

# A Barometrically Isolated Differential Calorimeter with Micro-Kelvin Resolution: a Feasibility Study for the Investigation of Non-Local Thermal Effects in Early “Ether Drift” Interferometers

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## *Abstract*

Micro-kelvin resolution of temperature measurement in atmospheric gas is shown to be achievable provided the sample is isolated thermally, electrically and barometrically from the environment. Such high-resolution measures should permit the investigation of thermal effects mediating the small signal residuals seen in historical data from ether-drift interferometers. The proposal of Consoli & Pluchino (2018) that small thermal gradients may result from a non-local effect brings the discussion into the framework of contemporary quantum physics and distances it from the discredited notions which motivated the original experiments.

## *Introduction*

This report addresses the practicalities of measuring the temperature of gases with micro-kelvin ( $\mu\text{K}$ ) precision, with a view to testing the hypothesis that the small signals in data from the late 19<sup>th</sup> and early 20<sup>th</sup> century ether-drift experiments were thermal effects. The signal residuals observed in such studies with Michelson interferometers were regarded by their original authors as instrumental systematics which should diminish with subsequent improvements in equipment design.

The exception was Dayton C Miller, who carried out extensive work in the 1920s and 1930s with a gigantic instrument (Miller, 1933). He believed that the small drift velocities implied by his data (substantially less than the orbital velocity of the earth) were the result of absolute motion, partly suppressed by the ether being “dragged” by the mass of the Earth. Shankland *et al.* (1955) concluded that Miller’s results were thermal artefacts, while Roberts (2006) argued that the data were merely random noise, massaged by the processing algorithm into a semblance of the desired signal. Manley (2019) used modelling and variance analysis to conclude that Miller’s data indeed contained a statistically significant signal, but with a spectral composition differing from that predicted by ether theories.

Consoli & Pluchino (2018), analyzing data from six ether-drift experiments, 1887-1930, found a consistent pattern, related to the refractive index of the gas (atmospheric air or helium) present in the optical path. They propose that the signals were caused by a temperature differential of  $0.26 \pm 0.06$  mK between the orthogonal limbs of the interferometers, the temperature gradient resulting from non-local coupling to the quantum-mechanical vacuum, thus revealing a cosmic vector (Consoli *et al.*, 2013, 2018). This proposal brings the effect into the framework of contemporary quantum physics and distances it from the discredited notions which motivated the original experiments. Importantly, the proposal of Consoli and colleagues raises the possibility of experimental tests with modern equipment.

Contemporary studies with resonant cavities excited by laser radiation in vacuum, e.g. Nagel et al. (2015), have residuals down towards the  $10^{-18}$  level. Testing the effects of introducing a gas into the cavities seems a logical step, though by no means as straightforward technically as it might first appear.

Another possible attack on the problem would be the direct measurement of gas temperatures. Quantitating differences as small as 0.26 mK, with the precision necessary to provide convincing data, is not a trivial task however. Worse, a modern laboratory may not be able to house equipment with the large physical dimensions of the historical interferometers. A smaller apparatus may damp the temperature differentials by proximity of the test gas to the solid walls of the containment.

In this report, we demonstrate temperature measurements with micro-kelvin resolution of an isolated gas sample in a differential calorimeter. Such resolution, some two orders of magnitude better than the 260  $\mu$ K signal found in the analysis of Consoli *et al.* (2018), suggests the practicality of a direct test for their hypothesis.

### ***Characteristics of the Expected Signal***

Any experiment struggling for resolution at the limits of its engineering can benefit from processing the signal in the frequency domain. High-pass filtering (rejecting low frequencies) may help reduce long-term drift, while low-pass filtering (rejecting high frequencies) will reduce thermal noise originating in the transducers and amplifiers. The design of such filtering circuitry must be matched to the characteristics of the signal.

Of the several attempts to measure an “ether drift” using a Michelson interferometer in the late 19<sup>th</sup> and early 20<sup>th</sup> centuries, that of Miller (1933) is the best documented, both in terms of the volume of data and the descriptive detail on the method of data acquisition.

The optics of Miller’s instrument were carried on steel girders 4.3 m long, with multiple reflections providing an effective limb length of 32 m. The shifts in the interference pattern on rotation of the instrument were typically about one tenth of a fringe in amplitude (an order of magnitude less than expected for the orbital velocity of the Earth according to the ether theory of the 19<sup>th</sup> century).

The machine, weighing over 1200 kg, was supported by a wooden float in an iron tub containing 275 kg of mercury, allowing nearly frictionless rotation. Once set in motion, the instrument would continue rotating with a period of around 50 seconds during a set of observations taken over half an hour. Sixteen readings were recorded in each rotation, at intervals of about 3 seconds. The desired signal was at the second harmonic of the rotation frequency: a period therefore of about 25 seconds.

For a modern experiment to reproduce the effect seen in Miller’s work, the recording system must therefore preserve data from at least a frequency corresponding to the 25 second period, to above its Nyquist sampling limit of 12.5 seconds (6.4 mHz – 12.8 mHz). Time constants of 100 seconds (high pass, 1.6 mHz) and 1 second (low pass, 160 mHz) should therefore be satisfactory to limit drift and thermal noise in the signal, while preserving its essential information.

### ***Temperature Measurement***

Modern electronics provides three convenient technologies for measurement of temperature: thermocouples, thermistors and solid-state temperature reporter devices.

