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An Acoustic System For Average Temperature Measurement Along a Distance

3D METROLOGY CONFERENCE

4th 3DMC - London

Novembre 5-7, 2019

Outline

- Introduction
- Description of the acoustic method for temperature measurement
- Presentation of the developed system
- Influence parameters of the temperature measurement
    - Distance measurement
    - Offset measurement
    - Uncertainty budget
- Conclusion

Introduction

$d = TOF \times c \,/\, n_{air}(T, p, RH, CO_2)$

- The accuracy of the optical distance measurements is limited by the knowledge of the air refractive index, which depends on environmental parameters (Elden's formula): Temperature, Pressure, Humidity, CO_2.
- In practice, high difficulty to determine the temperature along an optical path:
  uncertainty of 1 µm/°C/m on distance measurements induced by errors on the temperature.
- We aim at an accuracy on the distance measurement of 50 µm on a range of 50 m (i.e. 1°C).

➡ Determination of the average temperature along a pathway using an acoustic method

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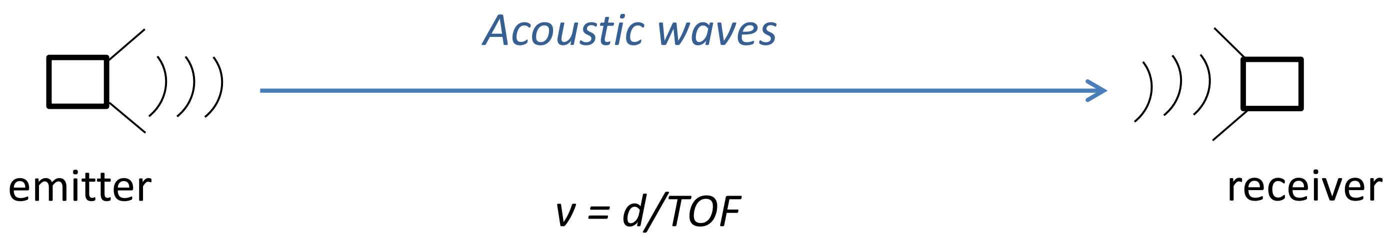
Description of the acoustic method for temperature measurement



- The speed of sound varies with the environmental parameters, mainly the temperature.
- Development of a system based the time of flight measurement of an ultrasonic acoustic wave between an emitter and a receiver (acoustic transducers) alongside with a distance measurement.

- Calculate the speed of the ultrasound: $v = d/TOF$
  with: d the distance between the transducers
  TOF the time of flight of the ultrasound

Relation between T and the speed of sound

- Speed of sound is a function of environmental parameters (Cramer's equation): *$v = f(T,p,RH,CO_2)$*

$$v(t,p,x_w,x_c) = a_0 + a_1 t + a_2 t^2 + (a_3 + a_4 t + a_5 t^2) x_w + (a_6 + a_7 t + a_8 t^2) p + (a_9 + a_{10} t + a_{11} t^2) x_c + a_{12} x_w^2 + a_{13} p^2 + a_{14} x_c^2 + a_{15} x_w p x_c ,$$

Empirical equation with an uncertainty of 300 ppm (0.1 m/s)

- for dT = 1 °C => dv = 0.616 m/s
- for dRH = 5 % => dv = 0.071 m/s (dT = 0.1 °C)
- for dp = 10 hPa => dv = 0.005 m/s (dT = 0.01 °C)
- for dCO_2 = 100 ppm => dv = 0.01 m/s (dT = 0.02 °C)

Only RH has a significant impact on the speed of sound measurement, and should be known in a range of 2-4 %

