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Development of a custom on-line ultrasonic vapour analyzer/flowmeter for the ATLAS inner detector, with application to gaseous tracking and Cherenkov detectors

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ABSTRACT: Precision sound velocity measurements can simultaneously determine binary gas composition and flow. We have developed an analyzer with custom electronics, currently in use in the ATLAS inner detector, with numerous potential applications. The instrument has demonstrated $\sim 0.3\%$ mixture precision for C_3F_8/C_2F_6 mixtures and $< 10^{-4}$ resolution for N_2/C_3F_8 mixtures. Moderate and high flow versions of the instrument have demonstrated flow resolutions of $\pm 2\%$ of full scale for flows up to $250\,\mathrm{l\,min^{-1}}$, and $\pm 1.9\%$ of full scale for linear flow velocities up to $15\,\mathrm{m\,s^{-1}}$; the latter flow approaching that expected in the vapour return of the thermosiphon fluorocarbon coolant recirculator being built for the ATLAS silicon tracker.

KEYWORDS: Detector cooling and thermo-stabilization; Gas systems and purification; Materials for gaseous detectors

Contents

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1 Introduction

We describe a combined ultrasonic gas mixture analyzer/flow meter for continuous real time composition analysis of binary gas mixtures. The instrument exploits the phenomenon whereby the sound velocity in a binary gas mixture at known temperature and pressure is a unique function of the molar concentration of the two components of differing molecular weight. The combined flow measurement and mixture analysis algorithm combines sound transit time measurements in opposite directions with measurements of the pressure and temperature of the mixture, and has many applications where knowledge of binary gas composition is required. The molar concentration of the two component vapours is determined from a comparison of on-line sound velocity measurements with velocity-composition look-up table data gathered from prior measurements in calibration mixtures or from theoretical derivations made with an appropriate equation of state.

Ultrasonic binary gas analysis was first used in particle physics for the analysis of the N_2/C_5F_{12} Cherenkov gas radiator of the SLD Cherenkov Ring Imaging Detector [1], and has subsequently been adopted in all the major ring imaging Cherenkov detectors, including DELPHI, COMPASS and LHCb.

The present development is mainly motivated by a possible future upgrade of the ATLAS silicon tracker evaporative cooling system [2, 3], in which the currently-used C_3F_8 fluorocarbon evaporative coolant will be blended with a more volatile C_2F_6 component [3, 4] to allow cooling at lower temperatures. Additionally, the present underground compressor-driven C_3F_8 circulation plant will be replaced by a thermosiphon [5]. A combined mixture analyzer/flow meter will be installed in the vapour return to the surface condenser, where a flow of $\sim 400\,\mathrm{l\,s^{-1}}$ is expected.

2 Principle of operation of the electronics

The electronics of the present instrument is based on a Microchip® dsPIC 16-bit microcontroller with communication to a SCADA computer running a graphical user interface and analysis package written in PVSS-II®. Figure 1 illustrates the major elements of the electronics, which is presently designed to operate with the SensComp 604142 instrument grade 50 kHz capacitative foil ultrasonic transducer, originally developed during the 1980s for the Polaroid autofocus camera.

