LIGO-T890032-00-R

58a

List of 3/15/89

Draft Summary of Requirements for Auxiliary Physical Measurements

PRS

March 8, 1989

1 Philosophy

To understand the performance of LIGO receivers, we will need quantitative information concerning the importance (or lack thereof) of a number of possible external influences.

To this end, we will need auxiliary sensors to record the values of external physical variables. In a number of cases, it will be very useful to be able to drive the system with excess noise to look for the response.

2 Physical Measurements

2.1 Temperature, Humidity, and Air Quality

A temperature sensor should be placed on each tank, on each laser, and on each mechanical pump.

Instruments to measure air temperature, humidity, and quality ("smoke detector") should be installed in each instrumentation building.

A small weather station should be installed outside the corner building, and perhaps outside the other buildings as well.

All of these sensors can be sampled at low bandwidth.

2.2 Vibration

A three-axis set of accelerometers (for high frequencies) and seismometers (for low frequencies) shall be installed in the foundation of each instrumentation building. These sensors shall be sufficiently sensitive to record the ambient noise level at the quietest times.

Provision shall be made in each of the support piers to mount a similar set of sensors.

These signals should be recorded at as high a bandwidth as there is significant signal level, probably around 1 kHz.

2.3 Sound

Each instrumentation building shall be equipped with a high quality microphone, capable of measuring the quiet noise spectrum from 0.3 Hz to 10 kHz.

2.4 Mains Power

The following aspects of the mains power shall be recorded: rms amplitude, frequency, harmonic content, and phase with respect to our master time base.

Recordings should also be made of the times at which fast spikes appear on the mains.

2.5 Magnetic Fields

Each instrumentation building shall be equipped with a three-axis set of magnetometers, with resolution of 1 milligauss or better. The output should be sampled at 1 Hz.

Each instrumentation building shall be equipped with a means of detecting and logging magnetic pulses with slopes of 1 gauss/sec and amplitudes greater than 10 $\mu gauss$.

2.6 Electromagnetic Interference

Each instrumentation building should be equipped with a set of broad-band electromagnetic field detectors (similar in style to auto radar detectors), covering a broad range of the RF spectrum. A suitable system should be installed to record the levels in each band (at low bandwidth), and to log spikes in the outputs of the detectors.

2.7 Vacuum Monitoring

Each vacuum tank should be equipped with a vacuum gauge, sampled at low bandwidth.

Ion pump currents along the vacuum pipe should be sampled at low bandwidth, as a measure of pressure along the pipe.

In the event that tests on the LIGO suggest that interferometer noise may be caused by non-Poisson fluctuations of the residual gas column density, we should develop and install a system to measure the column density at high bandwidth. One way to do this is to measure the absorption of light from a UV laser tuned to a resonance of a suspected gas species.

2.8 Cosmic Ray Muon Detectors

Each instrumentation building shall be equipped with a detector capable of detecting muons from a cosmic ray shower, to veto any rare large event which might mimic an impulsive gravitational wave.

Since single muons will not give impulses large enough for even the advanced detectors to see, it is not necessary to place a detector over each mass. There must be, however, a shower detector within 10 or 20 meters of each mass to be sure to see any event which may strike a mass.

BATCH
START

STAPLE
OR
DIVIDER

LIGO-T890032-00-R

#58

List of 3/15/89

1 PHILOSOPHY

Auxiliary Physical Measurements for the LIGO

PRS

Introduction

Auxiliary physical measurements come in a number of varieties, and need to be measured for a number of different reasons. Some quantities (seismic noise is the prime example) are likely to be an important noise source at some frequencies. It seems prudent to measure it with reasonable bandwidth, even though regressing out the noise may be difficult. A number of other environmental noise terms ought not to dominate the noise budget at any frequency. Still, there can be good reasons to have the capability to record them. Acoustic noise can sneak in if input optics is poorly designed, so it is good to be able to check it against interferometer noise. Other variables are unlikely to ever actually be a problem, but will be asked about by others (or ourselves when we wake up in the middle of the night.) Finally, some variables are so easy to monitor that it is a shame not to record them at low bandwidth, ''just in case". In what follows, I will indicate my guess as to how likely it is that each quantity might be a crucial one.

