A Breakthrough in Absolute Barometry

Kevin F Scott, Meteormetrics Limited, Kirklands, Craigend Road, Stow, Galashiels TD1 2RJ UK.
+441312080402 kevin.scott@meteormetrics.com

Abstract

This paper describes a new, patented, Low-Mercury and Zero-Mercury Absolute Barometer. This instrument is designed to replace traditional Fortin & Kew barometers everywhere, drastically reducing the Mercury content or eliminating it altogether, and bringing a new order of precision and accuracy to this well proven barometric principle. In the new instrument, there is still a barometer tube but it is only about 50 mm long overall and a millimetre in diameter. It is rotated on a disk, the same size as a CD, and is equipped with sensors to detect the meniscus to micron precision and the atmospheric pressure is displayed digitally on the disk as it rotates. The result is a compact, absolute instrument, very easy to read, accurate and highly stable. European and US patents have been applied for. Patent Application No EP11162336.9, and US Patent Application Serial No 13/085,747.

Introduction

The entirely new absolute barometer described here has all the great advantages of the Fortin and Kew barometers without the disadvantages. Like the traditional Fortin instrument, the instrument is an absolute barometer, yielding the atmospheric pressure from mass, length and time measurements only. In practice, as in its predecessors, this amounts to some dimensional measurements, a knowledge of the density of a fluid and a knowledge of the acceleration to which the instrument is subject. There is no zero setting, no adjustments to make, no calibration required. As in the Fortin barometer there is a temperature coefficient which can be calculated. This new Absolute Barometer shares with the Fortin another great advantage over semiconductor sensors: it is transparent to the user: The user can see the meniscus and verify that measurements are correct. Many scientists, meteorologists and technicians value this feature of transparency in instruments enormously.

The instrument described here, is, however, physically much smaller than the Fortin instrument, being, typically, about 130mm x130 mm x 90mm overall, compared with a traditional barometer which is over a metre long. Moreover, it need contain no mercury, and even if mercury is used in it, only 500 milligrams of the metal is used compared to the usual payload of the Fortin Barometer of about 1.5kg.

The single greatest disadvantage of the Fortin Barometer - that of uncertainty of the condition of its Torricellian vacuum, during the course of time - is completely overcome in the new instrument. In the course of its normal operation, this Absolute Barometer can determine the residual pressure, if any, in its Torricellian vacuum and can accurately compensate for any inadequacy therein.

The new Absolute Barometer has a tiny barometer tube, but this is mounted on the surface of a rotating disk. (figure 1) The stem of this barometer tube is fitted with an optical meniscus detector or a series of such detectors located at measured distances down the tube. When the disk is rotated, the barometric fluid suffers an increase in acceleration which, if the disk be rotated with sufficient speed, results in the fluid meniscus leaving the top of the closed limb of the barometer tube and moving progressively outwards to pass the meniscus detector(s). If the rotational speed is now reduced, the meniscus moves inwards once again until it reaches the closed end once more. By repeating this cycle continually, and recording the rotational speed at which the fixed meniscus detecting points are crossed, a simple hydrostatic calculation performed by a

