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# Review of Current and emerging technologies and update of the cimo guide

Surface T, P, RH Measurement Technologies

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| **Summary and purpose of document**  This document provides overview of the practices and experiences of observing T, P and RH at the surface. The focus is on the usage of electric devices for autonomous and frequent observations. Some alternative measurement techniques are also reported. |

**Action proposed**

The Meeting is invited to take notice of the findings reported in this document and to provide feedback on the contents. Also the Meeting should decide whether the document is suitable for publication as a separate IMOP report or whether information should be included in the CIMO guide.

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**Appendices:** N/A

**Surface Temperature, Relative Humidity, and Pressure Observations**

1. **REVIEW OF TEMPERATURE MEASUREMENT METHODS AND TECHNOLOGIES**

**LIQUID-IN-THERMOMETERS**

For routine observations of air temperature, including maximum, minimum and wet-bulb temperatures, liquid-in-glass thermometers are still commonly used. Such thermometers make use of the differential expansion of a pure liquid with respect to its glass container to indicate the temperature. The stem is a tube which has a fine bore attached to the main bulb; the volume of liquid in the thermometer is such that the bulb is filled completely but the stem is only partially filled at all temperatures to be measured. The changes in volume of the liquid with respect to its container are indicated by changes in the liquid column; by calibration with respect to a standard thermometer, a scale of temperature can be marked on the stem, or on a separate scale tightly attached to the stem.

The liquid used depends on the required temperature range; mercury is generally used for temperatures above its freezing point (–38.9 °C), while ethyl alcohol or other pure organic liquids are used for lower temperatures. The glass should be one of the normal or borosilicate glasses approved for use in thermometers. The glass bulb is made as thin as is consistent with reasonable strength to facilitate the conduction of heat to and from the bulb and its contents. A narrower bore provides greater movement of liquid in the stem for a given temperature change, but reduces the useful temperature range of the thermometer for a given stem length. The thermometer should be suitably annealed before it is graduated in order to minimize the slow changes that occur in the glass with ageing.

There are four main types of construction for meteorological thermometers, as follows: (a) The sheathed type with the scale engraved on the thermometer stem; (b) The sheathed type with the scale engraved on an opal glass strip attached to the thermometer tube inside the sheath; (c) The unsheathed type with the graduation marks on the stem and mounted on a metal, porcelain or wooden back carrying the scale numbers; (d) The unsheathed type with the scale engraved on the stem.

The stems of some thermometers are lens-fronted to provide a magnified image of the mercury thread.

Types (a) and (b) have the advantage over types (c) and (d) that their scale markings are protected from wear. For types (c) and (d), the markings may have to be reblackened from time to time; on the other hand, such thermometers are easier to make than types (a) and (b). Types (a) and (d) have the advantage of being less susceptible to parallax errors.

Whichever type is adopted, the sheath or mounting should not be unduly bulky as this would keep the heat capacity high. At the same time, the sheath or mounting should be sufficiently robust to withstand the normal risks associated with handling and transit.

For mercury-in-glass thermometers, especially maximum thermometers, it is important that the vacuum above the mercury column be nearly perfect. All thermometers should be graduated for total immersion, with the exception of thermometers for measuring soil temperature. The special requirements of thermometers for various purposes are dealt with hereafter under the appropriate headings.

**MECHANICAL THERMOGRAPHS**

The types of mechanical thermographs still commonly used are supplied with bimetallic or Bourdon-tube sensors since these are relatively inexpensive, reliable and portable. However, they are not readily adapted for remote or electronic recording. Such thermographs incorporate a rotating chart mechanism common to the family of classic recording instruments. In general, thermographs should be capable of operating over a range of about 60 K or even 80 K if they are to be used in continental climates. A scale value is needed such that the temperature can be read to 0.2 K without difficulty on a reasonably sized chart. To achieve this, provisions should be made for altering the zero setting of the instrument according to the season. The maximum error of a thermograph should not exceed 1 K.

*Bimetallic thermograph*

In bimetallic thermographs, the movement of the recording pen is controlled by the change in curvature of a bimetallic strip or helix, one end of which is rigidly fixed to an arm attached to the frame. A means of finely adjusting this arm should be provided so that the zero of the instrument can be altered when necessary. In addition, the instrument should be provided with a means of altering the scale value by adjusting the length of the lever that transfers the movement of the bimetal to the pen; this adjustment is best left to authorized personnel. The bimetallic element should be adequately protected from corrosion; this is best done by heavy copper, nickel or chromium plating, although a coat of lacquer may be adequate in some climates. A typical time constant of about 25 s is obtained at an air speed of 5 m s–1.

