3.6.6 Noise entering through the Vacuum chamber

At some moment the effect of diffused light in the beam tube has to be verified. A few dedicated tests are needed with hammering at different places in both arms with the interferometer locked. A first round of tests could be done rather soon. The following tests have to be foreseen:

1. Hammering on towers
2. Hammering on beam tube

The first test is likely to give coupling that are being addressed in the other noise reduction tasks. The second test should give negative results but this has to be verified.

3.6.7 Analog Electronics

The electronic circuits have undergone careful testing in the laboratory and on field. However their behaviour has to be verified on field under real conditions. Also the analysis capabilities are different using a large amount of data rather than online instruments in the lab. It is therefore suggested that the following points should be addressed using a combination of recorded data and triggered oscilloscopes when necessary. Here is a list of subjects that have to be studied:

1. 50 Hz line
2. Pulses
3. Surges (Air Conditioning machinery, pumps, motors)
4. Switching power supplies
5. Direct magnetic field coupling with electronics (e.g. mixers)
6. Ground loops
7. EM coupling (TV screen / Computer monitor sweep, Coupling at the various modulation frequencies)
8. Temperature behavior

Some of these studies overlap with what has to be done about test mass couplings.

3.6.8 Digital Electronics

In this case also electronic circuits have undergone careful testing in the laboratory and on field. However performance has to be verified and published to certify the good performance of the detector. The following items should be addressed:

1. Analog to digital conversion: analog filtering, ADC noise, linearity, time jitter, frequency response, calibration
2. Digital signal processing: digital filter approximation, arithmetic noise
3. Digital to analog conversion: DAC noise, linearity, antialiasing filters

Digital signal processing is made in many different places so that task 2 is relevant for DSP but also for code in general purpose computers.

3.6.9 Software

Although this point is a data analysis concern, it is felt that the performance and monitoring of the interferometer needs appropriate software tools and information management tools. This is justified simply thinking of the number of environmental channels that are read out, the broad frequency band in which they operate and finally the fact that months if not years of data will be stored on disk. Effort has obviously started long ago within the data analysis groups and several tools, like the quality monitor, are becoming available, with their performance improving. The collected information is however managed in a very primitive way, like lines list, trend data for rms values. A strong effort has to be put on:

1. Data analysis for coherences, glitches, lines, continuing what has already been done and repeating it over all channels
2. Designing a data model to manage the information we collect about noise in our data. This should allow to:
    a. Store a log of glitches in all channels
    b. Store noise levels in various frequency bands as function of time and channel
    c. Store level of known resonances, including following their frequency
    d. Allow interactive access as well as application access for further studies at least according to time, frequency band.
3. Implement the data model into a database management system

3.7 Optical characterization

3.7.1 Status

Most of the optical characteristics of the interferometer have already been measured. Table 1 gives the measured values of these parameters. The finesse of the Fabry-Perot cavities are as expected from the mirror reflectivities. The recycling gain of the carrier is smaller than the design value but is in agreement with the simulation prediction (NV) taking into account the measured maps of the mirrors: the smaller gain is due to losses inside the Fabry-Perot cavities due to mirror defects. The recycling gain and the transmission of the sidebands are smaller than expected in this simulation, this still has to be understood. The contrast defect is good and allows to work with a relatively small modulation index (~0.2-0.3). The common mode rejection ratio is as expected from the asymmetry of losses of the two arms predicted by simulation.

Table 2 gives the measured values of the IMC optical parameters. The finesse and radius of curvature are as expected. The losses are deduced from the decay time measurement and are about 10 times larger than the expected value deduced from a simulation including the real mirror maps. These losses can be due to dust or scatter from local defects on the mirrors.

Parameter	F	R_{00}	$R_{SB(00)}$	T_{SB}	1-C	CMRR	L_{rec}	ΔL	M	m
Measurement	50	33	20	0.13	3.10^{-5}	$3\text{-}510^{-3}$	12.07	0.844	93%	0.3
Design	50	50	36	0.4	$<10^{-4}$		12.07	0.85	100%	

Table 1: *Measured values of the ITF optical properties: finesse (F), recycling gain of the carrier TEM00 (R_{00}) and of the sidebands ($R_{SB,00}$) for the TEM00 mode, transmission of the sidebands (T_{SB}), contrast defect (1-C), common mode rejection ratio above 1 kHz (CMRR), recycling length (L_{rec}) and small Michelson asymmetry (ΔL) in meters, the input beam matching (M) and the modulation index (m). The design values are also given for comparison.*

Parameter	F	L (m)	R (m)	P	M	T_{IMC} (TEM00)
Measurement	1100	143.573	182	850 ppm	83%	73%
Design/expected	1000	143	180	115 ppm	100%	95%

Table 2: *Measured values of the IMC optical properties: finesse (F), length of the cavity (L), radius of curvature of the MC mirror (R), round trip losses (p), matching of the input beam (M) and the IMC transmission(T_{IMC}) for TEM00 deduced from the measurement of losses.*

Some of these properties will change with the new injection bench and the new power recycling mirror, therefore these quantities (recycling gain, beam matching,…) will have to be re-measured. The value of some of the measured quantities still need to be understood: this investigation should be carried on with a realistic simulation (NV). New investigations will also be done in order to understand if thermal compensation is needed and what is needed.

3.7.2 Measurement of the new optical characteristics of the interferometer

After the new input bench installation the new telescope will be tuned in order to obtain a beam which matches as well as possible the beam which resonates into the Fabry-Perot cavities. The size and position of the beam waist will be determined. The matching of the beam incident on the IMC will also be improved with a better alignment. Losses on the laser bench will also be investigated and possibly reduced in order to recover part of the power lost (now 25% is lost) between the laser and the IMC.

Once the input beam is matched to the cavities the output beam has to be matched to the output mode cleaner with the tuning of the output bench telescope.

The power incident on the ITF is measured by a photodiode receiving few per mille of the total power. It will be cross checked from the measurement of the power before the IMC combined with the measurement of the IMC losses and also from the power measured at the ITF output ports in simple configurations.

Since the PR mirror is also replaced its reflectivity will be cross-checked with data taken in the CITF configuration .

Then the recycling gains of the carrier and sidebands will be measured comparing the powers in the recombined and in the recycled configurations.

Measurements of the optical transfer functions using frequency noise will also be performed: transfer functions of the single cavities and of the full interferometer. This should allow to extract the pole of the Fabry-Perot cavities, the Anderson frequencies, the optical length of the arms, the pole of the double cavity and possibly the recycling gain of the sidebands.

3.7.3 Measurement and improvement of the common mode rejection ratio (CMRR)

As pointed out in section 4.1 the frequency noise might limit the sensitivity at high frequency. The contribution of the frequency noise to the dark fringe is proportional to the common mode rejection ratio (CMRR). Since the frequency noise will be limited by B5 shot noise which cannot be simply improved, the CMRR will have to be improved. A measurement of the CMRR will be done with frequency lines. At high frequencies the CMRR mainly depends on the arm loss asymmetry and on the quality of the alignment. The linear alignment should therefore be tuned in order to obtain the best rejection of the common mode noise and possibly reduce the loss asymmetry. An improvement by a factor 3 or 4 with respect to now is needed.

At lowest frequencies (below few hundred Hz) the finesse asymmetry also contributes to the CMRR. Thanks to the small Fabry-Perot effect in the flat-flat input mirrors the finesse of one arm varies with the thickness (i.e. the temperature) of the input mirror. Therefore it can in principle be tuned in order to match the finesse of the second arm and improve the CMRR (at low frequencies). This effect has not yet been observed in VIRGO. A measurement of this effect is proposed in order to quantify it. A temperature control of one of the two input towers should then be commissioned if needed.

3.7.4 Preparation for thermal compensation

The amplitude and the shape of the carrier and the sidebands will be measured independently to check if a thermal compensation is needed in order to correct the shape of the sidebands and obtain a better superposition of the sidebands and of the carrier.A scanning Fabry-Perot will first be used in order to measure the amplitude of each sideband. A phase camera (to be developed) will then be used to measure the shapes.

4. Commissioning Planning

4.1 Overview

A global planning for the VIRGO commissioning is presented here. The overview of the main steps is given. Details are given in the following sections.
As already explained, the first step is the commissioning of the new injection bench (section 4.2).

Once the beam is again available, the interferometer is restarted (section 4.3). When the interferometer is fully relocked, problems connected with the higher power stored (diffused light, thermal effects, saturations,…) can show up. If no major problems arises, a first sensitivity curve can be measured.

The following step is to complete the recycled interferometer commissioning (the phase C of the commissioning global strategy, described in section 1.2). During this phase all the control systems will be put in operation. When necessary, improvements in the control strategies will be done.

After this period a commissioning run (C8) of 1-2 weeks can be performed for detector characterization and data analysis purposes.

Once all the control systems are operating, the noise hunting (4.6) can start with a full efficiency.

We expect to have significant improvement of the sensitivity after 4 months of noise hunting. A tentative goal for this phase is to reach an horizon *(1)* for NS-NS inspirals 10 times greater than the one obtained for C7.

The curve of the figure 4.1 shows the horizon distance vs the lower frequency cut-off of the signal used. This plot shows that the SNR is accumulated mainly for frequencies above 50 Hz. Noise hunting connected with high and middle frequency regions (>50 Hz) will be then the priority of this first phase. This not excludes efforts and progress in the low frequency part of the spectrum (10 Hz –50Hz).

Figure 1 contains 2 curves: the solid one is computed using the Virgo design sensitivity (showed in section 1), the dotted one is computed including in the Virgo noise budget the effect of the Eddy currents in the recoil mass. Details of this effect can be found the advanced Virgo white paper. We should mention that at present, the uncertainties in the model of the Eddy currents are large, but this effect can prevent to reach the Virgo design sensitivity.

The problem of the Eddy current can be mitigated or even eliminated, maintaining the current aluminium reference mass, but reducing the magnets strength.This needs to relax the requirements on the force needed to acquire the locking. Obviously to dismount the payload will be a large time consuming activity and a lower impact solution must be found. This can be effectively done in situ or replacing the magnets or shielding the magnetic field through a metallic hat applied directly on the magnet. The second solution is preferable since it is considered cleaner.

(1) The "horizon" is the distance at which a NS-NS 1.4-1.4 solar masses, optimally oriented with respect to the detector, causes a signal having an SNR=8

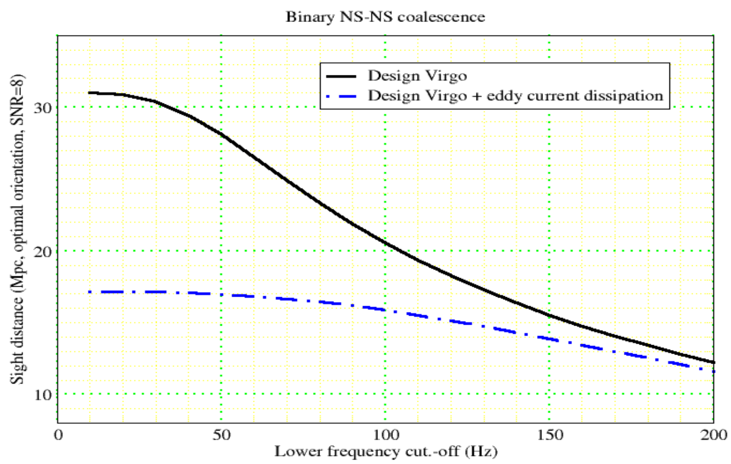


Fig 4.1 Horizon for NS-NS inspirals (in Mpc) vs lower frequency cut-off (in Hz) for the 2 configurations of Virgo design and Virgo design + eddy current dissipation

This first phase of noise hunting (noise hunting I) will be followed by a commissioning run (C9) and a long science run (science run I).

Evidences have been found of diffused light on the beam splitter. This can give extra noises that can prevent to reach the proposed sensitivity goals or make difficult the commissioning activity. The production of a larger beam splitter is already planned. A commissioning stop (shutdown II) to replace the present beam splitter is inserted in the planning after the first science run. At the same time other hardware improvements can be done, as the replacement of the mode-cleaner mirror in order to increase the mode-cleaner transmission and then the power stored in the interferometer.