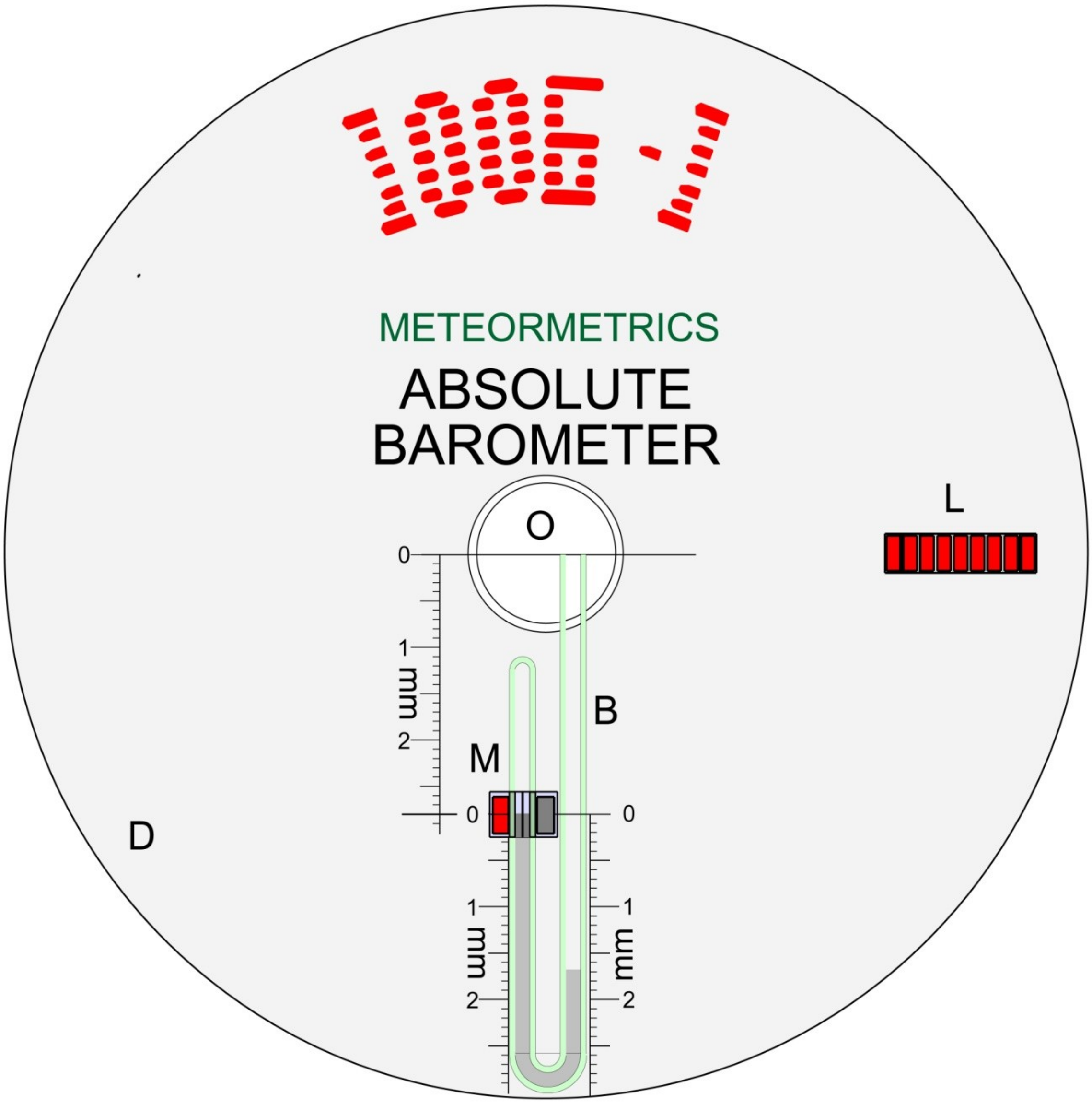

Figure 1 Essential features of the Absolute Barometer

microcontroller on the disk, yields the value of the atmospheric pressure.
A row of light emitting diodes disposed radially on the disk are used to display the current pressure, thus improving greatly on the readability of the Absolute Barometer over the traditional instruments. Finally, so that the user can observe the position of the meniscus, the top surface of the disk is illuminated with light synchronised with the disk rotation speed. It thus appears stationary so that the meniscus may be observed.