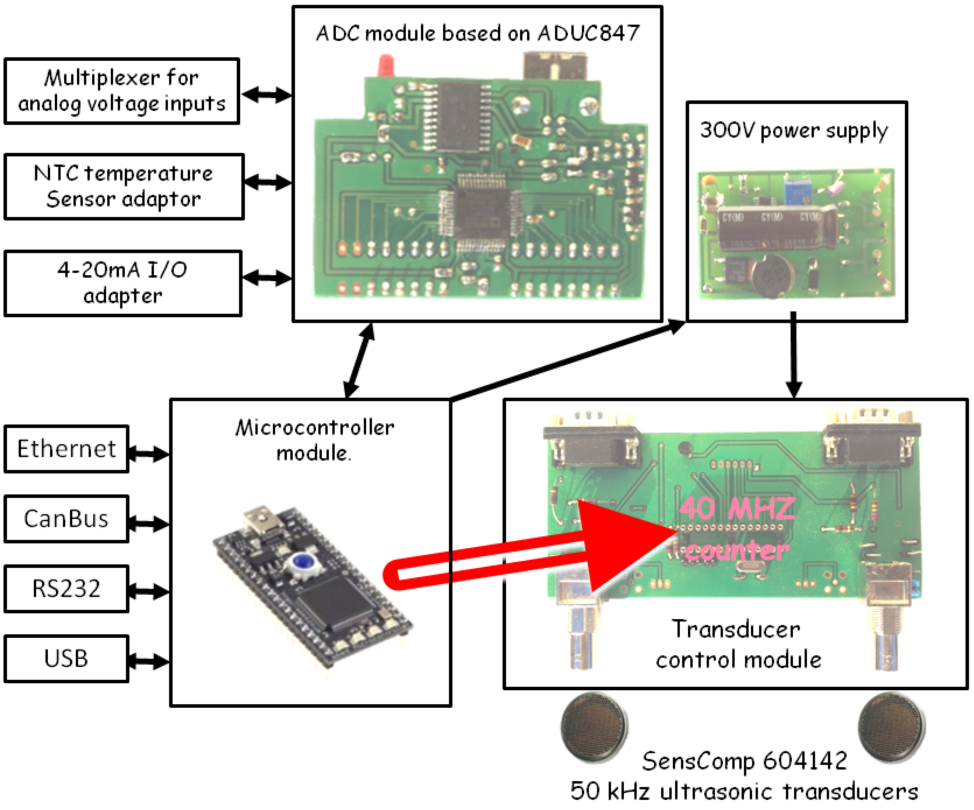

Figure 1. The principal elements of the local flowmeter/analyzer electronics and their interconnections.

The transducer biasing and amplification chain for a single channel is shown in figure 2. The transducer DC bias voltage of around +300 V is provided by a custom DC-DC converter. When transmitting, the transducer is excited by a downgoing (∼ 300 → 0 V) square wave pulse generated in a driver circuit from a TTL pulse from the microcontroller. The transducer is AC-coupled to a signal chain containing differential and programmable gain amplifiers followed by a fast comparator.

A fast (40 MHz) transit time clock, generated in the same microcontroller, is started in synchronism with the leading edge of the transmitted 50 kHz sound pulse. The first received sound pulse crossing the user-definable comparator threshold level stops this clock, as shown in figure 3. The time between the transmitted and first received sound pulses is measured by the microcontroller, which also handles communication via a USB/RS232 interface.

For flowmetry sound transit times are measured in opposite directions, which may be aligned with the flow of gas or inclined at an angle to it. Rolling average bi-directional transit times, temperature and pressure data continually stream from the FIFO memory to a supervisory computer in which the gas mixture composition and flow rate are continuously calculated using software implemented in PVSS-II version 3.8. When a measuring cycle is requested by the supervisory computer a time-stamped running average from the 300 most recent transit times in each direction in the FIFO memory is output, together with the average temperature and pressure, at a rate of up to 20 averaged samples per second. Analog temperature and pressure inputs are digitized with

