LIGO-T890031-00-R

#57

List of 3/15/89

"ENVIRONMENTAL SPECIFICATIONS

7 MARCH-88

ALEX

1.1.1 Drift Requirements

1. Buildings

In principle, the structure of instrumentation buildings should be designed to satisfy criteria like the ability to provide thermal insulation, sufficiently low acoustic noise, etc., while drift and creep should not be design drivers.

One should require that the connection between the building and the pipes be compliant, in order to avoid stress on the pipes.

It seems reasonable that the building be subject to a drift requirement similar to that of the pipes, that is the long term movement of the building should not exceed 1 cm.

2. Vacuum Tanks

Vacuum tanks are connected to the beam pipes and therefore should be subject to a similar limit on long term drift: 1 cm.

1.1.2 3. Test Mass Suspension Supports

The relative motion of two points on the ground is dominated by the solid Earth tide, as long as the space between them is filled with a continuous and relatively homogeneous material (see R. Weiss, Memo on Thermal Considerations for LIGO Tubes, December 1989). For a separation of 4 km, the change in spacing due to the tide is:

4x10**(-2) cm

The best case is when the supports are firmly anchored to the ground and therefore move with the Earth tide, while a compliant connection between the supports and the vacuum chambers ensures that no additional drift is caused by the movement of the tanks. The design of supports and their connection with the ground should be such that their drift is indeed not larger than the Earth tide, over the time span of one day.

It seems likely that one can design coil magnet systems for test mass position adjustment, which would develop a force of 1 N. For a 1 ton test mass suspended as a 1 m pendulum, that would provide a servo range of 0.1 mm. This range would allow to keep the 4 km resonators in lock for several hours before hopping a fringe due to Earth tidal motion, which seems adequate.

7-March-1989 Alex

Temperature Requirements Inside Instrumentation Buildings

1.2 a

1. Tanks, Supports and Interconnecting Tubing

- Assumptions
  - Various vacuum tanks in the instrumentation buildings are connected together rigidly either directly or with sections of pipe;
  - Tanks and pipe supports are connected to the foundation through industrial rubber-metal shock absorbers which allow for horizontal motions of at least 2 mm;
  - The distance between two points on the floor is not affected by the temperature variations inside the building;
  - Vacuum tanks are connected to test mass (or other) vibration isolation supports through compliant elements (bellows).

- Under the above assumptions, thermal expansion leads to some relative motion of the tanks with respect to each other and with respect to the ground. Since the vacuum enclosure is weakly coupled to either the vibration isolation supports or the ground, the latter do not impose restrictions on vacuum system expansion, as long as it does not become too large. One can get a feeling of the scales involved by noting that a 50 m steel structure expands 0.75 mm for each °K.

- Following the previous discussion, it is suggested that the temperature inside the instrumentation building be maintained at:

20°C ± 1.5°C

2. Lasers

- Assumptions:
  - Laser length: 2 m
  - Range of PZT used for tuning the laser length: 10**(-5) m (20 wave lengths)
  - Laser resonator spaers are made of invar, α=1.5x10**(-6) /C

- The temperature variation corresponding to the assumed PZT range is:

$$\Delta t = \frac{1}{\alpha}\frac{\Delta \ell}{\ell} = 3.3^\circ C$$

- It is suggested that the temperature in the laser area be maintained at:

20°C ± 1.5°C

NOTE: Implementation of this requirement will allow, in principle, to keep the lasers locked to the interferometer for as long as the 4 km resonators can be kept under control.

1.2 b

7-MARCH-1989 Alex

Power Dissipation by Electronics Instrumentation

1. Assumptions

- 2 racks, 4 scopes per test mass (TM) or beam splitter (BS)
- 1 rack, 3 scopes per beam conditioning optics tank serving one interferometer (BC1)
- 2 racks, 6 scopes per beam conditioning optics tank serving 2 interferometers (BC2)
- 4 additional racks, 5 additional scopes per interferometer in the corner building (I)

- Power dissipation per rack: 1.2 kW, resulting from fitting the rack with five 120 w NIM bins and two 500 W HV power supplies, all loaded at 75% of capacity
- Power dissipation per scope: 200 W

- 3.2 kW dissipation per test mass or beam splitter
- 1.8 kW dissipation per BC1
- 3.6 kW dissipation per BC2
- 5.8 kW additional dissipation pre interferometer

- The beam conditioning optics is housed in a succession of 6 chambers

2. Comments

- The total estimate for the power dissipated by the electronics in various type of buildings in Phase A and Phase B is given below.
- The number of interferometers, test masses, etc., used for the present estimate, are taken from LIGO: Mission, Evolution, Configuration and Early Operation, 1 March 1989, by W. Althouse, R. Drever, F. Raab, R. Vogt.
- The result of this estimate, which is no more than a somewhat educated guess, exceeds a previous estimate (LIGO Engineering Staff, LIGO Electrical Power, 30 November 1988) by approximately a factor of two.
- The present estimate refers to electronics instrumentation only and does not contain power dissipated by machinery and data processing equipment.
- It would be interesting to compare the present estimate with the estimated heat contributed by solar radiation. If, as it seems likely, the power dissipated by the electronics is comparable or higher than the one contributed by the Sun, a more accurate estimate will be required in order to specify the air conditioning system.

Table 1. Power dissipated by LIGO electronics

PHASE A

SITE 1		SITE 2	
- Corner building:		- Corner building:	
(8TM +4BS)x3.2 =	38.4 kW	(4TM + 2BS)x3.2 =	19.2 kW
2x6BC2x3.6 =	43.2 kW	2x6BC1x1.8 =	21.6 kW
4IX5.8 =	23.2 KW	2IX5.8 =	11.6 KW
TOTAL.............	104.8 KW	TOTAL...............	52.4 kW
- Mid/End building:		- End building	
2TMx3.2 =	6.4 kW	2TMx3.2 =	6.4 kW

PHASE B

SITE 1		SITE 2	
- Corner building:		- Corner building:	
(12TM + 6BS)x3.2=	57.6 kW	(6TM + 3BS)x3.2 =	28.8 kW
6x6BC1x1.8 =	64.8 kW	3x6BC1x1.8 =	32.4 kW
6Ix5.8 =	34.8 kW	3Ix5.8 =	17.4 kW
TOTAL.............	157.2 kW	TOTAL...............	78.6 kW
- Mid/End building:		End building:	
3TMx3.2 =	9.6 kW	3TMx3.2 =	9.6 kW

Environmental Specs relating to vibration and sound

1.4 Introduction

Engineering specifications related to vibration and sound deal mainly with what we have called ''imported noise". Once a site has been selected, giving due weight to how noisy it is (along with many other factors), its ambient noise spectrum is not under our control. Much work for the scientists will go into attenuating this noise before it reaches the critical parts of the interferometers, but this will be local isolation where it counts. No practical scheme exists to substantially attenuate the noise across the whole site or even throughout a whole building.

The spirit of imported noise specifications is that we should not bring in enough noise to make a noticeable difference to the sensitivity of the interferometers. For imported vibration, it is easy to cast this spec in terms of the pre-existing ambient spectrum. For imported sound, the specification is, of course, in different units. A physical model of the interaction between sound and the vibration which it causes is needed to justify the spec.

(There is a methodological problem with specifications set in this way. Ambient noise spectra are typically characterized as broad-band distributions of power. The specifications we will impose are also naturally given for the broad-band spectral component. But some noise sources, such as rotating machinery and electrical equipment such as transformers, produce a substantial amount of noise in rather narrow spectral lines. These can stand out in Fourier transforms of high resolution, even if the total power in the lines is small. For this reason, we will have to make a separate allowance for narrow-band noise.)

Vibration Specification

The total imported broad-band vibration power shall be small enough so that the vibration spectrum near any test mass is increased by less than 3 dB at any frequency from 0.3 Hz to 10 kHz, compared to its value before the site was developed. (For planning purposes, the spectrum can be estimated as 10**-7 cm/rHz independent of frequency below 10 Hz, falling inversely with the square of the frequency above 10 Hz.)

Imported narrow-band vibration power shall be limited in the following way:

Narrow-band noise is defined as having a characteristic frequency width narrower than one-fifth of its peak frequency.

The sum of the broad-band and narrow-band imported vibration shall be less than 3 dB greater than the pre-existing level, in any octave from 0.3 Hz to 10 kHz.

In a high resolution spectrum, fewer than 1 percent of the frequency bins in any octave may be allowed to exceed the pre-existing spectrum by greater than 3 dB.

Rationale

This specification spells out in detail the meaning of our desire not to increase our interferometer noise problems by a substantial amount.

