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Answers to "Isolation criteria for the LIGO-II Seismic Isolation System" LIGO-E990304-01-D

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Note: the report “Proposal of a seismic attenuation system SAS for the LIGO advanced configuration (LIGO2)” LIGO T990075-00-D has to be considered as integrant part of this report in response to “Isolation criteria for the LIGO-II Seismic Isolation System” LIGO-E990304-01-D.

The report “Low thermal noise accelerometers for the active control of very low frequency seismic isolators” LIGO T990077-07-D is also a complementary part of this report.

Two additional separate reports,

“E2E simulation of the SAS-SUS passive attenuation system for the LIGO Advanced Configurations (LIGO2)”LIGO T990078-00-D, and “Proposal for the SAS-SUS Active Control for the LIGO Advanced Configurations (LIGO2)” LIGO T990079-00-D are the replies to questions 2 and 3 respectively.

1) The SAS is a seismic attenuation system capable of supporting and controlling the GEO triple pendulum as is either directly or from a suspended optical bench common to other optical components. Coils mounted on the last SAS filter or on an optical bench provide action on the triple pendulum common top element.

2) The large overkill of the specifications provided by the SAS allows for a lot of leeway in simulations while in a marginal system the simulations would have to be iron-tight and cross verified with experimental data to make sure that the target is met. For this reason, and for the fact that in SAS seismic motion is equally and progressively attenuated in all d.o.f. thus reducing the modal cross coupling problems, the 3D simulations are considered less important for SAS development. Nevertheless the SAS group is developing a comprehensive 6D (3 spatial plus 3 angular) simulation package integrated into the e2e model in view of in depth system understanding, system and controls optimization and future trouble shooting of the interferometer operation. Some early results of this program are given below. The SAS design already relies more on actual measurements of components of the system at LIGO and of the entire chain in Virgo rather than on simulations.

   For a description of the SAS e2e simulation status, see also report “E2E simulation of the SAS-SUS passive attenuation system for the LIGO Advanced Configurations (LIGO2)” LIGO T990078-00-D.

3) The suspension control strategy is the triple pendulum one, based on a hierarchy of actuation authority, reacting from recoil masses, starting from the test mass going upwards. Each actuator must absorb the residual motion integrated over the reaction time of the actuator above. After this time the actuator in question is relieved from its load. The triple filter top element is actuated reacting against the stiffness of the bottom passive filter that carries a lower platform. This platform, in its turn, is equipped with the triple pendulum external drive coils.

   As the deeper stages, these magnets have to hold the triple pendulum in the intended position only for the reaction time of the pre-attenuator actuators. This reaction time is characterized by the period of the slowest mechanical resonance of SAS, i.e. a few tens of seconds. Given the small-required efforts and the small time lengths involved, the available stiffness of the bottom filter is more than sufficient.

See also report "Proposal for the SAS-SUS Active Control for the LIGO Advanced Configurations (LIGO2)" LIGO T990079-00-D.

4) All the payloads can be easily supported by the SAS, either directly or through an optical bench. The payload is suspended from the SAS axis. The SAS structure can be assembled either in conjunction with a centered or off-center inside the BSC chambers (see appended report "proposal of a seismic attenuation system SAS for the LIGO advanced configuration (LIGO2)"). In case of an intermediate optical bench, its fine positioning would be controlled from an intermediate mass (marionetta) equipped with coil/magnet actuators on all necessary 6 d.o.f. as in the Virgo optical bench controls.

The less stringent requirement of the HAMs allow the use of a variety of suspensions, varying from the 10 Hz active system, to scaled down low frequency passive attenuators. In the case that a low frequency passive attenuation was chosen, modified commercial seismic attenuation units would support the HAM optical tables. These units would be basically the proprietary and patented design of Minus K Technology. They would be used after incorporating into their design our low creep, no shear connection technology and using UHV compatible materials and design.

A key feature of this system is that it passively decouples horizontal and tilt motions. The system consists of two stages. The first stage uses three modified 1000SM-1 isolators and supports a weighted intermediate platform. This platform supports the second stage comprising the optical table structure and the telescopes supported on three modified 300SM-1 isolators. (The SM-1 Series isolators are described in the Minus K Website: www.minusk.com.) Features of the optical table and intermediate platform structures and ballast weights are omitted from the sketch. The purpose of the sketch is show the basic concept and the typical size and location of the isolators. Adequate space exists in the chamber for the necessary structure and ballast weight to achieve decoupling, as described below.