Data collected during C6 shows acoustic noise coupling in to the dark fringe. This effect has been temporary reduced by switching off part of the pumping system. As the sensitivity is improved, this effect can become more and more evident and may will require performant acoustic isolation. This upgrades can be done during this shutdown, if is not already implemented in 2006.

.A second noise hunting period (noise hunting II) is planned after this shutdown. During that period we will solve problems found to reach the sensitivity goals in the central and high frequency region and we will move the efforts more and more on the reduction of the low frequency noises (<50 Hz).

A commissioning run of 1-2 weeks and a second science run (science run II) are planned after this period.

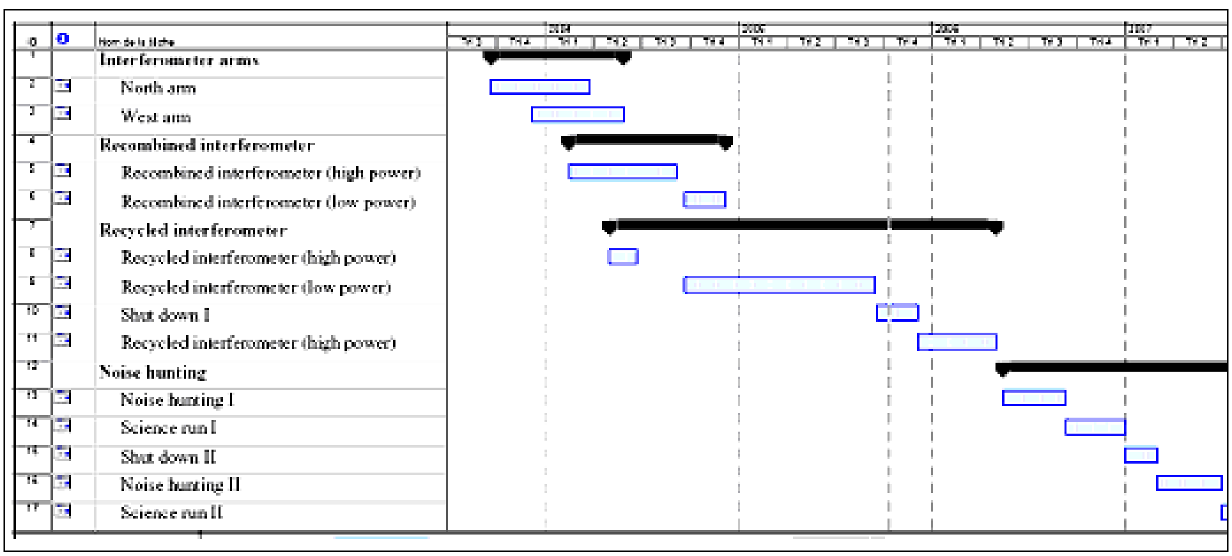
To summarize, the overview of the commissioning planning, with rough estimate of the time needed is the following:

Now: shutdown I (ends beginning of December 2005)

Injection bench commissioning: *1 month*
Interferometer restart: *1month*
Completion of the recycled interferometer commissioning: *3 months*
Commissioning run C8: *1-2 weeks*
Noise hunting I: *4 months*
Commissioning run C9: *1-2 weeks*
Science Run I: *3.5 months*
Shutdown II: *2 months*
Noise hunting II: *4 months*
Commissioning run C10:1-2 weeks
Science run II

The time estimate is an extrapolation of the same tasks already performed during previous steps of the Virgo commissioning, assuming no major problems

Figure 4.2 resumes the Virgo planning, from its beginning to the science run II.



The following chapters give details on each activity. *The 2007 part of the planning is very preliminary.*

4.2 Injection bench commissioning

The injection bench commissioning is detailed here. At the end of this phase a beam will be sent inside the interferometer with good alignment and frequency stability to start the re-locking of the interferometer.

Task sheets for the restart for the injection bench commissioning and the injection system restart are in **appendix A**. The time expected to complete this task is about 1 month.

a) Injection bench local control restart

The injection bench is locally controlled in 6 degrees of freedom, through a CCD camera read out (coarse sensing) and laser optical levers. This sensing system is not changed, and problems for the restart of the local controls are not expected.

Error signals from these two devices are extracted, a reconstruction of the bench position is performed, and the reconstructed degrees of freedom are sent in feedback after suitable filtering. The electronics and signal processing are the same of the ones used for the old bench.

In order to make a correct filter design, a careful re-measurement of the injection bench transfer function is needed. The mechanical and geometrical properties of the new bench in the range of frequencies important for the local controls are not different from the ones of the old bench. This should make easy the filter design and the overall control. Few changes in the current filter design strategy are expected.

After the filter design, the controls are closed, the closed loop performances are measured and compared with the specifications.

b) Mode-Cleaner frequency lock

Once the injection bench is controlled, the mode-cleaner can be aligned. The optical properties of the mode-cleaner (finesse, losses,…) are determined by the dihedron, no changes are expected.

The mode-cleaner is then locked, acting on the laser frequency, through the dedicated electronics. The electronics for the mode-cleaner lock has not changed and no problems are expected.

c) Mode-cleaner automatic alignment

The following step is to automatically align the mode-cleaner, using quadrant photodiodes placed on the mode-cleaner reflected beam. The present scheme of automatic alignment uses only one photodiode and acts on the mode-cleaner curved mirror. This scheme will be changed in the futures (see the planning for alignment activities), but not during this phase.

The optical properties related with automatic alignment of the mode-cleaner (distances between high order modes and finesse) are not changed, and the error signals are expected to be the same as before.

The mode-cleaner transfer functions are also not changed, and the old automatic alignment filter design can be used.

When the automatic-alignment loops are closed, the performances are measured and compared with the specifications.

Once the mode-cleaner is automatically aligned, the beam transmitted can be aligned with respect to the interferometer.

d) Reference cavity lock

In order to have an enough frequency RMS stability of the mode-cleaner out-coming beam and re-start to control the 3km cavities, the mode-cleaner mirror position should be locked with respect to the reference cavity.

Up to know the reference cavity error signal was produced picking-off a small fraction of the laser beam incoming in the mode-cleaner. In the new input bench configuration the reference cavity receives a fraction of the beam transmitted by the mode-cleaner. That beam is frequency and spatially filtered by the mode-cleaner cavity, and in particular is frequency filtered at the pole of the mode-cleaner cavity (500 Hz). This feature should be taken in account in the reference cavity filter design.

4.3 Interferometer restart

The goal of this task is to realign the interferometer and to re-start the main control systems, in order to measure a new sensitivity curve. The main issue of this task is to ensure that no problems are given by the increase of the power to 8W, and by the control of the new power recycling mirror.

The task sheets for the interferometer restart are in **appendix B**. The time expected to complete the interferometer restart is about 1 month

a) Interferometer realignment

Once a stable beam is available (after the mode-cleaner automatic alignment), it can be realigned. The mirrors on the bench and the bench itself will be steered until the beam will be transmitted at the interferometer output (centered in the photodiodes of the detection external bench). Then, with small adjustment, it should be possible to center the beam at the end of the north arm. During this phase, advantage is taken from the fact that the interferometer is close to the correct alignment position (references of the last alignment position before the shutdown are stored).

b) Matching

The mode matching consists in adjusting the input telescope in order to match the mode parameters of the input beam (waist size, distance to waist) to the long arms' cavity eigenmodes (radius of curvature of the mirrors of the cavity, length of the cavity).

This action can be performed by finely adjusting the positions of the 2 parabolic mirrors (old input telescope consisted of 3 elements: 2 spherical mirrors and one lens, the PR mirror). Each mirrors is equipped with 3 closed-loop picomotors. Besides, the mounting of the first mirror is fixed on a bi-directional translation stage.

The input bench telescope has been designed to, both, match the input beam to the cavities and minimize the aberrations introduced by the telescope itself. Actually, using parabolic mirrors should allow to reach a perfect matching; spherical aberrations and astigmatism should be negligible (astigmatism was limiting the matching performances to 95% of the power coupled into the TEM00 mode for the old input telescope).

c) Photodiodes

After the change of the injection bench all the photodiodes, except B2 (see below), will receive about 10 times more power than now. It is therefore needed to adapt the electronic gains as well as, in some cases the optical setups. Each beam is splitted on at least 2 photodiodes, the fraction impinging on each photodiode varying between 1% to 50% depending on the needs as discussed in the following. The error signals used to control the interferometer in the final step are B2_3f_ACp, B5_ACp, B5_ACq and B1_ACp. Since the noise of these photodiodes might propagate to the sensitivity via the control loops, care is taken in order to minimize the impact of shot noise and electronic noise.

B2 photodiodes

Due to the high transmission of the M6 mirror of the old injection bench (90%) B2 received a large fraction of the light reflected by the interferometer and about 100 mWatts are already impinging on the photodiodes. This power cannot be increased without damaging the photodiode therefore a large fraction of the beam reflected by the Faraday isolator will be dumped before being sent to B2. The power on B2 photodiodes will therefore remain of the same order of magnitude (around 100 mW). Therefore the electronic of these photodiodes will not be modified. In these conditions the shot noise will dominate the electronic noise for both B2_3f and B2.

B1 photodiodes

In order to keep the impact of electronic noise as small as possible and since once the lock is acquired the signal is small enough (there will be 50mW on DC and few mW on AC channels), only one photodiode should be used on B1. However, during the transition from B1p to B1 the error signal (B1_ACp) will saturate. It is therefore foreseen to use two photodiodes on B1: B1_d1 will receive 1% of the beam and will be used for lock acquisition and B1_d2 will receive the remaining 99% and will be used to provide the error signal as soon as the interferometer is fully locked.

B5 photodiodes

Both ACp and ACq channels are used to control the interferometer (for the SSFS and Beam Splitter control). These two signals should be taken from the same photodiode with the same type of electronic chain in order to avoid any dephasing or offsets between the signals. In the present setup 8% of the beam is sent to d1 photodiode while 70% is sent to d2 (the remaining fraction been shared between the linear alignment quadrants and B5_2f photodiode). Like before, B5_d2_ACp will be used as error signal for the SSFS and B5_d2_ACq for the beam splitter control. The gain of the electronic chains will be adjusted in order to avoid saturation in normal (ITF fully locked) operation. On B5_d2, used for the final control, the shot noise will dominate the electronic noise.

Since during lock acquisition the ACq channel will saturate, B5_d1 will be used for the lock acquisition of the beam splitter and the transition to B5_d2 will be performed when the full lock is acquired.

B1p photodiodes
B1p is used to control the differential degree of freedom only in an intermediate step since the control is then switched to B1. The beam is equally shared between the two photodiodes. No change of setup is foreseen and only the electronic gains will be adjusted.

B7 and B8 photodiodes
These photodiodes are also only used during the lock acquisition phase. The power on these beams varies by several orders of magnitude during the lock acquisition phase, therefore 90% of the light is received by d1 photodiode which is used in the first steps of lock acquisition while 10% is impinging on d2 which is used to provide the DC power in the later steps. The AC signal is always taken from d1 since it never saturates. This setup will remain the same and the electronic gains will be adapted.

Photodiode damage issues
During the lock acquisition or during the unlock events there will be several Watts on B1 and B1s beams. Care has therefore to be taken in order to avoid damaging the photodiodes. Since closing the shutter might create diffused light which can disturb the lock acquisition these beams will be dumped until the interferometer is locked on the dark fringe.
When the interferometer unlocks the shutter should be closed as fast as possible. The present setup does not allow a fast action and modifications might be needed like the use of shutters directly triggered by the DC analog signal.

d) Cavities lock

The locking of the single cavities with the increased power is not expected to be a difficult task. The procedures for the tuning of the photodiode demodulation phase and of the gain will be identical to the one used in the past.

e) Cavities linear alignment

This servo system aligns the 2 mirrors of each of the North and West cavity with respect to the incident beam, without power recycling mirror (which is misaligned); it is activated regularly during switch-on of the interferometer for refining the pre-alignment of the cavity mirrors before passing to the full recycled configuration. For retuning this system after the shutdown, the optics and electronics need to be adapted to the power increase due to the new injection bench; moreover, for removing the already mentioned ghost beams, the beam splitters in the quadrant diode paths will be replaced. For better understanding of the effects, this will be done only after a first successful test of the “cavities alignment” system. After the change, a retuning step is necessary.