I think it will not be difficult to meet this spec. (For detailed justification, see the Report on Imported Noise by PRS, a draft of which is presently circulating.) Most small pieces of equipment can be used without special care. Large items like laser power supplies should be placed on compliant isolators, but the isolators can be made quite effective. Free-standing air-conditioning units should probably be avoided, in favor of quiet units such as the chilled-water fan-coil type (or equivalent). Items on which the LIGO team needs more information are noise from large transformers, and from the pumps and other gear for the laser cooling system. In addition to choice of quiet equipment and use of isolators, siting heavy equipment (such as the power sub-station) some distance from the instrumentation buildings should be considered where it is appropriate.

1.5 Sound Specification

The sound spectrum in the vicinity of any instrumentation chamber shall be limited in a manner like the vibration spectrum, except that the threshold''3 dB greater than the pre-existing spectrum" should be replaced by ''10**-3 dyn/cm**2-rHz".

Rationale

The choice of this particular spectral density is justified by two lines of argument.

Firstly, this noise level roughly corresponds (above 1 kHz) to the sound level of +45 dBA specified as the maximum recommended level in the ISA ''Recommended Environments for Standards Laboratories". This is justified mainly on psychological, rather than physical grounds. The document notes that this is a typical noise level for private offices. The MIT 1.5-meter lab had a noise level about 10 dB higher than this when all equipment was running. Most people thought it was unpleasantly noisy. There seems to be no reason that the lower noise level should be hard to achieve. The Caltech lab is considerably quieter (to the ear, anyway). This is due in large measure to banishing the laser power supplies and computers to a separate room.

Secondly, sound at the level of our spec is small enough so that the vibration it induces in our appartus should be small compared with the level caused by the pre-existing vibration spectrum. Detailed justification of this statement will appear in a forthcoming document.

1.6

Yekta; March 8, 1989

Cleanliness Specifications

(a) Global Building Specifications:

(i) The building should be sealed against insects and and small animals (None allowed).

Any of these could get into a vacuum chamber or into a high intensity laser beam. In either case, high precision optics can be contaminated.

(ii) The building should be over-pressurized with at least a positive pressure of 10 pascals. (10^{-4} ATM)

This is necessary to stop dust from entering the building through cracks and door ways.

(iii) The part of the building which houses the vacuum chambers and lasers should not have any fenestration (No windows or sky lights which let the sun shine on the equipment).

(iv) There should be no water leakage into the building from outside.

1.3

(v) The relative humidity level in the building should be 40 percent plus or minus 5 percent.

This level of humidity has sufficiently low dew point temperature at the ambient temperature of 75 degrees Fahrenheit in order not to cause condensation on the laser coolant hoses and tubes. If the level humidity is lower, static charges build up very fast and the air is uncomfortably dry.

(vi) There should be no visible or concealed condensation in the building. Any part of the building with a temperature below the dew point for the specified relative humidity must be thermally insulated to prevent condensation.

(vii) There should be no detectable (by humans) unpleasant odors in the building.

(viii) The levels of toxic dusts, fumes and mists must be below the federal standards (ASA standards MAC, and ACGIH 1959).

(ix) There should be no radioactive contaminants in the building.

(x) There should be NO aerosols or mists of oils in the ambient air in the building. Mechanical pumps that produce such mists must have vent hoses which carry the mist out of the building to a condensation chamber.

(xi) The global air quality of the building should be Class 50,000 (50,000 particles per cubic foot).

The cleanest part of the MIT lab is Class 15,000; the shuttle assembly bay at Cape Caneveral is Class 100,000.

(xii) The ventilation of the building should be within the comfort levels for humans with sufficient number of air exchanges to keep the air healthy. This is extremely important if dry nitrogen is used to fill and purge the vacuum tanks.

(xiii) The ~~in~~filtration of outside air into the building should be regulated to keep the global air quality within the specified limit.

(xiv) There should be no concealed or visible growth of fungi or moss in the building.

(b) Local Cleanliness Issues:

(i) Hazards and Advantages of Cleaning high-precision Large Optics:

Although successful cleanings of super mirrors which are 2 inches in diameter have been achieved at Caltech Gravitational Physics Laboratory, successful in-place drag wiping of larger super mirrors have not yet been demonstrated.

In place cleanings of large diameter mirrors can be extremely difficult especially with the tight and space saving designs under consideration.

The chances of stirring up settled dust is large when in place cleaning is attempted.

Cleaning at a remote location with specially designed equipment has the largest chance of being successful. This requires a design which allows the main optical components to be removed from suspensions. In the designs under consideration such an operation will be extremely difficult.

Dust caps are required when the interferometer components are assembled. Once the components are in place, removable remotely-controlled dust caps are required. Unless a very ingenious design is developed, these caps will be difficult to use and they waste valuable vacuum chamber space. No such design is available at the present time.

We conclude that keeping the LOCAL environment around the chambers clean when the tanks are open to air is the only feasible solution. This can be achieved by using removable and portable clean rooms which are lowered in place once the tank covers are removed. Such clean rooms are commercially available and one can be designed to seal against the main flange of the chamber when the top is removed. These clean rooms have air cleaners in them to keep the air free of dust at all times.

(ii) The Local Clean Room Specifications:

The LOCAL air quality in the portable clean rooms should be Class 200.

A calculation performed by Rai Weiss indicates that for exposure times of the order of a day, the air quality in the clean rooms should be Class 20 for HORIZONTAL surfaces. Measurements by R. P. Young (Degradation of Low scatter mirrors by particle contamination, AEDC Air force station, 1975) and by R. P. Ruel, et al. (A forecasting technique for accumulated particle contamination on spacecraft assemblies, TRW systems, 1977) indicate that the amount dust accumulation on vertical surfaces is 0.0023 to 0.10 times the the amount of accumulation on the horizontal surfaces.
The calculations performed by Yekta Gursel show that the amount of dust accumulation on the vertical surfaces as measured by the people above can be accounted for by estimating the static charges on the cleaned surfaces. For a value of the electric field which is at the breakdown level for ordinary air, the amount of dust accumulation on a vertical surface is comparable to the amount of dust accumulation on a horizontal surface under the influence of gravity. Since the amount of accumulation is proportional to the square of the electric field, a field which is one third of the breakdown field will cause 10 times less accumulation.

RW
3/17/89

1.7 POWER CONDITIONING IN THE FACILITIES AND GROUNDING FOR DISTRIBUTION SYSTEM

THE INSTRUMENTATION BUILDING POWER DISTRIBUTION SYSTEM HAS NO SPECIAL REQUIREMENTS THAT WOULD NOT BE THE STANDARD FOR A RESEARCH LABORATORY WITH DISTRIBUTED APPARATUS

THE SERVICE SHOULD INCLUDE:

440	3ϕ	LASERS, ROTATING MACHINERY
220	3ϕ	POWER SUPPLIES, MACHINERY
110		GENERAL LABORATORY INSTRUMENTATION

SINCE ALL CRITICAL INSTRUMENTATION IS RECOMMENDED TO HAVE LOCAL VOLTAGE REGULATION, THE SPECIFICATION FOR GLOBAL LINE VOLTAGE VARIATION ARE LOOSER THAN FOR A STANDARDS LABORATORY

1.7.1 $\Delta V/V\big|_{RMS} < 0.02$ LONG TERM $t >$ MINUTES
ZERO TO FULL LOAD

1.7.2 $\Delta V/V\big|_{PEAK} < 0.001$ TRANSIENTS $t < 10^{-2}$ SECONDS

1.7.3 HARMONIC CONTENT

$$V(t) = \sum_{n=1}^{\infty} V_n \sin(n\omega_1 t + \varphi_n)$$

$$\frac{\left(\sum_{n=2}^{\infty} |V_n|^2\right)^{1/2}}{V_1} < .05$$

GLOBAL SPECIFICATIONS

1.7.4 GROUNDING AND NEUTRAL LINES

1) EARTH GROUNDING CONSISTENT WITH LIGHTNING SAFETY IS ASSURED. IN [illegible] A [illegible]

2) SINCE THE INSTRUMENTATION IS DISTRIBUTED OVER A SUBSTANTIAL AREA IT WILL BE IMPORTANT TO HAVE A WELL DEFINED GROUND CONNECTION AT EACH LOCATION.

A RECOMMENDED GOAL IS TO ESTABLISH A STAR GROUND SYSTEM IN EACH BUILDING USING AN EARTH CONNECTION WITH RESISTANCE TO GROUND OF LESS THAN 1 Ω.