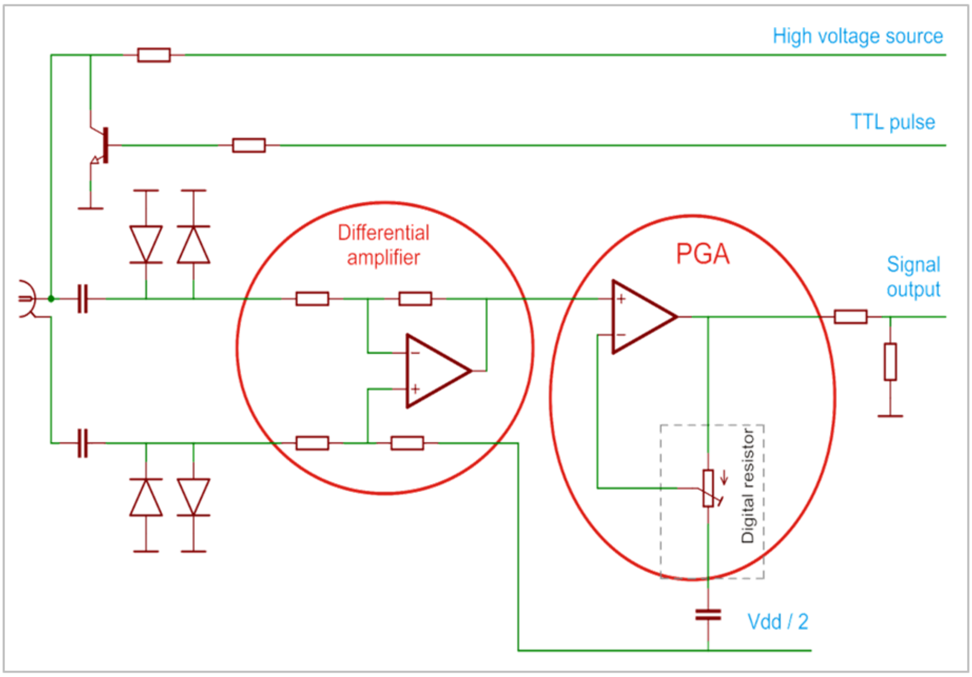

Figure 2. Ultrasonic transducer bias and amplification chain (one of two channels).

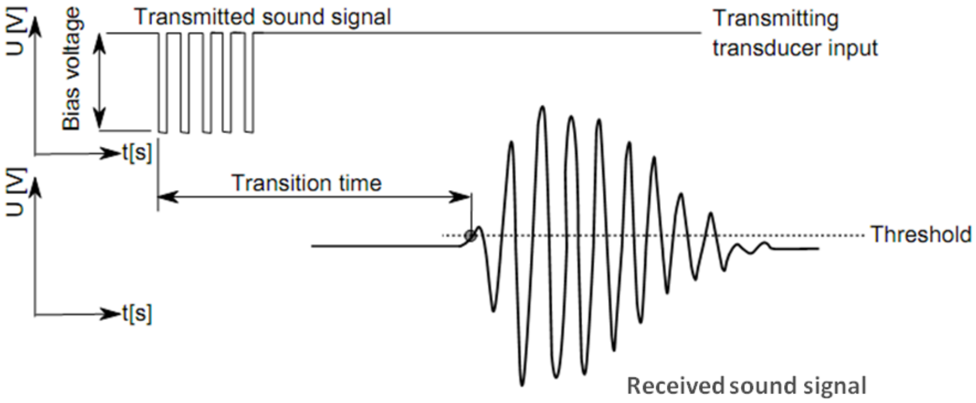

Figure 3. Principle of measurement of transit time between the first transmitted sound pulse and the first over-threshold detected pulse.

an ADC in an ADuC847 microcontroller. Additionally, two (4–20 mA) analog outputs provide feedback for adjustment of the C_3F_8/C_2F_6 mixing ratio in an external gas mixture control system.

3 Results from different implementations of the instrument

The "pinched axial" implementation of the flowmeter/analyzer — intended for gas flows up to $\sim 250\,\mathrm{l\,min^{-1}}$ — is illustrated in figure 4. Between the transducers, mounted 660 mm apart, vapour flows through a "pinched" tube of inner diameter 44.3 mm, comparable with the transducer diameter of 42.9 mm. Vapour is diverted around the transducers using PEEK® flow-deflecting cones.