So the sequence of works is:

1. adaptation of optics and electronics to the increased light power
2. matrix measurement: N & W beam quadrant diode signals as a function of the two arm cavity mirrors; closing N & W arm cavity linear alignment loops.
3. change of the N & W bench beam splitters; retuning of quadrant diode telescopes
4. repetition of step 2 (matrix measurement and closing of autoalignment loops for the two cavities).

f) Recycled interferometer lock

The interferometer will be locked again in different intermediate configurations: *Central Interferometer*, *Single arms* and *Recombined configuration*. Then the variable finesse technique will be employed to lock the recycled interferometer. The difference with respect to the previous plan, it is that the second stage frequency stabilization will be implemented only on the full recycled interferometer (and not also in the recombined configuration, as in the past). The entire procedure to tune the locking loop gains and the photodiode demodulation phases once a higher power beam will be injected in the interferometer is already defined. A few training tests have been also performed. No special problem is expected in this phase, even if the achievement of a stable locking on all the configurations mentioned above could require a few weeks.

g) Differential mode linear alignment

This tasks consists in controlling the arm cavities differential mode of misalignment by using the error signal obtained from the dark fringe quadrant diode (beam B1p); the two corresponding degrees of freedom of misalignment had already been controlled in this way during C6, together with the slow drift control system on the other mirrors; the latter, however, is not foreseen this time. The differential mode is the most important degree of freedom, since it determines the power loss from the recycling cavity through the dark fringe port due to an incomplete destructive interference. Its control allows a first sensitivity curve measurement before proceeding to a complete linear alignment scheme.

h) Restart of the hierarchical control and low noise coil drivers

The suspension control system should be independent from the power circulating in the interferometer. No problems should be present during this phase.

i) Set-up of the automatic procedures to bring the detector in science mode

After each task, the automatic ALP procedures are updated with the new parameters (filter gains and phases, etc…). Since the procedure to bring the detector in science mode is the same as with the low power, no big problems are expected.

At the end of this phase a sensitivity curve is measured, which will allow to start noise projection and preparation for the noise hunting. Since the automatic alignment is not yet implemented, we don't expect to have a long term stability to perform a long data taking.

4.4 Completion of the recycled interferometer commissioning

This task includes all the actions needed to increase the stability and the robustness of the interferometer and start an efficient noise hunting. Task sheets for this section are under preparation.

We can divide the work in the following topics:

a) *Control systems*

The implementation of the remaining control systems (mainly alignment and hierarchical control on the beam splitter) and the improvements of the control systems which showed problems before the shutdown (offsets in the angular and longitudinal error signals, diagonalization of longitudinal sensing and driving matrices, etc…).

This task includes:

- The restart and improvements of the linear alignment configuration (described on section 3.2.2)
- The implementation of beam control and mode-cleaner automatic alignment (described on section 3.2.2)
- The longitudinal control improvements (described on section 3.1.3)
- The BS marionetta reallocation (described on section 3.3.4)

b) *Automatic procedures*

The implementation of automatic procedures to measure important parameters of the control systems (optical gains, demodulation phases of photodiodes, alignment matrices, etc…).

- The automatic procedure for locking (described on section 3.1.3)
- The automatic procedure for the automatic alignment (section 3.2)

c) *Interferometer characterization*

The complete characterization of the interferometer (stored power, recycling gain, coupling between signals etc..) in order to prepare the future upgrades.

This task includes:

- The optical characterization of the interferometer (described on section 3.7)
- The characterization of the locking parameters (described on section 3.1.3)

This phase will end with a commissioning run (1-2 weeks), in order to collect data for detector characterization and data analysis. This commissioning run should demonstrate the stability and robustness of the control systems, and the reliability of the automatic procedures.

If possible, the noise of the interferometer will be investigated during this phase and reduced.

4.5 Noise hunting and reduction

For practical reasons this sections is divided in 3 parts:

- Noise reductions at high frequency (>200-300 Hz). In this region the sensitivity is mainly limited by read-out noises and laser noises.
- Noise reductions at intermediate frequency (50-300 H). In this region the sensitivity is currently limited by actuator noises, diffused light and acoustic noises.
- Noise reduction at low frequency (<50 Hz). In this region the sensitivity is mainly limited by control noises, angular and longitudinal.

4.5.1 Noise reductions at high frequency

Introduction

Above 1 kHz the sensitivity is now limited by frequency noise originating from B5 shot noise, B1 shot noise with comparable contributions, B1 electronic noise and the oscillator phase noise being slightly smaller. The total noise at 1 kHz is typically $7.10^{-22}/\sqrt{Hz}$, the Virgo design for an input power of 10 Watts is $7.210^{-23}/\sqrt{Hz}$ therefore a factor 10 has to be gained at these frequencies.
In the following the typical noise budget before the shutdown, during C7 run (with 10 LA loops closed) is given as well as the foreseen improvements to reach the Virgo design sensitivity.

a) Noise sources

The noise budget for high frequencies (typically above 500 Hz) is detailed here. It is given here in units of B1_ACp (Watts/√Hz): the present total noise is typically $10^{-10}W/\sqrt{Hz}$. The noise budget is detailed in first line of Tables 1&2 in Watts (Table 1) and h (Table 2). The analysis has been done with data taken on Sep 16th , during C7 run.

a.1) Frequency noise

The frequency noise is intrinsically limited by the shot noise of the photodiode B5_d2 used for frequency stabilization. The impact of B5 shot noise has recently (Aug 23rd) been reduced by increasing as much as possible the fraction of the beam incident on this photodiode (x3). The frequency noise can be monitored with the frequency line at 1111Hz. The amplitude of this line on the dark fringe signal depends on the common mode rejection ratio (CMRR). At high frequency the CMRR depends mainly on the losses asymmetry between the two arms and on the alignment of the interferometer. It is expected to be flat above 1 kHz. The contribution of the frequency noise on the dark fringe is estimated when the common mode rejection is bad assuming most of the noise on the dark fringe is frequency noise. For other periods of data this noise is normalized according to the amplitude of the 1111 Hz line. When the 10 loops of the linear alignment are engaged the typical frequency noise is about $6 10^{-11}$W/√Hz.

The impact of this noise can be reduced with the increase of the input beam power and a or by improving the CMRR.

When the impact of B5 shot noise will be reduced, other sources of frequency noise might show up. As an example a jitter of the beam incident on the IMC is turned into frequency noise at the output of the IMC. If this noise is observed on the dark fringe, it will be reduced by an improvement of the beam jitter (see section 4.6.3) and an improvement of the alignment of the beam with respect to the IMC (see section 4.3) and possibly a better tuning of the frequency stabilization.

a.2) B1 shot noise and electronic noise

The impact of B1 electronic noise has been reduced by √2 during C6 run by using one photodiode instead of 2 and cannot be further reduced with the present ITF settings. The shot noise cannot be reduced with the present ITF settings since the whole beam transmitted by the output mode cleaner is incident on the photodiode. During C7 the electronic noise is two times smaller than the shot noise.

The impact of both electronic and shot noise will be reduced with the increase of the input beam power (see b.1). The impact of the shot noise can also be optimized with a tuning of the modulation index (see b.2).

a.3) Oscillator phase noise

Another source of noise at these frequencies is the oscillator phase noise. The phase noise is proportional to the amount of the signal (integrated rms) in the phase orthogonal to the gravitational phase: $\delta ACp = ACq_{rms}\,\delta\varphi$, where $\delta\varphi$ is the phase noise induced by the Marconi after the demodulation process. It is expected to be 0.2 μrad/√Hz at 1 kHz (see Figure1) for the present generator (Marconi). The signal on the ACq channel depends on the quality of the alignment and has been well reduced with the implementation of the automatic alignment loops: a factor 20 to 50 has been gained between C5 and C6 runs. With $ACq_{rms} = 2.10^{-4}$ W (typical integrated rms with automatic alignment loops closed) and $\delta\varphi$=0.2 μrad/√Hz at 1 kHz (from the present generator data sheets) the estimated present phase noise on B1_ACp is $\delta ACp = 4.10^{-11}$W/√Hz. The phase noise is therefore equivalent to B1 standard electronic noise but is expected to limit the sensitivity with the increase of the input power. This noise has therefore also to be considered for the future. It should be improved with a lower phase noise oscillator.

a.4) Laser power noise at the modulation frequency

The laser power noise at the modulation frequency (6MHz) couples to the dark fringe through the DC power: $\delta B1\_ACp = \sqrt{2}\delta P/P \times B1\_DC$. A measurement of this noise was performed on the present laser: $\delta P/P \sim 1.5.\ 10^{-9}\ /\sqrt{Hz}$. During C7 this noise was negligible ($10^{-11}\ W/\sqrt{Hz}$) while for P=8 Watts this should give a noise on the dark fringe: $\delta B1\_ACp \sim 10\ 10^{-11}\ W/\sqrt{Hz}$. This noise might therefore be as high as the shot noise. If it turns out to be the case it is foreseen to install a pre-mode cleaner which will allow to reduce it by 32dB and result in a negligible contribution.

a.5) Power noise

The input beam power noise ($\delta P/P$) couples to the dark fringe through the locking accuracy (ΔL_{rms}) of the dark fringe: $\delta L = \Delta L_{rms} \times \delta P/P$. The power noise observed up to now was related to the jitter of the beam on the input mode cleaner: a beam jitter is transformed into power and frequency fluctuations at the output of the mode cleaner. It was found that the beam jitter was related to environmental noise in the laser lab (see section 3.6). At the beginning of C6 run the power noise was limiting the sensitivity in some regions between 200 and 900 Hz. A projection on the dark fringe allowed to deduce a locking accuracy of $\Delta L_{rms} = 2.10^{-12}$ m. At the end of C6 run the power stabilization was improved by using the photodiode located after the IMC as error signal instead of that located before. The power noise was then no more visible on the dark fringe.
An extrapolation of the present power noise measured after the IMC allows to conclude that this noise will be at the same level as the shot noise for P = 8Watts. It can be further reduced by improving the locking accuracy: a factor 2-3 can be easily gained by tuning the control loop. The improvement of the acoustic and seismic isolation in the injection laboratory (see 4.6.3) as well as a better alignment of the beam on the IMC (see 4.3) will also help to reduce this noise below the design.

b) Shutdown improvements

Here are given the improvements which will be obtained after the shutdown i.e with the increase of input power by a factor 10, an improved beam matching, the new PR mirror, the increase of modulation index and the new signal generator.

b.1) Increase of the power on the Beam Splitter

The incident power is only about 0.8 Watts and will be increased up to 8 Watts after the replacement of the injection bench.
With the new PR mirror it is expected that the recycling gain increases by about 30%.
The beam matching after the IMC is also expected to be improved (by 5-10%) with the use of parabolic mirrors for the new IB telescope.
Therefore the power incident on the Beam Splitter is expected to increase by a factor about 14 (25 Watts to 350 Watts).
Therefore the impact of B5 and B1 shot noise will be reduced by a factor 4 and B1 electronic noise by a factor 14. The impact of phase noise will remain the same and therefore dominate B1 shot noise at 1kHz.

b.2) New signal generator

As just mentioned the phase noise will limit the sensitivity of the ITF at 1 kHz with 8 Watts input power. This noise comes from the oscillator (Marconi) intrinsic phase noise. A lower noise generator (LNFS-100) is now available and will replace the Marconi (during the shutdown). Figure 1 shows the intrinsic noise of the LNFS-100 compared to the Marconi as well as the phase noise after demodulation on B1_ACp. The impact of the LNFS-100 phase noise on B1 is expected to be almost frequency independent: $\delta\varphi$=0.02 µrad/√Hz. A projection to the dark fringe gives a noise estimate $\delta ACp = 4\ 10^{-11}$ W/√Hz, and therefore comparable to the B1 standard electronic noise and well below the shot noise.

