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

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8th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging

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Sestri Levante (Genova)

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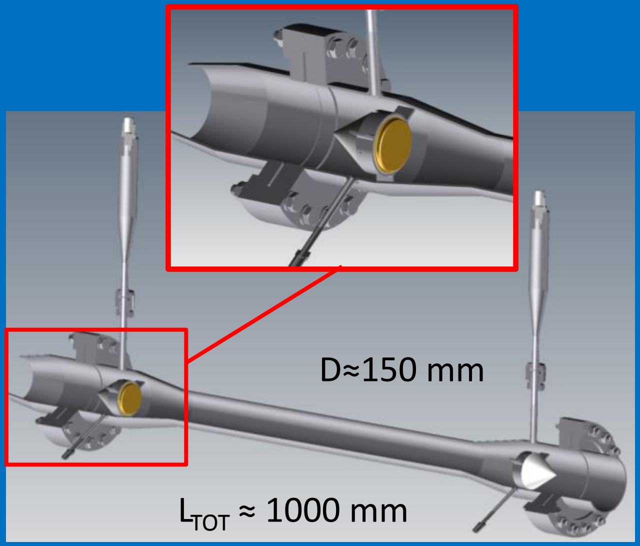
Overview

1. The instrument
2. Implementation in the ATLAS Detector Control System
3. Pixel detector measurements for C_3F_8 leak detection
4. Degassing sonar measurement during thermosiphon commissioning
5. Conclusion

The instrument

The electronic transducer or “sonar” is uses the phenomenon whereby - for a given pressure and temperature - the sound velocity is a binary gas mixture depends exclusively on the component molar concentration.

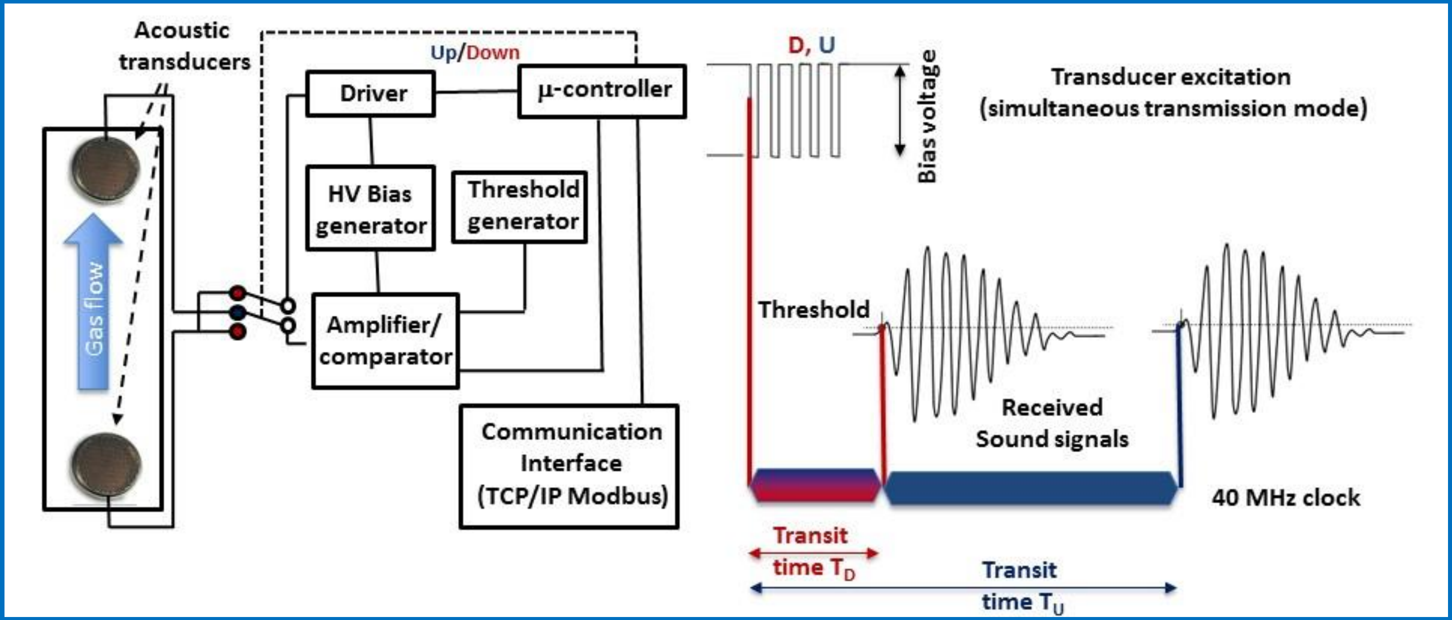
Pair of capacitative ultrasonic transducers placed facing each other in a flanged envelope through which gas flows (parallel or angled to the acoustic path).



Flanged stainless steel envelope housing a pair of 50 kHz capacitive ultrasonic transducers together with pressure and temperature sensors.

The instrument

The transmitting transducer is excited by a 1-8 high voltage (≈ 350V) wave pulse →
The signal is received by the 2nd transducer and passed to an amplifier and a comparator.



A 40MHz transit time clock is started in synchronism with the 1st transmitted wave and stopped when the amplified signal crosses a user-defined comparator threshold.
The time between the first transmitted and received signal is then measured.

The instrument

Real time measurements:

Difference in opposed direct transit time	→	gas flow rate
Average transit time + distance between transducers	→	sound velocity
Sound velocity + temperature and pressure + database	→	binary gas composition