Horizontal-tilt decoupling is achieved by configuring the system so that the centers-of-mass (CM) of both stages are at the same height and the horizontal "force center" of the isolators are also at that height. The horizontal "force center" is the point on the isolator at which a horizontal force produces only a horizontal displacement. It is located near the top of the isolator. Mass is added near the base of the optical table structure (not shown) in order to compensate for the mass of the table top and the telescopes and thereby lower the CM of the second stage. Similarly, mass is added near the top of the intermediate platform structure (not shown) in order to compensate for the mass of the platform and thereby raise the CM of the first stage.

Their possible use of these commercial units is illustrated in the sketch of figure 1 (provided by Minus K) showing one of various possible configurations that will fit into the existing HAM chamber.

The first stage would be operated under active damping feedback like the IP/F0 of the SAS system; the second would be passive.

Horizontal and vertical transfer functions of these attenuators are shown in figure 2. Please also refer to the appended Minus K report.

5) The proposed SAS system is the result of a long series of small and large prototypes. Our experience is that in real size prototype the internal structural resonances always shift down and may interfere with the feedback loops. At Virgo the full scale prototypes were necessary to identify and neutralize these dangerous structural resonances. Following this experience a full-scale prototype has already been designed and partially built at Caltech. The filters are already under test while the inverted pendulum is going to be ready end of August, controls will be implemented in the fall; see also point 22.

The development team is presently composed of:

Giancarlo Cella (Postdoc of University of Pisa) for the simulations
Virginio Sannibale (Postdoc LIGO-Caltech) for controls and testing
Riccardo DeSalvo (Scientist LIGO-Caltech) for mechanics
Mark Barton (Scientist LIGO-Caltech) mechanics and diagnostics
Alberto Gennai (Electronics engineer- Livingstone) for electronics (part time)
Alessandro Bertolini (graduate student, University of Pisa) advanced accelerometers and active damping issues
Akiteru Takamori (graduate student, University of Tokyo) low frequency seismic attenuation issues
Erika D'Ambrosio (Ph.D., visiting from University of Pisa) theoretical studies on non-Gaussian noise generation from system non-linearities and for seismic excess noise studies.
Nicolas Viboud, (engineering student on 6 months stage from INSA, University of Lyon) finite element studies of structural components of the system Eugene W. Cown (Prof. Emeritus-Caltech) is starting a study of noise generation for prototype testing
Hiro Yamamoto (scientist LIGO-Caltech) is assisting for integration in the more general e2e simulation system

See also point 27 for commitment levels.

Other persons or groups may be interested in participating, for example the Firenze Urbino accelerometer group of Virgo has just manifested a possible interest in taking some responsibility on the LIGO SAS development.

Ken Libbrecht (professor Caltech), Erik Black (Postdoc Caltech) and Phil Willems (Scientist LIGO-Caltech) are dedicated to suspension work and will assist on the suspension end of the SAS.

We expect to substantially reinforce the SAS group with the expertise and at least part of the manpower of the 10 Hz active group once and if the seismic attenuation technique choice is made in favor of the SAS. The 10 Hz group physicists have similar knowledge than the components of the SAS group. The combined group will obviously be much stronger and sufficient for the task.

6) The SAS is a direct development of the Virgo super attenuation chains; it will support and control the GEO triple pendulum in a manner substantially equivalent to the Virgo marionetta.

   For a trace of the acquired know how please consult the appended reference list. All technical improvement on that design has been already successfully tested in full-scale prototypes.

   Also the SAS is very similar in design to the passive attenuation chains proposed and designed for AIGO. Frequent interactions with that group contribute to the advancement and enlargement of the know how base in passive attenuation techniques. For a trace of that work please check out the recent publications from David Blair.

   Last but not least, apart from the radically different geometry and the reliance on inertial damping rather than internal one, the SAS can be seen (and logically is) an advanced and frequency-expanded version of the passive LIGO attenuation stack philosophy. Recourse of active techniques is kept to a minimum to minimize the risk inherent in the departure from the passive attenuation concept. All active inertial damping loops are also kept safely shielded from the test masses by a large passive attenuation protection factor.

