Workshop on Suspensions and Isolation Interfaces for LIGO II

Glasgow, Dec 16-17, 1999

Thursday

- **9.30 Intro**
  - » 9.30 Welcome/Logistics (NR)
  - » 9.45 Objectives (DHS)
  - » 10.00 LIGO Lab Outlook (GS)
- **10.15-11.30 Requirements**
  - » 10.15 Suspension Requirements (DHS)
  - » 10.30 Isolation Requirements (DC)
  - » 11.10 Suspension-Isolation Interfaces (DC)
- **11.30-15.30 Reference Designs**
  - » 11.30 Suspension (GEO)
  - » (lunch 13-14h)
  - » 14.00 'Stiff' Isolation system (JG)
  - » 14.45 'Soft' Isolation system (RD)
  - » (15.30 break)
- **15.45-17.45 Interfaces**
  - » 15.45 Controls (DC)
- **Lab Tour**
  - » 17.45 - 18.45

Friday

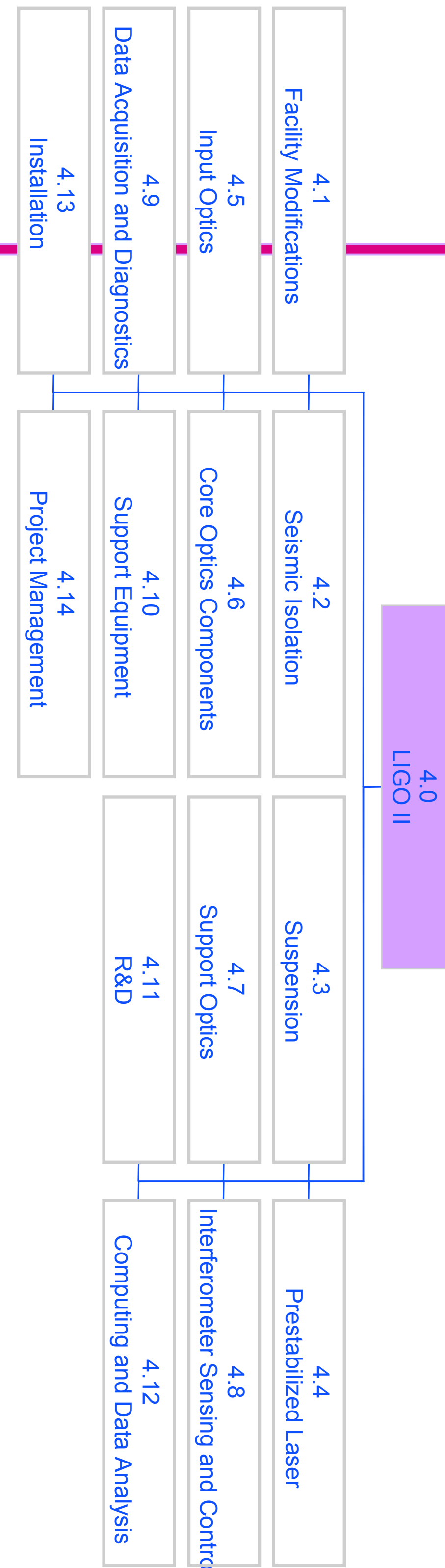
- **9.00 Welcome/Logistics**
- **9.15-16.00 Interfaces** continued
  - » 9.15 Static Mechanical (DC)
  - » (11.05 break)
  - » 11.15 Dynamic Mechanical (DHS)
  - » (lunch 13-14h)
  - » 14.00 Simulation and Physical Models (DC)
- If time permits:
  - » - Schedule interface (GS)
  - » - Stiff current activities/plans
  - » - Soft current activities/plans
  - » - GEO current activities/plans
  - » - Seismic Isolation Advisory Committee status/plans
- **16.00 Summary/actions** (DHS)

Workshop Objectives

- **Focus on interfaces**
  - » e.g., thermal noise *per se* to take ‘back seat’
- **Not an evaluation of the designs**
  - » would be pleased to find evaluation criteria improved by technical exchange
  - » focus on interface issues which are likely to bear upon feasibility
- **Mutual understanding of the reference designs for suspensions and isolation, especially as they relate to interfaces**
  - » don’t anticipate designs to be final now, but must have common understanding of present best guess and driving concerns
- **Explore limits of design interface flexibility**
- **Resolve interface issues or define actions to resolve**

LIGO II subsystems

- **Similar to LIGO I map**
- **Some lessons learned**
- **Subsystems self-contained**
  - » constrains design, but
  - » allows parallel efforts
  - » flexibility within constraints
- **Process milestones:**
  - » Design Review
    - – slots for values
    - – some values
    - – conceptual design
  - » Preliminary Design Review
    - – all requirement values
    - – conceptual design consistent with these requirements
  - » Final Design Review
    - – all prototype tests completed
    - – system ready for procurement



Interactions between subsystems

- **Interfaces must be developed jointly**
  - » purpose of this meeting
  - » mediated by system-wide trades, standards
- **Internal design of subsystems more independent**
  - » the pair of efforts in isolation illustrate why and how
  - » review process allows formal input from neighboring subsystems
  - » again, mediated (and at the ultimate mercy of) systems considerations
    - – e.g., materials, margins, risk
- **GEO to undertake Suspension subsystem**
  - » experience base with displacement-sensitive prototypes
  - » design effort for GEO 600
  - » responsibilities and obligations
  - » perogatives

Notions of Suspension Requirements for LIGO II

David Shoemaker

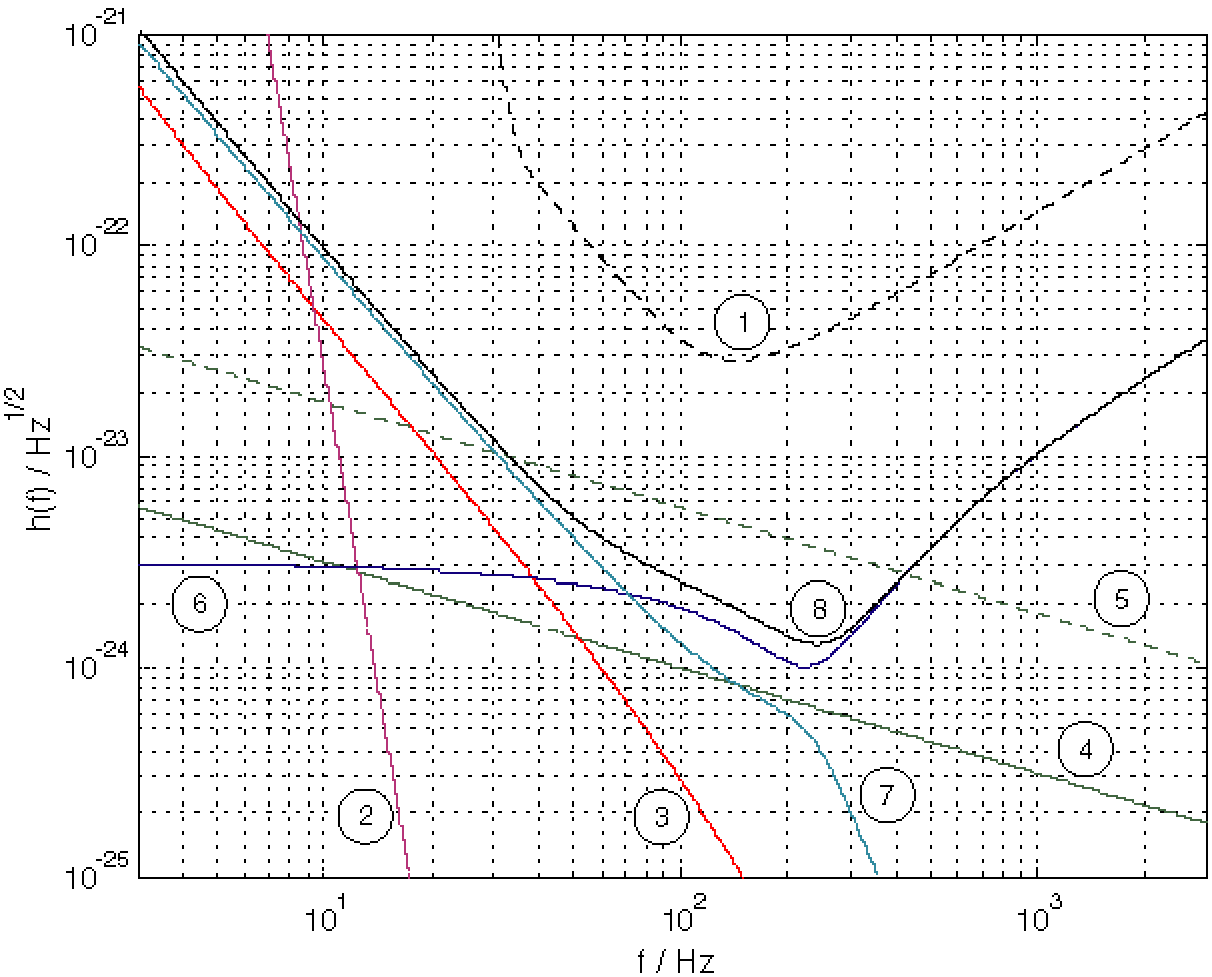
16 December 1999

LIGO-G990___-00-R

Status of Requirements for LIGO II

- **No systematic flowdown of requirements for LIGO II subsystems to date**
  » Isolation system ahead of the game (dc/dhs Requirements Document)
- **Suspension requirements just starting to take form**
  » here, show outline of critical parameters, some known constraints
- **LIGO I process was…**
  » establish conceptual design for all subsystems
  » establish initial performance model, contributors: 'Bench' tool, etc.
  » charge individual subsystems with task of establishing model, parameterization
  » system engineering to work with subsystems to coordinate early 'trades'
  » review of requirements, conceptual design by larger group

Top-level Requirements



1 LIGO I total
2 Filtered seismic noise
3 Suspension thermal noise
4 Internal thermal noise - sapphire
5 Internal thermal noise - fused silica (fallback)
6 Shot noise
7 Radiation pressure noise
8 LIGO II total

Suspension "rules"

- **Suspension at limits of materials understanding**
- **Make best estimates of thermal noise, then adopt these as top-level requirements**
- **Put high cost on trades which increase or mask thermal noise**
  - » but trades possible
- **In general, too early for many numbers**
- **Separate question: conceptual design**
  - » may find internal trades or trades between SEI and SUS which help meet requirements

SUS Requirements: Internally Generated Noise

- **Thermal noise**
  - » best effort sapphire test masses
    - – recent modification for thermoelastic noise
    - – wonderful opportunity to do system engineering
  - » best effort fused silica ribbons
  - » angular thermal noise: to be addressed; trade with beam centering requirement (1 mm point of departure)
- **Excess noise**
  - » no good characterization at present
- **Controller-related**
  - » to be a fraction (e.g., 1/10) of overall performance curve
  - » start with optimistic thermal noise performance estimate
- **Radiation Pressure**
  - » nominal 30 kg
  - » also subject to system engineering

SUS Requirements: Control Functions

- **TBD, substantially**
  - Overall SEI-SUS: Acquire and Operate in existing environment and to top-level requirements
  - Preliminary to make a flow-down to suspension
  - Requires complete SEI-SUS models for now
- **Ultimately must flow down and set distinct SEI and SUS requirements for real design effort**
  - to enable system engineering, subsystem test, tracking of project….
- **Acquisition**
  - SUS must provide sufficient force to 'catch' lock
  - in e.g., 3 minutes
- **Operational**
  - continuous lock for e.g., 1 week
  - without compromise of overall performance

SUS Requirements: Seismic Attenuation

- **Optical axis**
  - » as determined by optimal overall SUS design
    - – thermal noise top concern
    - – ease of damping design, construction, secondary
  - » require SEI to make up difference to reach top-level requirements
  - » modeling to date based on triple pendulum; open
- **Vertical**
  - » can dominate if this leads to the best overall design
  - » important to choose correct cross-coupling factor (site average angle is 3x10^-4 rad)
- **Angular**
  - » in trade with beam centering; 1mm easy centering requirement to fulfill

SUS Requirements: Interfaces

- **Optical/Optics**
  - » test mass material, size, mass
    - – hope to choose a test mass dimension independent of material
  - » cross-section of beam tube
    - – e.g., suspension must not block second interferometer
  - » baffling
    - – baffles in LIGO I attached to suspension ‘cage’
  - » …can start with LIGO I as-installed for point of departure
- **Mechanical**
  - » subject of this workshop

Mode Cleaner Suspension

- **Similar set of requirements**
- **Relatively large mass**
  - » to keep motion due to technical intensity fluctuations small
- **Relaxed thermal noise performance**
  - » present estimate is factor 20 less stringent Mode Cleaner mirror motion requirement
  - » easier thermal noise requirement
  - » probably still requires fused silica suspension etc.
- **Reduced SUS height due to mechanical interface limitations**
  - » results in lower seismic attenuation by MC suspension
  - » greater proportional attenuation in SEI
  - » …similar (read 'identical') isolation required for BSC and BAM isolation systems

Isolation Requirements & Interface Issues

Dennis Coyne

LIGO-II Suspension Working Group (SWG)
Meeting at University of Glasgow
12/16-17/99

Isolation Requirements Issues

- Draft requirements defined in LIGO-E990303-01
- Performance:
  - » does not separate the isolation performance requirements between the suspension and the seismic isolation system
    - – set by the isolation resulting from thermal noise considerations
  - » maximum torques/forces expected (or stipulated) from the suspension reaction cage?
    - – suspension --> max. expected for the “high frequency” design?
    - – “low frequency” design --> max. allowable for the suspension?
  - » Maximum accelerations permissible from the seismic system at the interface in the event of a power failure?
    - – Revise the +/- 100 micron positional change and 10 micron/sec velocity requirement?

Isolation Requirements Issues (continued)

- Mechanical
  - » Clarification: seismic system provides an optics breadboard at the interface with the suspension system (the suspension system provides it's reaction frame)
  - » does not define the suspension length (from laser beam to mtg. interface)
    - – set by the minimum suspension length to meet thermal noise requirements
  - » should state interface stiffness as a frequency dependent impedance rather than a DC stiffness; Different requirement for each seismic design?
  - » In principal, the HAM seismic isolation system can extend above the optic table in the 4 corners (e.g. to allow for a suspension length); physical limits need to be established
  - » define explicit maximum payload limit (propose 600 kg) and clarify that payload mass (but not moments of inertia) can be fixed at the maximum

Isolation Requirements Issues (continued)

- Mechanical (continued)
  - » payload & seismic isolation system dimensional envelopes not completely defined (e.g. to prevent obscuration)
    - – not a significant issue
  - » attachment -- optics table grid implied; unless strain release noise from a bolted connection (“excess noise”) is a concern, propose an optics table hole grid as interface for attachment (for flexibility)
  - » alignment
    - – drift requirement (<100 microrad per 30 day period) implies suspension range of ~500 microrad -- OK?
    - – Initial alignment range and resolution for seismic system not defined
  - » mass, moments of inertia, c.g. locations
    - – rough payload description given (less moments of inertia -- TBD)
  - » Dynamic model exchange required
    - – integrated with control system
    - – shared software/model -- not just data exchange

Isolation Requirements Issues (continued)

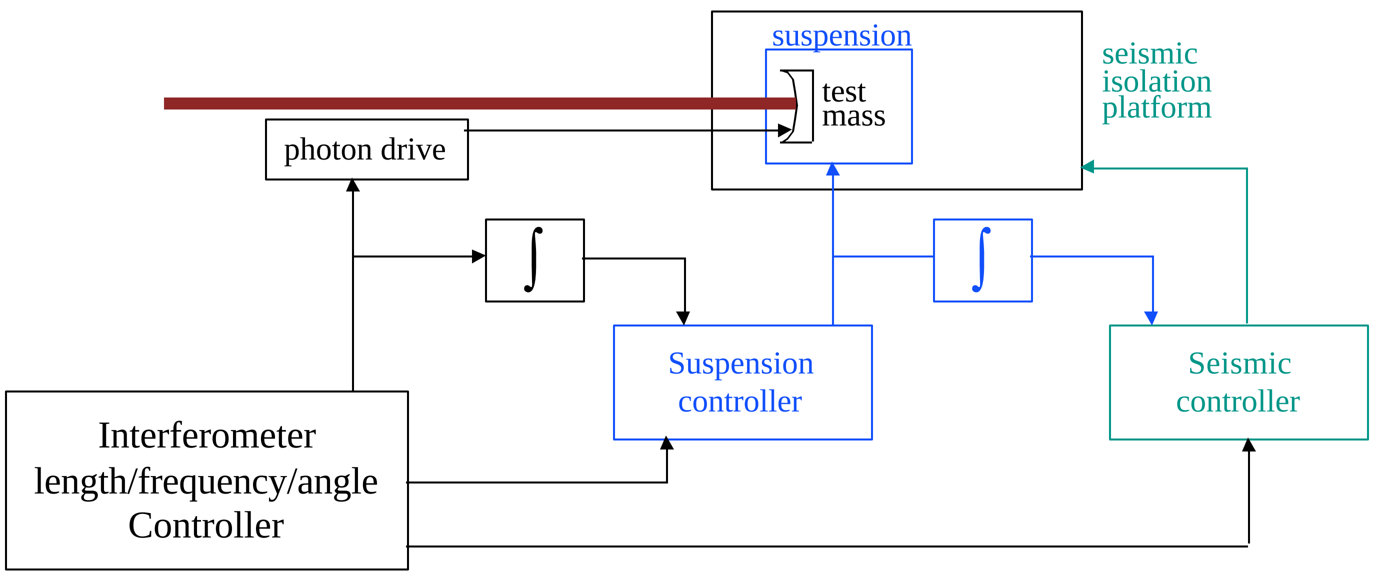
- Thermal
  » any requirements?
    – Maximum & steady-state dissipation?
    – Conductance (max. & min.)?
    – Operating temperature range?
  » LVEA temperature range is ~25C +/- 2C (seasonal)

Isolation Requirements Issues (continued)

- Control
  - » Control system overall topology needs to be baselined
  - » Propose: separate suspension & seismic isolation controllers (for subsystem testability)
  - » Propose: Separate control units coordinated by an overall control system (part of the Length Sensing & Control system)
  - » control allocation between the suspension and seismic isolation system?
    - – Different for the two seismic designs?
  - » Control system states?
  - » Violin mode control (via the suspension subsystem)?
  - » Data Acquisition (archival) signals?

Isolation Requirements Issues (continued)

- Control configuration
  - » propose separate suspension and seismic controllers for testability & well defined interfaces
  - » crossover frequency and control allocation defined & implemented (over pre-defined limited range) by the interferometer global control system
  - » integrated offload from suspension to seismic system



SWG mtg at Univ. of Glasgow, 12/17/99 (typed version of handwritten notes)

INTERFEROMETER GLOBAL CONTROL MODES

ISC Global Modes	Requirements on Seismic Isolation	Requirements on Suspension
IFO Installation	No requirements	No requirements
IFO Maintenance	No requirements; Default state is local control	No requirements; Default state is local control
IFO Off	No requirements; Default state is local control	No requirements; Default state is local control
IFO Alignment	SEI local inertial damping control and commanded yaw, x, y, z position	SUS local inertial damping control and commanded 5 dof position (yaw, pitch, x, y, z)
IFO Initialization (power up, boot up, self test, etc.)	No requirements; Default state is local control	No requirements; Default state is local control
IFO Self test	No requirements; Default state is local control	No requirements; Default state is local control
IFO unlocked; standby	SEI Local control (default) SEI Self Test/calibration SEI diagnostic	SUS Local control (default) SUS Self test/calibration SUS diagnostic state
IFO Diagnostic modes (many)	TBD, generally (but not always) cavities locked and diagnostic signals injected into SEI controller; SEI local inertial damping control and commanded position	TBD, generally (but not always) cavities locked and diagnostic signals injected into SUS controller; SUS local inertial damping control and commanded longituidinal position
IFO Strain calibration (via commanded SUS position or photon drive actuation)	No requirements beyond detection mode	No requirements beyond detection mode
IFO Acquisition	No requirements beyond detection mode	Local damping control + Electrostatic actuation for longituidinal dof (increased range)
IFO Detection (photon actuator for cavity length control)	SEI local inertial damping control and commanded longituidinal position (for tidal compensation)	Local damping control (except for longituidinal dof of test masses) with reduced gain

SWG mtg at Univ. of Glasgow, 12/17/99 (typed version of handwritten notes)

SUSPENSION & SEISMIC ISOLATION CONTROL MODES

Need to be defined, with requirements on other subsystems (if any) identified, e.g.

Suspension Initialization Mode sequence:

- Power up
- Boot up
- Self test
- Message to IFO global controller -> functional (or not OK)
- Local inertial damping control
- Message to IFO global controller -> in local damping control
- Monitor modes including violin resonances
- Message to IFO global controller -> modes > allowed
- Modal cool down
- Message to IFO global controller -> modes “cool”

Suspension Initialization Mode requirements on seismic isolation system:

- SEI must be in local inertial damping control mode

Isolation Requirements Issues (continued)

- Electrical
  - » are any sensors required on the seismic system to directly support the suspension system?
  - » Confirm 70 conductors/channels per suspension (provided by the seismic system, from a LIGO provided feedthrough to the suspension interface)
    - – current capacity?
    - – Shielded? Twisted? (or frequency range & max. electrical crosstalk?)
    - – interface pin assignments & connector type TBD
  - » No power provided across the suspension/seismic isolation interface; power derived from LIGO detector power bus
    - – each subsystem provides a LIGO standard rack(s) in the vicinity of the chamber
    - – power is derived from rack mounted supplies (supplied by the subsysytem)
    - – max. power per chamber should be <20A at 110v, continuous (soft requirement)
  - » EMC -- need to operate in LIGO LVEA (reference LIGO EMC control plan & environment surveys); not an interface issue

Isolation Requirements Issues (continued)

- Electronic & Software interfaces?
  - » Command signals?
    - – Format
    - – rates
  - » Data signals?
    - – Format
    - – rates
    - – input
    - – output
    - – accuracies
  - » EMC (electromagnetic compatibility) requirements for wireless transmssion
- Data
  - » messages
  - » protocols

Isolation Requirements Issues (continued)

- Installation & Test
  - » installation support across the interface?
    - – E.g. clamped attachment while installing?
  - » Test support requirements?

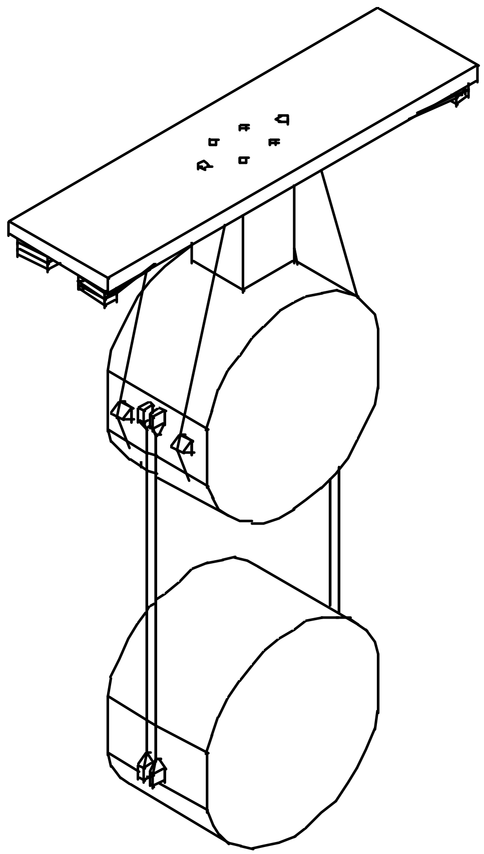
Suspension Design for LIGO II - Current Status

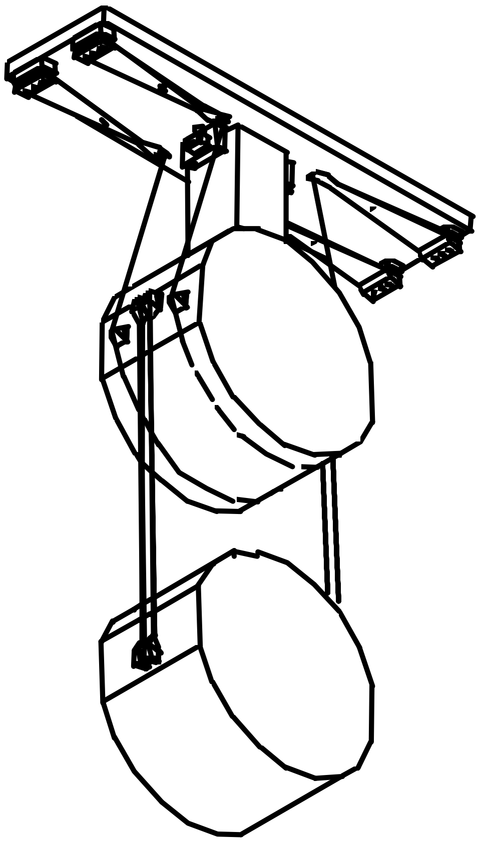
- Introduction and general outline - mechanical parameters, isolation characteristics etc (NAR)
- Thermal noise considerations (GC)
- Control issues (local and global) (KAS)

Introduction and Background

- Suspension design based on modified GEO 600 triple pendulum
- Key points
  - fused silica fibres/ribbons for final stage suspension
  - local control (continuous) by 6 co-located sensors and actuators on upper mass
  - global control on intermediate and lower mass (electrostatic at lower)
  - 2 stages of enhanced vertical isolation

GEO Triple Pendulum





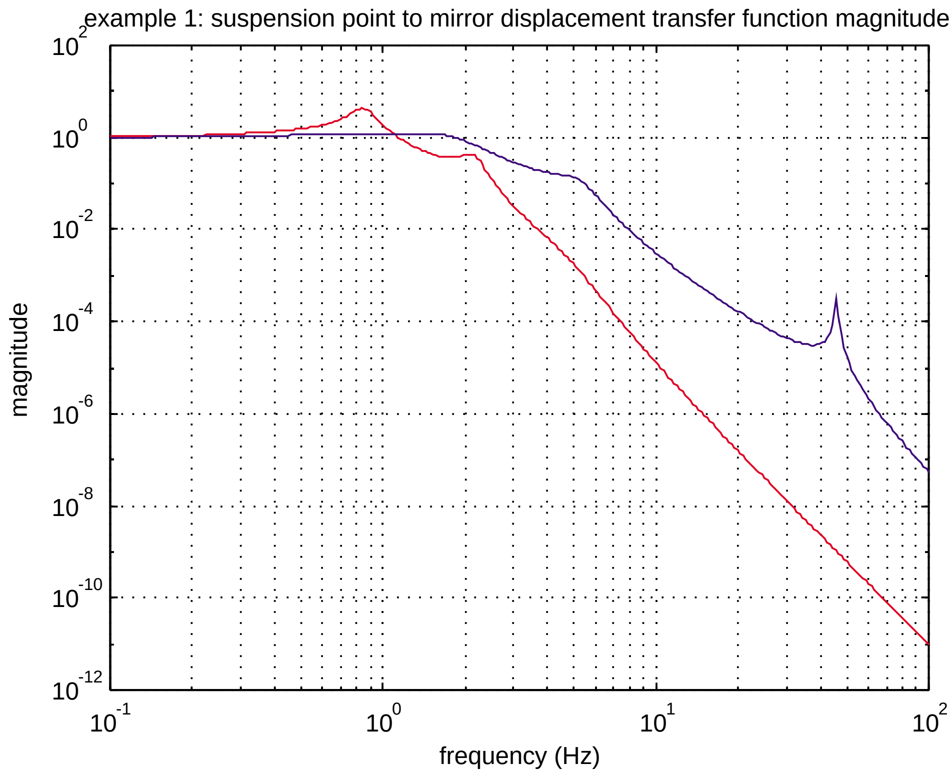
Current Design Issues

- Design presented in MIT (May 1999) modified due to change to cut-off : 20 Hz to 10 Hz
- Key points
  - triple pendulum offers inadequate isolation of control noise at upper mass (assuming certain noise/range performance - see KAS talk)
  - thermal noise from upper stages requires to be reduced

Current Design

- Quadruple pendulum incorporating 3 stages of enhanced vertical isolation using blades
- fused silica ribbons suspending mirror
- local control sensors/actuators on top mass
- final “blade” stage has a lower vertical frequency (~2 Hz uncoupled)
- overall length no longer than proposed triple
- all controlled freqs. in range 0.44 - 4.2 Hz

Small optics suspension parameters and performance



l1 = 0.25;   %upper wire length   nw1 =2;   % number of wires
l2 = 0.15; %intermediate wire length nw2 =4   = no. of blades;
l3 = 0.21;   %lower wire length   nw3 =4;

wire 1 and 2 are steel, 3 is silica

the top mass is steel mass ~11 kg
the intermediate and mirror masses are 6.9 kg (200 mm dia. 100 thick)

local control algorithm: as for large optics

local control sensors: occultation (~1e-11 m/rtHz)

damping of all modes <10 Hz to low Q (<~4)

overall height above beam axis: 0.61m
overall height above optical table 0.71m(+ clearance)

mounting frame outer dimensions 0.4 * 0.3 * 0.8 m maximum
(for a pair of suspensions)

blade lengths (top)   = 28cm*6cm*2mm
(lower) = 10cm*2.3cm*1mm

actuator ranges are similar to the original GEO triple pendulum
described previously

Revised Pendulum Design

Following discussions during the Glasgow meeting, and taking into account considerations of thermal noise issues associated with the “bounce” mode , it was agreed that the baseline design which the SUS group would work to has the following features:

- quarduple pendulum with overall vertical length, i.e. top suspension point to centre of test mass, ~2 m
- masses from top to bottom, ~30, ~30, ~60, ~30 kg
- lowest stage silica ribbons of length ~0.8 m

A full description is being prepared for 31 Jan 2000 deadline.

Pictures of GEO triple pendulum

Pictures similar to those shown during the Glasgow meeting can be found on the GEO 600 home page:

http://www.geo600.uni-hannover.de/

and then look under "The GEO 600 diary" and under "June 99".

Slide 1

Local control issues for LIGO II large optics suspensions

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Slide 2

Aims

- To show how the large-optics suspensions can be damped
- To discuss the options that have been identified
- To explain the remaining challenges
- To illustrate the expected performance

Slide 3

Local control of large-optics suspensions

- Sensing and feedback will be co-located and in 6 *dof* between the optics platform and the top stage of the 2 suspensions.
- All modes up to $\sim 5\,$Hz will be damped.
- Feedback will be done at the top stage of a 3 or 4 stage suspension.
- The actuators are electro-magnetic.
- The sensor design is critical in achieving the desired performance.

Slide 4

Required sensor performance

- 4 local control arrangements have been identified, each requires its own level of sensor performance (sensor noise at 10 Hz).
- If the loops (mainly) controlling *longitudinal, pitch* and *yaw* may be turned down or off after lock acquisition, the sensor may be about 40 dB noisier and still be acceptable. It is expected that this will be done.
- The choice between a triple and quadruple pendulum is entirely tied to the availability of appropriate local control sensors. With about 40 dB greater tolerance of noise in the quadruple case.

