Custom ultrasonic instrumentation for flow measurement and real-time binary gas analysis in the CERN ATLAS experiment

To cite this article: M. Alhroob *et al* 2017 *JINST* **12** C01091

View the [article online](#) for updates and enhancements.

Related content

- [Development of a custom on-line ultrasonic vapour analyzer/flowmeter for the ATLAS inner detector, with application to gaseous tracking and Cherenkov detectors](#)
R Bates, M Battistin, S Berry et al.
- [A combined ultrasonic flow meter and binary vapour mixture analyzer for the ATLAS silicon tracker](#)
R Bates, M Battistin, S Berry et al.
- [Development of a custom on-line ultrasonic vapour analyzer and flow meter for the ATLAS inner detector, with application to Cherenkov and gaseous charged particle detectors](#)
M. Alhroob, R. Bates, M. Battistin et al.

PIXEL 2016 INTERNATIONAL WORKSHOP
SEPTEMBER 5 – SEPTEMBER 9, 2016
SESTRI LEVANTE, GENOVA, ITALY

Custom ultrasonic instrumentation for flow measurement and real-time binary gas analysis in the CERN ATLAS experiment

M. Alhroob,^a M. Battistin,^b S. Berry,^b A. Bitadze,^c P. Bonneau,^b G. Boyd,^a
O. Crespo-Lopez,^b C. Degeorge,^d C. Deterre,^e B. Di Girolamo,^b M. Doubek,^f G. Favre,^b
G. Hallewell,^g S. Katunin,^h D. Lombard,^b A. Madsen,^e S. McMahon,ⁱ K. Nagai,^j
A. O'Rourke,^{c,e} B. Pearson,^a D. Robinson,^k C. Rossi,^{l,1} A. Rozanov,^g E. Stanecka,^m
M. Strauss,^a V. Vacek,^f R. Vaglio,^b J. Young^a and L. Zwalinski^b

^aDepartment of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, U.S.A.

^bCERN, 1211 Geneva 23, Switzerland

^cSchool of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, U.K.

^dPhysics Department, Indiana University, Bloomington, IN 47405, U.S.A.

^eDeutsches Elektronen-Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany

^fCzech Technical University, Technická 4, 166 07 Prague 6, Czech Republic

^gCentre de Physique des Particules de Marseille, 163 Av. de Luminy, 13288 Marseille, France

^hB.P. Konstantinov Petersburg Nuclear Physics Institute (PNPI), 188300 St. Petersburg, Russia

ⁱRutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, OX11 0QX, U.K.

^jDepartment of Physics, Oxford University, Keble Road, Oxford, OX1 3RH, U.K.

^kDepartment of Physics and Astronomy, Cavendish Laboratory, University of Cambridge, CB3 0HE, U.K.

^lINFN Genova, Via Dodecaneso 33, 16146 Genova, Italy,

^mInstitute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland

E-mail: cecilia.rossi@cern.ch

ABSTRACT: The development of custom ultrasonic instrumentation was motivated by the need for continuous real-time monitoring of possible leaks and mass flow measurement in the evaporative cooling systems of the ATLAS silicon trackers. The instruments use pairs of ultrasonic transducers transmitting sound bursts and measuring transit times in opposite directions. The gas flow rate is calculated from the difference in transit times, while the sound velocity is deduced from their average. The gas composition is then evaluated by comparison with a *molar composition vs. sound*

¹Corresponding author

velocity database, based on the direct dependence between sound velocity and component molar concentration in a gas mixture at a known temperature and pressure.

The instrumentation has been developed in several geometries, with five instruments now integrated and in continuous operation within the ATLAS Detector Control System (DCS) and its finite state machine. One instrument monitors C_3F_8 coolant leaks into the Pixel detector N_2 envelope with a molar resolution better than $2 \cdot 10^{-5}$, and has indicated a level of 0.14 % when all the cooling loops of the recently re-installed Pixel detector are operational. Another instrument monitors air ingress into the C_3F_8 condenser of the new C_3F_8 thermosiphon coolant recirculator, with sub-percent precision. The recent effect of the introduction of a small quantity of N_2 volume into the 9.5 m^3 total volume of the thermosiphon system was clearly seen with this instrument.

Custom microcontroller-based readout has been developed for the instruments, allowing readout into the ATLAS DCS via Modbus TCP/IP on Ethernet. The instrumentation has many potential applications where continuous binary gas composition is required, including in hydrocarbon and anaesthetic gas mixtures.