7) The SAS is built all in metal, ceramic and other UHV compatible components (Kapton, and similar materials). Additionally it is foreseen to bake out the assembled units to a temperature (still to be determined) between 120 and 200 degrees Celsius to burn out all creep associated with residual stress in the materials. The simplicity of SAS assembly procedures will help keep its assembled components UHV grade clean. This, together with the carefully designed open geometry, will assure the highest levels of vacuum compatibility.

8) SAS fits into the BSC without modifications. Upgrades and scope expansions are possible by simply adding an extension pipe between the BSC and its hat (but without modifying the BSC itself), see report.

9) The HAM tables are subject to much less stringent isolation requirements than the BSC optical elements. For this reason we see no objections in using a 10 Hz active seismic isolation system in the HAMs. No detailed work was done to design passive low frequency attenuators to fit into the HAM chambers. In case it was needed the passive low frequency techniques (negative stiffness mechanisms and inverted pendula) can be applied in a nested geometry to support the HAM tables, using units of commercial derivation.

10) Offset assembly of SAS towers up to 60 cm from beam pipe axis is foreseen. Larger offsets of optical components positioning would be obtained with counterweights (the SAS can handle with no problem payloads up to a ton). The extended tower version of SAS has also the possibility of mounting 2 independent intertwined suspensions as close as 20 cm separation and as far as 120 cm. Optical components at closer quarters would be mounted from a suspended optical bench.

11) The SAS is designed to be pre-assembled, pre-baked and tested before installation. The finished entire unit would craned in place for rapid installation (see report).

12) One dimensional simulations show SAS largely exceeding all isolation performance requirements in all d.o.f. These same simulations have been found in excellent agreement with full scale, full functionality prototype measurements without having to introduce 3D corrections. This indicates that the SAS design is (according to expectations) either mostly free or insensitive to most cross couplings. The insensitivity to cross couplings is a design feature of the SAS. In SAS all d.o.f. are progressively attenuated by similar amounts to keep possible cross couplings from feeding energy into quieter modes and degrading the progressive SAS performance. A 3D simulation, essential for most other attenuation schemes, is therefore less important to estimate the attenuation performance of the SAS. A comprehensive 3D simulation package is presently being integrated and tested within the e2e model as a tool to generate detailed comprehension of all aspects and help in control design, optimization and finalization

13) The SAS r.m.s. noise piles up at low frequency and is controlled by the low frequency inertial damping, a preliminary measurement made on the taller Virgo 7-stage attenuation tower, in air, with marionetta and mirror controls off, found an upper bound of residual motion of 2 microns above 100 mHz. Much better results are expected in vacuum (few 10^{-8} m, see figure 11 of appended report). The air contribution is particularly deleterious, not only perturbing the chain itself, but especially on the feed back accelerometers that, in case of Virgo, are designed for vacuum operation and are more sensitive to air perturbation than commercial units. The Virgo measurement was done against ground, the 2 microns measured also contain a non negligible contribution from ground motion. Also the IP legs were not properly aligned in this measurement, introducing a ground tilt contribution to this measurement that will be greatly reduced with proper leg alignment. The measurement was performed without any passive internal damping (see report), which may be implemented also in Virgo and that is calculated to substantially reduce the r.m.s.. It is important to note that the achieved r.m.s. movement are already well within the hierarchical actuation range of the mirror-marionetta double pendulum system and will a fortiori easily fit within the wider GEO triple pendulum control range (specs needed from GEO).

14) The low frequency design of the SAS, together with its low r.m.s. performance insures low speeds for easy locking.

In the same preliminary measurement mentioned in the preceding point an upper limit of 4 micron/second was measured. The much better r.m.s. performance calculated for in vacuum operation are expected to drive the residual velocity well below the level required for lock acquisition (specs needed).

15) Alignment and positioning in 4 d.o.f. is provided by the I.P./F0 over millimeters and milliradians at negligible power consumption levels. The I.P./F0 have enough actuation range to compensate for earth tides and thermal drifts indefinitely, with no disturbance on data flow. Earth crust drifts can be similarly absorbed up to few mm range. Larger movements (beyond end stop limits) can be obtained acting on the pier's actuators with disturbances to data taking measured in minutes if lock is not lost.

16) SAS is designed with an ULF pre-isolator with the specific aim to deal with the micro seismic peak, which is first suppressed passively and then further by inertial damping F.B. Please cfr. Virgo results and our simulation in the report on this matter.