INTERCONNECTION BETWEEN THE LOCAL GROUND AND THE STAR SHOULD BE MADE WITH LOW INDUCTANCE AND LOW RESISTANCE LEADS

L/ℓ = INDUCTANCE/METER < 0.05 HENRYS/METER

R/ℓ = RESISTANCE/METER < 10^{-4} OHMS/METER

A SUGGESTED TECHNIQUE IS TO USE COPPER TUBING FOR THE GROUND NETWORK

3) NEUTRAL POWER LINES SHOULD BE SEPARATE FROM GROUND LINES

4) INDIVIDUAL LOCATIONS, — AT EACH INSTRUMENTATION TANK OR SEPARABLE COMPLEX — SHOULD DERIVE POWER FROM A SEPARATE SUB TRANSFORMER THE INDIVIDUAL TRANSFORMERS SHOULD HAVE ELECTROSTATIC SHIELDS BETWEEN PRIMARY AND SECONDARY WINDINGS WHICH ARE GROUNDED

5) UNBALANCED NEUTRAL CURRENTS IN Y TRANSFORMATIONS SHOULD NOT EXCEED 1% OF THE AVERAGE LOAD CURRENT IN ANY OF THE LEGS

6) THE INSTRUMENTATION TANKS AND VACUUM TUBES SHOULD BE GROUNDED BY KNOWN CONNECTIONS USING LOW INDUCTANCE CIRCUITRY. (THE GROUNDING LINE SHOULD BE REMOVABLE FOR DIAGNOSTICS)

* → 7) THE OVERALL GROUNDING AND INTERCONNECTION BETWEEN STATIONS ESPECIALLY THE CURRENTS RUNNING ALONG THE BEAM TUBES

UNCERTAIN

MUST BE STUDIED FURTHER. THE LARGE INDUCED EMFS FROM MAGNETIC STORMS AND LIGHTNING MAY REQUIRE INSULATED SECTIONS AND ARC SUPPRESSION BETWEEN SECTIONS. THE REQUIREMENTS FOR THIS ARE SITE DEPENDENT

8) IT IS WORTH CONSIDERING INDIVIDUAL ELECTROSTATICALLY SHIELDED ISOLATION TRANSFORMERS AS A MEANS OF FREEING EACH SEPARABLE INSTRUMENTATION COMPLEX TO FURTHER REDUCE THE CHANCE OF LARGE GROUND CURRENTS

1.8

MAGNETIC FIELDS IN THE INSTRUMENTATION BUILDINGS FROM THE POWER DISTRIBUTION SYSTEM

1) THE DISTRIBUTION SYSTEM WIRING SHOULD BE ARRANGED SO THAT LINE FREQUENCY AND HARMONIC MAGNETIC FIELDS AT MASS SUSPENSION LOCATIONS ARE LESS THAN 1 MILLIGAUSS rms.

THIS SPECIFICATION REQUIRES SOME CARE IN TRANSFORMER PLACEMENT AND THE GEOMETRY OF THE DISTRIBUTION LINES. IN MOST CASES IT WILL BE SATISFIED BY STANDARD PRACTICE

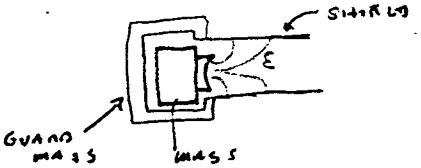
SOME COMMENTS MORE RELEVANT TO THE SECTION ON RECEIVER / FACILITY INTERFACES

1) INTERCONNECTION OF SIGNALS BETWEEN INSTRUMENTATION COMPLEXES (INSTRUMENTATION STATIONS, TANK COMPLEXES etc) WOULD BE BEST DONE DIGITALLY USING OPTICAL FIBRES TO AVOID INDUCED GROUND CURRENT TRANSIENTS

2) ELECTROSTATIC SHIELDING IS REQUIRED ON ALL INSULATORS IN THE INSTRUMENTATION TANKS
FOR EXAMPLE:
CONDUCTING COATINGS ON VIEW PORTS
CONDUCTING COATINGS ON PLASTIC OR GLASS PARTS
FARADAY SCREENS ON THOSE PARTS WHICH CANNOT BE CONDUCTING

THE FIELD LINES FROM UNCONTROLLED STATIC CHARGES MUST NOT GET TO THE SUSPENSION MASS

UNCERTAIN * ⟹ A SPECIAL PROBLEM ARE THE DIELECTRIC COATING ON THE MIRRORS THEMSELVES, THIS NEEDS FURTHER THINKING. I HAVE OFTEN IMAGINED A TUBULAR SHIELD ATTACHED TO THE GUARD (OR RECOIL) MASS ASSOCIATED WITH THE SUSPENSION



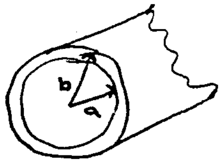
NOTE ON LOW INDUCTANCE CONNECTIONS

L/ℓ = $\frac{\text{INDUCTANCE}}{\text{LENGTH}}$

STRAIGHT SOLID CYLINDER $\frac{\mu_0}{4\pi}$

BRAID
N: # OF STRANDS $\sim \frac{\mu_0}{4\pi N}\ {}^{1}/_{2}$

TUBING $\frac{\mu_0}{4\pi}\left[1 - \frac{2a^2}{b^2-a^2}\ln b/a\right]$



$\approx \frac{\mu_0}{8\pi}\left(\frac{b-a}{a}\right)$

$\frac{b-a}{a} \ll 1$

1.9

Yekta; March 8, 1989

Cooling System Specifications For the Argon-Ion and Nd-YAG Lasers:

(a) The cooling system of each laser should be an independent closed loop of chilled water system. The system should be able to remove a power of 100 kW for each laser.

This is to prevent defects of one laser from affecting another. It may not be necessary to do this for the Nd-YAG lasers since the power dissipated in them is very small compared to the power dissipated in a typical Argon-Ion Laser head. Since initial ligo detectors are going to use Argon-Ion lasers, the cooling system should be capable of handling them. Current Argon-Ion lasers consume 50 KW to produce 5 W of visible light. We assume that a 10 W argon laser (single frequency and single mode) will consume near 100 KW.

(b) The heat exchanger for each laser should be in close proximity ~~of~~ To that laser.

This is to minimize the length of pipes which connects the laser to its heat exchanger.

(c) No corrosion is allowed in the part of the loop which is directly connected to the laser.

The sludge that results from the corrosion process accumulates in the laser shortening its useful life considerably. This means that a metal known for its resistance to corrosion in the presence of ionized warm water should be used in the loop that is connected to the laser. Stainless steel is suggested because almost all parts of the loop can be constructed out of it including the couplings. Note that the amount of corrosion is proportional to the length of the pipes in the system. Only one kind of metal should be used in all connections. Different metals will form a battery in the presence of ionized water and will cause electrolytic corrosion. Reinforced nylon hose can be used to form flexible connections.

(d) No living organisms should be present in the cooling water which circulates through the laser tube.

These will clog the cooling channels in the tube causing it to fail. One suggested way of doing this is to form an anti-bacterial and anti-algae device by inserting a quartz tube into the flow and exposing the flow to high intensity ultra-violet radiation. Note that this method avoids adding anything to the cooling water which could accumulate in the cooling channels of the tube.

(e) A water filter should be present in the loop that is connected to the laser to catch the dislodged particles thus preventing their accumulation in the tube.

(f) A de-ionizer should be present in the loop that is connected to the laser to reduce corrosion.

(g) The water flow through the laser is set according to the Laser manufacturer's specifications.

Usually the water flow will be set close to the minimum value recommended by the manufacturer to reduce the water induced noise in the laser. At Caltech's Gravitational Physics Laboratory, the flow rate through the Coherent Innova-200 lasers is 25 liters per minute. The cross-sectional area of the tube cooling inlets is about 1 square centimeter resulting in a Reynolds number of 35,000 indicating a very turbulent flow through the laser tube. For ligo specially constructed tubes with larger channels may have to be ordered to reduce the turbulence. Laminar flow through the tube will carry away less heat per unit volume of water, so the flow rate may have to be increased. It is recommended that the loop is capable of a flow rate 50 liters/minute. The rest of the cooling loop should be constructed with large enough diameter pipes to make the flow through them totally laminar. This is crucial in reducing the flow induced noise.

(h) The variation in the water flow should be kept within laser manufacturers specifications.

(i) The pressure at the tube cooling inlets should be set according to the laser manufacturer's specifications.

Caltech's Coherent Lasers require a pressure of 60 pounds per square inch at the tube inlets. The pumps in the loop should be able to produce twice ? this value in order to compensate for the pressure drop across the connecting tubes.

(j) The variation of the pressure at the tube cooling inlets should be within 1 percent of the total pressure.

The piston pumps should not be used in the part of the cooling loop that is connected to the laser. A suggested pump type is the centrifugal pump. Note that the flexible hoses which connects the pump and the heat exchanger to the laser head supplies an attenuation for the pump induced noise. The amount of this attenuation depends on the pipe material and the pipe length. Seperate "capacitors" may have to be installed to attenuate the variations depending on the type of the pump.

(k) The temperature of the cooling water should be set according to the laser manufacturer's specifications.