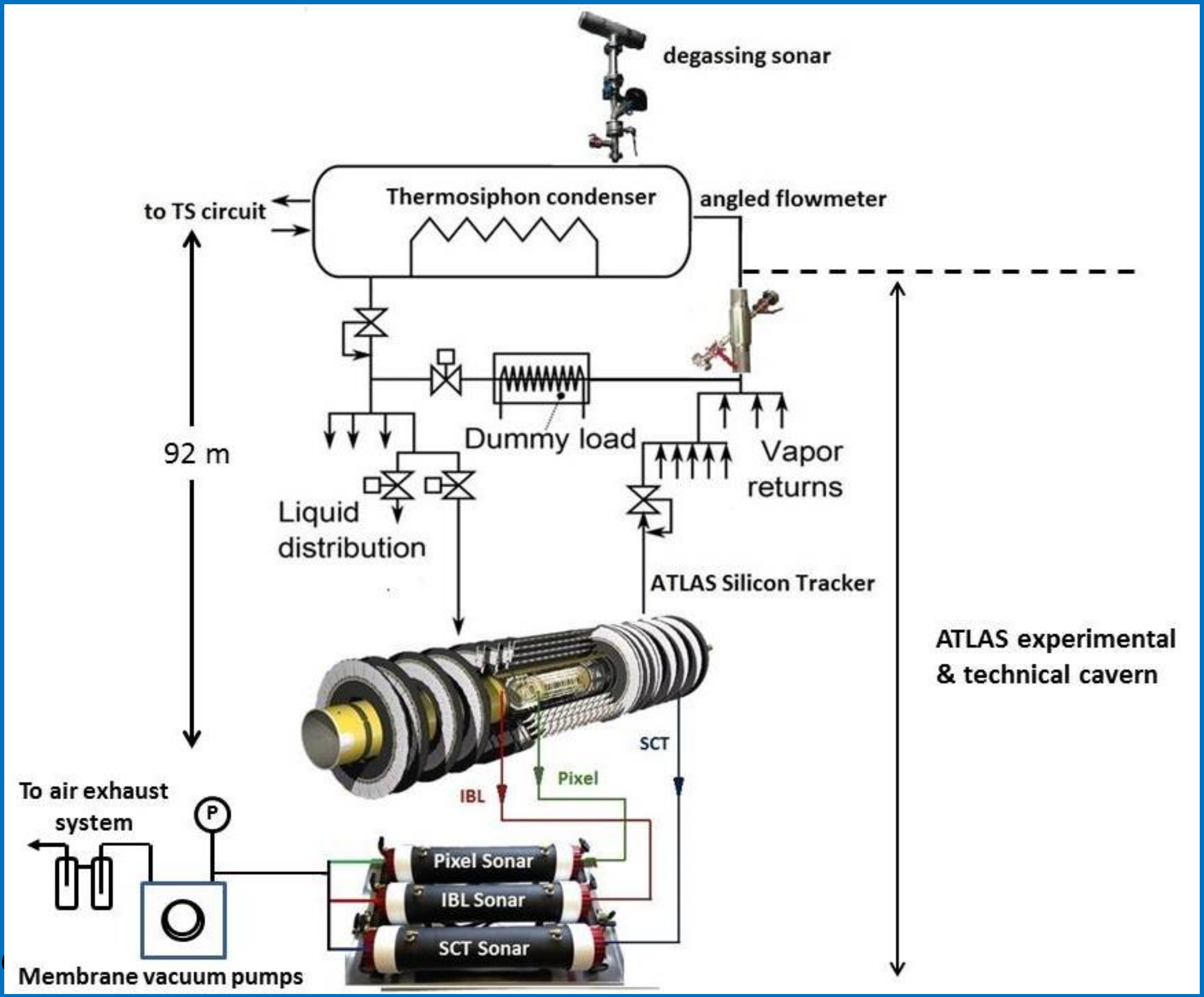
Gas composition vs. sound velocity database table created from prior measurements in calibration mixtures or theoretical thermodynamic calculations and stored in a supervisory computer (SCADA) connected to the sonar electronics.

The relative precision of the mixture determination depends on the precision of sound velocity measurements and on the molecular weight difference between the two gases.

Velocity uncertainty ± 0.025 m/s

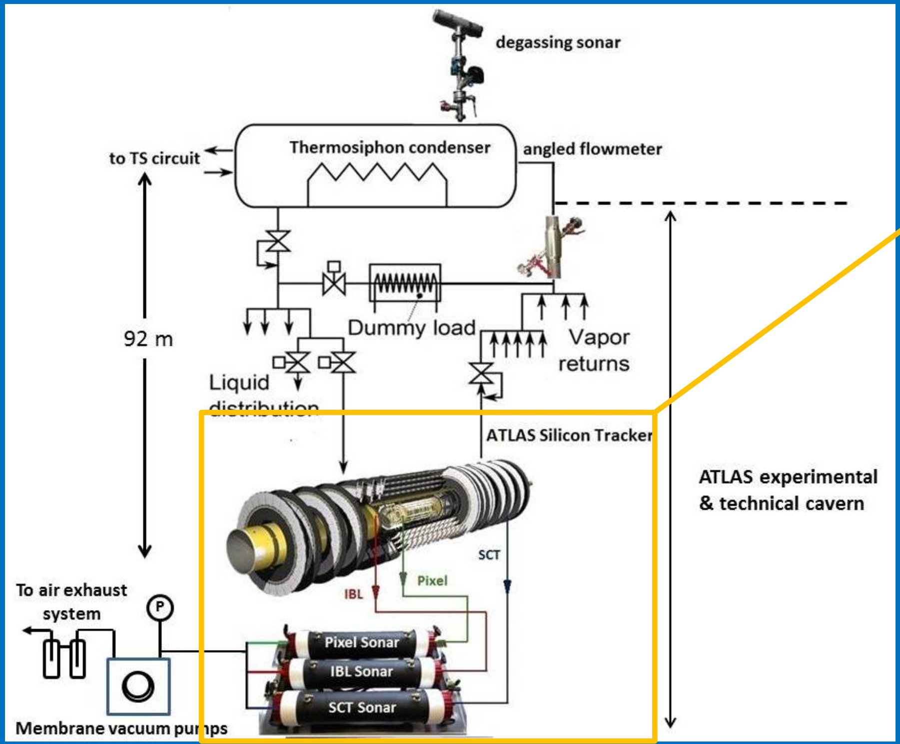
Implementation in the ATLAS Detector Control System

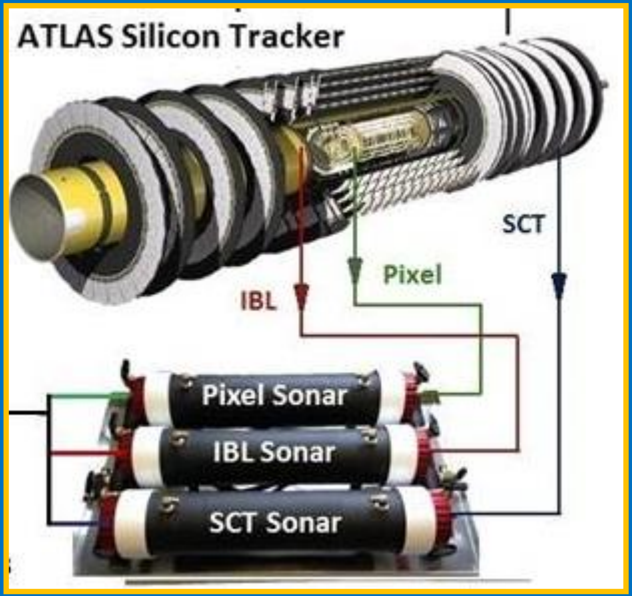
5 ultrasonic instruments are integrated into the ATLAS Inner Detector Control System :



Implementation in the ATLAS Detector Control System

- Triple sonar: aspirate gas from the N_2 -purged SCT, Pixel and IBL environmental envelopes to respectively monitor leaks of C_3F_8 and CO_2 coolant.
- Detectors are expected to work at very low temperature – Leak monitoring is crucial.





Pure N_2-purged environment envelope to avoid icing.