A consequence of the considerations listed above is that as we gain experience with the LIGO receivers and facility, we will know better which environmental variables to record, and at what bandwidth. The best that can be done in advance is to specify a prudent complement of measurements to have available at the beginning of operations. With luck and care, this list won't be missing any essential measurements, and can be pruned of its superfluous elements in the field.

Understanding the performance of the LIGO interferometers will require more than just recording a variety of signals. We will want to be able to actively test the importance of external noise by increasing it, and looking for response in the interferometer. In simple cases, we will actually be able to determine transfer functions between external environmental variables and interferometer output. (Then we could subtract that noise contribution from the interferometer signal if we chose, if it were impractical to reduce the coupling to a negligible level.) In the more complicated cases (which will probably be more common), it may be too difficult to record enough information to construct a coherent transfer function. Acoustic noise, if it is significant at all, will likely be in this category. Seismic noise will also probably be in this category, unless we measure many external variables. Still, it will be extremely important to learn how strongly these noise sources couple to interferometer output. Simple comparisons of power spectra from driven and quiet conditions will show the magnitude of the effect, and hopefully suggest ways to reduce the coupling.

For this reason, we will need to have the capacity to excite the variables we suspect are important to the interferometer. Vibration can be driven with electromagnetic shakers, sound with loudspeakers, magnetic fields with Helmholtz coils, etc. In most cases, we will want a portable driver which we can set up when we want to conduct a noise audit. Shakers are bulky and expensive, so they should be set in place when needed. Loadspeakers may be set up for a paging system anyway -- if so, they could double as noise drivers.

2.2 Seismic Noise

Our estimates of the LIGO receiver noise budget indicate that there should be three dominant noise sources. At high frequencies, shot noise should be strongest. In an intermediate frequency band, we will be fighting thermal noise in the suspensions. Finally below some frequency in the vicinity of 100 Hz or lower, we expect to be dominated by insufficiently isolated seismic noise. Note that seismic noise is the only one of these dominant noise terms which arises from an external influence on the interferometer, so it is the only one amenable to monitoring with external instruments.

The most important frequencies to record are from a few tenths of a Hertz to a few hundred Hertz. The bottom of the range includes the resonances of our likely suspension designs. Above the top of this range, the noise amplitude is small and isolation systems work well, so we are unlikely to get into trouble. Still, in case there are problems we don't understand in advance, we should have the ability to record with as large a bandwidth as is useful, maybe up to 1 kHz.

Ideally, the sensors should be sensitive enough to see the seismic background spectrum at the quietest times. The sensitivity of piezoelectric accelerometers is limited by the current noise of the preamplifier. AT LOW FREQ AND VOLTAGE NOISE AT HIGH FREQ. The Endevco model 7707, which delivers 1000 pC/g, has been used in the MIT lab at a sensitivity which can detect the benchmark seismic noise spectrum 10**{-5}cm/rt{Hz} above 10 Hz. Probably more care with the amplifier would extend the response to lower frequencies. The Bruel & Kjaer piezoelectric accelerometer Model·8306 has a response of 1000 pC/m-sec**{-2}, an order of magnitude more sensitive. This model has been used at Caltech. The listed frequency range extends down to 0.1 Hz.

Better response at the low frequency end of the spectrum is available from seismometers (which are similar to accelerometers except that they have resonant frequencies below or within the frequency band of interest, instead of above.) The seismometer used for the Livingston site survey, the Teledyne Geotech model S-13, had sensitivity to burn -- the signal to noise ratio at a canonical site would be in excess of 20 dB in the band 1Hz to 10 Hz.