*Bourdon-tube thermograph*

The general arrangement is similar to that of the bimetallic type but its temperature-sensitive element is in the form of a curved metal tube of flat, elliptical section, filled with alcohol. The Bourdon tube is less sensitive than the bimetallic element and usually requires a multiplying level mechanism to give sufficient scale value. A typical time-constant is about 6 s at an air speed of 5 m s–1.

**ELECTRICAL THERMOMETERS**

Electrical instruments are in widespread use in meteorology for measuring temperatures. Their main virtue lies in their ability to provide an output signal suitable for use in remote indication, recording, storage, or transmission of temperature data. The most frequently used sensors are electrical resistance elements, semiconductor thermometers (thermistors) and thermocouples.

*Electrical resistance thermometers*

A measurement of the electrical resistance of a material whose resistance varies in a known manner with the temperature of the material can be used to represent the temperature.

For small temperature changes, the increase in resistance of pure metals is proportional to the change in temperature, as expressed in equation 2.2:

(2.2)

where is small; is the resistance of a fixed amount of the metal at temperature T; is its resistance at a reference temperature , and is the temperature coefficient of resistance in the vicinity of .

With 0 °C as the reference temperature, equation 2.2 becomes:

(2.3)

For larger temperature changes and for certain metallic alloys, equation 2.4 expresses the relationship more accurately:

(2.4)

With 0 °C as the reference temperature, equation 2.4 becomes:

(2.5)

These equations give the proportional change in resistance of an actual thermometer, so that values for the coefficients *α* and *β* can be found by calibration of the thermometer concerned. Based on these results, the inverse function, namely, *t* as a function of *R*, can be derived. Such a function may be expressed in terms of a power series of (*R*0 – *R*T), namely, *t* = *t* (*R*0 – *R*T) = c1 (*R*0 – *R*T) + c2 (*R*0 – *R*T)2 + …

A good metal resistance thermometer will satisfy the following requirements:

(a) Its physical and chemical properties will remain the same through the temperature measurement range;

(b) Its resistance will increase steadily with increasing temperature without any discontinuities in the range of measurement;

(c) External influences such as humidity, corrosion or physical deformations will not alter its resistance appreciably;

(d) Its characteristics will remain stable over a period of two years or more;

(e) Its resistance and thermal coefficient should be large enough to be useful in a measuring circuit.

Pure platinum best satisfies the foregoing requirements. Thus, it is used for the primary standard thermometers needed for transferring the ITS-90 between instrument locations. Platinum thermometers are also used for secondary standards and for operational sensors.

Practical thermometers are artificially aged before use and are commonly made from platinum alloys, nickel and occasionally tungsten for meteorological purposes. Usually they are hermetically sealed in a ceramic sheath. Their time constant is smaller than that of liquid-in-glass thermometers.

**SEMICONDUCTOR THERMOMETERS**

Another type of resistance element in common use is the thermistor. This is a semiconductor with a relatively large temperature coefficient of resistance, which may be either positive or negative depending upon the actual material. Mixtures of sintered metallic oxides are suitable for making practical thermistors, which usually take the form of small discs, rods or spheres and are often glass-coated. The general expression for the temperature dependence of the resistance, *R*, of the thermistor is given in equation 2.6:

(2.6)

where *a* and *b* are constants and *T* is the temperature of the thermistor in kelvins.

The advantages of thermistors from a thermometric point of view are as follows:

(a) The large temperature coefficient of resistance enables the voltage applied across a resistance bridge to be reduced while attaining the same sensitivity, thus reducing or even eliminating the need to account for the resistance of the leads and its changes;

(b) The elements can be made very small, so their very low thermal capacities can yield a small time-constant. However, very small thermistors with their low thermal capacity have the disadvantage that, for a given dissipation, the self-heating effect is greater than for large thermometers. Thus, care must be taken to keep the power dissipation small.

A typical thermistor has a resistance which varies by a factor of 100 or 200 over the temperature range –40 °C to 40 °C.