17) All body modes of SAS are outside the band of interest (below 5 Hz). All of these modes that produce IP recoil above the accelerometer sensitivity level are damped actively by a multi-notch F.B. loop (private communication by G. Losurdo, Virgo). Any other deleterious body mode not visible on IP can be passively damped by means of eddy current dampers suspended from F0 and acting on the first filter.

    All filter internal modes affecting the transfer function (up to 200 Hz) will be properly damped. As the F.B. loop is relegated below 5 Hz and at the IP level, filter internal modes, which appear above 50 Hz, will not interfere with it. Resonances in the mechanical structure of the active inertial damping were found to interfere with and limit the FB loop operation. These resonances (9Hz), found in the Virgo system, have been eliminated in the LIGO prototype design. The full size prototype in construction will be checked for other dangerous internal resonances.

18) Material choice, stress levels, geometry and pre-baking of the pre-loaded structure are designed to burn out overall SAS drifts to less than a micron per year. Thermal expansions levels are at the 400 mm/°C vertically and 15 mm/°C horizontally completely inside the envelope of the tidal/thermal/crust drift control actuators. Geometrical antisprings filters and inverted pendula present a particularly advantageous ratio of dynamic range versus thermal excursions. Please cfr. Calculations in report.

19) The SAS 3D simulation has been designed already integrated within the e2e model in view of future interferometer trouble shooting and system comprehension. The SAS has been designed with the help of partial or ad hoc simulations that are presently being integrated or generalized in the e2e. The partial simulations have been already validated with cross checks with the prototype performances. Their excellent agreement with data is a reflection of the highly detailed SAS description already taken into account (and so far proven sufficient to describe the observed performance). The

modular e2e SAS simulation is built to grow to integrate the growing experimental know-how for an ever more detailed system understanding.

20) The GEO triple pendulum is already suspended from cantilever blades derived from the Virgo and SAS ones. There is an advantage in this homogeneity of techniques in the SAS and triple pendulum and there is acquired experience on how to suspend it from a SAS-like system with no need of any significant further developments.

21) The SAS is directly descending from the IRAS 7 filter suspended interferometer seismic attenuation system. In the SAS the IRAS gas bag filters have been replaced with the cantilever spring concept. The magnetic anti-springs of the Virgo filters have been successfully, and with advantage, replaced in the LIGO filters by the simpler Geometric Anti Spring GAS concept. Virgo and the LIGO SAS are going to use much more advanced control systems than the IRAS system. The LIGO SAS control system could also be enhanced taking advantage of the JILA experience.

    The Australian Seismic Attenuation Design is conceptually identical to the SAS one although it relies even more on ULF passive techniques and less on active inertial damping.

    Finally the SAS team is providing assistance for the development and construction of a scaled down mini SAS system for use in TAMA.

    It should not be forgotten that SAS is a passive system, logically equivalent to the LIGO stacks, even if built to operate at lower frequencies.

22) An engineering, full-scale prototype made of two filters and a filter 0 has been already built and is under test. Although improvements can and will be added to this design, it represents an already viable seismic attenuation mechanical design that could be implemented in an interferometer as is. As already mentioned the performance of a single and double filters were found to be in excellent agreement with the simulations. The performance of the 3 filter chain prototype is presently being tested and will be confronted with the 3D simulation program to validate it. (We will not consider the simulation program operational until then, despite its already partial validation with one filter.) In the preliminary 3 filter tests we found no evidence of unexpected or excessive cross couplings even with artificially unbalanced filters. Beginning September we will add the inverted pendulum to the test chain. This setup will then represent 80% of the system proposed for the short tower and will allow testing of 99including controls of dummy triple pendula. Controls will be applied to this test chain in the fall, initially using Virgo accelerometers, provided on loan by the Firenze Urbino University group (they will participate to the measurements). Later the Virgo accelerometers will be replaced by advanced accelerometers currently being designed and produced for LIGO by the Pisa University (with scientific support from the Firenze Urbino group). Additionally our results are continually confronted with the Virgo results. This exchange complements, confirms and strengthens our prototype results.

23) The SAS is made up of just 2 basic units, the inverted pendulum and the GAS filter. Any filter can be reconfigured into any other one by simply changing its blades and its load disk, except for filter0 that on its external chassis is provided with hooking points for sensors and for the IP legs. Electronics is based on a ADC-DSP-DAC-analog driver chains many already common in LIGO. The analog drivers of the voice coil actuators are particularly simple because, thanks to the mechanics softness nowhere is requires more than a watt of peak power.