Slide 5

Sensor noise and range

- The sensor must be capable of working linearly over a range large enough to allow for, initial alignment errors, thermal expansion and feedback applied between the suspensions (in decreasing importance). We conservatively take the range to be at least 100 microns *rms* at present, but this is subject to review.
- The sensor noise must not contribute more than $10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ mirror motion at 10 Hz. For the quadruple pendulum this requires a $10^{-11}\mathrm{m}/\sqrt{\mathrm{Hz}}$ class sensor, for the triple a $10^{-13}\mathrm{m}/\sqrt{\mathrm{Hz}}$ class sensor (100 times better if the gain is not reduced while running).
- The former sensor has moderate dynamic range, the latter has large dynamic range.
- Precise specifications may differ by factors of order 3 from the above.

Slide 6

Work and conclusions

- We are working on large dynamic range sensors for this purpose (optical, electrostatic and electro-magnetic are all in consideration).
- We are confident that there is a solution with the quadruple pendulum.
- We anticipate that there may be a solution with a triple pendulum.

Slide 1

Global control issues for LIGO II large optics suspensions

Kenneth A. Strain
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Slide 2

Aims

- To show how the large-optics suspensions can be controlled
- To show at which frequencies pre-isolation is most necessary (from the point of view of global control)
- To explain the remaining challenges
- To illustrate the expected performance

Slide 3

Control of large-optics suspensions

1 Feedback is possible at 3 or 4 masses, from the reaction pendulum or the optics table

– masses: n, 1,2,3 going down

2 The actuators are tailored to provide the required maximum force at each stage

– maximum use made of control re-allocation

3 The actuators are mostly electro-magnetic, with electro-static/photon at the mirror stage

– all stages have longitudinal, pitch and yaw feedback with similar bandwidths in these degrees of freedom at one stage

Slide 4

Required force at each actuator

- Upper-limits have been calculated based on **no** pre-isolation and a 'typical' seismic curve.
- The method is in place for re-correct calculation when isolation performance is known.
- The main need for isolation is in region from about 0.5 to 3 Hz, to allow a weak actuator to be used to control the mirror.

(This calculation has been done for longitudinal feedback only, at present)

Slide 5

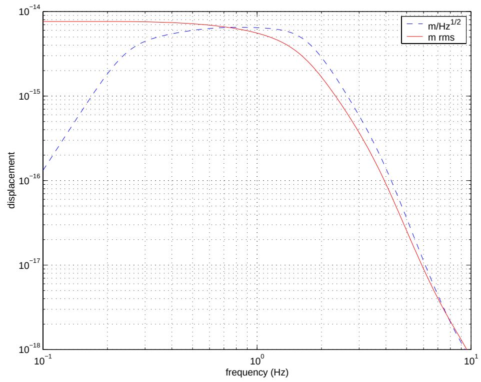
Actuator noise and dynamic range

- Mass 2 actuator: 10^{-7}m/N at 10 Hz, 1 mN *rms* range, so to obtain 10^{-19}m/$\sqrt{(\text{Hz})}$ require a dynamic range of 180 dB (1 Hz) (DC signal to 10 Hz noise). (Quite hard, but possible.)
- Mass 1 actuator: $< 2 \times 10^{-9}$m/N at 10 Hz, 10 mN *rms* range, so to obtain 10^{-19}m/$\sqrt{(\text{Hz})}$ require a dynamic range of 160 dB (1 Hz) (DC signal to 10 Hz noise).
- The mass 1 actuator would provide a range of $>$ 30 microns at 0.1 Hz.
- With a triple pendulum these would also be local control actuators, with a quadruple the local control actuators, one stage further up are easier to design.

Slide 6

Residual motion (*rms*)

- Calculated residual motion with quiet seismic spectrum
- 200 Hz global control bandwidth (feedback to mirror)



Slide 7

Some conclusions from this

- Actuation at 3 stages provides all control from ca. 0.01 Hz up
- Control re-allocation for long-term drift (thermal/earth tides $\sim 200\,\mu$m) interfaces trivially.
- The main motivation for pre-isolation is reduction of actuation force further down the chain.

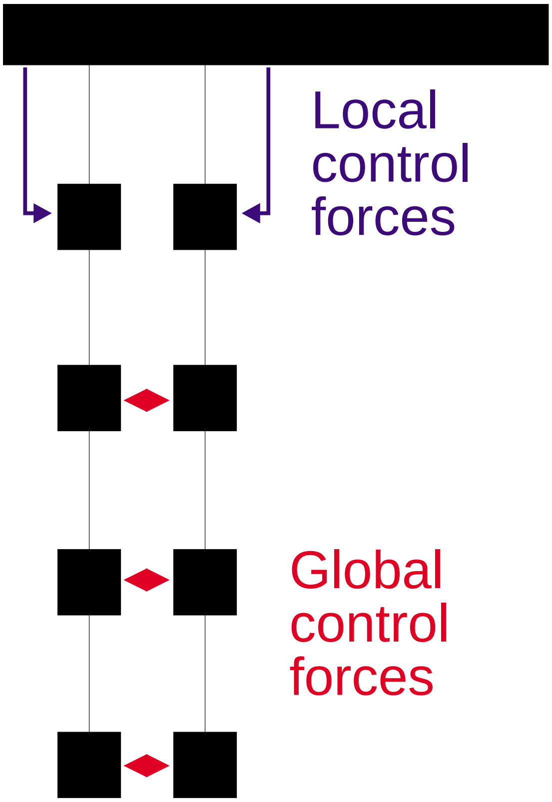
Slide 8

Residual challenges

- Actuator design (all actuators, including electronics)
- Design of controller to operate with violin modes present (not included in the model, but necessary for GEO work soon).

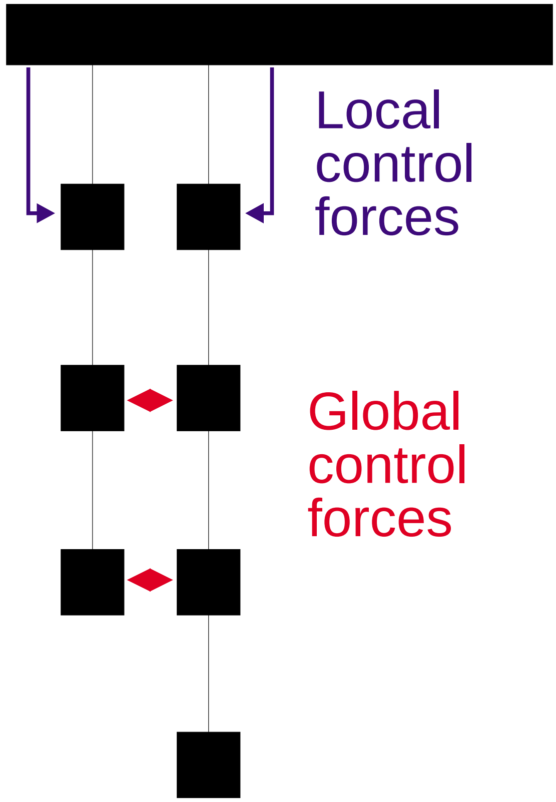
Reaction Forces, Control and Suspension Types

ETM Suspension
-clearest requirements



long: reactionless
pitch:reactionless
yaw: can be
reactionless

ITM Suspension
-intial sketch

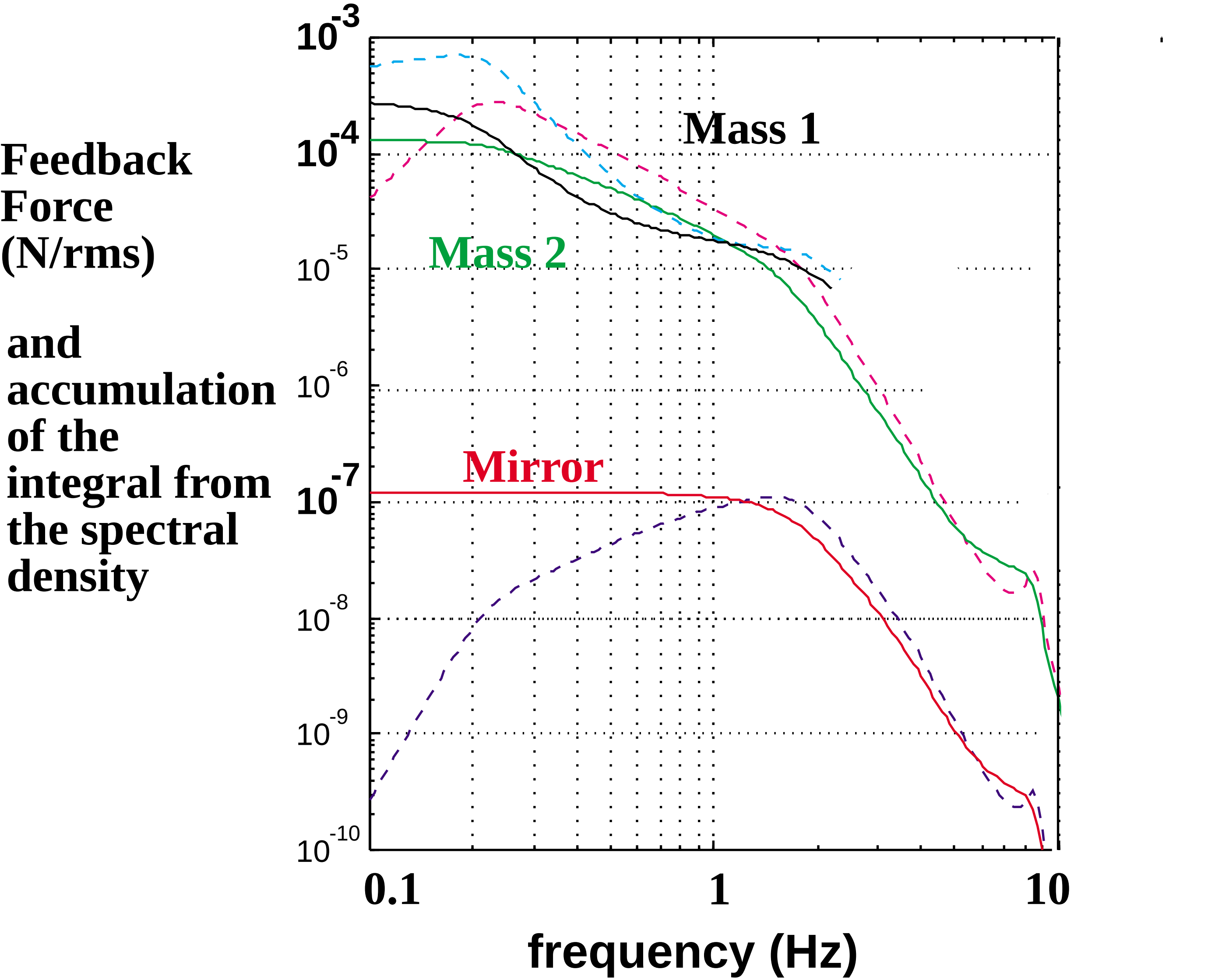


long: some transient
pitch reaction
pitch:reactionless
yaw: some transient
reaction

LOCAL CONTROLS:
inevitably react to disturbances of the support structure within their operating bandwidth of ca. 0.2 to 6 Hz
Transients resulting from GLOBAL CONTROL transients can be minimised by trimming

Orientation (control at <<0.01 Hz and beyond the range of the global actuators) is expected to be done within the isolation.
Some analysis is needed of how to apply this in cases where multiple mirrors are suspended.

Force supplied by each length control actuator



Forces calculated assumping suspension point directly connected to ground (GEO_EXAMPLE model)

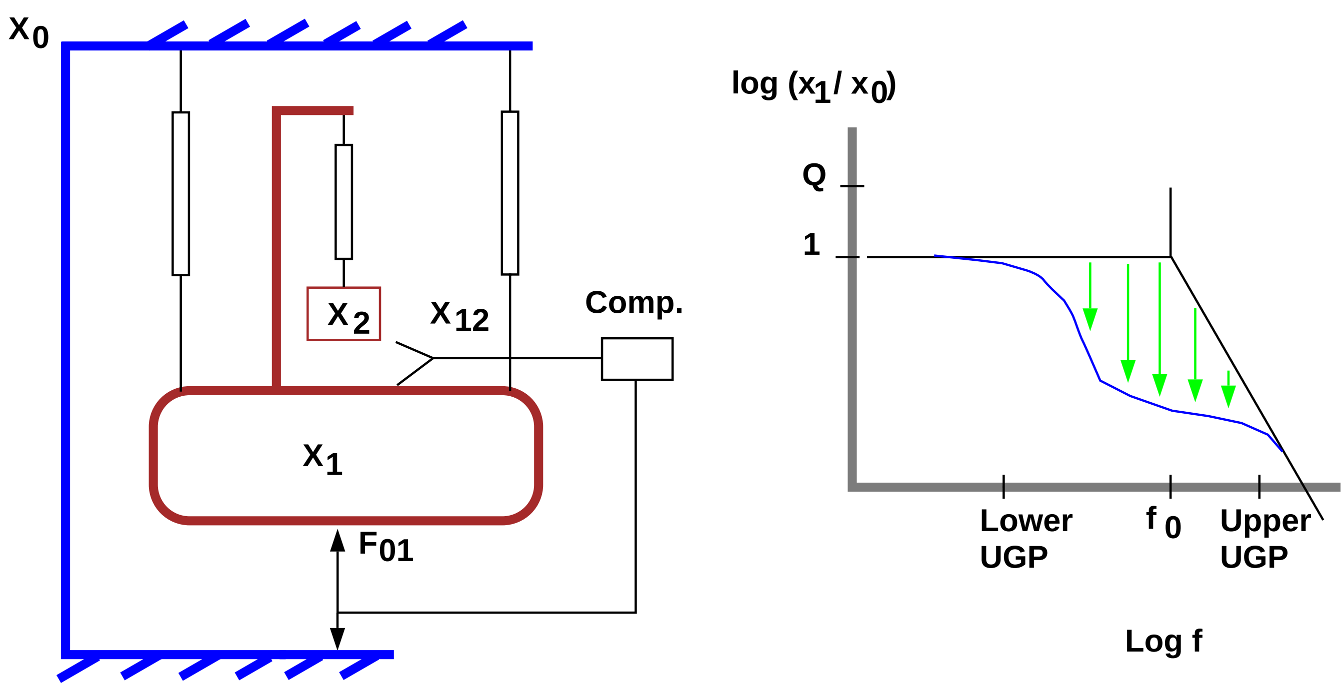
Stiff Active System for Enhanced LIGO Detectors

Joe Giaime, Dan DeBra, Giles Hammond, Corwin Hardham, Jonathan How, Hong sang-Bae, Weng-sheng Hua, Warren Johnson, Brian Lantz, Sam Richman, Tuck Stebbins

for the "stiff" active isolation group

Active Mechanical Noise Reduction:

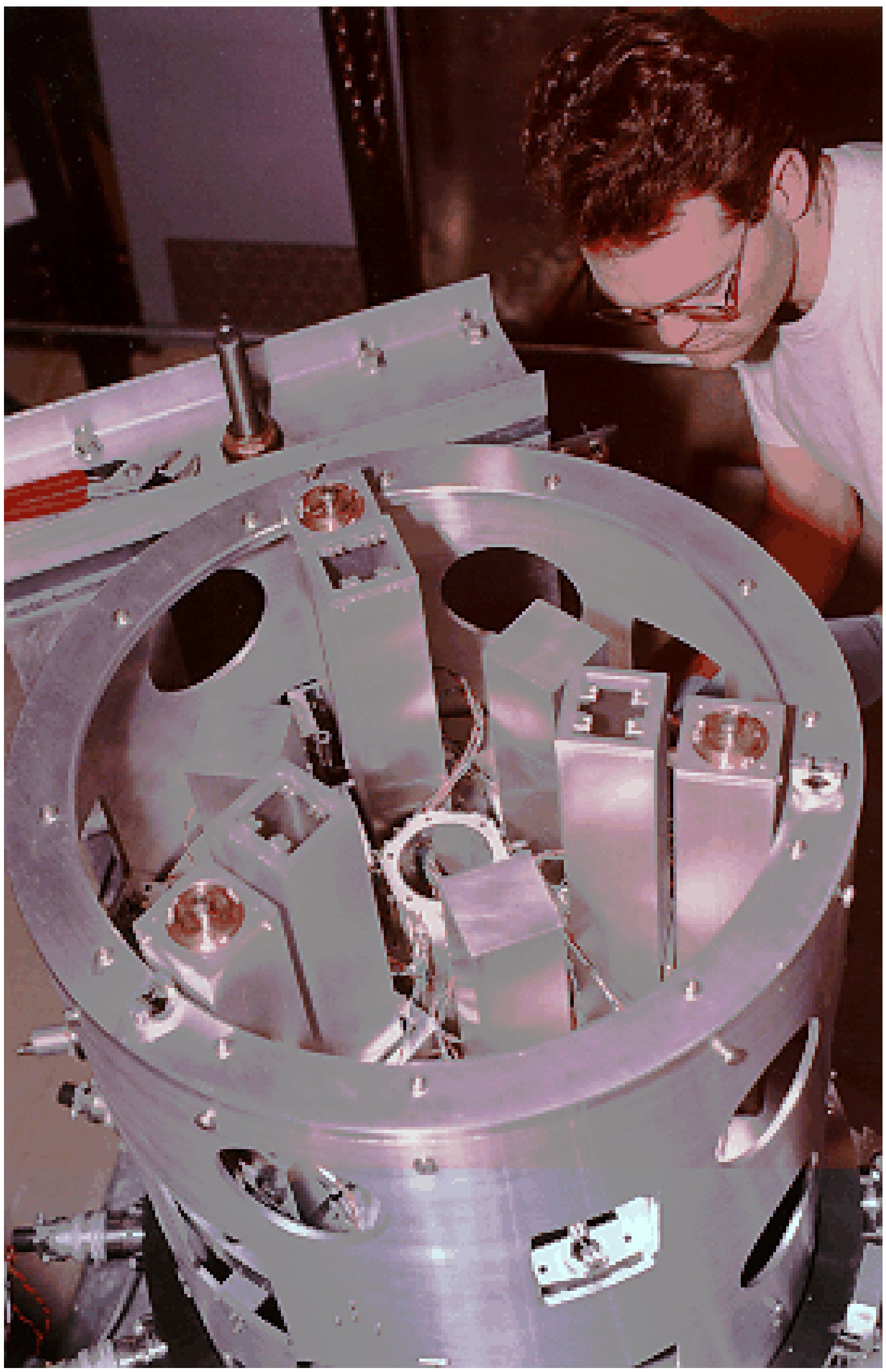
- Control forces are applied to a payload to reduce its motion with respect to an external reference frame or inertial space.

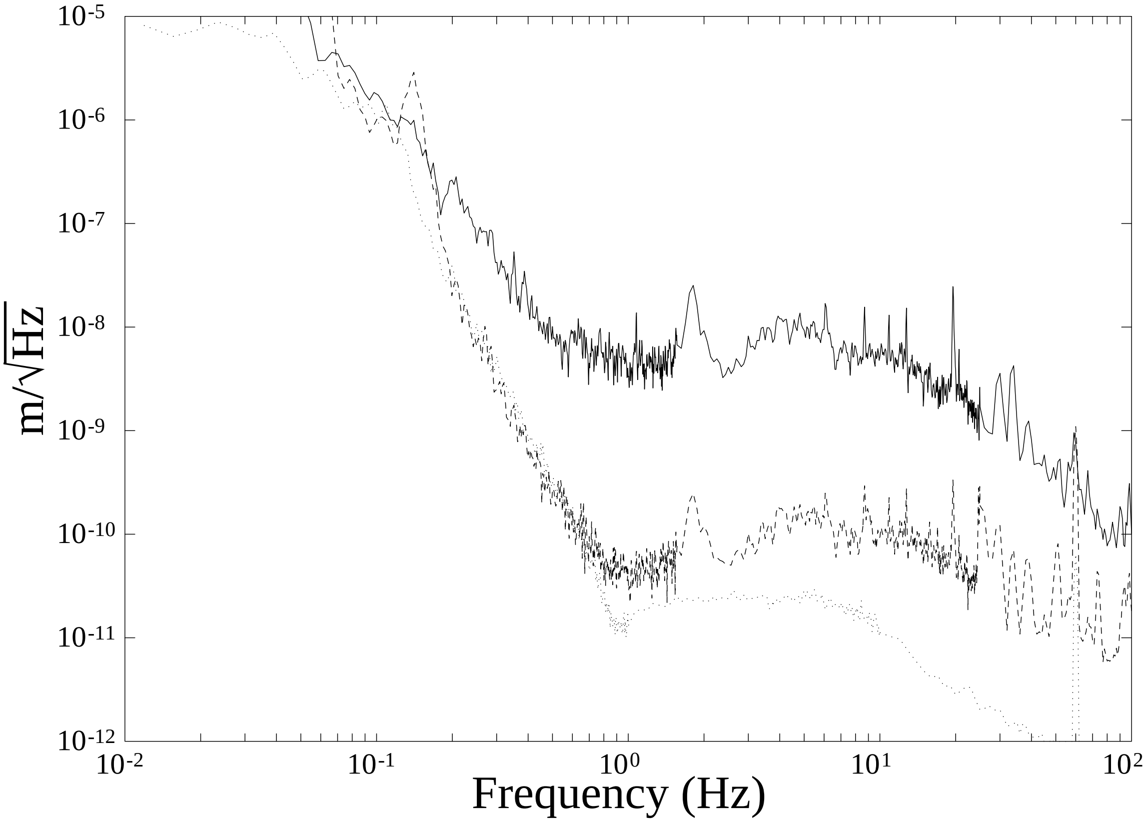


- error signal can come from local reference (shown) or global reference such as length or angle sensing interferometers.

GW Community Experience:

- JILA Platform: Two cascaded 6 DOF active stages plus one passive stage.





Data from the 1994 single-stage JILA platform, showing the noise performance of a 6-DOF active isolation system. The lines are, top to bottom, the ground motion, the platform noise, and the measurement noise.

Requirements of Seismic Isolation Subsystem, when cascaded with GEO-designed quadruple pendulum: These three requirements are likely to be satisfied with three distinct layered systems.

1. Reduce seismic noise to the best anticipated thermal noise in fused silica test mass suspension at the frequency where we expect the bulk to meet the suspension thermal noise. The DRD takes this to be:

$$x(f) = 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}, \quad f = 10\ \mathrm{Hz}.$$

- A two-stage active isolation platform reduces ground noise to a modest level,

- The GEO quad. pendulum, considered to be the baseline for LIGO-II, provides most of the seismic isolation in the GW band, largely replacing both the LIGO-I passive stack and the suspension. Its transmission is expected to be about

$$x(f) \leq 10^{-7}, \quad f = 10\ \mathrm{Hz}.$$

2. Reduce the RMS displacement of the test mass to a level that allows the interferometer length and angle sensors to operate at their required sensitivity.

$$x_{\text{RMS}} = \sqrt{\int x^2(f)df} \leq 10^{-14} \text{ m}.$$

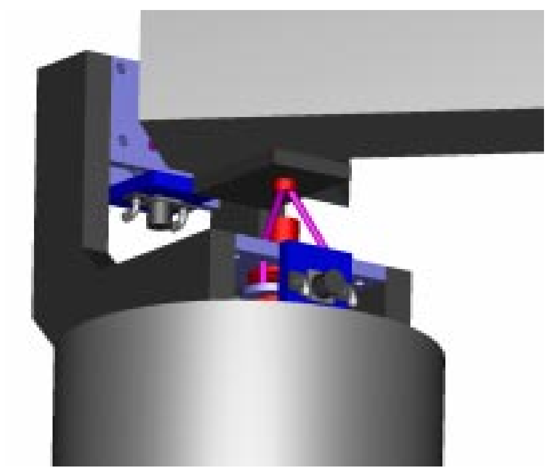
- This integral is dominated by the microseismic ground motion (10^{-6} m/$\sqrt{\text{Hz}}$ at 0.15 Hz) and the resonances in the isolation and suspension system ($\approx$ 0.5 - 2 Hz).

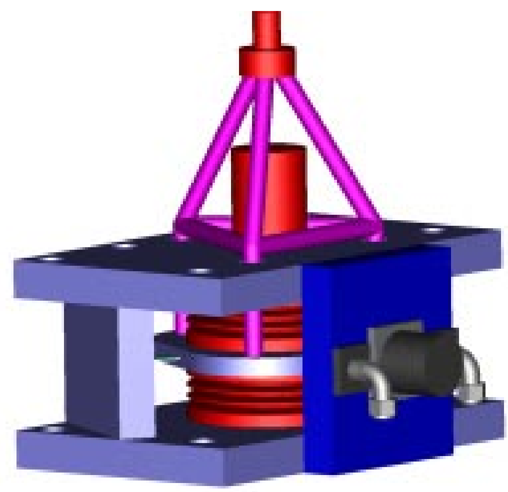
- Very low frequency motion to be largely reduced by main interferometer length control loop, as in LIGO-I.

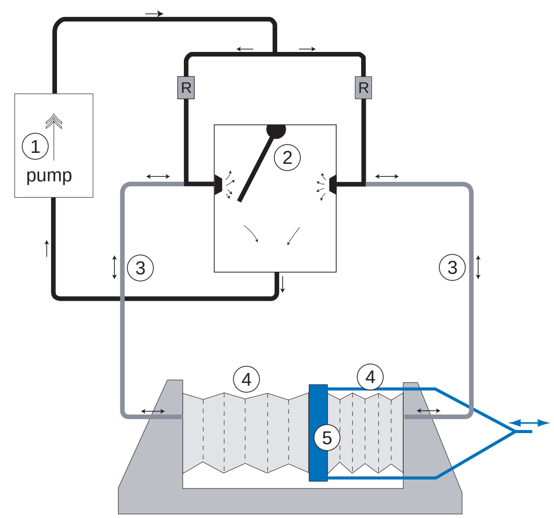
- Microseism and resonance peak noise to be reduced by locally referenced active siesmic isolation loops as well as by global loops.

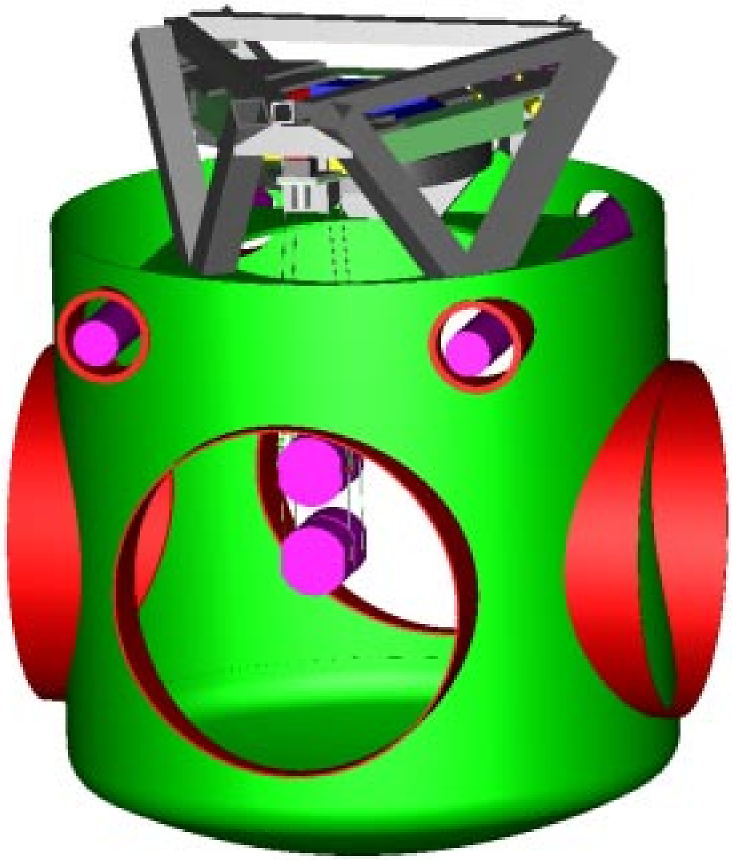
3. Provide a method to displace the test mass over mm-scale distances for instrument alignment from DC to (perhaps) several hertz, and tracking of thermal effects and tides.

   Can be done external to the vacuum system, using a quiet hydraulic system. (naturally high-impedence.)





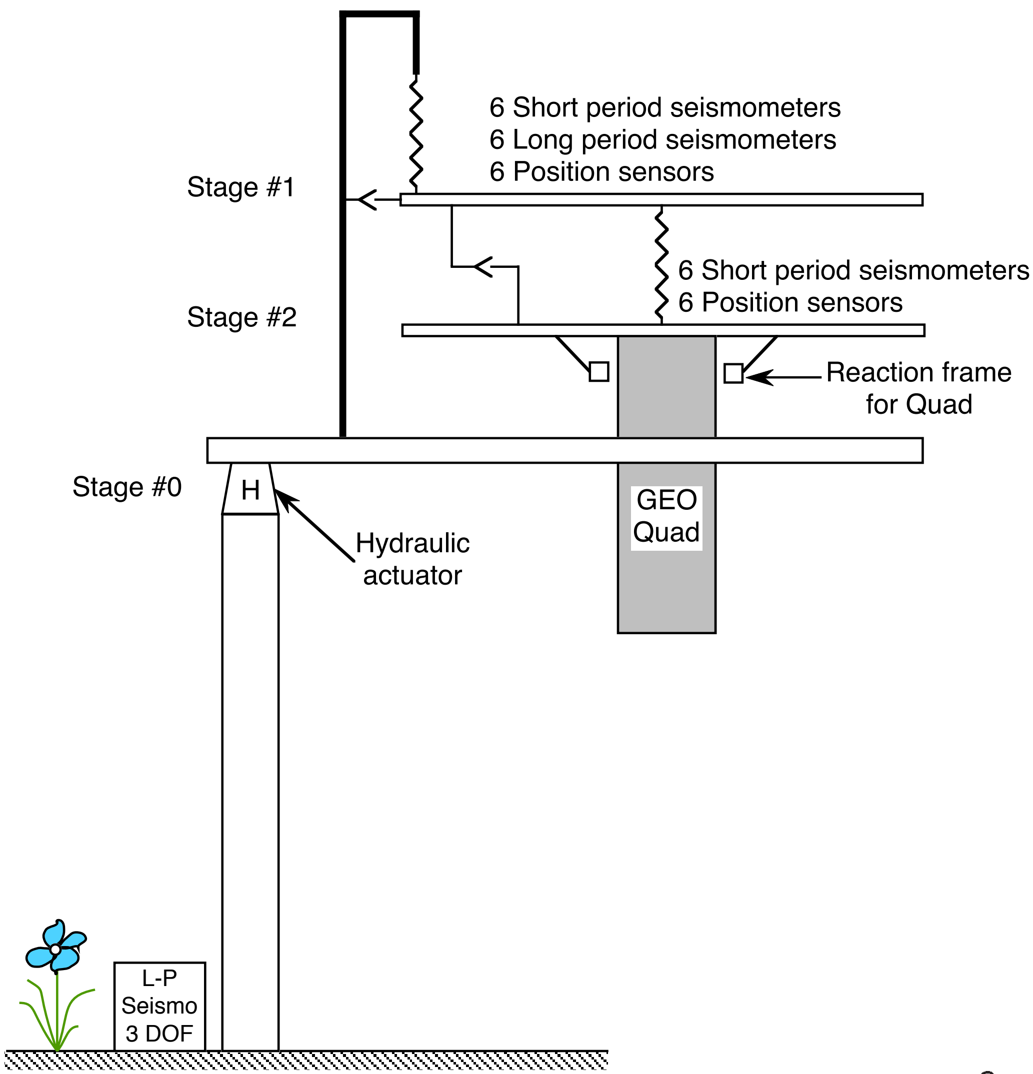




Two active plus passive quadruple pendulum system:

- Two stages of active allows greatly reduced upper unity gain frequency in main inteferometer length control loop.