The system has to be monitored in real-time to promptly intervene in the unlikely event of leaks

→ Sonar instruments

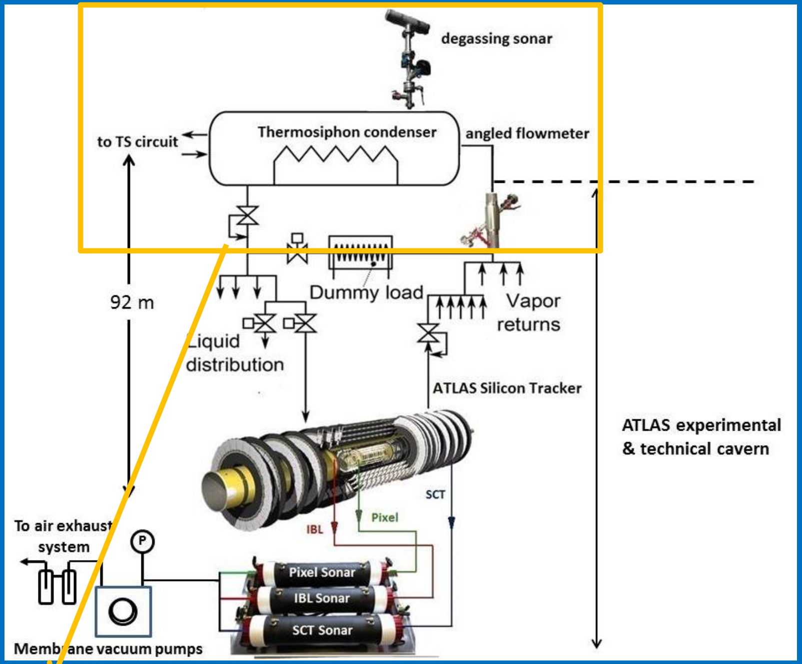
Implementation in the ATLAS Detector Control System

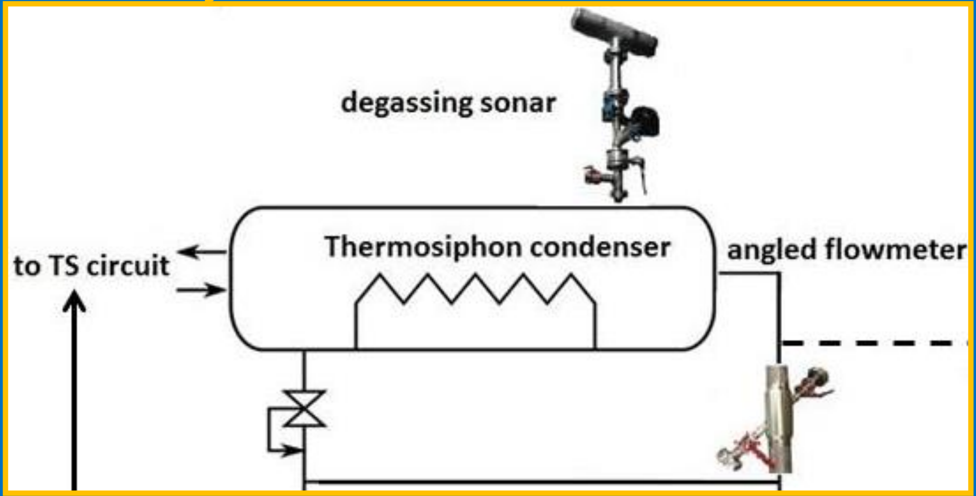
- Triple sonar: aspirate gas from the N_2 -purged SCT, Pixel and IBL environmental envelopes to respectively monitor leaks of C_3F_8 and CO_2 coolant.

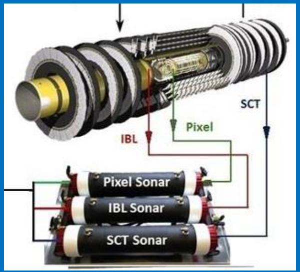
- Detectors are expected to work at very low temperature – Leak monitoring is crucial.

2 sonars are integrated in the new thermosiphon (TS) C_3F_8 evaporative cooling system:

- Degassing sonar: to detect/eliminate air ingress and prevent pressure increase in the condenser.
- Angled flowmeter: low impedance flowmeter placed in the vapour return line.







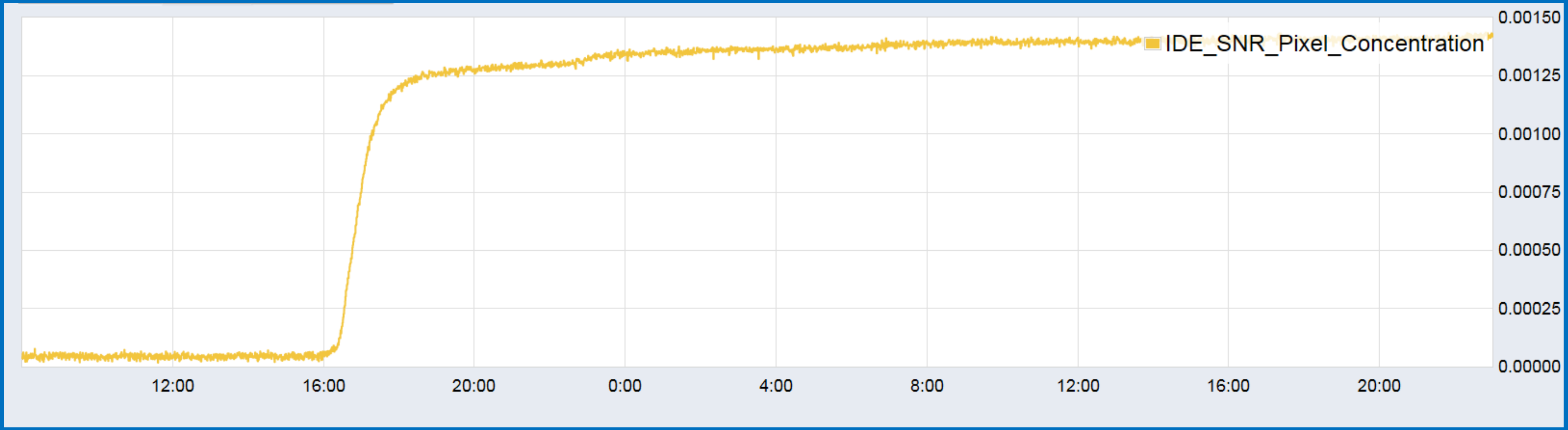
Pixel detector: Measurements of C_3F_8 concentration

The sonar instrument integrated in the Pixel detector measures the C_3F_8 concentration in the detector N_2-flushed anti-humidity enclosure.

<u>The absence of leaks monitored in real-time with high precision</u>

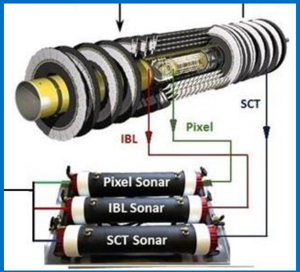
Mixture resolution $= 2 \cdot 10^{-5}$

During the powering of the Pixel detector in January 28, 2016, the instrument showed a steep rise in C_3F_8 concentration , due to the simultaneous start of all 88 Pixel detector cooling circuits.