24) Optimization problems might arise to mate the SAS to the different payload topologies; otherwise we expect the general design to be already adequate for the BSCs. More extensive developments are required in the HAMs, where compact geometries of attenuators will be necessary.

25) The IP are well known devices and will be used within well known utilization parameters. The GAS filter represent a new technology used to achieve in a simpler way the filtering performance of the older gas bag IRAS filters and of the magnetic anti spring filters of Virgo. Working prototypes have been built in a fully engineered and UHV compatible form, already viable for installation. Of course they are undergoing cosmetic changes in the course of an optimization process but they already perform very satisfactorily. SAS can use the standard Virgo accelerometers for the inertial damping; advanced accelerometers will be implemented when available for further performance improvements. The active control system will similarly evolve from the Virgo one.

    Units of commercial derivation would be used in the HAM isolation. These units benefit of well established working experience. No fundamental change is expected to be necessary for this job.

26) The baseline short tower SAS can be easily tested at LASTI MIT.

    Taller options need more ceiling space and may be tested later on in a dedicated vacuum enclosure at TNI Caltech.

    Advanced accelerometers would be tested at ETF Stanford.

27) The SAS development started in August 1998. The development team comprised

    Giancarlo Cella (Postdoc of University of Pisa) for the simulations
    Virginio Sannibale (Postdoc LIGO-Caltech) testing and controls
    Riccardo DeSalvo (Scientist LIGO-Caltech) for mechanics
    Giancarlo Cella has devoted his Pisa university Postdoc to LIGO simulations. He is organizing the mechanical part of the e2e system implementing the SAS as the first e2e test bed simulation.

    Virginio Sannibale presently has a 50% commitment with the PSL installation but he plays a major role in SAS testing and control loops design.

    Riccardo DeSalvo is full time organizing and coordinating the SAS development effort.

In the fall 1998Alessandro Bertolini (graduate student, University of Pisa) joined the group to make a thesis on development of advanced accelerometers and active damping issues. He operates on University of Pisa resources with support from Prof. Francesco Fidecaro but works specifically for LIGO under the supervision of RDS.

In spring 1999 Akiteru Takamori (graduate student, University of Tokyo) joined the group to make his thesis on low frequency seismic attenuation issues under the supervision of RDS. It is understood that two years from now he will bring back to Japan the passive low frequency technology for possible implementation in their interferometer.

End of spring 1999 Erika D'Ambrosio (Ph.D., visiting from University of Pisa and applying for a Postdoc position at Caltech) joined to apply her thesiss theoretical studies on non Gaussian noise generation from system non-linearities and for seismic excess noise studies.

Mark Barton (Scientist LIGO-Caltech) has recently joined the SAS team bringing in his acquired know how on the cross pendulum. Although his time sharing for SAS is presently low because of his commitments with the LIGO I optics implementation, he expects to soon shift a majority of his attention to SAS.

Alberto Gennai (Electronic engineer, joining LIGO Livingstone) has designed the Virgo control and data acquisition electronics and plans to spend part of his time on SAS electronics and controls.

These scientists are all committed or intend to, on the medium or long term, to help in the development, construction and installation of the SAS. The group also makes use of more temporary help like Nicolas Viboud, (student on 6 months stage from INSA, University of Lyon) working on finite element studies of structural components of the system, David Ahkvan (summer student) and Henry Lubatti (technical help). Hiroaki Yamamoto (scientist LIGO-Caltech) assists us in integrating the SAS simulation package into the LIGO e2e system in view of future interferometer control issues.

External support is provided by the Firenze/Urbino accelerometer group of Virgo (they will assist us in the first accelerometer implementation and are interested in later taking advantage of our advanced accelerometers).

Additional external support comes from the Perth group of AIGO. Presently this collaboration consists only of a tight exchange of ideas and experiences. Recently they expressed their interest in concretely expanding the collaboration by common development of parts of the system, exchanging personnel, or even taking direct responsibility of some SAS subsystem development and production. All of this is still at the very preliminary level and one must take into account their present tight financial situation.

Design and construction have been done with outside companies. The SAS development progress have been slow because of lack of manpower, the main limitations having been in characterizing the prototypes for further optimization.