Probably the most sensible strategy for monitoring seismic noise would be to mount three orthogonal accelerometers (one vertical, the two horizontal ones aligned with the interferometer arms) and an equivalent set of seismometers in the foundation of each instrument building, somewhere in the vicinity of a tank. This would serve as a monitor of the background level, and as a flag for large impulses. These sensors would probably not be very useful for actually subtracting seismic noise from the data.

To collect enough data to regress out seismic noise from the interferometer signal would require a substantially larger set of sensors. One strategy might be to make provision in each of the test mass suspension supports for a 3-axis set of sensors similar to the ones described above. Note that actually implementing the measurements necessary to carry this program out could be expensive (in sensors, data bandwidth, and computer time).

An alternative way to acquire some related information is to record the output of the mass damping sensors.

The anti-seismic interferometer system is intended to perform a similar function. To the extent that it works as planned, these other measurments may be superfluous.

2.3 Acoustic Noise

Acoustic noise should not be a significant noise source in a properly designed interferometer, since all of the susceptible components should be in vacuum or otherwise shielded. But in the development stages our optics won't always be ''properly designed", and then acoustic coupling is a potential problem. (Sound can also drive mechanical motion of the floor and tanks, which is then transmitted through the isolation systems.) For this reason, it is prudent to be able to measure the acoustic noise, especially during shakedown.

Acoustic noise should be measured from a few tenths of Hertz up to the highest frequency at which we record gravitational wave signals (10 kHz?), since the coupling is often through high frequency mechanical resonances in sensitive optical parts.

It should be possible to buy microphones and preamps sensitive enough to detect the background noise level in the vicinity of our apparatus. Noise level is usually specified as an rms figure known as the ''A-weighted sound level" in dB with respect to 20 microPa, which is roughly the threshold of hearing. (The A-weighting is designed to emphasize high frequencies, as it has a 1 to 2 pole high-pass filter with 3 dB point at around 1 kHz.) A typical office has the same sound level as a large transformer at a distance of 200 feet, about 45 to 50 dBA. A motion picture sound stage has a sound level of 20 dBA. (These numbers come from Peterson and Gross, Handbook of Noise Measurement, published by General Radio Company.) Bruel & Kjaer offers a number of microphones with rms levels of around 10 dBA, including models with response flat down to 0.1 Hz. Other models, with reduced sensitivity, can measure down to a few mHz, if we should deem that worthwhile.

We should have a high quality microphone installed in all the instrumentation buildings. The most critical information will likely come from the vertex building, where the exposed optics is concentrated. I think it is extremely unlikely that we would ever use these instruments for noise subtraction, since the phase relationships in acoustic transfer functions are notoriously complicated.

Miscellaneous

2.1 Here are a few things which may fall through the cracks.

A complete set of weather measurements, perhaps at each building.

We will need a good clock and/or WWV or GPS receiver.

8-MARCH-19889 Alex

2.1 Temperature Monitoring:

It is suggested that the temperature of the tanks be individually monitored, in order to detect possible problems in a timely manner. For example, liquid nitrogen spill may cool the tanks and generate undesirable structural stress and/or condensation. *

PRIMARILY USEFUL FOR DRIFT DIAGNOSTICS

2.6 RF Monitoring:

I suggest that in each building there be a RF monitoring station consisting of the following parts:

1. Receiver
2. Level detectors for selected frequencies and frequency bands, with digital outputs for recording and further processing
3. Threshold detectors at each of the above frequencies and frequency bands, connected to adequate alarm systems

2.4

Yekta; March 8, 1989

The parameters of the mains power
which should be monitored:

(a) The line voltage should be logged once every second with the standard data system precision (16 bits).

This will enable us to correlate the performance levels of various instruments to the line voltage in an incoherent way. Spurious signals at the interferometer outputs may be vetoed if they are correlated with the values of the line voltage.

(b) The times at which the the line voltage exceeds the standard value by plus or minus 10 percent should be logged as they occur.

This monitor should be fast enough to catch fast line spikes and dips. Some of these spikes have a very short duration, typically around a microsecond.