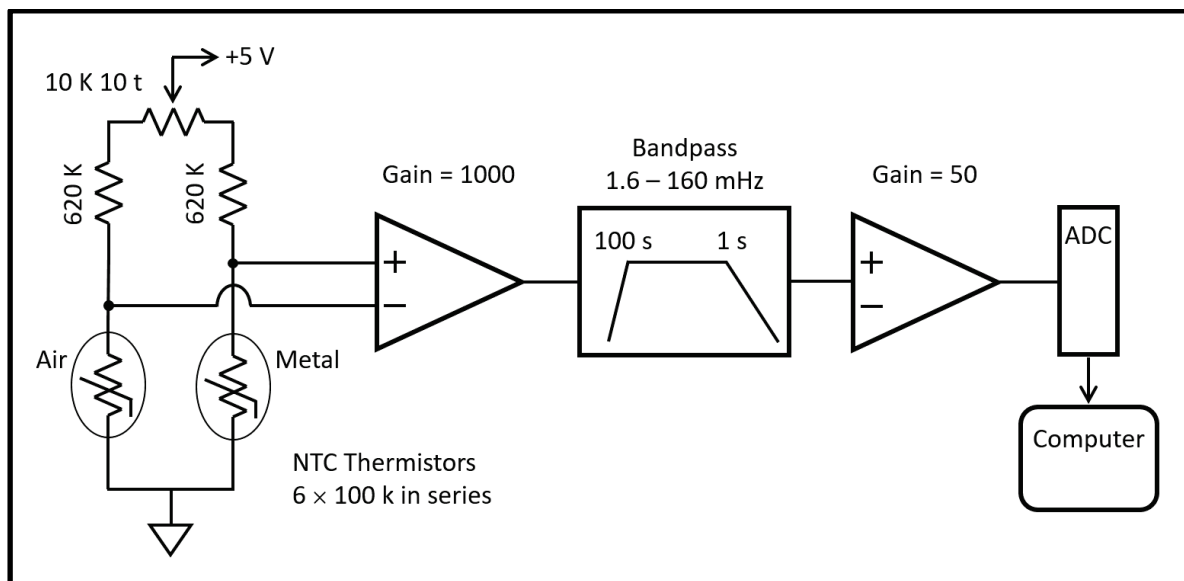
The National Semiconductor type LM335 integrated circuit acts as a 2-terminal Zener diode, reporting absolute temperature as a voltage, at 10 mV/K, over a range of -40 to +100 °C (233 to 373 K). These devices are ideal for measuring the temperature of ambient air, water baths or metal parts. Micro-kelvin resolution, however, is unobtainable. In our

tests of these devices, noise measured around 3  $\mu\text{V}$  RMS, corresponding to a temperature fluctuation of 300  $\mu\text{K}$ , with the spectrum dominated by a  $1/f$  component below a corner frequency of about 100 Hz.

Thermocouples, fabricated as welded junctions of dissimilar metals, generate a DC voltage with respect to a device at a different temperature, typically of a few tens of microvolts per kelvin. The popular type K (alloys of chromium, nickel and aluminium) has a sensitivity of 41  $\mu\text{V}/\text{K}$  at room temperature. It would require an array of 50 such devices (25 at each of the “hot” and “cold” specimens) to yield a sensitivity around 1  $\text{mV}/\text{K}$ . Nano-volt measurements would thus be required to achieve temperature resolution of micro-kelvins. Commercial nano-volt meters are costly and somewhat challenging to operate.

In this study, we chose to use thermistors, which are thermally-sensitive resistors. Those designed for temperature measurement are typically fabricated from ceramic materials encapsulated in glass or epoxy resin and have a negative temperature coefficient (NTC) at room temperature of around 4 percent change in resistance per kelvin. Maximizing thermal sensitivity while minimizing self-heating requires a high resistance.

In the studies reported here, six type RN3446 Glass 100  $\text{k}\Omega$  NTC thermistors<sup>1</sup> were connected in series for a total resistance of 600  $\text{k}\Omega$  and fed with a current of 4  $\mu\text{A}$ , thus achieving a thermal sensitivity of 100  $\text{mV}/\text{K}$ . With dissipation of 1.6  $\mu\text{W}$  per device, self-heating in still air was calculated from the manufacturer’s data to be 1.6  $\text{mK}$ . The time constant of the thermistors for recording temperature changes in still air was specified as 12 seconds.



Two thermistor arrays were connected in a bridge configuration to record the temperature difference between the air sample and a thermal mass (metal heat-sink), acting as a stable reference. A ten turn potentiometer was used to null the bridge.

An AD627 instrumentation amplifier, chosen for its low noise with high-impedance sources, was set to a voltage gain of 1000. A filter block followed, with a high-pass time constant of 100 seconds (second-order Butterworth, 1.6 mHz) to suppress drift and a low-pass time constant of 1 second (first-order Bessel, 0.16 Hz) to reduce electronic noise. A further gain of 50 yielded a sensitivity of 5  $\text{mV}/\mu\text{K}$ , allowing an analog-to-digital converter acquiring 10-bit data over a range of 5V to achieve a resolution of 1  $\mu\text{K}$ . Technical details of the circuitry are given in the Appendix.

<sup>1</sup> Jaycar Electronics, 320 Victoria Road, Rydalmere, NSW, 2116, Australia. Web: [www.jaycar.com.au](http://www.jaycar.com.au)

## *Thermal Isolation from the Environment*

Miller's data has been interpreted in the mainstream literature as artifacts generated by thermal effects. Any modern experiment will require thermal isolation from environmental influences, not only to improve the quality of the data, but to achieve any credibility. The choice is between active and passive strategies.

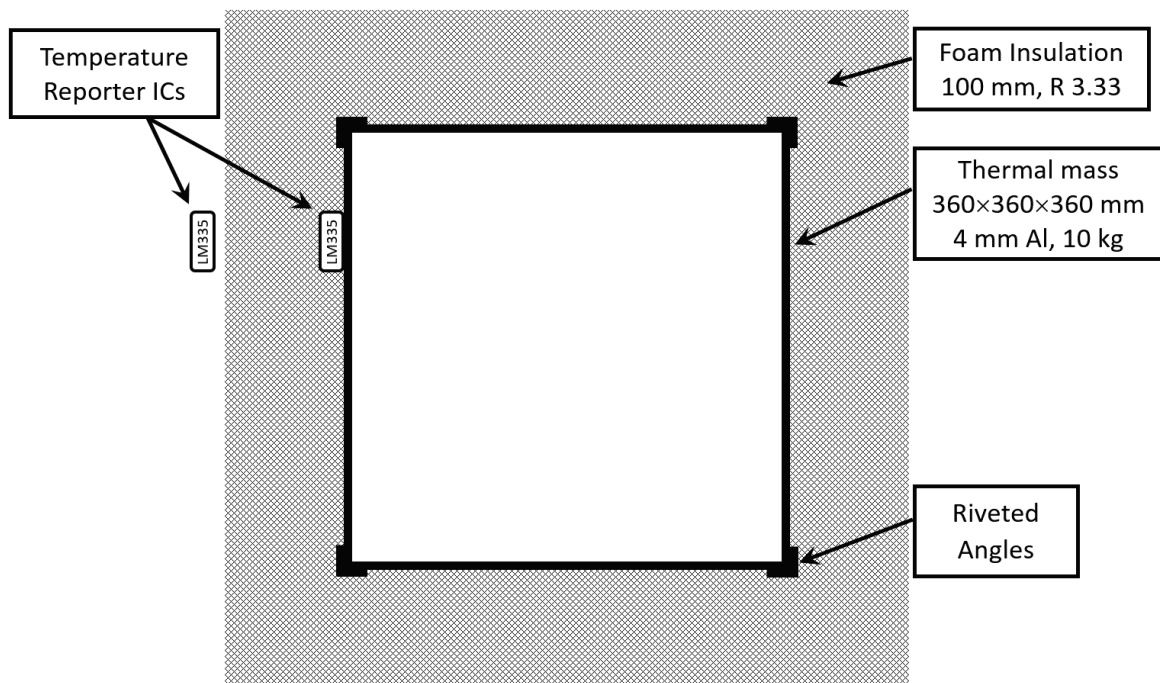
Active control, such as a thermostat-regulated water bath, requires precision measurement of temperature to switch the heating elements, and achieving micro-kelvin stability would be a considerable engineering challenge. Passive shielding, which aims to limit the rate of change of temperature in the apparatus – rather than hold it absolutely constant – is far less problematic.