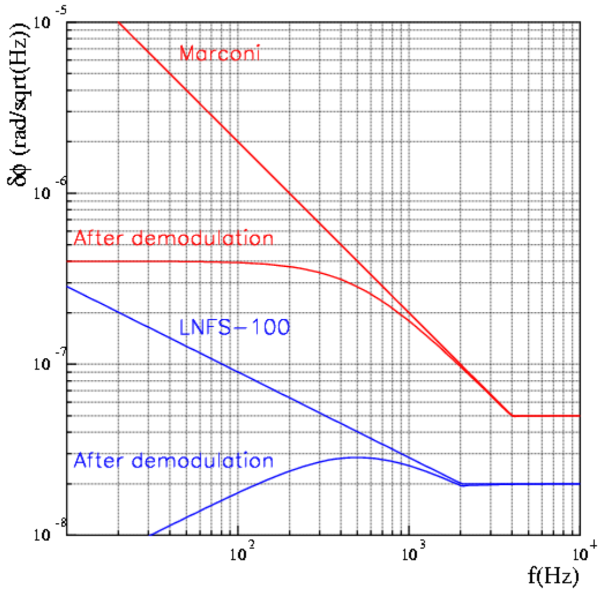


Figure 1: Signal generator phase noise for both Marconi (red) and LNFS-100 (blue) according to their respective specifications. In the two cases the upper curve gives the intrinsic generator phase noise (as given by the constructor) and the lower curve gives its projection on the dark fringe, i.e. after demodulation.

b.3) Effect of modulation index

The frequency noise induced by B5 shot noise will be a dominant source of noise for Virgo (if the CMRR remains the same). A possibility to reduce the impact of B5 shot noise is to increase the modulation index: the error signal increases proportionally to the modulation index while the shot noise remains unchanged. The original modulation index was around 0.16 and has been increased before C7 to 0.3, therefore reducing the frequency noise by a factor 2. It is not planned to increase it further more since the optimum value for B1 shot noise is between 0.2 and 0.3 (see below).

A higher modulation index also allows reducing the impact of B1 shot noise but much less than for B5: since B1 shot noise is dominated by the sidebands contribution its shot noise will also increase with the modulation index. Figure 2 gives the shot noise limited sensitivity as a function of the modulation index. The sidebands transmission is between T=0.1 and T=0.2 and the contrast defect about 1-C= 6.10^{-5}. An improvement of 10-15% is reached increasing the modulation index from 0.16 to 0.3 in the case T=0.1. A similar improvement is also reached if the sidebands transmission can be increased.

Before C7 run the modulation index has been increased up to m=0.3 and it was observed that the high frequency noise decreased by about 30% as expected.

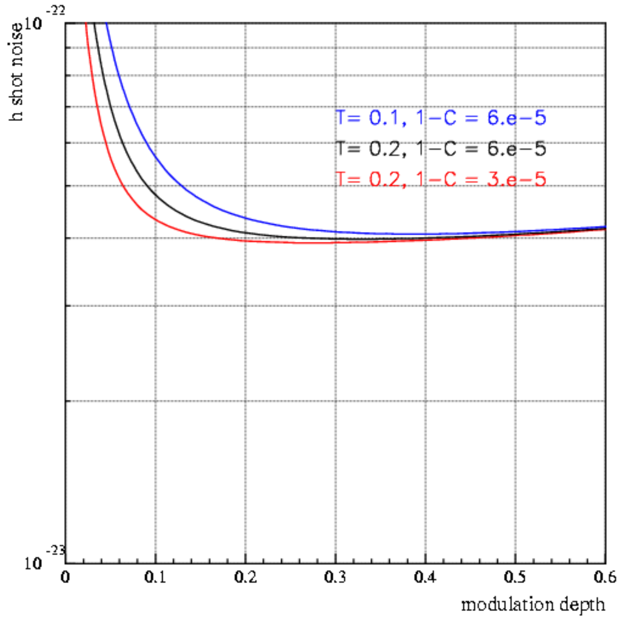


Figure 2: Projection of B1 shot noise on Virgo sensitivity as a function of the modulation index for a recycling gain R=31 as measured on the data and 3 plausible combinations of sidebands transmission (T) and contrast defect (1-C). The modulation effect is taken into account. These curves have to be multiplied by the cavity transfer function (cut off at 500 Hz) in order to get the shot noise limited sensitivity for a given frequency.

b.4) Summary

Tables 1 and 2 summarize the present and expected noise budget (resp. in W/√Hz and in h at 1 kHz) for the following configurations:

- C7 : measured during C7 with P_{in} = 0.8 Watts, m = 0.3, the Marconi generator and the 10 linear alignment loops closed.
- P_{in} = 8 Watts: expected with 10 times more power on BS and no other change
- P_{in} = 8 Watts & LNFS: expected with 10 times more power on BS and the replacement of the signal generator (Marconi) by the LNFS-100.
- 350 W on BS & LNFS: as previous plus the increase of recycling gain by 30% and an improvement of the beam matching by 10%, i.e. an increase of 40% of the power on the Beam Splitter leading to about 350 Watts.

The design is given for an incident power on the Beam Splitter of 500 Watts and a negligible contrast defect.

At the restart the extrapolated sensitivity is still about a factor 2 above the design and limited by the dark fringe shot noise and B5 shot noise turned into frequency noise. Note that a conservative value of the mirror actuator gain (m/V) is used in the calibration function so that the total estimated noise could be up to 30-40% smaller than the values given here.

	B1 elec	B1 shot	B5 shot	Phase noise	Total	Design
C7	$3.6\ 10^{-11}$	$5.6\ 10^{-11}$	$5.8\ 10^{-11}$	$3.5\ 10^{-11}$	$9.5\ 10^{-11}$	$1.0\ 10^{-11}$
P_{in} = 8 Watts	$3.6\ 10^{-11}$	$18.\ \ 10^{-11}$	$18.\ \ 10^{-11}$	$35.\ \ 10^{-11}$	$43\ 10^{-11}$	$10.0\ 10^{-11}$
P_{in} = 8 Watts & LNFS	$3.6\ 10^{-11}$	$18.\ \ 10^{-11}$	$18.\ \ 10^{-11}$	$3.5\ \ 10^{-11}$	$26\ 10^{-11}$	$10.0\ 10^{-11}$
350 W on BS & LNFS	$3.6\ 10^{-11}$	$21.\ \ 10^{-11}$	$22.\ \ 10^{-11}$	$4.9\ \ 10^{-11}$	$31\ 10^{-11}$	$14.0\ 10^{-11}$

Table 1: Noise budget in different configurations as observed on B1 for frequencies above 1kHz (in W/√Hz).

	B1 elec	B1 shot	B5 shot	Phase noise	Total	Design
C7	$2.6\ 10^{-22}$	$4.1\ 10^{-22}$	$4.3\ 10^{-22}$	$2.6\ 10^{-22}$	$7.0\ 10^{-22}$	$7.2\ 10^{-23}$
P_{in} = 8 Watts	$2.6\ 10^{-23}$	$13.\ \ 10^{-23}$	$13.\ \ 10^{-23}$	$26.\ \ 10^{-23}$	$32\ 10^{-23}$	$7.2\ 10^{-23}$
P_{in} = 8 Watts & LNFS	$2.6\ 10^{-23}$	$13.\ \ 10^{-23}$	$13.\ \ 10^{-23}$	$2.6\ 10^{-23}$	$19\ 10^{-23}$	$7.2\ 10^{-23}$
350 W on BS & LNFS	$1.9\ 10^{-23}$	$11.\ \ 10^{-23}$	$11.\ \ 10^{-23}$	$2.6\ 10^{-23}$	$16\ 10^{-23}$	$7.2\ 10^{-23}$

Table 2: Same as Table 1 but noise budget is expressed in sensitivity units (/√Hz) at 1 kHz. Note that a conservative value of the actuator gain (m/V) is used in the calibration function so that the total estimated noise could be up to 30-40% smaller than the values given here.

c) Further improvements

The last line of Table 2 gives the noise budget which should be obtained at the restart of the interferometer assuming the recycling gain is increased by 30% thanks to the new PR mirror and the beam matching is improved by 10%.
In order to reach the design sensitivity the shot noise has to be reduced as well as the impact of frequency noise.

c.1) Reduction of the shot noise

To reduce B1 shot noise (and therefore B5 shot noise) it is mandatory to increase the power incident on the beam splitter up to 500Watts (by about 40%) and therefore to increase the input power and/or the recycling gain.
About 55% of the laser power is lost between the laser output and the PR mirror: losses on the laser bench optics (25%), mismatching of the beam on the IMC (~17%) losses inside the IMC (~25%). Reducing these losses to 30% will allow to reach 500 Watts on the Beam Splitter. The mismatching will be reduced during the shutdown. The replacement of some optics (polarisers, HR mirrors) might be needed and will be investigated in order to reduce the losses on the laser bench.
The recycling mirror reflectivity could also be increased in order to increase the recycling gain: the PR reflectivity had been safely chosen to be 95% since the Fabry-Perot reflectivities were not very well measured. A more precise estimation of the FP reflectivities should be

possible with the new ITF setup and will allow to define the optimal value of the reflectivity of PR.

c.2) Reduction of frequency noise:
The impact of B5 shot noise will improve following B1 shot noise, it will nevertheless be mandatory to further reduce its impact in order to reach the design sensitivity.
Its effect is proportional to the common mode rejection ratio (CMRR, see above). The CMRR depends on the quality of the alignment. More time would have been required before the shut down in order to tune the linear alignment but, from the smallest value reached so far, it can be assumed that the CMRR could be improved by a factor about 3.
It should also be mentioned that other laser frequency noise might show up when the impact of B5 shot noise is reduced. No evidence for theses noises has been found until now.

Conclusions

The improvements done on the injection bench during the shutdown, in order to reduce the losses and improve the matching should result in a significant increase the input beam power. Combined with the increase of recycling gain, the incident power on the Beam Splitter is expected to reach 500 Watts as foreseen in the Virgo design. Further improvements will imply the change of the mode cleaner mirrors and/or of the ITF mirrors in order to reduce losses.
A reduction of the frequency noise will be needed and should result from the tuning of the linear alignment.
The work done on the environmental noise reduction in the laser lab, during the shut down, as well as the improved alignment of the IMC will reduce the power noise and the frequency noise (induced the beam jitter) so that these should remain well below the shot noise.

4.5.2 Noise reduction at intermediate frequency

a) Actuators noise reduction

The present configuration of the coil drivers is not the final one. Further actions are required to reduce the DAC noise at the VIRGO sensitivity level. The figure 4.2 shows, with respect to VIRGO design sensitivity:

a. an estimation of the actuation noise with full coil driver gain (including contributions of BS and cavity mirrors);
b. an estimation of actuation noise level during C7, after locking force reallocation to marionette and switch to low noise coil driver;
c. an estimation of the actuation noise expected with the new coil drivers, when emphasis-deemphasis filters will be added.

Even in case (c) VIRGO sensitivity is not reached at all frequencies. But the goal is at reach. A factor 2-3 is missing at 10 Hz, attainable by increasing the bandwidth of marionette control and further reducing the coil driver gain in low noise state (this is already possible in the present configuration: the saturation level is presently 3-5 times larger than the maximum correction applied, see fig 4.3). Moreover, a very simple 1st order de-emphasis filter is being considered. The use of more aggressive filters would further improve the noise rejection.

The noise estimation has been done assuming a DAC noise of 300 nV/rt(Hz). Recently we have measured a larger noise when the DAC is driven by a signal with a spectrum similar to the typical Virgo correction. Such non linear effect is due to a bad tuning of the DAC LSB. A check and tuning of all the DAC channels LSBs is being done during the shutdown in order to solve the problem.

