Development of Peltier Cooled Frost point Hygrometer PCFH

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IAC Institute for Atmospheric and Climate Science ETH zürich mylab elektronik GmbH

Stratospheric Water Vapor and the Frost Point Hygrometer

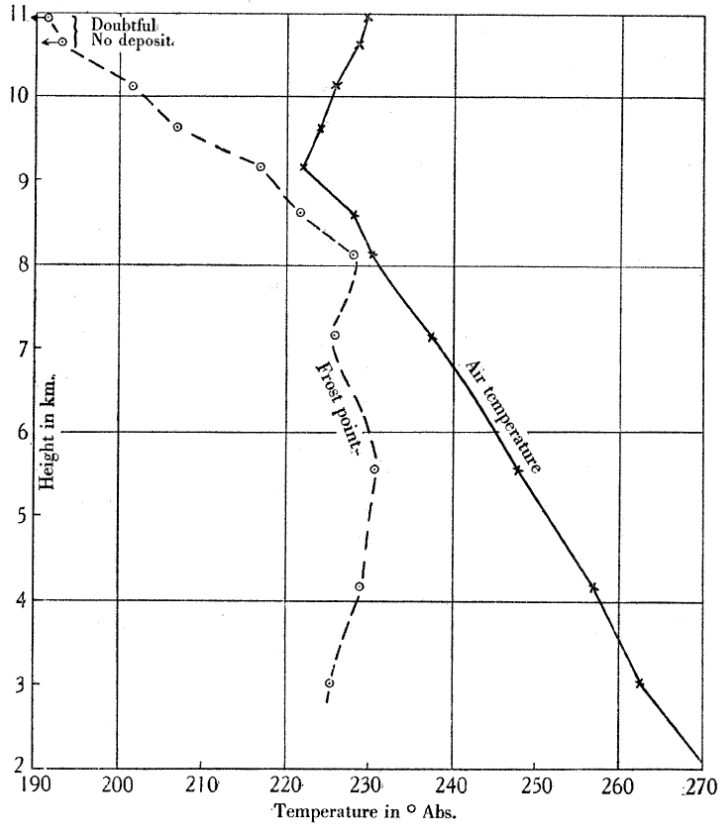
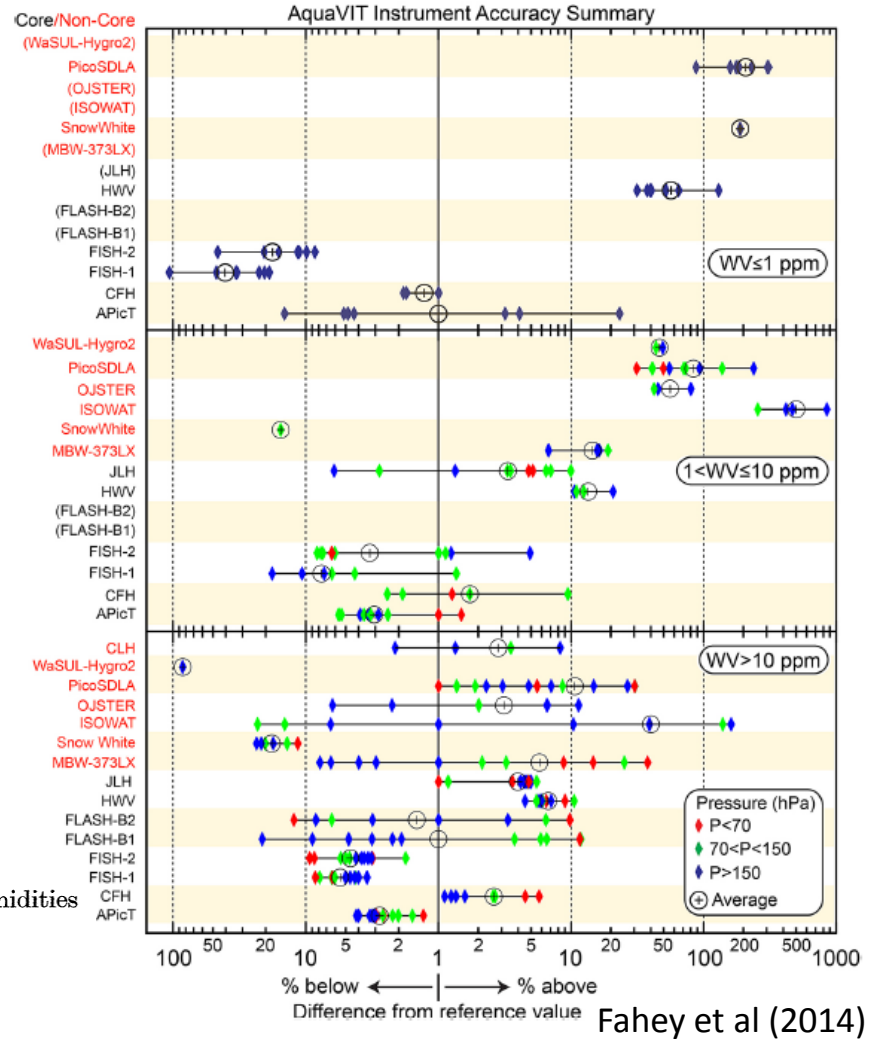


FIGURE 4. Frost-points and air temperatures observed on the first ascent when humidities were measured in the stratosphere, Boscombe Down, 22 December 1943.