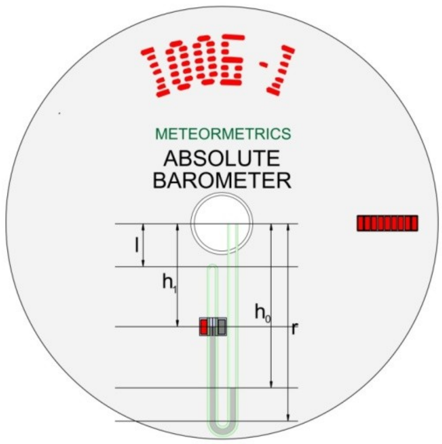

Figure 2 Dimensions for a Single Detector Disk

Theory

If the atmospheric pressure is P_a, and the density of the barometric fluid is ρ, the acceleration to which a Fortin Barometer is subject is *g,* and the height of the fluid column is *h*, we can write,

$$P_a = \rho.g.h$$

Whence, if the disk of the Absolute Barometer under consideration is rotating at an angular velocity of ω and the dimensions are taken as depicted in figure 2, then we can write:

$$P_a = \frac{\rho.(h_0 - h_1)(h_0 + h_1)\omega^2}{2} \qquad (1)$$

If the angular velocity is expressed as S in rotations/sec, equation (1) becomes

$$P_a = 2.\rho.(h_0 - h_1)(h_0 + h_1)\pi^2 S^2 \qquad (1a)$$

If the value of S is determined by the operation of the barometer at the point when the fluid meniscus crosses the meniscus detector (M in figure 1), and the values of the distances h_0 and h_l have been measured, the atmospheric pressure P_a, can be determined.

A correction for the compressibility of the air in the open limb of the barometer tube.

In the Absolute Barometer described, the open limb of the barometer tube extends to the centre of rotation. This is to obviate Bernoulli effects modifying the pressure in the open limb arising from air velocity across it. However, the air in the open limb is subject to considerably greater acceleration than standard gravity. This results in a slight but calculable pressure difference along the length of the open tube.

The variation of atmospheric pressure due to height above sea level is given by:

$$P_a' = P_a e^{-\frac{Mlg}{RT}}$$

Where P_a' is the pressure at height l, P_a is the Pressure at $l = 0$, M is the average molecular mass of atmospheric gases, R is the universal gas constant and T is the absolute temperature.
Substituting the rotational acceleration for g, we obtain

$$P_a' = P_a e^{-2.Mh_0\frac{(h_0+h_1)\pi^2 S^2}{RT}} \qquad (2)$$

Applying equation (2), the magnitudes of the pressures needed to be added to the measured pressure for several different rotational speeds are given in Table 1.

Rotational Speed RPM	Pressure Correction
1000	-0.2mB
2000	-0.7mB
3000	-1.6mB
4000	-2.8mB

Table 1 Pressure correction due to compression in open limb

Correction for variations due to temperature

As in the Fortin Barometer, the variation of the reading with temperature is due to linear and cubical expansion coefficients of the barometer components. Two expansivities need to be considered: (i) the linear coefficient of thermal expansion of the disk along its radius, and (ii) the cubical expansion coefficient of the barometric fluid. In the prototype instrument, the disk material was fibreglass printed circuit board sheet with a specified linear expansion coefficient of 1.5×10^{-5} deg C^{-1}. This was applied to h_l in figure 2 to give a value of $h_1^0(1+T.1.5 \times 10^{-5})$ where h_1^0 is the value of h_1 at 0 C and T is the temperature in degrees C. The volume expansivity of the barometric fluid gave rise to two necessary corrections. The first, as in the Fortin instrument, is the correction for the density of the fluid, ρ, which is replaced by $\rho^0(1-\beta T)$ where β is the volume expansion coefficient of the fluid and ρ^0 is the fluid density at 0 C. The second correction is for the increase in the fluid plug length in the barometer tube arising from its thermal expansion. This decreases the value of h_0, by a factor dependent upon the diameter of the barometer tube. In the prototype instrument described here this coefficient amounted to -1.9833×10^{-4} deg C^{-1}.

From these values, a theoretical thermal coefficient was calculated for the prototype instrument using mercury as the barometer fluid, of 0.908 mB deg C^{-1}. This compared well with the measured coefficient of an uncorrected prototype of 0.907 mB deg C^{-1}.