KEYWORDS: Control and monitor systems online; Detector cooling and thermo-stabilization; Particle tracking detectors (Solid-state detectors)

Contents

1	Introduction	1
2	The instruments and implementation in the ATLAS Detector Control System	2
3	Measurement of C_3F_8 concentration in the environmental envelope of the pixel detector	6
4	Testing the degassing sonar sensitivity during thermosiphon commissioning	6
5	Conclusions	8

1 Introduction

Five custom ultrasonic (or “sonar”) instruments have been developed and integrated into the ATLAS Detector Control System (DCS) in applications related to the evaporative cooling of the ATLAS Inner Detector (ID) silicon tracker. They are installed at several different surface and underground locations in ATLAS, as illustrated in figure 1.

Figure 1. The five sonar instruments included in the ATLAS DCS and the ATLAS Inner Detector evaporative cooling systems: the degassing sonar is placed on the top of the thermosiphon condenser, the angled flowmeter is inserted in the vapour return line of the thermosiphon plant and finally the triple sonar tube installation monitors gas aspirated from the anti-humidity environments of the IBL, Pixel and SCT sub-detectors.

Three instruments aspirate gas from the N_2 - purged environmental envelopes surrounding the SCT, Pixel and IBL detectors to monitor leaks of C_3F_8 (octafluoropropane) and CO_2 coolant, while

two more are integrated into the control system of the new thermosiphon (TS) C_3F_8 evaporative coolant recirculator [1].

In the TS external plant — intended to replace the present compressor-driven system [2] for the cooling of the ATLAS SCT and Pixel detectors — the required liquid delivery pressure is provided by the hydrostatic column in a 92 m tube descending from a condenser to the ATLAS underground technical cavern. The TS external plant has been commissioned with pure C_3F_8 using an electrical dummy load (figure 1) representing the full 60 kW combined power dissipation of the SCT and Pixel detectors. It will maintain the present evaporating temperature of -25°C in the on-detector cooling structures, corresponding to a pressure of 1.67 bar_{abs} in pure C_3F_8 . Some results from recent commissioning studies are discussed in section 4.

Since the condenser is both the highest point and lowest (sub-atmospheric) pressure component of the TS recirculator, it is here where any ingressed air from leaks would accumulate. Such air ingress must be avoided to prevent its partial pressure from raising the condenser pressure from the nominal value of 309 mbar_{abs} thereby eroding the pressure differential needed to propel the required $1.2\text{ kg}\cdot\text{s}^{-1}$ C_3F_8 vapour flow back to the condenser against gravity. A “degassing” (DG) sonar is located above — and open to — the vapour space of the TS condenser volume. The sonar has a 50 cm vertical acoustic path, topped by a collection reservoir (figure 1). Ingressed air is detected through changes in measured sound velocity, causing a sequence of valves to be operated to evacuate it.

A second sonar device is configured as a low impedance angled flowmeter and is located underground, near the lowest point of the tube returning ascendant C_3F_8 vapour to the TS condenser. This device will operate initially as a C_3F_8 vapour flowmeter, but is also capable of providing simultaneous analysis of blends of C_3F_8 and C_2F_6 (hexafluoroethane). Future operation with C_3F_8/C_2F_6 blends containing up to 25% C_2F_6 is also possible in the present internal cooling system of the Pixel and SCT sub-detectors [3, 4] and would allow lower temperature operation of their silicon module substrates, providing a higher level of protection against radiation damage as the LHC luminosity increases.

The working principle of the ultrasonic instruments is described in section 2, while new measurements made with Pixel detector envelope sonar and the TS degassing sonar are discussed in following sections.

2 The instruments and implementation in the ATLAS Detector Control System

The ultrasonic instruments exploit the physical phenomenon whereby in a binary gas mixture at known temperature and pressure, the sound velocity depends only on the component molar concentrations. Pairs of 50 kHz capacitive ultrasonic transducers [5] are placed facing each other in flanged envelopes through which gas flows, either parallel or at an angle to the acoustic path. Sound bursts are transmitted in opposite directions and their transit times are measured in each direction, as illustrated in figure 2. Temperature and pressure are also measured simultaneously with sound transit times.

The transmitting transducer is excited by a burst of 1–8 high voltage ($\sim 350\text{ V}$) 50 kHz square wave pulses, generated from low-voltage precursors in a dsPIC33F microcontroller [6]. A 40 MHz transit time clock is started in synchronism with the leading edge of the first transmitted pulse and stopped when the amplified signal from the opposite transducer crosses a user-defined comparator

Figure 2. Principle of operation of the bidirectional ultrasonic transit time measurement.

threshold. Transmission in the opposite directions can be simultaneous or alternate: $500\ \mu\text{s}$ noise “blanking” is applied to both transducers; an interval corresponding to $\sim 1/3$ of the shortest expected transit time in the fastest component gas (pure N_2) over the typical 50 cm acoustic path lengths used in the instruments.