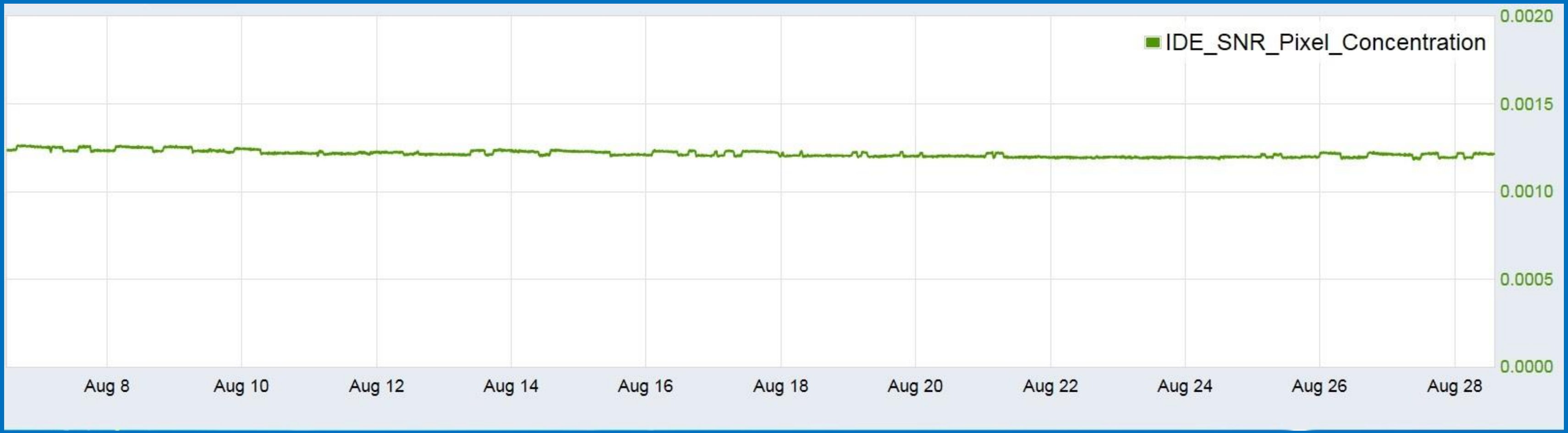


Trend of the C_3F_8 concentration during the simultaneous start of all Pixel detector cooling circuits in January 28, 2016.

Pixel detector: Measurements of C_3F_8 concentration



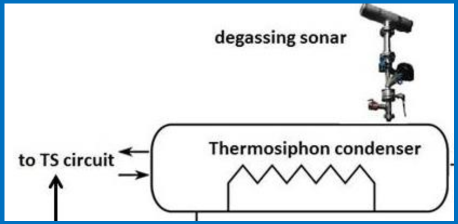
The Pixel detector cooling circuits and its sonar are now in operation.
The instrument Is measuring a stable C_3F_8 concentration in the N_2 envelope.



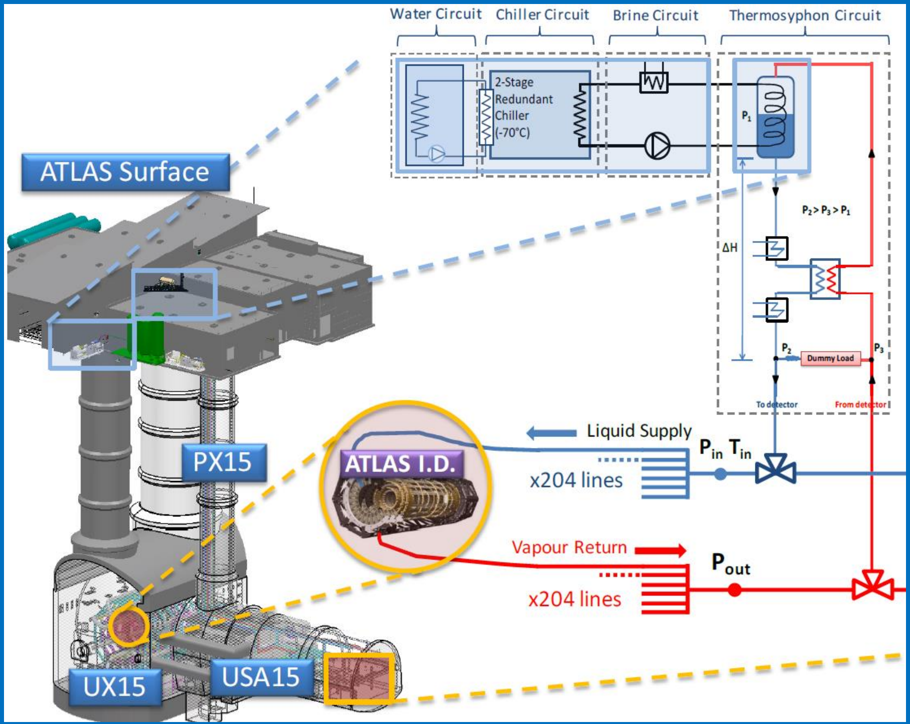
Concentration of C_3F_8 in the Pixel detector N_2-flushed anti-humidity enclosure monitored from 06 to 29 August 2016

Additional stress tests are planned when the Pixel detector will be turned off.

Measurement of degassing sonar



Thermosiphon (TS) plant: natural circulation system taking advantage of the great height difference between ATLAS experimental cavern and ground level (92m), aimed to replace the present compressor-driven cooling system.



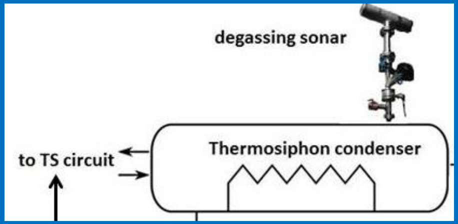
The driving force of the circuit is given by the 92m liquid column, starting from the condenser: refrigerant (C_3F_8) is condensed at a lower temperature/pressure but at the highest elevation, exits the detector at -25°C and 1.67bar_{abs} and then returns to condenser against gravity due to pressure differential.

Thermosiphon system :

- 60kW of on-detector cooling capacity,
- vapour pressure of 1.67 bar_{abs} /25°C at the end of the on-detector cooling loops
- Mass flow 1.2 $kg \cdot s^{-1}$.

During the TS commissioning several tests were done on the Degassing (DG) Sonar.

Measurement of degassing sonar



Sensitivity test:

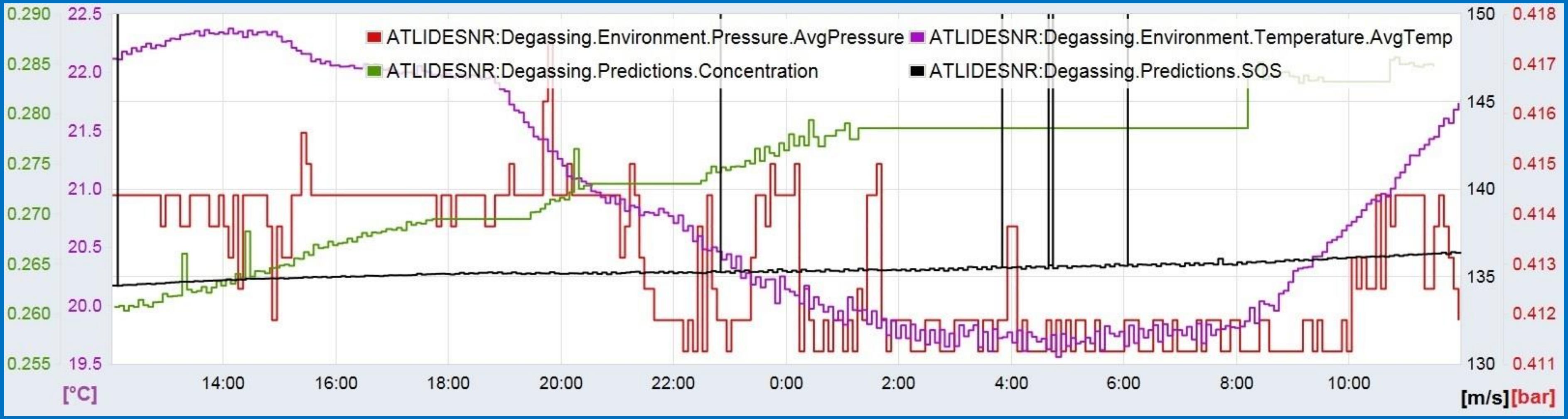
To simulate air ingress without risk of icing → 20L of N_2 in TS circuit vapor side (V_{TOT}≈9700L)

A rise in apparent air concentration of 2.6 % in the vapour is measured

→ sonar is sensitive to small injections

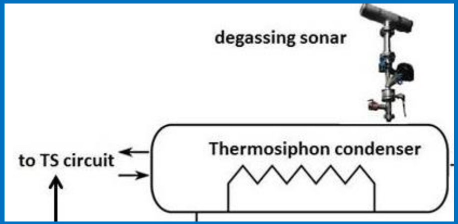
Temperature: 2.5 °C day-night variation. Rise in concentration not affected by regular day/night sonar tube temp variations.