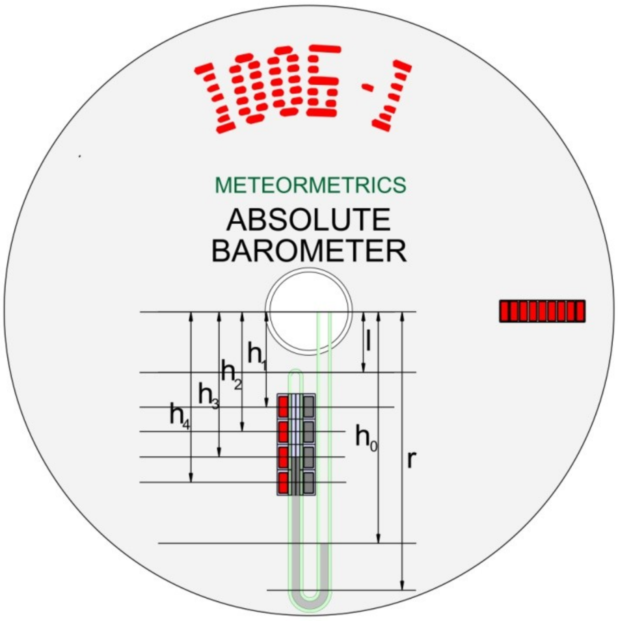

Figure 3 Using multiple meniscus detectors

The use of multiple meniscus detectors to enhance precision.

The use of multiple meniscus detectors provides a number of advantages to the Absolute Barometer. First, it allows a greater precision in measurement per cycle of meniscus travel.

Noting that, because the length of the fluid in the barometer tube is a constant, say, *x*, we can write equation 1a as

$$P_a = 2.\rho.x(x-2h_1)\pi^2.S^2$$

By recording the speed of rotation for each meniscus crossing, the processor can perform a least-squares regression of a plot of the square of the rotation speed against $1/(x\text{-}2h)$ and obtain a gradient of $P_a/2\rho x\pi^2$, from which the best estimate of P_a can readily be calculated.

The use of multiple meniscus detectors can also yield another valuable asset. Since the bore of the barometer tube is known, the volume of the Torricellian space can be calculated for each value of *h*. If the Torricellian vacuum is degraded for some reason, and a residual number of moles of air, *n*, remain in the Torricellian space, in each case that residual gas will exert a pressure of *p*, given by

$$p = \frac{nRT}{(h-l)a}$$

Where *a* is the cross-sectional area of the barometer tube. If there is a residual pressure, the value of P_a in equation (1a) will be modified thus

$$P_a = 2.\rho.(h_0-h)(h_0+h)\pi^2\,S^2 - \frac{nRT}{(h-l)a} \qquad (3)$$

With multiple values of S and h available to the processor, it will be possible to solve for the best value of P_a and *n*, which will give a corrected value for the atmospheric pressure and a quantitative estimate of the condition of the Torricellian vacuum.

Surface Tension Effects

Liquids rise in capillary tubes or are depressed according to the sign and magnitude of the surface tension between them and the glass surface of the capillary. If T is the surface tension, g is acceleration due to gravity, r is diameter of the capillary, d is the elevation of the surface and ρ is the density of the fluid, then

$$d = \frac{2T}{\rho g r}$$

Because the exact value of T depends upon the state of cleanliness of the glass and the purity of the fluid, narrow bore barometers have not been possible because of the uncertainty in the precise correction to be applied. However, in the case of the rotating Absolute Barometer, the value of the acceleration is at least 100 times higher than that of gravity and so the effect of surface tension is reduced by the same factor. This means that, while a Fortin Barometer must have a bore of not less than 6mm, in the case of the rotating instrument, this can be set 100 times lower for the same precision. The bore could thus be reduced to some 60 microns without surface tension effects becoming significant.