At Caltech, the inlet temperature is about 55 degrees Fahrenheit. The humidity specification for the building and the ambient temperature specification for the building results in a dew point temperature of about 50 degrees Fahrenheit. Hence no condensation will take place on the laser tube and the hoses even when the laser is not operating. This is crucial since the laser power supplies are also cooled by these same chilled water loop, and condensation in them will be fatal to the high-voltage and high-current electronics inside. The laser head also has high-voltage and high-current connections.

(l) The variation of the Laser inlet water temperature should match the temperature variation specification for the ambient air. So the variation should be plus or minus 1.5 degrees Kelvin.

We assume that there will be some heat flow between the tube and the invar frame of the laser. Holding the variations of the water temperature to this level guarantees that the variations in the water temperature will not have any adverse effect on the laser stability.

1.10

8-March-1989 Alex

Limits on RFI in LIGO Instrumentation Buildings

1. Assumptions

- The frequencies of interest are 10 kHz or more
- Circuits are in aluminum boxes about 10 cm in size, with 3 mm thick walls
- Front end input noise is 1nV/rHz
- Signal source impedance is ~~greater~~ lower than that corresponding to stray capacities at the input to the front end ←
- High frequencies are filtered out in subsequent stages, in order to prevent amplifier saturation
- The RF has AM with a unity modulation index, at the (?) low frequencies of interest
- A nonlinearity in the front end demodulates the RF, with 10% efficiency
- RF levels are acceptable if the resulting low frequency noise does not exceed the intrinsic noise level at the front end input
- The network at the front end input, subject to RF pick-up, has an area A=1 cm**2

2. Limit on RF in the Far Field Regime

This includes radio stations, radar stations, etc., as well as RF generated in the building with wavelength sufficiently short (approximately 1/6 of the building size).

Working backwards through the assunptions, one finds that the acceptable RF level inside the box housing the circuit is 100 nV/m*rHz. At frequencies above 10 kHz, the box attenuates field by at least 100 dB, so that an RF level of 10 mV/m*rHz is acceptable. This is probably too lenient.

Suggested limit: 1 mV/m*rHz

3. Limits on RF in the Near Field Regime

This includes such things like RF components in the spectrum of line spikes.

~~A. Electric Fields~~

~~The acceptable RF level in the circuit box is still 100 nV/m*rHz. Absorbtionloss in the walls of the box is about 30 dB. Reflection losses the field undergoes at the box walls are in the 150 dB range. It seems adequate to require that the electrical field should not exceed :~~

100 mV/m*rHz

B. Magnetic Fields

The voltage generated by a magnetic field B at frequency in a loop of are A is:

$$V = j\omega B A$$

At 10 kHz and under the above assumptions, the acceptable magnetic field in the box is 1.6 nG/rHz. Absorbtion loss in the box walls is again 30 dB. For a distance from the source equal to 1 m, the reflection loss is 52 dB. Thus,

the acceptable level of magnetic field in the building is:
the acceptable levelof magnetic field in the building is:

$$20\ \mu G/rHz$$

which is suggested as a requirement. For higher frequencies the shielding provided by the box is more efficient.

4. Acceptable RF Levels at the Modulation Frequencies

RF at the Pockels cell modulation frequency can be picked up at the front end and results upon demodulation in a DC signal that can saturate the high gain servo amplifiers or hamper the functioning of the servo in other ways. In order to derive a limit for this parameter, one notes the following:

- Since this signal is exactly at the frequency one is interested in, one should consider the full amplitude, not just 10%
- At the front end input, shot noise corresponds to a voltage noise of about 6 nV/rHz.

These two factors practically cancel, therefore one can carry the same requirement as for the far field RF (Point 2):

~~1 mV/m*rHz~~ 100μV/meter [illegible] Rms [illegible]

NOTE: The theory and data used for this estimate are taken from:
H. W. Ott: Noise Reduction Techniques in Electronic Systems, Wiley,1976

[illegible] Rms [illegible]

ALEX ON DC DRIFTS   ALEX.

2.1

LATERAL AND VERTICAL LONG TERM TUBE MOTION

1. In order to attenuate scattered light, the tubes will be baffled. At minimum, for a certain baffle density (spacing), the height is chosen to meet certain criteria. [See Rai's and Kip's notes on scattering]. To ensure that these criteria are met, a "safety height" ΔH is added to the baffle.

2. The worst case is the one which involves every other baffle moving transversely by more (e.g. twice) the safety height. In that case, a nonnegligible fraction of the pipe is exposed to scattered light. ~~with all the consequences~~.

3. The best case is the one in which the whole pipe moves transversely, while remaining straight (no bending), and in which the end tanks move together with the pipe, while everything at the central station is fixed*). In this case, ~~[illegible]~~ movement can be much larger without causing harm.

4. In view of the above, the requirement for the limi on ~~p~~ transverse pipe movement I would suggest is that at any point the pipe should move less than the safety height that has been chosen:

$$\boxed{\Delta X, \Delta Y \leq 1 \text{ cm}}$$

5. If the engineers decide that this requirement is too tough, ~~we shall refine it, knowing that refining it means relaxing it, in this particular case~~. ONE MUST ITERATE THE BAFFLE DESIGN.

---

*) The central station can be considered fixed, since it is relative movement that matters

2.2

TEMPERATURE OF THE BEAM TUBES

CONSTRAINTS ON THE TEMPERATURE EXCURSIONS OF THE TUBES ARE AT PRESENT NOT WELL DEFINED SINCE THE TEMPERATURE SPECIFICATIONS AND THERMAL GRADIENT SPECIFICATIONS DEPEND ON THE TUBE SUPPORT CONCEPT, THE CHOICE OF TUBE DESIGN – STRAIGHT VS CORRUGATED TUBE – AND THE TECHNIQUE BY WHICH WE REDUCE THE H_2O OUTGASSING.

2.2.1 PRELIMINARY SPECIFICATIONS: MECHANICAL

1) THE TUBES SHOULD NOT BEND MORE THAN ± 1 cm DUE TO THERMAL GRADIENTS. FOR STRAIGHT SIMPLY SUPPORTED TUBES THIS DICTATES

$$Y_D = \frac{\beta \nabla T \ell^2}{8}$$

WHERE Y_D IS THE DEFLECTION AT THE MIDDLE OF THE TUBE ∇T THE TEMPERATURE GRADIENT ACROSS A DIAMETER, ℓ THE DISTANCE BETWEEN SIMPLE SUPPORTS, β THE EXPANSION COEFFICIENT OF THE TUBE.

FOR $\ell = 70$ FEET, 304 S.S $Y_\ell = \pm 1$ cm

$$\nabla T < 1.4 \times 10^{-2} \ {}^\circ K/cm$$

DURING SEARCH AND DEVELOPMENT OPERATIONS IN THE LIGO.

2.2.2 2) THE TEMPERATURE CHANGES OF BEAM TUBES SHOULD NOT CAUSE VIBRATION EXCEEDING THE AMBIENT SEISMIC BACKGROUND TO BE IMPARTED TO THE INSTRUMENTATION CHAMBERS. THIS SPECIFICATION REQUIRES MODELLING OF THE STICK/SLIP AT TUBE SUPPORTS AND THE TRANSMISSION OF SOUND BY THE EXPANSION BELLOWS AND ANCHORS.

PRELIMINARY SPECIFICATIONS: VACUUM

2.2.3 1) DURING SEARCH AND DEVELOPMENT OPERATIONS, THE RESIDUAL GAS PRESSURE CHANGES INDUCED BY TEMPERATURE CHANGES OF THE TUBES ON HOURLY, DAILY AND SEASONAL TIME SCALES SHOULD NOT RESULT IN CAUSING THE INTERFEROMETER PHASE SENSITIVITY TO BE COMPROMISED BY INDEX FLUCTUATIONS OF THE RESIDUAL GAS.