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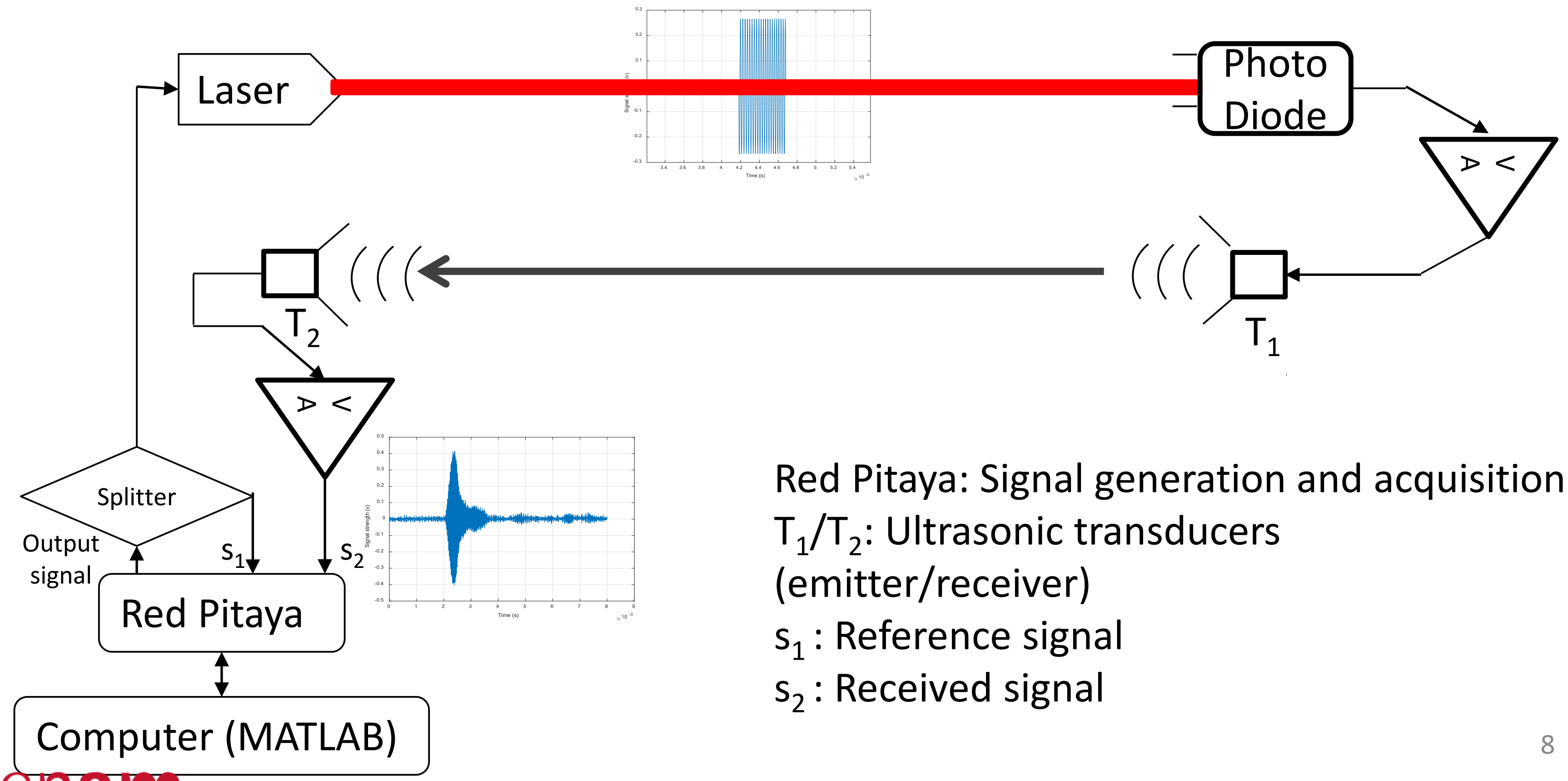
Description of the developed system



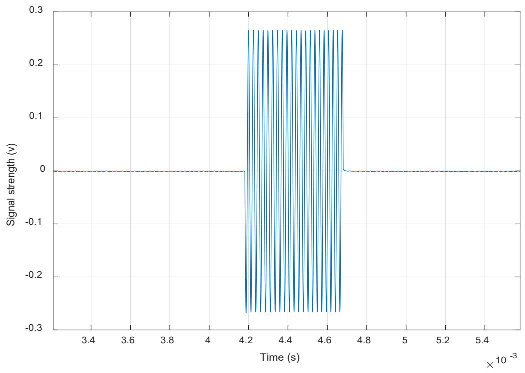
Red Pitaya: Signal generation and acquisition

T_1/T_2: Ultrasonic transducers (emitter/receiver)

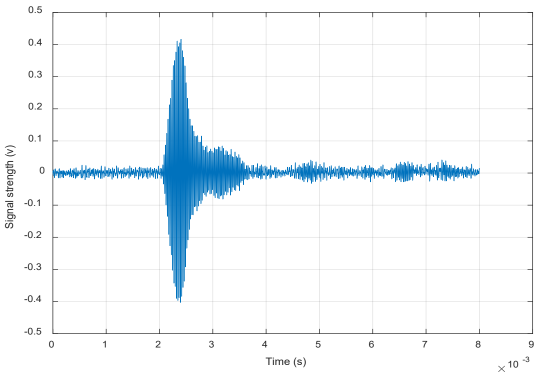
s_1 : Reference signal

s_2 : Received signal

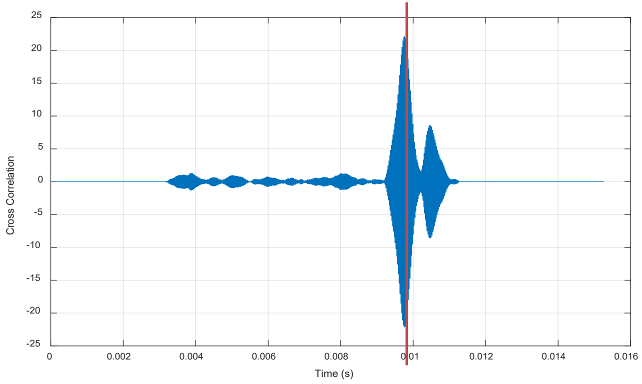
Description of the developed system



S_1: reference signal, linear chirp of 450 µs with frequencies going from 40 kHz to 44 kHz.



S_2: signal received after acoustic propagation and electronic amplification



Cross-correlation between S_1 and S_2: the maximum value indicates the difference time of arrival (DTOA).

