LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
– LIGO –

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	**DCC Number**	**Date**
Technical Note	**LIGO- T000029-00-D**	**14th of March 2000**

SAS Baseline Design and Prototypes Test Program Plan

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Distribution of this draft:
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Introduction

The SAS prototype and test plan has evolved substantially since the Glasgow meeting. Two new facts have produced these changes:

1) Further thinking have questioned the suspended optical bench requirement given at the Glasgow's meeting

2) Our TAMA colleagues asked for assistance to rapidly adapt and install SAS in their interferometer.

The SAS configurations.

About the requirement of a single seismic attenuated optical bench in the BSCs we challenge the idea of imposing an optical bench common to more optical elements (see letter to the TAG chairman dated January 11th 2000, appendix 1). SAS can effortlessly suspend, isolate and control the 800 Kg optical bench specified at Glasgow, so it would be trivial to satisfy those requirements. Actually, suspending an optical bench from which large dynamic range controls are applied to the multiple pendula is a much less demanding task than the SAS targets. SAS, on top of delivering outstanding seismic isolation, aims to strongly reduce the multiple pendulum dynamic range requirements. The reduction of these requirements would be achieved by means of better attenuation, positioning and control performances at low frequency for each individual interferometer mirror. The reduction, by orders of magnitude, of the multiple pendulum's required authority suppresses non Gaussian noise of the locking actuators on the suspension system. Installing two or more main mirrors on the same optical bench (as for example the inner and folding mirrors in the 2000 m interferometer) would require a large mirror authority, at least as large as the static misalignment between the two mirrors (up to a millimetre).

To avoid this problem the SAS group proposes an independent suspension of each main mirror and of ancillary optics in each BSC.

The HAM optical benches never carry more than a single main optics mirror. A seismically isolated optical bench is still the baseline SAS solution for the HAMs. Because of space requirements, until recently we favoured a supported bench solution. The latest results with the Monolithic Geometric Anti Spring Filter (MGASF, see later) and the results from the Glasgow's meeting brought us to reconsider a suspended solution.

The TAMA-SAS project.

TAMA scientists have found that low frequency attenuation deficiencies of their system prevent a reliable and low noise operation of their interferometer. Having ascertained the necessity of an efficient low frequency seismic isolation system, they have been seeking for an advanced system to upgrade TAMA. They found that the SAS is the best suited system and they asked for our assistance to implement it. The task is to rapidly build a first, shortened, version of the TAMA SAS system and, later, a full fledged TAMA SAS system. The first part of this work is detailed in the SAS R&D Program Plan[1] and TAMA-LIGO MOU Addendum 5; the plan outline is the following.

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[1] Available in DCC

- TAMA scientists joined the SAS team to use the present LIGO SAS prototype (an IP plus a GASF F0 and two completely passive GASFs supporting a dummy payload) to reproduce in air the Virgo controls and attenuation performances and to develop the control algorithms for TAMA and LIGO II (work ongoing)
- We have built and are testing a miniaturised and simplified MGASF that can fit in the TAMA vacuum vessel diameter.
- We have designed a TAMA compatible SAS system (IP + F0 + one GASF) and are finalising its engineering drawings (production ongoing).
- We will test this prototype in air at Caltech with a TAMA double pendulum payload in April/May.
- Following the above tests, engineering design optimisation and production will follow in the summer.
- Installation in the 3 meter Fabry Perot interferometer (at the University of Tokyo) and its operation is scheduled for the fall 2000.[2]
- Following the 3 m validation tests, refined engineering design should be used to build the TAMA SAS chains to be installed in Spring 2001 or whenever convenient to the operation of that interferometer.
- The acquired know how will be used for the final LIGO II SAS design.

TAMA may later proceed to the implementation of taller IP and additional MGASFs for further improvement of the performances, depending on the evolving requirements , schedule and budget available.

The testing of the LIGO SAS prototypes is being accelerated by the tight TAMA time constraints and personnel contributions. SAS development for LIGO II will profit from the knowledge that will be acquired by the TAMA SAS and will continue in parallel during its operation.

The increased manpower generated by the TAMA scientists[3] and other collaborators that have recently[4] or will join the group in the next few months[5], together with the support from University of Pisa, INSA of Lyon and the growing exchanges with the Virgo superattenuators group, will allow a speedy testing of the prototypes and verification of the calculated fulfilment of the LIGO II requirements.

After this rather long but necessary introduction, let's give more specific answers to the TAG questions.

The SAS philosophy

The passive attenuation of seismic motion using low frequency mechanical oscillators is a mature concept, which is being extensively used and demonstrated by the Virgo superattenuator group.

The SAS passive attenuation capability is more than sufficient to satisfy all present and foreseeable gravitational wave interferometer requirements. Active controls are used in SAS only to reduce the low frequency residual r.m.s. payload motion and to position it within a small fraction of a micron from its intended working point. No use of active

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[2] This project is the subject of the doctoral thesis of Akiteru Takamori, of University of Tokyo (MOU between Caltech-LIGO and University of Tokyo, addendum 1).

[3] Kenji Numata and Akiteru Takamori working in SAS-Caltech and other scientists collaborate from Japan.

[4] Joe Kovalik (postdoc), Szabolcs Marka (postdoc), Flavio Nocera (electronics engineer), Hareem Tariq (undergraduate full time for one year), Chenyang Wang (undergraduate)

[5] Frederick Seve, graduate student in mechanical engineering from INSA Lyon

feedback is made for seismic attenuation purposes. SAS Active controls are relegated upstream of the passive attenuation chain and well outside the frequency range of interest to avoid any risk of excess feedback and actuation noise.

