LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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Recommendation of a design for the OSEM sensors

K.A. Strain, S. M. Aston, C.A. Cantley, R.J.S. Greenhalgh, H. Ward, D.M. Hoyland, N.A. Lockerbie, N.A. Robertson, C.C. Speake, A. Vecchio,

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of the Advanced LIGO Project, prepared by members of the UK team.

Institute for Gravitational Research
University of Glasgow
Phone +44 141 330 5884
Fax +44 141 330 6833
E-mail k.strain@physics.gla.ac.uk

Department of
University of Birmingham
Phone +44 (0) 121 414 6447
Fax +44 (0) 121 414 3722
E-mail av@star.sr.bham.ac.uk

Engineering Department
CCLRC Rutherford Appleton Laboratory
Chilton, Didcot, Oxon OX12 0NA
Phone +44 (0) 1235 44 5297
Fax +44 (0) 1235 445843

Particle Physics and Astronomy Research
Council (PPARC)

http://www.ligo.caltech.edu/

http://www.eng-external.rl.ac.uk/advligo/papers_public/ALUK_Homepage.htm.

1 Introduction and scope

1.1 Purpose

This document is intended to present sufficient information to allow the UK proposal for the sensors of the OSEMs in Advanced LIGO to be approved by the project. In particular it

- states or summarizes the main requirements
- provides a means of comparing expected performance against the relevant requirements
- states the recommendation of the UK team and shows that the requirements can be met with low risk

1.2 Scope

The document discusses the displacement sensors forming part of the OSEMs to be fitted to the major suspensions within Advanced LIGO (i.e. mode cleaner, recycling mirror, beam splitter, folding mirror, and test mass suspensions). Minimal attention is paid to all other suspension components.

It is also necessary to consider any special requirements on cabling, electronics or algorithms needed to produce the displacement signal. Not all aspects are discussed in the documents provided at this stage.

1.3 Terminology

Several types of sensor have been considered for the present application, brief descriptions are given here with fuller information given in section 4.

- Interferometric sensors offer the most obvious route to high sensitivity, but it is challenging to find a design that is easy to use, simple and reasonably low cost.
- Geometric sensors are divided into several types, using combinations of techniques such as split-detectors, modulation/demodulation to reduce 1/f noise, optical amplification of the displacement signal, etc. This class of sensor can perform with moderately good sensitivity, but only at the expense of requiring relatively powerful light sources and using modulation techniques.
- Basic shadow sensors, like the designs employed in Initial LIGO and GEO 600, use an 880nm beam which is partially blocked by a moving opaque flag. The signal is obtained by monitoring the power in the beam beyond the flag, with a single-element detector. This type of sensor is considered for application in locations where low sensitivity is adequate (to reduce component cost).

1.4 Acronyms

ISC	interferometer sensing and control
LSC	length sensing and control
OSEM	optical sensor electromagnetic actuator

2 References

The document depends on

LIGO-T000051-01-D

G010086

E960050-A-E

G030339 (ALUKGLA0020).

E960020-B-E

T040001

T040045-00-K

Complete descriptions of the proposed sensors, and the work undertaken to verify performance please consult

T040043-01-K, T040044-01-K and T040052-00-K.

3 Primary requirements for OSEM sensors

3.1 Generic requirements

The following requirements, common to all suspension types, are given in outline form. Only the more significant requirements are stated.