Passive shielding from the environment may be achieved by combining two elements: an insulating layer to reduce heat transfer, and a thermal mass of substantial heat capacity to ensure that thermal fluctuations in the apparatus are slow and therefore approximately linear during the 10 – 100 seconds needed to record observations.

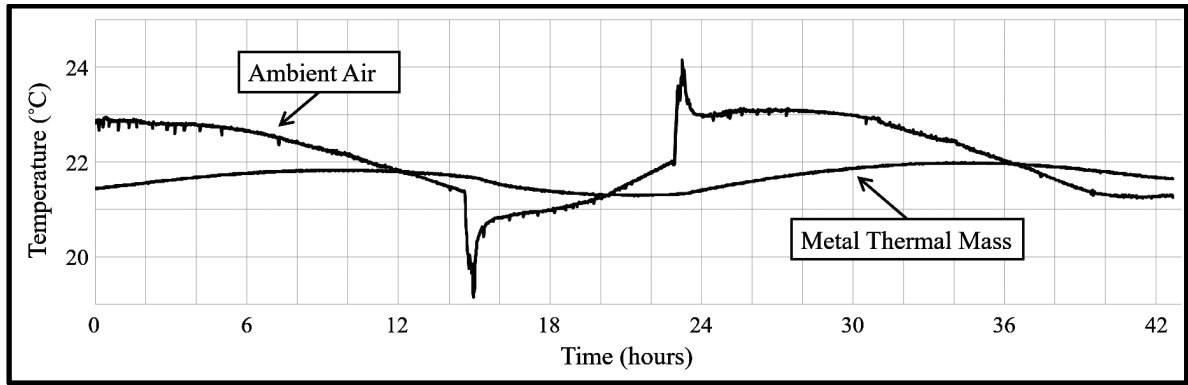
Miller used cork, a material which is variable and poorly documented, for insulation. Among contemporary materials, polystyrene foam insulation board, a commercial building material, has extremely low thermal conductivity and high reproducibility between samples. For the thermal mass, water has the highest heat capacity among common substances, but metal is much more convenient in practical use.

We chose the passive strategy, with foam insulation and a metal thermal mass.

A cubical box of sides 360 mm was fabricated from 4 mm aluminium plate, joined with angle extrusions which were riveted to ensure electrical and thermal conductivity. The mass of the box was 10 kg and the calculated heat capacity was 9 kJ/K. It was surrounded by 100 mm of foam insulation board with a conductivity of 0.030 W/m/K (R value of 1.0 for 30 mm), giving a calculated thermal time constant circa 10 hours.



The graph following shows temperatures of the atmospheric ambient and the aluminium metal recorded every 50 seconds over a period of 42 hours using LM335 ICs.

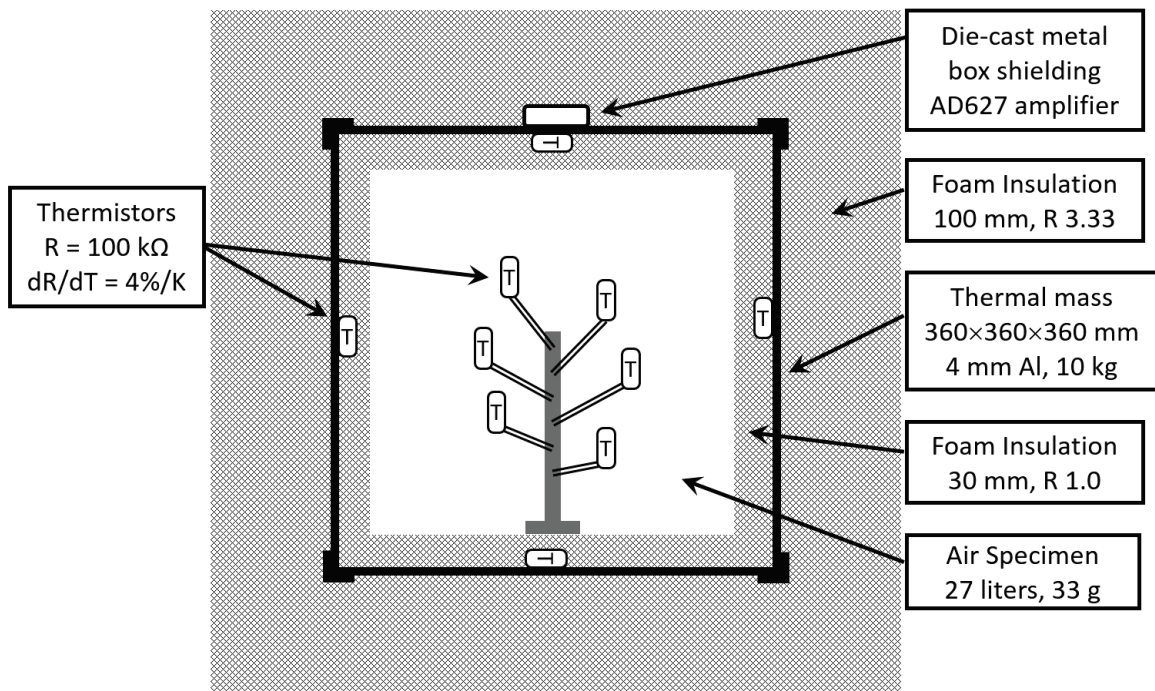


The diurnal temperature cycle is apparent. Opening windows into the laboratory on a cool morning, and later on a warm afternoon, induced sudden large changes in the temperature of the room air. The temperature of the metal box changed only slowly and smoothly, however. We conclude that such thermal isolation would be satisfactory for protecting apparatus recording small temperature gradients over periods of a few tens of seconds.