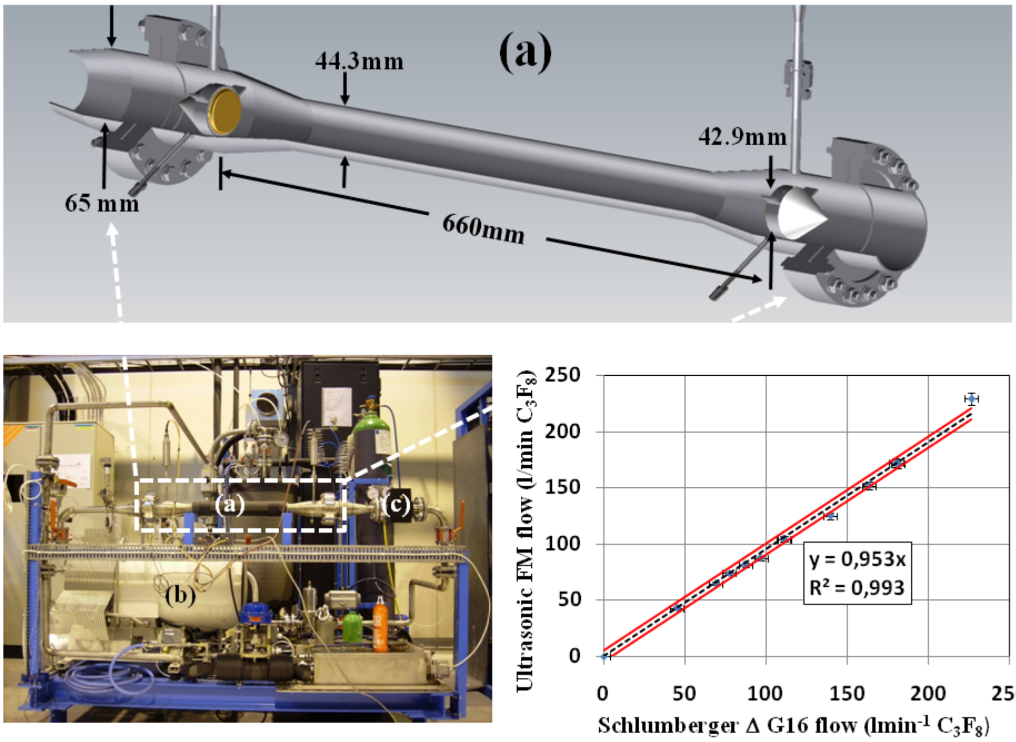

Figure 4. “Pinched axial” flowmeter/mixture analyzer: mechanical envelope (a), with transducers, mounts and flow-deflecting cones, together with installation at the C_2F_6/C_3F_8 blending and recirculation machine (b). Linearity comparison is with a Schlumberger Delta G16 gas meter [(c) downstream] in C_3F_8 at 1 bar_{abs} & 20°C (density $\sim 7.9\,\text{kgm}^{-3}$).

The temperature and pressure in the tube are monitored to a precision better than ± 0.3°C and ± 1 mbar.

In this geometry the vapour volume flow rate, V ($\text{m}^3\,\text{s}^{-1}$), is calculated from the sound transit times measured parallel, t_{down}, and anti-parallel, t_{up}, to the flow direction, according to:

$$V = \frac{LA(t_{\text{up}} - t_{\text{down}})}{2(t_{\text{up}} * t_{\text{down}})} \tag{3.1}$$

where L is the distance (m) between the foils of the transducers and A is the internal cross sectional area (m^2) of the tube linking them.

Figure 4 also illustrates the linearity of the ultrasonic flow meter element of the instrument in C_3F_8 vapour at 20°C and 1 bar_{abs} (C_3F_8 density $\sim 7.9\,\text{kgm}^{-3}$) through comparison with a Schlumberger Delta G16 volumetric gas meter (maximum flow rate $25\,\text{m}^3\,\text{hr}^{-1}$ [$417\,\text{l}\,\text{min}^{-1}$], with precision ± 1% of full scale — represented as horizontal error bars), at flows up to $230\,\text{l}\,\text{min}^{-1}$; the maximum possible in the presently-available C_3F_8/C_2F_6 blend recirculator shown in figure 4.

The vertical error bars reflect the combined uncertainties in the flowmeter tube diameter (± 0.5 mm), transit time measurement precision (± 100 ns) and transducer foil spacing (± 0.1 mm after distance calibration in an ideal static gas). The *rms* deviation of the ultrasonic flowmeter relative to the fit (shown as red bands) is $\pm 4.9\,\text{l}\,\text{min}^{-1}$, around 2% of the limiting flow of $230\,\text{l}\,\text{min}^{-1}$.