The LIGO-SAS group is building prototypes not to prove SAS functionality, which is already being proven by the Virgo group[6], but simply to:

1) Certify and characterise the performance of the more advanced LIGO components (GASFs, more rigid IP mechanics, accelerometers[7], MGASFs, etc.)
2) Reproduce the Virgo performances and verify the improvements with our advanced mechanics and LIGO geometry.
3) Test new components and concepts (for example magnetic damping of the passive chain internal modes).
4) Build and test a modified SAS systems for the HAM chambers.

Most of these tests can be done in air and will be performed at Caltech; test in vacuum will be performed at ETF, LASTI and (on a smaller scale) in TAMA.

Dimensioning and Designing the SAS Structures

SAS is conceived, both in its virtual and in its hardware components, as a toolbox of different units capable to be configured into seismic attenuation chains that individually satisfy all the seismic attenuation and control requirement of each optical element in LIGO.

The software side of SAS is represented by MSE, a C++, object oriented, 6 d.o.f., distributed mass and distributed elasticity Mechanical Simulation Engine.

To design a new seismic attenuation system using MSE, the different components, simple (wires, beams, etc.) or complex (GASF filters, IP, etc.) can be dimensioned and combined to form a system satisfying the desired specifications.

Virtual actuators and sensors allow the excitation of the system and the extraction of the signal respectively.

The virtual system can then be analysed both in the frequency and in the time domain. A display of the ellipsoids of inertia of the different components allows easy understanding of the modal shapes and easy monitoring of the system performance in the time domain.

MSE can also be connected to the e2e interferometer simulation program or to other programs like Matlab to simulate control loops.

These tools are used to tailor the SAS performance to each and individual optical payload.

Once the desired specifications have been met or exceeded in a MSE simulation, the hardware units can be rapidly designed and built. Simulated prototyped components are continuously compared.

During the prototyping phase sometimes the virtual design was ahead of the game, like for example the standard GASF performance (figure 1).

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[6] The LIGO II requirements are actually very similar (if not somewhat less stringent in the low frequency end) to the Virgo ones.

[7] The advanced accelerometer project is the doctoral thesis of Alessandro Bertolini of University of Pisa, he is a full SAS group member spending his University of Pisa grad student fellowship to develop these accelerometers on SAS specifications.

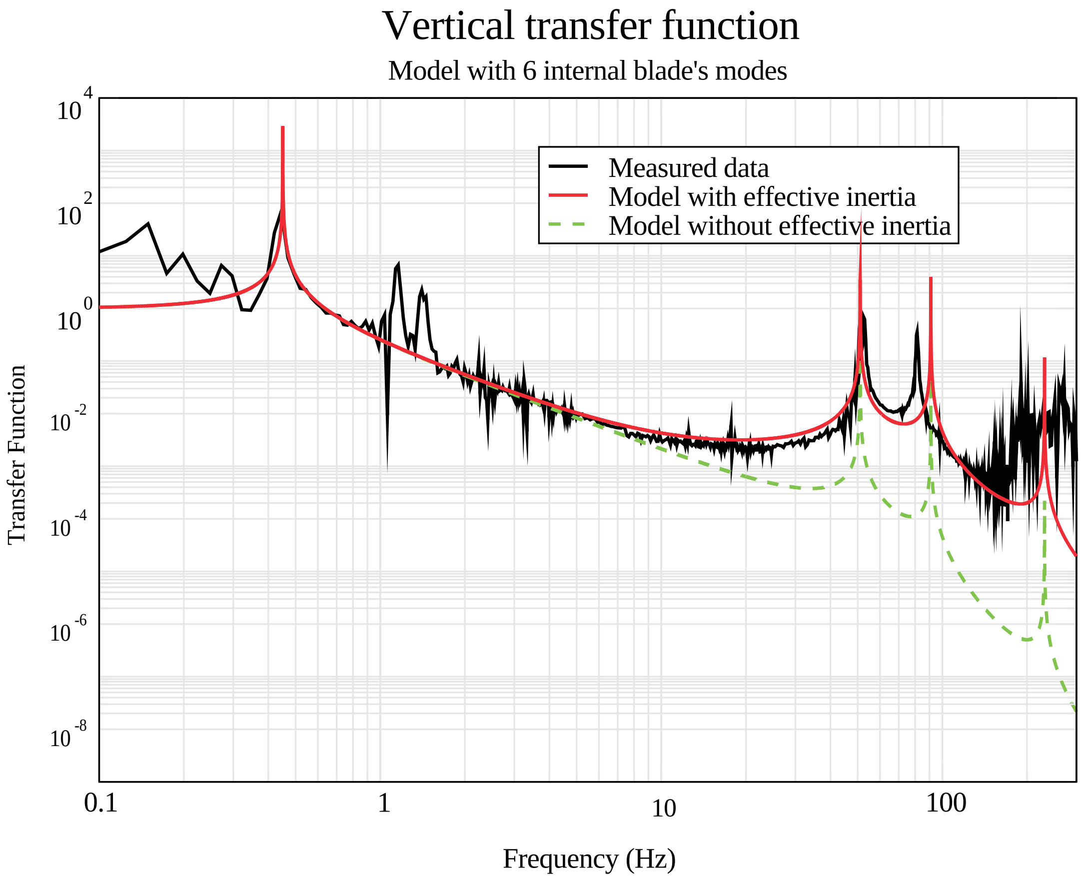

Figure 1: Simulated and measured performance of a GASF, the simulation predated the measurement, the red line is the complete simulation while the black line is the measured data, above 150Hz the data is acoustic noise dominated. The green line is a simulation where the effect of the distributed mass over the blade has been omitted. It shows that the Filter performance is limited at 40 - 50 dB by this mass effect.