Choice of Barometric Fluid

The main requirement of the barometric fluid is low vapour pressure and there are many non-toxic long chain hydrocarbons which will suit this application. Experiments were carried out with Aeroshell 3, aviation lubricant with good results. The pertinent difference between mercury and organic fluids is not in the case of the rotating instrument, the density, but rather the solubility of permanent gases which is rather high in the case of non-polar hydrocarbons. They can be satisfactorily degassed using a vacuum prior to use, and because the diffusion of dissolved gases in hydrocarbons can be very slow, the regassing of the fluids takes place only slowly. None-the-less, the degrading of the Torricellian vacuum does take place with time. Using multiple meniscus sensors as detailed above, can eliminate the otherwise adverse effects of this, and give the instrument a long working life despite it.

Absolute Barometer Design

To transform the theory of this simple Absolute Barometer into a working instrument, the design was resolved into two microprocessor controlled parts: a base unit with a speed controlled motor and a disk with an on-board processor to calculate and display the atmospheric pressure. The base unit was fitted with a magnet which aligned with a Hall-Effect magnetic sensor on the periphery of the disk. This allowed the disk-borne processor to measure accurately the rotational speed of the disk. Similarly, the disk was fitted with a small magnet, with a corresponding sensor attached to the base unit, so that the base processor would also have the rotational speed of the disk available to it.

The base unit processor was programmed to cycle the motor speed linearly between set limits which caused the meniscus to traverse repeatedly a path crossing the meniscus detector. A crossing of the meniscus detector was registered by continually calculating the derivative of the photo-transistor collector current and recording a maximum of this gradient as the meniscus performed its repeated cyclical movement. Each cycle generated two gradient maxima with their corresponding rotational speeds. These values were used to calculate the atmospheric pressure.

The Meniscus Detector

Figure 4 shows the general arrangement. The borosilicate barometer tube T was mounted on an ABS plinth R, on the disk substrate P and arranged to pass between two 0805 surface mount components: an infra-red light emitting diode (IR880 High Intensity Series 170 from OSA Opto Light GmbH) S, and an infra-red sensitive NPN phototransistor (Type OP501 from TT Electronics) N. These two components were soldered to the printed circuit

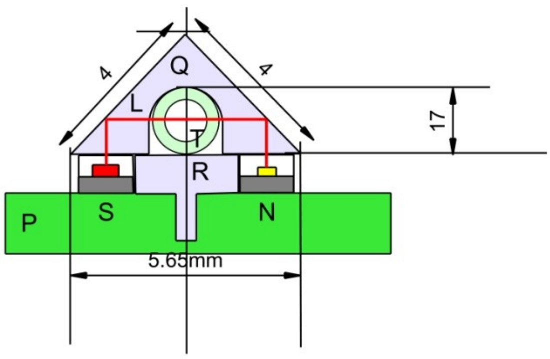

Figure 4 Meniscus Detector

board such that their radiating or detecting elements were directed along lines normal to the surface. The emission from the LED and the detection of the phototransistor were constrained within a 50 micron wide slit printed on the underside of the acrylic prism Q, which, with a slot machined across its hypotenuse, provided the optical path L from the LED, through the tube and thence to the phototransistor.

Balancing the Disk

In the design of the Absolute Barometer disk, the masses and positions of the components attached to the disk were taken into account to produce an accurately balanced disk for minimum vibration on rotation. It was, however, found that some small adjustment was necessary to provide smooth operation at high speeds. The device used to balance the disk took the form of a mounted motor fitted with an optical tachometer which provided an electrical pulse at a specific rotational position of the shaft. The vibration caused by the out of balance mass on the rotating sub-assembly was detected and measured by a single axis solid-state accelerometer, type MMA2301. This was mounted on the motor substrate at the same angular position as the motor tachometer null. The signal from the tachometer and the signal from the accelerometer were fed to two channels of an oscilloscope. When the disk was rotated the oscilloscope trace gave both the angular displacement between the tachometer null and the out-of-balance maximum, but also the magnitude of the necessary corrective moment that needed to be applied. The disk could be easily balanced in this way by cementing the appropriate small mass of acrylic to the periphery of the disk.