The system's time resolution is about 0.5 µs, and limited by the sampling frequency of the Red Pitaya

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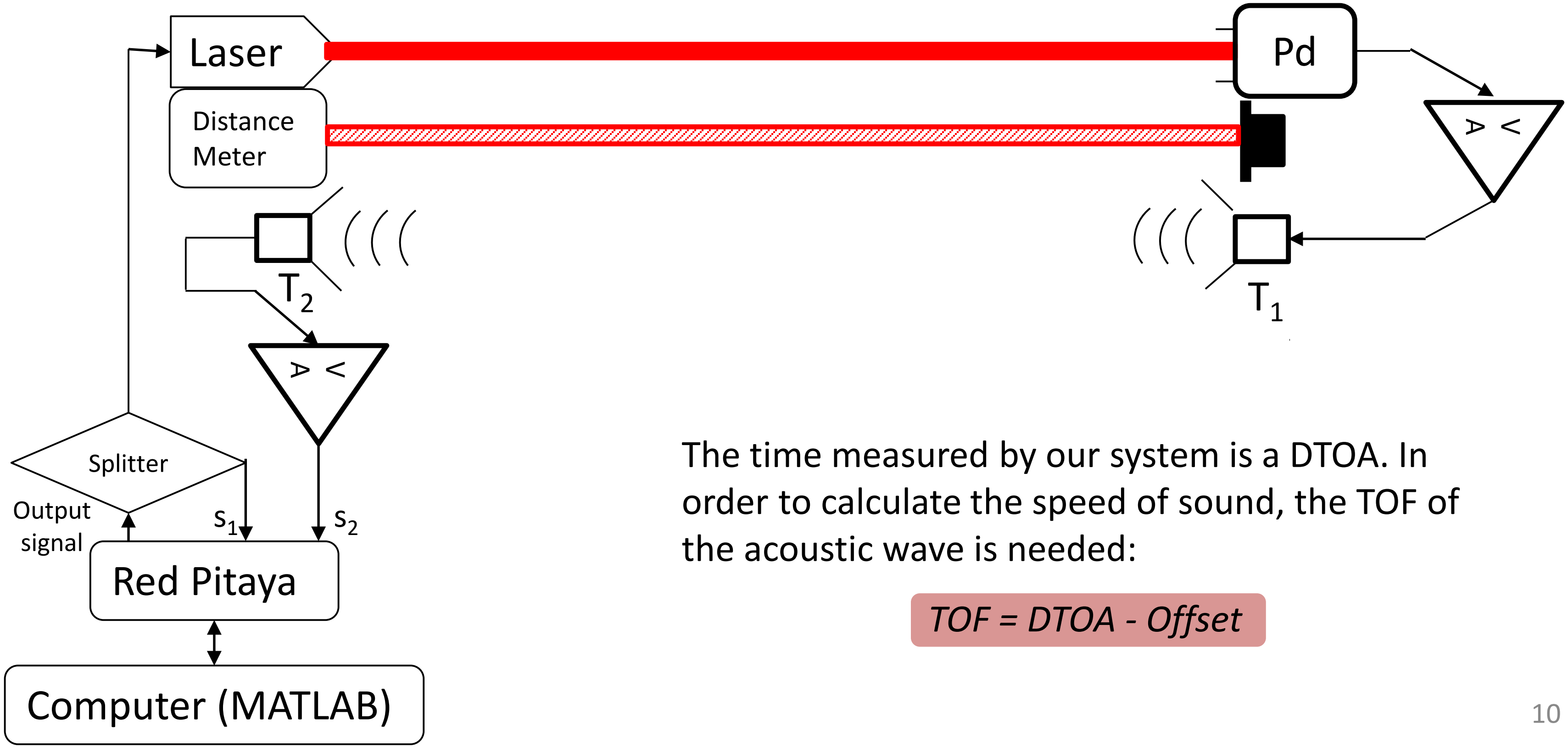
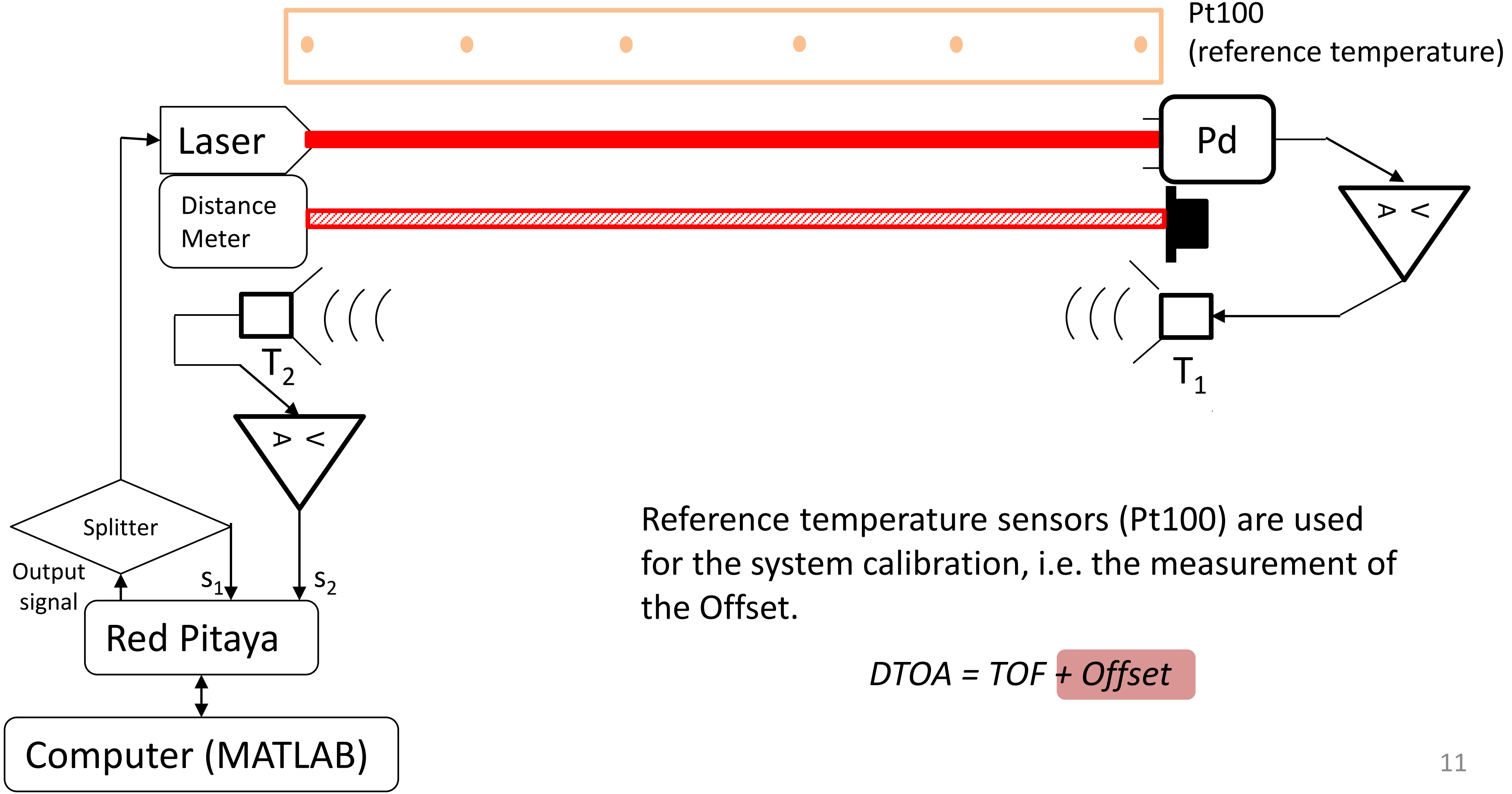
Description of the developed system