### *Influence of Micro-barometric Fluctuations*

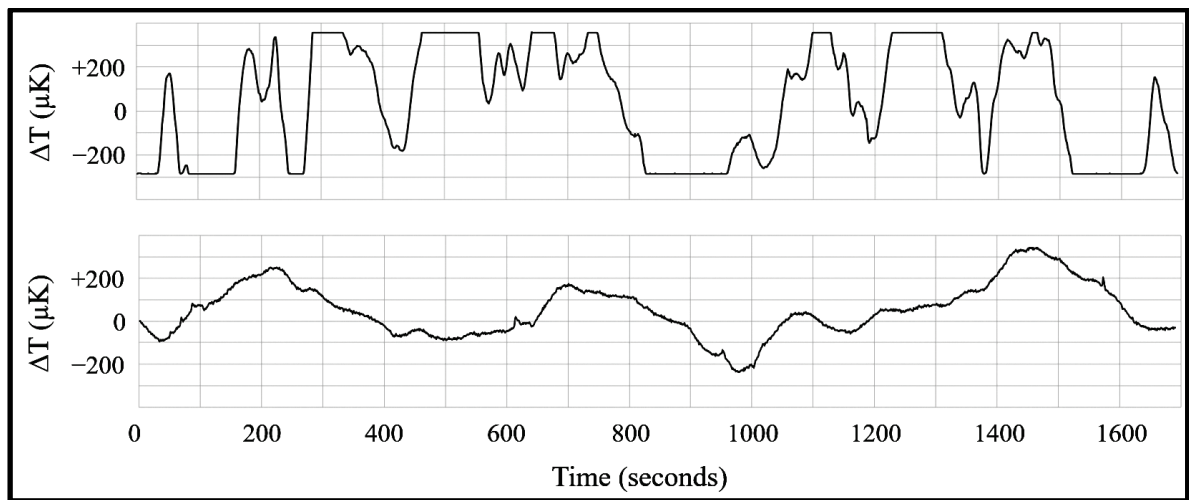
It is well known that atmospheric pressure fluctuations on a scale of micro-bars occur in time frames of seconds to minutes, particularly due to winds interacting with building structures and in association with atmospheric disturbances such as rainfall and thunderstorms. Adiabatic compression of air, which approximates a diatomic gas, will result in changes in temperature nearly proportional to the change in pressure.

The temperature difference between an air sample and the metal thermal mass was recorded at one second intervals over a half-hour period with the apparatus configured as in the diagram below. The air specimen was vented to the atmosphere through a plastic tube of length 1 m and internal diameter 2 mm.





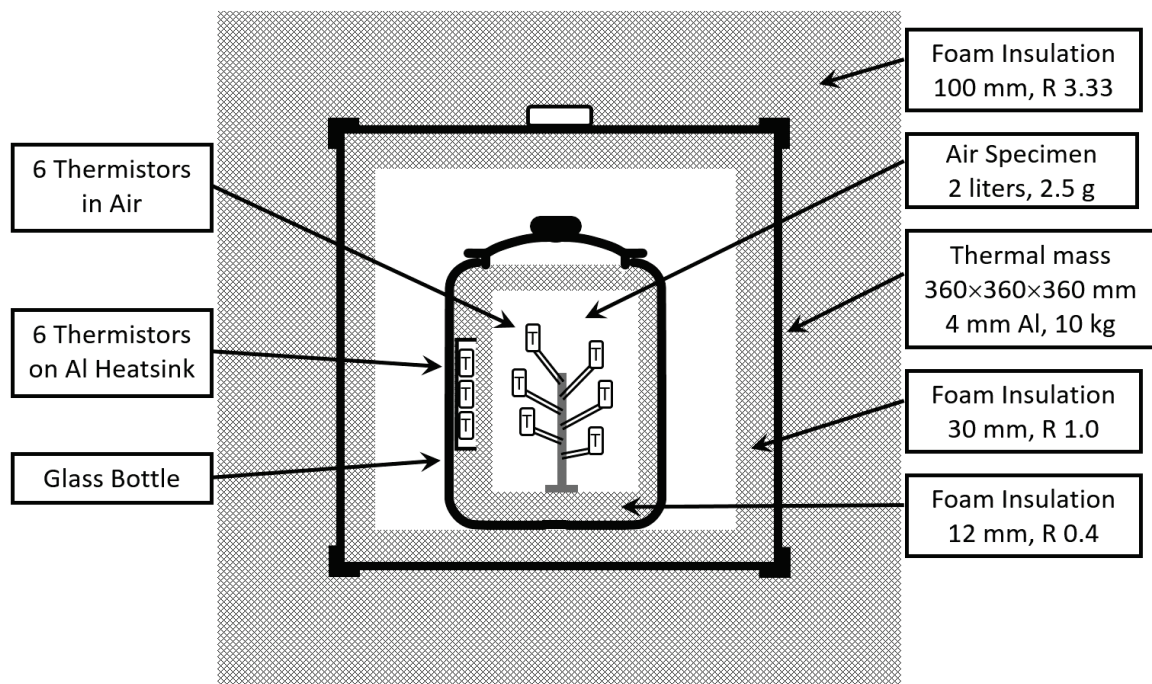
Temperature fluctuations, which appeared to be related to air movement, were noted. In the figure following, the upper trace was recorded on a windy afternoon, the lower on a calm morning.



The instability, amounting to hundreds of micro-kelvins, renders such a setup quite unsuitable for precision measurements.