- **Range**: the working range of OSEM sensors is required to be 3 mm end to end[1]. This is required to allow ±1 mm operating range plus an additional ±0.5 mm tolerance for relative positioning of OSEM and the sensed mass. This requirement may well be relaxed given more mature suspension conceptual designs (the positioning tolerance seems generous). The range requirement for global control sensors has not been defined, it is likely that reaction chains will have to be aligned with respect to main chains to within a few hundred micron accuracy to achieve correct alignment of electrostatic and electromagnetic actuators. In this circumstance initial LIGO OSEM sensors (something similar developed from them) should suffice for the global control OSEMs in terms of range (although, as noted below, extended range versions of these would be useful for various local control applications in any case).
- **Fit**: the sensors must fit the actuator, (the coil of which is constrained to be located at a predetermined distance from the moving magnet). The sensor must be able to sense the motion of the mass through the bore of the coil. The overall size of the OSEM must be smaller than approximately 40 mm diameter by approximately 70 mm long (cylinder), including connectors and mounts[2].
- **Vacuum compatibility:** the sensor components must meet the vacuum compatibility requirements appropriate to the Advanced LIGO vacuum chambers.
- **Electrical compatibility:** the drive and output signals for the sensor must be compatible with reasonable designs for the cables passing through the SEI system (ideally standard LIGO cables).

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[1] This requirement is not given to us formally, it is assumed appropriate by SUS on a relatively informal basis.

[2] Length given by Calum Torrie based on constraints in the current TM quad layouts.

- **Thermal compatibility:** the sensor components must not produce too much heat (see section 6)
- **MTBF:** the sensors must satisfy project MTFB requirements (see section 6)
- **Magnetic compatibility:** the sensor components must not exert significant magnetic forces on the actuator magnets (see section 6).

3.2 Global control OSEMs

Additional requirements that only apply to global control OSEM sensors.

- **Electrical compatibility:** global control OSEM sensors must tolerate the more limited cabling available down the reaction pendulum chains. This cabling must be soft compared to the stiffness of the suspension i.e. much less than of order 100N/m. (TBC)
- **Sensitivity:** the sensors must have sufficiently low noise in the ~10 Hz frequency range to allow TBD. The sensors must have sufficiently low noise in the 0.5 to 5 Hz band (TBC) to allow characterization of the rigid body modes and primary cross-coupling factors for the longitudinal, pitch and yaw modes of the suspension.

3.3 Local control OSEMs

The requirement for sensitivity of the local control OSEMs varies from suspension to suspension and among the degrees of freedom. Several assumptions were made in the analysis required to derive these requirements from the suspension design requirements and conceptual design. (Not all of these assumptions are significant to the recommended approach.)

- We assume uncorrelated noise sources at 10 Hz and above.
- The layout of OSEMs was taken into account in the noise calculations (2 or 3 in vertical and 2 or 3 in longitudinal alignments according to the latest information from SUS).
- The mirror displacement noise expected from OSEM sensor noise was modeled using the transfer functions provided for each suspension type (using available MATLAB models – all results were later updated with those provided by Norna Robertson). The GEO-style controller was set at nominal gain (to give less than 10s damping time). It is assumed that the noise at 10 Hz can be reduced by a factor of 30 in science mode by turning down the gain (by ~ 3 times) and by improving the filtering provided within the control algorithm[3].
- It is assumed that the suspension designs are essentially fixed (or at least the recommended OSEM performance will be kept in mind as any changes are approved).

For each suspension type there are requirements for longitudinally-acting sensors (longitudinal, yaw, and possibly pitch), the transverse-horizontal sensor, and the vertical-sensors (vertical, roll and usually pitch). In each case there are two considerations

- **Control band noise during acquisition**. Here the *rms* velocity of the mirror is taken into account. This is evaluated by comparing the figure for a suspension damped by noiseless and noisy sensors, in the presence of suspension point noise at the level set by SEI design requirements. It is observed that the most significant noise is that around 1 Hz (maximum

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[3] It is noted that, for at least some of the suspensions considered, the *rms* velocity, due to excitation through the SEI, is minimized by reducing local control gain by a factor of roughly 3. It is expected that the combination of gain reduction and enhanced filtering is conservative.

loop gain in local controls and minimum pendulum attenuation). This varies little among suspensions (if they are damped to a given settling time) so the effect is considered only for the TM suspensions, in the longitudinal direction.

- **Noise in science mode at 10 Hz**..