The time measured by our system is a DTOA. In order to calculate the speed of sound, the TOF of the acoustic wave is needed:

TOF = DTOA - Offset

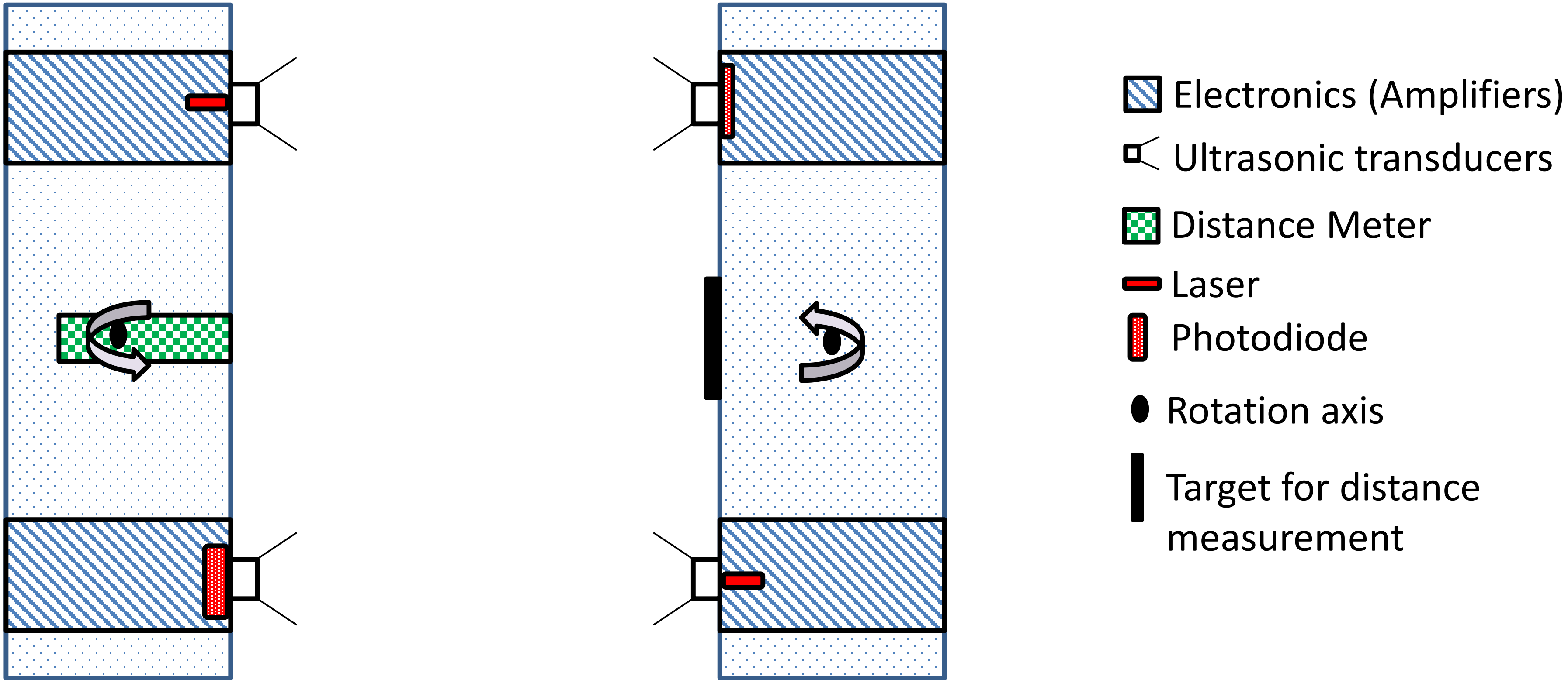
Description of the developed system



Reference temperature sensors (Pt100) are used for the system calibration, i.e. the measurement of the Offset.