### *A Barometrically Isolated Differential Calorimeter*

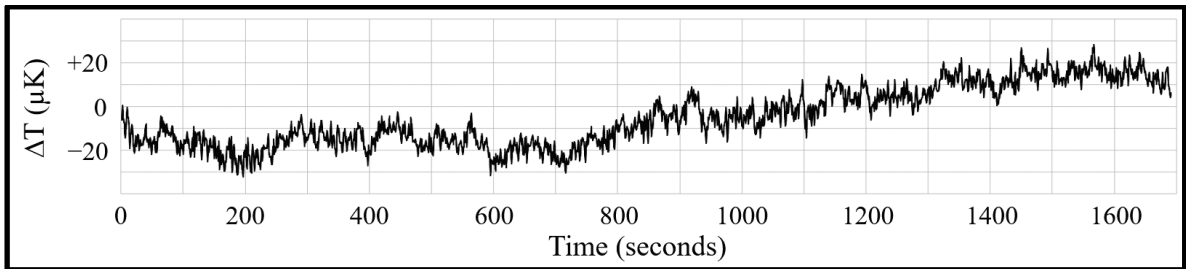
It is apparent that the test gas must be isolated from fluctuations in barometric pressure. An enclosure with rigid walls is therefore required. Metal panels are too compliant, unless they are enormously thick and heavy. Glass, however, is very rigid and glass-to-glass joints can conveniently be sealed with epoxy resin adhesive.



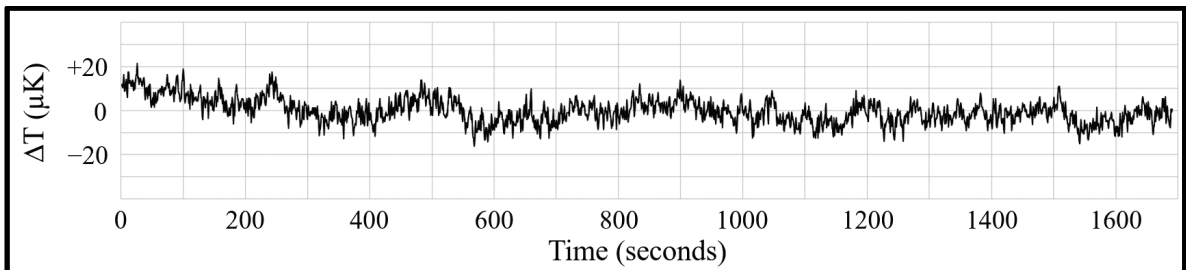
A 4-liter glass bottle with a glass lid was lined with foam insulation, which was cut to shape and installed as tight-fitting sections. An aluminium U-section extrusion, 12 × 12 mm and 100 mm long, served as a 15 g thermal mass to which the 6 reference thermistors were bonded with epoxy resin. The enclosed air volume was 2 liters, the air specimen

thermistors being supported on their  $30 \times 0.25$  mm wires, soldered to a central support of copper-fiberglass printed circuit board.

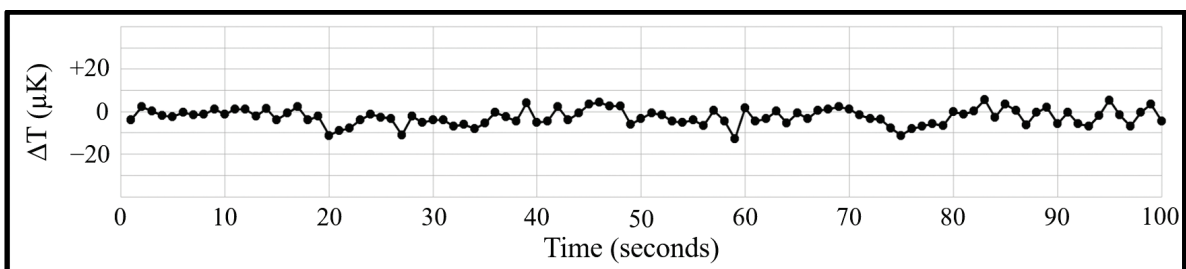
With the air specimen enclosed in a rigid container, the stability of the recording was greatly improved. The trace following was recorded over a half-hour period, without high-pass filtering.



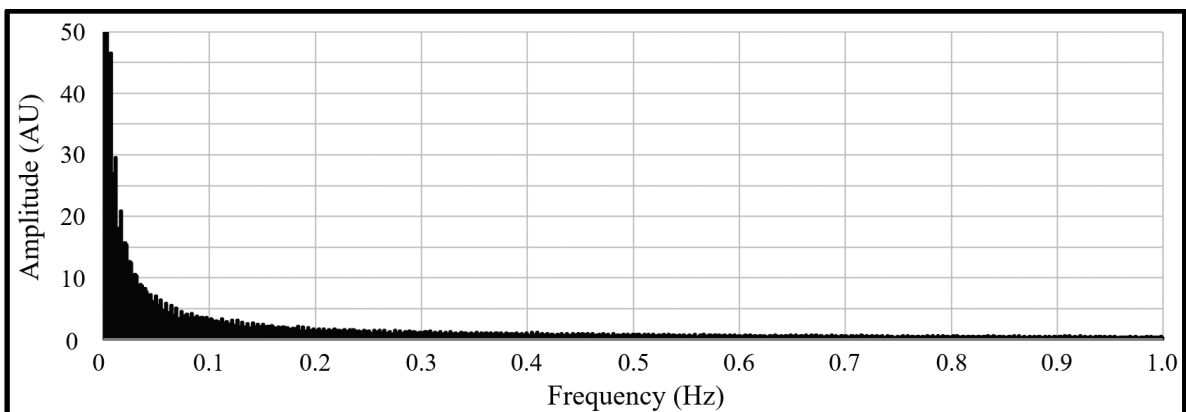
Some slow drift was visible, though the signal was fairly stable over any 100 second interval. With the high-pass filter (time-constant 100 seconds) in the electronic circuit, long-term stability was improved, drift over a half-hour recording being within a  $20 \mu\text{K}$  window, and noise about  $10 \mu\text{K}$  peak-peak.



Expanding the trace over a 100 second range revealed the spectral structure of the signal, dominated by low frequency components (below).



In the graph following, the Fourier transform of the signal shows the dominance of the  $1/f$  (reciprocal frequency) component in the noise spectrum.