Pressure: reflects the condenser pressure by communication (decrease due to the lowest N_2 vapour pressure).



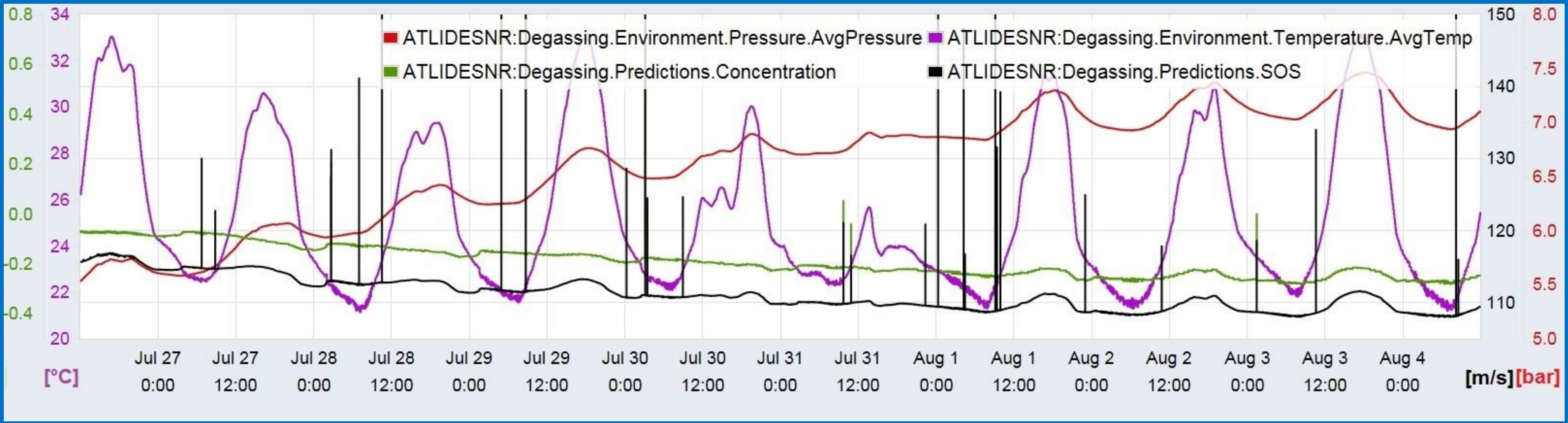
Effect on concentration and speed of sound of adding 20 litres of N_2 in TS circuit(July 12, 2016). Sonar temperature and pressure are also shown. Apparent air conc: N_2 is injected but the binary algorithm is set for air leaks into C_3F_8.

Measurement of degassing sonar



Warm-up test:

The condenser was isolated, C_6F_{14} cooling stopped and C_3F_8 allowed to warm-up
→ increase in C_3F_8 saturated pressure, slight decrease in concentration/speed of sound.
Negative apparent DG sonar air concentration due to the high condenser pressure (7.5 bar)
→ algorithm is reading a database from 300 $mbar_{abs}$ to 1.5 bar_{abs} (TS range).
The sonar was open to the condenser: day/night variation is visible on T and p.
Mixture resolution $5 \cdot 10^{-4}$



Effect on concentration and sound velocity during part of condenser warm-up (July 26 - August 4, 2016). Sonar temp. and pressure are shown. Apparent air conc: N_2 is injected but the binary algorithm is set for air leaks into C_3F_8.

Conclusion

ATLAS Tracker cooling system upgrade

A new instrument is required to monitor the system in real time.

Development of a combined ultrasonic instrument for leak detection and flowmetry

5 instruments now integrated in the ATLAS Detector Control System.

- Pixel detector: C_3F_8 coolant leaks are monitored in real-time into the Pixel detector N_2 envelope with a resolution better than $2\cdot10^{-5}$.
- TS system: Air ingress into the C_3F_8 condenser of the new thermosiphon coolant recirculator is monitored with high precision ($5\cdot 10^{-4}$). The effects of the introduction of a small N_2 volume into the total volume of the thermosiphon system can be clearly seen.

The instrument has many potential applications where continuous binary gas composition measurement is required: leak detection, hydrocarbon, anaesthetic gas mixtures, …

Thank you !

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Back up slides

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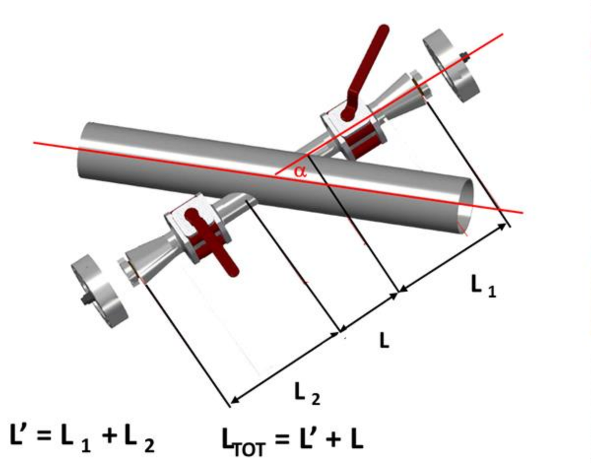
Formalism

$$t_{up} = \frac{L}{(c - v\cos\alpha)} + \frac{L'}{c}$$

$$v = \frac{c\left(ct_{up} - \frac{D_{Main}}{\sin\alpha} - L'\right)}{\cos\alpha\,(ct_{up} - L')}$$



<u>Where</u>:

t_{up} : transit time (the same values can be calculated for the transit time in the opposite direction (t_{down})
v : flow velocity in the main tube evaluated from transit time measurements

L : acoustic path length within the main flow tube
c : speed of sound in the gas
α : angle between the main pipe and the sonar tube
L' : remaining acoustic path length
D_{Main} : internal diameter of the main tube

Molar measurement precision in C_2F_6/C_3F_8 blends

The precision of the instrument for mixture determination depends on the uncertainty in measured sound velocity, **δc**; which itself depends on other measurement errors :

- Transducer spacing ± 0.1 mm
- Temperature in sonar vessel ± 0.1 °C
- Pressure in sonar vessel ± 1 mbar
- Electronic transit time measurement precision ± 25 ns

→ Overall sound velocity error ± 0.025 m/s

The precision on the concentration of the two components, **δ(mix)**, is given by

$$\partial(mix) = \frac{\partial c}{m'}$$

Where ***m'*** is the local slope of the sound velocity *vs.* molar concentration curve at the measured temperature and pressure