M. B. Dobson, A. W. Brewer and B. M. Cwilong (1946)

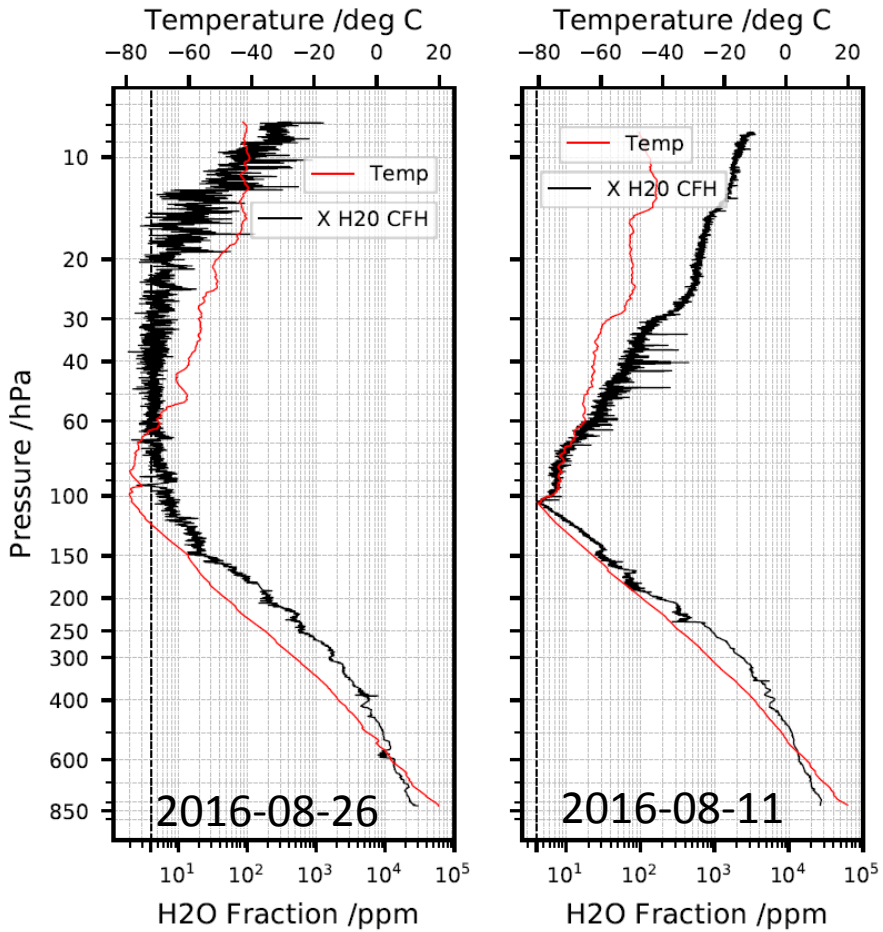


Fahey et al (2014)

Uncertain future for Cryogenic Frost point Hygrometers

Kigali Amendment to Montreal protocol 2016

Complicated dry ice and R23 logistics in Dhulikel Nepal 2017



Temperature and water vapor mixing ratio from RS41 + CFH balloon flights in Nainital India 2016

Outline

- Instrument Concept
- PCFH: 1st prototype
- PCFH: Outlook
- System identification
  - Cold side
  - Hot side
  - Reference Surface
  - Reflectance
- Take home message

Instrument concept

- **Double Instrument**
- 2 identical optical assemblies
- 2 individual flow tubes
- Single polystyrene housing

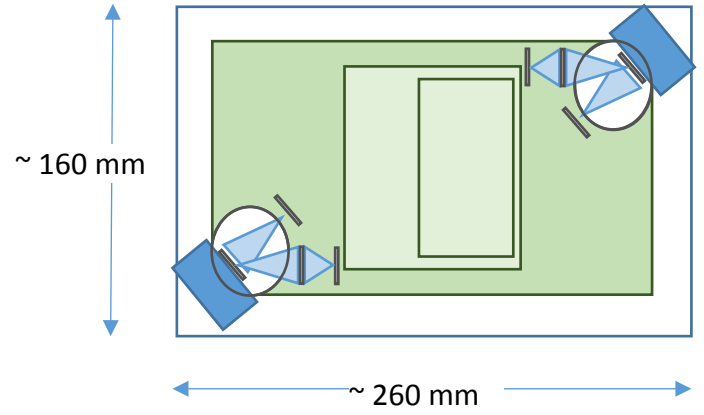
- **Double stage Peltier cooling**
- Lowest reachable T_{cold} at given T_{hot} :

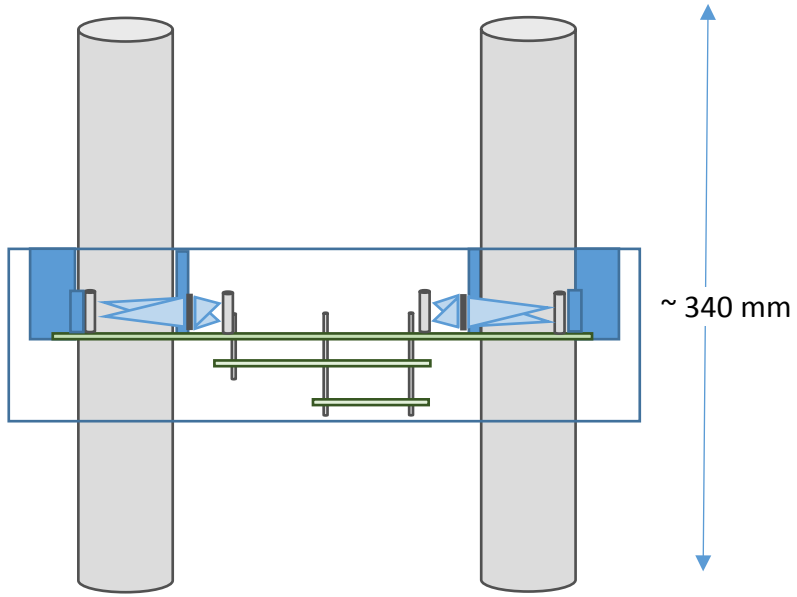
T_{hot}	T_{cold}	ΔT
-75°C	-110°C	35 K
-38°C	-92 °C	54 K
27°C	-59 °C	86 K