Sometimes the hardware prototype measured performance forced an upgrade of the virtual system, as it recently happened with the Monolithic GASF, that achieved 60 dB attenuation, as shown in figure 2, while 45 to 50 dB were expected by a simple extrapolation[8]. The better than expected MGASF performance may allow some simplification of the LIGO-SAS and maybe the elimination of a filtering stage.

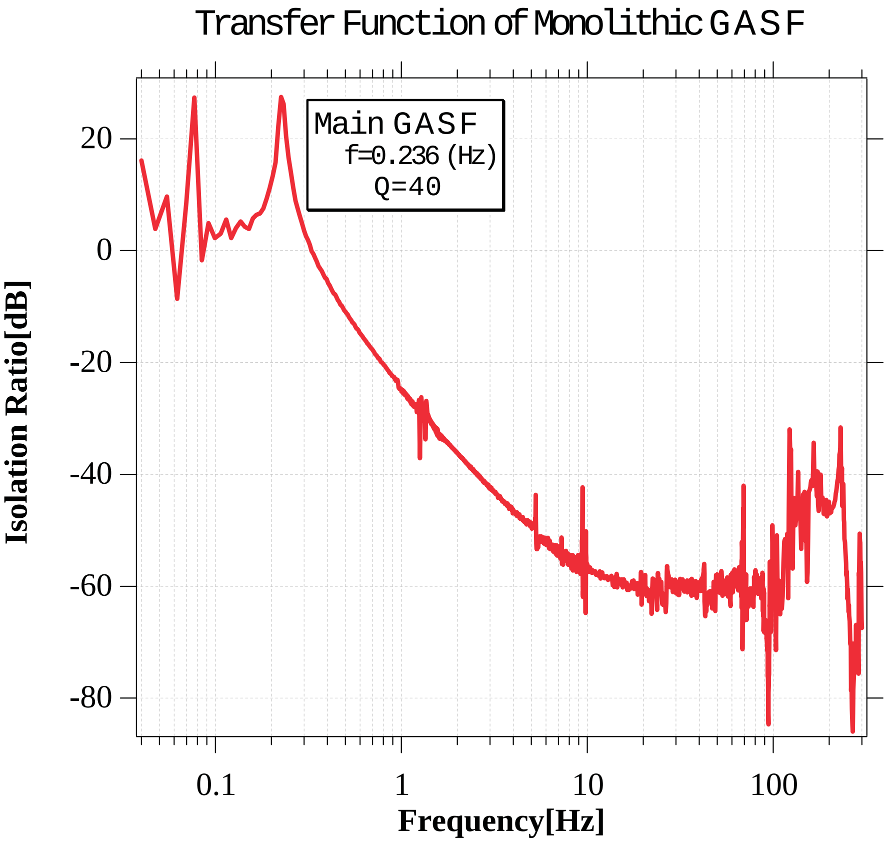

Figure 2: Measured attenuation performance of the new MGASF developed for TAMA 300. Above 100 Hz the measurement is probably dominated by acoustic noise.

By and large, the SAS toolbox components are already well known and tested and the simulation is detailed enough for reliable performance predictions. SAS chains can be configured to easily satisfy all present and new requirements.

This achieved versatility of SAS is proven by the speed of the TAMA-SAS development that started only in late December 99. Thanks to the accumulated know-how, the pre prototype has already been tested, and the entire prototype SAS chain is being built and testing should start in April 2000. TAMA-SAS chains should be installed in a test 3 m interferometer by fall 2000 and in TAMA in 2001.

The experience gathered in this development will lead to further refinements of the simulated units. This will allow LIGO-SAS design without surprises.

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[8] no complete MSE model was performed of that prototype because MSE was in the process of evolving from an ad hoc simulation to a modular system.

Meeting the Seismic Attenuation Requirements

There are several SAS configurations that satisfy the requirements of each LIGO optical payload. Some examples are shown in the following. They show older GASF and have not yet been updated to the new MGASFs.

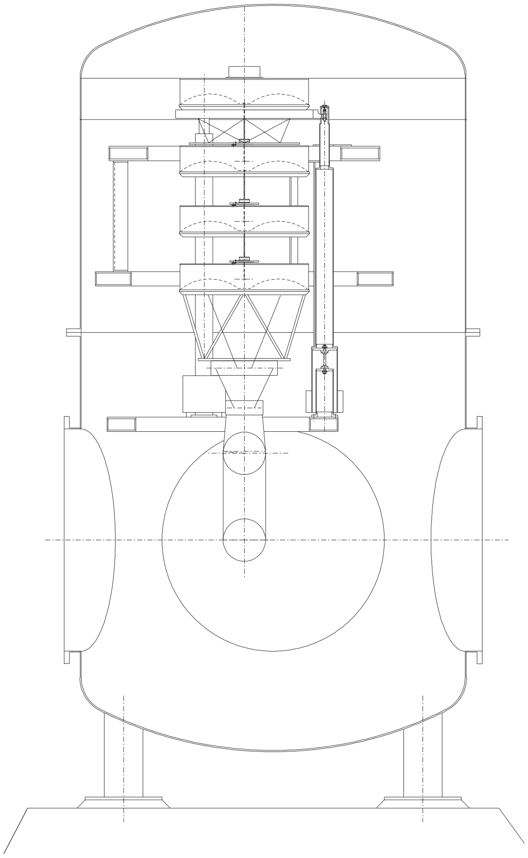

Figure 3: SAS chain supporting a GEO quadruple pendulum inside a BSC chamber. A small optical bench can be suspended from an independent IP-F0 unit (not shown). In order to implement a second main optics suspension the vacuum chamber should be extended vertically to allow interleaving of two complete SAS chains in addition to a small optics bench.