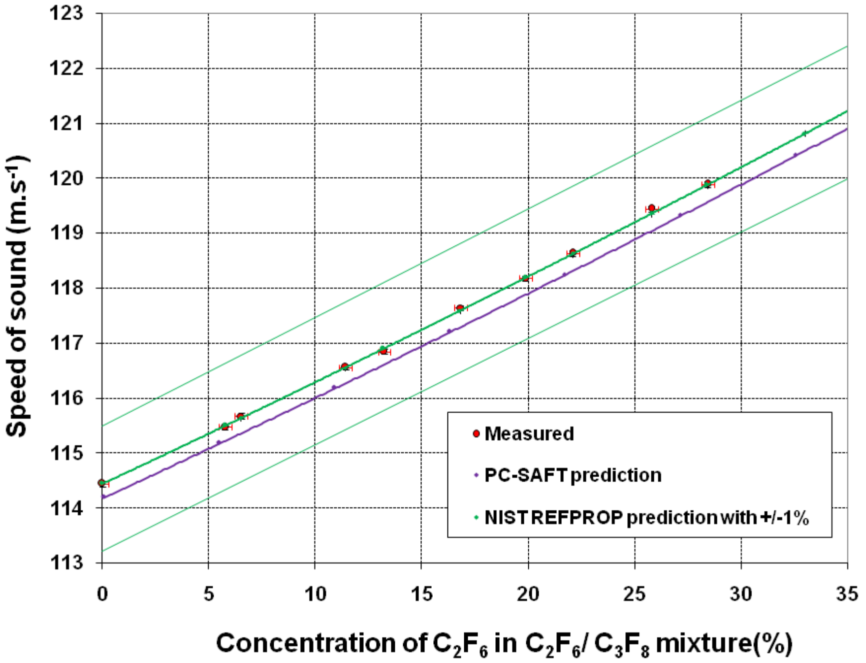

Figure 5. Comparison between measured sound velocity data and theoretical predictions in molar C_3F_8/C_2F_6 mixtures of thermodynamic interest. NIST-REFPROP predictions shown within a ± 1% band.

Figure 5 compares the sound velocity measured in the instrument in varying C_2F_6/C_3F_8 molar mixing ratios at a temperature of 19.2°C and a pressure of 1.14 bar_{abs} with predictions from two different theoretical models. The range of mixtures of C_3F_8 and C_2F_6 spans the region of thermodynamic interest to the ATLAS silicon tracker cooling application.

Contributions to the overall 0.05 m s^{-1} sound velocity measurement error, δc, were due to:

- ± 0.2°C temperature stability in the sonar tube (equivalent to ± 0.044 m s^{-1});
- ± 4 mbar pressure stability in the sonar tube (± 0.012 m s^{-1}) with the blend circulation machine in operation;
- ± 0.1 mm transducer inter-foil measurement uncertainty (± 0.018 m s^{-1});
- ± 100 ns transit time measurement (± 0.002 m s^{-1}).

The 16-bit precision of the analog input electronics results in an intrinsic accuracy 10–20 times finer than the operational stabilities in temperature and pressure quoted above.

The precision of mixture determination, $\delta(\text{mix})$, at any concentration of the two components is given by;

$$\partial(\text{mix}) = \frac{\partial c}{m} \tag{3.2}$$

where m is the local slope of the sound velocity/concentration curve ($\text{m s}^{-1}\,\%^{-1}$). From figure 5 it can be seen that the 0.05 m s^{-1} sound velocity uncertainty yields a concentration uncertainty $\sim$0.3% at 20% C_2F_6 in C_3F_8, where the slope of the velocity/concentration curve is $\sim -0.18\ \text{m s}^{-1}\,\%^{-1}$.