(c) The line frequency should be logged once every second by counting the crossings of the waveform for suitably long periods of time.

(d) The phase of the line voltage with respect to the laboratory master clock should be logged at every cycle of the line frequency (60 times a second).

This will enable us to hunt for the line frequency spikes and its harmonics in the output of the detector in a coherent way.

(e) The harmonic content of the line voltage should be monitored by taking its spectrum every 6 hours.

This function can be performed by the data system by digitizing the line voltage at a high enough rate to cover the highest significant harmonic.

Functions (a) to (c) can be performed by standard off the shelf items or the data system itself. Item (d) can be performed by a relatively easy to construct device. Item (e) can also be performed by a standard spectrum analyzer.

EW
3/8/89 MAGNETIC FIELD MONITORING

2.5

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 COMPONENT 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 SCHONSTEDT CORP SELLS 3-AXIS MAGNETOMETER 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, 197X)

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

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

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 UPTO 1 GAUSS IN THE TEST MASS VOLUME

RW 3/6/89
2.7

VACUUM MONITOR FOR INTERFEROMETER PHASE FLUCTUATIONS

FUNCTION: MEASURE COLUMN DENSITY FLUCTUATIONS OF THE RESIDUAL GAS IN THE 4 Km 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:

	10^{-23}	$10 < f < 100$ Hz	SQL
BURSTS $h_{rms} <$	$10^{-25} f$	$f > 100$ Hz	RECYCLING

MOLECULE	COLUMN DENSITY FLUCTUATION EQUIVALENT TO h_{rms} USE $h_{rms} < 10^{-23}$ 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

$h(f) <$	$3 \times 10^{-23}/\text{Hz}^{1/2} \,/\, f$	$10 < f < 100$ Hz	SQL
	$3 \times 10^{-25}/\text{Hz}^{1/2}$	$f > 100$ Hz	PERIODIC RECYCLING

MOLECULE	COLUMN DENSITY FLUCT. $\sigma(f)$ USE $h(f) < 3 \times 10^{-25}/\text{Hz}^{1/2}$ mol/cm^2 Hz$^{1/2}$	EQUIVALENT PRES. FLUCTUATIONS 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_{RMS} SMALLEST GRAVITATIONAL STRAIN MEASURABLE FOR BURSTS
$h(f)$ SMALLEST GRAVITATIONAL WAVE SPECTRAL DENSITY MEASURABLE

w = 1/2 RADIUS OF LIGHT BEAM
N = NUMBER OF MOLECULES IN BURST
σ = COLUMN DENSITY OF MOLECULES
$A = \pi R^2$ CROSS SECTION OF TUBE
δp = PRESSURE FLUCTUATION IN TORR AVERAGED OVER L

GAS NOISE IN BURST SEARCH

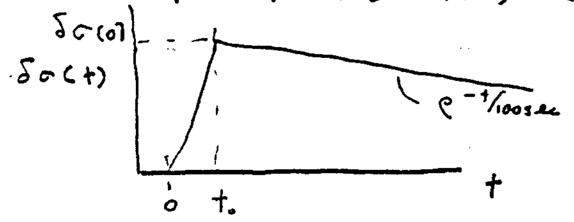
$$\delta\sigma < \frac{h_{RMS}\, L}{2\pi\alpha} \left(\text{mol}/\text{cm}^2\right) \qquad \Delta N = \delta\sigma\, A \quad (\text{mol})$$

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

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

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

PRINCIPAL GROUND STATE ELECTRONIC TRANSITIONS

OSCILLATOR STRENGTH ASSUME $f = 0.1$

MOLECULE	λ (Å)	ν (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	1.5×10^{-13}
H_2O	1450 → 1860 MANY STRONG LINES	53760 → 68965	4.4×10^{-13}

ABSORPTION IN COLUMN

2 COMES FROM DOUBLE PASS

$$I(\lambda_0, 2\ell) = I_0(\lambda_0)\, e^{-2Q_j(\lambda_0)\,\sigma_j \frac{\Delta\nu\,(\text{RADIATIVE})}{\Delta\nu\,(\text{DOPPLER})}}$$