Figure 3 shows a simple SAS chain suspending a quadruple pendulum mirror. This is the baseline SAS configuration for the BSC. It is formed by an Inverted Pendulum (IP) and a Filter Zero (F0) followed by a number of GASFs; the last GASF is also the recoil platform from which the top multiple pendulum masses are controlled. According to our simulations, the attenuation performance of this chain is adequate to uncover the mirror thermal noise below 10 Hz (figure 4).

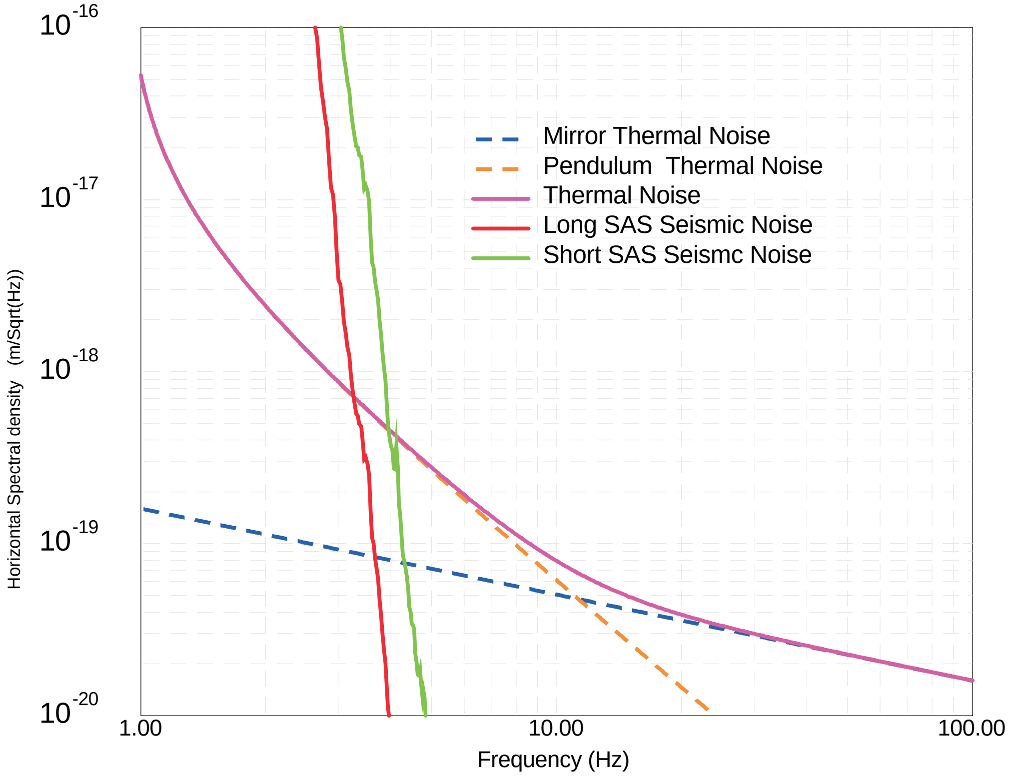

Figure 4: Simulated attenuation performance for short and long SAS chains, the short SAS chains fit inside the existing BSC chambers.

Smaller optics would be carried on a light optical table separately suspended from an independent simplified SAS (an IP and F0). There is enough space in the BSC to accommodate these two staggered systems[9].

For the specific case of the 2000 m folding and inner mirror it will be necessary to assemble two high performance SAS chains and a small optics table. In this case it may be necessary to extend vertically the BSC to house the three staggered SAS.

The advantage of this scheme is that precision positioning of all mirrors (and optical tables) is performed independently from the top of the passive attenuation chain. Minimising the actuation range requirements for the multiple pendulum may likely allow to reduce it to a simpler triple pendulum (with further space saving).

No fully detailed MSE simulation of an entire SAS chain is available yet because MSE development has given priority to the understanding of some of the LIGO I structures. MSE is already advanced enough to give us full confidence that SAS will completely satisfy the requirements. Some early examples of MSE simulations are given in figures 5,6 and 7. As MSE gets fully debugged and running it will be an extremely powerful design tool for SAS.

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[9] We have already performed an engineering study that proves that we can fit two completely independent SAS chains (the 2-in-1 concept) within a two meter diameter vacuum vessel. Fit a third SAS chain in the 2.6 meter diameter LIGO BSC is a simple engineering exercise especially if the miniaturised MGASFs are used.