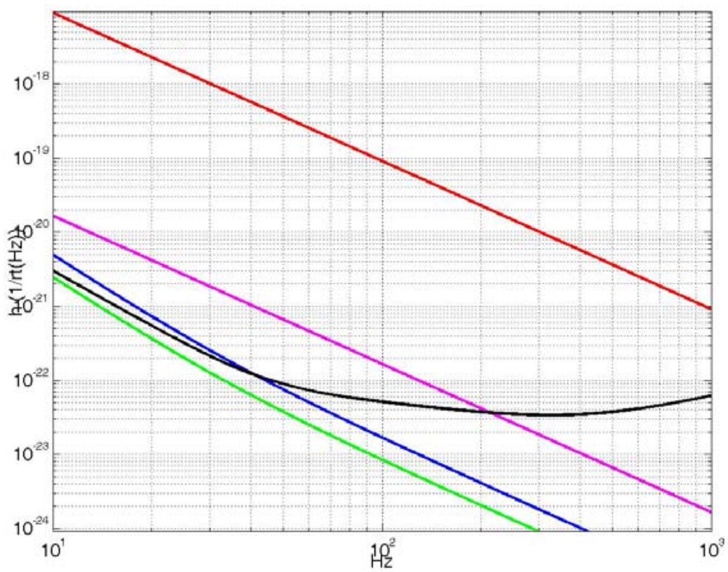


Fig. 4.2 - Estimated DAC noise contribution. The VIRGO sensitivity (**black**) is compared with the DAC noise injected when coil driver have maximum gain (lock acquisition phase, **red**), with that injected when switch to low noise coil driver is done (linear regime, hierarchical control engaged, **magenta**) and that attainable with the new coil drivers with emphasis-deemphasis filters (**blue**). The **green** curve shows either by reallocating more force on the marionette (twice) or reducing by a factor two the present dynamic range (we are working with correction signals at ~20 % of the saturation level).

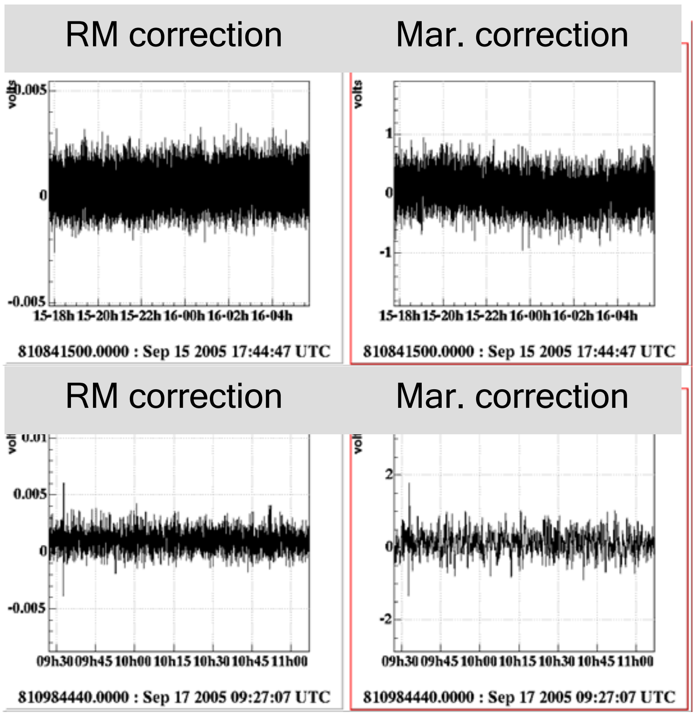


Figure 4.3: the upper figure shows the maximum value of the correction signal on the reference mass and the marionette respectively on a long stretch of data (12 hrs) in science mode during C7. The typical value on the RM is 3 mV (to be compared with a saturation level of 16 mV!). Notice that during C7 the WE mirror was not controlled. The marionette correction is below 1 V, showing that it is possible to increase the amount of correction reallocated upon the marionette.
The lower curve shows the same signal during a shorter (1.5 hrs) science mode stretch of C7 with very bad weather conditions. Except for a few isolated events with larger correction the amplitude of the signals is similar in the two cases.

b) Acoustic noise reduction

The main effects of sound and vibration noise have been seen in the laser laboratory and recently in the detection laboratory. Tests using a loudspeaker have been performed but also turning on and off scroll and turbomolecular pumps had a visible effect on the dark fringe. It is not completely clear at the moment whether the dominant noise comes from vibration of the ground of from the acoustic noise in the laboratories. It is likely that there is a mixture of both so that a multistep approach has to be undertaken. Moderate acoustic isolation above 400 Hz encounters only practical difficulties due to the lack of room around the optical tables. On the other hand vibration isolation is bound to introduce long term drifts, in particular with temperature and may thus require active control.

The following actions have to be considered.

a) reduce noise level in the laboratories by isolating acoustically the electronics.
b) provide acoustic isolation around the optical tables and possibly from the floor in the laser laboratory
c) have a better control of pumps and other noisy equipment like the laser chiller
d) provide vibration isolation from the floor in the laser laboratory and from the tower in the detection laboratory

During the shutdown it is possible to implement points a) and b). It is also advisable to review the position of optics on the tables to avoid vibration nodes that will give maximum angular amplitude. Shorter mounts and their damping is also an option to be considered. Point c) should be examined with the vacuum people.

Milestones

- Select isolation solution including sound absorption capabilities.
- Design solution in laser lab
- Order material End October 2005
- Install in labs when work on optics is finished. End November 2005

During 2006 dedicated data analysis on stability has to be performed, including tuning of air conditioning, due to the new configuration for clean air distribution.

c) Diffused light investigations

For the first time, during C6, diffused light was clearly identified as a limiting factor in the sensitivity curve: a stray beam was diffused on the baffle of one terminal optical bench; this light was then modulated by environmental noises (acoustical and thermal noises) before being reintroduced inside the arm cavity. This noise induced a bump on the sensitivity curve between 100 and 300 Hz.

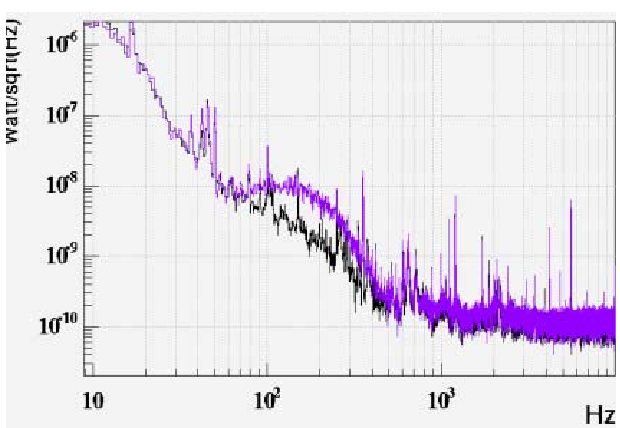


Fig.4.3 - Evidence of diffused light effect on dark fringe spectrum (black curve measurement after installation of a beam dump)

Peculiar attention was made when designing the new optical injection benches to prevent from stray beams. Moreover, beam dumps have been installed in many places and beam splitters are to be replaced with wedged ones to avoid creating secondary beams or spurious cavities effects. Nevertheless, in order to definitively prevent from diffused light reintroduction noise, acoustic noise test should be made systematically to validate the various optical setups' "cleanliness".

4.5.3 Noise reduction at low frequency

a) Longitudinal degrees of freedom noise reduction

In order to keep the interferometer at its working point, four degrees of freedom has to be controlled (see 3.1 section).

The differential length DARM is the gravitational wave channel. The other lengths are referred as *auxiliary* degrees of freedom. Due to optical couplings of the interferometer, fluctuations of the auxiliary lengths of the interferometer produce signals at the anti-symmetric port. For instance, a displacement of the BS mirror induces a differential phase shift of the beams recombined at the anti-symmetric port.

Presently, as it has been shown in the previous sections, the control noise of l_{PRCL} and l_{MICH} are one of the limiting noise sources below 100 Hz. It is not the case for the L_{CARM} control noise, since this length is feed-back to the laser frequency in order to stabilize it, with a very large control bandwidth. The gain at low frequency is so high that the CARM control noise limits the sensitivity only in a very higher frequency region, above 1 kHz, as it will be discussed in..

In the last two data taking C6 and C7 several solutions for the reduction of the control noise of l_{PRCL} and l_{MICH} have been designed and tested. In order to decrease further these noises several improvement are needed.

Increasing of the signal-over-noise ratio (SNR) of the signals involved in the auxiliary degrees of freedom

In order to increase the SNR of the signals involved in the control scheme of the interferometer, several solutions can be applied:

- Increasing of the light impinging the photodiodes

- Use more sensitive signals in the control scheme.

  The *variable finesse* technique has been designed to use the reflected 3f-demodulated signal to control the recycling cavity length during the full lock acquisition sequence to control l_{PRCL}. The light impinging this photodiode is presently at its maximum limit. An increasing of a factor 10 of the light coming into the interferometer will require an attenuation of the signal to prevent saturation in approaching the dark fringe.

Despite its properties of stability and small sensitivity to other degrees of freedom, which makes it interesting for lock acquisition, the 3f signal has a bad SNR. Once the dark fringe will be reached, the switch to a more sensitive signal, as the reflected f-demodulated one, will be therefore needed.
An alternative solution is to move the control from the reflected 3f-demodulated signal to the demodulated signal extracted from the second face of BS: this requires previously to stabilize the laser frequency by involving the reflected f-demodulated signal.

Reduction of couplings between different degrees of freedom

The optimization of the demodulation phases of the involved signals plays a crucial role also in order to reduce the coupling in the read-out phase between the different degrees of freedom. A trial of fine tuning has been done, but better results are expected with the interferometer stably controlled under automatic alignment.

Not only in the read-out of the signals, but even in *driving* the mirrors a better diagonalization of the system can be performed. In particular, VIRGO is now applying a simplified diagonal driving matrix, which controls MICH and PRCL by acting on BS and PR independently. Since a BS displacement produces not only a variation of MICH, but also of PRCL, because of the geometry of the interferometer, a not diagonal driving matrix should be applied. If in the first part of the commissioning a hierarchical system of the feedback loops took care to keep them stably controlled, it will not be efficient anymore when the requirements on the reintroduced noise are more strict.

Optimization of the control filters

- The control filters have to be optimized in order to reduce the noise reintroduced in the detection band. The solution adopted so far has been to reduce as much as possible the bandwidth of these filters, (around 10 Hz for the Michelson loop and 30 Hz for the recycling cavity length loop) and to design aggressive roll-off around 50 and 100 Hz respectively.
  The following plot shows the Bode diagram of a simple derivative filter (blue) used for lock acquisition, with respect to the 7^{th} order elliptic filter designed to work in *science mode* (red): the reduction of the gain @ 100 Hz is about 20 dB. A further reduction of the gain, and a consequent reduction of the unity gain frequency, can not be applied without compromising the stability of the loop. It has been experimentally tested, for instance, that a unity gain frequency lower than 6 Hz can not be adopted for the MICH loop.

  Some work has been already started in order to find a better compromise between the stability of the loop, by increasing the phase margin at the unity gain frequency, and a low frequency cut-off.

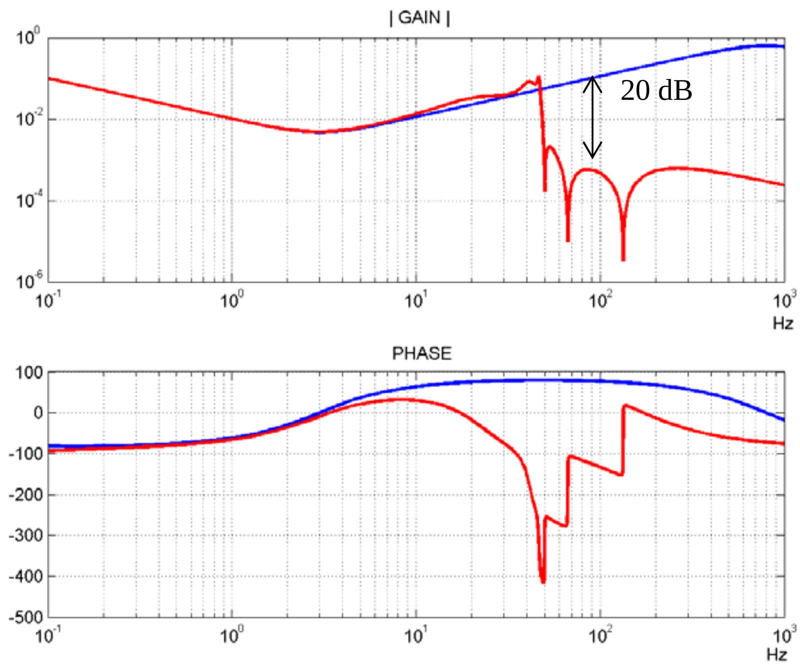


Fig.4.5 – Optimization of the control filters (see explanation in the text)

Subtraction of the control noise

One possible solution to overcome the problem of the strong requirements on the controller filters consists in applying the subtraction noise technique. The main idea is to use an independent measurement of the control noise in order to subtract it. The BS correction signal is added in differential mode to the end mirrors (see figure), so to cancel the noise reintroduced by this loop in the gravitational wave signal *B1_ACp*

In order to efficiently apply the subtraction technique, a fine measurement of the transfer functions $l_{MICH} \rightarrow B1\_ACp$ and $l_{DARM} \rightarrow B1\_ACp$ is needed. In particular, as it has been observed in Ligo, in order to have an attenuation of the BS control noise of about 20 dB, the transfer functions have to be known with 90% of accuracy. For this reason, an interferometer stably locked under automatic alignment is needed to perform precise measurements. A simple scheme of the subtraction technique for the BS control noise has been already implemented in the running locking algorithm.