$Q_j(\lambda_0)$ RESONANCE CROSS SECTION OF MOLECULE SPECIES j cm^2

σ_j COLUMN DENSITY OF MOLECULAR SPECIES j mol/cm^2

	AVERAGE PRESSURE $\langle P \rangle$ TORR	AVERAGE COLUMN DENSITY $\langle \sigma \rangle$ mol/cm^2	TOTAL ABSORPTION AT λ_0 db	LINEWIDTH (ESTIMATED) $\Delta\nu$ MHz (FN)	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}	25	124	3230

EXCEPT FOR HYDROGEN, 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 h_{rms} LIMITING BURST
SINCE LEVELS ARE ALL COMPARABLE USE
N_2 BURST AS SAMPLE

CHANGE IN DETECTED POWER DUE TO COLUMN DENSITY FLUCTUATION $\Delta\sigma$

$$\frac{\Delta I}{\Delta\sigma} = -\eta I_0 \, 2Q \frac{\Delta\nu_{RAD}}{\Delta\nu_{DOPPLER}} e^{-2Q\sigma\frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}}} = -\eta \, 2Q \frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}} I(L)$$

SHOT NOISE $\dot{n}^2(f) = 2\eta\dot{N}$

$\dot{n}(f)$ = SPECTRAL DENSITY OF PHOTON FLUCTUATIONS
$\dot{N}$ = AVERAGE PHOTON RATE = $I(L)/h\nu$

SHORTEST INTEGRATION TIME $t_{INT} \simeq 1$ sec

$$\Delta n_{SHOT} = \sqrt{2\eta\dot{N}/t_{INT}}$$

FOR SIGNAL/NOISE OF 1

$$\Delta n_{BURST} = \Delta n_{SHOT}$$

$$2\eta Q \frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}} \dot{N} \Delta\sigma = \left(\frac{2\eta\dot{N}}{t_{INT}}\right)^{1/2}$$

$$\dot{N} > \frac{1}{2\eta\left[Q\left(\frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}}\right)\Delta\sigma\right]^2 t_{INT}}$$

FOR N_2 $Q\frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}}\Delta\sigma = 1 \times 10^{-8}$

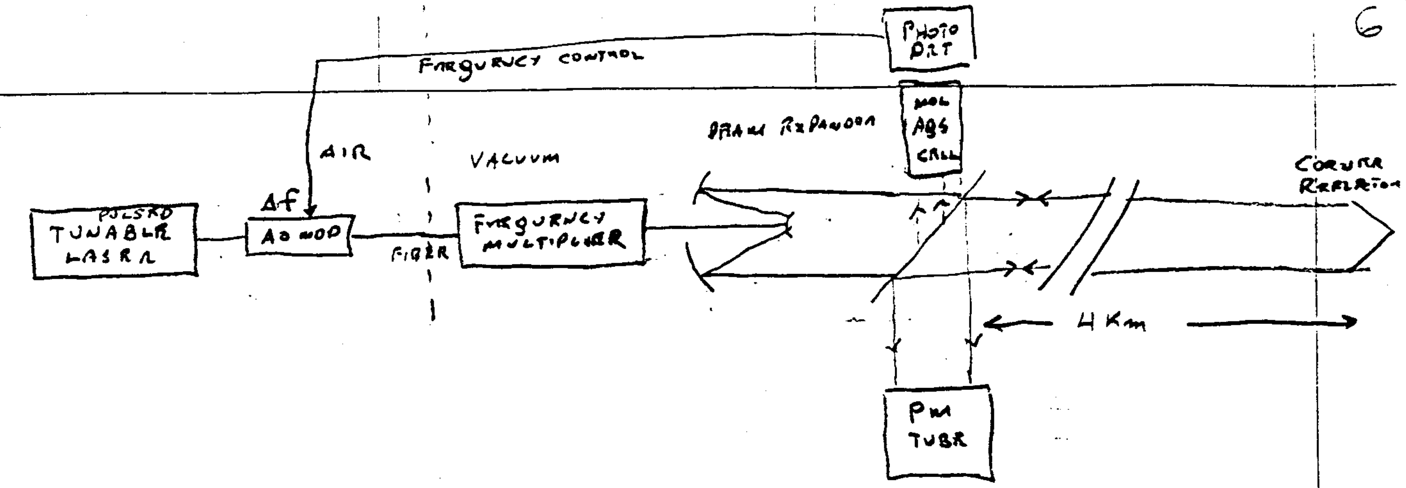
$\dot{N} > 7 \times 10^{15}$ /SEC $P = h\nu\dot{N} = 10$ MILLIWATTS