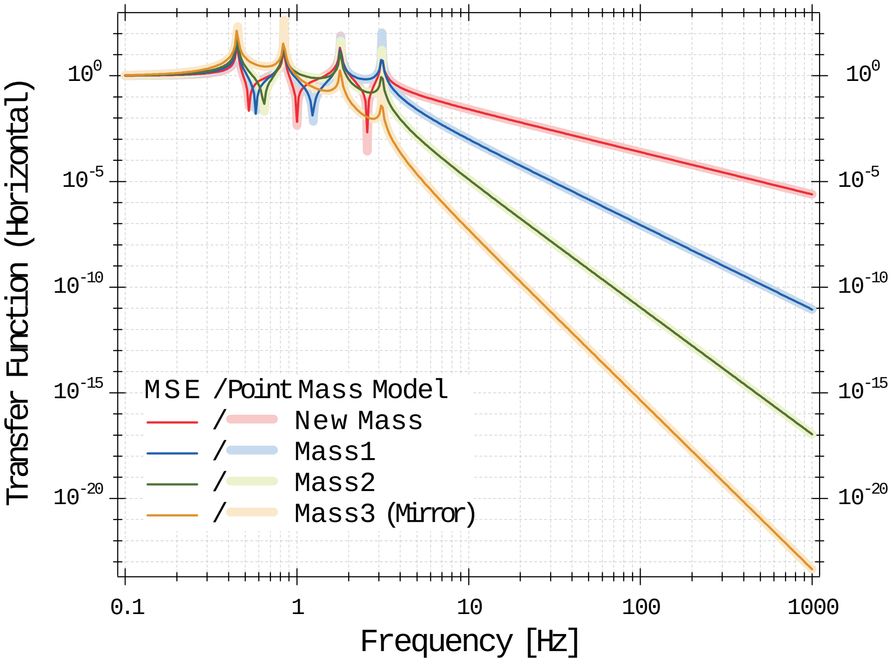

Figure 5: Transfer function in longitudinal direction simulated with MSE. Each wire is connected at the same level of the centre of mass of every stage. Shadows represent the transfer function obtained with a simple point mass model. These two results agree completely.

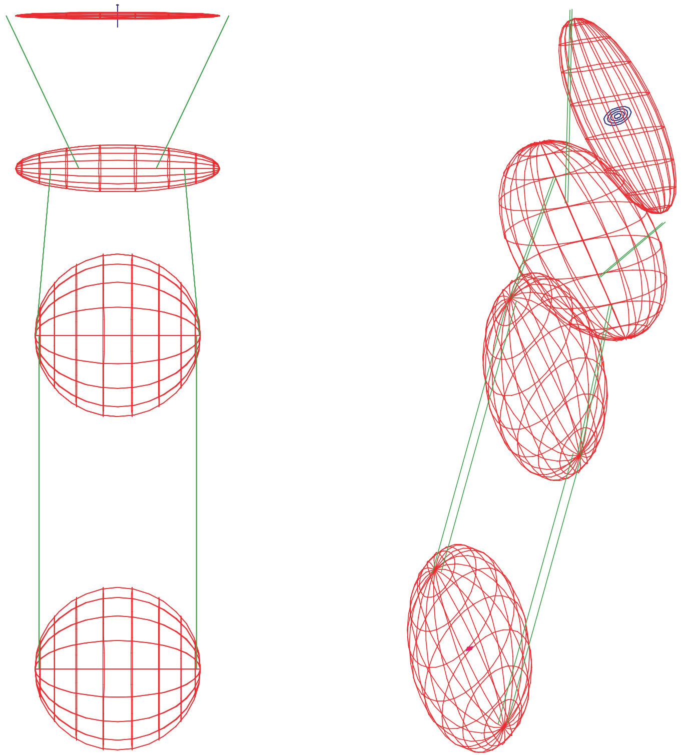

Figure 6: MSE provides schematic 3D view of the simulated system, which allows users to check easily the distribution of mass and moment of inertia and connection of each object. User can see the system from arbitrary view points. The system can be animated at given frequency also. This feature realises quick understanding of the eigen modes of the system

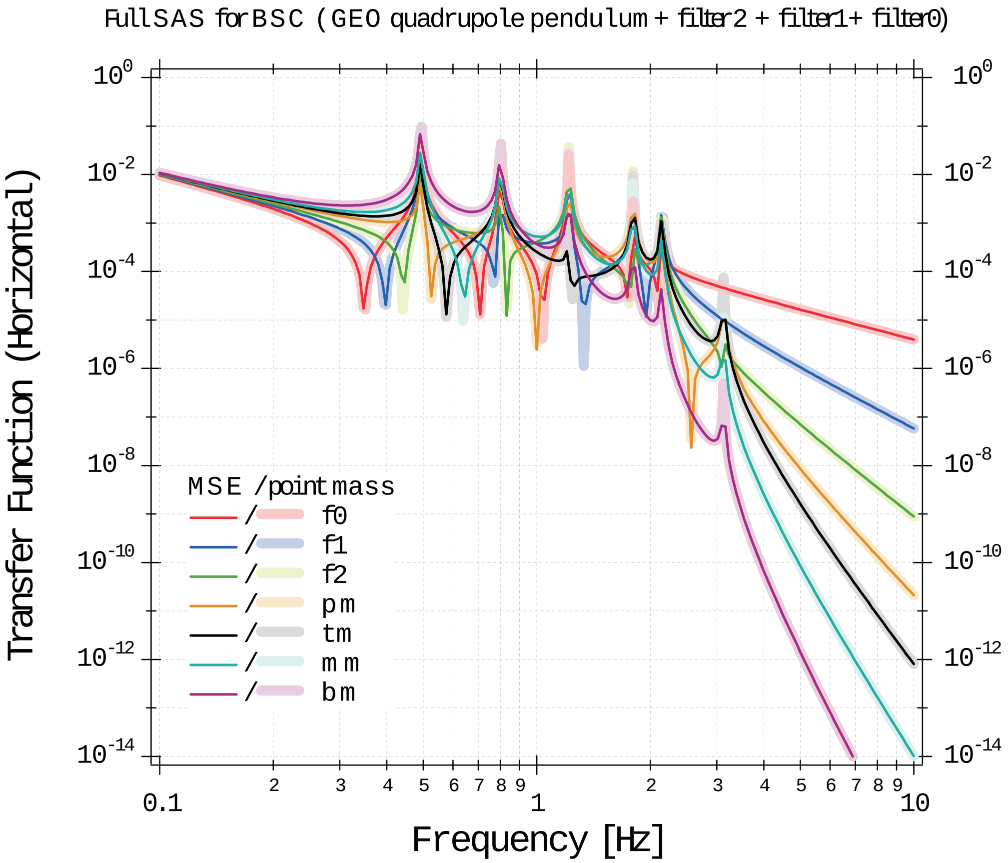

Figure 7: One dimensional projection of a 6 d.o.f. MSE simulation of a quadruple pendulum and BSC SAS chain compared with a standard one dimensional simulation.