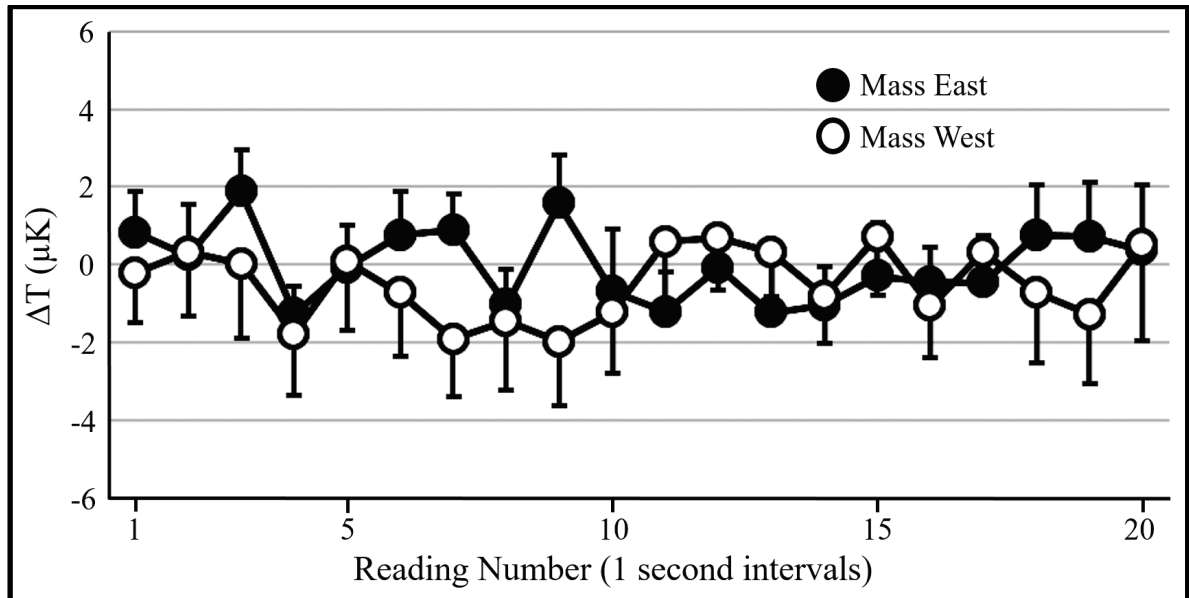
Such a spectrum indicates that less will be gained by extensive averaging of repeated measurements than might be expected for a purely random noise signature with equal energy per unit bandwidth.

### *A Sham Experiment*

To determine how such a system might function in an actual investigation, we carried out a sham study, recording 20 readings at intervals of 1 second for each of two test conditions, repeating the cycle ten times, for a total of 400 readings.

The test conditions were the placement of a 50 kg mass (a domestic wheeled garbage bin half full of water) on alternate sides of the apparatus, the separation of mass and test gas specimen being approximately 650 mm center-to-center.

The standard deviation of individual readings was around 5  $\mu\text{K}$ . The graph following shows the means and standard errors of the means of 10 readings of the temperature difference between the air specimen and the reference metal heat sink, for placement of the test mass east or west of the apparatus.



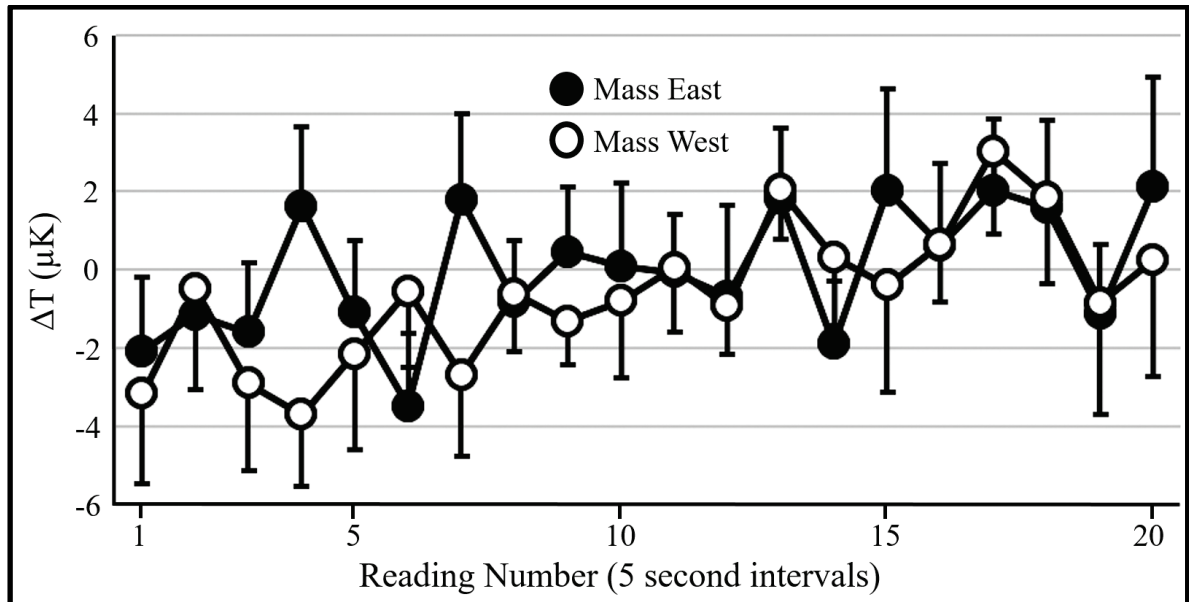
The readings lay within a window of  $\pm 2\mu\text{K}$  and there was no visible trend in the data. Several repetitions of the experiment, summarized in the table following, showed the difference in mean temperatures between placement of the test mass to the east and west, or to the north and south, was up to about 1  $\mu\text{K}$ . In the Null experiments, no mass was placed.

Local Time	Direction	$\Delta T$ ( $\mu\text{K}$ )	SEM
0455	N-S	+1.11	0.89
1130	N-S	+0.93	1.46
1635	N-S	+0.21	1.44
0415	E-W	+0.93	1.55
1100	E-W	+0.20	1.15
1600	E-W	+0.49	0.70
0455	Null	-0.52	0.38
1400	Null	+0.76	0.37



These results were clearly negative for any effect of moving a mass near the apparatus. They indicate the robustness of the equipment and the practicality of resolving signals of a few micro-kelvins in an actual experiment.