SYSTEM USED AS A COLUMN DENSITY MONITOR FOR SPECTRAL DENSITY

$$\sigma(f) \sim \left(\frac{f}{2\eta\dot{N}}\right)^{1/2} \frac{1}{Q\frac{\Delta\nu_{RAD}}{\Delta\nu_{DOP}}} \simeq 4 \times 10^5 f^{1/2} \quad (\text{mol}/\text{cm}^2\,\text{Hz}^{1/2})$$

OR PRESSURE MONITOR

$$\langle P(f)\rangle_L \simeq 3 \times 10^{-17} f^{1/2} \quad \text{TORR}/\text{Hz}^{1/2}$$



CONCEPT FOR METHOD 2
ABSORPTION MEASUREMENT
ROOM NEEDED IN LIGO
BEAM SIZES ~ 2.8 cm
FIBER COUPLING

1 METER x 1/2 x 1/2 VOLUME IN SOME TANK

2.8

Cosmic ray muons in ligo

Michael. Burka

8 March 89

1 Conclusion

A random cosmic ray muon which interacts with a ligo mass deposits insufficient energy to be a significant noise source. Therefore, it is not necessary to surround the ligo masses with particle detectors. Large numbers of muons from extensive air showers can impart enough momentum to a mass to mimic a burst signal. The rate for such events is likely to be a few per year. Therefore, detectors capable of resolving muon showers are required. Since the typical muon shower extends from tens to hundreds of meters laterally, every building which contains suspended masses will require a muon shower detector. These detectors need not be elaborate, but they will have to be within ten to twenty meters of the mass chambers, and they will have to be capable of fast timing and crude energy resolution.

2 Energy deposition in a ligo mass

Table 1 shows the parameters used in the calculation of the displacement spectral density resulting from a single muon incident on the mass along the direction of maximum displacement sensitivity. The calculation is done for two masses, one small and one large. Most of the cosmic rays which reach sea level are muons. A relativistic muon will deposit approximately 5 MeV of energy per g/cm^2 of column density. Non-relativistic muons have too little energy to affect us, even if they stop in the mass and impart all of their momentum to it. Muons incident at other angles have a correspondingly smaller displacement spectral density.

	Small mass	Large mass
Density ρ	3 g/cm^3	3 g/cm^3
Volume V	3×10^3 cm^3	3×10^5 cm^3
Mass m	9×10^3 g	9×10^5 g
Path length l	15 cm	70 cm
Cross sectional area A	200 cm^2	4.5×10^3 cm^2
Column density σ	45 g/cm^2	210 g/cm^2
Energy deposited E_{dep}	225 MeV	1 GeV
Momentum deposited p_{dep}	1.2×10^{-14} g·cm/s	5.3×10^{-14} g·cm/s
Suspension resonance f_0	1 Hz	1 Hz
Displacement Δx	2.1×10^{-19} cm	9.4×10^{-21} cm
Displacement spectral density $x(f)$	$\frac{2.1\times10^{-19}}{f^2}$ cm·Hz$^{1/2}$	$\frac{9.4\times10^{-21}}{f^2}$ cm·Hz$^{1/2}$

Table 1.