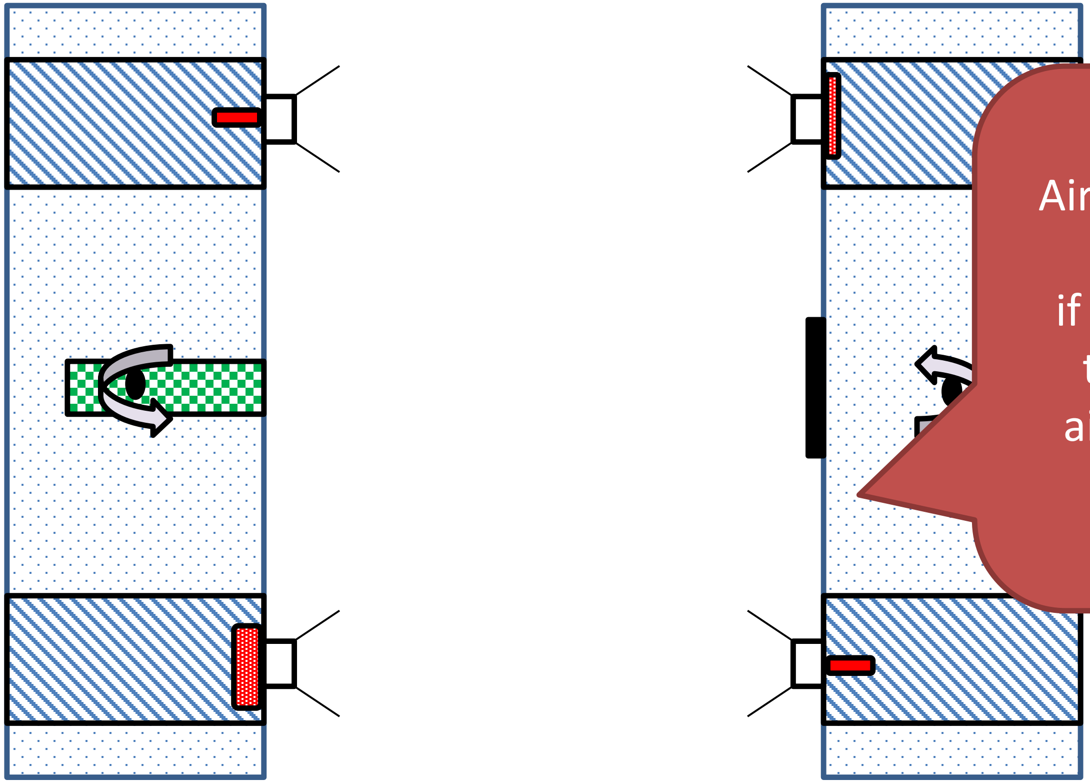
$$DTOA = TOF + Offset$$

Description of the developed system



Top view of the developed system

Description of the developed system



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measurement

Airflow has a direct impact on the speed of sound: if the the acoustic wave is in the same direction as the airflow, its speed increases, otherwise it decreases.

An airflow of 0.6 m/s induces an error of 1°C on temperature measurement

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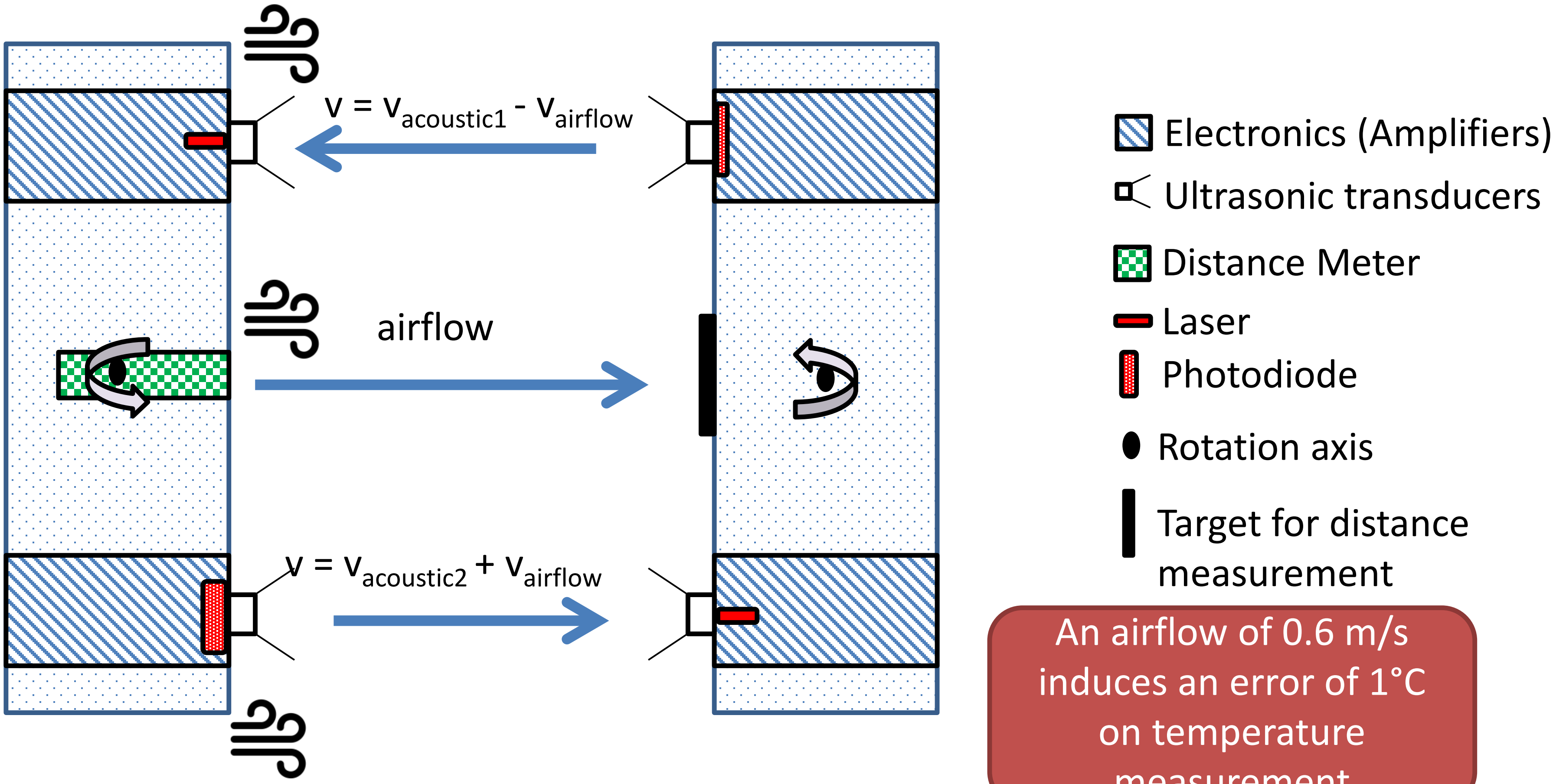
Top view of the developed system

