CNRS
Centre National de la Recherche Scientifique

INFN
Istituto Nazionale di Fisica Nucleare

Advanced Virgo ISC subsystem plan
DRAFT

François BONDU

ARTEMIS

VIR-085A-08
Issue: 1
Date : October 22, 2008

EUROPEAN GRAVITATIONAL OBSERVATORY - VIRGO Project
Traversa H di Via Macerata, 56021 S. Stefano a Macerata - Cascina (PISA), ITALY
Secretariat: Telephone (39) 050 752 521 * FAX (39) 050 752 550

1 Introduction

This note describes the identified AdV design activities and the corresponding tasks, as requested by [1], for Interferometer Sensing and Control (ISC). This updates the document [2]. The tasks are separated two phases, a design requirements one and a preliminary design one. The design requirement tasks define the necessary inputs to do the design, the tools needed, the interfaces with other sub-systems. The ISC design requirement document (ISC DRD) will be the first milestone. The preliminary design phase will be completed with a preliminary design document (ISC PDD), second milestone.

This document does not include tasks for the final design phase, not identified yet.

The scope of ISC activities follows the "Advanced Virgo preliminary cost plan and budget execution plan" [1]; in addition, it addresses the parametric instabilities issue, that might be a serious problem in the interferometer control. The tasks described here describe more precisely the ISC scope.

The ISC work is divided in four main activities:

- Linear Locking scheme,
- Linear lock acquisition,
- Alignment,
- Parametric instabilities.

2 Linear locking scheme

2.1 Main responsible

G. Vajente, INFN Pisa and Pisa university.

2.2 Scope

The goal of this activity is to define the modulation/demodulation scheme and the modulation frequencies; it defines a stable control strategy for the DARM, SSFS, CARM, MICH, PRCL, SREC degrees of freedom such that the DARM (dark fringe) is not sensitive to the noises of other degrees of freedom.

Its scope includes the second stage of laser frequency stabilization. Its scope does not cover the first stage of frequency stabilization (LAS), nor the laser power stabilization (LAS). This activity does not include the IMC locking and RFC locking when the second stage of frequency stabilization in not engaged (INJ); it includes these two servo loops when the second stage of frequency stabilization is engaged. It does not include IMC alignment loops. Its scope does not include the study of non degenerate recycling cavity (NDRC) in an optical point of view: tolerances on the radii of curvature of the mirrors (OSD), multi-modal study (TCS), etc. Its scope does not cover the definition nor the realization of electronics and software (DAQ). This activity defines the necessary pick-off beams, together with required demodulation frequencies; its does not cover the implementation design of photo-detection and demodulation (DET). The activity delivers the specifications on the mirror motion of all optics with respect to an inertial frame; this activity does not imply a choice on an actual realization to obtain the necessary performances (SAT/PAY).

2.3 Design requirements tasks

2.3.1 Tasks

Signal recycling: equations, lengths, modulations

Responsible: G. Vajente, INFN Pisa and Pisa university.

This task addresses the basic equations of an interferometer with Fabry-Perot cavitites in the arms, a power recycling mirror and a signal recycling mirror. The deliverables are technical notes with equations and explanations of frequency response of a Michelson interferometer with Fabry-Perot cavities and power and signal recycling mirrors. This task is now finished [3, 4].

Feed-forward techniques

Responsible: B. Swinkels, EGO.

The initial virgo sensitivity profited from the feed-forward techniques. The auxiliary degrees of freedom were acting as noise sources on the dark port (DARM), because of the non diagonal sensing matrix. The mitigation consists in adding, in the detection bandwidth, additional no-diagonal driving elements to compensate non-diagonal sensing ones. This task is finished [5].

Multi-modulation scheme

Responsible: G. Vajente, INFN Pisa and Pisa university.

The aim of this task is to compare the use of schemes with several modulations. In the first scheme, the demodulation is achieved with beating a pair of sidebands with the carrier; in the second one, the beating can be among pairs of sidebands. This task is finished: the note [6] shows that the non-diagonal sensing matrix elements are strongly reduced with the use of double demodulation schemes.

Transfer function simulation with radiation pressure

Responsible: G. Vajente, INFN Pisa and Pisa university.