- Quadruple triple pendulum provides majority of isolation in the GW band.



Active platform design features:

- Based on JILA pre-prototype mechanical topology and servo design, but with different sensors.

- Stages connected with bladespring/ thick wire suspensions, with individual natural frequencies between 2.5 Hz and 4 Hz. Each stage has mass approx. 200 kg.

- Stage 2 platform holds blade springs of the GEO quad. pendulum.

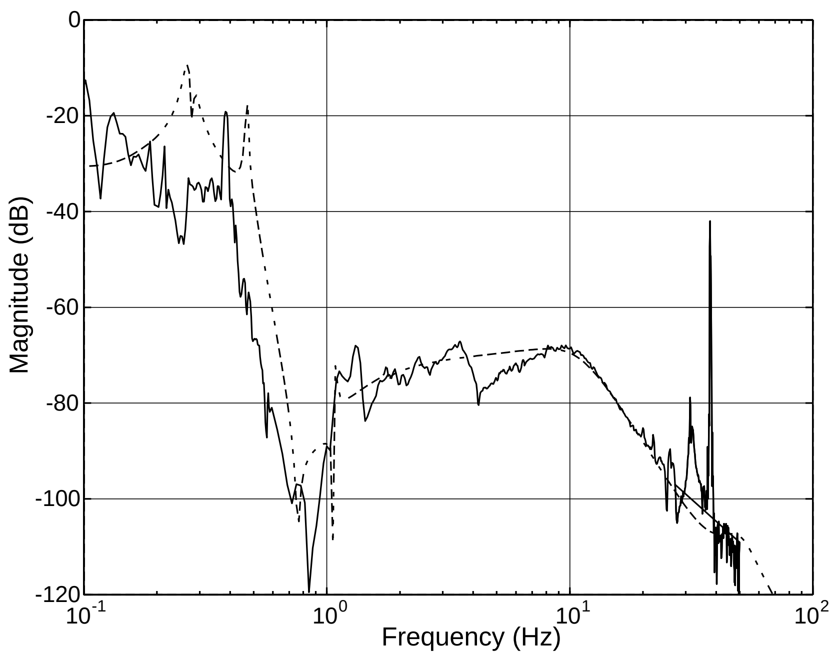
- Co-located sensors and actuators for 12 DOFs of active stages, each closed in SISO loop (present model). Designs with feed-forward and control reallocation are in process.

- Entirely in vacuum (except for hydraulic course actuation).

- Commercial, off-the-shelf sensors; vacuum-prepared electromagnet actuators.

Modeling:

- Preliminary model is slightly modified from Matlab code developed to design JILA platform; this has been extensively tested against hardware performance over several years.



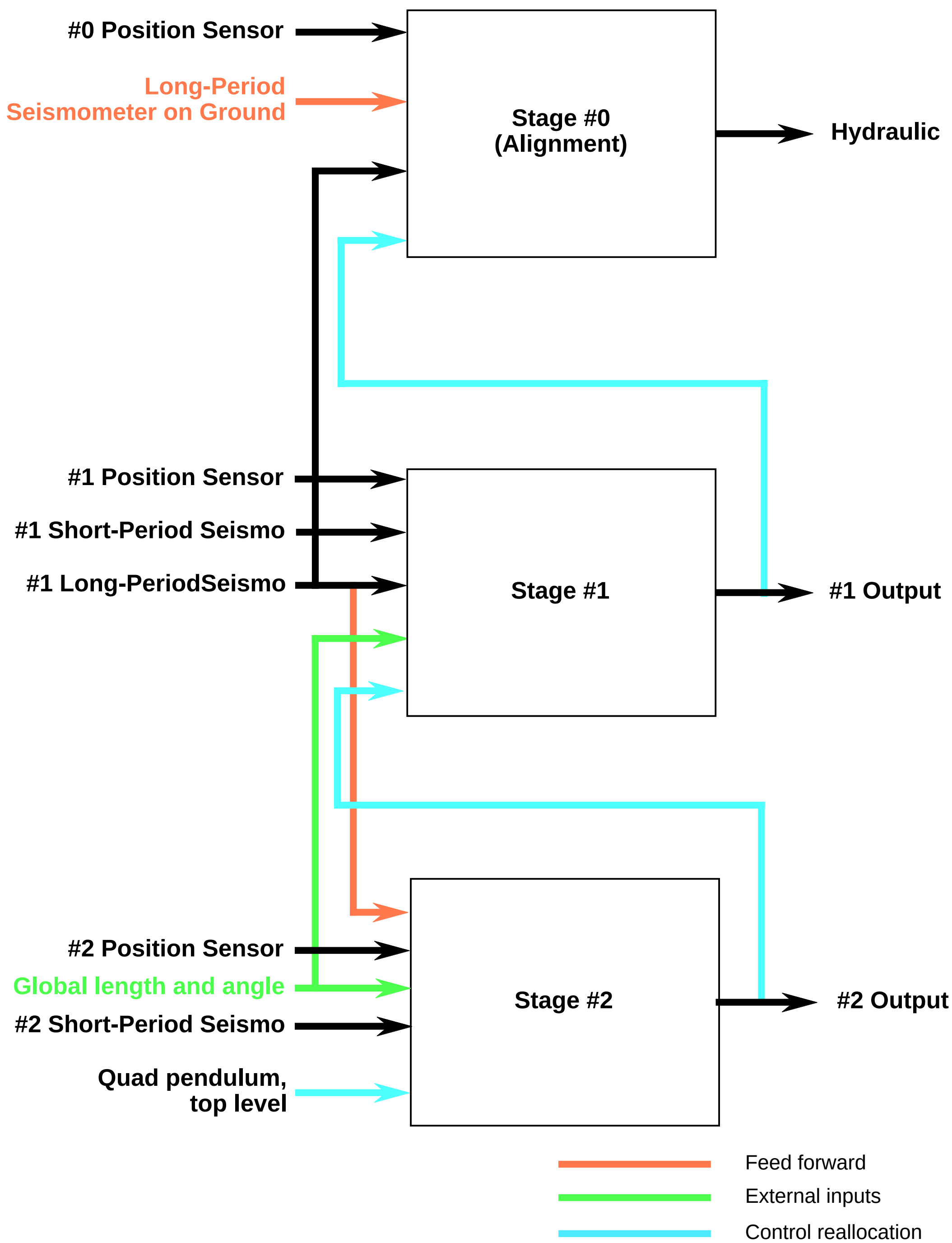
JILA driven horizontal transfer function.

- Fully 3D, all rigid-body Degrees Of Freedom modeled.

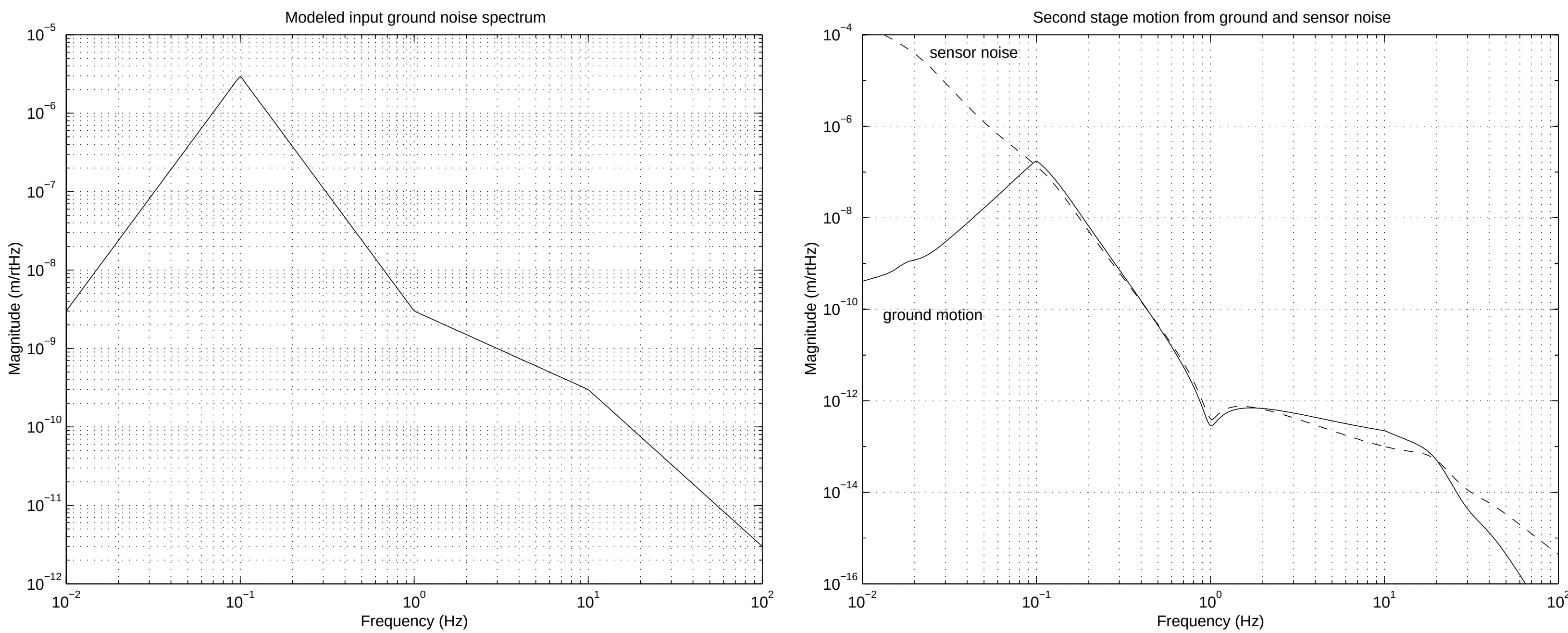
- Tilt-horizontal coupling and other 3-D/gravity effects taken into account.

- Noise predictions are made using published noise specs from commercial seismometers that are used for sensors, propagated through 3D model with loops closed as intended.

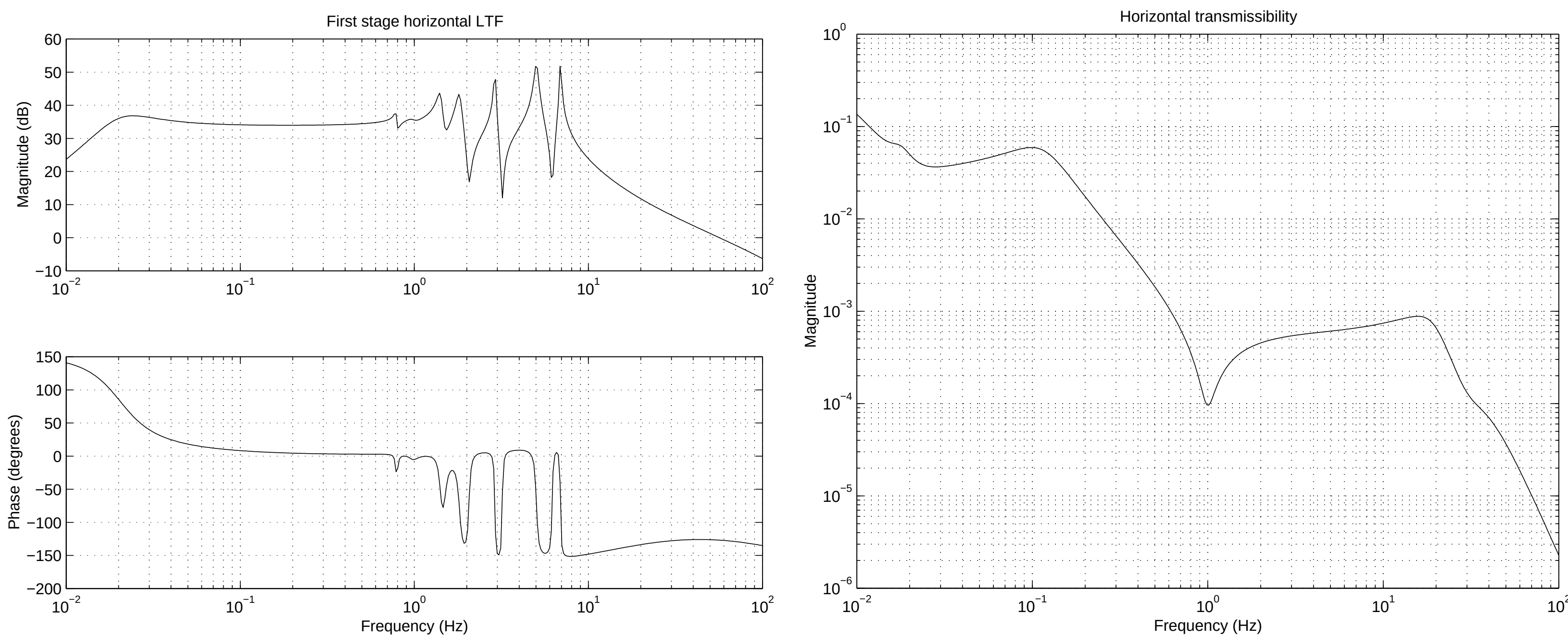
- New modeling effort well underway by Richman/ Lantz/ Hua at Stanford and MIT, supervised by How and DeBra. This is based on a “constructor” facility that allows rapid connection of various dynamical elements.



Black lines are control flow paths represented in current preliminary model. Colored lines represent control paths that are desirable but not necessary for performance goals.

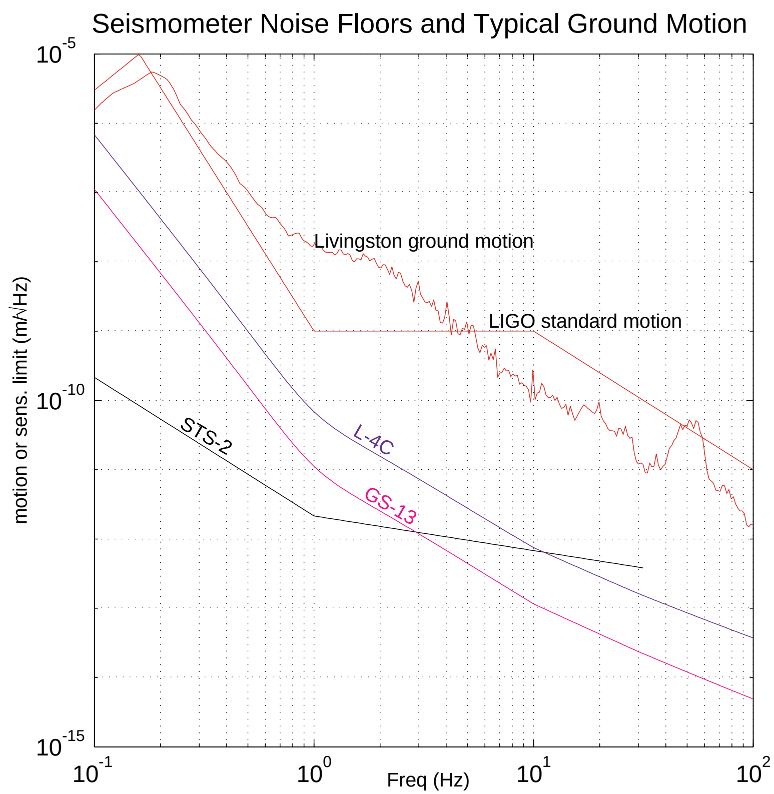


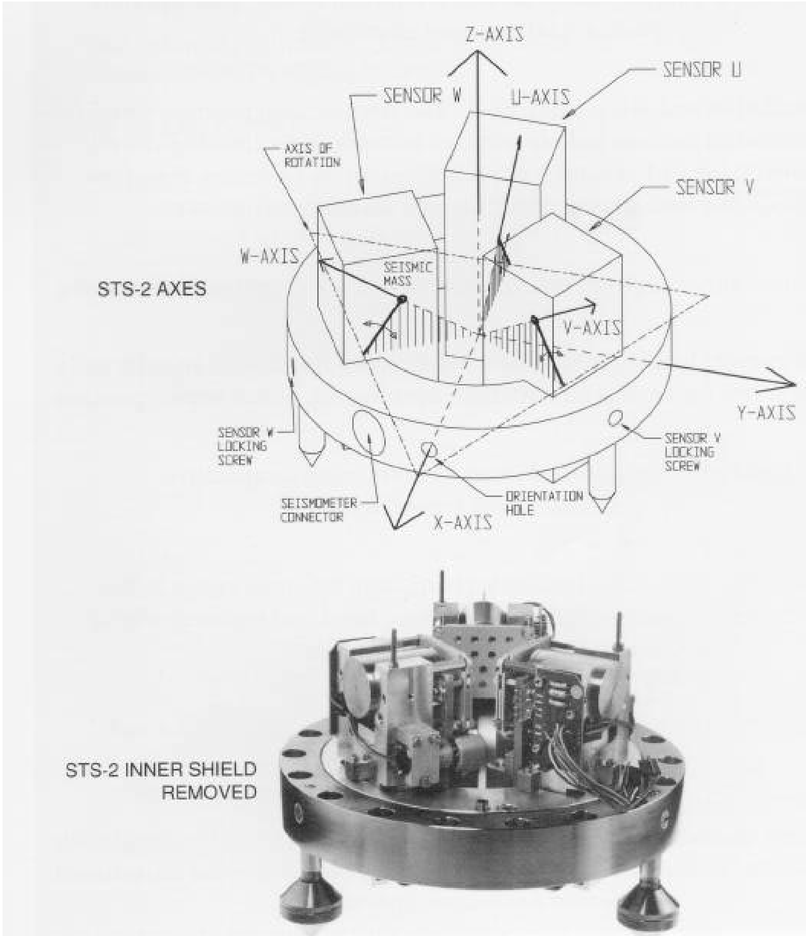
Modeled horizontal ground noise and two-stage active platform noise.



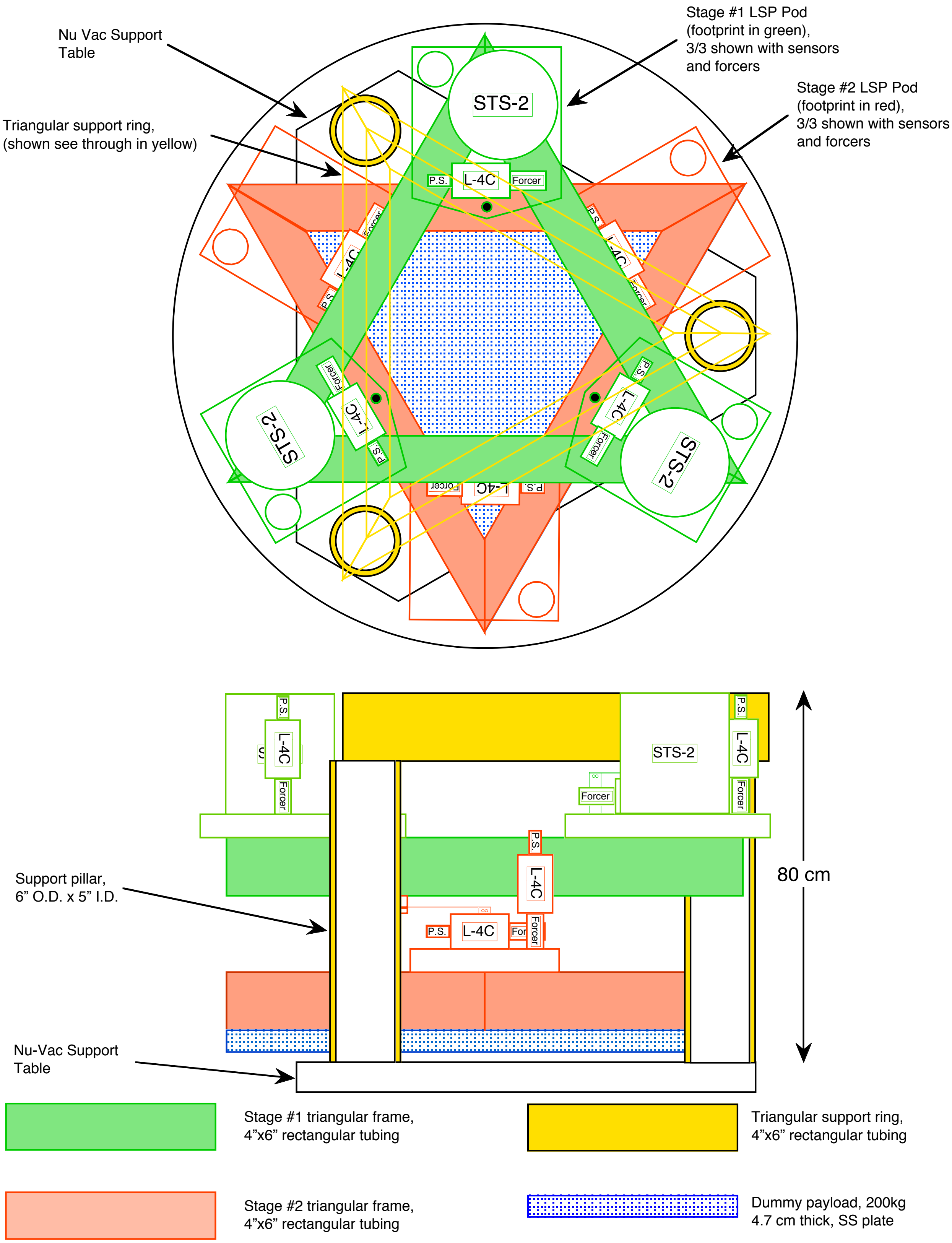
left: One horizontal (open) loop transfer function; right: horizontal transmission function of two-stage active platform.

Key vibration sensors: Streckeisen STS-2, Geophones





Rapid Prototype: to be built at JILA, tested at MIT



Tests at Stanford:

Half-scale test in ETF of single active stage supporting GEO triple pendulum mock-up. Main goal is to study strategies for control reallocation.

HAM design for MC and RM:

- We expect the overall height of the two-layer active platform to be 30", which nicely fits between the HAM support tubes and the CM of the optics table.

- An "uptube" or similar frame can be fitted inside the frame to bring the quiet platform up to support the HAM optics table, as currently positioned.

- The GEO short triple pendulum tentive design for HAM use provides 10^{-5} transmission at 10 Hz, giving approximately the required spec. of 3×10^{-18} m/$\sqrt{\text{Hz}}$.

Presentation of the SAS chains at the Glasgow meeting

SAS, Seismic Attenuation System, also called Soft SEI, is a passive system made of an Ultra Low Frequency [ULF] (15-20 mHz) Inverted Pendulum [IP] connected to a low frequency Geometric Anti Spring Filter [GASF] called F0, followed by a chain of 3 or 4 GASFs which in their turn support a GEO like Triple pendulum. (Tr 1)

The top IP and GASF are provided with accelerometers for Inertial Damping of the system's resonances, which are all confined below 3 to 4 Hz.

No active seismic attenuation is made at or near the frequency range of interest.

An eddy current damping system placed between F0 and the first passive GASF filter takes care of possible resonances internal to the chain excited by the triple pendulum actuation.

A structure extending from the bottom GASF supports the actuators to push on the first of the triple pendulum bobs.

Although this structure can be fit inside an existing BSC, an extended BSC can contain a two-in-one or even a three-in-one SAS chains for independent isolation and control of two or three optical elements (Tr. 2).

An existing prototype (Tr. 3) is currently being tested for performances.

The preliminary results from the IP prototype of Tr. 3 will be presented by Joe Kovalik.

The performances of individual and two filters will be presented by Akiteru Takamori, as well as the simulated performance of the entire SAS chain prepared by Virginio Sannibale.

Advances on high performance accelerometers will be presented by Alessandro Bertolini.

SAS achieves the mirror thermal noise level at 4 Hz for a tall structure (Tr.2) and at 6 Hz for a structure fitting inside existing BSC (Tr.1) thus making for a comfortable safety margin.

The demonstrated advantages of the soft nature of the SAS first stages are multiple.

- Soft system provide natural preattenuation at the lowest frequencies, including at the micro-seismic peak, as demonstrated by the Virgo results on IP (Tr. 4). Note that in the VIRGO IP the attenuation properties of the transfer function are interrupted at 9 Hz by the resonance of the bamboo like Virgo IP legs (Tr.5) while the LIGO prototypes are designed and have been measured to have that first resonance at 60 Hz.
- The IP and F0 provide a natural platform for the inertial damping accelerometers. These accelerometers, operating on a pre attenuated platform, may reach better performances, especially at low frequencies.
- The softness of the movements allow precision and negligible power positioning of the individual optical components, see for example Tr.6 where a payload of 750 Kg is moved up and down by 4 millimeters using less than 50 mW power in a small voice coil.
- The passive filters hanging from F0 effortlessly deliver the required attenuation factor with a comfortable safety margin.
- Inertial damping of an IP/F0 unit have already produced remarkable results in terms of residual r.m.s. motion of the payload; a measured r.m.s. residual motion of 50 nm

above 100 mHz (Tr. 7 figure 10 left) was measured in the small Virgo mode cleaner towers (Tr. 8) operating under UHV conditions. Even better r.m.s. motion performance is expected from the use of the advanced LIGO accelerometers on the LIGO IP.

- This excellent residual 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.
- All SAS components (see for example a filter in Tr. 9) are UHV compatible and fully bakeable to relax creep activity from the stressed materials.
- All metal to metal connections on the stress path are made in a creak free geometry.
- 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.

The instrumentation of the HAM chambers is still under study the following is very preliminary.

The HAM optical bench can be supported on low-frequency, six-dimensional movement feet (see side view Tr. 11 and bottom view Tr.12). The feet (tr. 13) are commercial items (minus-K technology) that can provide extremely good attenuation performances (see our measurements of one of these feet in Tr.14) but they still need to be creep proofed and UHV proofed.

The HAM optical bench will be provided with LVDTs, accelerometers and voice coil actuators and controlled just like an IP/F0 system (Tr. 11-12). Similar performance is expected.

In case that even more attenuation was required than what these HAM table can provide, we could hang the HAM triple pendula from a shortened version of the mini SAS developed for TAMA (tr. 15). The first filter and TAMA mirror actuation box would be replaced by the LIGO triple pendulum.

In this mini SAS small linkless GASFs would be used.

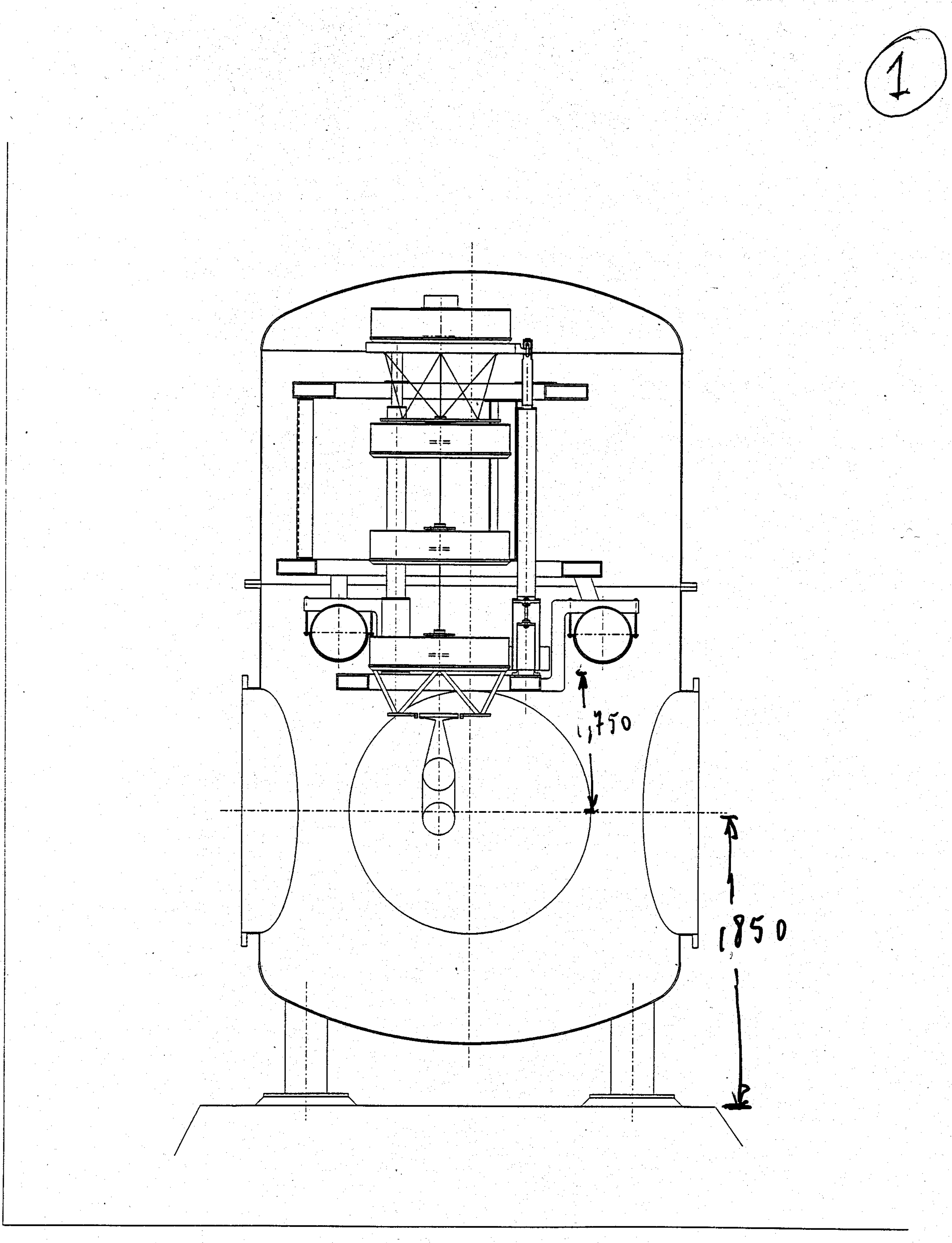
A tabletop prototype of linkless GASF is shown in Tr. 16. Its measured frequency vs. working point performances are compared in Tr. 17 with the correspondingly simulated (ANSYS) performances.

Tr. 18 compares the linkless GASF performance with that of standard GASF and Virgo's Magnetic Anti Spring filters (MAS).