Instrument sensitivity for different blends mixtures:

Sonar – more sensitive to low concentration of heavy additive into light carrier
(slope of sound velocity/composition curve is steeper)

→ sound velocity uncertainty (0.025m/s) divided by larger gradient to get mixture resolution

<u>C_3F_8 leaks into N_2</u> (e.g. Pixel Detector envelope):

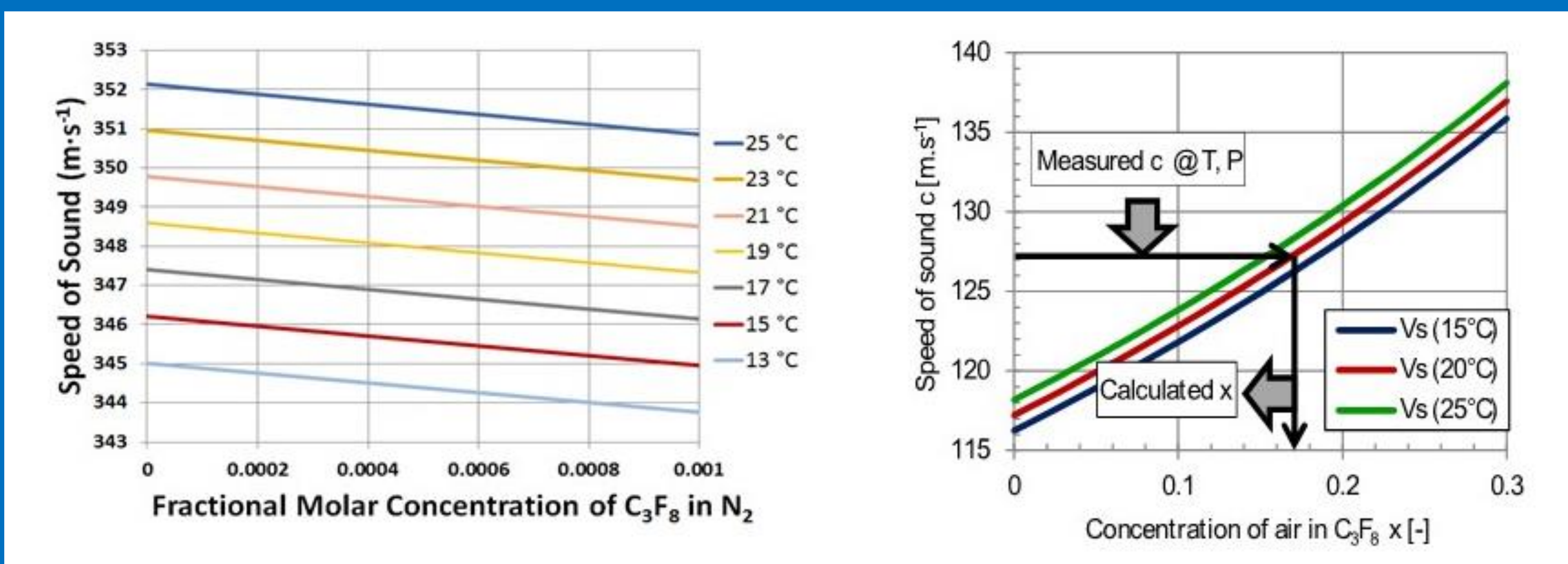
0 – 1 % C_3F_8 in N_2 → heavy additive (C_3F_8 : MW = 188) in light carrier (N_2 : MW = 28)

→ steep slope : -12.27 m/s/%C_3F_8 → Mixture resolution = 0.025/12.27 = 2 * 10^{-3} % = 2 * 10^{-5}

<u>TS Condenser</u>:

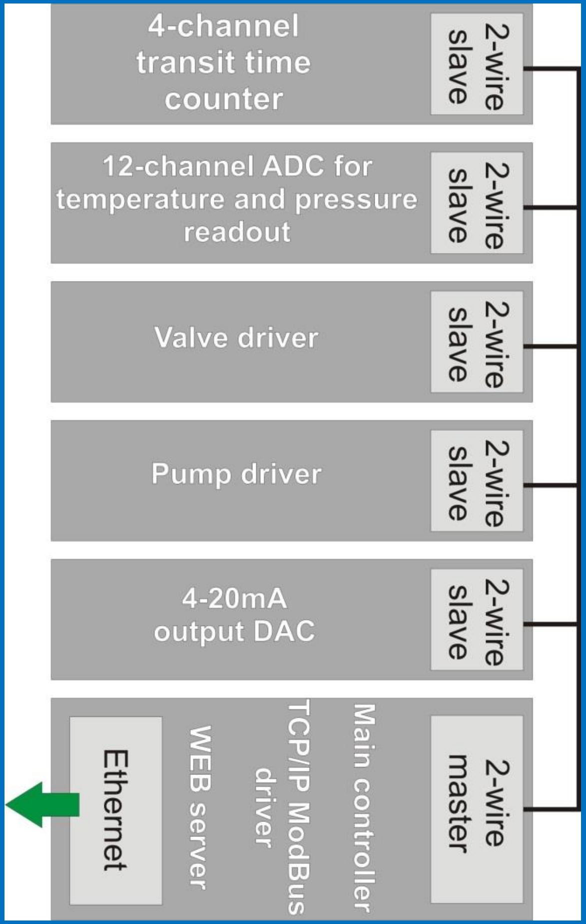
Air leaks into C_3F_8 → light contaminant (Air : MW = 29) into heavy carrier (C_3F_8 : MW = 188)

→ shallow slope : +0.53 m/s/%air → Mixture resolution = 0.025/0.53 = 0.05 % = 5 * 10^{-4}



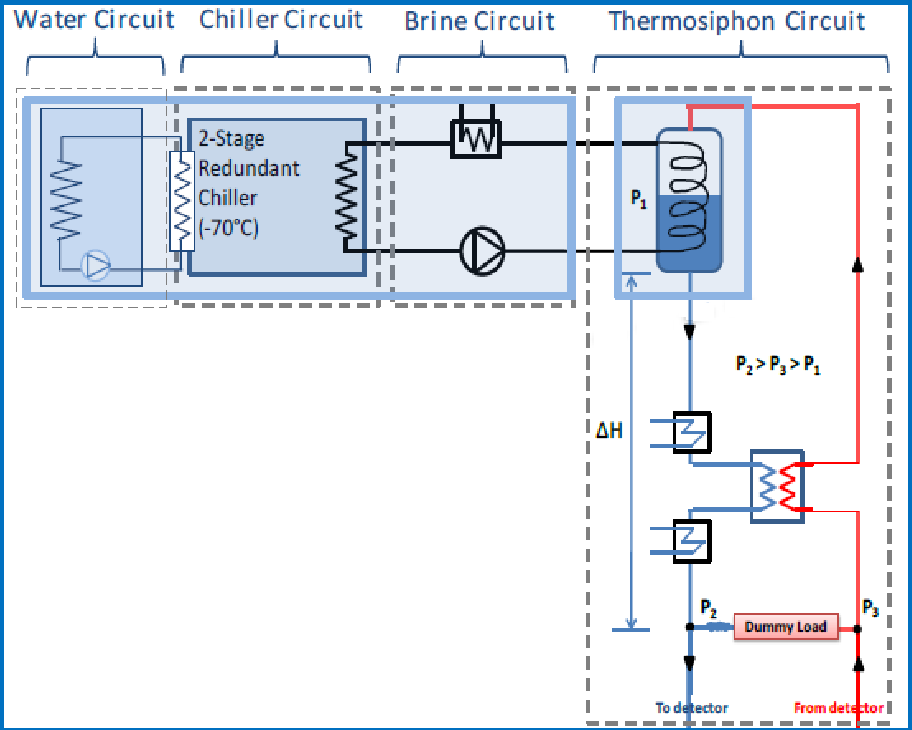
Implementation in the ATLAS Detector Control System

All the sonar are controlled via a dsPIC33F microcontroller and transmitted to a SCADA computer running a WinCC system. This sofware implements a graphical user interface (DDV) and archives data in the ATLAS DCS database via Modbus TCP/IP on Ethernet.