Taking readings over a longer time-frame incurred more serious drift, as it was necessary to omit the high-pass filter from the electronic circuitry. An example is shown in the graph following, where 20 readings were taken over a period of 100 seconds.



Some drift was apparent, though there seemed to be no trend in the differences between east and west placement of the test mass. Drift in the measurements was corrected by fitting a linear regression to the entire set of 400 readings and subtracting the values at each time point on the regression line. Although the variance of the data was improved by this manipulation, the results were noticeably more ragged than with the shorter reading time and electronic filtering. Several repetitions of the experiment are summarized in the following table.

Local Time	Direction	$\Delta T$ ( $\mu\text{K}$ )	SEM
0500	N-S	-0.14	0.51
1600	N-S	+3.83	0.54
1620	N-S	-1.41	0.76
0400	E-W	+2.11	0.51
0800	E-W	+1.77	0.70
1420	E-W	+0.26	0.83
1545	E-W	+0.62	0.63

The calculated standard errors of the mean temperature differences convey an unduly optimistic impression of the precision of the data. It is unlikely that any signal smaller than about 5 – 10  $\mu\text{K}$  could be resolved under these conditions, whereas with the shorter reading time a signal of 3 – 5  $\mu\text{K}$  would be clearly visible.

We emphasize that these experiments have no physical interpretation other than as a test of the robustness of the apparatus and of the precision of the gas temperature measurements. In particular, they should not be taken as a test of Miller’s idea that mass would affect the influence of “ether drift” or cosmic vectors on laboratory apparatus.

## Conclusions

Measurement of micro-kelvin temperature gradients in gases is feasible, provided the sample is isolated thermally, electrically and barometrically from the environment of the laboratory. Thus the hypothesis of Consoli and colleagues (2018) will be directly testable with equipment that is less demanding to implement than interferometers or laser-driven cavity resonators. The next step should be the development of a model of the gas-filled optical path in the early “ether drift” experiments. Such a model must be compatible with modern laboratory requirements and permit the necessary degree of isolation of the test gas from the environment.

## References

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## Appendix: Technical Notes

Electronic noise proved to be the limiting factor in our attempt to approach micro-kelvin resolution in the measurement of gas temperature. The thermal (Johnson-Nyquist) noise in the thermistors and their series resistors, which together form a source impedance of circa 300 k $\Omega$ , can be calculated from well-known theory as 0.03  $\mu$ V RMS at 20 °C. Input noise in the first stage amplifier was inevitably larger by orders of magnitude.

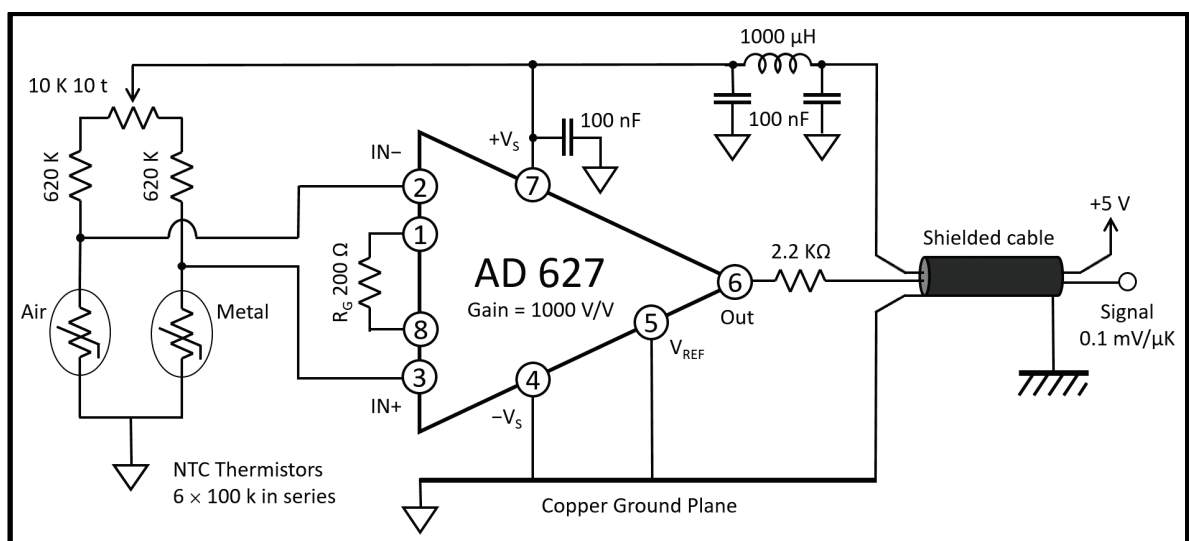
The signals in any practical experiment testing the Consoli hypothesis will be at extremely low frequencies, set by the thermal time-constant of the thermistors and perhaps by the – unknown – physics of the non-local effect. The most troublesome component of the electronic noise is therefore the 1/f noise, and the device must be chosen for the lowest possible corner frequency. Instrumentation amplifiers typically have better performance in this respect than operational amplifiers.

An additional requirement is imposed by the high source impedance of the thermistor array: the amplifier device needs to be chosen for the minimum possible *current* noise, rather

than *voltage* noise. The Analog Devices type AD627 integrated circuit instrumentation amplifier has an excellent current noise figure of 1 pA (p-p, 0.1 Hz to 10 Hz).