In these small GASFs a monolitic trefle blade (Tr.19) is pre-stressed in a filter body (Tr.20) to get the required performances.

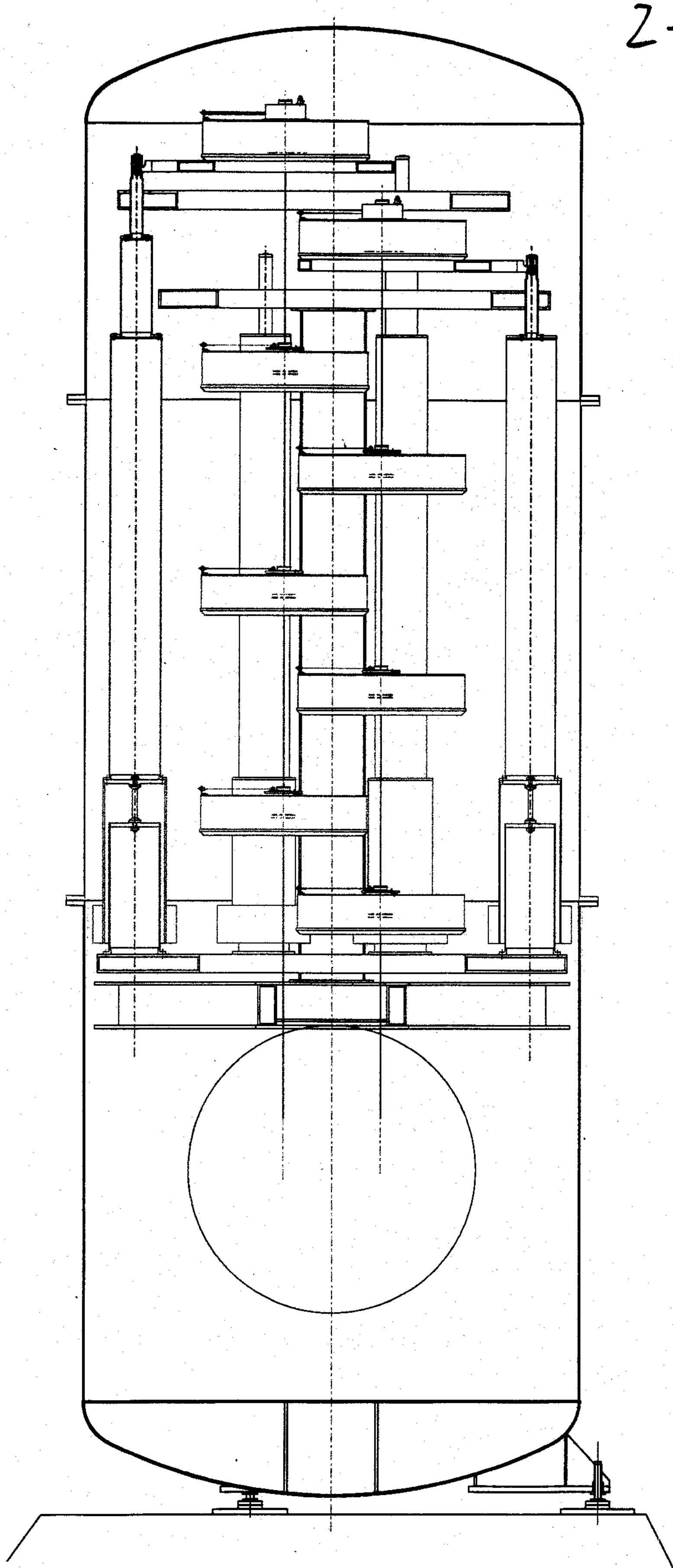
Even very short Ips like the ones envisaged for use on the HAM optical tables can deliver quite good attenuation factors. This is shown in Tr. 21 illustrating the measured performance of a 60 cm tall IP.

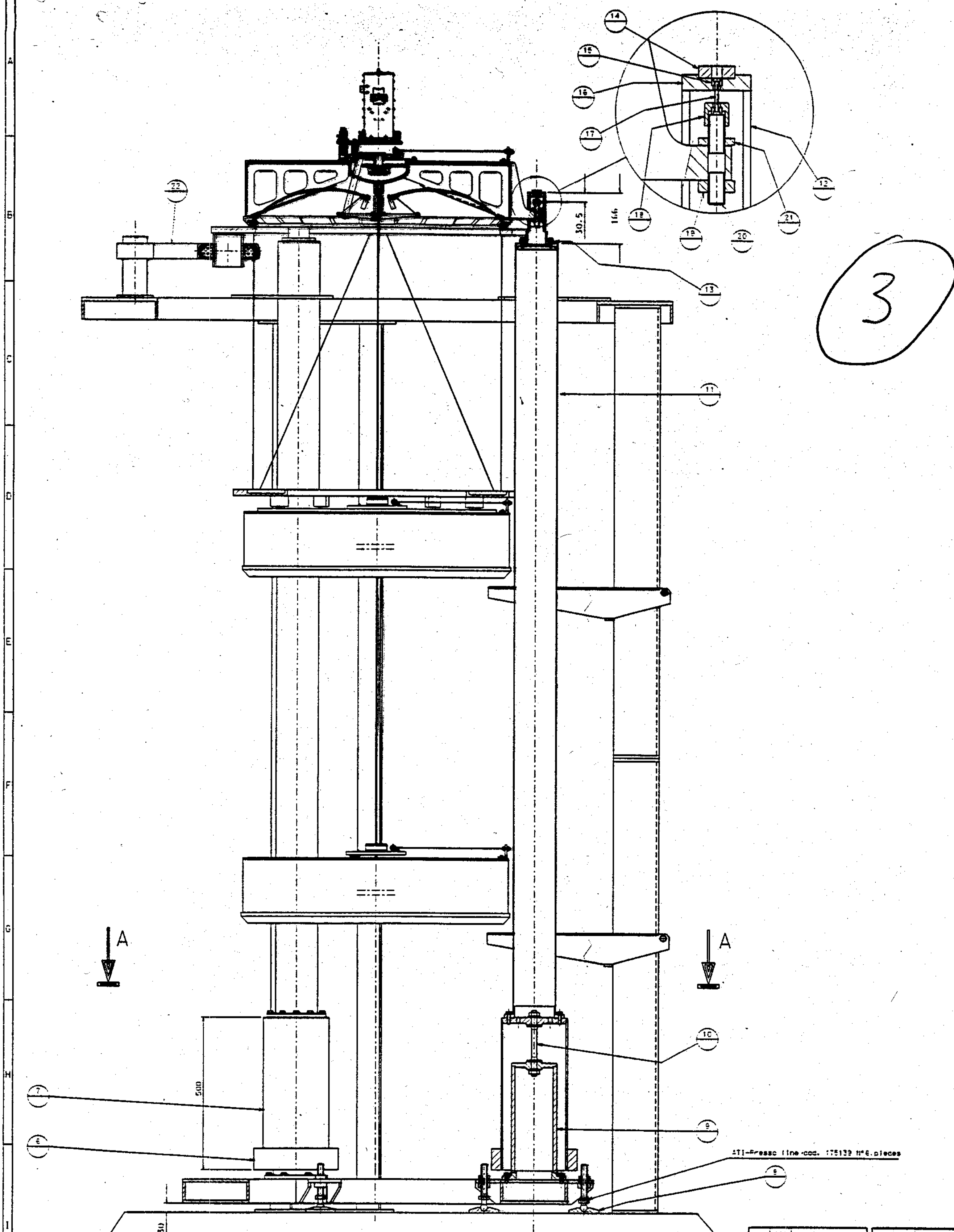
The damping in the bottom of Tr. 21 is obtained with a simple MIMO velocity damping generated by the LVDT signals.


1
1750
1850

2-IN-1

(2)





14	008	head's joint cap
13	008	leg's head rotation disk
12	008	leg's head
11	008	main leg
10	009	elastic joint
9	001	base column
8	008	footing
7	007	bell
6	008	counterweight
ref.	drw.	[illegible]

22	013	[illegible]
21	009	height tuning c'nut
20	009	height tuning rod
19	009	height tuning nut
18	009	height tuning cap
17	009	head's flex joint
16	008	leg's head top disk
15	009	head joint ½ cup
ref.	drw.	[illegible]

Size A1

	pendulum rotated	30-7-99	
ref.	[illegible]	date	signature
	modifications		

LIGO PROJECT

TEST-TOWER

LATERAL VIEW

R. De Salvo

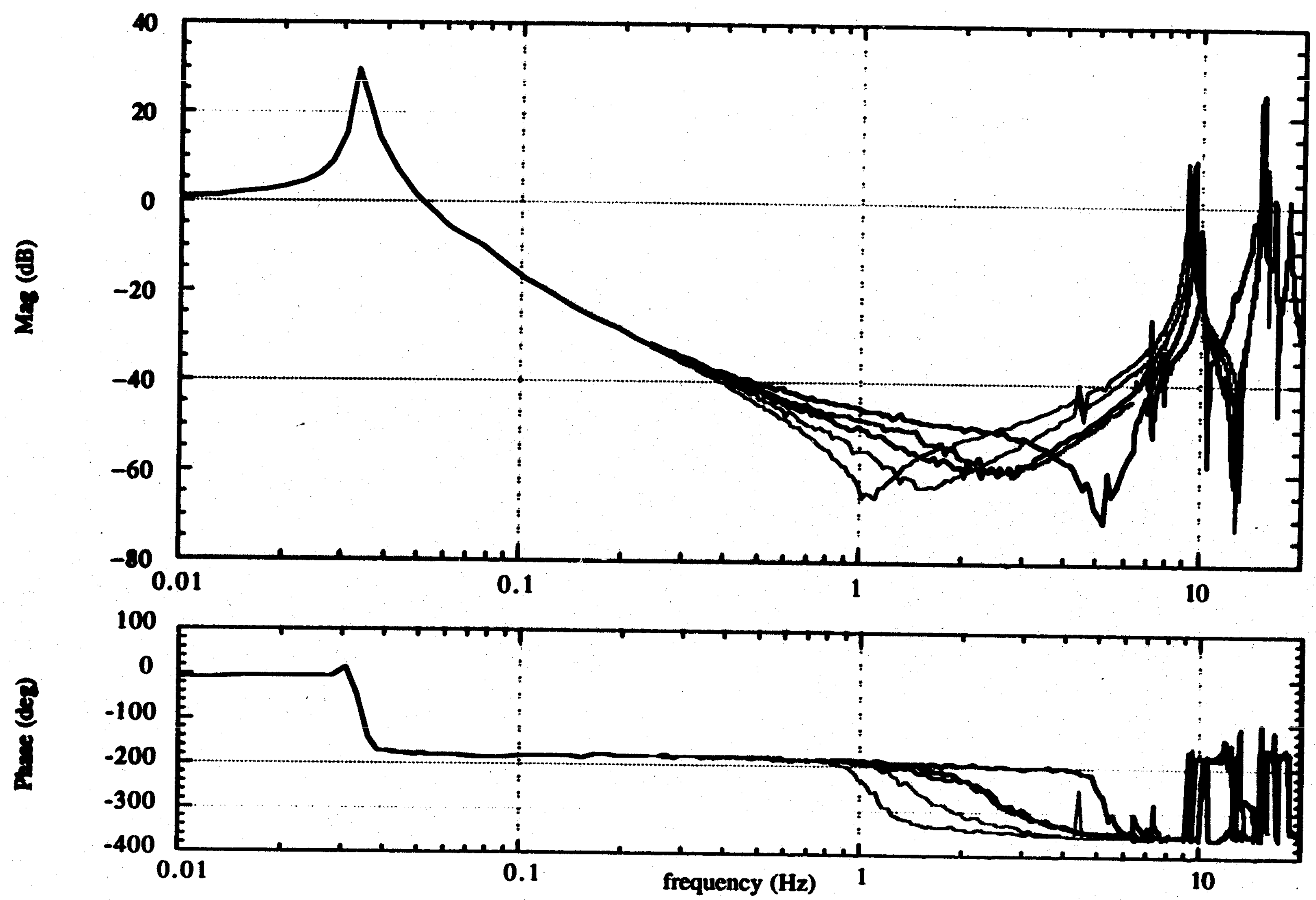
Test-tower.003

PROMEC 2-7-99

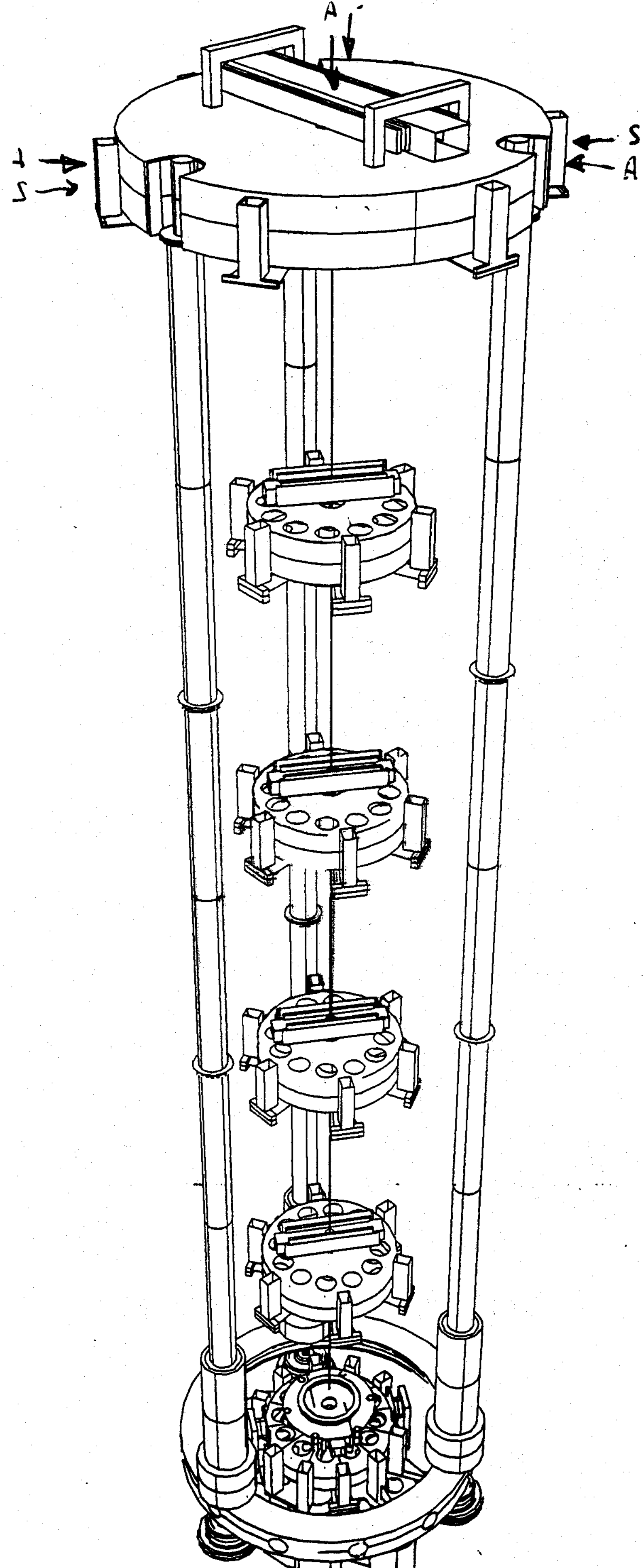
1:6

Inverted Pendulum Transfer Function

4

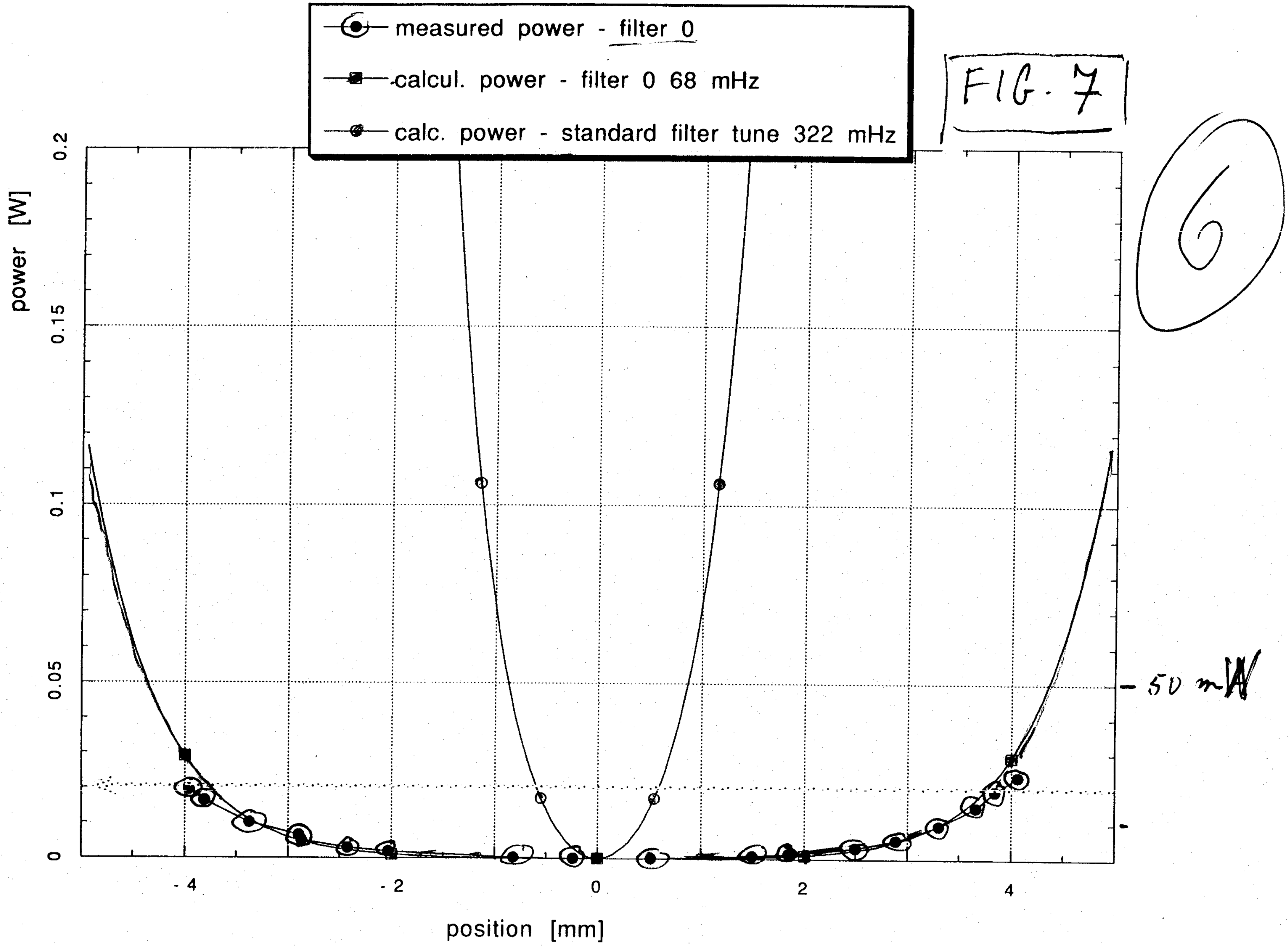


Giovanni Losurdo - Scuola Normale Superiore & INFN



5

FIG. 7


measured power - filter 0
calcul. power - filter 0 68 mHz
calc. power - standard filter tune 322 mHz
power [W]
0
0.05
0.1
0.15
0.2
- 4
- 2
0
2
4
position [mm]
- 50 mW
6

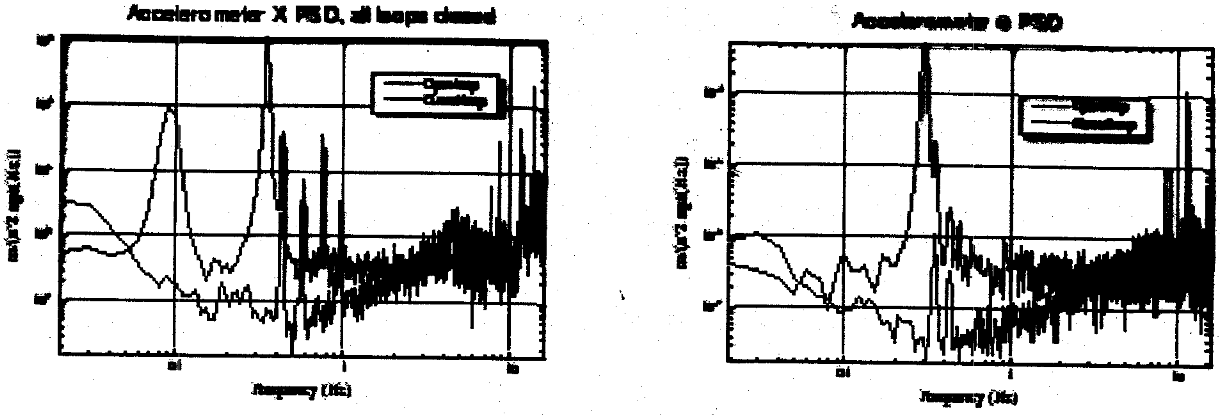


Figure 9: Spectra of the virtual accelerometers X and Θ with the damping ON and OFF.

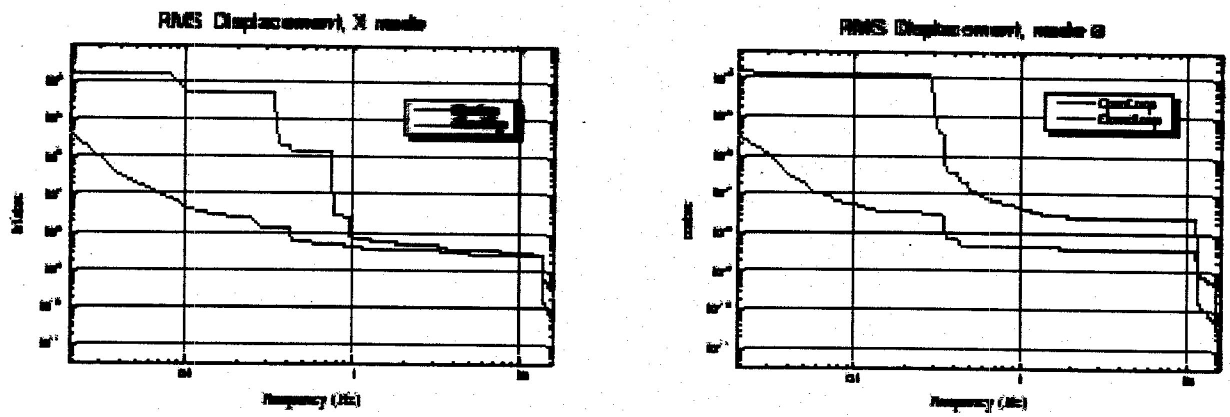
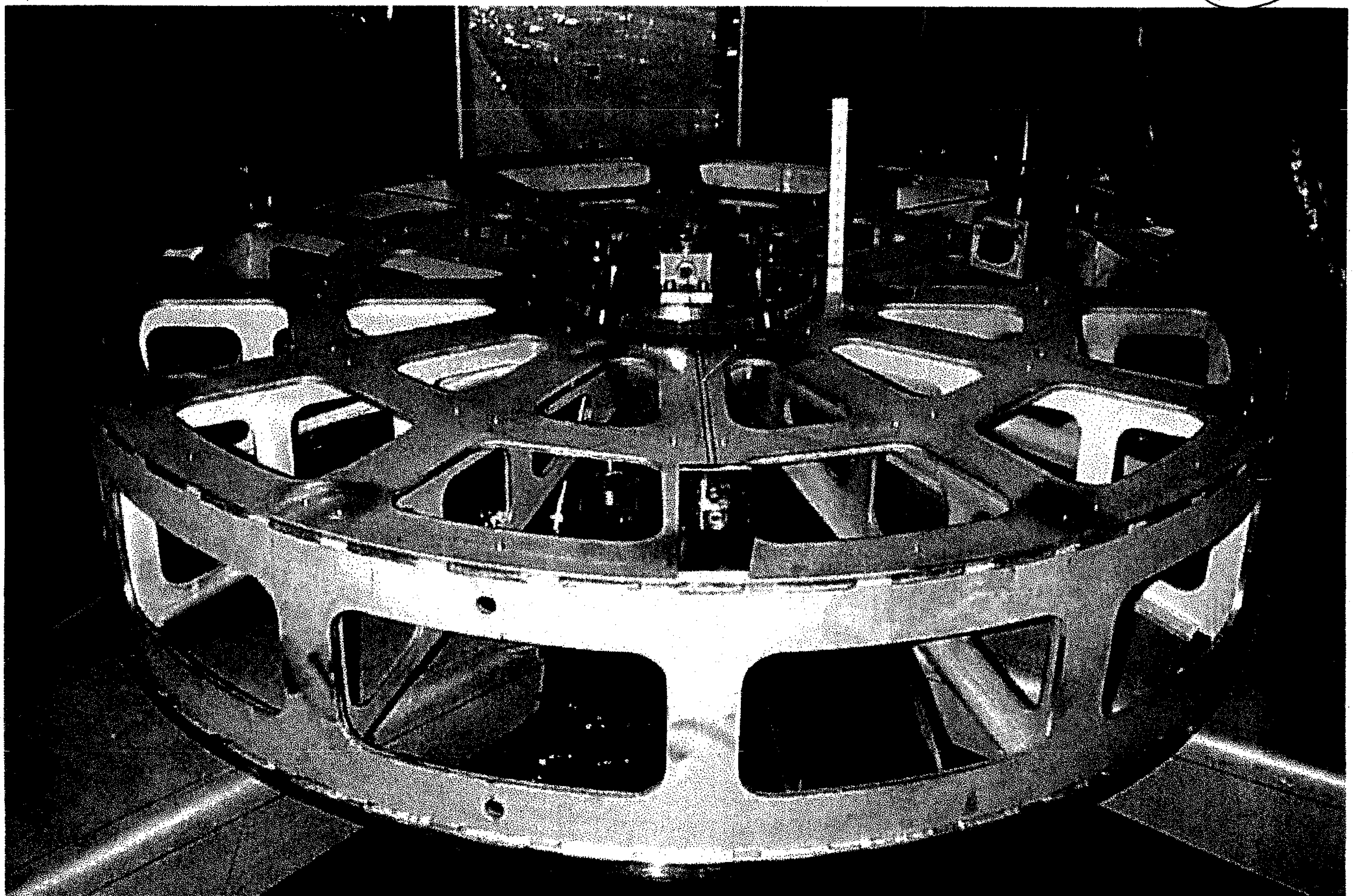
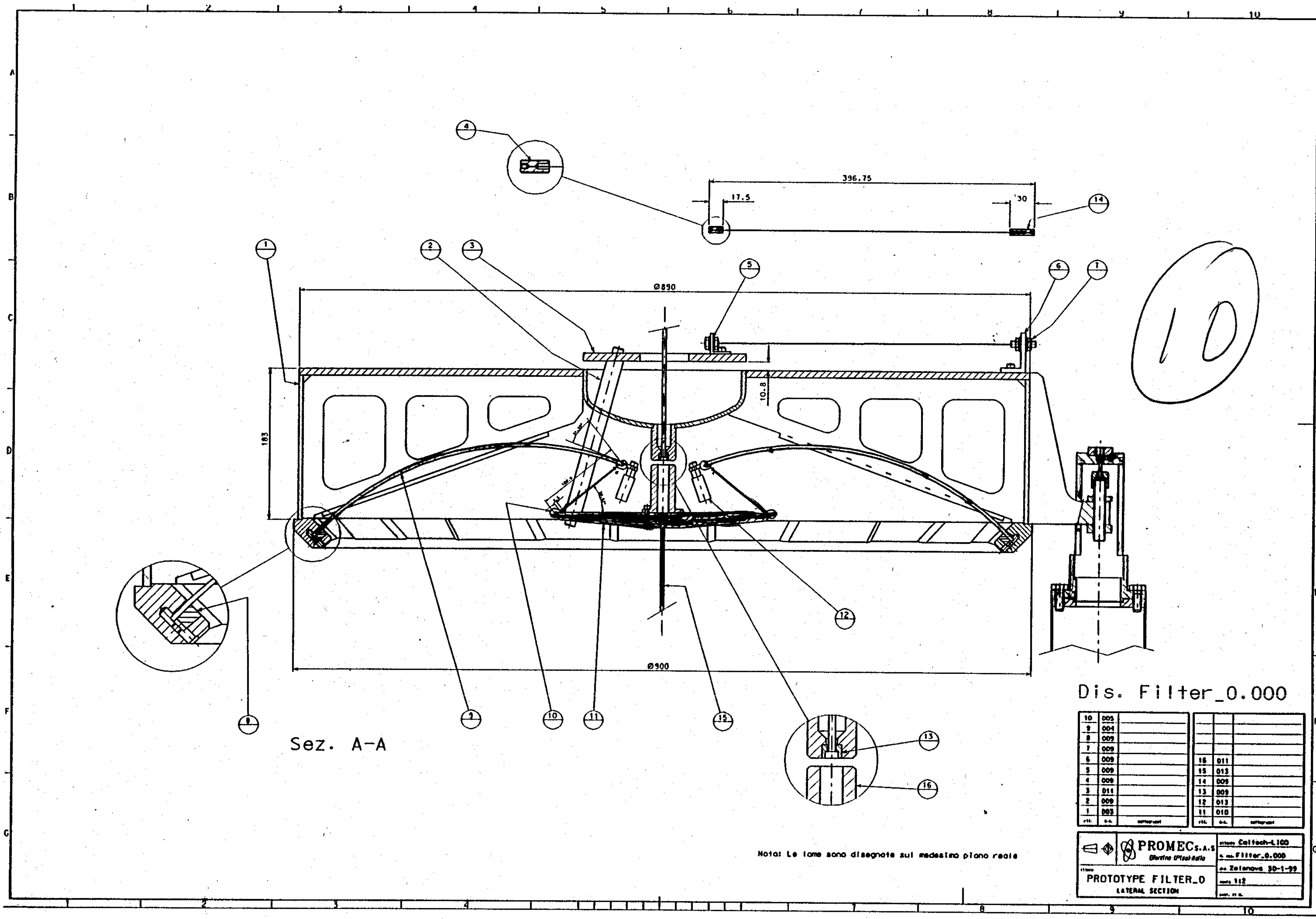
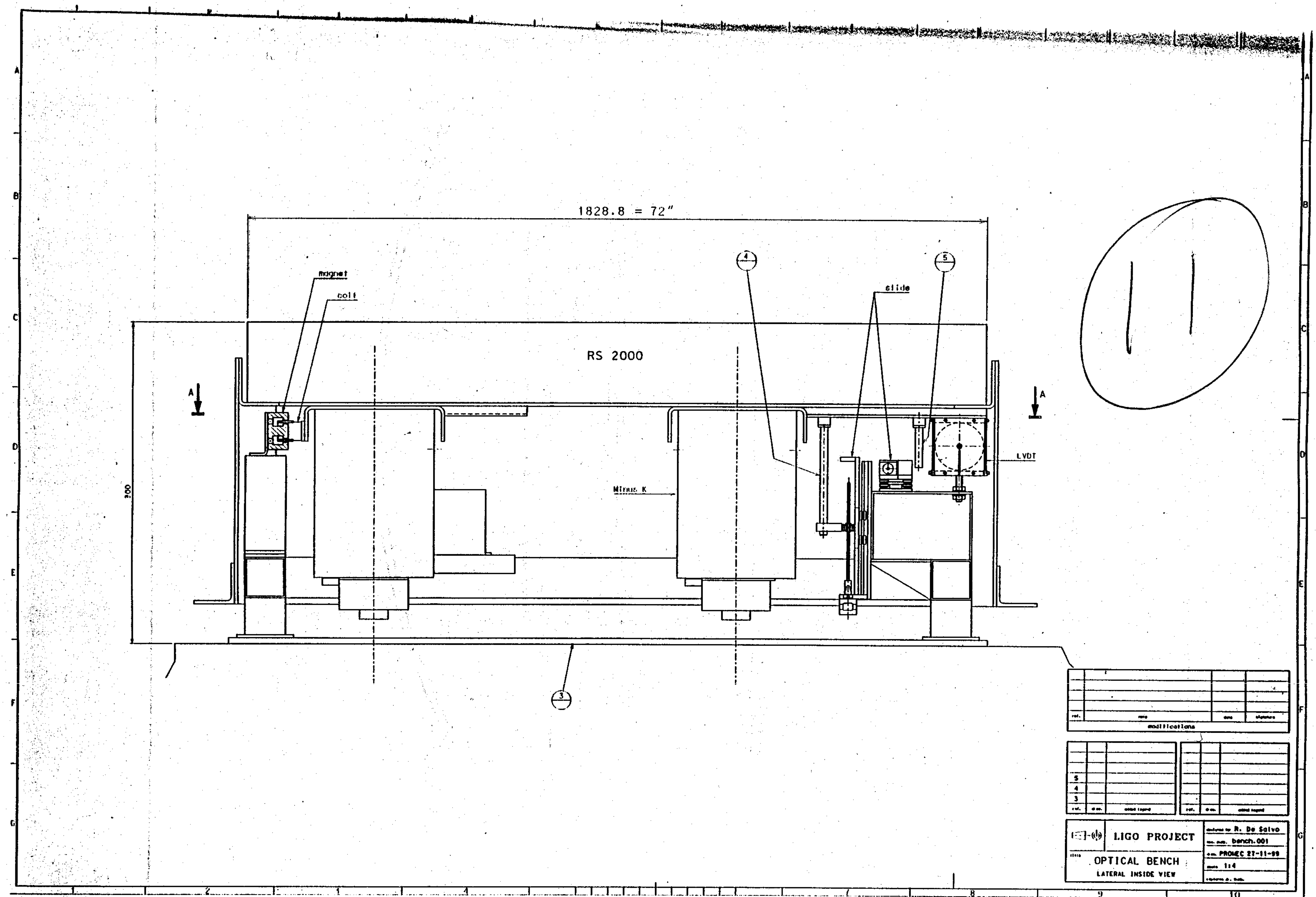