The aim of this task is to determine the role of the radiation pressure in the transfer functions used to lock the longitudinal degrees of freedom of the interferometer. The detuning of long arms in order to make a DC detection couples linearly the arm length variations to a force on the mirrors. This changes significantly the driving transfer functions. The Optickle software, developed by the LIGO collaboration [7], is able to perform simulations of opto-mechanical transfer functions. This task is finished [8].

Feed-forward and shot noise correlations

Responsible: A. Heidmann, LKB.

In a simplified power-stabilization loop, the in-loop shot noise and the out-of-loop excess shot noise are indeed correlated, if both measurement are shot noise limited. This task is finished (internal technical note to be written in english).

Frequency stabilization architecture

Responsible: F. Bondu, ARTEMIS.

The frequency stabilization used in initial Virgo proved to allow a lot of gain in the lower limit of the detection band, around 10Hz, where is it most needed. This task is finished.

2.4 Preliminary design tasks

2.4.1 Tasks

Specifications on core mirror motions

Responsible: G. Vajente, INFN Pisa and Pisa university.

The role of this task is to determine the specification on the RMS fluctuations of mirror longitudinal motion and on the spectral density motion within the detection bandwidth. This task is finished[9].

Specifications on mirror control noise

Responsible: TBD

This task determines the maximum spectral density of the control noise on core mirrors to not affect the gravitational wave channel.

Specifications on RF oscillator phase and amplitude noise

Responsible: TBD

This tasks determines if there are specifications on RF oscillators phase and amplitude noises.

Quantum noise subtraction in a Michelson interferometer with Fabry-Perot arms

Responsible: TBD.

This tasks determines the correlations of the in-loop quantum noise of the MICH loop and the DARM loop. It then asserts if a feed-forward technique is possible.

Quantum noise subtraction in AdV interferometer

Responsible: TBD.

This task determines the correlations of the in-loop quantum noise of CARM, PRCL, SRC, MICH with DARM loop. The two different quadrature have to be taken into account. It then asserts if a feed-forward technique is possible.

Interferometer as a Multiple Input Multiple Output system

Responsible: TBD

This task determines the rules for the stability of the interferometer when taking into account the non diagonal term in sensing and driving matrices.

Second stage of laser frequency stabilization

Responsible: F. Bondu, ARTEMIS

This task determines the optimal feedback loop given the simulated transfer function. It determines what is expected to be the best error signal. A trade-off analysis can give a recommendation on the arm cavity asymmetries (losses, finesse); it will be used by OSD to determine if input/end test masses etalons are required.

2.4.2 Deliverables

- Specifications on core mirror longitudinal motion (PAY/SAT)
- Pre-stabilized laser frequency noise after Input Mode Cleaner (ISC/INJ)
- Specifications on photodiode excursion in steady state (DAQ/DET)
- Specifications on photodiode gain and noise in steady state (DAQ/DET)
- A set of modulation frequencies, with quadratures to be modulated (DAQ/INJ/DET)
- Macroscopic lengths between suspension points (IME/VAC)
- Specifications on RF oscillators and RF PLL phase noise.
- Specifications on mirror control noise in steady state (PAY/DAQ)
- Specifications on digitization noise (DAQ)
- Recommendation on arm cavity asymmetry for frequency stabilization (OSD)

2.5 Inputs from other systems

- Photodiode maximum bandwidth (DET)
- Possible showstopper for modulation frequency choice in EMC and electronics teechnology constraint (DAQ)
- Possible showstopper for modulation frequency determination in electro-optics modulator (INJ)
- Possible showstopper for modulation frequency determination in RF oscillator stability (DAQ)

3 Longitudinal lock acquisition

3.1 Scope

The role of this activity is to define a lock acquisition technique and sequence. It describes what are the required laser beams, signals and modulation frequencies.

3.2 Design requirements tasks

3.2.1 Tasks

Power recycling cavity lock acquisition

The "Variable finesse" technique proved to be a successful deterministic lock acquisition technique. It consists of detuning the Michelson interferometer (differential distance between beam-splitter and arm cavity input mirrors) to a bright fringe to enlarge the recycling cavity bandwidth so that it is larger than the laser line-width. This task is finished.