The procedure used to derive the requirements is given here

- read the number for longitudinal, transverse horizontal, or vertical noise from the DRD (these include any cross coupling factors)
- divide by 10 (standard safety factor for technical noise)
- divide by the square root of the number of sensors acting (1, 2 or 3)
- divide by the transmissibility of the relevant suspension and degree of freedom (sensor to mirror, with standard GEO-style controller)

The transmissibility figures presented in this document were provided by Norna Robertson on 24th Feb '04, these were derived using the latest versions of the suspension models, most of the figures obtained were very close to provisional numbers derived by the UK team. The exceptions were those for the TM suspensions which now provide roughly a factor of 2 less isolation than was expected[4]. It turns out that the requirements arising from damping of angular degrees of freedom are always less stringent than those for the associated linear degrees of freedom, and are not reported here.

3.3.1 Main suspension chains

3.3.1.1 Test Mass suspensions

3.3.1.1.1 Science-mode noise

- Horizontal longitudinal sensors: in science mode feedback from these may be turned down and replaced by LSC/ISC signals.
- Horizontal transverse sensor: the requirement, for noise less than $2\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$, is easily met even by the basic sensor type (since this is the most stringent requirement for transverse horizontal other cases are not discussed in detail, see the summary tables).
- Vertical sensors: there are two options
  1. With eddy current damping of the suspension at a level appropriate for science mode, in which case there are no specific noise requirements
  2. With no eddy current damping, but with a better controller, when the requirement is noise less than $1.4\times10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$

3.3.1.1.2 Control-band noise

As stated above the control band noise is given for the two (or perhaps 3) longitudinally acting, local control OSEMs. The method described above was used to compare the *rms* velocity of the mirror with and without additional sensor noise. Several noise models were used, and it was clear that for most reasonable spectral distributions (white, pink, or any plausible, steeper slope) the noise around 1 Hz was most significant. To give a concrete example, with white noise at

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[4] This is due to length reduction to fit LASTI, a small change in the vertical direction has occurred, it is not certain why, but was probably due to using an incorrect model in early evaluations of the OSEM requirements.

$1\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ and with the nominal controller gain (~10 s damping time) the *rms* velocity was increased from $7\times10^{-10}\,\mathrm{m/s}$ to $11\times10^{-10}\,\mathrm{m/s}$ (integrating from $1\sim$ $7\times10^{-10}\,\mathrm{m/s}$. It is, therefore, suggested that sensors with displacement noise $<1\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at around 1 Hz are adequate, in this worst-case application. **Beam Splitter and Folding Mirror suspensions**

In this case we attempt to anticipate the change of the suspensions to triple pendulums, which puts a more stringent requirement on the sensors.

- Horizontal longitudinal sensors, in this case there is a difference between BS case (assume the ISC signals are used to provide control) and FM (no ISC control). The summary table shows only the requirement for the FM (or BS with no ISC control).
- Vertical sensors: see table, options similar to TM suspensions.

3.3.1.3 Recycling mirror suspensions

Neither eddy current damping nor the use of ISC signals is considered. The use of a revised controller allows basic sensors to be employed (although if performance is in doubt advanced sensors could also be afforded and fitted).

3.3.1.4 Modecleaner mirror suspensions

- Horizontal longitudinal sensors: requirement $1.7\times10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$
- Horizontal transverse sensor: requirement $1\times10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$
- Vertical sensors have a requirement of $1.1\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$

It is noted that the requirements for mode cleaner performance are only indirectly related to project science goals, relaxation of this particular set of requirements by a factor of 2 or3 should not be difficult if required. Depending on a closer analysis of requirements basic sensors may suffice for the vertical direction (again if in doubt advanced sensors can be fitted).

3.3.1.5 Summary tables

The tables are split in two for convenience.