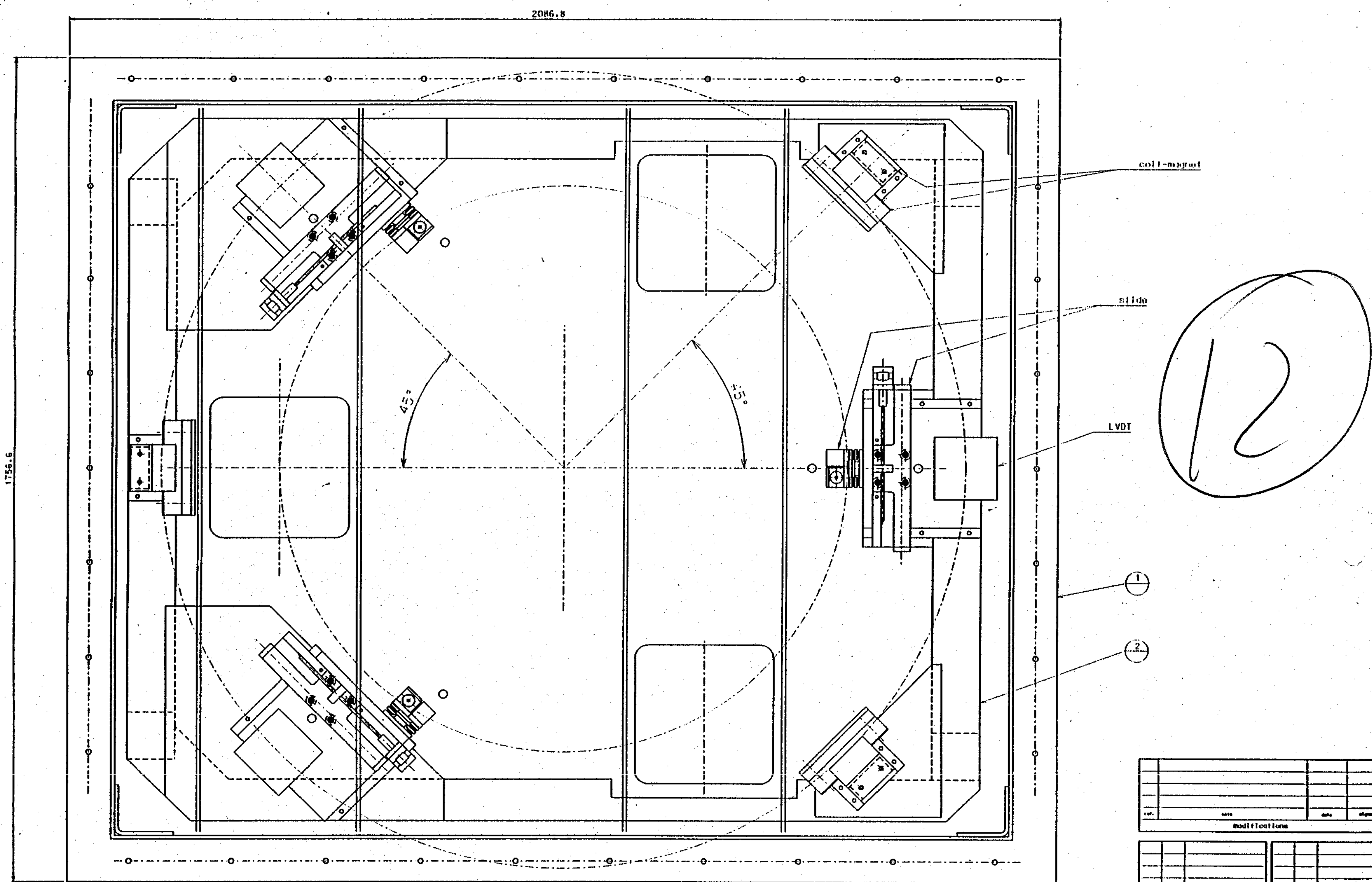
Figure 10: RMS motion of the IP top table, calculated from the spectra of fig. 9. The translational RMS motion at 100 mHz is reduced from $\sim 70\,\mu m$ (damping OFF) to ~ 50 nm (damping ON).





10	005				
9	004				
8	009				
7	009				
6	009		16	011	
5	009		15	013	
4	009		14	009	
3	011		13	009	
2	009		12	013	
1	003		11	010	


1828.8 = 72"
magnet
coil
slide
4
5
RS 2000
A
A
LVDT
Minus K
200
3
modifications
5
4
3
LIGO PROJECT
R. De Salvo
bench.001
PROMEC 27-11-99
1:4
OPTICAL BENCH
LATERAL INSIDE VIEW
11



	modifications		

ref.	dim.		ref.	dim.	
2					
1					

LIGO PROJECT

OPTICAL BENCH

SECTION A-A

R. De Salvo

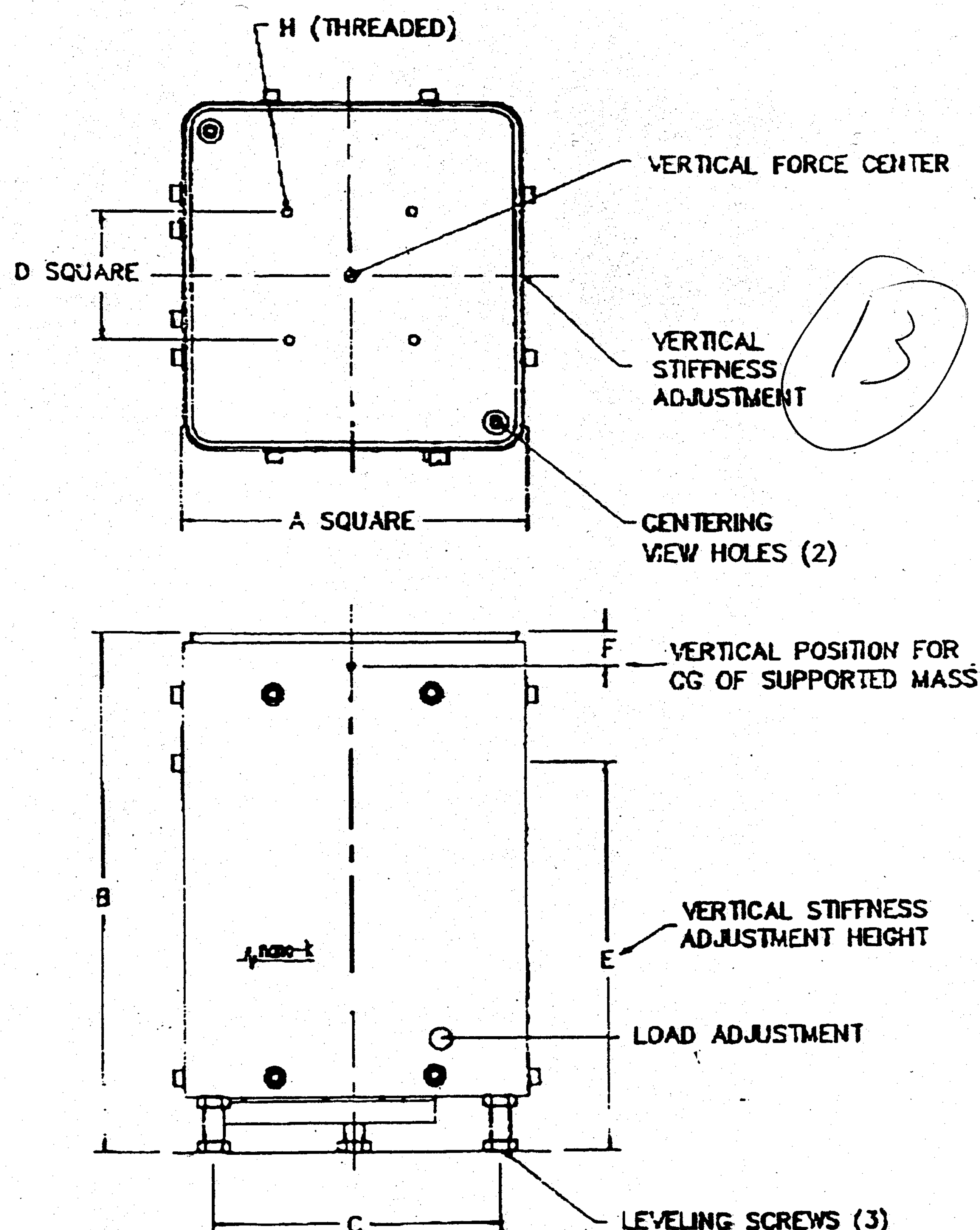
bench.000

PROMEC 27-11-99

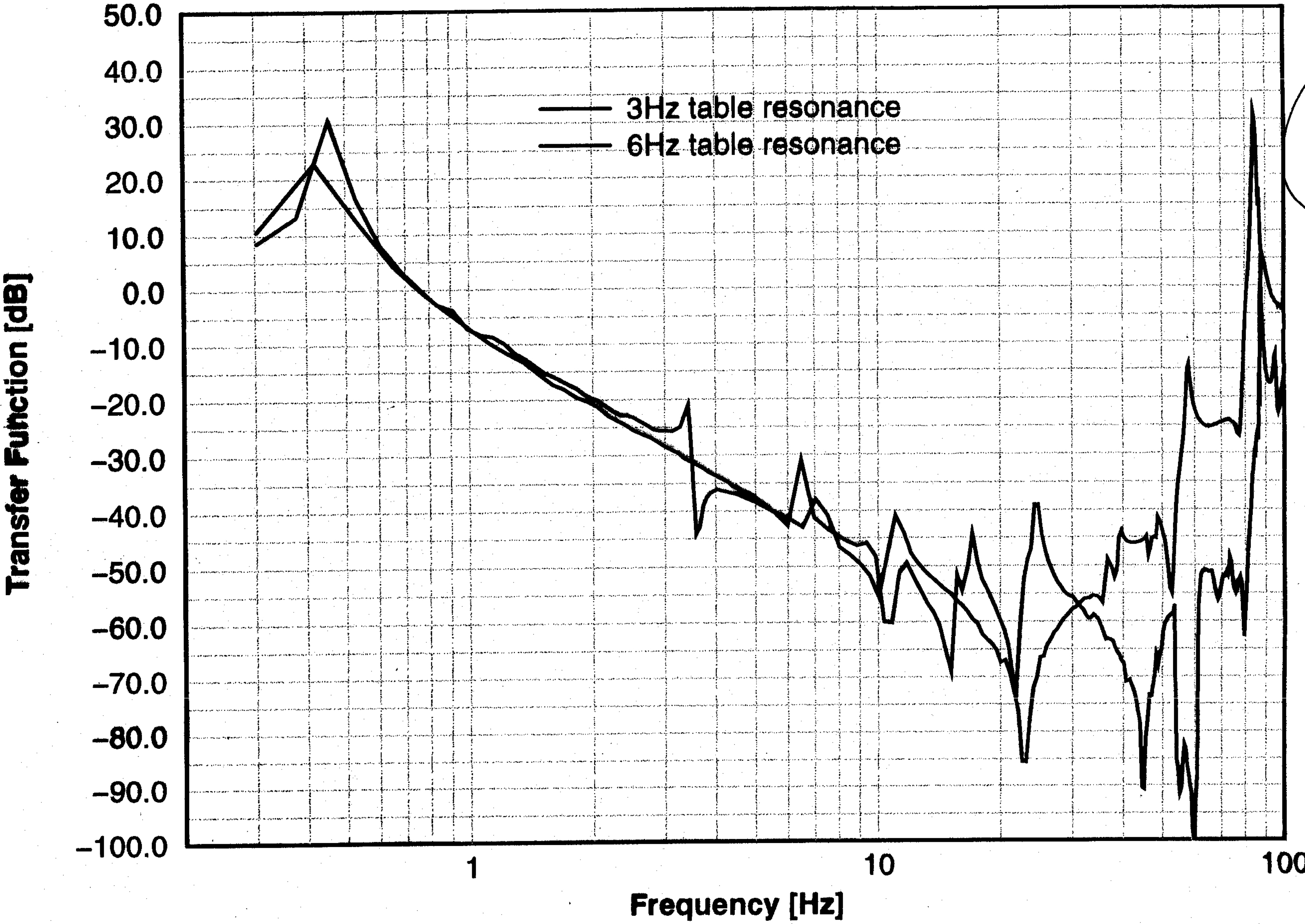
1:4

SERIES SM-1 VIBRAT

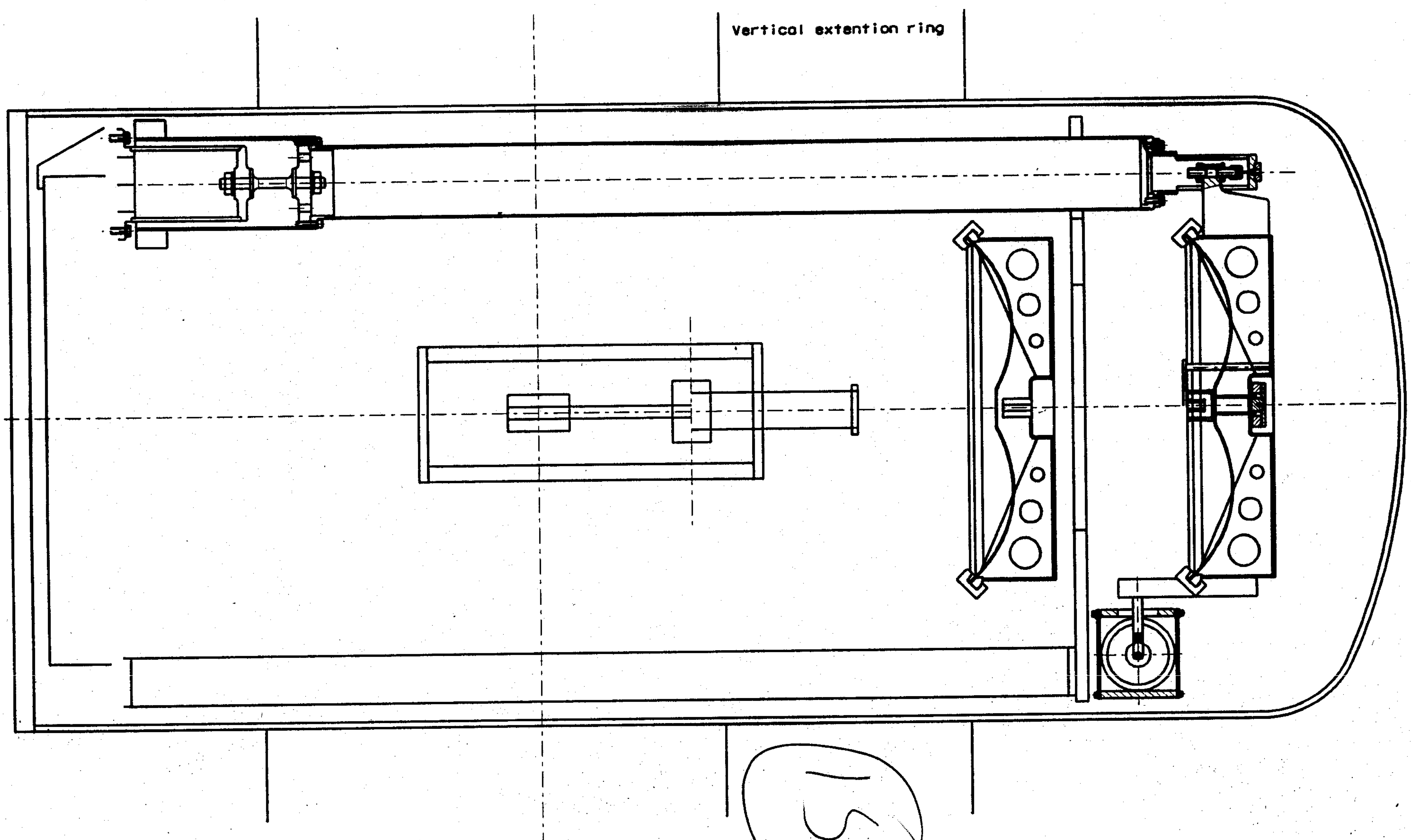
PHYSICAL DIMENSI



Vertical transfer function of Minus–K isolator

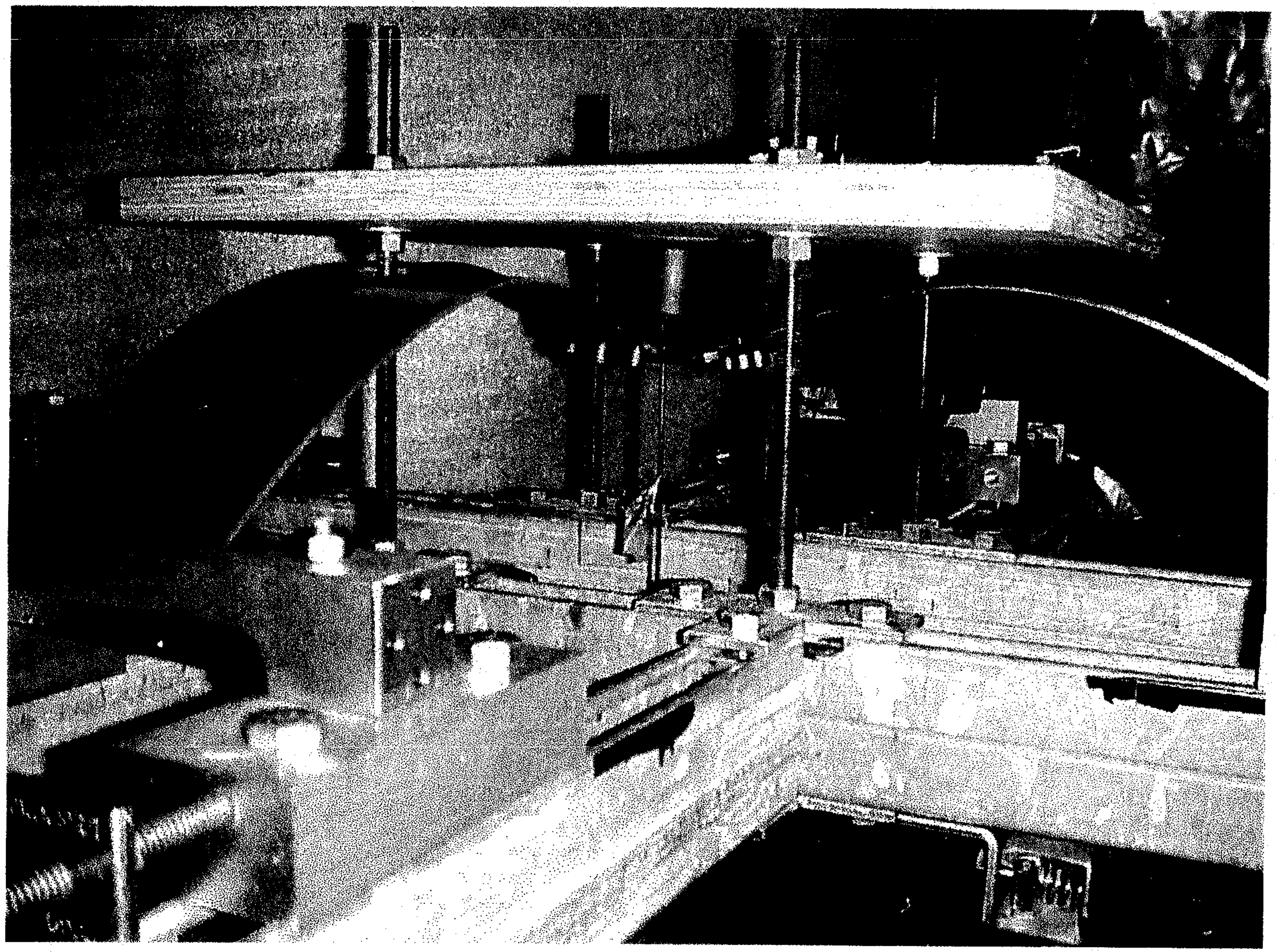


14


Vertical extention ring

GAS Filter : Current Work

"Link-less" GASF

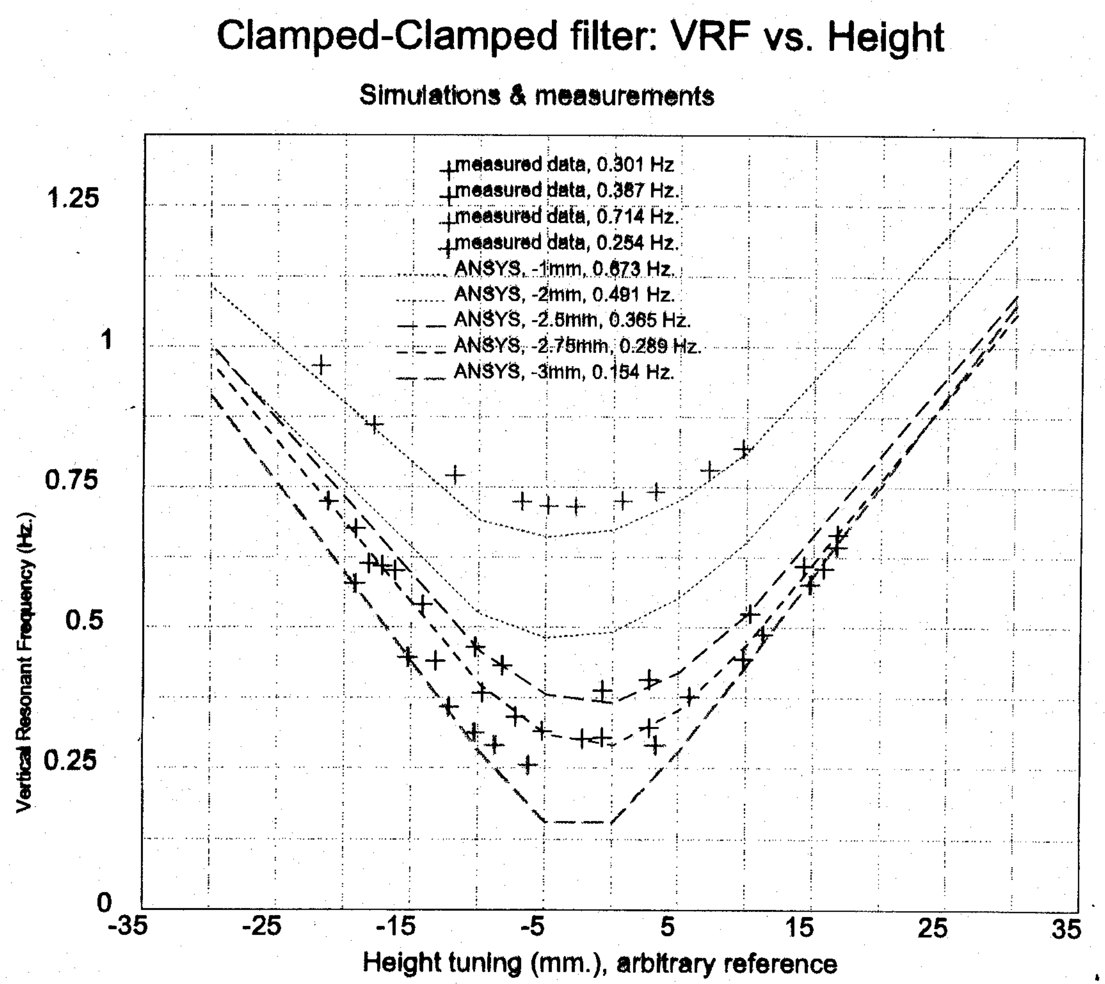


Pre-Prototype of "Link-less" GASF

16

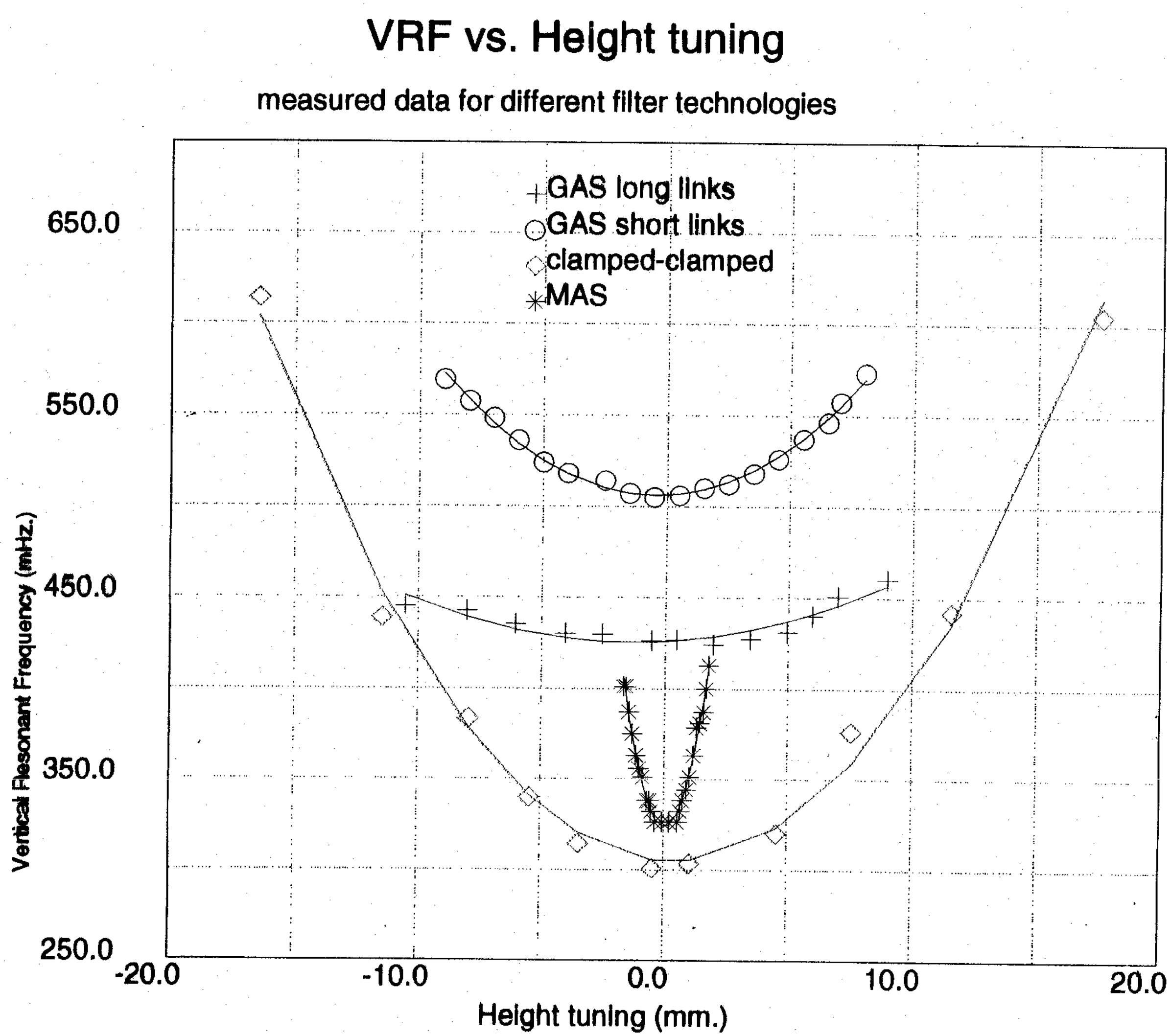
GAS Filter : Current Work

"Link-less" GASF



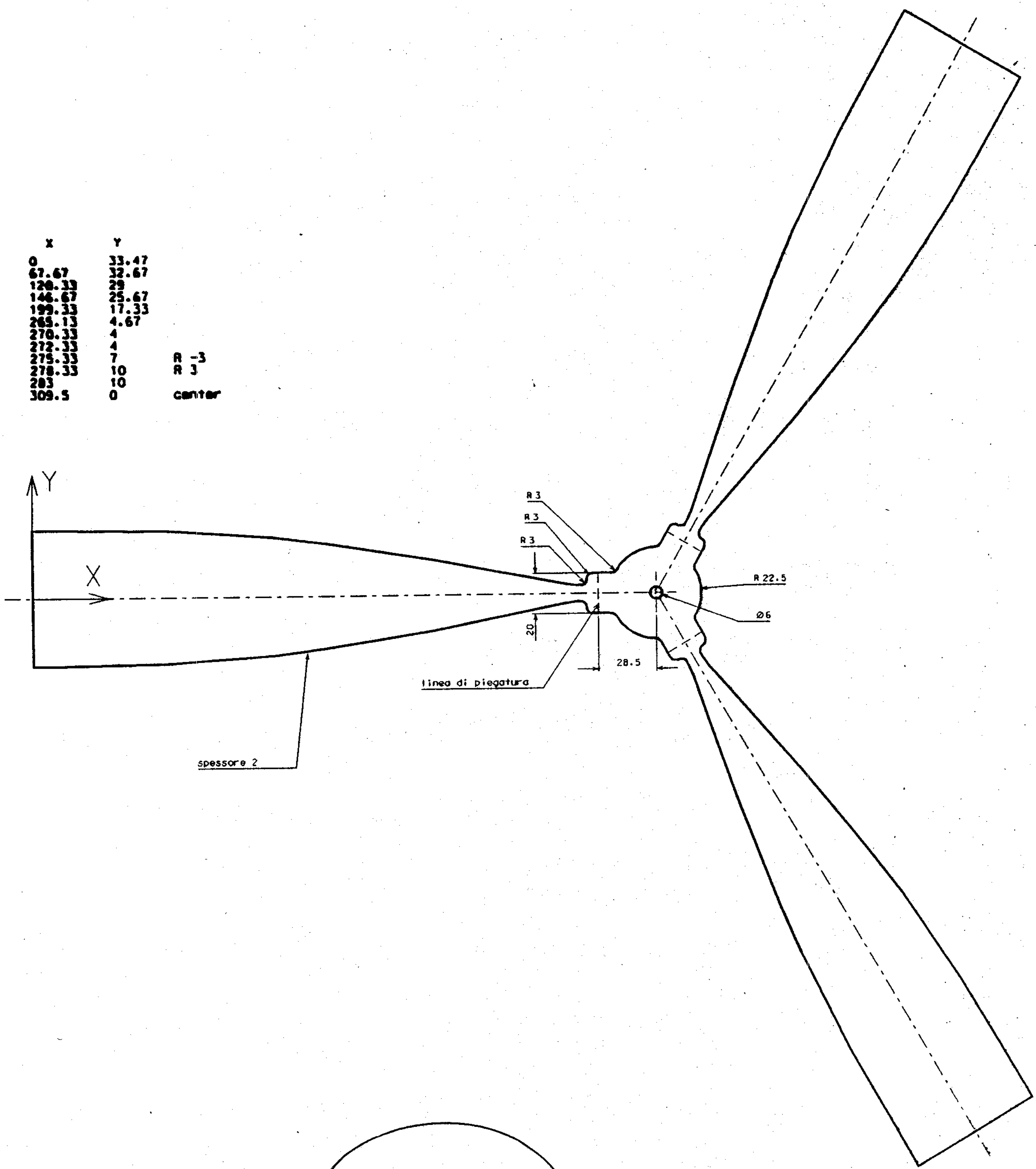
GAS Filter : Current Work

"Link-less" GASF



18

X	Y	
0	33.47	
67.67	32.67	
120.33	29	
146.67	25.67	
199.33	17.33	
265.13	4.67	
270.33	4	
272.33	4	
275.33	7	R -3
278.33	10	R 3
283	10	
309.5	0	center