The difference between transit times in opposite directions can be used to compute the gas flow rate; while the average of the transit times is used — together with the known distance between the transducers — to calculate the sound velocity. The sound velocity is then used, with the measured temperature and pressure, to calculate the binary gas composition in real-time by comparing the measured sound velocity data with a stored *molar composition vs. sound velocity* database encompassing the likely concentration, pressure and temperature range of the process gas mixtures.

Bi-directional transit times, vapour temperature and pressure measurements are buffered, averaged, time-stamped, and pipelined through a FIFO (First In First Out) memory implemented in the dsPIC33F microcontroller for transmission to a Dell PowerEdge R610 SCADA (Supervisory Control And Data Acquisition) computer running Siemens SIMATIC WinCC-OA [7] under Linux. This software also implements a graphical user interface, archives data to the ATLAS DCS database and generates alarms which are propagated through the ATLAS alarm hierarchy.

Since the five sonar instruments are widely dispersed — in height alone by over 90 meters — communication uses TCP/IP Modbus over Ethernet. MBED LPC1768 platforms are installed in the sonar local electronics. In addition, the electronics can send and receive data via 4–20 mA analog current signals for interfacing with hard-wired control systems, particularly those of the TS recirculator.

Presently the mixture calculations are made using the SCADA computer, but in future versions of the instrument these calculations may be made in the on-board microcontroller for full standalone operation.

The stored *molar gas composition vs. sound velocity* curves can be determined from measurements in calibrated mixtures and/or from thermodynamic data entered into the general formalism

linking the sound velocity in a gas mixture with the (temperature and pressure-dependent) molar specific heats at constant pressure (C_{pi}) and volume (C_{vi}) of the pure component gases [8]. This thermodynamic data can be obtained using adapted equations of state: a convenient package for this is NIST-REFPROP [9].

In this formalism the sound velocity, c , is given by:

$$c = \sqrt{\frac{\sum_i w_i C_{pi} RT}{\sum_i w_i C_{vi} \sum_i w_i M_i}} \quad (2.1)$$

Where R is the universal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), T is the absolute temperature (K), w_i are the molar concentrations of the components and M_i their molecular weights (kg).

The relative precision of the mixture determination depends on the precision of the sound velocity measurement, δc , and on the molecular weight difference between the two gas components. The precision of the sound velocity measurement depends itself on several component uncertainties:

- Transducer spacing $\pm 0.1 \text{ mm}$;
- Temperature in sonar vessel $\pm 0.1^\circ \text{ C}$;
- Pressure in sonar vessel $\pm 1 \text{ mbar}$;
- Electronic transit time measurement precision $\pm 25 \text{ ns}$

When combined, these component uncertainties result in a sound velocity uncertainty of $\pm 0.025 \text{ ms}^{-1}$. The resulting uncertainty in the molar mixture composition measurement, δf , is then defined by:

$$\delta f = \delta c / m' \quad (2.2)$$

where m' is the local slope of the *sound velocity vs. concentration curve*. This slope is conventionally expressed as ($\text{ms}^{-1} [\text{molar}\% \text{ of gas B present in gas A}]^{-1}$), where A is typically the lighter carrier.

Examples of *sound velocity vs. gas composition* curves are shown in figure 3 for studies with gas pairs discussed in this paper.

The concentration-finding algorithm applies a 2-D interpolation to the fit parameters of the stored molar gas *composition vs. sound velocity* curves to generate parameters for the corresponding measured temperature and pressure. Binary gas composition is extracted from the measured sound velocity and these interpolated parameters.

The curves in figure 3/left correspond to the situations where C_3F_8 coolant from the ATLAS Pixel and SCT sub-detectors might leak into their N_2 -purged anti-humidity enclosures. Curves in figure 3/right correspond to situations where air contamination might ingress into the C_3F_8 in the TS condenser, which operates — along with much of the TS vapour side — below atmospheric pressure. As illustrated in figure 3, the greater the slope of the *sound velocity vs. molar concentration* curve, the more precise evaluation of the mixture. As an example in the interval for 0–10% air contamination in C_3F_8 where the average slope of the velocity/concentration curve is $\sim 0.56 \text{ ms}^{-1} \%^{-1}$, a sound velocity measurement precision of $\pm 0.025 \text{ ms}^{-1}$ would yield an uncertainty in air concentration of $\pm 0.04\%$. Over the 0–0.1% molar concentration range for C_3F_8 coolant leaking into N_2 from the SCT and Pixel sub-detectors, the slope is $-12.55 \text{ ms}^{-1} [\% \text{C}_3\text{F}_8]^{-1}$ resulting in a mixture precision of $\pm 0.002\%$.