The full scale thermosiphon

Thermosiphon is composed of 4 separated circuits:



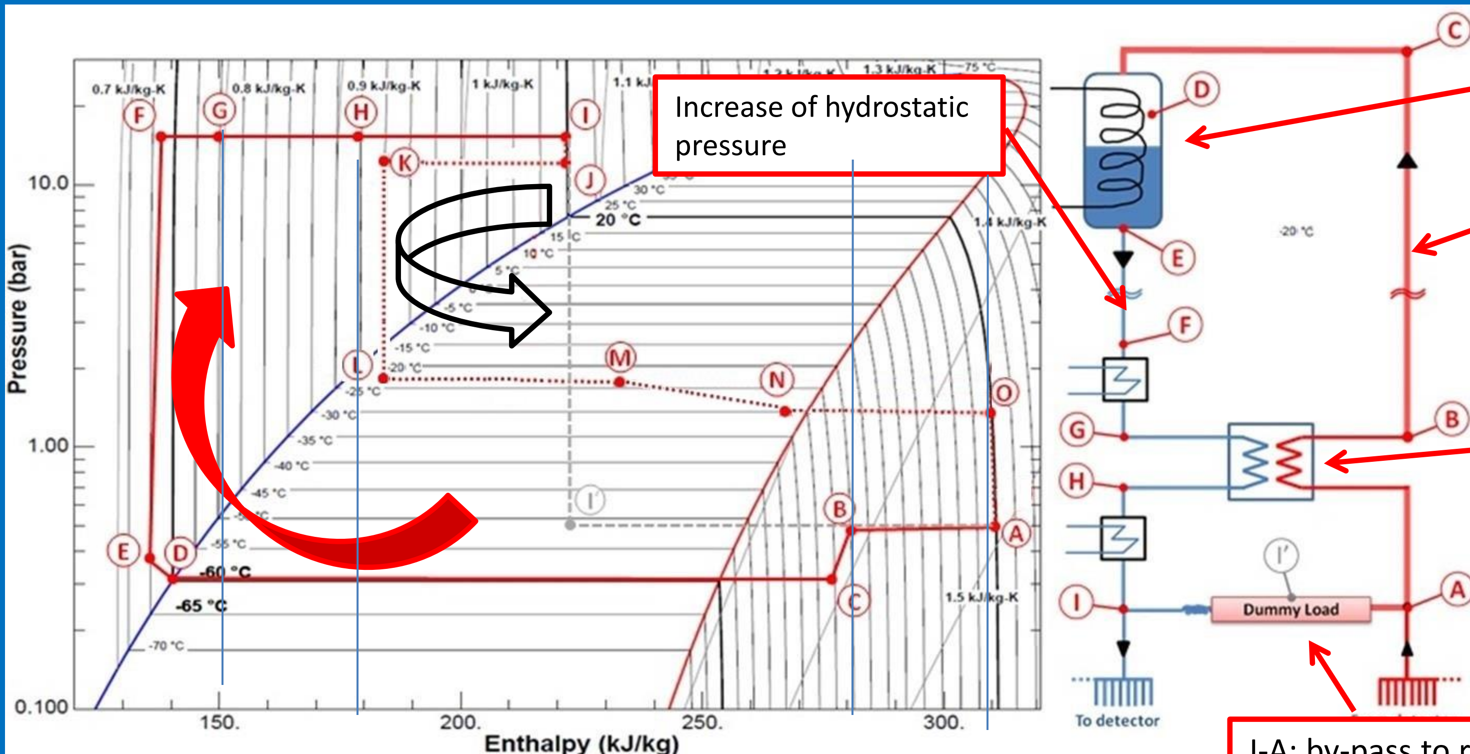
1. **Water circuit**: cooling the first stage of the chiller circuit: water from cooling towers at ~25°C:
2. **Chiller circuit**: two stage compression cycle to cool down perfluorohexane (C_6F_{14}) "brine" heat transfer liquid to -70°C. The chiller operates in cascade: the fist stage using R404a and the second stage R23;
3. **Brine circuit**: C_6F_{14} closed loop used to condense the C_3F_8 through heat exchange across the tubes in the condenser. C_6F_{14} is used as a transfer fluid mainly for its chemical similarity to C_3F_8;
4. **Thermosiphon primary circuit**: condensing C_3F_8 at surface to produce a liquid column from surface to cavern (exit pressure → hydrostatic column of 92 m of fluid). Liquid evaporates in the unchanged on-detector cooling channels and returns to surface as vapour by differential pressure. System must supply high pressure liquid to on-detector components, while guaranteeing the required evaporation pressure.

Compressors reliability → 1st reason for thermosiphon → also higher margin on required pressure/temp. @ detector
The target pressure (1.67 bar_{abs}) is specified at the end of on-detector cooling channels (point M).
→ Pressure drop in return line increases the operating temperature of the silicon detectors.

Compressor-driven cooling system → baseline pressure = min operable compressor pressure (1 bar_{abs});
Thermosiphon cooling system → baseline pressure = 500 $mbar_{abs}$ (point A)

→ Required evaporation pressure easier to achieve

The full scale thermosiphon



condenser and subcooling.
storage when system is stopped.

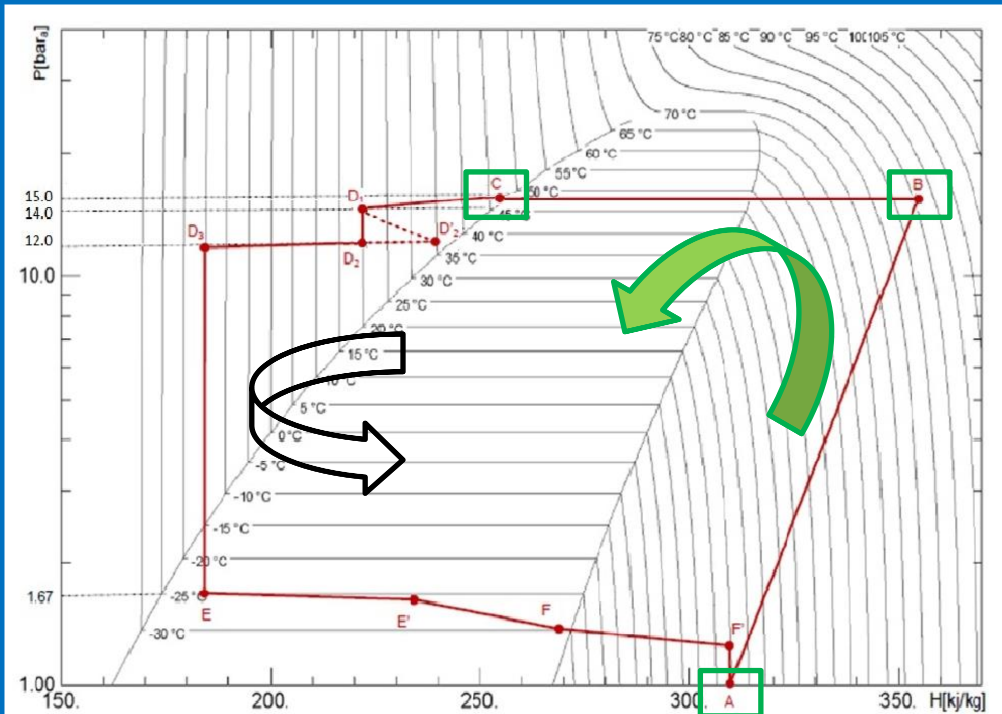
pressure drop along vapour return line (vapour column weight and frictional pressure drop)