The HAM optical tables

The HAM optical table technical problem is less demanding but more complex mechanically. The HAM SAS design is less advanced than the standard BSC-SAS[10].

The old HAM optical table design.

Until recently, for access and space reasons, the HAM-SAS baseline design was based on a supported (as opposed to suspended) optical bench. The bench would stand on semi-commercial, very low frequency, stands (2-300 mHz in all three directions) with passive attenuation capabilities comparable to the suspended SAS ones. The stands would be derived from commercial units (minus-K technologies). The optical bench would be controlled in 6 d.o.f. but otherwise much the same way as the IP and F0 of the standard SAS chains. The performances of the minus-K stands have already been measured, and found quite satisfactory. We designed a prototype to take advantage of the performance of these stands which has supposed to be built by end of March. Although the Minus-K test system would have supported the real optical bench recovered from the old HAM's mock up, it was not yet designed to completely fit inside the HAM chambers, not yet UHV compatible and not yet built in the SAS standard of creep and creak free materials and geometry. Unlike the standard SAS chains, this HAM SAS was to be considered simply as a capability demonstrator unit as the first GAS filter prototype was in fall 1998. Although a single attenuation stage may be sufficient, two layers of Minus-K stands at increasing resonant frequency could be nested in subsequent prototypes to provide sufficient attenuation. The small optics would have sat directly on the table while a mini IP/F0 stand, derived from the TAMA SAS, would have provided local attenuation and independent fine positioning for the triple pendulum suspension of a main mirror. This is now considered a backup solution.

The new HAM optical table.

As a consequence of the Glasgow's meeting requirements and of the very recent MGASF results in attenuation performance, mechanical simplicity and compactness, we have revised our HAM SAS conceptual design.

The new design, see figure 8, is now suspended and completely homogeneous, both in attenuation philosophy and in controls, to the BSC-SAS concept.

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[10] This project is intended to be the subject of the doctoral thesis of Frederick Seve, of INSA Lyon (MOU between Caltech and INSA-Lyon, addendum 1)

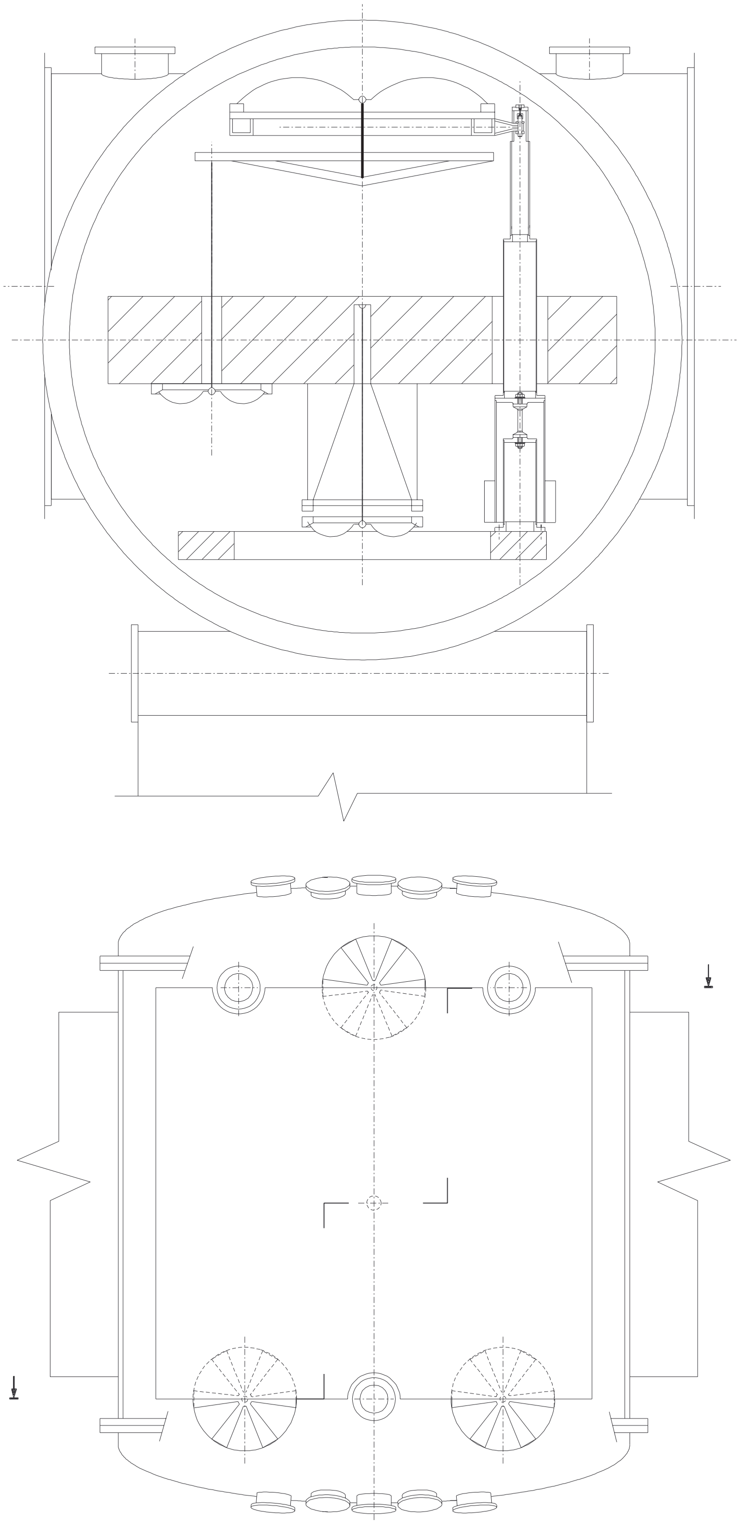

Figure 8: SAS geometry suspending a HAM chamber optical bench, side and top view.