SATISFYING THIS SPECIFICATION DEPENDS ON

a) THE STATE OF INTERFEROMETER PERFORMANCE AS A FUNCTION OF TIME

b) THE AVERAGE PRESSURE ATTAINED AT THAT TIME

A REASONABLE APPROACH TO THIS SPECIFICATION IS TO ASSUME THAT H_2O WILL DOMINATE THE RESIDUAL GAS

THE WATER RESIDUAL GAS PRESSURE THAT LIMITS THE $h(f)$ SENSITIVITY OF A FABRY-PEROT (SINGLE BEAM) INTERFEROMETER IS GIVEN

$$P_{H_2O}(\text{torr}) < \frac{h^2(f)\, V_{Th}\, \lambda^{1/2}\, \ell^{3/2}}{2^3\, \pi^{5/2}\, \alpha^2} \left[\frac{1}{3\times10^{16}}\right] \qquad f < \frac{V_{Th}}{(\lambda \ell)^{1/2}}$$

FOR $\ell = 4\times10^5$ cm $\qquad \alpha(H_2O) = 1.44\times10^{-24}$ cm^3

$V_{Th} = 6\times10^4$ cm/sec $\qquad \lambda = 5.145\times10^{-5}$ cm

$$P_{H_2O}(\text{torr}) < 1.25\times10^{40}\, h^2(f) \qquad f < 13\text{KHz}$$

WITH A GOOD STIFF DRINK, ESTIMATE	$h(f)$	$P_{H_2O}<$
1st YR OF OPERATION (?)	3×10^{-22}	1×10^{-3}
2nd YR OF OPERATION (?)	3×10^{-23}	1×10^{-5}
3rd YR OF OPERATION (?)	3×10^{-24}	1×10^{-7}
SOMETIME AFTER (?)	3×10^{-25}	1×10^{-9}

PRESSURE AS A FUNCTION OF TIME (NO BAKING)

ASSUME RATIO $\frac{A}{F}$ = AREA / PUMPING SPEED $\cong$ 5 sec/cm

$$P(t) = \frac{JA}{F} \qquad J_{H_2O} = \frac{1.7\times10^{-7}}{t(\text{hr})}\ \text{torr liter/sec cm}^2$$

$$= \frac{1.9\times10^{-8}}{t(\text{YEARS})}\ \frac{\text{torr cm}}{\text{sec}}$$

$$P(t)_{H_2O} = \frac{5\times1.9\times10^{-8}}{t(\text{YEARS})} = \frac{1\times10^{-7}}{t(\text{YEARS})}\ \text{torr}$$

IN THIS HYPOTHETICAL SCENARIO

THE H_2O PRESSURE BEGINS TO INTRUDE ON SENSITIVITY IN THE THIRD YEAR, IT IS THEN THAT THE TEMPERATURE CHANGES OF THE TUBES BECOME IMPORTANT

IN THE THIRD YEAR $P_{H_2O} \sim 3 \times 10^{-8}$ TORR

THE PRESSURE CHANGE WITH TEMPERATURE

$$\frac{P(\Delta T)}{P} = (2)^{\frac{\Delta T \, T_0}{T^2}}$$

T_0 IS ASSUMED = 1.2×10^4 °K FROM VTF MEASUREMENT AND DR THEORY FOR H_2O

T = AMBIENT TEMPERATURE

$$\Delta T = \frac{T^2}{T_0} \ln \frac{P(\Delta T)}{2P}$$

$$= 3^\circ K \qquad \text{FOR} \quad P(\Delta T)/P = 3$$

[RW P 8
MEMO 61588.TEX]

THE TEMPERATURE SPECIFICATION CLEARLY DEPENDS ON WHAT IS DECIDED ABOUT BAKE OUT AND WHAT ARE REASONABLE SENSITIVITIES TO EXPECT AS A FUNCTION OF TIME.

2) THE BURST RATE, IF IT IS A PROBLEM, WILL MOST LIKELY DEPEND ON TUBE TEMPERATURE, NO SPECIFICATION CAN BE GIVEN FOR THIS AT THE MOMENT

Specs on mechanical noise on vacuum pipes

2.3 Vibration of Vacuum Pipes

The total imported broad-band vibration power shall be small enough so that the vibration spectrum of the pipe walls is increased by less than 3 dB at any frequency from 0.3 Hz to 10 kHz, compared to the value it would have had if driven by the vibration spectrum present before the site was developed.

Allowance may be made for narrow-band vibration using criteria similar to those in the spec for vibration in the instrumentation buildings.

Rationale

The amount of noise from scattered light depends on the vibration of the vacuum pipe walls. The detailed calculations of KST and RW showed how the scattering noise can be held to acceptable levels, assuming that the walls of the pipes move by no more than 10 times the typical ambient seismic spectrum. This factor of 10 is NOT a safety factor, but represents a reasonable approximate correction for the resonant structure in the pipes. Thus, the control of scattering by the baffles they specified depends on the pipes being excited by no more than the typical ambient seismic spectrum. This leads to the same sort of vibration spec as we set for vibration in the instrumentation buildings. It is fortunate that scattering can be controlled with vibration at this level, as vibration isolation of the pipes would be a Herculean task.

2.4 Sound impinging on Vacuum Pipes

The sound spectrum in the vicinity of the vacuum pipes shall be limited to a level of 10**-3 dyn/cm**2-rHz, over a frequency band from 0.3 Hz to 10 kHz.

Allowance shall be made for narrowband noise in the same manner as is specified for the instrumentation buildings.

Rationale

Calculations show that a sound spectrum of the level of the spec is required to keep the acoustically-driven vibration of the vacuum pipe walls below the seismically-driven level.

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Draft Summary of Environmental Specifications

PRS,RW

March 8, 1989

1 INSTRUMENTATION BUILDINGS

1.1 Allowed drift (detailed spec by AA)

1.1.1

No part of the building foundation or walls should be allowed to drift by more than 1 cm after the beginning of installation of the vacuum pipe or chambers.

1.1.2

The piers which support the weight of interferometer components shall not move more than 4×10^{-2} cm in a day, the amplitude of the solid earth tide at 4 km baseline.

1.2 Temperature (detailed spec by AA)

The temperature throughout the instrumentation buildings shall be maintained at a temperature of $20\,\deg C \pm 1.5\,\deg C$.

The temperature at the lasers need only be controlled to the same precision.

Air conditioning to maintain this temperature should be designed to accomodate the heat load of the instrumentation electronics, estimated at 25 kW per interferometer in the corner building, in addition to other fixed building loads and the environmental load.

1.3 Humidity (detailed spec by YG)

The relative humidity throughout the instrumentation buildings shall be maintained at a level of $40\% \pm 5\%$.

1.4 Vibration (detailed spec by PS)

The imported (i.e. added) broad-band vibration noise at each test mass or beam-splitter chamber shall be less than the pre-existing noise level, at all frequencies from 0.3 Hz to 10 kHz. Narrow-band imported noise may violate this criterion in one percent of the bandwidth in any octave. For planning, we estimate the pre-existing noise spectrum as $10^{-7} cm/\sqrt{Hz}$ below 10 Hz, falling as f^{-2} above 10 Hz.

1.5 Sound (detailed spec by PS)

The broad-band sound spectrum throughout the experimental area in any instrumentation building shall be less than $10^{-3} dyn/cm^2\sqrt{Hz}$, at all frequencies between 0.3 Hz to 10 kHz. Narrow-band noise may violate this criterion in one percent of the bandwidth in any octave.

1.6 Cleanliness (detailed spec by YG)

1.6.1

The air quality of the experimental space shall be Class 50,000.

1.6.2

Provision shall be made to erect portable Class 200 clean rooms surrounding any open tank which contains exposed super mirrors.

1.6.3

Other good housekeeping procedures are given in detailed spec.

1.7 Mains Power Conditioning (detailed spec by RW)

1.7.1

The fractional deviation of the mains voltage from its nominal value shall be held to less than 0.02 on time scales of minutes, or longer, under all load conditions.

1.7.2

The peak fractional deviations allowed in transients lasting less than 10 msec shall be less than 0.001.

1.7.3

The fractional root-sum-square of the harmonics of the mains frequency shall be smaller than 0.05.

1.7.4

A grounding strategy is described in the detailed spec.

1.8 Stray Magnetic Fields (detailed spec by RW)

The power distribution shall be arranged so that stray magnetic fields due to the mains power shall be smaller than 1 milligauss rms.

1.9 Laser Cooling Systems (detailed spec by YG)

1.9.1

Indepedent closed-loop chilled water cooling systems shall be provided for each laser, each with a capacity of 100 kW.

1.9.2

Fractional pressure variations in the cooling water shall be limited to less than 0.01.

1.9.3

The inlet temperature of the cooling water at the laser shall be controlled to within $1.5\,\deg C$.

1.9.4

Other parameters of the cooling systems set per manufacturers recommendations or good housekeeping practice. YG raises the possibility of custom made cooling jackets for the laser tubes to allow laminar flow instead of turbulent flow. This needs checking.

1.10 Electromagnetic Interference (detailed spec by AA)

1.10.1

Externally generated electromagnetic waves at all frequencies greater than 10 kHz should not have amplitudes which exceed $1mV/m\sqrt{Hz}$.

1.10.2

Magnetic fields generated inside the building should be limited to amplitudes smaller than $20 microgauss/\sqrt{Hz}$.

1.10.3

At the interferometer phase modulation frequency, the stray field strength should be limited to less than $1mV/m\sqrt{Hz}$.

A spec on the rms should be set to avoid troublesome DC coupling. RW proposes that stray field at the modulation frequency be held to less than $100\mu V/m$.

2 ENVIRONMENT OF THE VACUUM PIPES

2.1 Alignment (detailed spec by AA)

The pipe should have its sections misaligned randomly with an amplitude of about 1 cm. Drift after set-up should be small compared to 1 cm.