- **Light detection scheme**
- Reference surface
- Kept 3°C to 5°C warmer than T_{air}

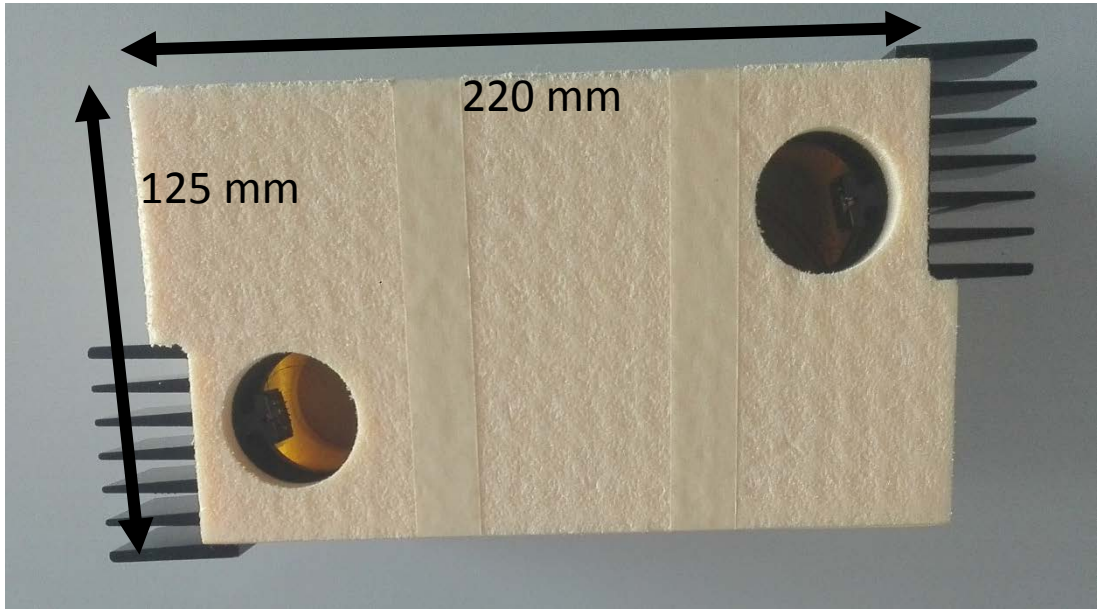
- **Thermocouples**
- Copper – constantan.
- Calibrated to Swiss national standards.
- Assembled precision 0.01 K and accuracy 0.1 K.
- Common reference temperature

- **Controller and Plant model**
- Linear Quadratic Regulator (LQR)
- Full state feedback offering superior robustness
- Replaces the common PID controller
- Mathematical/ physical description of the Instrument