Simulation of arm cavity lock with auxiliary laser lock acquisition

Responsible: F. Cavalier, LAL.

This task determines whether it is possible to acquire the lock with an auxiliary laser, and make a transition to the acquisition by the main laser. This task is finished. Reference TBD.

Arm cavity lock acquisition techniques

This task reviews the possible lock acquisition techniques (non linear speed reconstruction, auxiliary laser, etc) and makes a technique recommendation.

3.3 Preliminary design tasks

3.3.1 Tasks

Experimental demonstration of cavity lock acquisition with auxiliary laser

Responsible: F. Cavalier, LAL.

This task demonstrates the lock acquisition of a cavity where radiation pressure plays a role similar to the one in Advanced Virgo. The CALVA setup is based at LAL (Orsay).

Specifications of arm cavity mirror velocity

This tasks determines the maximum velocity of the test mass mirror and the maximum velocity of the auxiliary cavities mirror to allow lock acquisition. It discusses the case with loop bandwidth, cavity finesse, and laser frequency noise.

Specifications on required force magnitude for lock acquisition

This tasks determines the force required on mirrors at lock acquisition. This takes into account the minimum force to acquire lock (considering cases with reduced power and full power), and the constraint on magnetic noise coupling. This helps the design of the mirror actuation excursion range.

Full interferometer lock acquisition

Responsible: G. Vajente, INFN Pisa and Pisa university

This tasks determines the lock acquisition procedure and setup of the full interferometer assuming that the arm cavities are already locked. It makes recommendations to make a deterministic lock acquisition sequence.

Laser line-width for lock acquisition

Responsible: F. Bondu, ARTEMIS.

This task determines the maximum allowed line-width of the pre-stabilized laser locked on IMC, IMC locked on RFC, so that the lock acquistion of arm cavities and recycling cavity is possible.

3.3.2 Deliverables

- Force required for lock acquisition (PAY/DAQ)
- Recommendation on cavity finesse (OSD)
- Specification on mirror velocity (SAT)
- Input laser frequency noise line-width (INJ)

3.3.3 Inputs from other systems

- Recommendations for magnetic noise mitigation (NOISE)
- Expected mirror motion with improved inertial damping (SAT)

4 Alignment

4.1 Main responsible

M. Mantovani, EGO.

4.2 Scope

4.3 Design requirements tasks

4.3.1 Tasks

Simulation software simulation

Responsible: M. Mantovani, EGO.

The role of this task is to determine the needs for the alignment loop simulation. This task is now finished. Optickle includes TEM00 and TEM01 modes, allowing the simulation of alignment with radiation pressure. Finesse can include many high order modes and mirror surface defects, allowing the study of offsets in alignment error signals.

Comparison of Anderson-Giordano and Ward techniques

Responsible: M. Mantovani, EGO.

The role of this tasks is to evaluate the pros and cons of both methods. This task is now finished. The Ward technique releases the constraints on the modulation frequencies; it may help in mitigating the offsets on alignment signals encountered in initial Virgo.

Stability of angular degrees of freedom in High-power cavities

Responsible: M. Mantovani, EGO.

The role of this task is to determine if some modes can be instable in the Virgo arms once the radii of curvatures have been chosen, following a technical note from LIGO. This task is now finished.

4.3.2 Deliverables

The choice of the Ward technique imposes to have pick-offs of the light reflected by the arms, either from input test mass wedges (MIR) or from misaligned TCS compensating plates (TCS).

4.4 Preliminary design tasks

4.4.1 Tasks

Influence of etalon on alignment error signals

Responsible: M. Mantovani, EGO.

The role of this task is to determine possible offsets induced by etalons in arm cavity mirrors. This task is now finished [10].

Control scheme in the steady state case

Responsible: M. Mantovani, EGO.

This defines a scheme for the control of the 18 degrees of freedom. This requires the tuning of opto-mechanical parameters (Gouy phases, demodulation phases). Specifications on the spectral densities of control noises are extracted.

Influence of compensating plates on alignment error signals

Responsible: M. Mantovani, EGO.

Accuracy requirements for local controls

Responsible: M. Mantovani, EGO.

This task determines what are the specifications on the local controls to acquire the lock of the automatic alignment system.