Description of the developed system



Top view of the developed system

An airflow of 0.6 m/s induces an error of 1°C on temperature measurement

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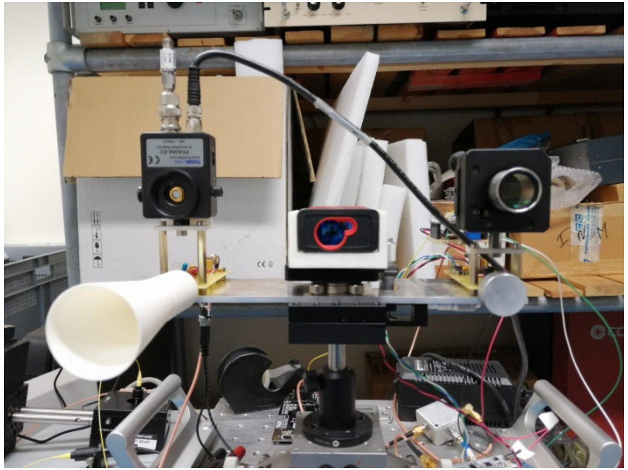
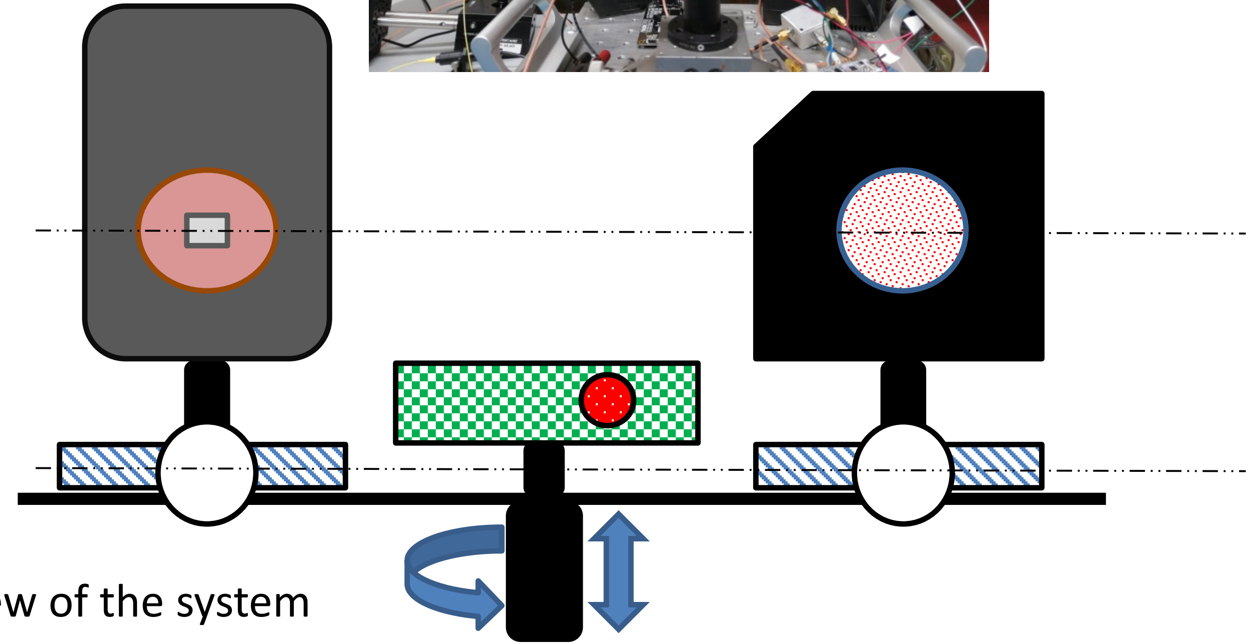