In general, the coupling is frequency dependent, where the present strategy uses a simple constant term α .

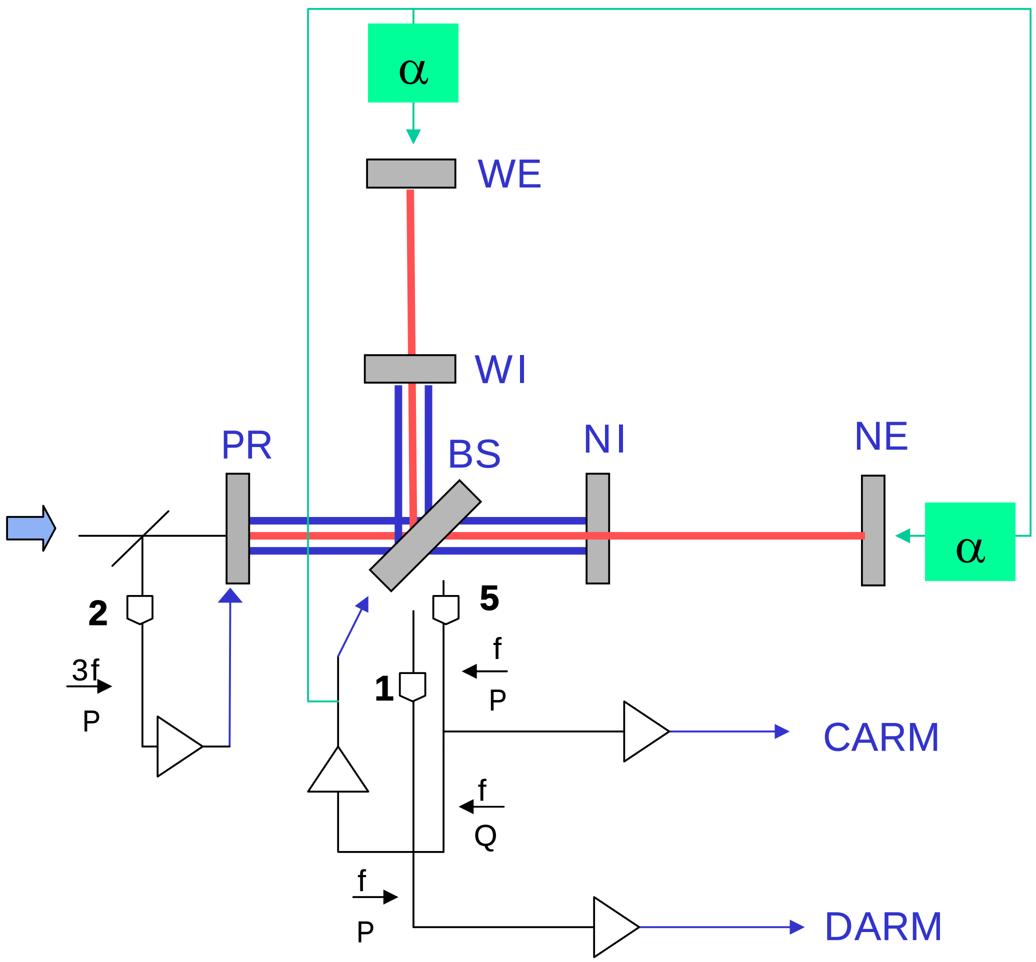


Fig.4.6 – Scheme of the BS noise subtraction

b) Angular degrees of freedom noise reduction

The reduction of alignment noise requires understanding of the noise sources; a useful tool for this is the noise projection, where noise is injected in one part of the interferometer, and the transfer function is measured with the dark fringe signal. This gives an estimate on how much the actually measured noise in that part contributes to the gravitational wave signal. Some initial noise projections have been done before the shutdown; this work will continue with increased intensity once a stable linear alignment configuration has again been reached.

A particular challenge is the reduction of low frequency noise, which might require realization of steep cut-off correction filters, for avoiding reinjection of control noise. The figure shows an example taken from C7: North input mirror control noise at 50 and 100 Hz was seen in the dark fringe signal; this extra noise was eliminated by optimizing the corrector for a steeper roll-off, without compromising its low-frequency characteristics (see figure).

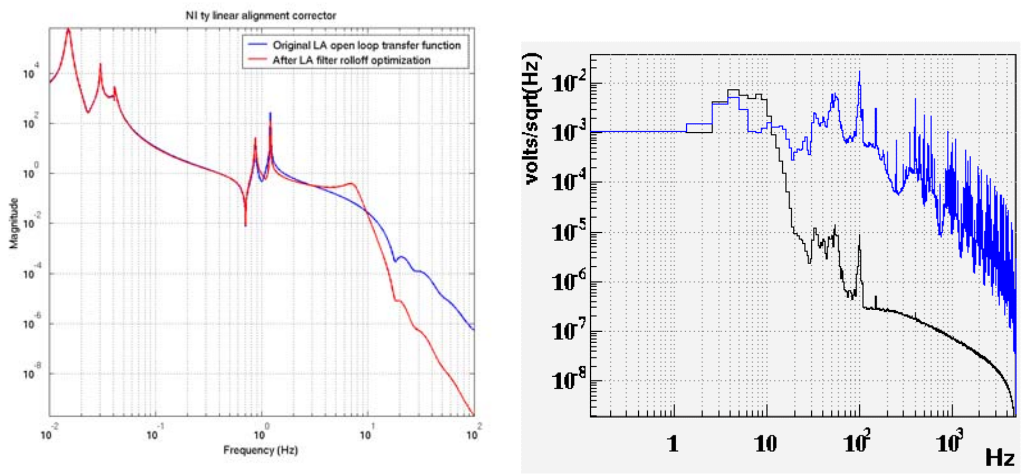


Figure: A comparison of the open loop transfer function of the horizontal angular degree of freedom of the North input mirror (left), and of the total control noise going to the coil actuators (right), before (blue), and after the optimization. The improvement is two orders of magnitude at 30 Hz, and four at 100 Hz.

In the present configuration of linear alignment, one of the mirrors (West input) remains under local control. During C7 the influence of this rather noisy control system on the dark fringe signal was clearly seen, and some improvement was obtained also here by modifying the corrector filters. In the final configuration, this mirror is supposed to be controlled by the West arm beam pointing system, using the West end quadrant diode DC signal, which is less noisy than the local control, but probably still be too noisy for a full bandwidth control (3 Hz). Reduction of the loop bandwidth allows a steeper roll-off with high noise reduction even at the beginning of the measurement bandwidth. By combining a low bandwidth loop (100 mHz) with a steep roll-off filter (like in Fig. ###), noise reinjection into the measurement bandwidth can be effectively suppressed.

The already mentioned beam/mirror centering will reduce the sensitivity of the dark fringe to the residual angular motion of the mirrors. Two possibilities are considered for determining an off-centering of the beam with respect to a mirror. The first one consists in shaking the mirror angularly by injecting a sinus voltage on its coils, and searching the perturbation in the dark fringe. By lateral or vertical shifting of the mirror, the perturbation can be minimized. This technique was already tested on the horizontal motion of the North end mirror, and has shown the capacity of improving the centering by at least a factor of 10, down to a few 100 um. The second technique consists in using the thermally excited internal vibrations of the mirror; again, their effect on the dark fringe signal is minimized by shifting the mirror. This technique should allow an absolute centering of the beam, independent of an eventual misbalancing of the actuator coils, which can then afterwards be corrected using the first technique. In Ligo (see thesis R. Adhikari) the line injection technique was used; they improved the equivalent beam decentering (including also the coil imbalances) from 0.1 to 0.0002 m/rad by adjusting the coil forces to 0.5%, without an absolute beam centering using the thermal mirror vibrations.

Appendix A:

Injection bench commissioning
and
Injection system restart
task sheets

Commissioning activity:	ISYS restart				
TASK:	Injection bench local control restart	**Task code**:	IB1	**Responsible:**	P. La Penna

Goal : Control the injection bench in the 6 degrees of freedom

Procedure:

1/ test the local control signals (Gx camera and laser signals)

2/ measure the injection bench transfer functions

3/ close the loops

ITF status: The injection bench is in the injection tower, in air.

Time required : 7 shifts

Required personnel: La Penna, Ruggi, Heitmann

On-call:

Needed prior work (simulation/off-line analysis): hardware checks (local controls laser, camera targets, etc…), DSP cards checks

Commissioning activity:	ISYS restart				
TASK:	IB rough alignment	**Task code**:	IB2	**Responsible:**	P. La Penna

Goal : Align the injection bench with the He-Ne

Procedure : send the He-Ne from MC tower and see the direct reflection from the fake dihedron, steering the injection bench through local controls

ITF status : Injection bench local controls closed

Time required : 1 shift

Required personnel: La Penna, Genin

On call: Heitmann, Ruggi

Needed prior work (simulation/off-line analysis) : check of the He-Ne functioning

Note :1/The shape and position of the fake dihedron is assumed to be equal to the angle of the true dihedron.
2/ a first fast trial to make this task with the bench blocked instead the bench controlled can be done 3/ It may be difficult to realign direcltly the bench with respect to the mode-cleaner mirror. A pre-alignment with a closer target can be necessary. To be verified.

Commissioning activity:	ISYS restart				
TASK:	YAG beam rough alignment	**Task code**:	IB3	**Responsible:**	P. La Penna

Goal : align the YAG input beam with respect to the mode-cleaner axis

Procedure : With injection bench under local controls, steer the input beam until light is detected on the mode-cleaner mirror.

ITF status : injection bench under local controls, laser YAG working (and attenuated, if's possible), fake dihedron on the bench

Time required : 1 shift

Required personnel : La Penna, Genin

On call: Ruggi, Cleva

Needed prior work (simulation/off-line analysis) :

Note : 1/The shape and position of the fake dihedron is assumed to be equal to the angle of the true dihedron.

Commissioning activity:	ISYS restart				
TASK:	Injection bench optics alignment	**Task code**:	IB4	**Responsible:**	P. La Penna

Goal : Align the optics on the bench, with the fake dihedron

Procedure : the bench is blocked on the position found through the local controls. The optics on the bench are manually aligned with respect to the YAG attenuated beam

ITF status : IB blocked, YAG beam working and attenuated

Time required : 1 shift

Required personnel : La Penna, Genin, Ruggi

On call: Heitmann

Needed prior work (simulation/off-line analysis) :

Note: It will be necessary to enter in the IB tower. The laminar flux is necessary

Commissioning activity:	ISYS restart				
TASK:	Check of the bench alignment with the true dihedron	**Task code**:	IB5	**Responsible:**	P. La Penna

Goal : check the overall bench alignment with the true dihedron

Procedure : the bench is blocked on the position found through the local controls.

1/ The true dihedron is installed.

2/ The laser polarization is turned

3/ The alignment of the bench is checked

4/ In case of bad alignment, enter in the tower and perform manual corrections

ITF status : IB blocked, YAG beam working and attenuated

Time required : 1 shift

Required personnel : La Penna, Genin, Marque

On call: Heitmann

Note: It could be necessary to enter in the tower

Commissioning activity:	ISYS restart				
TASK:	Mode-cleaner fine alignment	**Task code**:	IB6	**Responsible:**	P. La Penna

Goal : Align the mode-cleaner with the true dihedron until we see cavity resonances.