2.2 Temperature (detailed spec by RW)

2.2.1

Temperature gradients across the pipe should be limited so that thermoelastic bending does not cause displacement of the pipe by more than 1 cm. For one model tube section considered, this gives a limit of $1.4\,\deg C/m$.

2.2.2

Temporal variation of the temperature should not be allowed to introduce vibration into the pipes through the stick/slip process. If the pipe supports can be designed without any sliding or rolling contacts, then no requirement on temperature change is necessary for this effect.

2.2.3

Temperature variation can cause the pressure inside the pipes to change. Setting a spec for this mechanism depends on the interactions between the operations scenario and the vacuum system performance.

2.3 Vibration (detailed spec by PS)

The amount of imported vibration should be held to the same level as that specified for the instrumentation building.

2.4 Sound (detailed spec by PS)

The level of acoustic noise should be limited to the same level as that specified for the instrumentation building.

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FILE:envspeccom.tex

FROM: RW March 8, 1989

CONCERNING: Comments on the Environmental Specifications

The working group was busy upto the last minute in conceptualizing and writing the enclosed drafts. Peter Saulson in making the summary and I while reading the drafts had the first opportunity to look more critically at some of our assumptions. The following are a set of comments in the order of Peter's summary.

1.1.2 Allowed drift

The specification is reasonable, I suggest that the interferometer position servo systems be designed to accomodate the solid earth tide distortions. This will require position controllers for the points of support with a dynamic range of 1 mm.

1.4 Vibration

The definition of the acceptable level of narrow band noise as given in this section is at present the most reasonable assumption we can make. It will prove worthwhile to reconsider it when strategies for periodic searches are evolved. Experience with periodic searches by Livas was that it is important to separate frequency wandering oscillators and frequency stable oscillators in the data analysis when searching for candidate periodic sources in an unprejudiced search. A major means of determining whether a spectral feature is a gravitational wave is by looking for the Doppler correction appropriate to a specific location in the sky. A fixed frequency source can be rejected by this criteria, a wandering oscillator can be rejected if it wanders over more than a reasonable value for the doppler correction.

1.5 Sound

The specification for the sound pressure in the instrumentation buildings may have to be reduced by a factor of 10. This would cover older estimates I have made and will be better defined in a new document being prepared by Peter.

1.10 Electromagnetic Interference

No distinction should be made between RF fields originating from local and far sources. The specification 1.10.1 should stand for all electromagnetic fields.

Peter and I have changed the specification 1.10.4 for the leakage of coherent RF electric fields at the subcarrier frequencies used in fringe interrogation to less than 100 microvolts/meter rms.

2.1 Alignment of Tubes

The specification of 1 cm randomness in tube alignment is good providing that it is truly random. There is still uncertainty on a specification for the coherent displacements of the baffle system - in particular the tolerable bias displacements extending over many baffles. This will be addressed in the summary of the summary document on scattering.

Section on requirements for auxiliary physical measurements

Philosophy

The basis for the measurment system is twofold. The important one of behaving as a veto is strongly emphasized in the writings of the subgroup. A second function is in diagnostic studies during shake down and ultimately as a tool to search for correlations of the interferometers with the physical variables being measured. The desire to crosscorrelate will require the capability of placing sensors at the tanks.

2.7 Gas column density monitor

The system proposed may prove useful earlier than when the facilities and interferometers are at the higher gravitational wave sensitivity. The search for gas bursts in the VTF could use such an instrument now and diagnostics of excess noise with no apparent explanation in the early operations may well require knowledge of column density fluctuations.

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by R. Weiss, Env. Spec. 1.7–1.8, typed version
[received 4/19/89]

#57c

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1.7

Power conditioning in the facilities and grounding for distribution system

The instrumentation building power distribution system has no special requirements that would not be the standard for a research laboratory with distributed apparatus.

The service should include:

440	3ϕ	lasers, rotating machinery
220	3ϕ	power supplies, machinery
110		general laboratory instrumentation

Since all critical instrumentation is recommended to have local voltage regulation, the specifications for global line voltage variation are looser than for a standards laboratory

1.7.1 $\Delta V/V|_{\mathrm{rms}}$ < 0.02 long term $t >$ minutes zero to full load

1.7.2 $\Delta V/V|_{\mathrm{peak}}$ ¡.001 transients $t < 10^{-2}$ seconds

1.7.3 Harmonic content

$$V(t) = \sum_{n=1}^{\infty} V_n \sin\,(n\omega_1 t + \varphi_n)$$

$$\frac{\left(\sum_{n=2}^{\infty} |V_n|^2\right)^{1/2}}{V_1} < .05$$

Global specifications

1.7.4 Grounding and neutral lines

1) Earth grounding consistent with lightning safety is assumed.

2) Since the instrumentation is distributed over a substantial area it will be important to have a well defined ground connection at each location.

A recommended goal is to establish a star ground system in each building using an earth connection with resistance to ground of less than 1Ω.

Interconnection between the local ground and the star should be made with low inductance and low resistance leads.

$$L/l = \text{inductance/meter} < 0.05 \text{ henrys/meter}$$

$$R/l = \text{resistance/meter} < 10^{-4} \text{ ohms/meter}$$

A suggested technique is to use copper tubing for the ground network.

3) Neutral power lines should be separate from ground lines.

4) Individual locations - each instrumentation tank or separable complex - should derive power from a separate sub transformer. The individual transformers should have electrostatic shields between primary and secondary windings which are grounded.

5) Unbalanced neutral currents in Y transformers should not exceed 1% of the average load current in any of the legs.

6) The instrumentation tanks and vacuum tubes should be grounded by known connections using low inductance circuitry. (The grounding line should be removable for diagnostics.)

7)* The overall grounding and interconnection between stations especially the currents running along the beam tubes must be studied further. The large EMFs from magnetic storms and lightning may require insulated sections and arc suppression between sections. The requirements for this are site dependent.

8) It is worth considering individual electrostaticaly shielded isolation transformers as a means of feeding each separable instrumentation complex to further reduce the chance of large ground currents.

*(uncertain)

1.8

Magnetic fields in the instrumentation buildings from the power distribution system

1) The distribution system wiring should be arranged so that line frequency and harmonic magnetic fields at mass suspension locations are less than 1 milligauss rms.

This specification requires some care in transformer placement and the geometry of the distribution lines. In most cases it will be satisfied by standard practice.

Some comments more relevant to the section on receiver/facility interfaces

1) Interconnection of signals between instrumentation complexes (instrumentation stations, tank complexes, etc.) would be best done digitally using optical fibers to avoid induced ground current transients.

2) Electrostatic shielding is required on all insulators in the instrumentation tanks.

For example:

conducting coatings on view ports

conducting coatings on plastic or glass parts

Faraday screens on those parts which cannot be conducting

The field lines from uncontrolled static charges must not get to the suspension mass

* A special problem is the dielectric coating on the mirrors themselves, <u>this needs further thinking</u>. I have often imagined a tubular shield attached to the guard (or recoil) mass associated with the suspension

* uncertain

Note on low inductance connections

$$L/l \; = \; \frac{\text{inductance}}{\text{length}}$$

straight solid cylinder

$L/l = \frac{\mu_0}{4\pi}$

braid with N strands

$L/l = \frac{\mu_0}{4\pi N^{1/2}}$

tubing a = inner radius, b = outer radius

$$L/l = \frac{\mu_0}{4\pi}\left[1 - \frac{2a^2}{b^2-a^2}\, ln\; b/a\right]$$

$$\sim \frac{\mu_0}{8\pi}\left(\frac{b-a}{a}\right)$$

when $\frac{b-a}{a} \ll 1$

by R. Weiss, Env. Spec. 2.2, typed version
[received 4/19/89]

57d

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2.2

Temperature of the beam tubes

Constraints on the temperature excursions of the tubes are at present not well defined since the temperature specifications and thermal gradient specifications depend on the tube support concept, the choice of tube design - straight vs corrugated tube - and the technique by which we reduce the H_2O outgassing.

2.2.1

1) Preliminary specifications: Mechanical
The tubes should not bend more than ±1cm due to thermal gradients.
For straight simply supported tubes this dictates

$$y_0 = \frac{\beta \bigtriangledown T l^2}{8}$$

Where y_0 is the deflection at the middle of the tube, $\bigtriangledown T$ the temperature gradient across a diameter, l the distance between simple supports, β the expansion coefficient of the tube.

For l = 70 feet, 304 stainless steel $\quad y_d = \pm 1cm$

$$\bigtriangledown T < 1.4 \times 10^{-2} K/cm$$

During search and development operations in the LIGO.

2.2.2

2) The temperature changes of beam tubes should not cause vibration exceeding the ambient seismic background to be imparted to the instrumentation chambers. This specification requires modelling of the stick/slip at tube supports and the transmission of sound by the expansion bellows and anchors.