Figure 3. Speed of sound in N_2 with up to 0.1% molar concentration of C_3F_8 , at various temperatures and a pressure of 1 bar_{abs} (left). — Speed of sound in C_3F_8 with up to 30% molar concentration of air (right) at various temperatures and a pressure of 300 mbar_{abs}.

All five instruments are now incorporated in the ATLAS DCS and its reporting Finite State Machine (FSM). Figure 4, from the FSM graphical user interface, illustrates the Pixel environmental gas sonar panel and the valve control panel for aspirating sonars for the Pixel, SCT and IBL environmental volumes. In addition to the ultrasonic instrumentation, the control system for these instruments includes electronics to control the aspiration pumps and sequence the gas streams to be monitored. The sonar tubes can also be recalibrated when necessary with N_2 (figure 4) using the FSM user interface. The five sonar instruments are continuously sampled, with their transit times, sound velocity, gas composition, temperature and pressure data recorded in the ATLAS DCS database. Data are extracted for analysis using the ATLAS DCS Data Viewer (DDV) utility. In addition, on-line measurements of coolant leaks into the environmental volumes of the SCT, Pixel and IBL detectors and of air into the TS condenser DG sonar can generate alerts in the ATLAS alarm hierarchy, sending SMS messages requesting expert intervention.

Figure 4. Left: the Pixel environmental gas sonar panel of the ATLAS DCS Finite State Machine (FSM). Right: valve control panel for the aspirating sonars for the Pixel SCT and IBL environmental volumes.

3 Measurement of C_3F_8 concentration in the environmental envelope of the pixel detector

Figure 5 shows the concentration of C_3F_8 in the N_2 flushing gas around the Pixel detector and its on-detector cooling tubes. A steep rise in C_3F_8 concentration is observed following the simultaneous start of all 88 Pixel detector cooling circuits, followed by a slower increase to a concentration of about 0.14%.

A similar measurement was performed during the in 2012 Pixel turn-on [4] with groups of cooling circuits turned on sequentially. At that time a C_3F_8 concentration in the N_2 -purged envelope of 0.04% was reached with the majority of leaks coming from repaired cooling tubes in specific groups of the barrel pixel detector outer layer (layer “2”). In long term operation the C_3F_8 concentration in the pixel detector environmental volume also depended on the N_2 purge rate [4]. The overall leak rate appears to have increased from 2012 to 2016: a period which included the pixel detector removal and reinstallation. Additional layer-by-layer investigations are planned when the Pixel detector will be turned off in late 2016.

Figure 5. C_3F_8 concentration in the N_2 -flushed anti-humidity enclosure of the ATLAS pixel detector during turn-on of the detector cooling, January 28, 2016.

4 Testing the degassing sonar sensitivity during thermosiphon commissioning

During the commissioning of the TS with C_3F_8 circulation through a dummy load in July 2016 several tests were performed on the DG sonar. Figure 6 illustrates results with condenser operating at a temperature of around $-60^\circ C$ in July 2016. Around 12.00 on July 12, 20 litres of N_2 were injected into the lowest point of the vapour side of the TS recirculator (around 90 metres below the condenser) to simulate an air ingress, without the risk of icing. A rise in apparent air concentration of $\sim 3.5\%$ in the vapour seen by the DG sonar was observed over the next 48 hours as the N_2 gas migrated through C_3F_8 vapour in the chicane and baffle structure of the condenser toward the DG sonar. This increase was relative to a baseline level of around 26.5% from previous N_2 injections and the unvented accumulation from small leaks encountered and repaired over several weeks of running with the dummy load. Temperature and pressure of the sonar tube are simultaneously monitored. Also shown in figure 6/right is the temperature of the sonar tube itself. The sonar is

thermally insulated from the condenser beneath. The rise in apparent “air” concentration is not affected by the regular day/night temperature variations of the sonar tube and is indicative of the robustness of the “air in C_3F_8 ” concentration-finding algorithm.