- Electronics (Amplifiers)
- Ultrasonic transducers
- Meter
- Laser
- Photodiode
- Rotation axis



Front view of the system

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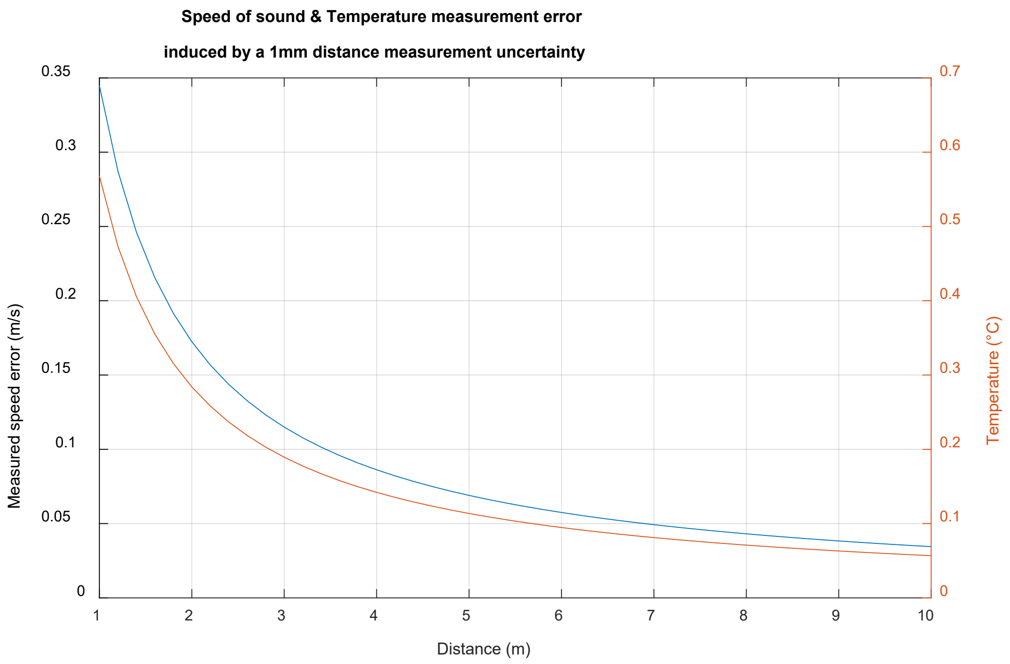
Distance measurement

- TOF measurement is associated with a distance measurement in order to calculate the speed of the acoustic wave.
- The accuracy we require on the distance measurements will depend on the uncertainty needed on the temperature.
- The uncertainty on the distance is caused by:

  - the used distance meter (Leica Disto d210), uncertainty of 1 mm (k=1).

  - misalignments of the different elements of the system, error less than 12 µm after alignment procedure.

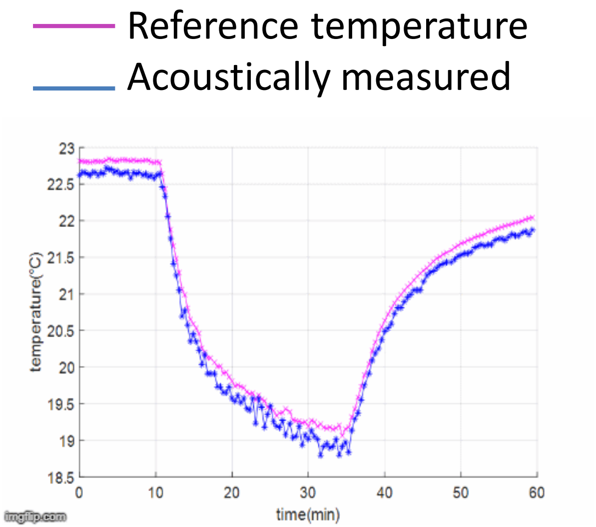


Correction of the DTOA due to offset in electronics and cables

Offset = DTOA – TOF

- The offset is supposed constant, mainly caused by the electronics and the propagation time in the cables.

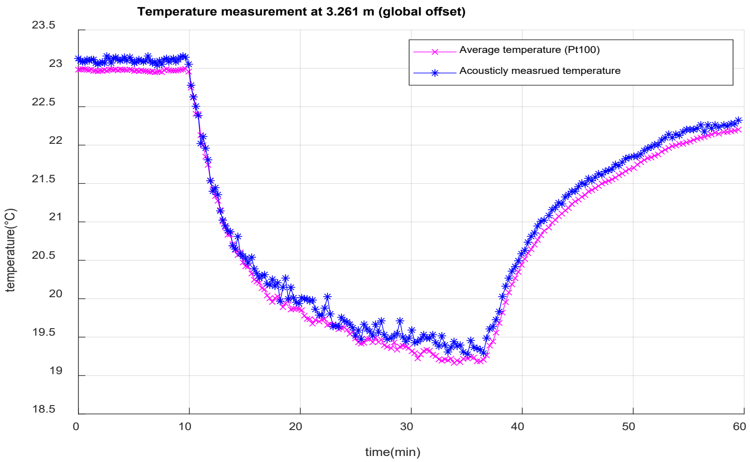
- Based on measurements done at different distances, the offset is determined by calculating the optimal value in the sense of weighted least square method (WLS) that minimizes the error between the temperatures measured from the DTOA only and the reference temperatures Pt100