Preliminary specifications: Vacuum

2.2.3

1) During search and development operations, the residual gas pressure changes induced by temperature changes of the tubes on hourly, daily and seasonal time scales should not result in causing the interferometer phase sensitivity to be compromised by index fluctuations of the residual gas.

Satisfying this specification depends on
   a) the state of interferometer performance as a function of time
   b) The average pressure attained at that time

A reasonable approach to this specification is to assume that H_2O will dominate the residual gas.

The water residual gas pressure that limits the $h(f)$ sensitivity of a Fabry-Perot (single beam) interferometer is given

$$P_{H_2O}(torr) \quad < \quad \frac{h^2(f)v_{Th}\lambda^{1/2}l^{3/2}}{2^3\pi^{5/2}\alpha^2}\left[\frac{1}{3\times10^{16}}\right] \qquad f \quad < \quad \frac{v_{Th}}{(\lambda l)^{1/2}}$$

For $\quad l \;=\; 4\times10^5 cm \qquad \alpha(H_2O) \;=\; 1.44\times10^{-24}cm^3$

$\qquad v_{Th} \;=\; 6\times10^4$ cm/sec $\qquad \lambda \qquad = 5.145\times10^{-5}cm$

$P_{H_2O}(torr) \;<\; 1.25\times10^{40}\ h^2(f) \qquad f \;<\; 13KHz$

Estimate	$h(f)$	P_{H_2O} <
1st yr of operation (?)	3×10^{-22}	1×10^{-3}
2d yr of operation (?)	3×10^{-23}	1×10^{-5}
3rd yr of operation (?)	3×10^{-24}	1×10^{-7}
Sometime after (?)	3×10^{-25}	1×10^{-9}

Pressure as a function of time (no baking)

Assume ratio $\frac{A}{F}$ = area/pumping speed $\cong$ 5 sec/cm

$$P(t) \;=\; \frac{JA}{F} \qquad\qquad J_{H_2O} \;=\; \frac{1.7\times10^{-7}}{t(\mathrm{hr})}\ torr\ liter/sec\ cm^2$$

$$P(t) \;=\; \frac{5\times1.9\times10^{-8}}{t(\mathrm{years})} = \frac{1\times10^{-7}}{t(\mathrm{years})}torr \qquad\qquad = \frac{1.9\times10^{-8}}{t(\mathrm{years})}\ \frac{torr\ cm}{sec}$$

In this hypothetical scenario

The H_2O pressure begins to intrude on sensitivity in the third year, it is then that the temperature changes of the tubes become important.

In the third year $\qquad P_{H_2O} \sim 3\times10^{-8}torr$

The pressure change with temperature

$$\frac{P(\Delta T)}{P} \;=\; (2)^{\frac{\Delta T\ T_0}{T^2}}$$

T_0 is assumed = 1.2×10^4K

from VTF measurement and

DR theory for H_2O

$$\Delta T \;=\; \frac{T^2}{T_0}\ ln\ \frac{P(\Delta T)}{2P}$$

T = Ambient temperature

$\left[\begin{array}{c}\text{RW p8}\\ \text{memo 61588.tex}\end{array}\right]$

$$= 3^oK \text{ for } P(\Delta T)/P \;=\; 3$$

The temperature specification clearly depends on what is decided about bake out and what are reasonable sensitivities to expect as a function of time.

2) The burst rate, if it is a problem, will most likely depend on tube temperature, no specification can be given for this at the moment.

by R. Weiss, Env. Spec. 2.5
[received 4/19/89]

57e

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2.5

Magnetic Field Monitoring

Long period fluctuations

B_x, B_y, B_z should be measured in each building which contains test masses and analog sensitive electronics.

Each field conponent should be measured to a precision of 10^{-3} Gauss at a sampling period of ~ 1 sec.

Standard flux gate (peaking strip) magnetometers will do this. Schoenstedt Corp. sells 3 axis magnetometers that will satisfy the specification.

Short period fluctuations

Magnetic pressures on the masses are imparted by time dependence and gradients in the magnetic field.

Magnetic pulses of millisecond duration and milligauss amplitude have been measured (Gordon, M. MIT physics senior thesis, 1973)

Recommend: 1 meter^2 loops with 100 turns to measure rise time and amplitude of magnetic pulses. The information is sampled and held when it exceeds a threshold.

$$dB/dt > 1 gauss/sec \qquad B_{\max} > 1 \times 10^{-5} gauss$$

The slope and $B_{\max}$ are held in a shift register for insertion in the facility data stream with a time tag.

one coil / building

Transfer function measurements

Each tank should have a 3 axis pair of Helmholtz coils to stimulate magnetic fluctuations up to 1 gauss in the test mass volume.

by R. Weiss, ENV. SPEC. 2.7
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57f

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2.7

Vacuum monitor for interferometer phase fluctuations

Function: Measure column density fluctuations of the residual gas in the 4km beam tubes at a sensitivity sufficient to determine the contribution of gas bursts and other coherent residual gas fluctuations to the most sensitive burst, periodic and stochastic gravitational wave searches.

Sensitivity required:

$$\textbf{Bursts} \quad h_{\rm rms} \quad < \quad \begin{array}{lll} 10^{-23} & 10 < f < 100\, Hz & \text{SQL} \\ 10_{-25} f & f > 100\, Hz & \text{recycling} \end{array}$$

Molecule	Column Density Fluctuation Equivalent to $h_{\rm rms}$ use $h_{\rm rms}<10^{-23}$ mol/cm^2	Equivalent Pressure Fluctuation (torr) L=4km	Number of Molecules R=61cm
O_2	4.4×10^5	3.7×10^{-17}	5.2×10^9
N_2	4.0×10^5	3.3×10^{-17}	4.7×10^9
CO	3.5×10^5	3.0×10^{-17}	4.1×10^9
H_2	8.6×10^5	7.1×10^{-17}	1.01×10^{10}
H_2O	4.5×10^5	3.7×10^{-17}	5.2×10^9
He	3.3×10^6	2.8×10^{-16}	3.9×10^{10}
A	4.2×10^5	3.5×10^{-17}	5.0×10^9

Periodic and stochastic sources

$$h(f) \quad < \quad \begin{array}{lll} \frac{3\times 10^{-23}}{f} \Big/ Hz^{1/2} & 10 < f < 100 Hz & \text{SQL} \\ 3 \times 10^{-25} / Hz^{1/2} & f > 100 Hz & \text{periodic recycling} \end{array}$$

Molecule	Column Density Fluctuation $\sigma(f)$ use $h(f)<3\times 10^{-25}/Hz^{1/2}$ mol/cm^{2}Hz$^{1/2}$	Equivalent Pressure Fluctuation torr/Hz$^{1/2}$
O_2	1.2×10^4	1×10^{-18}
N_2	1.1×10^4	9×10^{-19}
CO	9.5×10^3	8×10^{-19}
H_2	2.4×10^4	1.9×10^{-18}
H_2O	1.2×10^4	1×10^{-18}
He	9.1×10^4	7.5×10^{-18}
A	1.2×10^4	1×10^{-18}

The sensitivity requirements cannot be met with standard vacuum gauges

Proposed methods:

1) Colinear interferometers at several wavelengths

   The method uses the dispersion in the molecular polarizability of the residual gas molecules. It could measure both the statistical fluctuations in gas column density - (those due to the Poisson distribution of the column density) and the coherent fluctuations - (bursts and other global column density fluctuations). The method would require multiple interferometers with comparable sensitivity limited by the residual column density fluctuations. It is a cumbersome and expensive method.

2) Molecular constituent specific absorption measurement

   The method uses absorption measurements of the total column of molecules. The absorption is from the ground state of the molecule. The method is most sensitive using UV beams running double pass along the tubes. Frequency multiplied tunable Ti: sapphire or Dye lasers light is sent from the central building to a corner reflector at the 2nd building and detected in the central building. A separate wavelength is needed for each molecule.

   The method has adequate sensitivity. The UV beams are not colinear with the interferometer beams so that only coherent column density fluctuations are measured.

   The technique can be adapted for fast leak hunting by using a tracer molecule or atom with ground state absorption that falls into the tunable laser band.

3) Either method will require development.

