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Acoustic thermometry for accurate measurement of air temperature

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Abstract.

Acoustic thermometry is a technique of primary thermometry that has recently been used to make low-uncertainty estimates of the Boltzmann constant, in preparation for the revised kelvin definition in the new SI. Additionally it has been used to make measurements of differences between thermodynamic temperature and the temperature estimated using the *International Temperature Scale* of 1990. The technology used for both these activities has involved simultaneous acoustic and microwave measurements inside a quasi-spherical resonator. Here we report early developments of an application of acoustic thermometry used to determine the temperature of atmospheric air in a workspace over path lengths up to several metres.

The acoustic measurements are made by means of an acoustic interferometer constructed from a parabolic acoustic mirror and a plane acoustic reflector. The acoustic frequency of the interferometer is servo-controlled to maintain a constant number of wavelengths in the interferometer. One problem with acoustic measurements in air is the variable composition of air due mainly to changes in humidity. In the system we have developed, the humidity is measured simultaneously using a Tuneable Diode Laser Absorption Spectrometer (TDLAS) which measures in the same volume of air. Together the TDLAS and the acoustic thermometer correct each other to produce a self-consistent estimates for air temperature and humidity. Importantly, the device reports the *average* air temperature along a path. In the implementation developed at NPL, independent measurements are available 30 times per second. Around room temperature, the uncertainty is < 0.1 °C for temperature and approximately 1 %RH for humidity.

We are reporting this development here because we can foresee potential applications of this technology in the field of precision engineering where *in situ* real-time knowledge of the average refractive index of air along a known path is relevant for the correction of interferometer measurements.

Keywords
Thermometry, Acoustic Thermometry, Air temperature, Humidity, Non-contact, TDLAS

1. Non-contact Temperature and Humidity Measurement

One long-standing challenge in precision manufacturing is the measurement of the environmental temperature in which components are assembled or made. Contact sensors such as thermistors or platinum resistance thermometers can make excellent measurements of temperature when they are in good thermal contact with a solid. However, in air their relatively large thermal inertia coupled with the poor thermal conductivity of air means that they cannot respond to rapid temperature changes. In many applications this is an advantage because they report a temporally-averaged temperature. However to record the temperature over a long distance necessarily requires the use of many contact sensors.

In some applications of precision engineering, interferometers are used to measure the distance between key parts of a large object. For these devices to correctly report the distance to a target, they must use knowledge of the refractive index of air. This is a function of air pressure, air temperature and humidity along the path taken by the laser.

The measurement of air pressure is not expected to vary by more than a few parts per million along a beam path unless the path changes height significantly (ΔP ~ 11 Pa per metre of height). So a single pressure measurement is generally sufficient to characterise the environmental pressure.

In contrast air temperature and humidity can vary significantly along the beam path. Even in a laboratory situation, temperature fluctuations of several tenths of a degree are commonplace, corresponding to changes in air density of up to 0.1%. The effect of humidity variations at a similar level to temperature fluctuations depends strongly on the temperature and relative humidity. In factory situations the variability could easily be greater.

Fluctuations in temperature and humidity will add noise to a dimensional estimate but will not be recorded by even a large number of conventional sensors distributed along the beam path. And if many measurements are required it is expensive and time consuming to deploy an array of contact sensors throughout a large measurement volume.

In this paper we report early developments of a technology which can report the average temperature and humidity along beam paths several metres in length. In principle, this could be incorporated into an interferometer in order to measure the average temperature and humidity along the beam path. Together with a pressure measurement this would allow *in situ* real-time estimates of the density of air and its refractive index.

Currently our instrument produces 30 independent measurements of temperature and humidity per second. Temperature measurements have a standard deviation of approximately 0.003 °C and an overall uncertainty <0.1 °C. The relative humidity is reported with a resolution of < 0.1 %RH and an overall uncertainty < 1 %RH.

2. Instrumental Details

Our *Non-Contact Thermometer and Hygrometer* (NCTAH) combines a tuneable diode laser absorption spectrometer

(TDLAS) and an acoustic thermometer. Working together, these devices provide rapid, non-contact temperature and humidity measurements.