Procedure :

1/ replacement of the fake dihedron with the true one.

2/ Injection bench unblocking

3/ steering of the mode-cleaner mirror until the mode-cleaner resonates

4/ actions on all the degrees of freedom (beam, IB and MC mirror) to have a fine aligment

ITF status : YAG beam working (better if attenuated), local controls working

Time required : 2 shifts

Required personnel: La Penna, Genin, Marque

On call: Ruggi, Heitmann

Needed prior work (simulation/off-line analysis) : the photodiode receiving the mode-cleaner reflection is correctly centered until it receives the beams from the input bench, by Marque

Commissioning activity:	ISYS restart				
TASK:	Mode-Cleaner lock	**Task code**:	IB7	**Responsible:**	P. La Penna

Goal : lock the input mode-cleaner

Procedure :

1/ Remove the security block IB-PR

2/ pump off the IB tower and open valves

3/ The laser frequency is locked on the mode-cleaner TEM00 resonance. The input mode-cleaner is freely swinging

ITF status : mode-cleaner aligned, IB local controls working

Time required : 1 shift + pumping time (mainly during the night)

Required personnel : La Penna, Genin, Cleva

On call: Coulon, Ruggi

Needed prior work (simulation/off-line analysis) : Check of the rampeauto electronics, check of the photodidoe gains and demod phases

Note : According to the previous experience, the mode-cleaner can not be locked in air

Commissioning activity:	ISYS restart				
TASK:	Check of the IB overall alignment	**Task code**: IB8		**Responsible:**	P. La Penna

Goal : The correct alignment of the IMC transmitted beam through the IB optics is checked

Procedure : Lock the IMC and check with PSD , cameras, and outgoing beams. Actions on the IB actuators if needed

ITF status : Input mode-cleaner locked

Time required : 1 shift

Required personnel : La Penna, Genin

On call: Ruggi, Marque, Moins

Needed prior work (simulation/off-line analysis) : Install the Gx camera version which allows to switch off the light and then see better the beam path

Note :

Commissioning activity:	ISYS restart				
TASK:	Check of the ITF/beam alignment	**Task code**:	IB9	**Responsible:**	La Penna

Goal : Check the rough alignment of the beam entering in the interferometer

Procedure : remove the security vacuum block from the IB-PR link. Look at the YAG beam position on the ITF outputs

ITF status : ITF mirror aligned on the C7 position (Sept 19^{th}), PR mirror controlled, IMC locked in air

Time required :1 shift

Required personnel : La Penna, Genin

On call: Marque, Ruggi

Needed prior work (simulation/off-line analysis) : vacuum group should be contacted to open the link between injection tower and injection bench tower

Note : Cameras and photodiodes on the external bench working

Commissioning activity:	ISYS restart				
TASK:	Mode-Cleaner automatic alignment	**Task code**:	IB10	**Responsible:**	F.Cleva

Goal : Restart the automatic alignment of the mode-cleaner in the version already running before the shutdown

Procedure :

1/ check the quadrant signals

2/ measure optical matrix

3/ close the loops acting on the mode-cleaner mirror

ITF status : IMC locked

Time required : 3 shifts

Required personnel: Cleva, La Penna, Genin

On call: Ruggi

Needed prior work (simulation/off-line analysis) :

Note : It may be needed to have first a rough beam matching before to make the mode-cleaner automatic alignment.

Commissioning activity:	ISYS restart				
TASK:	Beam matching with input mode-cleaner	**Task code**: IB11		**Responsible:**	F.Cleva

Goal : march the incoming YAG beam with the TEM00 of the input mode-cleaner

Procedure : optimise the mode-cleaner matching using beamscan, BMS telescope (camera), IMC_Refl contrast, TE02 amplitude

ITF status : IMC locked

Time required : 3 shifts

Required personnel: Cleva, La Penna, Genin

On call: Marque

Needed prior work (simulation/off-line analysis) :

Note :

Commissioning activity:	ISYS restart				
TASK:	Reference cavity alignment	**Task code**:	IB12	**Responsible:**	P. La Penna

Goal : Aign the reference cavity until resonances are observed

Procedure : lock the IMC, move mirrors M13 and M14 and/or M15 M16 until fringes are observed

ITF status : IMC locked

Time required : 1 shift

Required personnel and/or technical support : La Penna, Genin, Cleva

On call: Moins, Ruggi

Needed prior work (simulation/off-line analysis) : check of the reference cavity transmission and reflection

Note : The matching of the reference cavity could require to re-enter in the tower

Commissioning activity:	ISYS restart				
TASK:	RFC lock	**Task code**:	IB13	**Responsible:**	P. La Penna

Goal : lock the reference cavity

Procedure :

1/ modify the RFC filter to take in account the pole of the IMC

2/ center the RFC photodiodes

3/ close the loop

ITF status : IMC locked, RFC aligned

Time required : 1 shift

Required personnel: La Penna, Genin

On call: Heitmann

Needed prior work (simulation/off-line analysis) : simulation of the reference cavity new filter, DSP card preparation

Note :

Commissioning activity:	ISYS restart				
TASK:	RFC automatic alignment	**Task code**:	IB14	**Responsible:**	F.Cleva

Goal : Put in operation the reference cavity automatic alignment with a very slow bandwitdh (~10 mHz)

Procedure :

1/ Check quadrant error signals

2/ Implement very simple integrator loop

3/ Close the loops

ITF status: Reference cavity locked

Time required: 2 shift

Required personnel: La Penna, Genin, Cleva

On call: Heitmann

Needed prior work (simulation/off-line analysis): Check of the quadrant hardware

Commissioning activity:	ISYS restart				
TASK:	Beam monitoring system implementation	**Task code**:	IB15	**Responsible:**	F.Cleva

Goal : Implement the beam monitoring system

Procedure :

1/ the BMS optics is mounted on the bench

2/ a rough feedback is implemented with very low bandwidth (~1-10 mHz)

ITF status: Input mode-cleaner locked

Time required: 2 shifts

Required personnel: Cleva, Marque

On call: La Penna

Needed prior work (simulation/off-line analysis) : rio23 cabling ready (Masserot, Cavalieri)

Note :

Appendix B:

Interferometer restart
Task sheets

Commissioning activity:	ITF restart				
TASK:	Beam alignment	**Task code**:	R1	**Responsible:**	La Penna

Goal: Align the input beam with respect to the interferometer

Procedure: The beam is aligned with respect to the interferometer, using picomotors on the injection bench

ITF status: mode cleaner locked and automatically aligned. All the interferometer mirrors controlled and aligned. Cameras on B7/B8/B1/B5 workings. Note: a priori we don't need to lock the RFC and to have the BMS working, and this task can start in parallel with those activities.

Time required: 1 shift

Concerned HW & SW: injection bench picomotors

Required personnel: La Penna

On-call: Moins

Needed prior work:

Commissioning activity:	ITF restart				
TASK:	Mode matching I (rough)	**Task code**:	R2	**Responsible:**	Marque

Goal: The mode matching consists in adjusting the input telescope in order to match the mode parameters of the input beam (waist size, distance to waist) to the long arms' cavity eigenmodes (radius of curvature of the mirrors of the cavity, length of the cavity). A matching performance of more than 99% of the power coupled into the TEM00 mode of both arms should be reached.

Procedure: The matching can be tuned by adjusting the distance between SIB_M5 and SIB_M6. This can be done by tuning the position of SIB_M6 with the help of the 3 closed-loop picomotors. If the dynamics of the picomotors of M6 is not sufficient, the position of SIB_M5 can be changed with the help of 2 translation stages. At the same time, the beam has to be kept aligned in the 3 km arms by compensating the effect of the tuning of the distance M5-M6 with the picomotors of M6 (M5, M4 and M3 if necessary). 3 quality parameters are used to make this tuning: the beam size on Cam5, Cam7p and Cam8p.

ITF status: Direct beam aligned inside the arms, all mirrors under LC

Time required: 3 shifts

Concerned HW & SW: Translation stages of SIB_M5, picomotors of SIB_M3,4,5,6.

Required personnel: Marque

On call: Christophe Moins (support for software control) and Eric Genin (support for optical simulation with Zemax).

Needed prior work: Beam has been pre-aligned inside north and west arm. North and west arm don't need to be locked for a first coarse tuning of the telescope.

Commissioning activity:	ITF restart				
TASK:	DBA restart	**Task code**:	R3	**Responsible:**	Dattilo

Goal: The direct beam alignment and BS alignment procedure are restarted (“DBA” macro)

Procedure: The B7 and B8 camera signals are checked. The DBA algorithm is tuned with correct threshold values. The picomotors actions are tested

Time required: 1 shift

Concerned HW & SW: IB picomotors

Required personnel: Dattilo, Marque

On call: De Rosa, La Penna

Needed prior work:

Commissioning activity:	ITF restart					
TASK:	North and West cavity nonlinear alignment	**Task code**:	R4	**Responsible:**	Heitmann	

Goal: Fine alignment of the north and west cavity (align the mirrors NE, WE, NI, WI), to have the TEM00 resonant in the cavities and tune the non linear alignment macros.

Procedure: Steer the input mirrors until the reflected beams on the dark fringe cameras fall on the still existing reference position. If mirrors are too much misaligned, then center reflections through the IB output hole, then try to find the reflected beam on the MC mirror. Steer the end mirrors for seeing higher order mode flashing. Fine tuning: superpose reflected beams on the input mirrors' reflected beam on the B1 camera. Observe resonances, parametrize the coarse alignment function of the NaServer. Try auto-prealignment with NeServer.

ITF status: IMC locked, all the ITF mirrors controlled and roughly aligned, N and W beams centered with respect to the terminal cameras.

Time required: 2 shifts

Concerned HW & SW: NaServer configuration. DSP (Db) mirror reference positions.

Required personnel: Heitmann, Marque, Dattilo

On call: La Penna, De Rosa

Needed prior work: Beam matched

Commissioning activity:	ITF Restart				
TASK:	North Cavity Lock	**Task code**:	R5	**Responsible:**	Braccini

Goal: Aquire and maintain the lock of the north cavity

Procedure:

1/ check of the error signals (B1p_ACp and B7_ACp) and tuning of the demodulation gain

2/ rough estimation of the optical gain and adjusting of the filter gain and triggers in the database

3/ lock acquisition

4/ simple characterization of the locking behaviour (locking accuracy, stability, etc…)

5/ Measurement of the frequency noise of the injection system (Sc_IB_zErrGc) using the north cavity as a frequency reference

ITF status : Injection system working within the specifications for locking achievement (mainly frequency noise). North cavity NLA working. PR mirror and the two mirrors of the West cavity are kept misaligned.

Concerned HW & SW: Global control, photodiodes B7,B1p

Time required : 1 shift

Required personnel : Braccini, Vajente

On call: Heitmann, Tournefier, Leroy

Needed prior work (simulation/off-line analysis) : Photodiode electronics tuned for the new (x10) power. Check the global control algorithm.

Commissioning activity:	ITF Restart				
TASK:	West Cavity Lock	**Task code**:	R6	**Responsible:**	Braccini

Goal : Aquire and maintain the lock of the north cavity

Procedure : Same procedure used for the north cavity

ITF status : Same for the north cavity. NLA of west cavity working

Time required : 1 shift

Concerned HW & SW: Global control, photodiodes B8,B1p

Required personnel : Braccini, Vajente

On call: Heitmann, Tournefier

Needed prior work (simulation/off-line analysis) : Same for the north cavity

Note: north and west cavities have already been locked with the “full” input power. No issue of excess of light inside the interferometer are expected

Commissioning activity:	ITF restart				
TASK:	3 km arms mode matching (fine)	**Task code**:	R7	**Responsible:**	Marque

Goal: See task sheet for mode matching rough. Here the goal is to have a fine matching, maximizing the coupling of the beam with the cavities.

Procedure: Same procedure used for the rough tuning. In order to maximize the matching the high order modes relative to mismatching transmitted by the cavities are minimized.