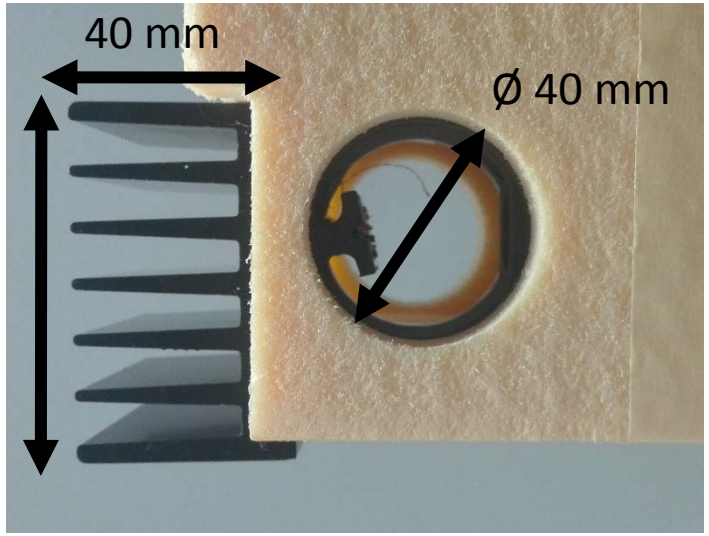


PCFH: 1st prototype



Box - top view

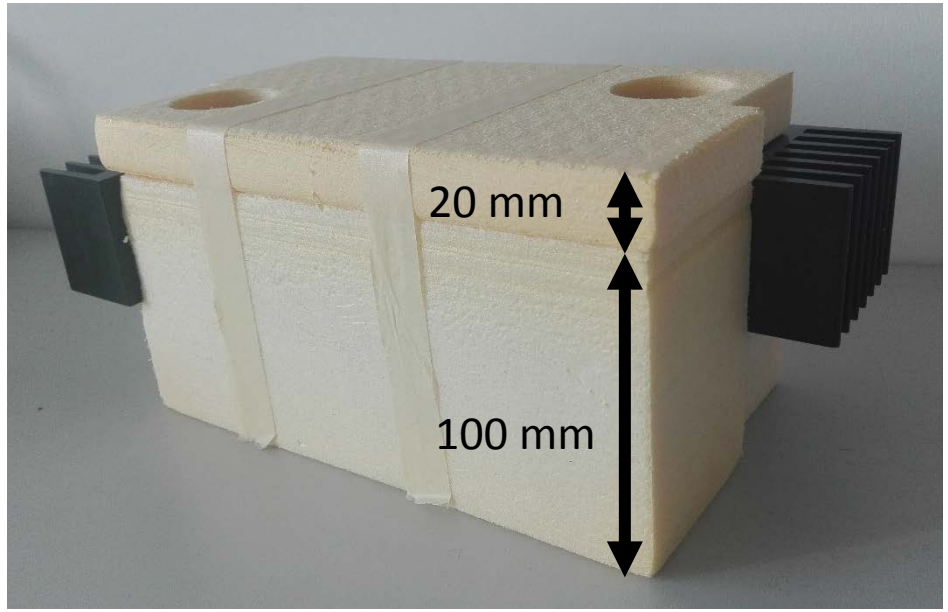
66 mm



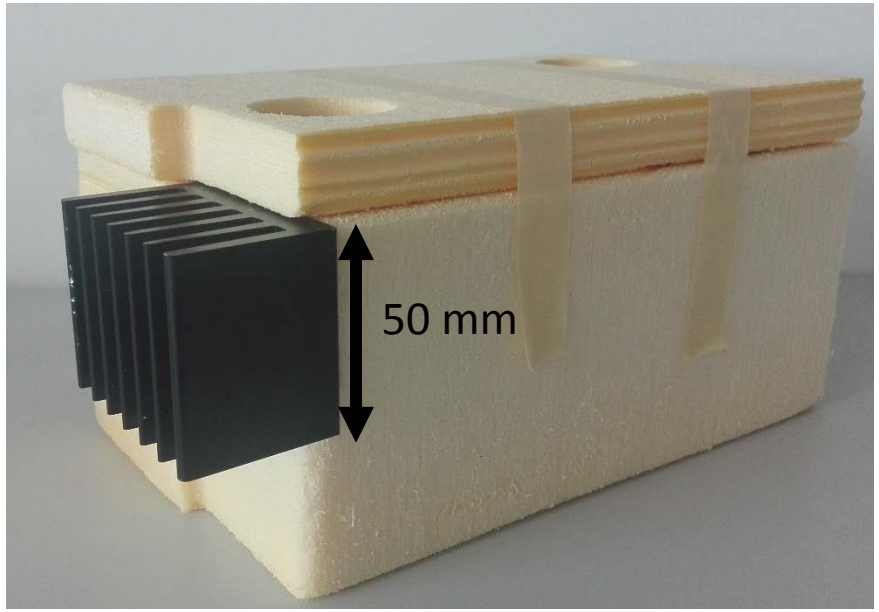
Inlet – detail view

Weight: ~800 g

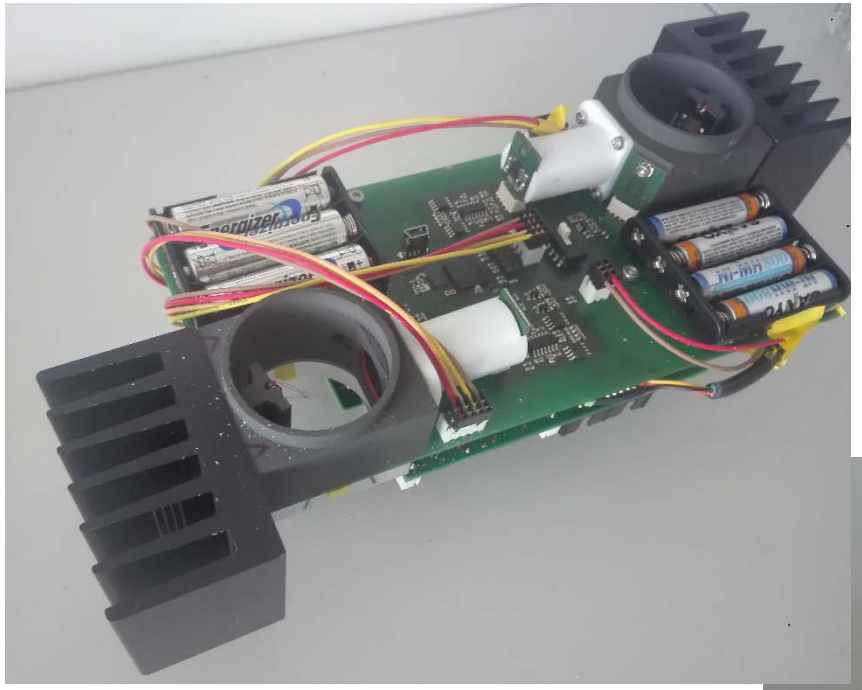
PCFH: 1st prototype



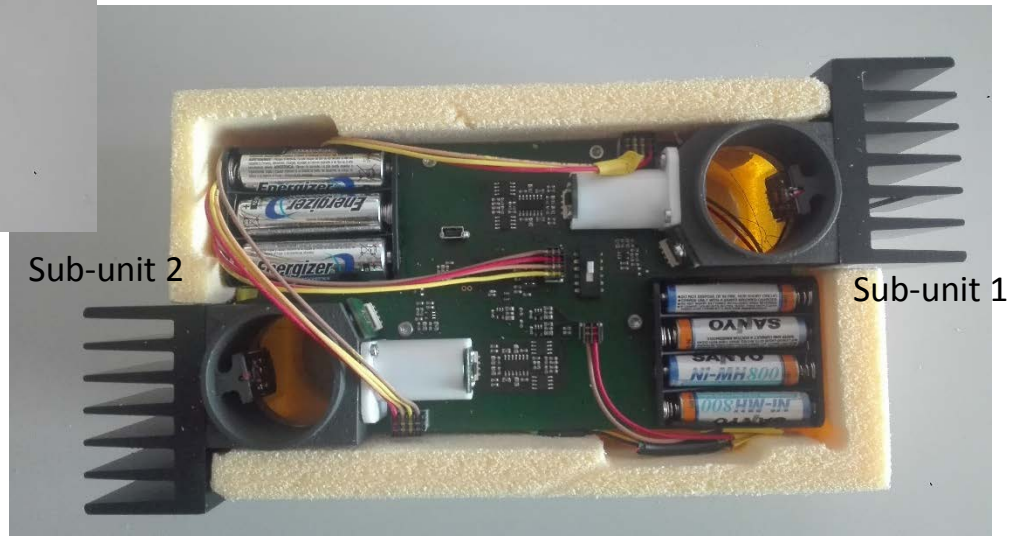
Box – side view



PCFH: 1st prototype

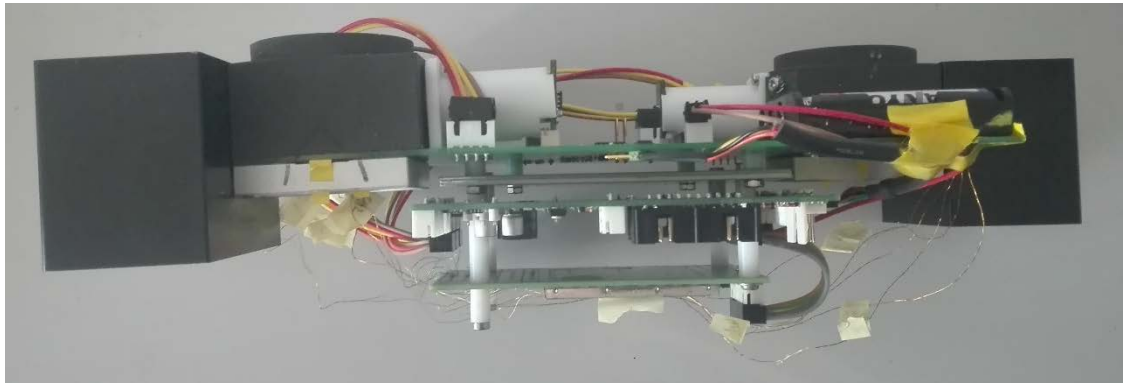


Mirror detail

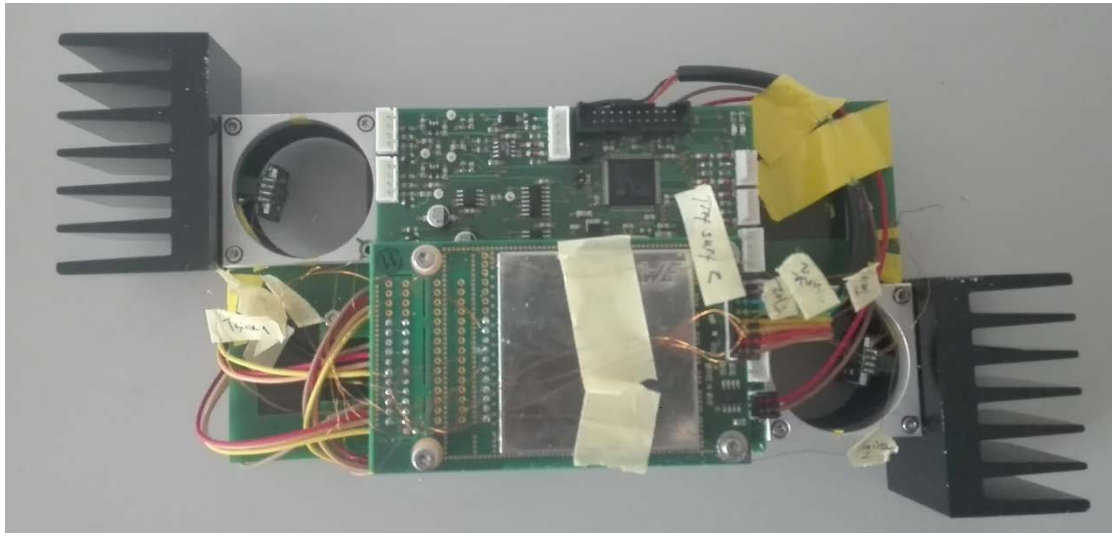


Top view

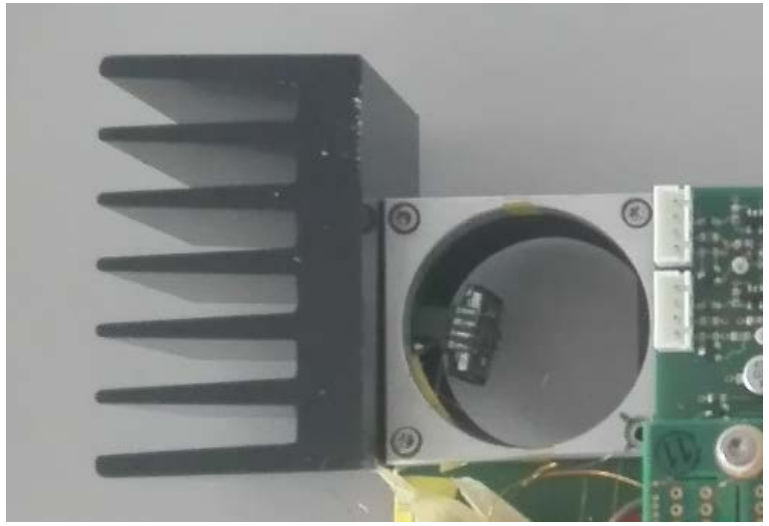
PCFH: 1st prototype



Side view



Bottom view



Bottom view - detail

PCFH: Outlook

Work Packages	Details	Milestones	2015 1 2 3 4	2016 1 2 3 4	2017 1 2 3 4	2018 1 2 3 4	2019 1 2 3 4	2020 1 2 3 4	2021 1 2 3 4	Who
WP1 Literature Research	UTLS air properties Peltier device selection ANSYS fluent tutorial Control theory MatLab control system box									TJ TJ TJ FGW FGW