A schematic diagram of the instrument is shown in Figure 1 and Figure 2 shows a photograph of the instrument.

(a)

(b)

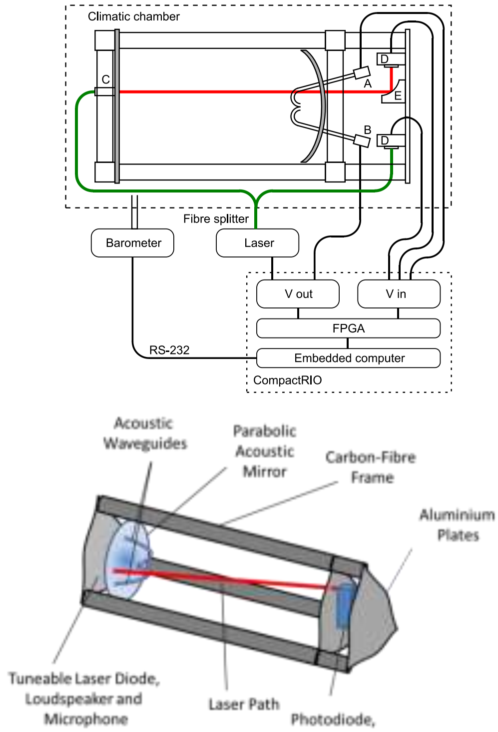

Figure 1. Schematic diagrams showing (a) the conceptual organisation of the instrument and (b) the location of the key components of NCTAH. The instrument measures the average temperature and humidity within the volume of air enclosed between the parabolic dish and the end-plate.

Figure 2. Photograph of the assembled instrument.

The use of TDLAS for humidity measurements is well established [1, 2]. The technique infers the humidity along a line of sight from a laser diode to a detector using measurements of the absorption profile of a water line. The inference of the corresponding humidity requires knowledge of air density which can be inferred from auxiliary measurements of temperature and pressure. Around room temperature the uncertainty of measurement is ~ 1 %RH with a resolution of <0.1%.

The use of acoustics for measurements of air temperature is not common, but ultrasonic anemometers (e.g. Gill RS50) commonly have an output called 'acoustic temperature'. However, although they are able to respond to rapid temperature changes, these instruments are generally rather inaccurate [3].

Acoustic thermometry infers the temperature from changes in speed of sound, which may be calculated as a function of the molecular composition and density of the air [4]. Since water vapour is the largest variable in the composition of air, accurate inference of temperature additionally requires knowledge of the amount fraction of water in the air.

The variation of the speed of sound with humidity is significant. For example, at 20 °C, varying the humidity from 0 %RH to 100 %RH would cause an error in the inferred temperature of 1.9 °C if the speed of sound in dry air were used in its calculation. We account for the interdependence of the temperature and humidity estimates using an iterative procedure.

To test the efficacy of this correction, NCTAH was placed in an environmental test chamber alongside 4 PRTs. Figure 3 shows the difference in the temperature reported by NCTAH with the temperature reported by the PRTs. It is seen that varying the humidity within the test chamber causes no systematic effect on the reported temperature even though the change in the speed of sound is equivalent to an error of 1.9 °C.

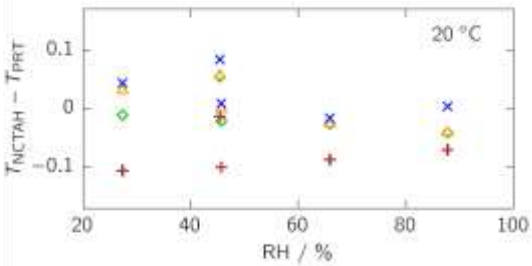

Figure 3. Data showing the efficiency of the iterative correction. The left-hand axis shows the

3. Potential Applications

The current NCTAH device has a path length of ~600 mm and a reflector rigidly attached to the transmitter. This configuration was adopted to satisfy a particular meteorological application. However the combination of TDLAS and acoustic thermometry can be applied more generally.

Measurement distances on the order of 10 metres are conceivable and there is no need for the transmitter and reflector heads to be rigidly attached. We believe that the combination of these two non-contact technologies may provide solutions to a large number of measurement requirements where the average temperature of large volume of air is required.

References

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