***THERMOCOUPLES***

In 1821 Seebeck discovered that a very small contact electromotive force was set up at the place where two different metals touched. If a simple circuit is made with two metals and with the conjunction at the same temperature, there will be no resultant electromotive force in the circuit because the two electromotive forces, one at each junction, will exactly oppose and cancel one another. If the temperature of one junction is altered, the two electromotive forces no longer balance and there is a net electromotive force set up in the circuit; a current will then flow. When there are several junctions, the resultant electromotive force is the algebraic sum of the individual electromotive forces. The magnitude and sign of the contact electromotive force set up at any one junction depend on the types of metals joined and the temperature of the junction point, and may be empirically represented for any two metals by the expression:

(2.7)

where *ET* is the contact electromotive force at a temperature *T* and *Es* is the electromotive force at some standard temperature *Ts*, *α* and *β* being constants. If there are two junctions at temperatures *T*1 and *T*2, the net electromotive force *En* (the thermal electromotive force) is given by (*E*1 – *E*2), where *E*1 is the electromotive force at temperature *T*1 and *E*2 is the contact electromotive force temperature *T*2. *En* can also be represented by a quadratic formula of the type given for (*ET* – *Es*) to a good approximation:

(2.8)

(2.9)

where *a* and *b* are constants for the two metals concerned. For most meteorological purposes, it is often possible to neglect the value of *b*, as it is always small compared with *a*.

Thermocouples are made by welding or soldering together wires of the metals concerned. These junctions can be made very small and with negligible heat capacity.

When used to measure temperature, a measurement is taken of the electromotive force set up when one junction is maintained at a standard known temperature and the other junction is allowed to take the temperature whose value is required. This electromotive force can be directly related to the difference in temperature between the two junctions by previous calibration of the system, and thus the unknown temperature is found by adding this difference algebraically to the known standard temperature.

In meteorology, thermocouples are mostly used when a thermometer of very small time-constant, of the order of 1 or 2 s, and capable of remote reading and recording is required, usually for special research tasks. A disadvantage, if the absolute temperature is required, is the necessity for a constant-temperature enclosure for both the cold junction and ancillary apparatus for the measurements of the electromotive force that has been set up; thermocouples are best suited for the measurement of differential temperatures, since this complication does not arise. Very high accuracy can be achieved with suitably sensitive apparatus, but frequent calibration is necessary. Copper-constantan or iron-constantan combinations are suitable for meteorological work, as the electromotive force produced per degree Celsius is higher than with rarer and more expensive metals, which are normally used at high temperatures.

**TECHNOLOGIES:**

The USA National Weather Service utilizes the following Temperature sensors:

* Rosemount Model 162CE Standard Platinum Resistance Thermometers (SPRT) (Electrical Thermometers)
* Omega Model PR-11-3-100-3/16-4-E-240 PRT (Electrical Thermometers)

1. **REVIEW OF RELATIVE HUMIDITY MEASUREMENT METHODS AND TECHNOLOGIES**

**Gravimetric hygrometry**

This method uses the absorption of water vapour by a desiccant from a known volume of air (gravimetric hygrometer; used for primary standards only). The gravimetric method yields an absolute measure of the water-vapour content of an air sample in terms of its humidity mixing ratio. This is obtained by first removing the water vapour from the sample. The mass of the water vapour is determined by weighing the drying agent before and after absorbing the vapour. The mass of the dry sample is determined either by weighing or by measuring its volume. The method is restricted to providing an absolute calibration reference standard, and such apparatus is found mostly in national calibration standards laboratories.

**Chilled-mirror method**

When moist air at temperature T, pressure p and mixing ratio rw (or ri ) is cooled, it eventually reaches its saturation point with respect to water (or to ice at lower temperatures) and a deposit of dew (or frost) can be detected on a solid non-hygroscopic surface. The temperature of this saturation point is the dewpoint temperature Td (or the frost-point Tf ). The chilled-mirror hygrometer are used to measure Td or Tf . The most widely used systems employ a small polished-metal reflecting surface, cooled electrically by using a Peltier-effect device, and sense condensation with an optical detector. Instruments using condensation method are used for observational purposes and might also be used as working standards and/or reference standards.