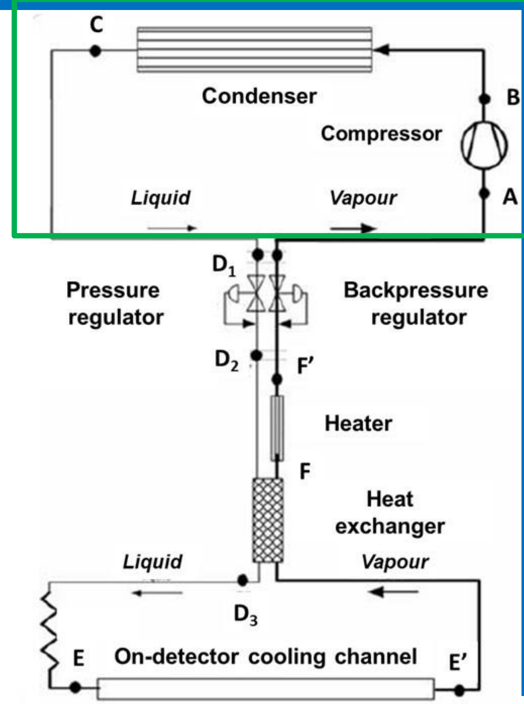
counter flow heat exchanger

I-A: by-pass to rapidly ramp down at start-up. Stable performance even when SCT and Pixel trackers are off (minimum thermal load).

Thermodynamic cycle of the thermosiphon circuit and corresponding schematic. Thermosiphon circuit (A-I). Beyond these points C_3F_8 enters the internal cooling circuits. Fluid exits the detectors at point M point (E' in the previous compressor evaporative cycle)

Operating point	Pressure [bar_{abs}]	Temperature [°C]	Density [kg/m^3]	Enthalpy [kJ/kg]	Physical State
A	0.5	20	3.90	310.8	Superheated vapour
B	0.495	-20	4.65	280.6	Superheated vapour
C	0.309	-25	2.85	277.4	Superheated vapour
D	0.309	-60	1699	140.3	Saturated liquid
E	0.4	-65	1717	135.7	Sub-cooled liquid
F	16.1	-62	1712	139.0	Sub-cooled liquid
G	16.1	-51	1672	149.2	Sub-cooled liquid
H	16	-20	1552	179.4	Sub-cooled liquid
I	16	20	1365	222.0	Sub-cooled liquid
I'	0.5	-51	7.89	222.0	Two-phase x=0.6





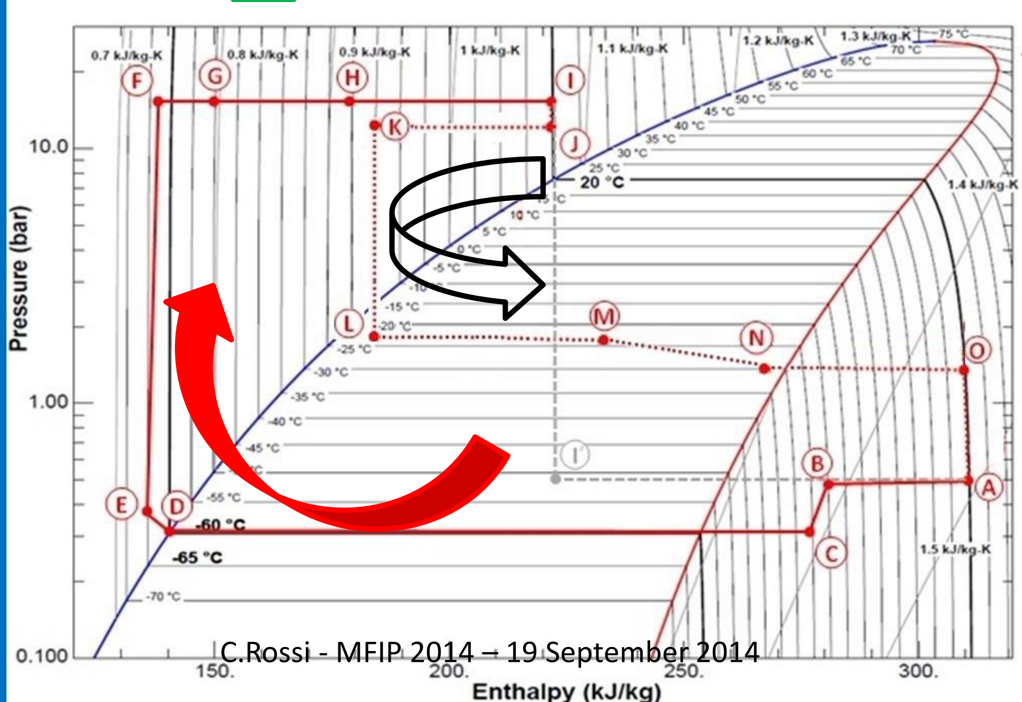
Compressor driven evaporative system (A-C)

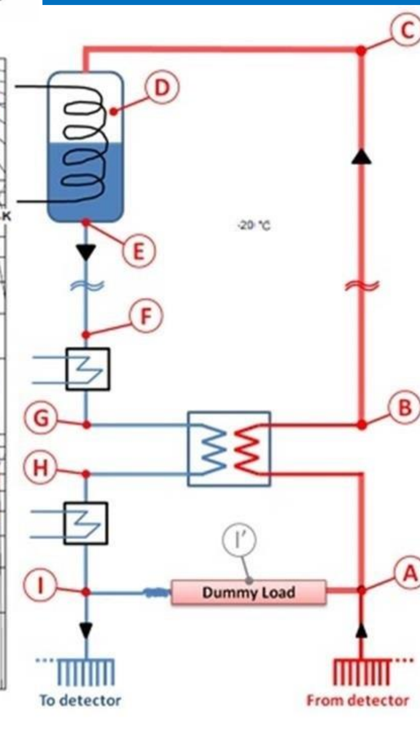
Internal circuit (D1 – F')

Thermosiphon circuit (A-I)

Internal circuit (J – O)

Evap	TS
D1	I
D2	J
D3	K
E	L
E'	M
F	N
F'	O





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