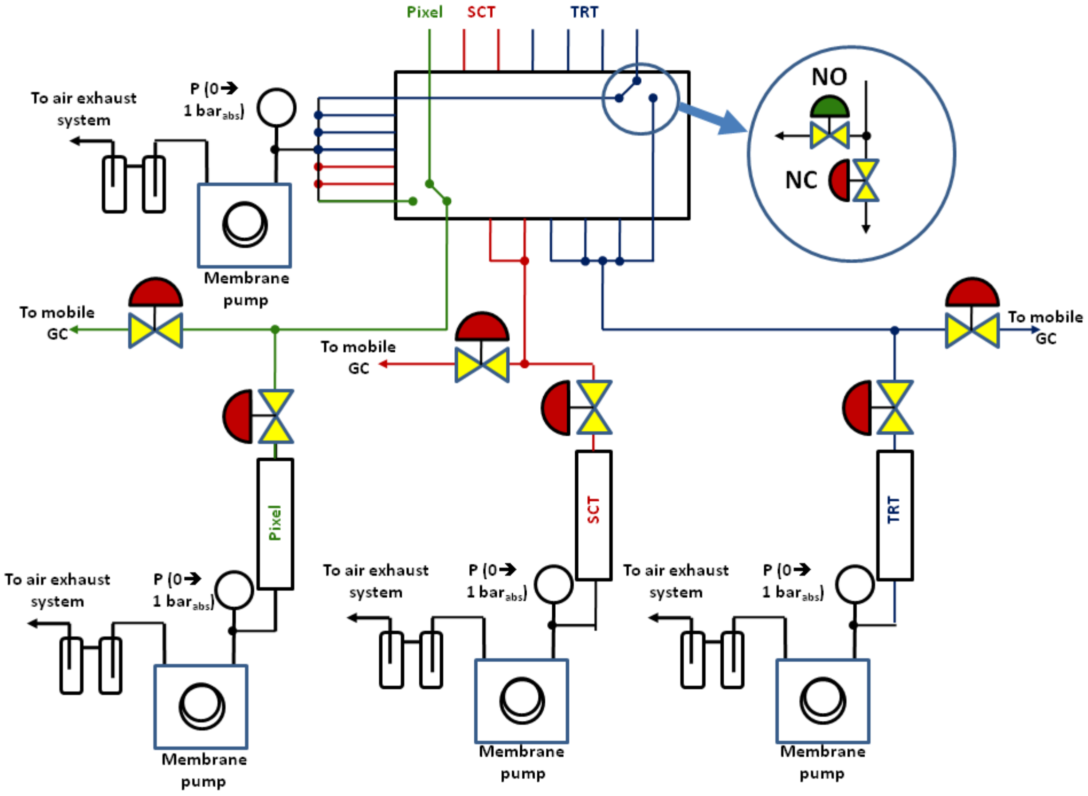

Figure 6. Automated sampling system for ultrasonic gas mixture analysis for continuous monitoring of C_3F_8 coolant leaks into the N_2 volumes surrounding the ATLAS silicon pixel and SCT trackers, and for future acoustic frequency mixture analysis of Xe leaks into the CO_2-containing volume surrounding the ATLAS TRT.

Our sound velocity measurements agree to within $\pm 0.05\,\mathrm{m\,s^{-1}}$ of the predictions of the NIST-REFPROP theoretical package [6], which are shown with $\pm 1\%$ variation in figure 5 for reference.

In a second application related to the ATLAS evaporative cooling system [7], we have been using real-time ultrasonic binary gas analysis for more than a year to detect low levels of C_3F_8 vapour leaking into the nitrogen environmental gas surrounding the ATLAS silicon pixel detector.

The gas extraction and sampling system is currently being extended (figure 6) to allow measurement of C_3F_8 leak rates into the N_2 gas envelope of the silicon microstrip (SCT) tracker, and also Xenon leaks from the straw tubes of the TRT (Transition Radiation Tracker) into its external CO_2 envelope. For the latter application new electronics is under development for operation in the acoustic frequency range 800–3000 Hz: a shift due to the high absorption of sound at ultrasonic frequencies by CO_2. This electronics will be reported at a later date.

Under PVSS control gas will be continually aspirated from 7 points (pixel: 1; SCT: 2; TRT: 4) on the ATLAS ID sub-detector environmental gas envelopes and sampled for sequenced analysis via a matrix of normally-open (NO) and normally-closed (NC) pneumatic valves into three simultaneously-operating analysis tubes. Gas exiting the three analysis tubes is vented to an air extraction system for return to the surface. Attachment points for periodic analysis using a portable gas chromatograph (GC) are also available. The sampling rates in the tubes are small enough

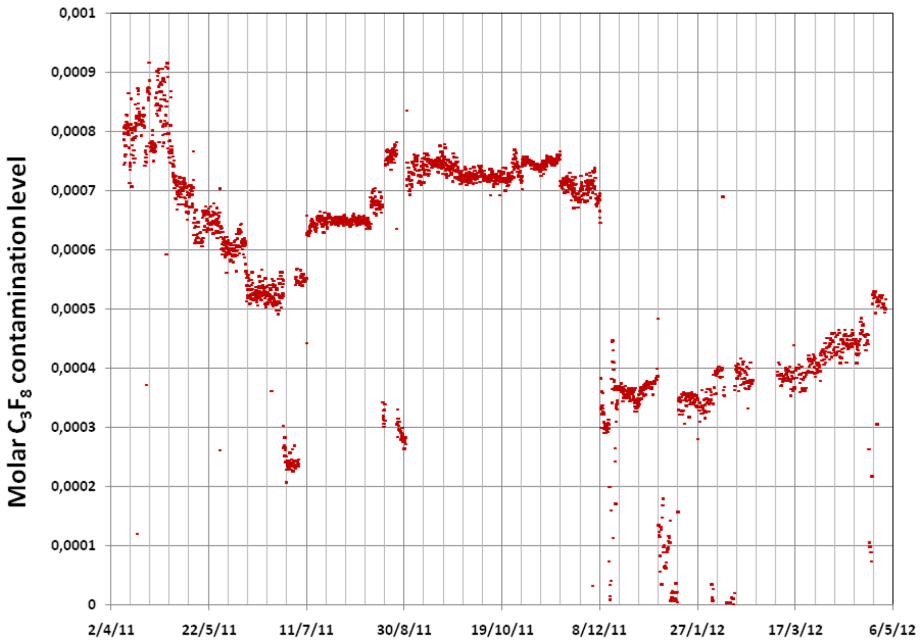

Figure 7. Long duration (1 year) log of C_3F_8 leak contamination in the N_2 environmental gas surrounding the ATLAS pixel detector.