**Heated salt-solution method**

The equilibrium vapour pressure at the surface of a saturated salt solution is less than that for a similar surface of pure water at the same temperature. This effect is exhibited by all salt solutions but particularly by lithium chloride, which has an exceptionally low equilibrium vapour pressure. An aqueous salt solution (whose equilibrium vapour pressure is below the ambient vapour pressure) may be heated until a temperature is reached at which its equilibrium vapour pressure exceeds the ambient vapour pressure. At this point, the balance will shift from condensation to evaporation and eventually there will be a phase transition from the liquid solution to a solid hydrate (crystalline) form. The transition point may be detected through a characteristic decrease in the electrical conductivity of the solution as it crystallizes. The temperature of the solution at which the ambient vapour pressure is reached provides a measure of the ambient vapour pressure. For this purpose, a thermometer is placed in good thermal contact with the solution. The ambient dewpoint (namely, with respect to a plane surface of pure water) may be determined by using empirical data relating vapour pressure to temperature for pure water and for salt solutions. The most frequently used salt solution for this type of sensor is lithium chloride. This method is used for observational purposes, especially for automatic weather stations.

**The psychrometric method**

A psychrometer consists essentially of two thermometers exposed side by side, with the surface of the sensing element of one being covered by a thin film of water or ice and termed the wet or ice bulb, as appropriate. The sensing element of the second thermometer is simply exposed to the air and is termed the dry bulb. Owing to evaporation of water from the wet bulb, the temperature measured by the wet-bulb thermometer is generally lower than that measured by the dry bulb. The difference in the temperatures measured by the pair of thermometers is a measure of the humidity of the air; the lower the ambient humidity, the greater the rate of evaporation and, consequently, the greater the depression of the wet-bulb temperature below the dry-bulb temperature. The size of the wetbulb depression is related to the ambient humidity by a psychrometer formula. This method is in widespread use for observational purposes. Instruments using the psychrometric method are also commonly used as working standards.

**Sorption methods**

Certain materials interact with water vapour and undergo a change in a chemical or physical property that is sufficiently reversible for use as a sensor of ambient humidity. Water vapour may be adsorbed or absorbed by the material, adsorption being the taking up of one substance at the surface of another and absorption being the penetration of a substance into the body of another. A hygroscopic substance is one that characteristically absorbs water vapour from the surrounding atmosphere, by virtue of having a saturation vapour pressure that is lower than that of the surrounding atmosphere. For absorption to take place, a necessary condition requires that the ambient vapour pressure of the atmosphere exceeds the saturation vapour pressure of the substance. The following are two properties of sorption:

(a) Changes in the dimensions of hygroscopic materials: Certain materials vary dimensionally with humidity. Natural fibres tend to exhibit the greatest proportional change and, when coupled to a mechanical lever system, can be incorporated into an analogue linear displacement transducer. Such a transducer may be designed to move a pointer over a scale to provide a visual display, or be an electromechanical device which provides an electrical output.

Human hair is the most widely used material for this type of humidity sensor. Synthetic fibres may be used in place of human hair. Because of the very long lag time for synthetic fibres, such sensors should never be used below 10 °C. Goldbeater’s skin (an organic membrane obtained from the gut of domestic animals) has properties similar to those of human hair and has been used for humidity measurements, though most commonly in devices for taking upper-air measurement.

(b) Changes in electrical properties of hygroscopic materials: Certain hygroscopic materials exhibit changes in their electrical properties in response to a change in the ambient relative humidity with only a small temperature dependence. Electrical relative humidity sensors are increasingly used for remote-reading applications, particularly where a direct display of relative humidity is required. Properties commonly exploited in the measurement of relative humidity include sensors made from chemically treated plastic material having an electrically conductive surface layer (electrical resistance) and sensors based upon the variation of the dielectric properties of a solid, hygroscopic material in relation to the ambient relative humidity (electrical capacitance).

**Absorption of electromagnetic radiation by water vapour**

The water molecule absorbs electromagnetic radiation in a range of wavebands and discrete wavelengths; this property can be exploited to obtain a measure of the molecular concentration of water vapour in a gas. The most useful regions of the electromagnetic spectrum for this purpose lie in the ultraviolet and infrared regions, and the principle of the method is to determine the attenuation of radiation in a waveband that is specific to water-vapour absorption, along the path between a source of the radiation and a receiving device. There are two principal methods for determining the degree of attenuation of the radiation, namely: (a) The transmission of narrowband radiation at a fixed intensity to a calibrated receiver; (b) The transmission of radiation at two wavelengths, one of which is strongly absorbed by water vapour and the other is either not absorbed or only very weakly absorbed. Both types of instruments require frequent calibration and are more suitable for measuring changes in vapour concentration rather than absolute levels

**Electrical resistance**

Sensors made from chemically treated plastic material having an electrically conductive surface layer on the non-conductive substrate may be used for meteorological purposes. The surface resistivity varies according to the ambient relative humidity. The process of adsorption, rather than absorption, is dominant because the humidity-sensitive part of such a sensor is restricted to the surface layer. As a result, this type of sensor is capable of responding rapidly to a change in ambient humidity.