Displaying the Pressure Reading

The rotation of the disk can be conveniently exploited to provide a digital display of the determined pressure. A series of 8 light emitting diodes L in figure 1, mounted radially and illuminated by the microcontroller according to the desired digits to be displayed provided a highly visible indication of the measured pressure.

Performance

The performance of the Absolute Barometer was investigated by enclosing the entire instrument in a sealed transparent box rated to IP67 which then could be pressurised in the range of 950 mB to 1050 mB. The pressure was independently measured using a Meteormetrics Meteor2000CBV2 calibrator with a calibration traceable to a UK National Physical Laboratory Standard.

At a constant temperature of 40 C, The calibration graph obtained across the range is shown in figure 4. The slope of the graph of 0.9996 mB/mB demonstrates that the new Absolute Barometer will perform at least as well as the Fortin barometers it is designed to replace.

The results reported here are confined to an Absolute Barometer with a single meniscus detector and the minimum of data post-processing. With this minimum in place, the standard deviation on a set of readings of a single pressure was 0.6mB. With multiple

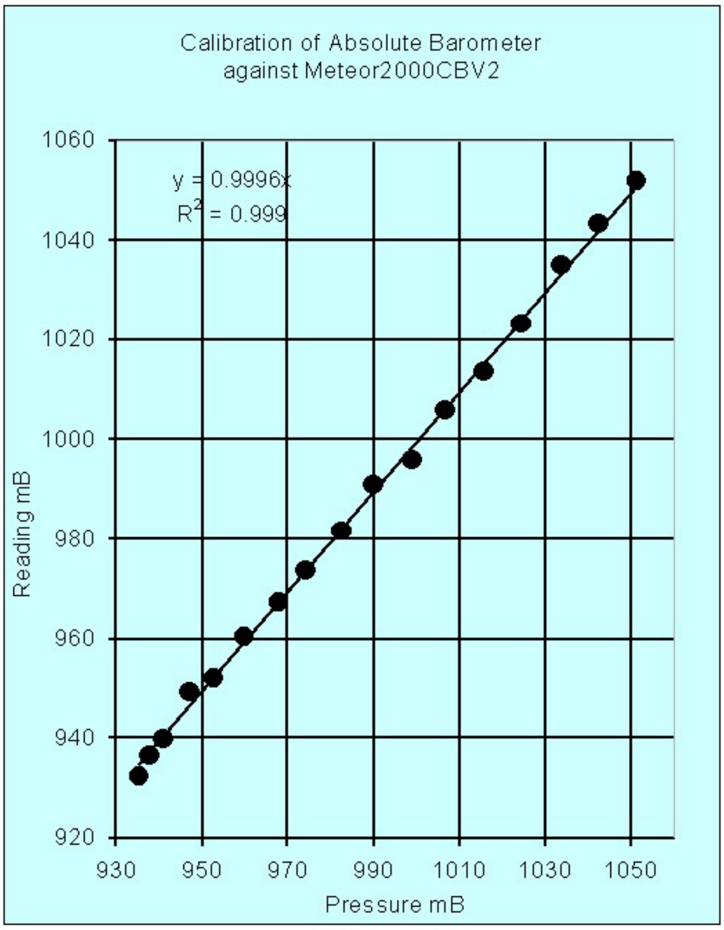

Figure 5 Calibration Graph for the Absolute Barometer

meniscus detection and least-squares treatment of each data set, it is not unreasonable to expect a 5 – 10 fold improvement on this figure, which would place this Absolute Barometer in an unchallenged position with respect to both traditional absolute instruments and secondary devices.

Patent Protection

European and US patents have been applied for. Patent Application No EP11162336.9, and US Patent Application Serial No 13/085,747.