Figure 6. Effect on concentration (in green) and speed of sound (in black), of adding 20 litres of N_2 to the vapour side of the TS system (July 12–14, 2016). The temperature and pressure in the sonar tube are also shown respectively in purple and red in the figure 6/right.

Later during the commissioning tests the condenser was isolated from the rest of the C_3F_8 circulation system and sealed with approximately 1500 kg of C_3F_8 liquid inside. It was then allowed to warm up, increasing the saturated vapour pressure of the C_3F_8 confined within it and consequently decreasing the sound velocity and the effective air concentration seen in the DG sonar. As the condenser was no longer actively temperature controlled it followed the day/night temperature and pressure fluctuations also seen in the DG sonar. Figure 7 illustrates these parameters for part of the warm up period (July 26 to August 4, 2016). The negative apparent air concentration seen in the DG sonar (figure 7) is due to the high condenser pressure, which was far outside the normal range of TS thermodynamic operation and beyond the pressure range of the *sound velocity vs. {concentration @ temperature, pressure}* database. Alarms were disabled during this warm-up study. Temperature and pressure of the sonar itself were simultaneously measured and are illustrated in figure 7/right. The sonar pressure reflects the condenser pressure by communication and the increase in the C_3F_8 saturated pressure due to the warm up is therefore noticeable also in the sonar.

Figure 7. Effect on effective air concentration (in green: see text) and sound velocity (in black) seen in the DG sonar (July 26 – August 4, 2016) during part of the period when the condenser was sealed and allowed to warm up. Pressure and temperature of the DG sonar are also shown respectively in red and purple in the figure 7/right.

5 Conclusions

We have developed custom ultrasonic instrumentation for continuous real-time flow measurement and monitoring of possible leaks in the evaporative cooling systems of the ATLAS silicon tracker. Binary gas compositions are evaluated by comparison of measured sound velocity with *molar composition vs. sound velocity* databases for gas pairs covering the expected ranges of temperature and pressure.

The instrumentation has been developed in several geometries, with five instruments now integrated in the ATLAS Detector Control System and its Finite State Machine. One instrument monitors C₃F₈ coolant leaks into the Pixel detector N₂ envelope with a resolution better than $2 \cdot 10^{-5}$, and has recently shown a level of 0.14% when all the cooling loops of the recently re-installed Pixel detector are operational. Another instrument monitors air ingress into the C₃F₈ condenser of the new thermosiphon coolant recirculator, with sub-percent precision. The effects of the introduction of a small N₂ volume into the 9.5 m³ total volume of the thermosiphon system were clearly seen with this instrument.

Custom microcontroller-based readout has been developed for the instruments, allowing readout into the ATLAS DCS via Modbus TCP/IP on Ethernet. These instruments have many potential applications in processes requiring continuous monitoring of binary gas composition, including for hydrocarbon and anaesthetic gas mixtures.

References

- [1] M. Battistin et al., *The thermosiphon cooling system of the ATLAS experiment at the CERN Large Hadron Collider*, *Int. J. Chem. Reactor Eng.* **13** (2015) 511.
- [2] D. Attree et al., *The evaporative cooling system for the ATLAS inner detector*, *2008 JINST* **3** P07003.
- [3] R. Bates et al., *A combined ultrasonic flow meter and binary vapour mixture analyzer for the ATLAS silicon tracker*, *2013 JINST* **8** P02006 [[arXiv:1210.4835](https://arxiv.org/abs/1210.4835)].
- [4] R. Bates et al., *The cooling capabilities of C₂F₆/C₃F₈ saturated fluorocarbon blends for the ATLAS silicon tracker*, *2015 JINST* **10** P03027.
- [5] Originally designed by Polaroid® for autofocus cameras: now available and marketed as the SensComp model 600 transducer, <http://www.senscomp.com/ultrasonic-sensors/>
- [6] M. Alhroob et al., *Development of a custom on-line ultrasonic vapour analyzer and flow meter for the ATLAS inner detector, with application to Cherenkov and gaseous charged particle detectors*, *2015 JINST* **10** C03045.
- [7] Siemens SIMATIC WinCC, <http://siemens.com/wincc>.
- [8] M. Alhroob et al, *Implementations of Custom Sonar Instruments for Binary Gas Mixture and Flow Analysis in the ATLAS Experiment at the CERN LHC*, *IEEE Trans. Nucl. Sci.* **63** (2016) 1659.
- [9] E. Lemmon, M. Huber and M. McLinden, *REFPROP Standard reference database 23*, version 9.0 U.S. 2010, National Institute of Standards and Technology.