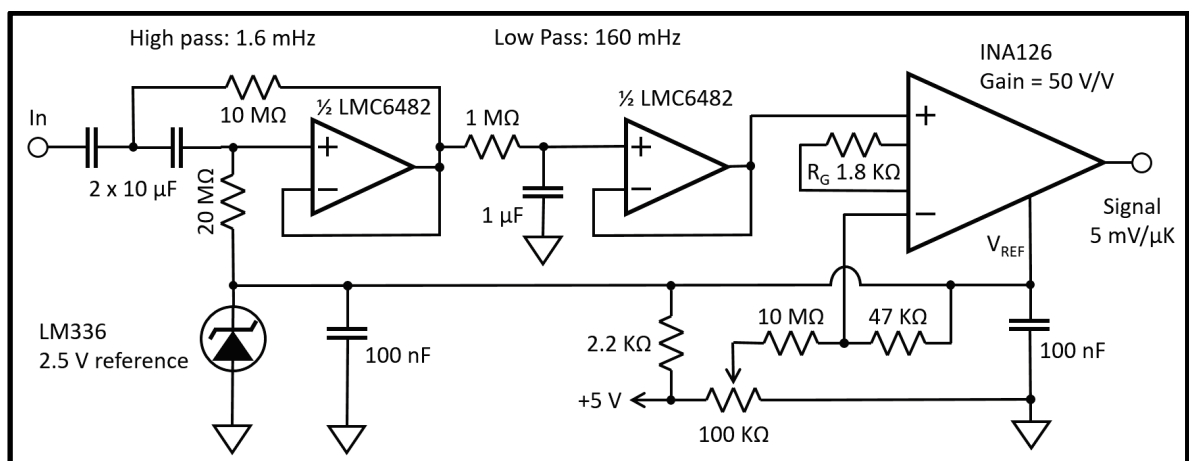
Electromagnetic screening is essential when recording micro-volt signals in a laboratory environment, inevitably pervaded by fields emanating from power mains wiring and electrical equipment. The heavy aluminium box which provided the thermal mass was also an excellent electrostatic screen. It provided no magnetic screening at power mains frequencies, however. While mains interference will be reduced by low-pass filtering later in the signal processing chain, the head-stage can be overloaded by Faraday induction from alternating magnetic fields passing through wiring loops in the transducer array. This problem is addressed by minimizing the area of any loop in the wiring: using twisted pairs or figure-8 flex for connections and keeping the leads of the thermistors closely parallel.

The head-stage was housed in a small die-cast metal box riveted to the aluminium thermal mass. The AD627 was operated on a single-ended 5 V supply, the  $V_{REF}$  terminal tied to ground, and the bridge offset by 2.5 mV to bring the signal output to the mid-point of the supply at 2.5 V.



The filter block and final amplifier stage, with their 5 volt power supply, can be located conveniently distant from the head-stage and calorimeter. The signal, now at millivolt levels, is relatively invulnerable to electromagnetic interference, provided it is transmitted by a shielded cable with a substantial braided outer conductor.

The high-pass filter was implemented as a conventional Sallen-Key configuration with 2<sup>nd</sup> order Butterworth characteristic. The unusual feature was the very long time-constant of 100 seconds, requiring large capacitance and high resistance.



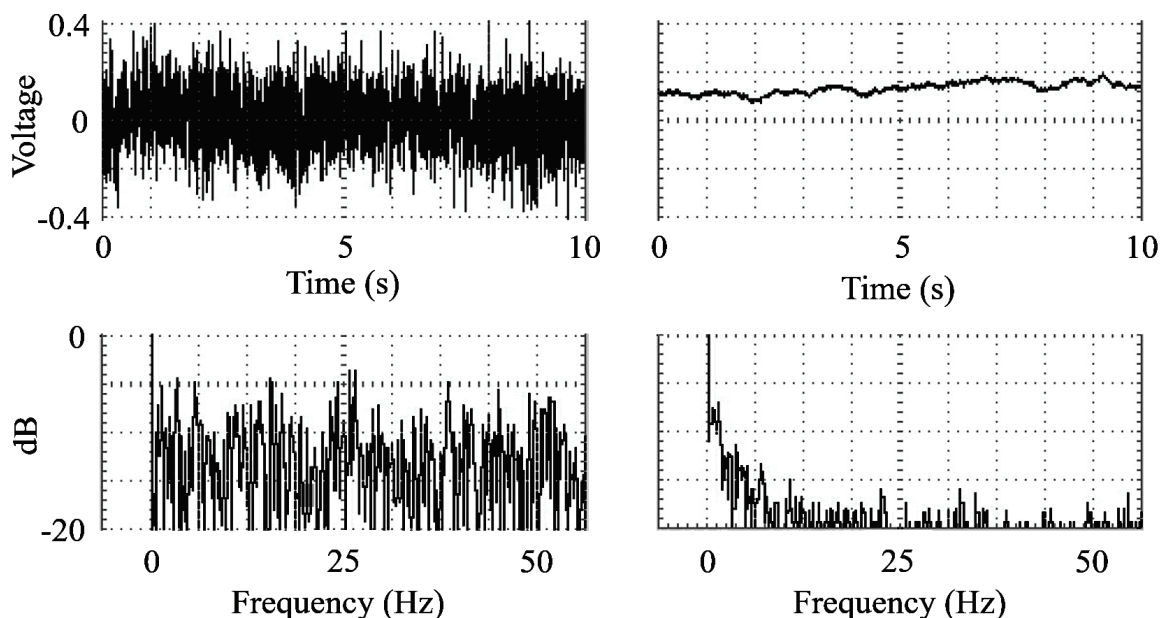
The 10  $\mu\text{F}$  capacitors must be metallized polypropylene, and definitely not electrolytic, which have vastly too much leakage to operate with 10  $\text{M}\Omega$  resistances. The operational amplifier buffer must have extremely high input impedance, a requirement satisfied by the National Semiconductor LMC6482 dual CMOS device.

The low-pass was a simple R-C (1<sup>st</sup> order Bessel) filter.

Final amplification by a factor of 50 V/V, to give a convenient signal for an analog-to-digital converter operating in a 0 – 5 volt range, was provided by a Texas Instruments INA126 instrumentation amplifier. The filter block and final amplifier were referenced to a stable 2.5 V provided by an LM336 reference IC fed with a current of about 1 mA from the 5 V power rail through a 2.2  $\text{K}\Omega$  resistor. A small voltage offset adjustment was provided through a 10  $\text{M}\Omega$  – 47  $\text{K}\Omega$  divider fed from a 100  $\text{K}\Omega$  trim potentiometer across the 5 V supply.

For data acquisition, a microcontroller (such as an Arduino, which has 10-bit A-D conversion onboard) is convenient, requiring only a few lines of program code, without the distraction of the operating system overheads in a full-scale desktop machine.

In the DSO screen-grabs below, the signal is shown without (top left) and with (top right) low-pass filtering. The corresponding spectra (FFT function) are shown below.



Broadband noise dominates the unfiltered signal, while slow drift dominates after filtering. It is notable that the local power mains frequency (50 Hz) was absent from the spectra, being effectively eliminated by the heavy aluminium enclosure and the wiring precautions to reduce the area of loops intersecting alternating magnetic fields.