The MGASF units are located below the bench. The HAM bench surface is left clear and enough vertical clearance is provided for the beam telescopes. No impediment is left on the forward part of the bench at the SRE mirror location.

Three IP legs extend up from the existing HAM base plate. They are positioned at 90°, 240°, and 300° with respect with the beam axis, on the two sides of the HAM table. They carry a large MGASF that, like the F0 of the BSC-SAS, is provided with sensors and actuators for inertial damping and positioning.

A wire descending from it will suspend an upside-down, shallow, tetrahedral spider. The spider legs hold three suspension wires that suspend the optical bench. These three wires, positioned at 60°, 120°, and 270° with respect to the beam axis, traverse the bench thickness and connect to three, upside down, MGASFs for vertical compliance and additional attenuation.

A wire descending from the bench centre will suspend a 4th, upside down, MGASF. Eddy current dampers between this filter and the bench will damp all body resonances of the HAM-SAS chain. This unit satisfies the same requirements of the Eddy current brake mounted between F0 and the first GASF in the BSC-SAS.

Small, motorised counterweights will provide DC bench balancing in pitch and roll.

The inertial damping of HAM-SAS is the same as the BSC-SAS and will have virtually identical controls. Using GASF modules in the HAMs automatically solved all vacuum compatibility, creak and creep issues already which were still open with the Minus-K solution.

These reasons brought us to prefer this as the baseline HAM-SAS solution.

Future R&D and readiness level

While aggressively testing and refining the GASF and IP prototypes, we already have a perfectly viable and tested versions of each SAS chain component. We base the SAS control on the now quite advanced and provenVirgo control scheme[11]. A real life vacuum interferometer test will be realised within a year with the TAMA installation

Being ready for a 2004 LIGO II installation will simply require the freeze of the design of the day and the straightforward engineering adaptation to the individual specifications of the different payloads.

Final tests in vacuum are foreseen to be performed in LASTI and/or in the ETF.

Full scale prototypes, integrated with multiple pendula, would be tested in LASTI. Shorter wires between GASFs or a smaller number of GASFs could be used to allow vacuum capping within the lower LASTI hall roof.

ETF would serve mostly for individual GASF, accelerometer, LVDT or actuator testing.

Most of these tests will be anticipated, although to a smaller scale, by the TAMA SAS project in Japan.

We do not have a detailed and fully viable design of the HAM SAS. The development program is underway, with adequate resources, and we see no substantial technical obstacle ahead of us. Judging from the past advancement rate on the standard SAS, we believe that we can bring it to production technical readiness level within 1 year.

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[11] Reports on the advancement can be found in the Virgo site or in our web page "http://www.ligo.caltech.edu/~citsas/"

Costs

SASwill easily fit within the budget limits foreseen for the Seismic Isolation section of the LIGO II upgrade. In order to allow free choice between the stiff active system and SAS, that budget was tailored on the stiff(er) price tag. As an indication the mechanics of the full size, UHV compatible, SAS chain prototype did cost approximately $100,000 and we do not expect higher costs for the production items. Similar costs are expected for the HAM SAS system. Even including all the sensor, actuation and instrumentation costs we expect no limitations within the projected cost envelope (TAMA SAS mechanics is expected just above $50,000/chain, less than $100,000 including most of the control electronics).

Conclusions

We believe that the passive characteristics of the SAS will guarantee the best reliability and performance for the LIGO II suspensions. The system is being aggressively prototyped and tested and can easily satisfy all LIGO II specifications.

The ultra low frequency of the IP (10-30 mHz) which dominates the mirror's dynamics, coupled to the small absolute value of the residual motion (a small fraction of a micron), will generate very small mirror velocities for easy lock acquisition.

All the mirror control structures will be virtually identical, including the folding and inner 2000 m mirror pairs, thus simplifying the overall interferometer operation.

Independent positioning and attenuation effectively remove any actuation cross talk.

Several components of SAS have been tested already and compared with the corresponding simulations.

All components and system tests confirm that SAS will exceed all LIGO II requirements in attenuation factors, frequency range, residual motion speed and integrated residual motion. Mechanical templates exist and can readily be parameterised for specified loads and performances.

We do not expect any technical risk in using the SAS technique. Moreover we will take advantage of the experience of other groups, and we will have a field test in an interferometer within a year. That experience will allow us to weed out and eliminate any possible nonessential feature or add any necessary one to ensure good SAS performance for LIGO II.

Appendix 1

My considerations on the choice between the stiff and the SAS (soft) suspension system.