3.3.1.5.1 Longitudinal and vertical

SUS	MC	MC	RM	RM	TM	TM	BS/FM	BS/FM
DOF	L	V	L	V	L	V	L	V
No.	2	3	2	3	2	3	2	3
DRD	3.00E-18	3.00E-15	4.00E-17	2.00E-14	1.00E-20	1.00E-17	2.00E-18	2.00E-15
TR	3.70E-06	4.90E-04	6.10E-06	4.50E-04	2.10E-07	1.20E-04	9.40E-07	2.30E-03
1	5.73E-13	3.53E-12	4.64E-12	2.57E-11	3.37E-14	4.81E-14	1.50E-12	5.02E-13
2	1.72E-11	1.06E-10	1.39E-10	7.70E-10	1.01E-12	1.44E-12	4.51E-11	1.51E-11

Key: SUS: suspension; DOF: degree of freedom; No: No. of OSEMS in that DOF; DRD: requirement from DRD (units of displacement noise spectral density); TR: transmissibility from N.A. Robertson (MATLAB models); 1: result assuming standard controllers (units of displacement noise spectral density); 2: result assuming improved controllers. Shaded regions show requirements removed by switching to ISC feedback and eddy current damping. Basic sensors are probably adequate in some cases.

3.3.1.5.2 Transverse horizontal

SUS	MC	RM	TM	BS/FM
DOF	TH	TH	TH	TH
No,	1	1	1	1
DRD	3.00E-15	2.00E-14	1.00E-17	2.00E-16
TF	4.00E-06	6.00E-06	2.00E-07	1.00E-06
1	7.50E-10	3.33E-09	5.00E-11	2.00E-10
2	2.25E-08	1.00E-07	1.50E-09	6.00E-09

The key is as above. Basic sensors are adequate in all cases with improved local controls (or even just modestly reduced gain)

3.3.2 Reaction suspension chains

The reaction pendulum chains are fitted to provide quiet actuation platforms from which to operate the global control actuators. Apart from the TM suspensions it is clear that basic OSEM sensors are going to be adequate. The use of basic sensors for longitudinal damping of the TM reaction chains should be no problem if the global actuators transfer less than 1% of the motion from the reaction chain to the main chain (at 10 Hz), or with higher coupling if the local control gain is reduced. Our interim conclusion is that all reaction chain local control OSEMs may be of the basic type.

4 Technical features of the proposed techniques and risks

4.1 Interferometric sensor

The interferometric sensor uses a diode laser, and a polarizing beamsplitter that gives quadrature outputs from the 2 ports, as needed to allow fringe counting in addition to fractional fringe measurements. Output from a 3rd port with a phase of 180^o allows dc offsets to be subtracted. The 3 outputs are subtracted in pairs using two difference amplifiers leaving 2 dc-corrected channels to be read-out. Single-element detectors are needed to measure the fringes at the three ports. The two arms are fitted with plane mirrors and a cat's eye reflector is incorporated into the interferometer avoiding the need for a retroreflector on the suspension mass. Two significant features of this approach are

- Each degree of freedom requires two signals to be recorded
- There is no automatic DC position reference. The range is limited by the coherence-length of the laser, and no adjustment in the sensed direction is required.

It is relatively straightforward to achieve the desired performance without large light power, use of modulation/demodulation etc.

The measured noise at about 10 Hz is $\leq 5 \times 10^{-13} \mathrm{m}/\sqrt{\mathrm{Hz}}$.

The perceived risks with the interferometric sensor are complexity of construction and laser MTBF. The latter problem is adequately addressed by the addition of a second laser which can be activated should the first fail (promptly, automatically), we expect the laser lifetime (after testing for early mortality) to be >100,000 hours. There is some risk associated with the selection of the laser (reliability, noise performance). We note that component and assembly cost is higher than the alternative geometrical sensors, but there is a large saving if the need for eddy current damping can be removed. It is necessary to ensure that units are tested for susceptibility to back-scattered light. Each finished OSEM will need to be qualified in this respect.