At the present level of manpower it may be difficult (but not impossible) to match the 2004 installation timeline. Still some quite substantial achievemant have been made.

The development has generated a wide interest which has resulted into a the rapid growth of the group and a rapid improvement of our R&D and production capabilities. Enough scientists may be expected to join the effort in the next future to insure critical mass for the SAS development and installation in LIGO II. Additionally we expect a quite substantial contribution from the 10 Hz active group once the choice of the seismic attenuation technique is made. The added manpower will accelerate the development pace.

28) A substantial fraction of the SAS design effort has been in the direction of fast and clean assembly, starting from the component level, up to the complete unit. Considerable effort was spent both in keeping the design simple and effective and in devising adequate assembly jigs and techniques. Early success on this front is given by the fast filter assembly procedure (a complete filter was properly assembled from scratch in two hours by an untrained theorist) and by the snap on connections of the wires between filters. This attention to ease of installation extends to all details like the earthquake safety structure, the ground support structure, etc. We expect to pre-assemble the entire SAS in a pre-tested, pre-baked unit that can be installed in the BSCs and made operational in a matter of few days.

29) Several main avenues of non Gaussian noise have been evaluated: transient ambient vibrations, material creep, joint slippages, cable relaxation noise, electronics pickup noise, non linearity up-conversions, feed-back and control electronics noise.

Material creep has been extensively studied, in view of material choice, stress management in the system, peak stress limitation in components and stress relieving techniques. The best recognition of this extenuating effort came from the introduction of the cantilever blades in the GEO triple pendulum design.

Joint slippages have been treated by eliminating all sheer-effort joints in the SAS structure. All surfaces joining component are perpendicular or close to perpendicular to the stress and will be coated with a thin coating of low melting alloy to spread the stress. Also all screws have been eliminated from the stress paths because screws have shear loaded stress surfaces. Incidentally the latest joint slippage elimination techniques have not been introduced in the original GEO triple pendulum and will have to be introduced in the GEO pendula for LIGO.

Cable relaxation noise is particularly dangerous in the SAS to triple pendulum interface. Cables are non elastic, highly hysteretic components. Their damping effects have been observed. The main concern is in the quantized nature of their damping that is very likely to generate non Gaussian noise. The only real solution is in the complete elimination of cables, replacing them with wireless triple pendulum controls.

Electronics pickup noise also can be eliminated with the elimination of cables and using digital data transmission techniques.

Non linearity up-conversions have been studied. They appear when a system has a non linear response and have been a concern especially in the vertical anti-spring systems. It was calculated that the measured geometrical anti-spring non linearities are well in the safe side and that up-conversions extend up to three times above the last resonance. With the filters tuned at 0.3 Hz any possible up-conversion is kept well below the frequency region of interest.

Active feedback up-conversion noise is similarlygenerated by non linearities in sensors, digitalization, data treatment and actuator. It may cause significant up-conversions, up to three times the frequency of the upper unitary gain point (cfr. Erika DAmbrosio doctoral thesis). This danger is completely eliminated in the SAS by relegating the feedback action below 3 Hz and this only in the early stages of the chain. Any up-conversion noise is safely out of the frequency region of interest and it is filtered out by the passive stages of SAS.

Adequate specifications are in any case advisable to limit non-linear effects from electronics control, especially for high-gain systems which might internally work near their limit linearity.

30) The main effect of imprecision of manufacturing, assembling or imbalances is to introduce cross coupling between modes. The SAS is built on the principle of progressively and uniformly attenuating the seismic noise on all six d.o.f. explicitly to render the system resilient to assembly imperfections. Modal cross talk is consequently of little effect on the overall attenuation curve. The sheer simplicity of the filters makes it easy to make them quite symmetric, modal cross talk, except for the natural mixing of the translational and tilt modes, will remain at the percent level with no particular technical effort. The filters should be tuned below half an Hz in order to keep the vertical attenuation slightly ahead of the vertical one. To achieve this a machining accuracy of the order of a fraction of millimeter is required, a tolerance much larger than the standard machining tolerances on pieces of these dimensions. The vertical working point of the filters is so much wider than in the Virgo magnetic anti spring filters that in the SAS all filter tuning systems (active and passive) have been suppressed. No particular temperature control is needed.

    The physical separation of the horizontal d.o.f. from the vertical one in the IP/F0 system allows a very simple and sturdy 3 d.o.f. active damping feedback loop structure.