WP2 Electronics and Mechanics	Controler board Thermocouple board Reflex board Mirror Peltier assembly	Prototype boards								TB TB FGW FGW
WP3 Computational Fluid Dynamic Simulations	Inlet tube Sensor housing Heat exchanger	Design recommendations Publication								TJ TJ TJ-UW
WP4 Instrument integration	Fit all parts and proof of concept	PCFH prototype								TJ-UW-FGW-TB
WP5 Controller development and implementation	Instrument mathematical model LQR method Subroutines	Controller prototype								TJ-FGW FGW TB-TJ-FGW
WP6 In-flight Evaluation	Comparison: CFH-FPH-SnowWhite Controller scheme Set-point testing Ice growth and evaporation	Optimized contoller schedule Ice growth and evaporation Publication								TJ
WP7 Uncertainty Characterization	Temperature reference comparison FPH temperature comparison Controller stability	Instrument publication								TJ-TB TJ-FGW TJ-FGW
WP8 Test Flights within Monitoring Networks	Design pre-flight procedures Recovery technique building Post-flight data analysis	Biweekly flights GRUAN Lead Ctr. Monthly flights with MeteoSwiss and MOSES (Jülich)								FGW-TP
WP9 Participation in Field Campaigns	Organization Shipping Data collection Data analysis	PCFH flown in midlats, tropics and polar regions CIMO (2019) publication								FGW-UW-TP
WP0 Other project related tasks	Publications & reporting Training courses & conferences Project management									TP-TJ-FGW

First prototype and Lab tests –March-June 2018

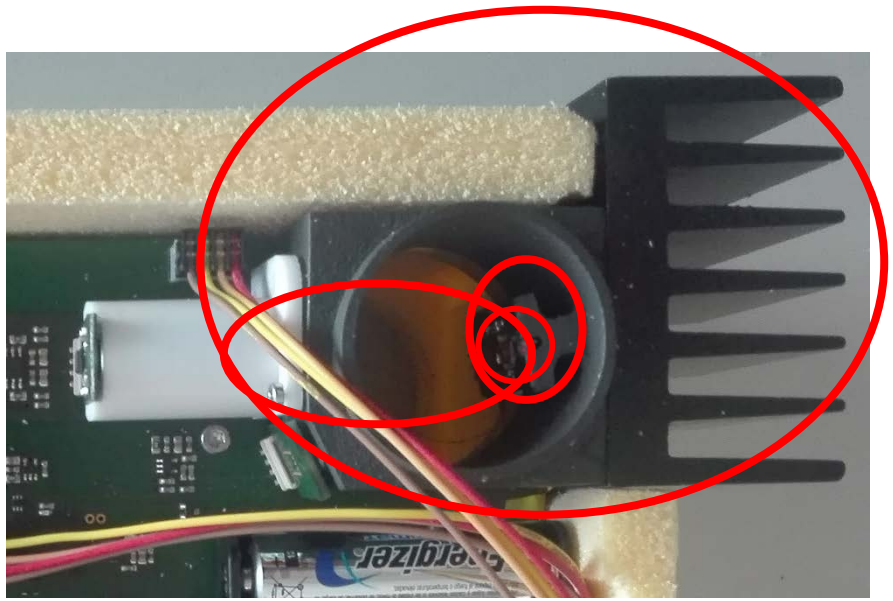
First flights – July 2018 – Lindenbergh D – August –September 2018 – Payerne CH

Monitoring network integration –2019

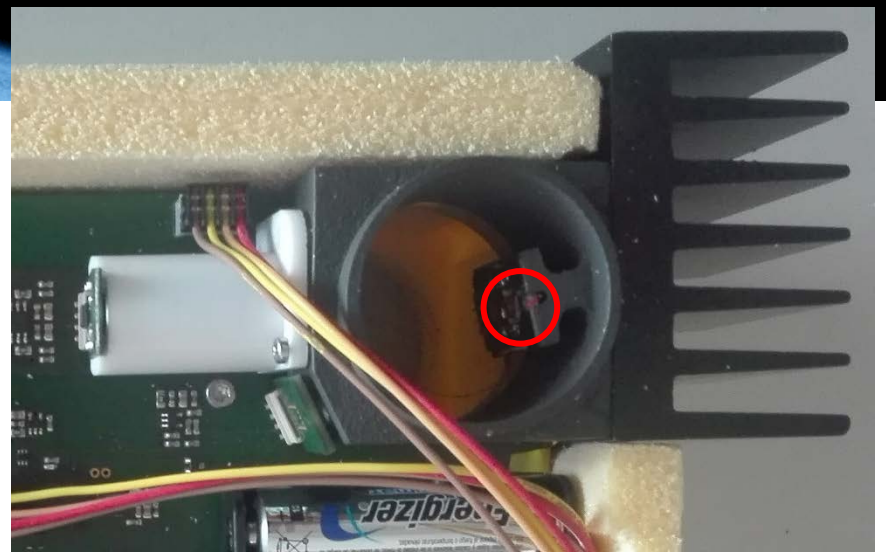
- GAW+ proposal accepted (for GRUAN integration of PCFH)
- Intern from June to October 2018