4.2 Geometric sensor(s)

The details of these sensors are given in the full technical documentation, but the basic idea is to produce a strongly modulated, bright, reasonably collimated IR beam of at least 3 mm extent. This is then directed though an optical system which is partly mounted on an extension of the sensed mass, and falls on a split photo detector. The detected photocurrents are demodulated coherently to produce sum and difference signals. The sum signal can be used to regulate the drive to the emitter, and the difference is the useful signal. A significant feature of this design is

- Relatively high AC drive current is needed

The shot noise at about 10 Hz is $\leq 1.5\times10^{-11}\mathrm{m}/\sqrt{\mathrm{Hz}}$, and this is essentially flat to ~1 Hz, but it was not possible to achieve the optimum noise performance over the entire working range. The reasons for the excess noise were not fully understood, but were observed in a number of slightly different designs. The common element was the emitter, and this is suspect as the source of excess noise. Given the shortage of alternative emitters it is likely that exchange of the emitter although possibly removing the excess noise, would most likely raise the shot noise by a factor of about 3. There is a major risk that no sufficiently low noise, high power, good beam quality emitter is available. These designs require high light power and strongly modulated high-current signals that must not contaminate the low current output signals. Heat production and signal handling are additional risks, as high light power is needed to achieve the desired dynamic range (SNR).

4.3 Basic “Modified Initial detector” sensor

The simplest sensor design consists of an emitter (as per geometric sensor, but driven at lower current and probably at DC), with a simple occlusion sensor to determine position (flag and single element detector). If DC drive is used it may be necessary to fit filters to screen the detector from stray light from the main interferometer, otherwise AC drive is possible. This design is under consideration for the global control OSEM sensors, transverse horizontal sensors on all suspensions and a few other less critical degrees of freedom on RM and MC suspensions. This is worthwhile as over half of the OSEMs fit one or other of these categories.

The noise at about 10 Hz is $\sim 1\times10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$. The noise in the control band is TBC at 1 Hz. It will probably be necessary to redesign the layout of the basic sensors to work with new coils and magnets, allow simpler mass-production, and (probably) to extend the operating range.

To achieve a 3 mm range, the largest under consideration, at least 38µA of photocurrent is needed to achieve the target noise performance.

5 Proposal

5.1 Constraints and summary recommendation

The choice of sensor is constrained by technical (fit, electrical requirements, thermal considerations and noise performance) and financial considerations (development costs, production costs). **We recommend the use of the interferometric design wherever high sensitivity is required together with basic OSEMs for global control, local control of reaction chains, and transverse horizontal local control.**

5.2 Summary of rationale

The interferometric approach provides the most secure approach to the sensitivity requirement. The high component cost is partly offset by elimination of eddy current dampers. It is likely to be difficult to deploy the interferometer design on the global control OSEMs, due to fit and cost. The requirements for the sensors on global control OSEMs are not completely clear, but it is expected that a simple "GEO style" (or Initial LIGO style with increased range) shadow sensor is adequate. The interferometer design avoids problems with heat production and the need for high current AC drive associated with the geometrical sensor design.

	Interferometer	Shadow/imaging
sensitivity	5e-13	2e-11 (but only at null)
range	3 mm	3 mm
Thermal	No issue	Probably OK
Cables	Fine	Fine unless we regulate emitter with AC to stabilize (radiates noisy AC)
Size Cylinder <40mm by <70 mm	Small risk *	No risk
Reliability	Laser (worse? Soak test? 2 for redundancy?)	LED (better?)

Table of risks used to aid selection of interferometer. * although there is no complete drawing of the interferometer, it seems relatively easy to fit it into the required volume, so the risk is very small.

5.3 Proposal

5.3.1 Global control OSEMs

We propose to fit basic shadow sensors with 3 mm range and displacement noise of $\sim 1 \times 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 Hz. This would apply on all suspensions requiring global actuation by OSEMs.

5.3.2 Local control OSEMs (not reaction pendulums)

We propose to fit interferometric sensors on most degrees of freedom of most suspensions. Transverse-horizontal local control does not require sensitivity $\leq 1\times10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$ and basic sensors are considered for this application to reduce cost.