ITF status: Direct beam alignment working (DBA), north and west cavities locked.

Time required: 2 shifts

Concerned HW & SW: Translation stages of SIB_M5, picomotors of SIB_M3,4,5,6.

Required personnel: & support: Marque

On call: Christophe Moins (support for software control) and Eric Genin (support for optical simulation with Zemax).

Needed prior work:

Commissioning activity:	ITF restart				
TASK:	North cavity automatic alignment	**Task code**:	R8	**Responsible:**	Heitmann

Goal: Restart the automatic alignment of the north cavity

Procedure:

1/ adaptation of B7 optics and electronics

2/ close N cavity autoalignment

3/ B7 beam splitter replacement, telescope tuning

4/ close again N cavity autoalignment

5/ NaServer “fine mode” tuning for prealignment automation

ITF status: North cavity locked, PR misaligned and under control

Time required: 4 shifts

Concerned HW & SW: Q7 quadrants, end bench telescopes, shutters, attenuators, global control (alignment part)

Required personnel: Heitmann, Marque, Mantovani

On call: De Rosa, Ruggi, Leroy

Needed prior work:

Commissioning activity:	ITF restart				
TASK:	West cavity automatic alignment	**Task code**:	R9	**Responsible:**	Heitmann

Goal: Restart the automatic alignment of the West cavity

Procedure:

1/ adaptation of B8 optics and electronics

2/ close W cavity autoalignment

3/ B8 beam splitter replacement, telescope tuning

4/ close again W cavity autoalignment

5/ NaServer "fine mode" tuning for prealignment automation

ITF status: West cavity locked, PR misaligned and under control

Time required: 3 shifts

Concerned HW & SW: Q8 quadrants, end bench telescopes, shutters, attenuators, global control (alignment part)

Required personnel & support: Heitmann, Marque, Mantovani
On call: Leroy, De Rosa, Ruggi

Needed prior work:

Commissioning activity:	ITF restart				
TASK:	Interferometer alignment automation	**Task code**:	R10	**Responsible:**	Dattilo

Goal : Restore the cavities alignment macros, and PR manual alignment and global check of the alignment macro

Procedure: The alignment macros thresholds are set. Tests of macro functioning are performed

ITF status : automatic alignment of the north and west cavities working.

Time required : 1 shift.

Concerned HW & SW : mainly ALP server, a few IB picomotors, BS and cavity mirrors

Required personnel : Dattilo, Marque,

On call: Heitmann, DeRosa

Needed prior work (simulation/off-line analysis) :

Commissioning activity:	ITF Restart				
TASK:	PR control test	**Task code**:	R10	**Responsible:**	S.Braccini

Goal : Lock the PR-NI cavity in order to check the ability to control the (new) PR mirror. Measurement of the new PR transfer function (the new monolithic mirror is expected not to exhibit spurious resonances in the region of the hundreds of Hz).

Procedure :

1/ check the B2 and B2_3f error signals

2/ Rough estimation of the optical gain. Adjustment of the feedback gain in the database

3/ Lock of PR-NI cavity

4/ Measurement of the PR new transfer function (up to the kHz region), check the theoretical TF.

ITF status : PR, NI and BS aligned. Other mirrors misaligned by a few hundreds of microns.

Time required : 2 shifts

Concerned HW & SW : global control, photodiodes B2 and B2_3f

Required personnel: Braccini, Vajente

On call: Leroy, Tournefier

Needed prior work (simulation/off-line analysis) : B2 and B2_3f photodiode correctly tuned. Global control 2 length algorithm working, PR (new) local controls under specifications.

Commissioning activity:	ITF Restart				
TASK:	CITF Lock	**Task code**:	R11	**Responsible:**	S.Braccini

Goal : Lock the central interferometer on the sidebands to make preliminary measurements for the full interferometer lock.

Procedure :

1/ Check the B2_3f_ACp and B2_3f_ACq signals and tuning of the demod phases

2/ Check the B5_2f photodiode and tuning of the demod phases

3/ Rough measurement the optical gain and adjustment of the feedback gain in the database

4/ Lock of the CITF

5/ Measurement of the frequency noise of the injection system with the PR aligned, using Sc_IB_zErrGc (calibrated with the north cavity)

ITF status : CITF aligned, while end mirrors are misaligned by a few hundreds of microrads.

Time required : 1shift

Concerned HW & SW : B2 and B2_3f photodiodes, global control

Required personnel : Braccini, Vajente

On call: Heitmann

Needed prior work (simulation/off-line analysis) :

Commissioning activity:	ITF Restart				
TASK:	Tuning of the photodiodes setup	**Task code**: R14		**Responsible:**	Tournefier

Goal : Tune the photodiode electronics and optical setups

Procedure : During the first interferometer locking tentatives the gain of the demodulation boards is retuned if needed, in case of saturation or too low gain. The optical setup will also be modified if needed: as an example, it might be needed to use two photodiodes instead of one on B1.

ITF status : all locking steps

Time required : 2 shifts

Concerned HW & SW : photodidoe electronics

Required personnel : Tournefier

On call: Braccini

Needed prior work (simulation/off-line analysis) : the gain of the demodulation electronics are tuned before the restart assuming the amplitude of the signals is 10 to 20 times higher than before the shutdown.

Commissioning activity:	ITF restart				
TASK:	Recycled ITF lock in step1-2	**Task code**:	R14	**Responsible:**	L.Barsotti

Goal : Lock the ITF up to STEP 2 (before the SSFS engagement).

Procedure : Repeat one by one the same steps followed in the Commissioning plan for the longitudinal locking activities (without SSFS).

ITF status : Injection system working within the specifications for locking achievement and itf aligned in the different configurations.

Time required : 2 shift

Concerned HW & SW : global control algo, photodiodes

Required personnel : Barsotti, S.Braccini, G.Vajente

On call: Leroy, Heitmann

Needed prior work (simulation/off-line analysis) : Commissioning of the new injection system, pre-alignment of the itf in all configurations, new PR local control working within the specification. All the other sub-systems, not affected by the upgrades, have to work properly.

Note : The SSFS (see next task) will be implemented directly on the recycled ITF, skipping the task in the recombined configuration.

Commissioning activity:	ITF restart				
TASK:	SSFS engagement (step3)	**Task code**:	R15	**Responsible:**	F.Bondu

Goal : Engage the SSFS during the variable finesse technique (offset=0.4, step3)

Procedure : The triggers for the SSFS engagement are sent directly by the global control when we move to step4. Maybe, a manual procedure is needed first, in order to better diagnostics the system.

ITF status : interferometer locked at STEP 2 (i.e. gray fringe with PR misaligned and boost on PRCL and MICH).

Time required : 1 shift

Concerned HW & SW : SSFS electroniccs

Required personnel: Bondu, Barsotti

On call: Heitmann, Coulon

Needed prior work (simulation/off-line analysis) : The SSFS electronics gai(s) have to be checked. A complete computation (simulation) of the gains included in the control chain has to be done (B5, SSFS, ecc…)

Commissioning activity:	ITF restart				
TASK:	Complete variable Finesse Locking	**Task code**:	R16	**Responsible:**	L.Barsotti

Goal : Lock the ITF with the *Variable Finesse* technique up to the dark fringe (DARM controlled by B1p).

Procedure : Move from offset=0.4 to dark fringe step by step, measuring the transfer functions for each step.

ITF status : ITF locked on Step 3 (SSFS engaged).

Time required : 2 shifts

Concerned HW & SW : global control, photodiodes

Required personnel : L.Barsotti, S.Braccini, G.Vajente.

On call: Heitmann, Leroy

Needed prior work (simulation/off-line analysis) : All previous restart tasks.

Notes: Problems with light excess and light scattering from suspended optical components (i.e. BS) can arise during locking trials

Commissioning activity:	ITF Restart				
TASK:	Interferometer lock automatic procedure with ALP	**Task code**:	R16	**Responsible:**	V.Dattilo

Goal : Readjust the present ALP locking macro in order to achieve the locking acquisition in an automatic way up to step 11.

Procedure : Only a few changes of the values of the on-fly parameters to be sent from Alp to the Gc are expected to change with respect to the situation before the shut-down. The work will be done at the end of the task R15, when the values are stabilized.

ITF status : ITF locked

Time required : 1 shift

Concerned HW & SW :ALP environment

Required personnel : S.Braccini, V.Dattilo

On call:

Needed prior work (simulation/off-line analysis) : All previous restart tasks.

Commissioning activity:	ITF Restart				
TASK:	Differential mode automatic alignment	**Task code**:	R16	**Responsible:**	Heitmann

Goal : Control ITF differential mode alignment with full bandwidth

Procedure :

1/ Adaptation of gain of quadrant diodes B1p (B5)

2/ Retuning of B1p (B5) telescopes (if necessary)

3/ Close end mirror common mode loop using B1p signals

ITF status : ITF fully locked

Time required : 2 shifts

Concerned HW & SW :quadrant photodiodes, global control alignment part

Required personnel : Heitmann, Mantovani, Ruggi

On call: Barsotti, Leroy

Needed prior work :

Commissioning activity:	ITF Restart				
TASK:	Preliminary optical characterisation	**Task code**:	R18	**Responsible:**	Tournefier

Goal : Measure the new optical parameters of the ITF: input power, input beam matching, modulation index, new PR reflectivity, recycling gains.

Procedure :

1- The input beam power (incident on PR) is deduced from:

- the measurement of the beam incident on the IMC and the IMC losses measurement (through decay time measurement)
- the power incident on the photodiodes in a simple configuration like only NI and BS aligned.

2- The matching of the input beam with the FP cavities is deduced from the power measured on TEM02 mode with free FP cavities.

3- The modulation index is deduced from the relative amplitude of the SB and carrier with the small Michelson and with the free FP cavities.

3- PR reflectivity is cross checked from the measurement of the recycling gain in the CITF configuration.

4- The recycling gains (carrier and SB) are deduced from the ratio of the power measured on B5 and B5_2f with the ITF in the recombined and recycled configuration.

ITF status : ITF fully locked with differential mode automatic alignment / CITF locked / NI aligned / small Michelson aligned

Time required : 2 shifts

Concerned HW & SW : none

Required personnel: Tournefier, Bondu

On call: Barsotti

Neeprior work (simulation/off-line analysis) :

Commissioning activity:	ITF restart				
TASK:	Tidal control, marionette re-allocation and switch to low noise coil driver	**Task code**:	R19	**Responsible:**	Losurdo

Goal: Reallocate locking force to IP/marionette with usual frequency bands (DC-10 mHz, 10 mHz-5 Hz) and switch to low noise coil drivers.

Procedure: As C7. Check for any unpredicted problem. New WE driving matrix should be tried.

ITF status: fully locked

Time required: 1 shift

Shaked HW & SW:

Required personnel: Losurdo, Ruggi

On call: Braccini, Heitmann

Needed prior work (simulation/off-line analysis):

Commissioning activity:	ITF restart				
TASK:	ALP macro restart to science mode	**Task code**:	R20	**Responsible:**	Dattilo

Goal: restart and tuning of the ALP macro up to science mode (without complete alignment)

Procedure: The ALP macro to science mode is checked. Robustness test of the ALP procedure are performed. The ALP macro is validated

ITF status: fully locked, marionetta and Low noise coil drivers switched working

Time required: 1 shift

Shaked HW & SW: whole ITF.

Required personnel: Dattilo

On call: Barsotti, Ruggi

Needed prior work (simulation/off-line analysis):

Notes & comments:

Commissioning activity:	Restart				
TASK:	Sensitivity measurement	**Task code**:	R21	**Responsible:**	Tournefier

Goal : Measure the sensitivity and make the noise budget

Procedure : In step 15 the calibration curve is measured with white noise injection. Transfer functions are measured in order to make noise projection: white noise is injected in PRCL and MICH degrees of freedom and in the SSFS. A first noise budget is done with the known noise sources. Additional sources of noise are investigated offline through coherences.

ITF status : ITF fully locked in low noise and differential mode automatic alignment

Time required : 2 shifts

Shaked HW & SW : all

Required personnel : Tournefier, F. Bondu

On call: Barsotti

Needed prior work (simulation/off-line analysis) :

Notes & comments :