System Identification

- Black, Grey and White box models
- Combination of flows and reservoirs: dynamic behavior
- Thermodynamic system
- Differential equation form
- State variables, inputs and output
- Advantages: validate model at ground conditions
  - Extrapolate behavior in “atmospheric” conditions



System Identification – cold side



$$\dot{m}_{ice} \cdot C_{P\,ice} \cdot T_C + ((m_{ice} \cdot C_{P\,ice} + m_{Al} C_{P\,Al}) \cdot \frac{\boldsymbol{dT_C}}{\boldsymbol{dt}} = -\dot{\boldsymbol{Q}}_{\boldsymbol{P}} + \frac{\dot{\boldsymbol{Q}}_{\boldsymbol{J_P}}}{\boldsymbol{2}} + \dot{\boldsymbol{Q}}_{\boldsymbol{\Delta T}} - \dot{Q}_C + \dot{Q}_L$$

$\dot{\boldsymbol{Q}}_{\boldsymbol{P}} = \boldsymbol{I_P \cdot \alpha_P \cdot T_c}$ **Heat removed by Peltier effect – α_P: Seebeck coefficient**

$\dot{\boldsymbol{Q}}_{\boldsymbol{J_P}} = \boldsymbol{R_P \cdot I_P^2}$ **Joule heating by the Peltier**

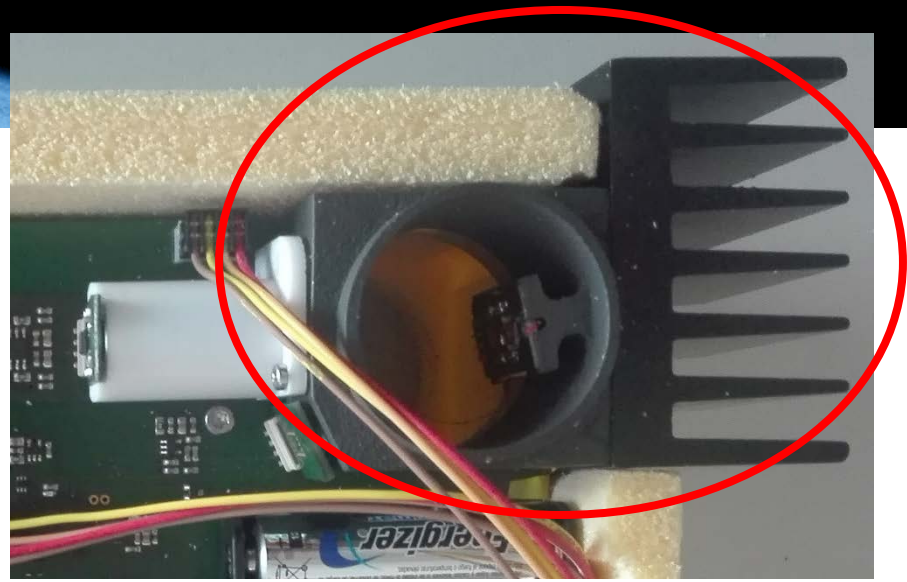
$\dot{\boldsymbol{Q}}_{\boldsymbol{\Delta T}} = \boldsymbol{K_P \cdot (T_H - T_C)}$ **Heat transfer from hot side to cold side due to temperature difference**

$\dot{Q}_C = (m_{air} \cdot C_{P\,air}) \cdot (T_{air} - T_C)$ Heat removed or added from the ambient air

$\dot{Q}_L = \dot{m}_{ice} \cdot L_V$ Ice sublimation and condensation heat due to change in the mass of the ice layer

$\dot{Q}_P$ (W)	$\dot{Q}_{J_P}$ (W)	$\dot{Q}_{\Delta T}$ (W)	$\dot{Q}_C$ (W)	$\dot{Q}_L$ (W)
0.65 – 2	0.7 – 1.7	0.16 – 0.33	10^{-5} – 10^{-4}	0.001 – 0.01

System Identification – hot side



$$(m_{MB} \cdot C_{P\,MB} + m_{HS} \cdot C_{P\,HS}) \cdot \frac{dT_H}{dt} = \frac{\dot{Q}_{J_P}}{2} + \frac{\dot{Q}_{J_{RS}}}{2} + \dot{Q}_{HS} + \dot{Q}_{inlet} + \dot{Q}_{inst} + \dot{Q}_{R_{HS}}$$

$\dot{Q}_{J_P} = R_P \cdot I_P^2$ Joule heating by the Peltier

$\dot{Q}_{J_{RS}} = R_{RS} \cdot I_H^2$ Joule heating from the reference mirror board

$\dot{Q}_{HS} = 7 \times \sqrt{k_{Al} \cdot A_c \cdot h_{HS} \cdot p} \cdot (T_H - T_{air}) \cdot \tanh(a \cdot L_c)$

Forced convection from 7-fin heat sink too ambient air when base is at the temperature of the hot side.