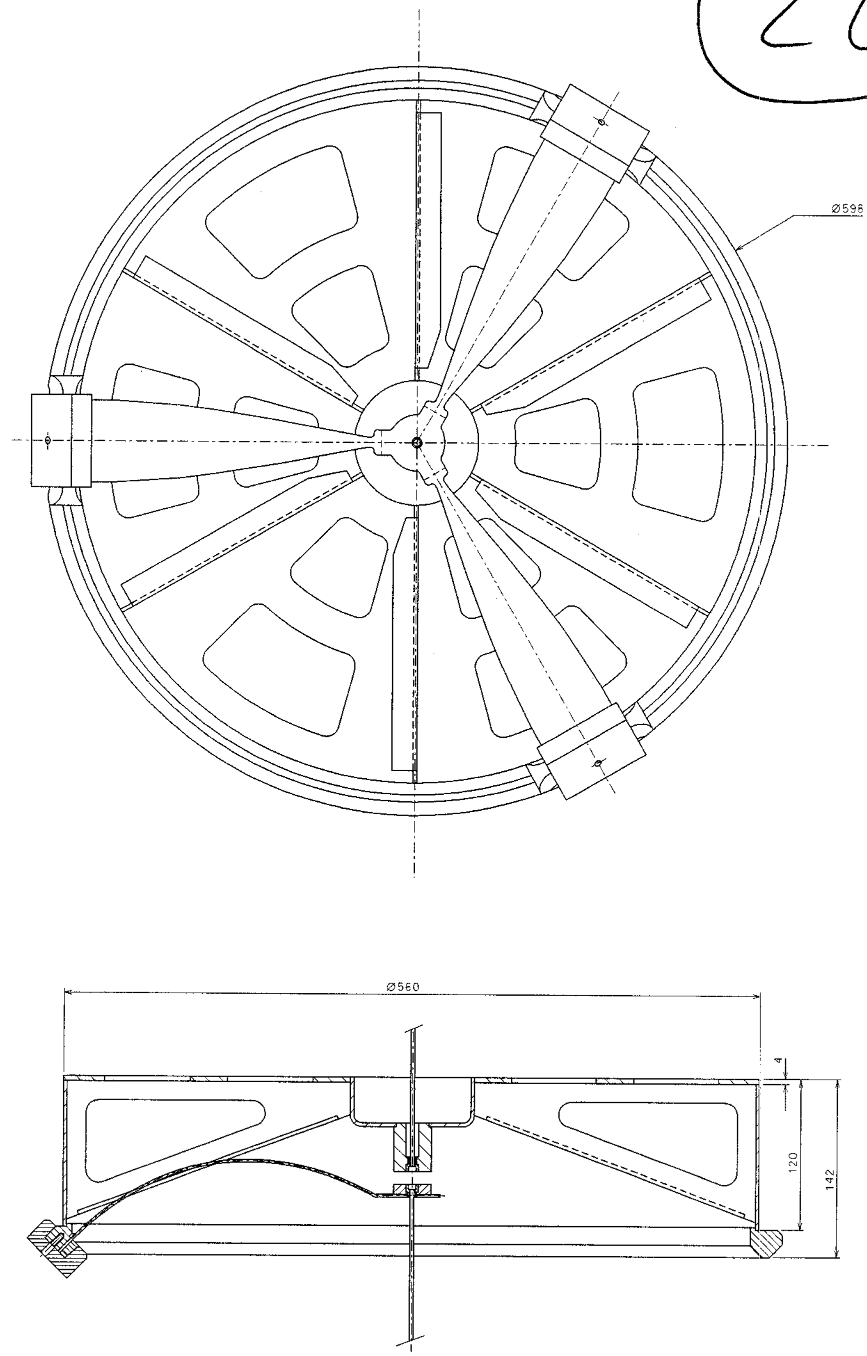


4	1	maraging	1:1

LIGO PROJECT

A1

20



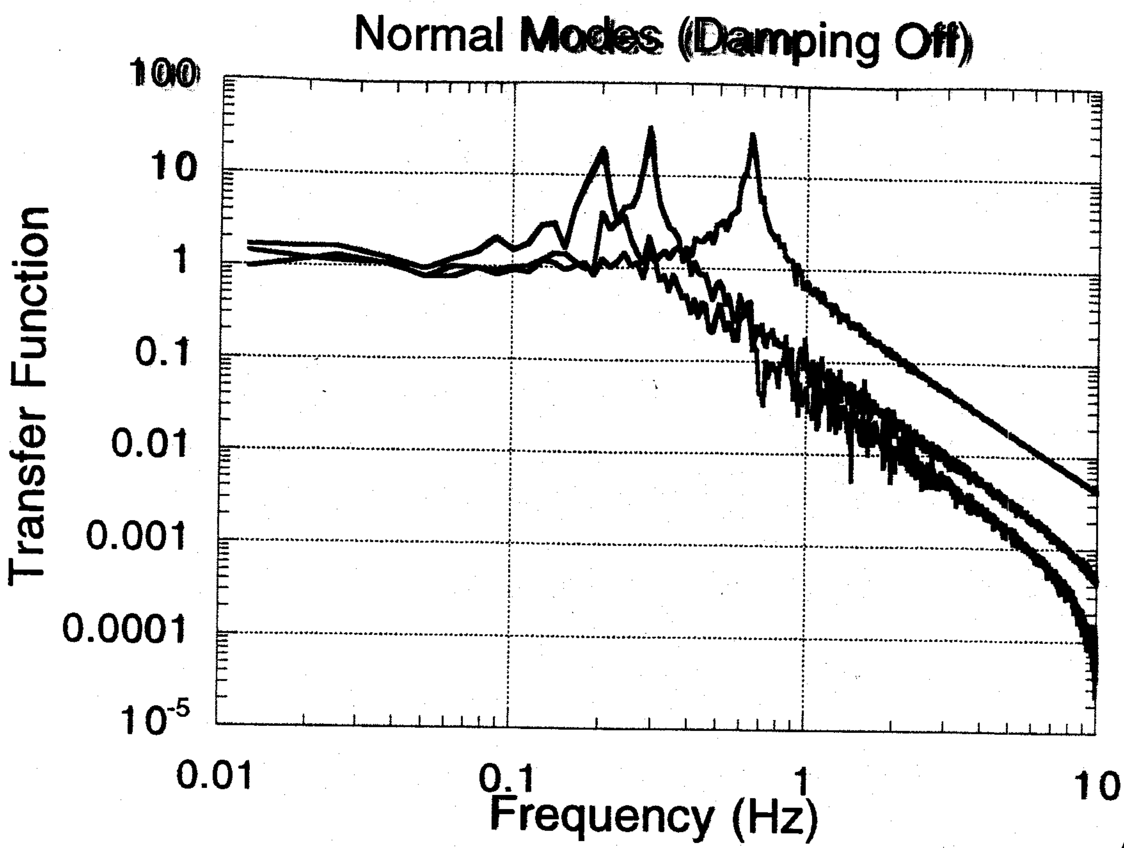
ref.	draw.	added legend	ref.	draw.	added legend

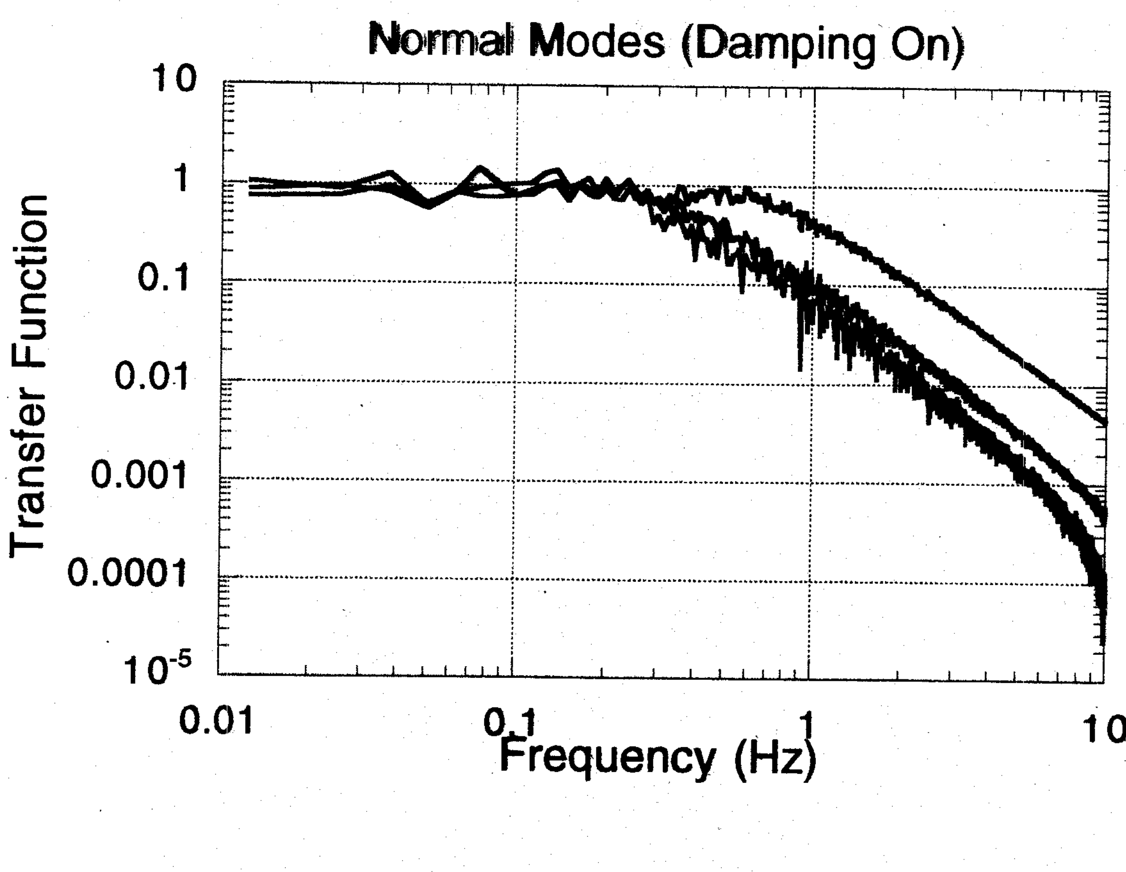
LIGO PROJECT

designed for R. De Salvo
ass. numb. Tama.000
draw. PROMEC 19-12-99
scale 1:2
replaces dr. Numb.

title TAMA-SAS-TOWER
SMALL FILTER

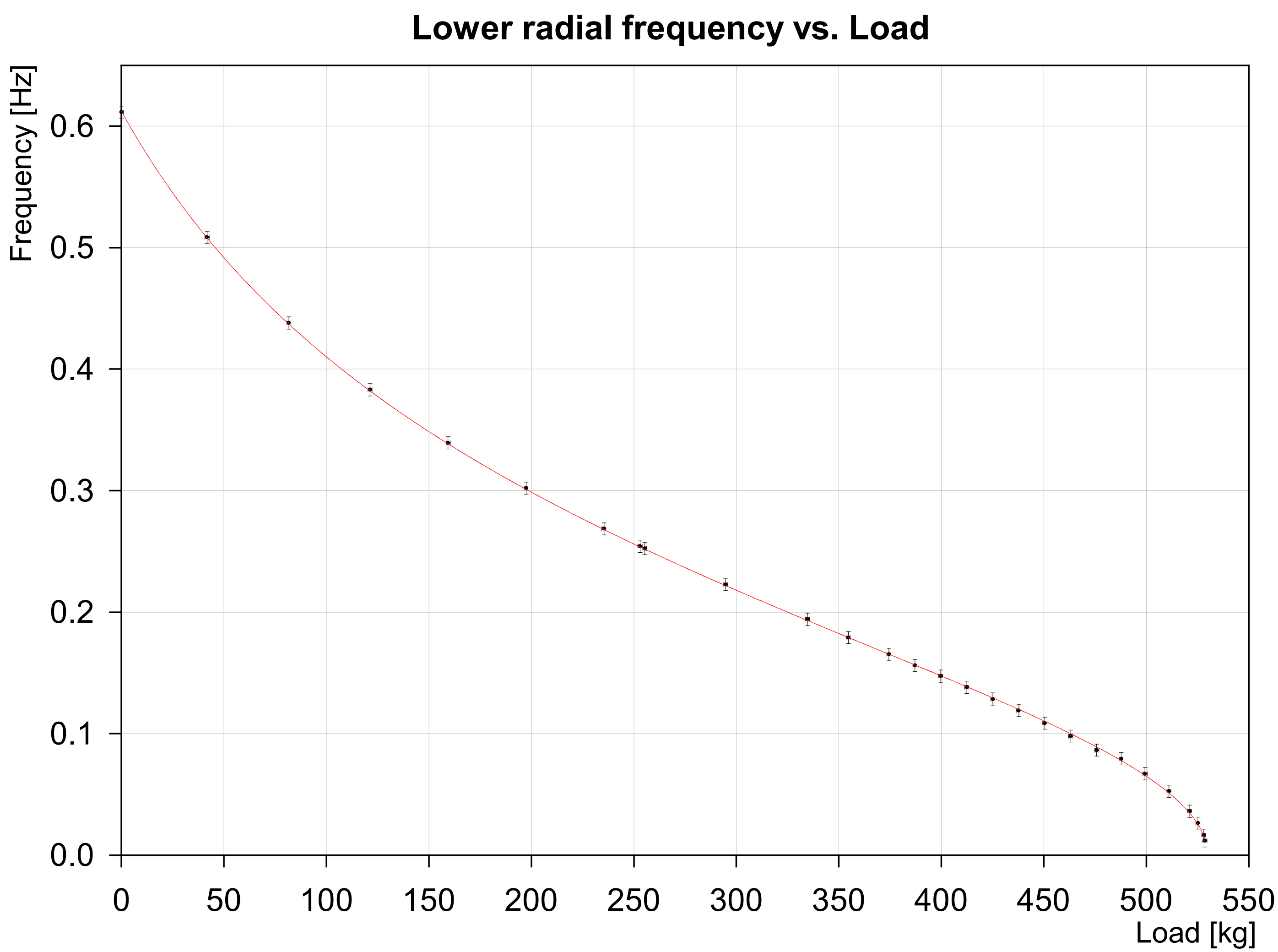
A1

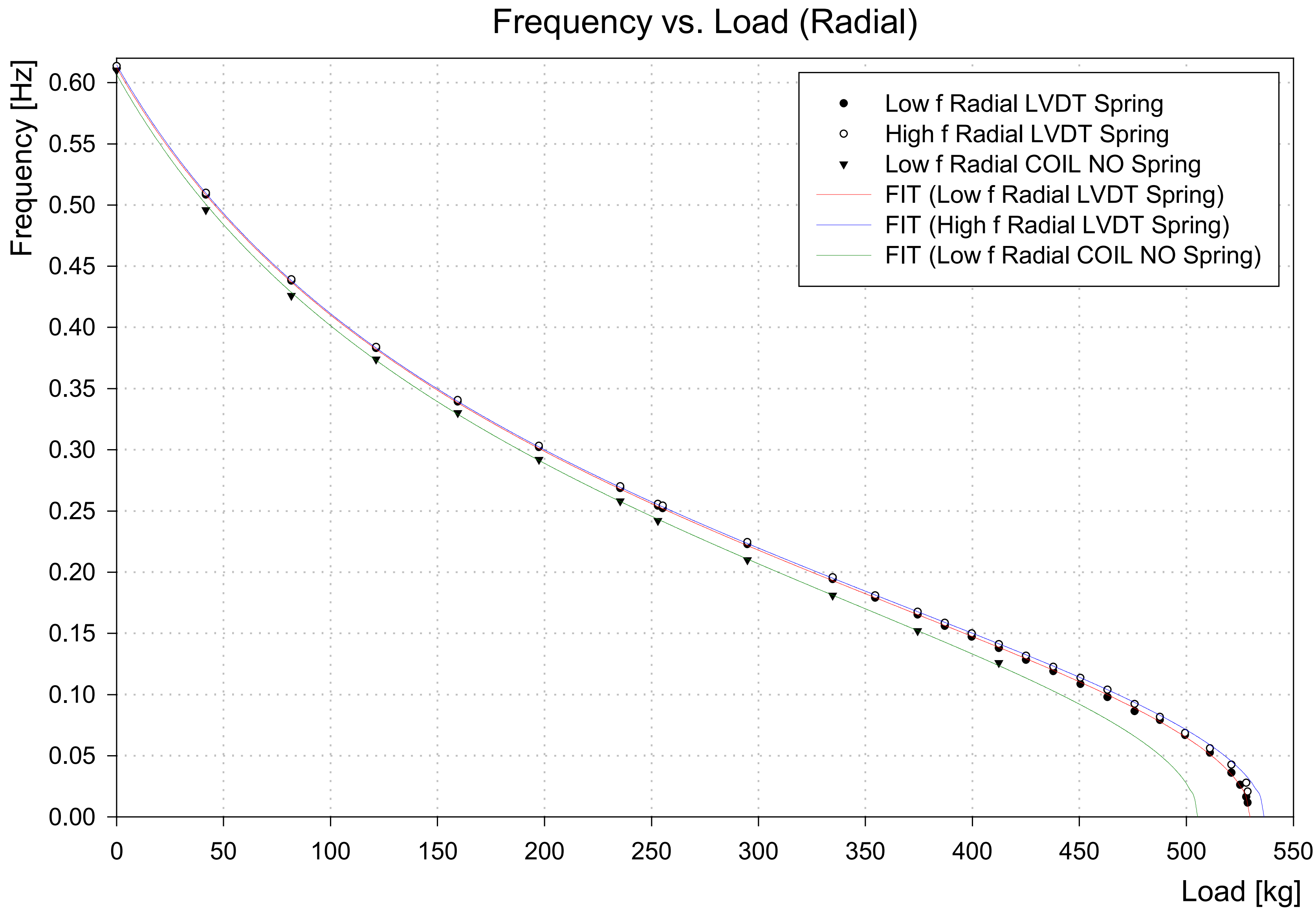

Normal Modes (Damping Off)
Transfer Function
Frequency (Hz)
100
10
1
0.1
0.01
0.001
0.0001
10^{-5}
0.01
0.1
1
10

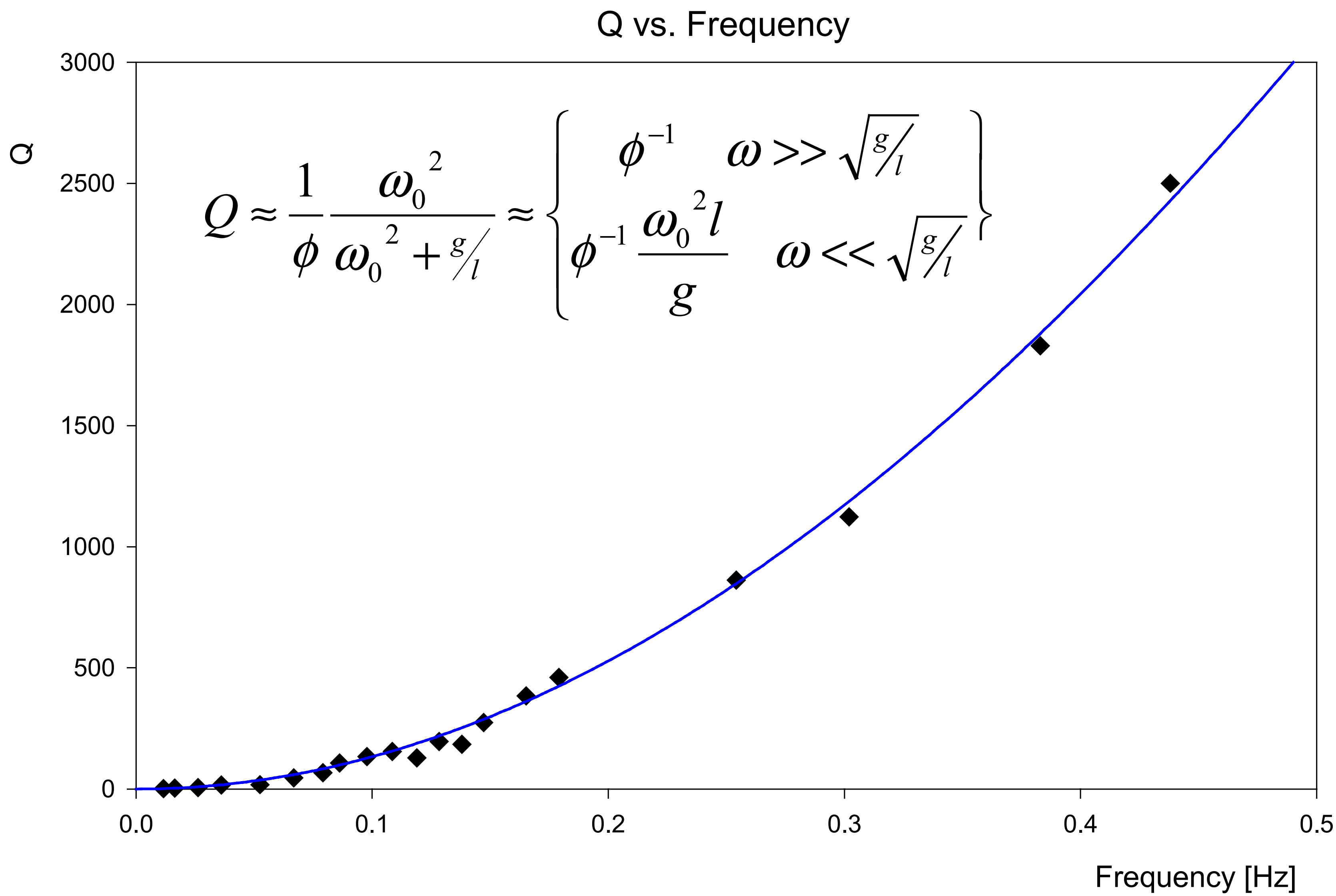

Normal Modes (Damping On)
Transfer Function
Frequency (Hz)
10
1
0.1
0.01
0.001
0.0001
10^{-5}
0.01
0.1
1
10

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k - (M + M_0 + \frac{m}{2})\frac{g}{l}}{M + M_0 + \frac{m}{3}}}$$

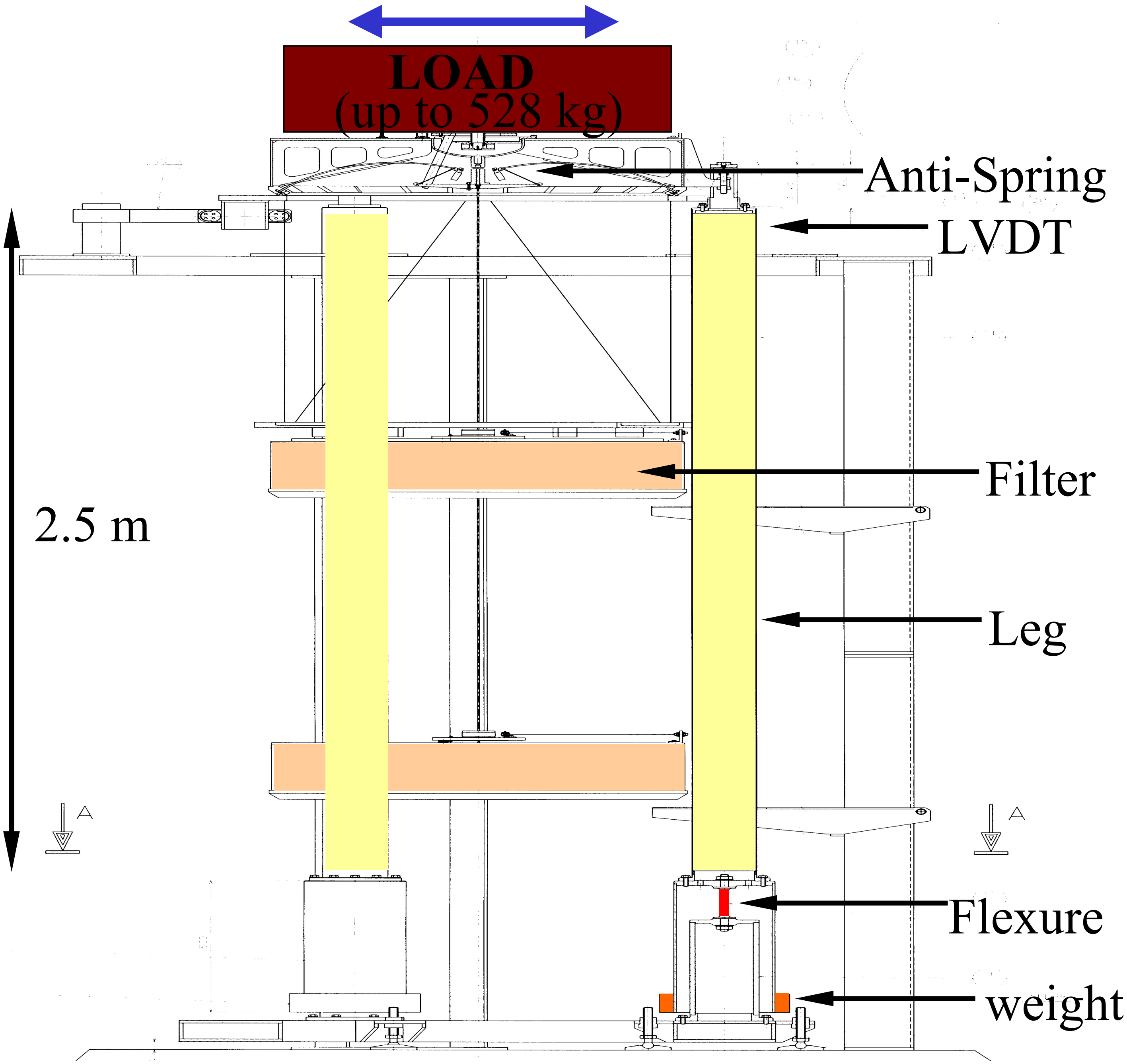
Experiments performed by Szabolcs Márka




Frequency vs. Load (Radial)
Frequency [Hz]
Load [kg]
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
450
500
550
Low f Radial LVDT Spring
High f Radial LVDT Spring
Low f Radial COIL NO Spring
FIT (Low f Radial LVDT Spring)
FIT (High f Radial LVDT Spring)
FIT (Low f Radial COIL NO Spring)



Q vs. Frequency
Q
Frequency [Hz]
3000
2500
2000
1500
1000
500
0
0.0
0.1
0.2
0.3
0.4
0.5
$Q \approx \frac{1}{\phi}\frac{\omega_0^{\,2}}{\omega_0^{\,2} + g/l} \approx \begin{cases} \phi^{-1} & \omega >> \sqrt{g/l} \\ \phi^{-1}\frac{\omega_0^{\,2} l}{g} & \omega << \sqrt{g/l} \end{cases}$


LOAD
(up to 528 kg)
Anti-Spring
LVDT
Filter
Leg
Flexure
weight
2.5 m

Status report on Geometric Anti-Spring Filter (GASF)

Presented by Akiteru Takamori

Prototypes of Geometric Anti Spring Filter (GASF) have been already assembled and their vertical isolation performance is well studied. A vertical transfer function (black) of single GASF measured in the setup shown in Tr.2 is presented in Tr.3 compared with simulations (red for realistic and green for an inertia-less blade). Two peaks just above 1Hz come from the tilt resonance of the payload, but they will vanish once the payload is well-balanced (see Tr.6). Except for those peaks, the transfer function agrees with simulation very well. Note that the simulation was performed before the measurement.