At Glasgow it was decided to make LIGO II seismic attenuation specifications based on the concept of having a seismically attenuated optical bench from which to hang down up to three multiple pendula or other optical component.
The most complex requirements coming from the last BSC in the short interferometer in Handford that house a folding mirror, an inner mirror and a telescope.
The proposed specifications lead to a fine and internally consistent design, but it has to be considered the long term price for LIGO.
A true optical table has an attractiveness because it gives a degree of flexibility as it allows the re-localisation of the optical components by simply moving them around the optical table surface and repositioning some counterweights.
However, because of the fact that the optical components can be aligned between themselves only up to a certain level, a lot of control authority is required at the multiple pendulum level. Large authority at this low level in the seismic attenuation chain requires large forces close to the mirrors and the possibility of large re-injected noise. To keep this noise in check it is then necessary to introduce a quadruple pendulum geometry, in which the second (passive) layer is present only to filter out the actuation noise.
Also having large standing forces near the mirror opens the way to possible non Gaussian noise pick-ups either from the electrical cabling and/or from direct coupling to the standing force itself or from the recoil mass from which the test mass chain is actuated.
The quadruple pendulum then necessarily looks like a double passive attenuation chain, including the vertical attenuation on both the test and the recoil mass chains.
The optical bench, which is said to simplify the seismic attenuation chain concept, in reality increases the complexity of the suspensions and mixes seismic attenuation issues with thermal noise and actuation ones in a much more profound way. Incidentally the argument that the optical bench is a visible and well-defined interface between seismic isolation and suspension system here fails.
Additionally having feedback loops directly attached to the same suspension table may produce cross talk problems.
It is also worth mentioning that the present LIGO HAM optical benches are quite practical and easy to use because the optical units sit on them and can easily be first aligned and then clamped down. The proposed optical benches for the BSCs would be, like the present ones, overhanging optical roofs from which the multiple pendula hang down. From these roofs it is not that easy to internally align optical elements. The optical bench then does not give much of a simplification to the system. Also in many BSCs the bench may be completely superfluous and eliminating it will entail a significant cost reduction and real simplification.
The Glasgow meeting requirement of an optical bench for the new LIGO seismic attenuation and suspension chains is then clearly a heavy mortgage on the future of

LIGO. This is especially true in view of the fact that we are likely to upgrade the seismic isolations only once and it would be difficult to justify a second upgrade later on if the first one is too timid.

It seems to me that having fully separate and independent seismic attenuation systems for all the optical elements with nulled standing forces around the mirrors is an advantage that should not be given away lightly, especially if effortless suspension point positioning and negligible test mass residual motion can be delivered as well. This is one of the main advantages that can be delivered by the soft SAS that we propose. We have already shown how to fit two independent SAS chains within the diameter of 2 meters and three chains can be easily fit within the 2.5 meter diameter of the BSCs. The much criticised attenuation overkill capacity comes as a bonus and should be sneered at.

Note that independent, remote and analogue positioning of all suspension points within 10 mm range is trivial in SAS. This feature may actually make optics tuning easier than having the same elements sitting on a bench, not even mentioning hanging under an optical roof. (Large re-positioning of payloads in SAS can be achieved by simply changing the lengths of the arms between the IP legs and the top filters, this level of flexibility is similar to that of accessing an optical table and moving around payloads and counterweights.)

While we are working to modify a SAS design that fulfils the Glasgow's meeting specs, it seems to me that those specs are outdated and should be re-evaluated by us or by the committee that will have to decide between the two solutions.

LIST of perceived SAS advantages

- Soft systems provide natural pre-attenuation at the lowest frequencies, including at the micro-seismic peak.
- Inertial damping of an IP/F0 unit have already produced measured residual r.m.s. motion of the payload of less than 50 nm integrated above 100 mHz . Even better performance is expected from the use of the advanced LIGO accelerometers on the more advanced LIGO IP.
- The IP and F0 provide a natural platform for the inertial damping accelerometers. These accelerometers, operating on a pre attenuated platform, may be expected to reach better performances, especially at low frequencies.
- The passive filters hanging from F0 effortlessly deliver the required attenuation factor with a comfortable safety margin both in amplitude and in frequency range.
- The inertial active damping controls are all safely relegated outside the frequency range of interest, all the rest is safely passive.
- The passive filters also shield the mirror from possible accelerometer and actuator excess noise (note that in the stiff system the requirements are marginally achieved considering only the sensor's white noise and disregarding any excess noise in sensing, signal processing and actuation)
- The excellent residual IP/F0 motion performance enormously reduces the triple pendulum actuation dynamic range requirements (maximum required dynamic range below the micron) thus allowing the use of electrostatic actuators on the intermediate triple pendulum masses and photon drive on the mirror. The danger of mirror actuation introducing excess noise is proportionally reduced.

- The softness of the movements allows precision positioning of the individual optical components at negligible power consumption levels.
- The capability of interleaving two or even three independent chains in the same tower allows for independent and full control of (for example) inner and folding mirrors and of ancillary optics without reintroducing large actuation dynamic range requirement for trivial static alignment reasons.
- Sub micro metric positioning of the mirrors from the chain head minimise all standing forces near the mirror thus minimising chances of actuation excess noise and external noise couplings.
- The large dynamic range of the SAS allows the rotation of individual optical elements off axis by as much as 10-20 mrad for tuneup reasons. Large longitudinal positioning range is trivial.
- Despite the low dissipation and very small internal damping of the materials used, the low frequencies of the SAS elements naturally generate large effective damping and low oscillation quality factors.
- All metal to metal connections on the stress path are made in a creak free geometry.
- All SAS components are UHV compatible and fully bakeable to relax creep activity from the stressed materials.
- Fully separated chains cannot produce actuation cross feeding between optical components.
- SAS is readily upgradable and reconfigurable in performance and load.
- know-how on soft techniques (Virgo, TAMA, AIGO) is rapidly growing.