Sensitivity Calculation:

α = molecular polarizability

L = length of antenna arm

R = radius of tube

$h_{\rm rms}$ = smallest gravitational strain measurable for bursts

$h(f)$ = smallest gravitational wave spectral density measurable

ω = $1/e$ radius of light beam

N = number of molecules in burst

σ = column density of molecules

A = πR^2 cross section of tube

δp = pressure fluctuation in torr averaged over L

Gas noise in burst search

$$\delta\sigma \ < \ \frac{h_{\rm rms}L}{2\pi\alpha}\left(\mathrm{mol/cm^2}\right) \qquad AN \ = \ \delta\sigma A \ \ (\mathrm{mol})$$

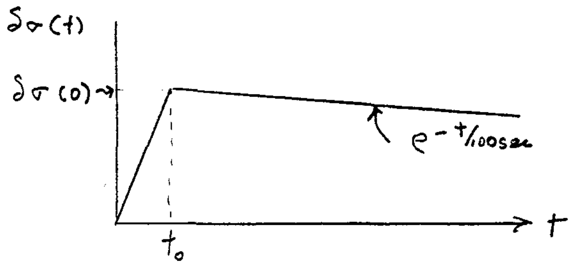
$$\delta p \ = \ \frac{\delta\sigma}{L}\left(\frac{1}{3\times10^{16}}\right) torr$$

Typical gas burst will have time dependence

$$\delta\sigma(t) \ = \ \delta\sigma(0)\ e^{-t/\tau} \qquad \tau \ = \ \frac{V}{F} \approx 100 \text{ seconds}$$

Where V = volume of system

F = pumping speed of system



$$t_0 \ \sim \ \frac{2w}{V_{th}} \ \simeq \ \frac{5}{4\times10^4} \ \simeq \ 0.12 \text{ millisec}$$

Expressed as spectral density

$$\sigma(f) \ < \ \frac{h(f)L}{2\pi\alpha}\left(\mathrm{mol/cm^2}\right) \qquad P(f) \ = \ \frac{\sigma(f)}{L}\left(\frac{1}{3\times10^{16}}\right) torr/Hz^{1/2}$$

Principal ground state electronic transitions

Molecule	$\lambda(A^o)$	$r(cm^{-1})$	cross section if radiative decay $Q_j(\lambda_0)=f\lambda_0^2/8\pi^2$ cm^2
N_2	1450	68956	2.7×10^{-13}
O_2	2800	35713	1×10^{-12}
CO	1544	64746	3×10^{-13}
H_2	1103	90634	4.4×10^{-13}
H_2O	$1450 \rightarrow \underline{1860}$	$\underline{53760} \rightarrow 68965$	4.4×10^{-13}

f = oscillator strength
assume f=0.1

many strong lines

Absorption in column

2 comes from double pass

$$I(\lambda_0, 2l) = I_0(\lambda_0)\; e^{-2Q_j(\lambda_0)\sigma_j\,\frac{\Delta\nu(\text{radiative})}{\Delta\nu(\text{doppler})}}$$

$Q_j(\lambda_0)$ resonance cross section of molecule species j cm^2

σ_j column density of molecular species j mol/cm^2

	Average Pressure $<P>torr$	Average Column Density $<\sigma>mol/cm^2$	Total absorption at λ_0 db	Linewidth(estimated) $\Delta\nu$ MHz(FW)	Linewidth Doppler $\Delta\nu$ MHz
H_2	10^{-8}	1.2×10^{14}	10	580	9060
N_2	10^{-9}	1.2×10^{13}	3	260	2760
O_2	10^{-9}	1.2×10^{13}	3.5	36	1070
H_2O	10^{-9}	1.2×10^{13}	2	124	3230

Except for hydroden, the absorption at λ_0 is proportional to, σ, the column density; hydrogen absorption is saturated but still usable on resonance with a saturation correction.

Estimated sensitivity — assume shot noise limit at PM tube
quantum efficiency $\eta = 0.7$

UV power required to detect h_{rms} limiting burst

Since levels are all comparable use N_2 burst as example

Change in detected power due to column density fluctuation $\Delta\sigma$

$$\frac{\Delta I}{\Delta\sigma} = -\eta I_0 \, 2\, Q \frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Doppler}}} \, e^{-2Q\sigma\frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}}} = -\eta \, 2\, Q \frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}} I(L)$$

Shot noise $\quad \dot{n}^2(f) = 2\eta\dot{N}$

$\dot{n}(f)$ = spectral density or photon fluctuations
$\dot{N}$ = average photon rate = $I(L)/h\nu$

Shortest integration time $\quad t_{\mathrm{int}} \simeq 1$ sec

$$\Delta n_{\mathrm{shot}} = \sqrt{2\eta\dot{N}/t_{\mathrm{int}}}$$

For signal/noise of 1

$$\Delta n_{\mathrm{burst}} = \Delta n_{\mathrm{shot}}$$

$$2\,\eta\, Q\frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}}\,\dot{N}\;\Delta\sigma = \left(\frac{2\eta\dot{N}}{t_{\mathrm{int}}}\right)^{1/2}$$

$$\dot{N} > \frac{1}{2\eta\left[Q\left(\frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}}\right)\,\Delta\sigma\right]^2 t_{\mathrm{int}}}$$

For $N_2 \qquad Q\dfrac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}}\,\Delta\sigma = 1\times10^{-8}$

$\dot{N} > 7\times10^{15}/sec \qquad P = h\nu\dot{N} = 10$ milliwatts

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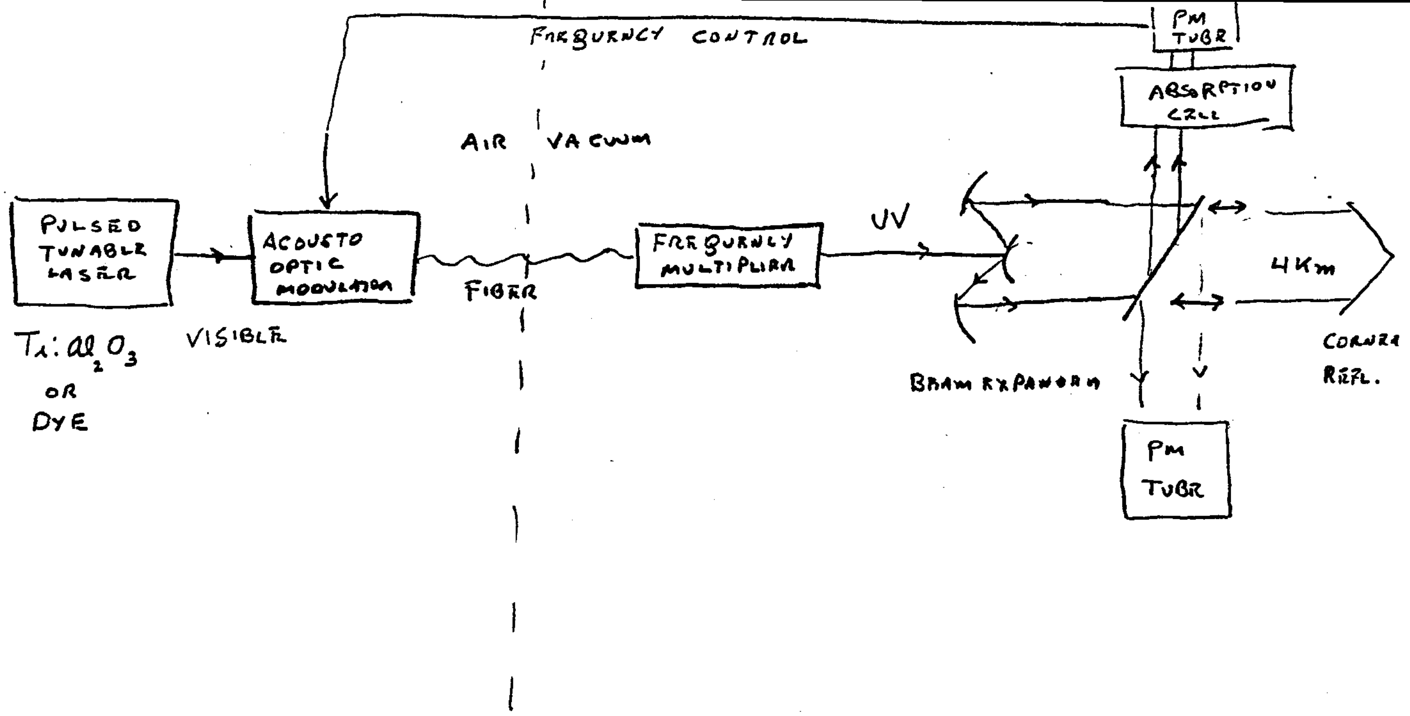
System used as a column density monitor for spectral density

$$\sigma(f) \sim \left(\frac{f}{2\eta\dot{N}}\right)^{1/2}\frac{1}{Q\frac{\Delta\nu_{\mathrm{rad}}}{\Delta\nu_{\mathrm{Dop}}}} \simeq 4\times10^5\, f^{1/2} \quad \left(\mathrm{mol/cm^2}\; Hz^{1/2}\right)$$

or pressure monitor $< P(f) >_L \simeq 3\times10^{-17}\, f^{1/2}$ $\quad torr/Hz^{1/2}$



Concept for method 2

Absorption measurement

Room needed in LIGO for the monitor system

Beam sizes ~ 2.8cm diameter

Fiber coupling

1 meter $\times 1/2 \times 1/2$ volume in some tank