Vertical transfer functions of multiple GASFs prototypes shown in Tr. 5 were measured as described in Tr.4. The transfer function between Filter1 and Filter2 (blue) and between Filter1 and a well-balanced payload (red) are shown in Tr. 6. Just with one layer, the attenuation factor reaches –40 dB around 10 Hz (blue line). For 2 filters the measurement was limited by the sensitivity of a commercial accelerometer which shows about –90 dB attenuation around 10 Hz (red line).

One can notice there is a peak around 50 Hz in both measurements. It is an internal resonance of GAS blades. To damp the resonance, we are planning to put passive dampers on each blade (Tr. 7 left). The amplitude profiles of the blades' internal modes are shown in right hand of Tr. 7. Putting small oscillators with eddy current damping on the belly of the first resonance (Tr.7 right) can easily dissipate the kinetic energy stored in the resonance. The expected performance of the damper is shown in Tr. 8. The important point is that with this method, we can avoid any active actuation for damping in the observation band of GWs, which may inject some noise.

Status Report on Geometric Anti-Spring Filter (GASF)

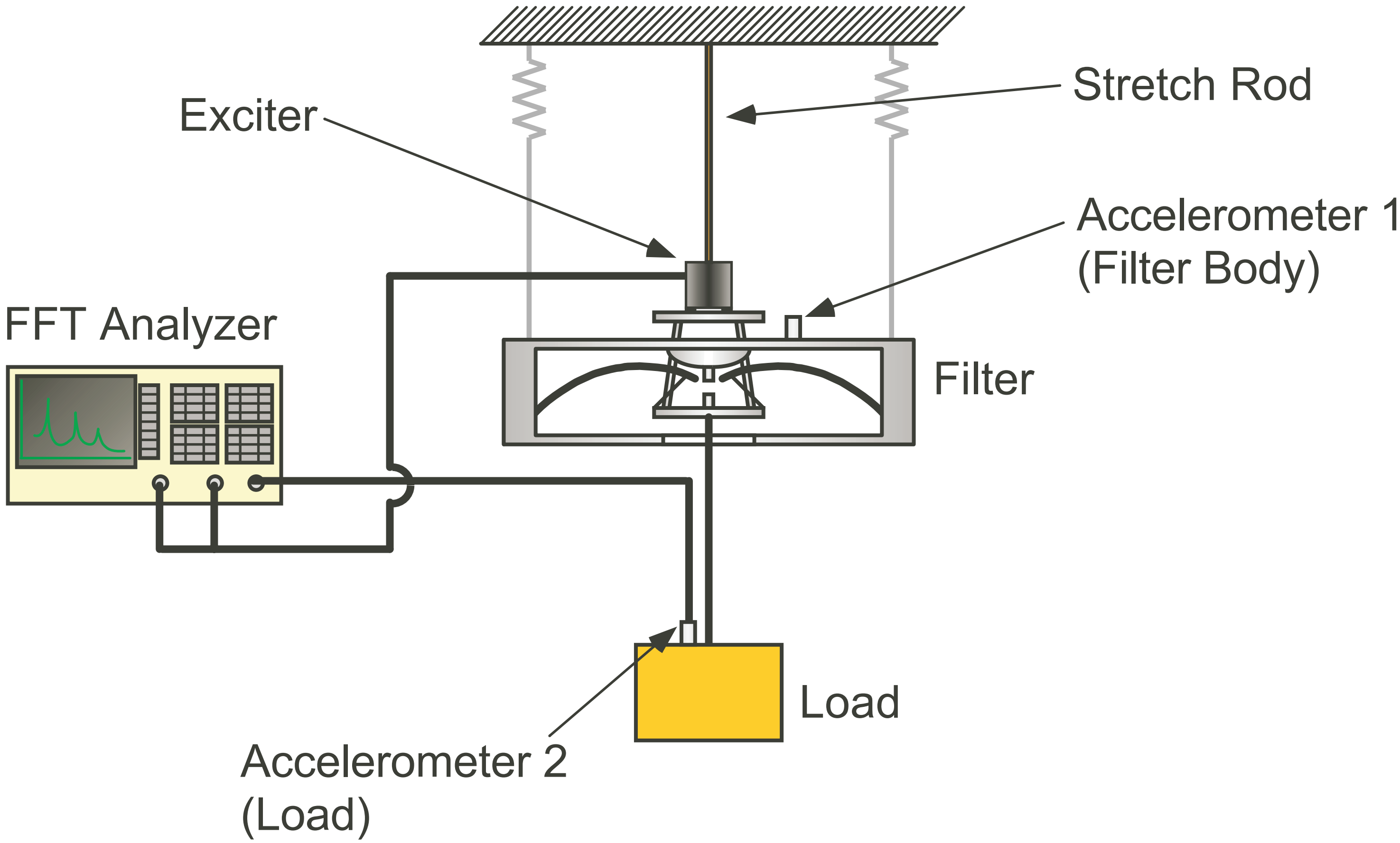
SEI-SUS meeting
Glasgow,
December 16-17, 1999

Presented by Akiteru Takamori

GAS Filter : Measurements

Vertical Isolation Performance

- Single GASF

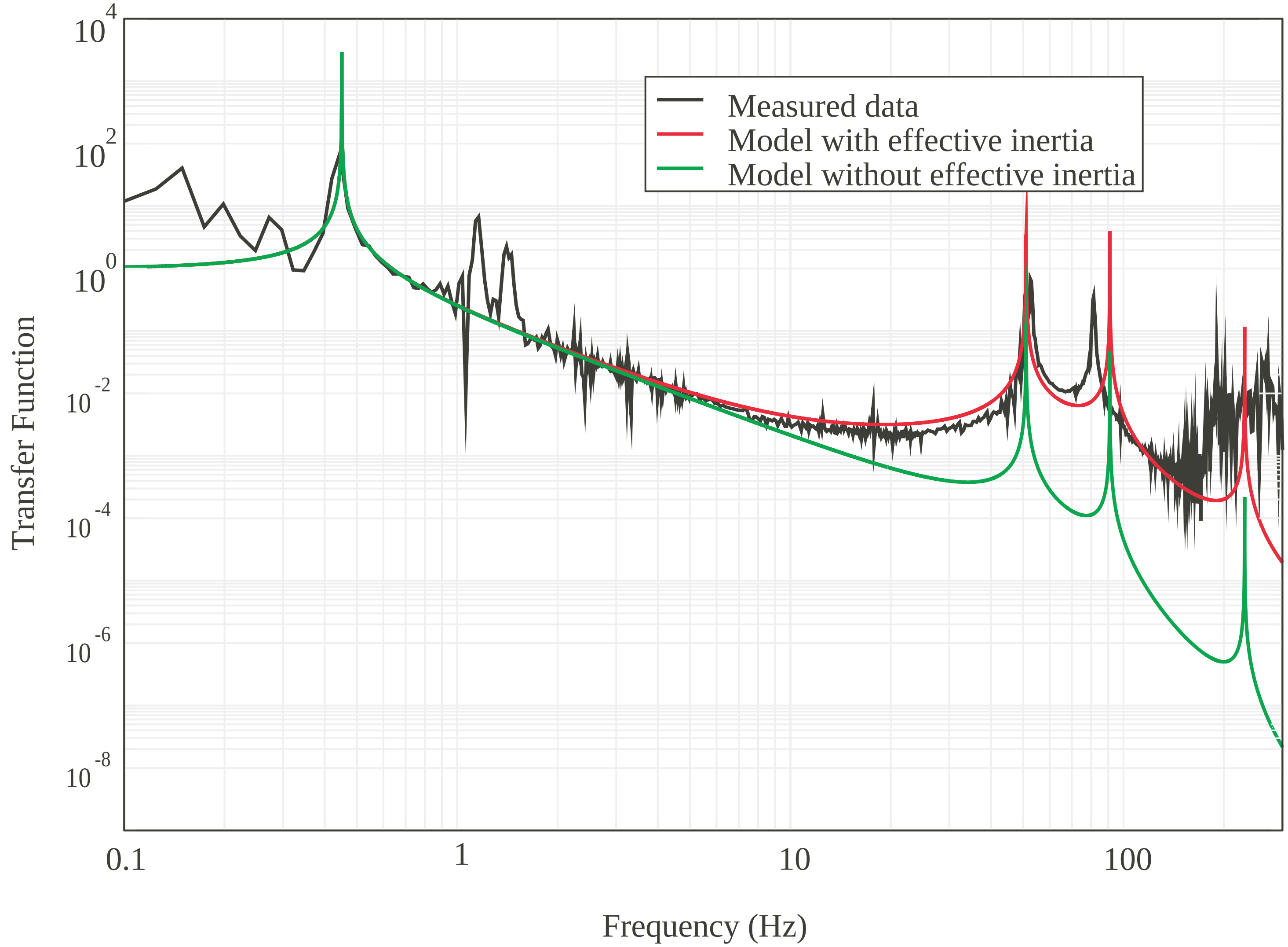


Experimental Setup

GAS Filter : Measurements

Vertical Isolation Performance

- Single GASF



Vertical Transfer Function

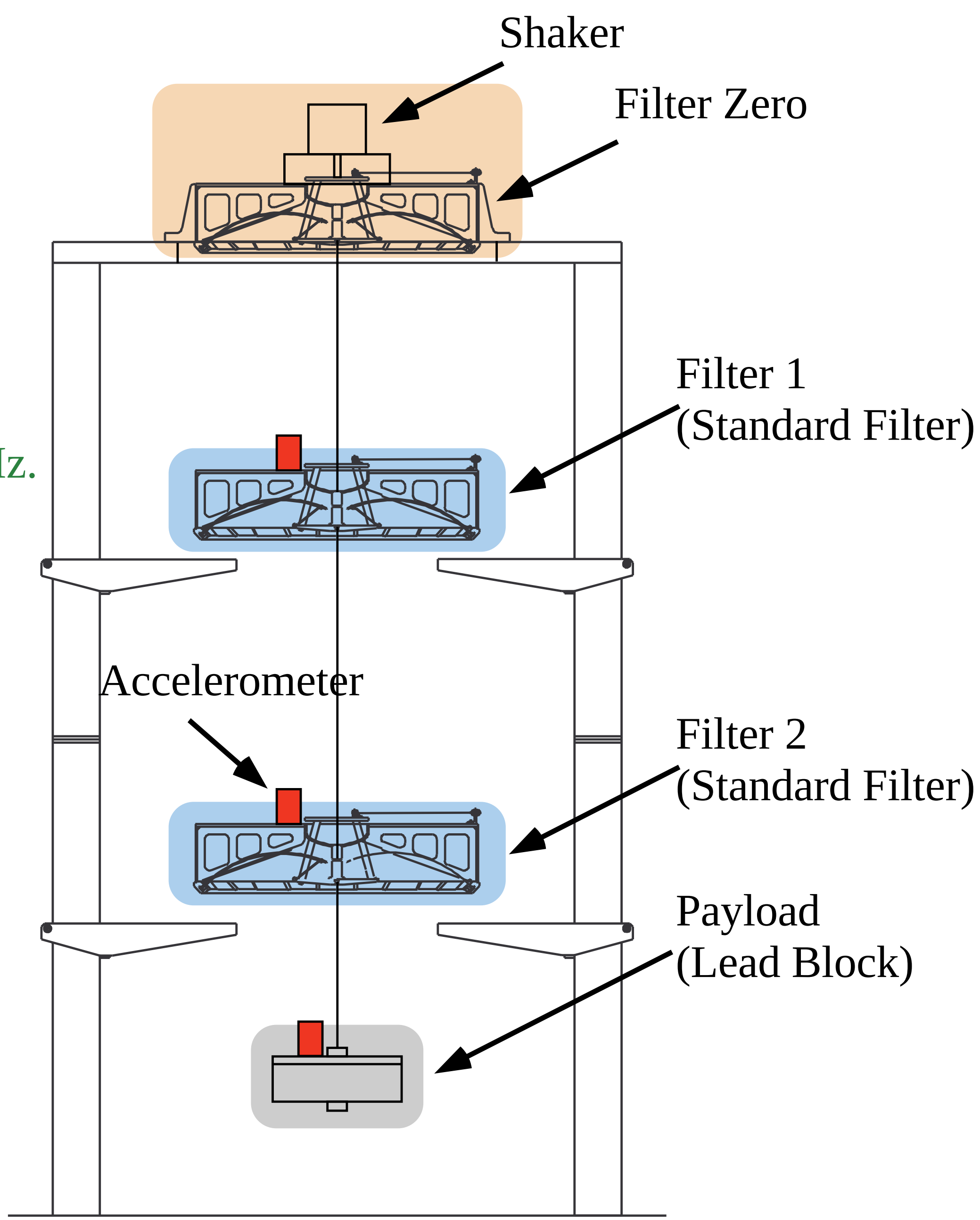
Vertical Isolation Performance

- Double GASF Chain

    - GASF Chain + Payload

    - Filter Zero is connected to a shaker.

    - Standard Filters are tuned to about 450mHz.

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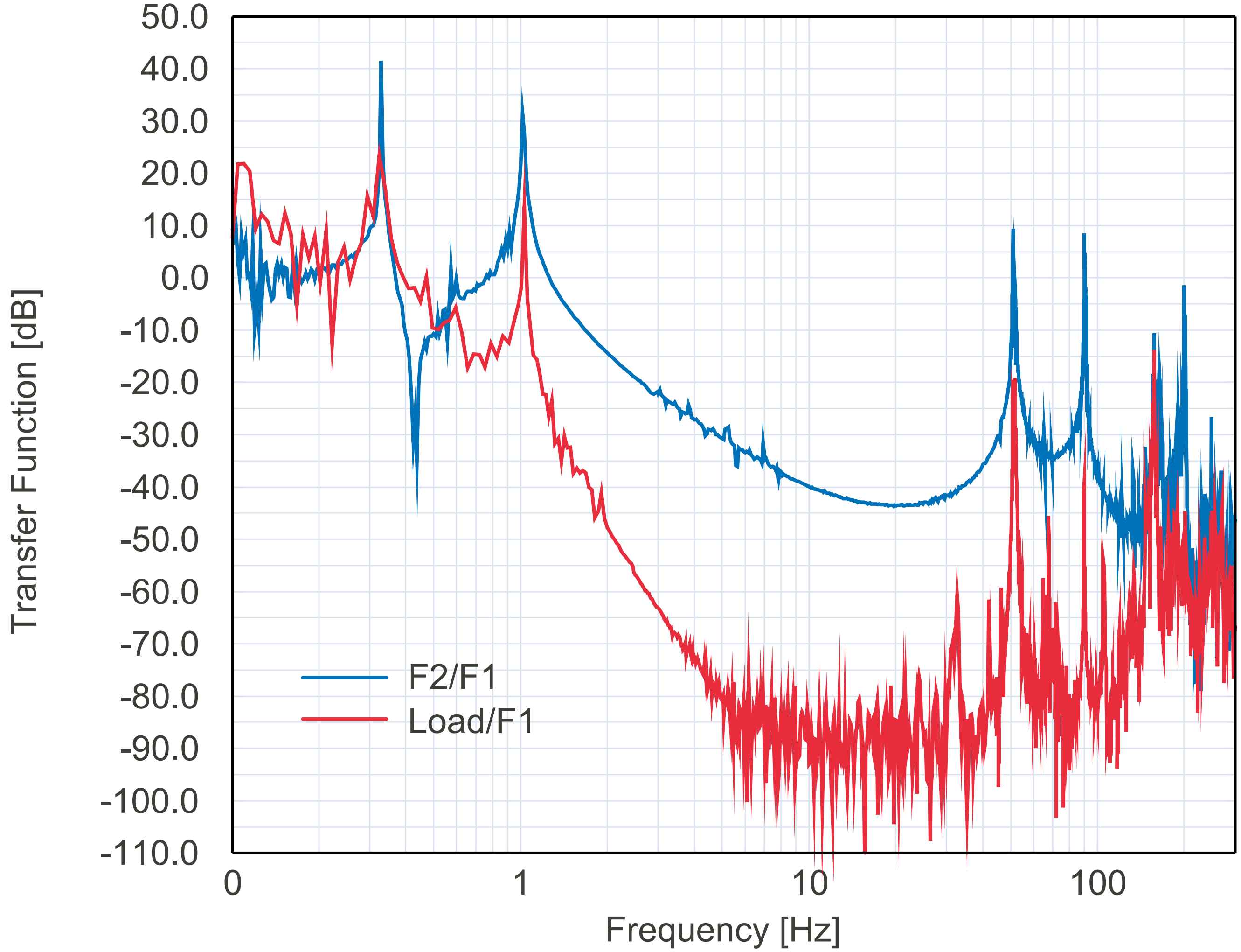
Test Tower

Vertical Isolation Performance

- Double GASF Chain

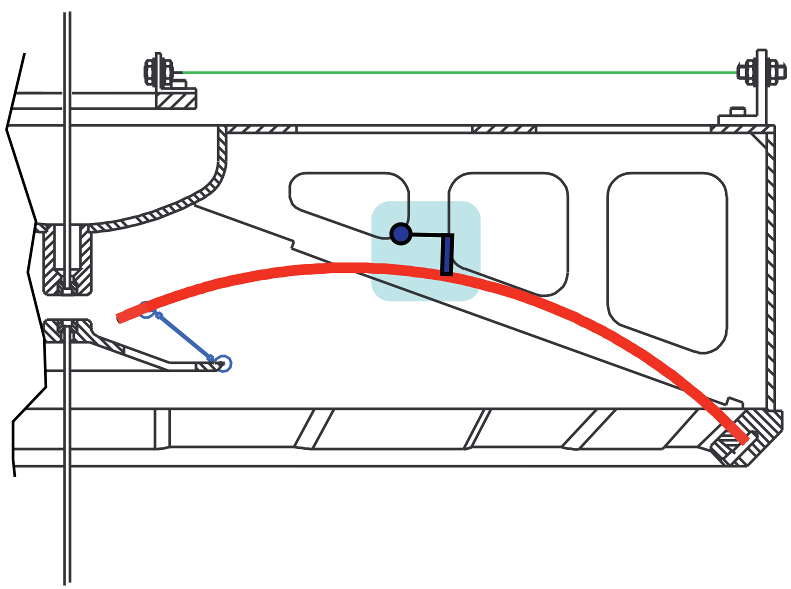


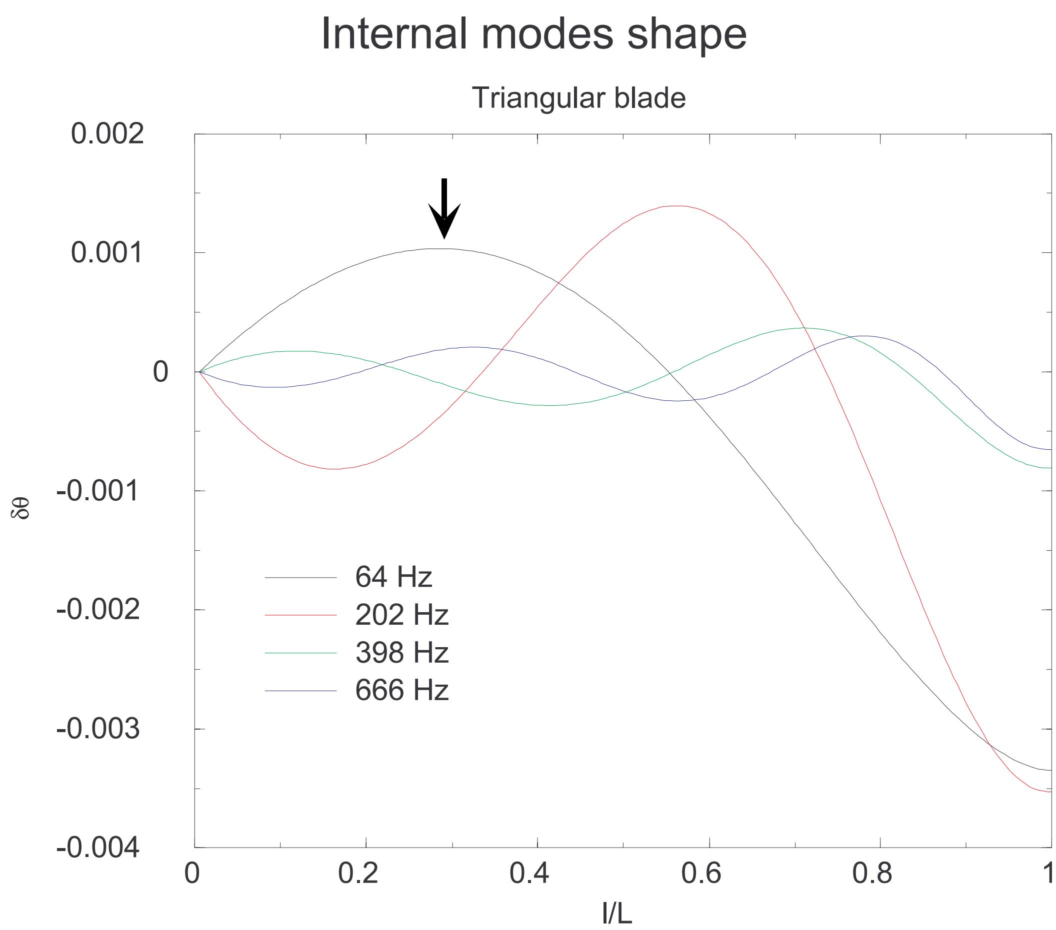
Vertical Transfer Function

GAS Filter : Current Work

GAS Blade Internal Resonances

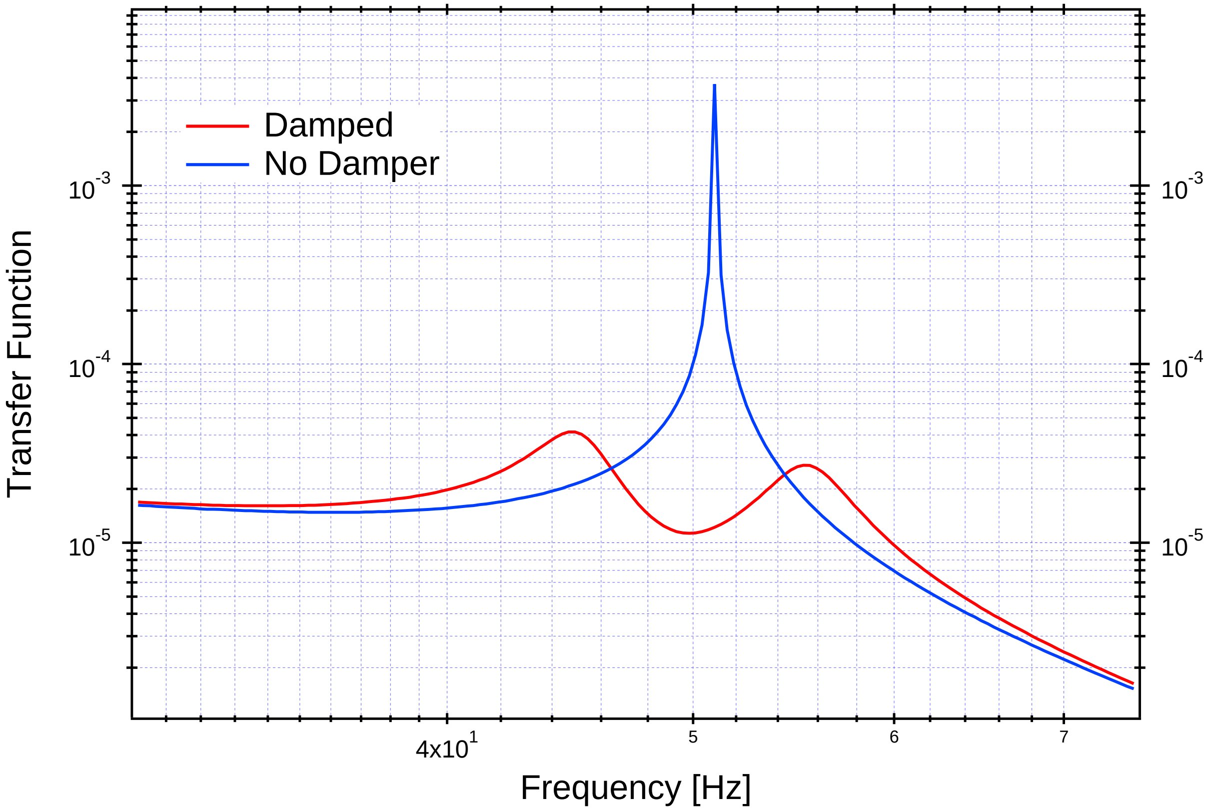
- Passive Damper
  - Small Oscillator on Blade
  - Eddy Current Damping
  - No Lossy Materials





GAS Blade Internal Resonances

- Passive Damper



Vertical Transfer Function with/without a Damper
(Simulated, Preliminary)

SEI-SUS control

Prepared by Virginio Sannibale
Presented by Akiteru Takamori

The SAS behaves as a completely passive attenuator in the frequency band of interest (above 10Hz). The control band on a SAS-SUS system will be limited only up to a few Hz. This control will be implemented just to damp rigid body modes of the system (Inertial Damping). The control has three targets as DC positioning, RMS reduction for easy locking acquisition and global control for observation (Tr. 3).
Those controls will be realized by a hierarchical scheme as shown in Tr. 4.

The simulated SAS-SUS performance based on measured seismic noise at Livingston site is shown in Tr.2.

Combination of LVDT position sensors and coil actuators at a pre-isolator (an inverted pendulum and a ULF GAS filter) provides the transversal and yaw DC control of a test mass. Thanks to an extreme softness of the pre-isolator, this control can be done with very small power such as a few mW for several hundreds kg. DC tilt of a suspended mirror will be corrected by remote controlled counter weights on the last stage of SAS chain (a suspension point).

The rigid body modes of the SAS chain will be detected by the accelerometers mounted on the pre-isolator stage. The signal will be fed back to the coil actuators (also used for the DC positioning) through an adequate filter (Tr. 6) to reduce the RMS motion of the chain (Inertial Damping). The unity gain frequency of the control loop will be put below 10 Hz to guarantee that it doesn't affect the GW signal in the observation band (Tr. 6). Damping of the rigid body modes of the suspension should be done by local feedback in the way that doesn't make recoils on the pre-isolator stage in principle.

In the observation phase, DC control at the pre-isolator stage will be done with the interferometer signal. AC control should be done at the suspension stages.

Frequency band of each control is shown in Tr. 5.

The expected horizontal displacement power spectrum density at the pre-isolator stage with (blue and green) and without (red) the inertial damping is shown in Tr. 8. The blue line is an example of a 'conservative' damping while the green line shows something more aggressive (the unity gain frequency is close to 10 Hz). Horizontal displacement spectrum density (top) and RMS integrated from infinite frequency (bottom) of the test mass are shown in Tr. 8. The expected RMS displacement integrated from 10 mHz to infinity is about 15 nm. (Note 50 nm >100 mHz is already achieved by VIRGO.)

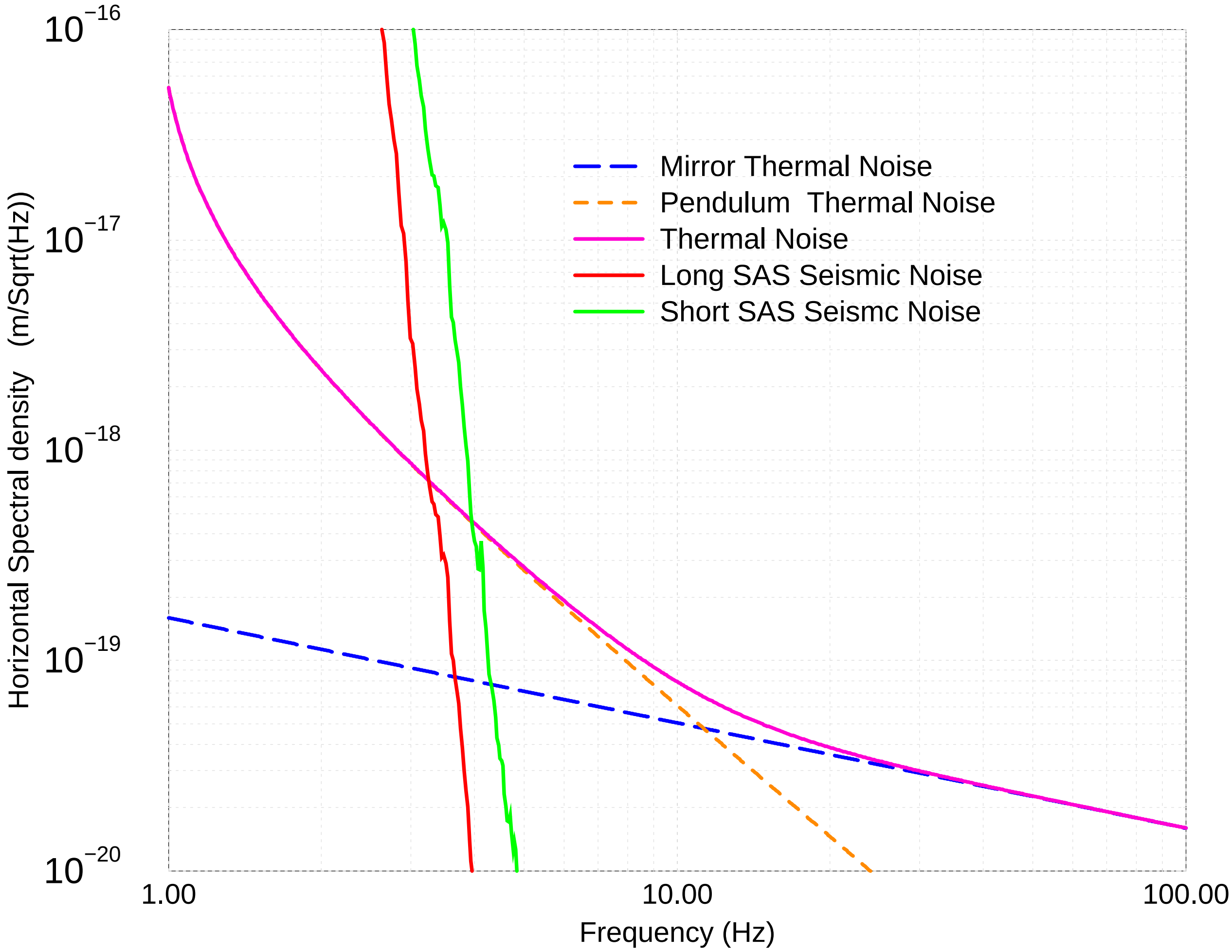
Tr.10 shows the expected performance of SAS-SUS system calculated with GEO triple pendulum code including the calculated response to an impulsive excitation.