Negative optical torque mitigation

Responsible: M. Mantovani, EGO.

This task determines what are the necessary changes in the control software to cope with the negative optical torque for some angular modes.

4.4.2 Deliverables

- Requirements on mirror local control angle alignment (PAY)
- Requirements on angular control noise (PAY)
- Requirements on global control software for negative torque mitigation (DAQ)

4.5 Inputs from other systems

5 Parametric instabilities

5.1 Main responsible

P.-F. Cohadon, LKB.

5.2 Scope

The parametric instabilities consist in the coherent ringing of a mechanical mode of a cavity mirror by the circulating power. In arm cavities it involves a 3-mode coupling between the main optical mode, a mechanical mode and a second optical mode. The frequency difference of the two optical modes matches the mechanical mode, and the excited optical mode matches the mirror surface deformation under the vibration. The role of this task is to evaluate the number of modes potentially at risk, propose passive and active mitigations, so that the performance of the interferometer are only marginally affected at most.

5.3 Design requirements tasks

Simulation of parametric instabilities with Virgo parameters

Responsible: P.-F. Cohadon, LKB.

The role of this task is to simulate the R factor of the instabilities. It could be done using the same software as the one from LIGO (Perth - D. Blair's group).

Experimental demonstration in a 3-mode configuration

Responsible: P.-F. Cohadon, LKB.

The experiment currently in progress at the Laboratoire Kastler Brossel in Paris, in collaboration with the Perth's group, is based on a hemi-confocal cavity with a mirror coated on a micro-resonator. The cavity and the resonator geometries, together with the cavity length (4 cm), are optimized in order to get a strong spatial overlap between two optical modes, namely the TEM0,0 and TEM0,3 modes, and one mechanical mode. The cavity length can be accurately tuned so that the three-mode interaction process becomes resonant. The cavity is already built and the tuning ability checked. The objectives of the experiment are first to observe the three-mode coupling and the resulting mirror dynamics through the light emitted in the TEM0,3 optical mode. We then plan to characterize the parametric instabilities and test table-top solutions to reduce their effects.

5.4 Preliminary design tasks

5.4.1 Tasks

Parameter accurate determination

The role of this task is to give precise predictions for the optical losses of each possible optical mode, and give precise predictions for losses of each mechanical mode.

Parametric instabilities active control

The role of this activity is to determine a possible active control of parametric instabilities.

Parametric instabilities passive mitigation

The role of this activity is to evaluate the performance of the passive solutions developed within the LIGO collaboration (hairy dampers, coated bands on mirror barrels, etc.).

5.4.2 Deliverables

- Software of hardware for control of PIs, if possible (DAQ)
- Passive/active damping elements on test masses (MIR)

5.5 Inputs from other systems

6 Activity risks

The risks of each task will be evaluated in a future release of this document.

7 Execution plan

The task planning will be available in an other document.

References

[1] The Virgo Collaboration. Advanced virgo *preliminary* cost plan and project execution plan. Virgo note VIR-043A-07, 2007.

[2] E. Calloni. Advanced virgo isc tasks. VIR-057A-08, 2008.

[3] G. Vajente. Note on signal recycling I: field equations. Virgo note VIR-030B-08, 2008.

[4] G. Vajente. Note on signal recycling II: length and modulations. Virgo note VIR-032A-08, 2008.

[5] B. Swinkels, E. Campagna, G. Vajente, L. Barsotti, and M. Evans. Longitudinal noise subtraction: the *alpha*, *beta* and *gamma* technique. Virgo note VIR-050A-08, 2008.

[6] G. Vajente. Advanced virgo length and sensing control: double demodulation vs. single demodulation. Virgo note VIR-050A-08, 2008.

[7] `http://ilog.ligo-wa.caltech.edu:7285/advligo/ISC_Modeling_Software`.

[8] G. Vajente. Simulation of advanced virgo length and sensing control system. Virgo note VIR-068B-08, 2008.

[9] G. Vajente. Requirements for the advanced virgo length sensing and control system. Virgo note VIR-083A-08, 2008.

[10] S. Hild M. Mantovani, A. Freise. The consequences of using the etalon effect to tune the arm cavity finesse on the alignment signals for advanced virgo. Virgo note VIR-027A-08, 2008.