($< 100\,\mathrm{cm}^3\,\mathrm{min}^{-1}$) for the gas to be considered static — flowmetry is of no particular interest in this sampling system.

Figure 7 illustrates a 1-year continuous log of the C_3F_8 contamination of the pixel detector environmental N_2 envelope. Fluctuations of the measured C_3F_8 contamination are correlated with the development of leaks in some of the 88 individual cooling circuits, which have been identified by progressive turn-on or turn-off.

A reduction in sound velocity of $\sim 0.86\,\mathrm{m\,s}^{-1}$ from that of pure nitrogen is typically observed when the full pixel detector cooling system is operating.

From the $\sim -12.27\,\mathrm{m\,s}^{-1}\,\%^{-1}$ average gradient of the sound velocity-concentration curve for concentrations in the range $0 \rightarrow 0.5\%$ C_3F_8 in N_2 this sound velocity difference indicates, via eq. (3.2), a C_3F_8 leak ingress of 0.07% (figure 7). The intrinsic sound velocity measurement uncertainty of $\pm 0.05\,\mathrm{m\,s}^{-1}$ correspondingly yields a mixture uncertainty of $\pm 0.004\%$ (4.10^{-5}).

Following replacement of the present underground compressor-driven C_3F_8 circulation plant by a thermosiphon [5], a combined ultrasonic gas mixture analyzer/flow meter will be installed in the single 133 mm diameter vapour return tube to the surface, where fluorocarbon linear flow rates of around $22\,\mathrm{m\,s}^{-1}$ are expected. Computational fluid dynamics (CFD) studies have shown [7] that only an angled crossing geometry with the transducers not impinging on the gas flow is suitable in this application. A prototype angled flowmeter built in PVC tubing with 45° crossing angle was tested — using electronics identical to that used in the pinched axial flowmeter/analyzer — in comparison with a commercial anemometer, in airflows up to $15\,\mathrm{m\,s}^{-1}$ [7]. The *rms* accuracy of the ultrasonic flowmeter was $\pm 1.9\%$ of full scale. These positive results have allowed us to construct the final instrument with 45° crossing angle in stainless steel tubing.

4 Conclusions and future applications

We have developed a combined real-time flow meter and binary gas analyzer with custom electronics and dedicated SCADA software running under PVSS-II, a CERN standard.

One version of the instrument has demonstrated a resolution of 3.10^{-3} for C_3F_8/C_2F_6 mixtures with $\sim 20\%$ C_2F_6, and a flow precision of $\pm 2\%$ of full scale for fluorocarbon mass flows up to $30\,\mathrm{g\,s^{-1}}$. A sampling instrument [7] has also been in use for more than 1 year to monitor C_3F_8 leaks into part of the ATLAS silicon tracker nitrogen envelope. Sensitivity to C_3F_8 leak concentrations of $< 10^{-4}$ has been demonstrated in this instrument. The gas sampling system is presently being upgraded to allow two additional analyzers, including an acoustic frequency (1–3 kHz) version for the monitoring of Xenon leaks into the CO_2 gas envelope of the ATLAS TRT.

A high flow instrument with a sound path angled at 45° to the gas flow has been developed for the 60 kW thermosiphon recirculator currently under construction for the ATLAS silicon tracker where flow rates of $< 400\,\mathrm{l\,s^{-1}}$ ($22\,\mathrm{m\,s^{-1}}$) are expected. Tests with a prototype [7] in air at flows up to $15\,\mathrm{m\,s^{-1}}$ have demonstrated a flow measurement precision of $\pm 1.9\%$ of the full scale. A final instrument is under construction and will be tested in air and with fluorocarbons.

The instruments described in this work have many potential applications where precise and rapid binary gas mixture analysis is required in real-time. Such applications include the analysis and flowmetry of Cherenkov detector radiator gas mixtures, hydrocarbon mixtures, vapour mixtures for semi-conductor manufacture and anaesthetic gas mixtures.

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2013 JINST 8 C01002