SEI-SUS meeting

Glasgow,

December 15th, 1999

SAS Goals



$$\delta\tilde{x}(\nu \simeq 6\ \mathrm{Hz}) \simeq 10^{-18}\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

$$\delta x_{rms} \simeq 10^{-7}\ \mathrm{m_{rms}}$$

High Reliability and robustness

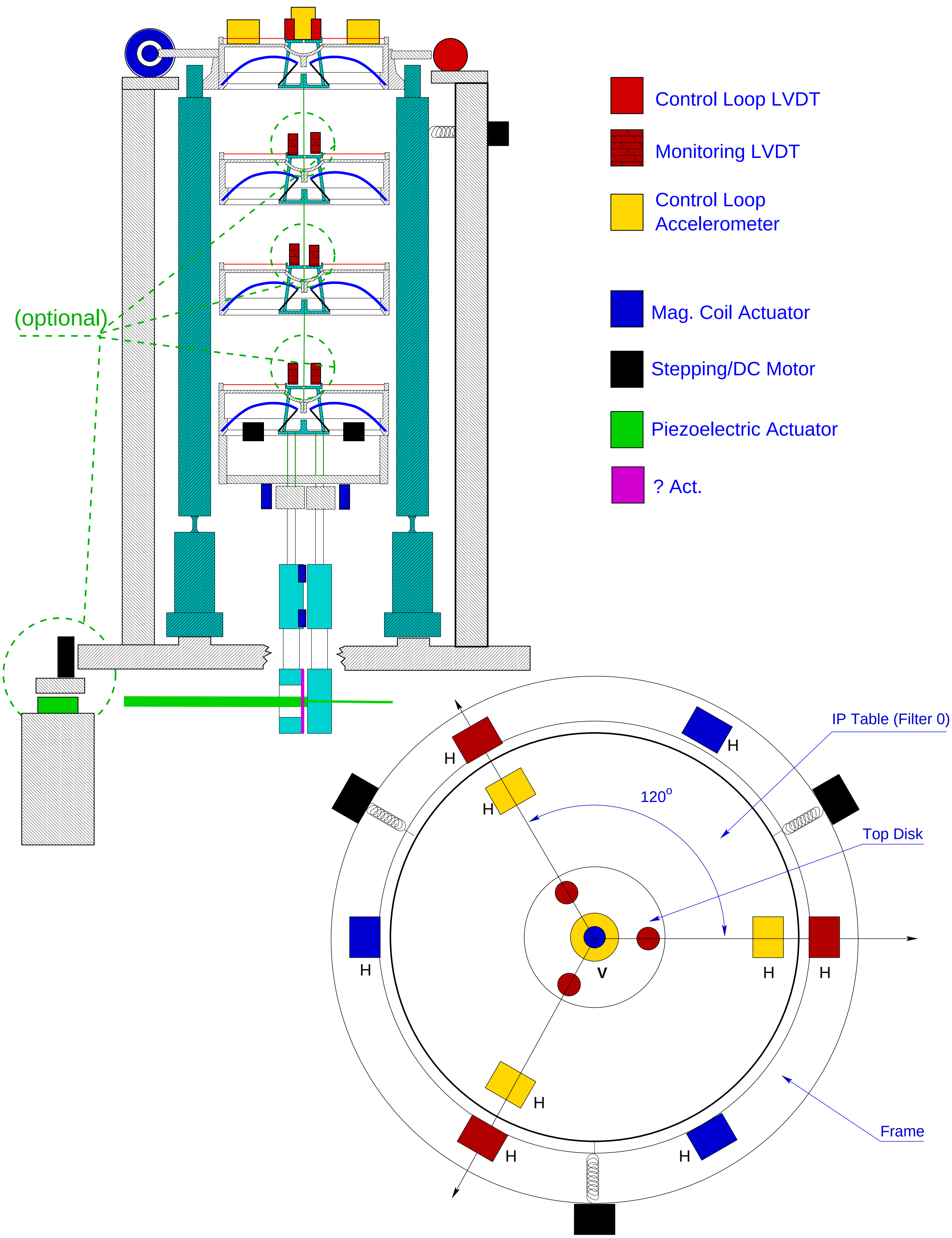
=>

uninterrupt run time of the order of months

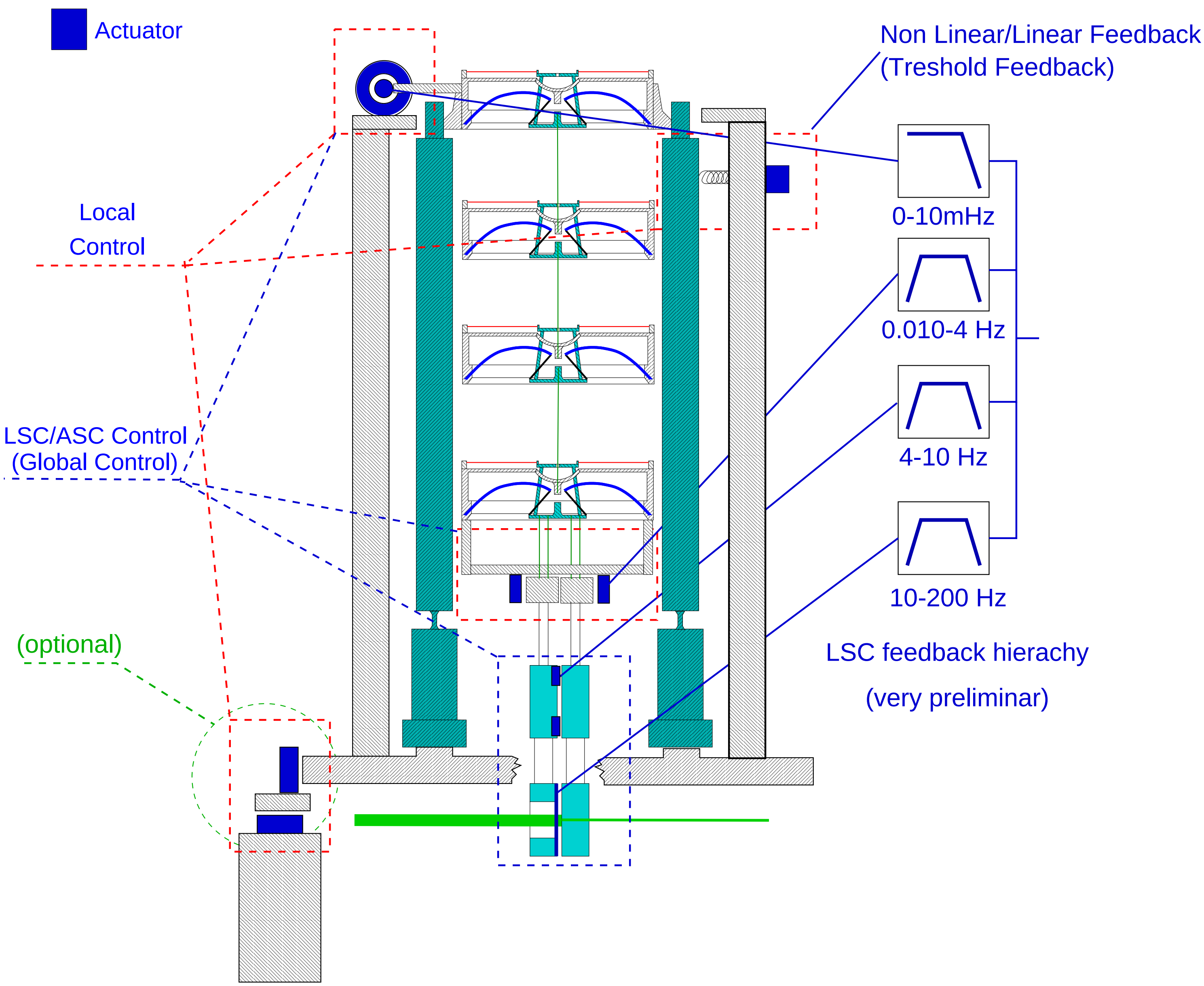
SAS-SUS Control

- Local Frame Positioning System (DC Positioning)
  - LVDT Sensors between the reference frame and the IP table
  - Coils actuators and stepper/DC motors.
  - Coils actuators between the susp. point and the triple pendulum top mass and counter-balances on the susp. point for pitch (roll?).
- RMS Noise Reduction for locking acquisition
  - SAS Chain Modes
    - Chain modes inertial damping with accelerometers on the IP table.
    - Coils actuators between the reference frame and the IP table
  - Triple Pendulum Modes
    - Modes damping with position sensors between the top masses (internal forces => in principle no noise injected) or between the suspension point and the top masses.
    - Coils actuators mounted as the position sensors.
- Global Control Actuation (integration with LSC-ASC).
  - DC control with coils actuators on the IP table.
  - AC control on the three stages of the triple pendulum.

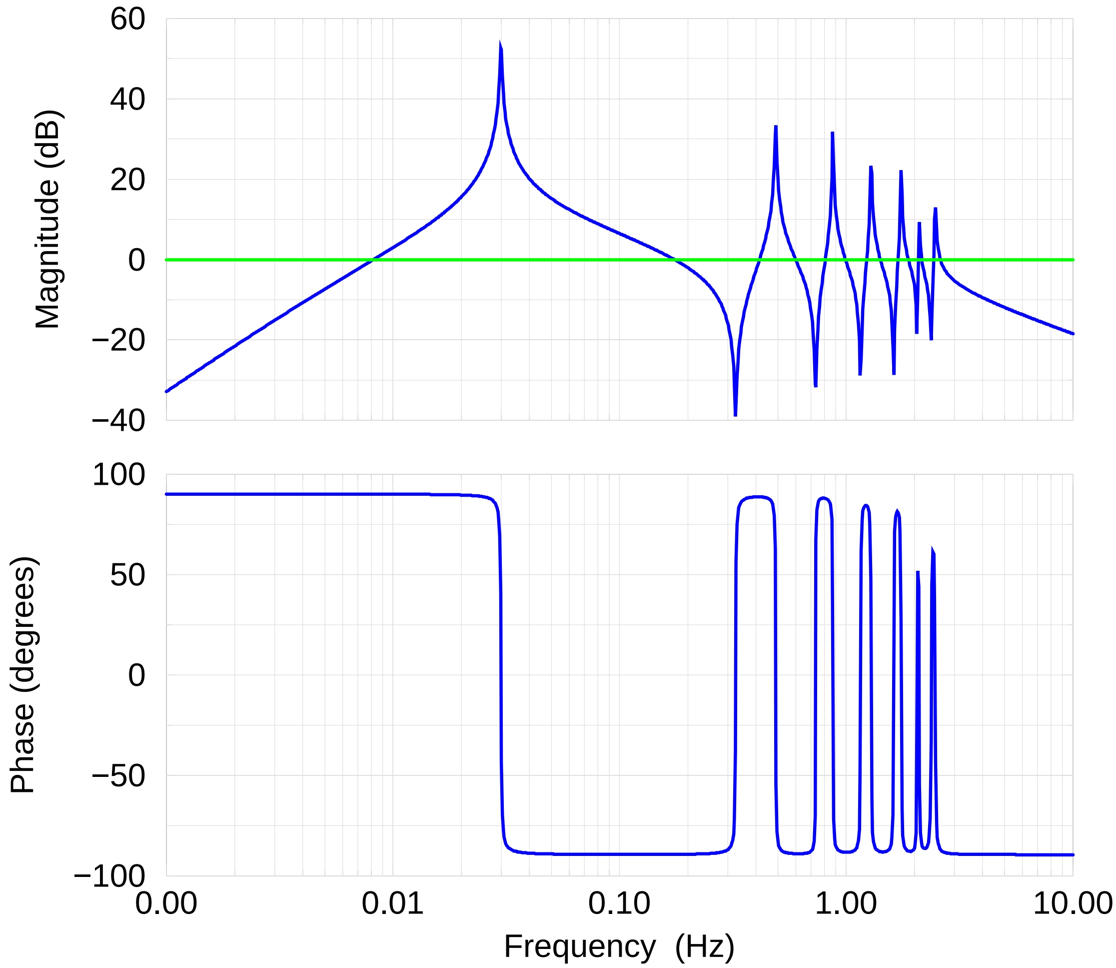
SAS-SUS Control
Sensors Actuator Map



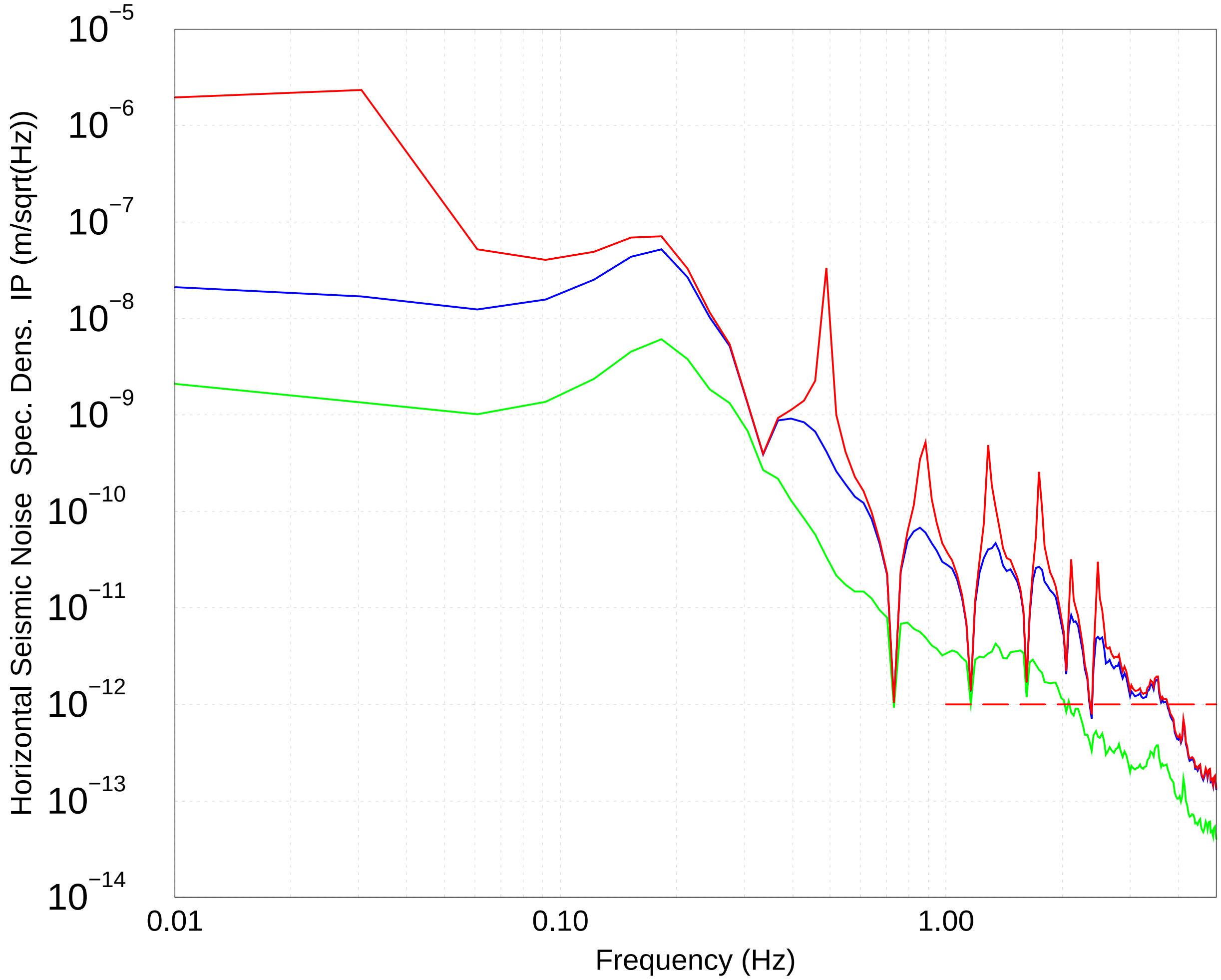
SAS-SUS Control
LSC-ASC Control Hierarchy



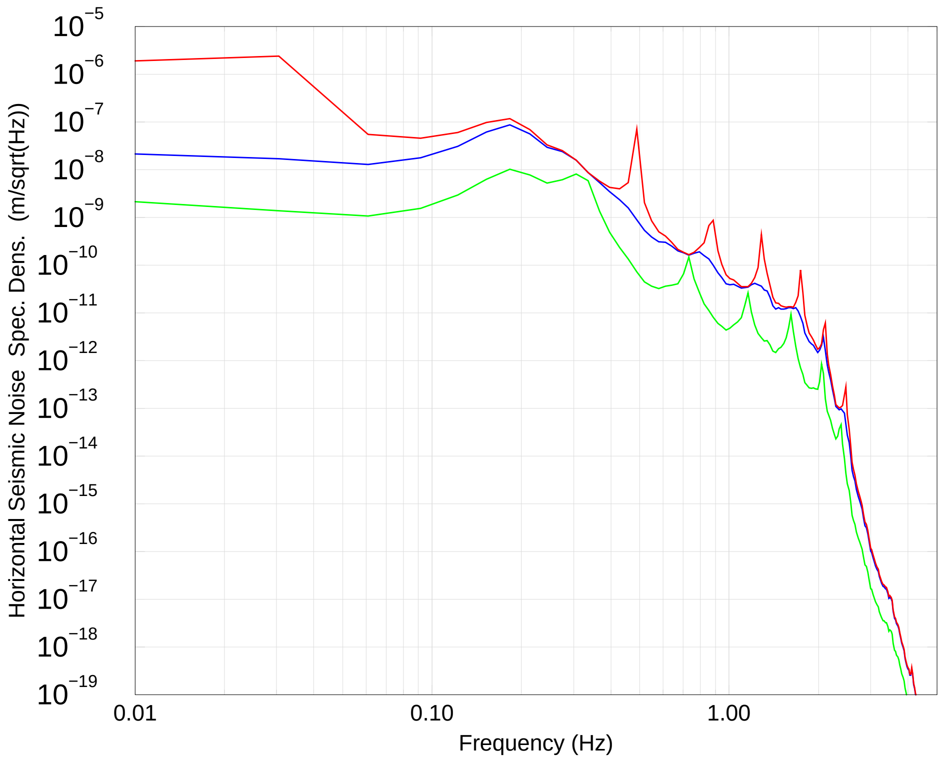
IP Inertial Damping , Open Loop Transfer Function



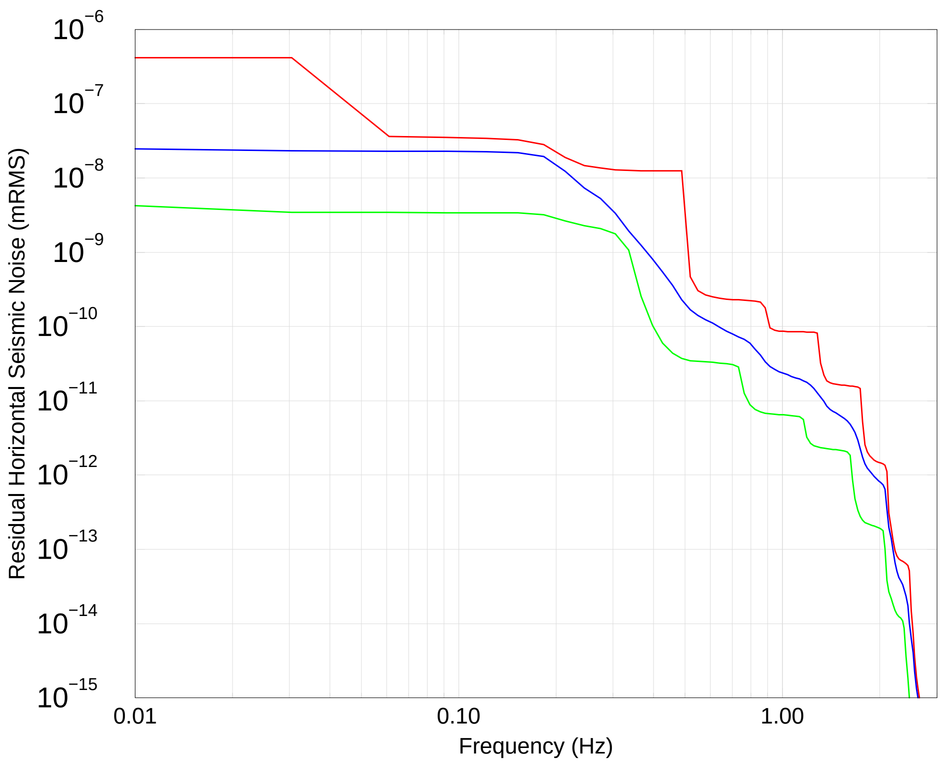
IP Inertial Damping , Open and Closed Loop Spec. Dens



SAS-SUS Inertial Damping

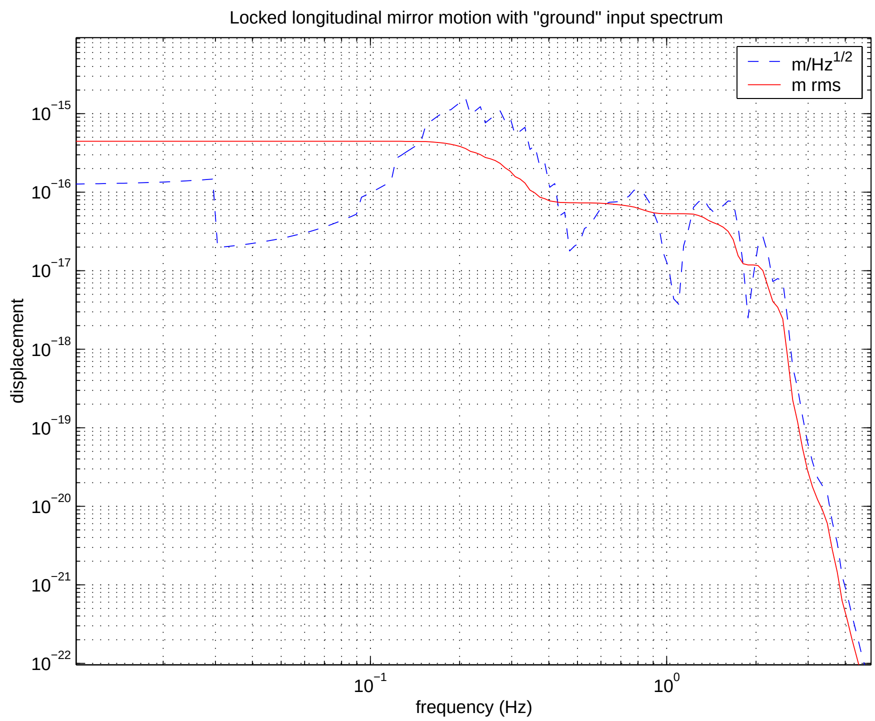


Horizontal Seismic Noise Spectral Densities

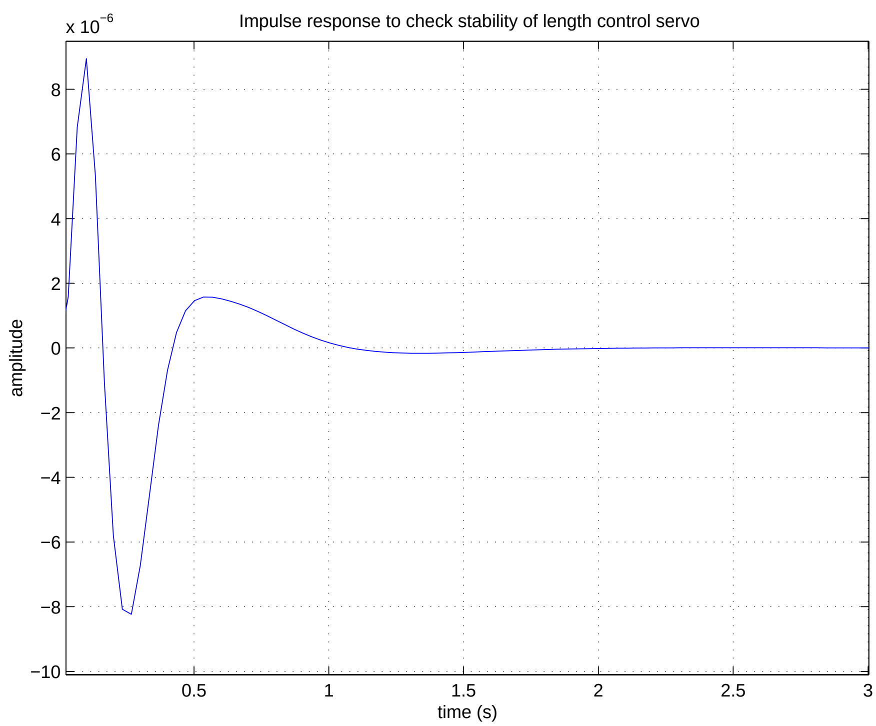


Horizontal Seismic RMS Residual Displacement

SAS-SUS Global Control Simplified Model with GEO Code



Global Control Spectral Density and RMS Res. Displ.



Global Control Impulse Response

LIGO II
Suspension - Isolation
Dynamic Mechanical
Interfaces

17 December 1999

Forces exerted on SEI platform

- **Suspension design depends on exerting reaction forces**
  - » quasi-DC for pointing (100 secs)
    - – true DC force is zero?
  - » dynamic for dynamic alignment/positioning
    - – can be minimized in symmetric system
- **SEI must handle excitation due to reactions**
  - » I.e., no undamped DOF

Impedance

- **need to define a (possibly frequency-dependent) required impedance**
  - » point of departure: 3e-4 rad/N-m at zero frequency for rotational DOF
  - » dynamic requirement needed for all DOF: translational and rotational
  - » propose to require minimum of equal impedance for suspension reaction cage and isolation mounting surface, up to TBD freq (e.g., 100 Hz)
- **Multiple suspensions per chamber**
  - » interaction must be limited
  - » risk if platform is common between suspensions
  - » propose 10^-2 motion of SEI platform at all frequencies
- **Solid body mode coincidences**
  - » interactions of SEI - SUS if overlaps in principal modes

Transitions/Accidents

- **Power up/down**
  - » better characterized as a requirement driven by practical suspension design considerations
  - » intentional
  - » accidental
- **Earthquakes etc.**
  - » safety limits on SEI motion
  - » SUS cage

LSC Suspensions/Isolation Working Group

Summary of the meeting on Seismic - Suspension Interfaces, Glasgow, 16-17 December 1999

David Shoemaker

A meeting was held to discuss the interfaces between the seismic isolation system and the suspension system for LIGO II. This note has a very brief summary of the significant outcomes of the meeting and a list of the action items coming from the meeting. The agenda and the viewgraphs from the meeting will be posted on the SWG website.

A review of the LIGO II Concept by the NSF was altogether very encouraging. However, it became clear to all that very close coordination of the LSC-driven Research and Development is needed if we are to meet our schedule goals (as laid out in the White Paper and the Lab Concept document) with an R&D program which falls in the maximum funding envelope available from the NSF. Thus, the NSF has requested an integrated R&D program from the LSC and LIGO Lab by 15 February 2000. Gary Sanders and David Shoemaker will be contacting each of the groups in the SWG in January to work through this challenge.

Quadruple Pendulum Baseline

We adopted a conceptual design for the Suspension system which consists of a quadruple pendulum: the test mass and three upper masses. This choice is driven by the ease of obtaining a suitable sensor for damping the internal modes of a quadruple pendulum, in contrast to a triple pendulum. The design parameters are being refined, but a relatively long final stage and heavy penultimate mass are planned to minimize the thermal noise from the 'bounce mode' (stretching of the final suspension fibers) and from previous stages.

Crossover frequency from Suspension to Isolation
The crossover frequency for the seismic isolation system and suspension system was selected to be 0.01 Hz; the suspension can handle the dynamic range down to and below the microseismic peak. Control below this frequency will be accomplished by the seismic isolation system and Control above this frequency will be the responsibility of the suspension system (real crossovers of course should tend to be conservative and will not be sudden in any event). It was also decided that the seismic isolation system and suspension system controllers will be separate (and separately testable), stand alone subsystems, with an offload signal from the suspension system to the seismic isolation system. Coordination of the controls modes/states of these controllers is the responsibility of the global interferometer controller.

Optical table inteface between Suspension and Isolation

We adopted a standard mechanical interface between the seismic isolation (SEI) and suspension (SUS) systems. An optical table will be provided to which multiple suspensions and other auxiliary optics can be attached. This appears to be the best choice to enable both a best use of the GEO suspension design experience and to meet LIGO requirements for flexibility in placement of optics. Both isolation groups will work to fit their design within these confines; if it can be shown that a design is excluded because it cannot meet the performance requirements with these boundary conditions, a variance in the interface will be worked.

A number of actions for the refinement of the SEI (seismic isolation) and SUS (suspension) requirements documents were taken by SYS (for now, Dennis Coyne and David Shoemaker) to allow the design work to go forward with this paradigm. In particular, noise mechanisms or compromises in performance or flexibility due to a common optics table will be studied by mid-January.

ACTION ITEMS:

SYS is defined as David Shoemaker and Dennis Coyne for these actions.

SUS is the GEO Suspension group, Norna Robertson as contact.

SEI is each of the two groups working on Seismic Isolation approaches.

SYS: issue meeting minutes 21 Dec

SYS: develop ICD draft 17 Jan

SYS Establish requirements for the isolation requirement for
 signal recycling mirror
 power recycling mirror

SYS Evaluate cost of change of height of beam 17 Jan

SYS Update Seismic Requirements Document 17 Jan
 control modes
 control signal interface
 reaction forces --> impedence
 thermal requirements
 suspension point height (?)
 load specification
  (800 kg, 2 (?) suspensions + load)
  table in SUS
 layout on table (45 deg); parallel for MIT test?
 quad suspension: length, mass, etc.
 ham corner space availability
 separate SEI requirements in 'table'
 testability: no suspension required
 power/channels required update
 installation requirement at atmosheric pressure
 crossover frequency of 0.01 Hz
 system-required inputs/outputs (real time interconnects)

SYS: Calculate velocity for adiabatic locking
 possibly update requirements

SYS: Don't forget wedges in optical components!

SYS: Create Suspension Requirements Document Draft 14 Feb
(to be iterated with GEO)
  photon control in SUS
  power required
  safety cage (coarse notions)
  management of violin modes
  misalignment for optical config tests

SUS group to produce baseline suspension description 31 Jan
  quad
  length as described
  mass (with 60kg intermediate mass)
  dimensions well defined
  vertical and horizontal XF
  reaction chain; designs without reaction masses
  control authority for freqs. less than 0.01 Hz
  mounting dimensions

SUS: Reaction force magnitudes, impedance 14 Feb

SUS: Document 10^-3 V->H coupling

SYS: investigate noise mechanisms associated with offsets 14 Jan
    V, H, angles
  determine approach for centering beam on multiple optics
    on a single optical plate
  coupling of dynamics of multiple suspensions on a single
    optical plate

SUS: update channel count, power 14 Feb

SYS: number/type of suspensions, of channels in a HAM (and BSC)

SYS: define a precise combination of SEI and SUS to model 10 Jan
  off-center single GEO
  dead weight to balance
  optical table size, resonant frequency
  global control scheme (if needed)

SYS: draft global control concept 2/15
  control modes for overall system

SUS: internal control modes; what demands on other subsystems? 21 Feb

SEI: internal control modes; what demands on other subsystems? 21 Feb