This class of sensor includes various electrolytic types in which the availability of conductive ions in a hygroscopic electrolyte is a function of the amount of adsorbed water vapour. The electrolyte may take various physical forms, such as liquid or gel solutions, or an ion-exchange resin. The change in impedance to an alternating current, rather than to a direct current, is measured in order to avoid polarization of the electrolyte. Low-frequency supply can be used, given that the DC resistance is to be measured, and therefore it is possible to employ quite long leads between the sensor and its electrical interface.

**Electrical capacitance**

The method is based upon the variation of the dielectric properties of a solid, hygroscopic material in relation to the ambient relative humidity. Polymeric materials are most widely used for this purpose. The water bound in the polymer alters its dielectric properties owing to the large dipole moment of the water molecule.

The active part of the humidity sensor consists of a polymer foil sandwiched between two electrodes to form a capacitor. The electrical impedance of this capacitor provides a measure of relative humidity. The nominal value of capacitance may be only a few or several hundred picofarads, depending upon the size of the electrodes and the thickness of the dielectric. This will, in turn, influence the range of excitation frequency used to measure the impedance of the device, which is normally at least several kilohertz and, thus, requires that short connections be made between the sensor and the electrical interface to minimize the effect of stray capacitance. Therefore, capacitance sensors normally have the electrical interface built into the probe, and it is necessary to consider the effect of environmental temperature on the performance of the circuit components

**TECHNOLOGIES:**

The USA National Weather Service utilizes the following RH sensors:

* Vaisala Model DTS1 Dewpoint Temperature Sensor (Electrical capacitance)
* Vaisala Model HMP155A Humidity Probe (Electrical capacitance)
* E+E EE35 dew point transmitter (Electrical capacitance)

1. **REVIEW OF PRESSURE MEASUREMENT METHODS AND TECHNOLOGIES**

**Mercury Barometers**

There is an increasing move away from the use of mercury barometers because mercury vapour is highly toxic; free mercury is corrosive to the aluminium alloys used in air frames (for these reasons there are regulations proscribing the handling or carriage of mercury barometers in some countries); special lead glass is required for the tube; the barometer is very delicate and difficult to transport; it is difficult to maintain the instrument and to clean the mercury; the instrument must be read and corrections applied manually; and other pressure sensors of equivalent accuracy and stability with electronic read-out are now commonly available.

**Electronic Barometers**

Most barometers with recent designs make use of transducers which transform the sensor response into a pressure-related electrical quantity in the form of either analogue signals, for example, voltage (DC or AC with a frequency related to the actual pressure), or digital signals, for example, pulse frequency or with standard data communication protocols such as RS232, RS422, RS485 or IEEE488. Analogue signals can be displayed on a variety of electronic meters. Monitors and data-acquisition systems, such as those used in automatic weather stations, are frequently used to display digital outputs or digitized analogue outputs.

Current digital barometer technology employs various levels of redundancy to improve the longterm stability and accuracy of the measurements. One technique is to use three independently operating sensors under centralized microprocessor control. Even higher stability and reliability can be achieved by using three completely independent barometers, incorporating three sets of pressure transducers and microprocessors. Each configuration has automatic temperature compensation from internally mounted temperature sensors. Triple redundancy ensures excellent long-term stability and measurement accuracy, even in the most demanding applications. These approaches allow for continuous monitoring and verification of the individual sensor performances.

The use of digital barometers introduces some particular operational requirements, especially when they are used with automatic weather stations, and formal recommendations exist to ensure good practice (see the Abridged Final Report of the Eleventh Session of the Commission for Instruments and Methods of Observation (WMO-No. 807), Annex VII). Meteorological organizations should:

(a) Control or re-adjust the calibration setting of digital barometers upon receipt and repeat these operations regularly (annually, until the rate of drift is determined);

(b) Ensure regular calibration of digital barometers and investigate the possibility of using calibration facilities available nationally for this purpose;

(c) Consider that certain types of digital barometers may be used as travelling standards because of their portability and good short-term stability;

(d) Consider that the selection of a specific type of digital barometer should not only be based on stated instrument specifications but also on environmental conditions and maintenance facilities.