5.3.3 Reaction pendulum Local control OSEMs

It is assumed that all OSEMs on reaction pendulums are of the basic type (sensitivity $\sim 1\times10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$).

6 Requirements common to all sensor types

6.1 Alignment and adjustments

The basic and geometrical sensors require 3D adjustment to within about 0.5 mm of the best alignment. The interferometer requires initial angular alignment, but no fine-alignment along the sensed direction.

6.2 Vacuum compatibility

All sensor designs (except possibly the basic one) require the use of metal bodied, glass-lens emitter/detector packages, glass optical components, metal mounts, screws, flex-rigid circuits, and glass-ceramic, PEEK and Kapton insulation. Although some tests are required, this is not thought to be an issue that distinguishes among sensor proposals as all involve similar parts and materials.

6.3 Electrical compatibility/requirements

The different sensor technologies have differing requirements for cabling. This could have significant cost impact so is considered here. Note that the geometric sensor has some risk associated with required screening levels. The basic and interferometric sensors should work with existing cables as used in Initial LIGO.

6.4 Thermal compatibility

It is necessary to operate all components at a low enough temperature to control the risk of temperature-induced aging. This is most likely to be a problem for the geometrical designs and for the global control OSEM sensors to be mounted on the reaction pendulum chain, where there is a lesser heat-sinking effect than on the suspension support structure.

6.4.1 Heat produced by the coil

Requirements on actuator strength and practical limits on magnet strength determine the heat budget for the coil. Local control actuators are likely to be similar to those in GEO 600. There the coil resistance is 50 Ω and the maximum current is 100 mA, so the maximum power dissipation is ~0.5W. Starting from Peter Fritschel’s talk (G010086) it seems that using the strongest magnets allowed would allow slightly lower maximum power.

6.4.2 Heat produced by the sensor

The interferometer and basic designs produce around 50 to 100 mW of heat. The geometric sensor would produce about 500 mW.

6.4.2.1 Local control OSEMs

We assume infinite heatsinking (effectively) – no problem is expected with any type.

6.4.2.2 Global control OSEMs

Radiation provides the dominant heat removal process, the higher dissipation associated with the geometrical sensors could be problematic on the reaction chains.

6.4.2.2.1 Conduction through wires

Quad reaction pendulum suspension stages are generally supported on 4 ~1 mm diameter steel wires (therefore total area $\sim 3\times10^{-6}\mathrm{m}^2$), and there is probably of order ½ m of effective wire length between the typical OSEM location and the SEI. The conductivity of steel is $\sim 30\mathrm{W/Km}$, and so these wires do not conduct significant heat.

6.4.2.2.2 Radiation from mass

The quad pendulum masses have effective radiating areas of about $\sim 0.05\mathrm{m}^2$. The emissivity is highly uncertain, but Stephan's law suggests a temperature rise of ~30 K for 2 W of dissipation with an emissivity of 0.2, a typical value for stainless steel. [A better estimate would be useful.]

6.5 Interface to actuator

It is thought that all sensors can interface to the actuator coil form relatively simply.

6.6 Magnetic properties of components

Some of the components of the proposed sensors are magnetic material (mainly metal semiconductor packages). These will exert forces on the magnets in the actuator. The forces must be kept very small compared to the bias forces applied to the suspension. A reasonable target for the maximum force due to this effect is 1 mN.

The forces between the largest magnetic component (OD-50L emitter, expected to be similar to a laser diode in terms of ferromagnetism) and a 10 mm diameter 10 mm long Ne:Fe:B magnet were measured. With an offset of 10 mm the force was found to be 40 mN, falling as the cube of the offset as expected. The 1 mN threshold requires a separation of at least 34 mm. This has some bearing on the design of the sensor. This is easier to deal with in the interferometer than in the other designs (as the laser and photodiodes are at the "back" of the sensor in that case).