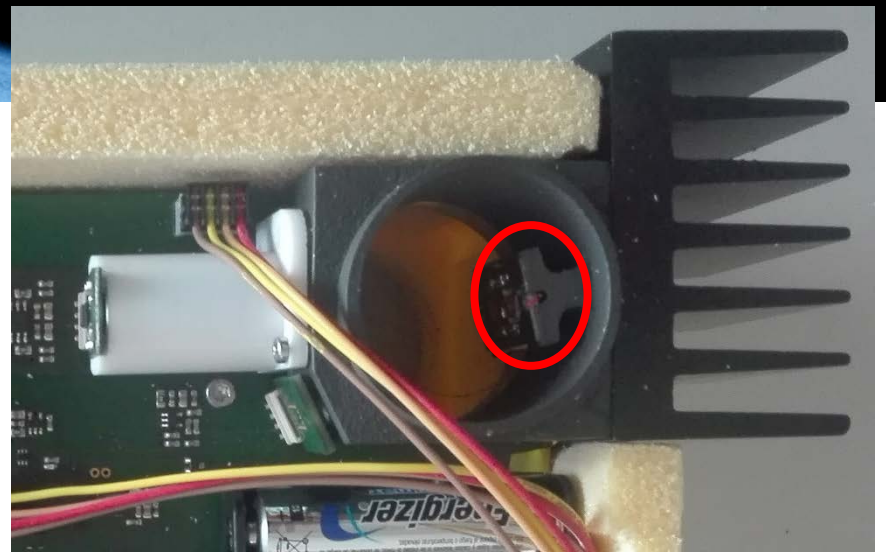
$\dot{Q}_{inlet} = h_{inlet} \cdot A \cdot (T_H - T_{air})$ Forced convection from inside inlet tube

$\dot{Q}_{inst} = h_{inst} \cdot A \cdot (T_H - T_{inst})$ Natural convection from the interior of the instrument

$\dot{Q}_{R_{HS}} = \epsilon \cdot \sigma \cdot A_C \cdot (T_H^4 - T_{rad}^4)$ Radiative heat transfer from the environment

$\dot{Q}_{J_P}$ (W)	$\dot{Q}_{J_{RS}}$ (W)	$\dot{Q}_{HS}$ (W)	$\dot{Q}_{inlet}$ (W)	$\dot{Q}_{inst}$ (W)	$\dot{Q}_{R_{HS}}$ (W)
0.65 – 2	0 – 8	0 – 20	0 – 0.4	-0.5 – 0.2	1 – 6

System Identification – reference surface



$$m_{RS} \cdot C_{P\,RS} \cdot \frac{dT_{ReSur}}{dt} = \dot{Q}_{RS} + \frac{\dot{Q}_{J\,RS}}{2}$$

$\dot{Q}_{J\,RS} = R_{RS} \cdot I_H^2$ Heat added by joule effect from the reference mirror board

$\dot{Q}_{RS} = h_{inlet} \cdot A_{RS} \cdot (T_{RefSurf} - T_{air})$ Heat removed by convection by the air in the inlet tube

$\dot{Q}_{J_{RS}}$ (W)	$\dot{Q}_{RS}$ (W)
0 – 8	0 – 0.2

System Identification – reflectance

$$\frac{dR}{dt} = -A \cdot \dot{m} = -B(T_{fr}) \cdot \left(T_{fr} - T_c\right)$$

$$T_{fr} < T_c \;\; : \dot{m} < 0 \;\; : \;\; \frac{dR}{dt} > 0$$

$$T_c \; < T_{fr} \;\; : \dot{m} > 0 \;\; : \;\; \frac{dR}{dt} < 0$$

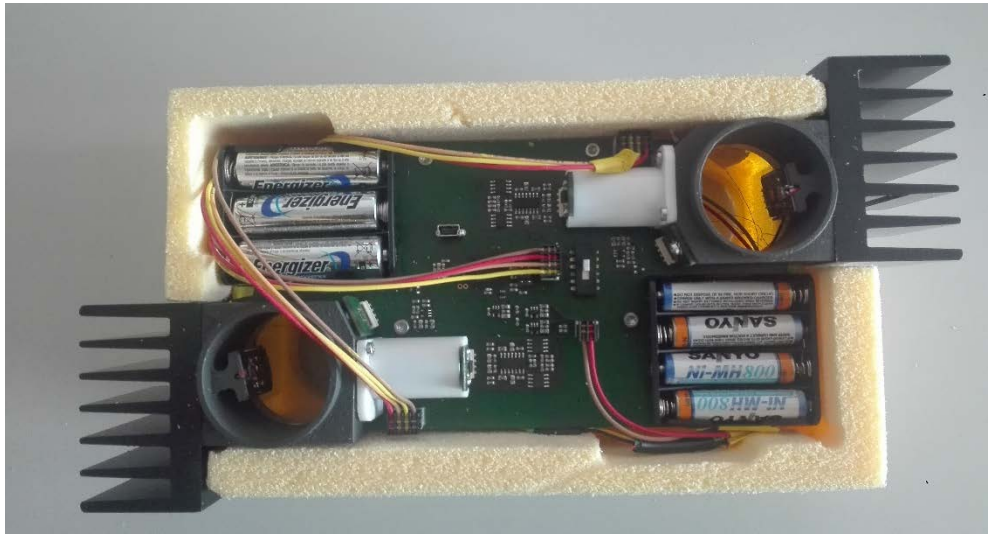
Take home message

- New Peltier Cooled Frost point Hygrometer - PCFH

- Developed as a GRUAN worthy instrument
  - Temperature measurement traceable back to measurement standards
  - Transparency of implementation

- Flight tests to start in July 2018

- Novelty on the controller development
  - System Identification and Modelling



Thank you for your attention

Questions?