Manufacturers should:

(a) Improve the temperature independence and the long-term stability of digital barometers;

(b) Use standardized communication interfaces and protocols for data transmission;

(c) Enable the power supply of a digital barometer to function over a large range of DC voltages (for example, 5 to 28 VDC).

**Digital piezoresistive barometers**

Measurements of atmospheric pressure have become possible by utilizing the piezoelectric (piezoresistive) effect. A common configuration features four measuring resistors placed onto the flexible surface of a monolithic silicon substratum interconnected to form a Wheatstone bridge circuit.

Axially loaded crystalline quartz elements are used in digital piezoresistive barometers and are a type of absolute pressure transducer. Crystalline quartz has been chosen because of its piezoelectric properties, stable frequency characteristics, small temperature effects and precisely reproducible frequency characteristics. Pressure applied to an inlet port causes an upward axial force by means of flexible bellows, thus resulting in a compressive force on the quartz crystal element. Since the crystal element is a substantially rigid membrane, the entire mechanical structure is constrained to minute deflections, thereby virtually eliminating mechanical hysteresis.

The fully active Wheatstone bridge mentioned above may consist either of semiconductor strain gauges or piezoresistive gauges. The strain gauges are either bonded to a thin circular diaphragm, which is clamped along its circumference, or atomically diffused into a silicon diaphragm configuration. In the case of diffused devices, the silicon integrated chip itself is the diaphragm. Applied pressure presents a distributed load to the diaphragm which, in turn, provides bending stress and resultant strains to which the strain gauges react. This stress creates a strain that is proportional to the applied pressure and which results in a bridge imbalance. The bridge output is then proportional to the net difference in pressure acting upon the diaphragm.

This mode of operation is based on the fact that the atmospheric pressure acts on the sensor element covering a small evacuated cell, through which the resistors are submitted to compressive and tensile stresses. By the piezoelectric effect, the values of resistance change proportionally with atmospheric pressure. To eliminate temperature errors, the sensor often incorporates a built-in thermostat.

The output from the Wheatstone bridge, which is fed from a direct-current source, is transduced into a standard signal by an appropriate amplifier. A light-emitting diode or liquid crystal display usually presents the measured pressure values.

In a modern version of the pressure transducer using a piezoelectric transducer, two resonance frequencies of the piezoelectric element are determined. By calculating a linear function of these frequencies and with an appropriate set of variables obtained after calibration, a pressure is calculated by a microprocessor which is independent of the temperature of the sensor

**Cylindrical resonator barometers**

Cylindrical resonator barometers use a sensing element which is a thin-walled cylinder of nickel alloy. This is electromagnetically maintained in a “hoop” mode of vibration. The input pressure is sensed by the variation it produces in the natural resonant frequency of the vibrating mechanical system. Cylinder wall movement is sensed by a pick-up coil whose signal is amplified and fed back to a drive coil. The air pressure to be measured is admitted to the inside of the cylinder, with a vacuum reference maintained on the outside. The natural resonant frequency of vibration then varies precisely with the stress set up in the wall due to the pressure difference across it. An increase in pressure gives rise to an increase in frequency.

The thin cylinder has sufficient rigidity and mass to cater for the pressure ranges over which it is designed to operate, and is mounted on a solid base. The cylinder is placed in a vacuum chamber and its inlet is connected to the free atmosphere for meteorological applications. Since there is a unique relationship between the natural resonant frequency of the cylinder and the pressure, the atmospheric pressure can be calculated from the measured resonant frequency. However, this relationship, determined during calibration, depends on the temperature and the density of the gas. Temperature compensation is therefore required and the air should be dried before it enters the inlet.

**TECHNOLOGIES:**

The USA National Weather Service utilizes the following Pressure sensors:

* Paroscientific, Inc. Digiquartz Model 760-16B Portable Barometer (Resonator Barometer)
* Fluke Electronics Ruska Model 6220 Portable Pressure Gauge (Resonator Barometer)

Coastal Environmental Systems Model Precision Digital Barometer, Model PDB-1 (Resonator Barometer)