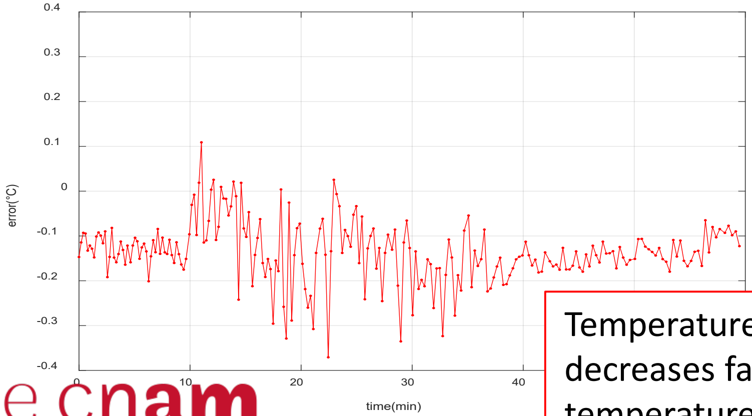


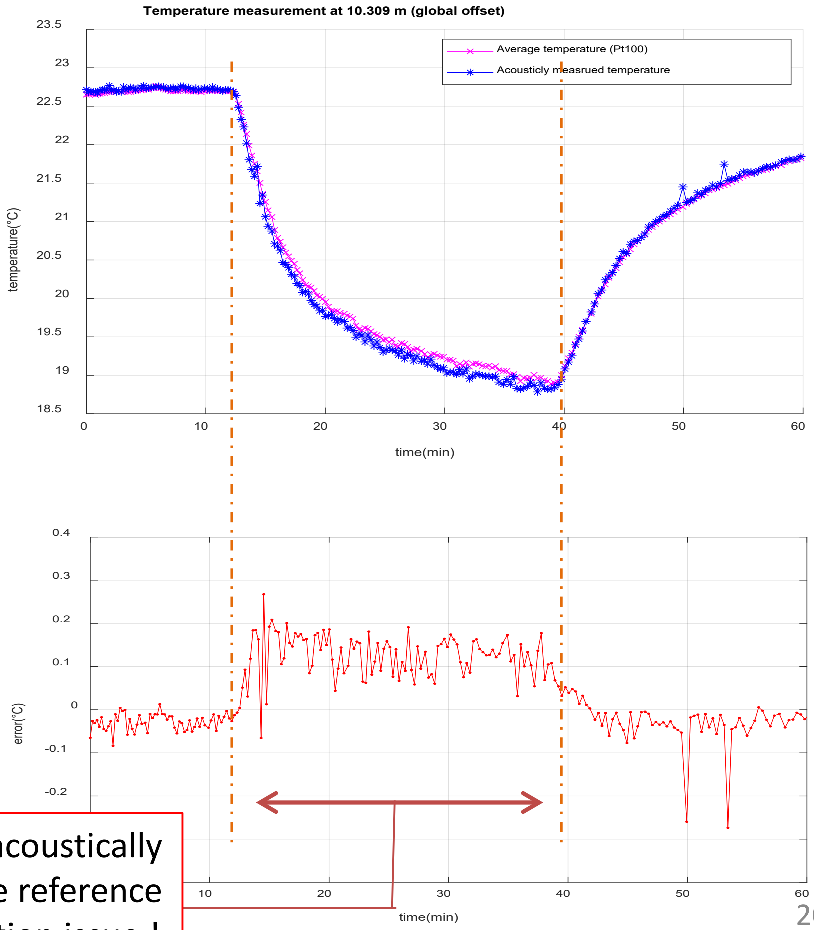
Correction of the DTOA due to offset in electronics and cables

Distance (m)	3.261	4.989	7.795	10.309	11.767
Global Offset (µs)	179.16	179.16	179.16	179.16	179.16
Average error (°C)	-0.14	-0.19	-0.11	-0.02	+0.02
Standard deviation (°C)	<0.1	<0.1	<0.1	<0.1	<0.1

Some measurements results







Temperature measured acoustically decreases faster than the reference temperature: thermalisation issue !

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Uncertainty budget

Parameter	Source	Estimated value	Uncertainty on temperature
Distance “d”	Accuracy of the distance meter	u = 1 mm (k=1)	< 0.6 °C at 1 m < 0.06 °C at 10 m
	Misalignment of the beam	error < 20 µm	neglectable
Time of flight measurement “DTOA”	Red Pitaya (Sampling frequency, SNR, multipaths, ...)	resolution of 0.5 µs	< 0.1 °C at 1 m neglectable at 10 m
Offset	Depends on other parameters: d, $T_{ref,}$ DTOA	u = 3.1 µs (k=1)	< 0.6 °C at 1 m < 0.1 °C at 10 m
Speed of sound “v”	Results from Cramer’s equation	u = 0.1 m/s	= 0.15 °C
Relative humidity “RH”	Humidity sensor	u = 4%	< 0.1 °C

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Conclusion and future work

Conclusion

An acoustic thermometry system tested on a range of temperatures 18 °C < T < 24 °C and a distance up to 12 m

highlighted different sources of uncertainties on the temperature measurement of the system and estimated their impact

Overall performances of the system from the different measurement series gives, at worst, an error of 0.2 °C with a standard deviation of 0.1 °C

Future work

Work on the improvement of the offset measurement and stability, which is the main source of uncertainties

Improvement on the design for the integration in our developed ADM

Increase the range of temperatures and distance tested on

Thank you for your attention!

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