3 Interaction rate and muon shot noise

The flux of penetrating muons from near the zenith at sea level is

$$j(\theta = 0, \phi) = 8 \times 10^{-3} \quad cm^{-2} \cdot s^{-1} \cdot sr^{-1}.$$

θ and ϕ are the zenith and azimuthal angles, respectively. Away from the zenith, the flux falls off as $\cos^2\theta$. Thus, the total flux of muons from above is 1.3×10^{-2} cm^{-2}·s^{-1}. Using the cross sectional areas of Table 1, the hit rates for the small and large masses are 2.6 hits/s and 59 hits/s, respectively.

An upper limit for the displacement spectral density due to the Poisson statistics of the muon hits is given be

$$x(f) = \frac{p_{dep}\frac{dn}{dt}^{1/2}}{m\pi^2 f^2} \quad cm/Hz^{1/2}.$$

This is an upper limit because it neglects the fact that nearly all of the momentum deposited by muons will be directed transverse to the optic axis, because the muon arrival directions are strongly clustered around the zenith. The formula yields displacement spectral densities of $\frac{2.2\times10^{-19}}{f^2}$ cm/Hz$^{1/2}$ for the small mass and $\frac{4.6\times10^{-20}}{f^2}$ cm/Hz$^{1/2}$ for the large mass. Neither of these spectral densities is significant in terms of the advanced detector sensitivity goals.

4 Extensive air showers

The muon component of an air shower constitutes a relativistic "pancake" with a thickness of 3-4 meters and a lateral extension in the tens to hundreds of meters. Such a pancake will traverse a ligo mass in a time of order 10 nanoseconds, so it constitutes an impulsive force. As will be shown below, only the highest energy showers can affect the ligo.

The burst sensitivity goal of the advanced detectors is assumed to be $h(f) = \frac{10^{-23}}{\sqrt{f}}$ in the region of 10 to 100 Hz, and $h(f) = 10^{-25} \times \sqrt{f}$ above 100 Hz. At 100 Hz, this corresponds to a displacement of 4×10^{-19} cm in a bandwidth equal to the frequency. For a shower to cause this displacement at 100 Hz, the necessary number of particles interacting with the mass is 3.8×10^3 for the small mass, and 8.6×10^4 for the large mass. We approximate the shower as having a uniform flux over a circular area of 100m, so the area of the shower is 3×10^8 cm^2. Dividing the shower area by the area of the mass yields $N_{sh} = 5.7 \times 10^9$ for the threshold of sensitivity for both the small and the large masses. N_{sh} is a minimum, so the rate must be integrated over all N greater than N_{sh}. A shower with this many particles at sea level corresponds to an incident primary of approximately 5×10^{18} eV. The rate of occurrence for showers with N greater than or equal to $N_{sh} = 5.7 \times 10^9$ is approximately 1.4×10^{-17} cm^{-2}· s^{-1}· sr^{-1}.

SHOULD USE h_{RMS} IN THESE CALCULATIONS

Assuming that the directions of origin of the showers lie within one steradian, an event rate is obtained by multiplying the shower occurrence rate by the area of the shower. The event rate is 4.2×10^{-9} s^{-1}, or one per mass per decade. This rate is probably an over-estimate, since most showers will come from near the zenith, where they will have a minimal effect upon the receiver.

5 Summary

The displacement due to the interactions of random muons with the ligo masses is not an appreciable noise source. Clusters of muons from extensive air showers could mimic a burst. A calculation of the rate of such events has been done using many approximations, some pessimistic estimates, and some optimistic estimates. The conclusion is that muon showers large enough to mimic a burst may occur at the rate of a few per year, and so a shower detection system is needed as a veto. Due to the lateral dimension of these showers the particle detector need not be located directly atop each ligo mass, but can be located within ten or twenty meters. One detector per site is insufficient; each building containing masses must have one. The detectors will need crude energy resolution and fast-timing capability in order to discriminate between high energy showers and the random background.