31) Production prices for the prototypes and the series production are given in the report. Before passing to production in series it will be necessary to produce a final prototype and its tooling. Typically a first article and its tooling have a cost double to that of the series. It is assumed that the LASTI vacuum chamber would be used for testing, otherwise an additional 80 K$ would be necessary for a dedicated, simplified vacuum test enclosure.

32) Costs have been evaluated adding up the production costs encountered in building the prototype. Where missing, the Virgo production cost was used for equivalent parts. Actual costs may come down following a competitive bidding process in a production

in series. The total cost for mechanical construction of SAS (see report for details) is estimated around 150 K$ per short tower plus 30 K$ per tower for sensing and actuating (accelerometers, coils and LVDTs). And 10 K$ for in vacuum remote control motors. These costs do not include external components like electronics, cabling etc. Actual costs, including overhead, salaries et c. are better left to an expert on the matter.

33) The SAS are designed to be built in a separate location. An adequate clean assembly hut have to be provided, also a clean bakeout oven must be built. Transport containers must be built as well to maintain cleanliness during shipments. Craning fixtures will be necessary for installation in the BSCs. A precise estimation is difficult without specific design, but a rough estimation should be around a quarter million $ for fixtures.

34) The development and optimization of SAS is ongoing, however the design of SAS for BSCs could be frozen within a short time and pre-production run could be started. The final prototype/first article could be tested in 2000 and production could be rushed for installation in 2002. The longer time available would be spent to improve, simplify, optimize the design and above all devise and test a rapid installation scheme to minimize observatory down time.

    A longer time would be necessary to properly engineer low frequency passive attenuation systems for the HAMs. Judging from the time required to reach the present SAS development level, an additional year should be budgeted, as well as an appropriate manpower level.

35) The SAS is a modular structure; it can be modified and extended in performance like a Lego set. In its tall version is capable of performances exceeding all LIGO II requirements and beyond. Its hanging chain geometry easily accepts all sorts of advanced final attenuation and suspension systems. It is also possible to intertwine two independent SAS systems for implementation of multiple interferometers hanging inside a same BSC chamber. The volume surrounding the mirror has been kept free for possible cryogenic suspensions. The entire SAS can be refrigerated if necessary with minimal changes.

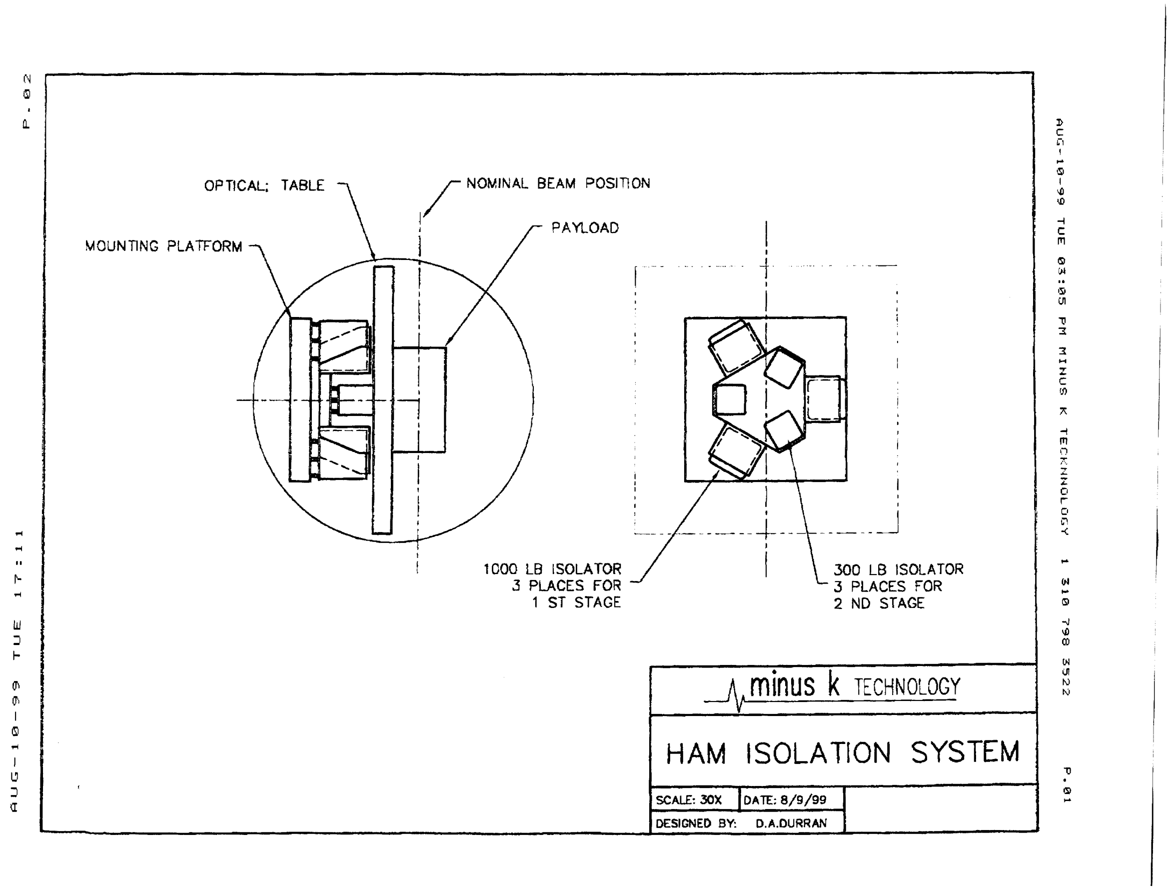

Figure 1: Platform sketch. The sketch shows one of various possible configurations using Minus K isolators that will fit into the existing HAM chamber.

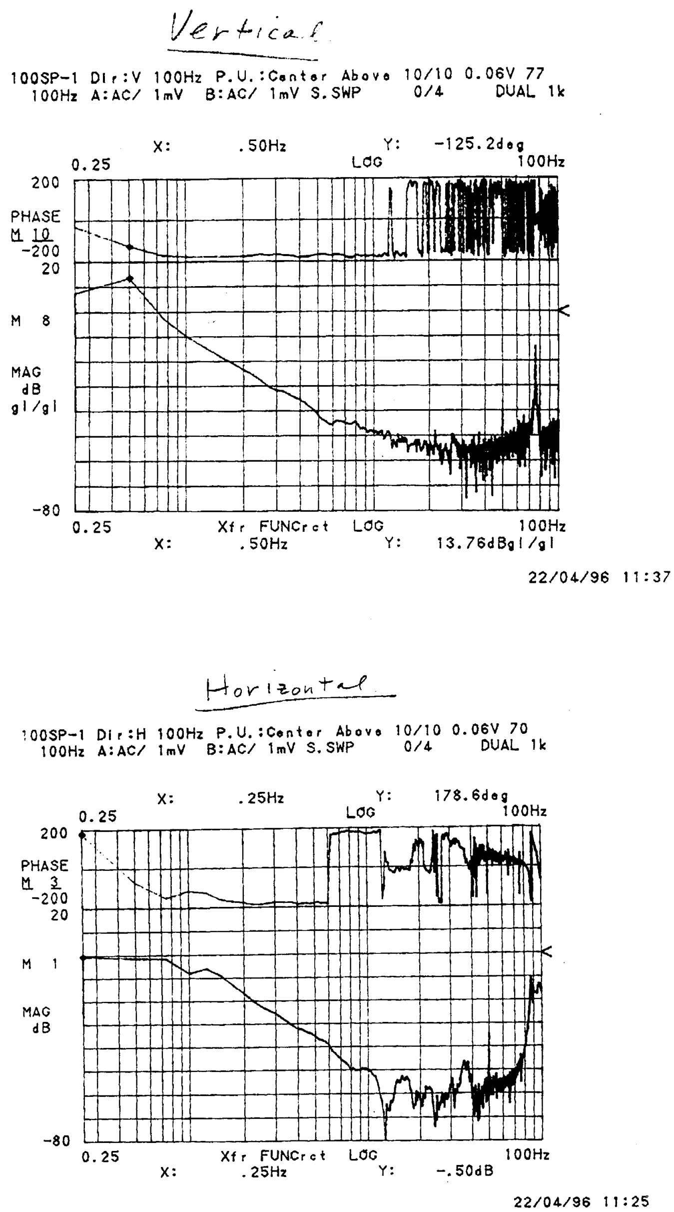

Figure 2: Transfer functions. Horizontal and Vertical transfer function of a single stage Minus K low frequency passive seismic attenuation system.

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