Development & Application of the Peltier Cooled Frostpoint Hygrometer (PCFH)

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1 Motivation

Water vapor

- strongest natural greenhouse gas
- small changes in stratospheric abundance → significant impact on radiative forcing (0.6 Wm^{-2} @ 2 K global surface temperature change)
- atmospheric footprint with high dynamic range (10^5) and vertical variability (50 m)
- cloud radiation interaction (depends on p_{H2O}, T, and cloud microphysics)
- required: long-term high-quality measurements in upper troposphere and lower stratosphere (UTLS)
  - monitor water vapor changes
  - improve understanding of cloud formation

Balloon-borne frostpoint hygrometers

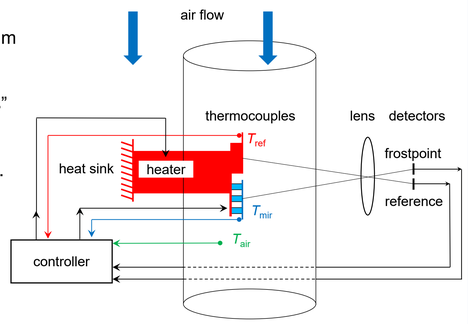
- chilled mirror principle: measurement of the frostpoint temperature directly determines the water vapor content
- refrigerant R23 has phased out in 2023 by the Kigali Amendment to the Montreal Protocol
- alternative: PCFH with Peltier cooling
- cover region of interest: the UTLS
  - from the surface through the UT
  - to the midlat. tropopause + 12 km
- two independent sub-units
  - improve reproducibility
  - contamination detection
  - allow independent measurement

2 PCFH: Simple Application by Peltier Cooling

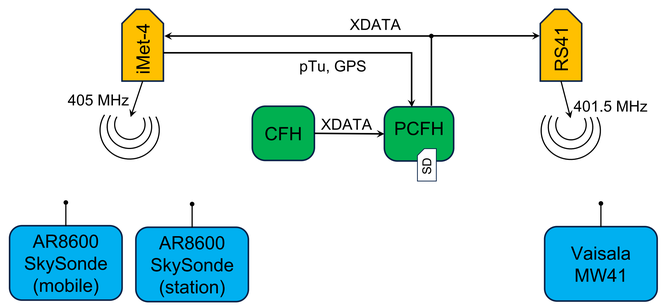
The control of the mirror temperature by optical detection tries to keep the condensate thickness constant.

At the thickness extrema the condensate is in thermodynamic equilibrium with the air.

For these “Golden Points” the mirror temperature equals the frostpoint temperature by definition.

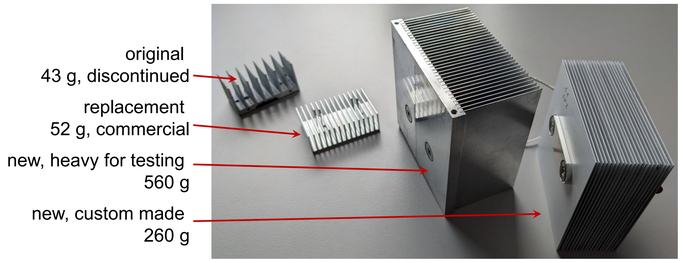


3 Dual Telemetry and Data Logging



4 Heatsink Development

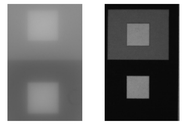
Using Peltier coolers instead of cryogen asks for custom made heatsinks adapted to pressure and flow conditions:



Improvement of coupling to ambient air: ΔT = 25 K → 15 K
Increase of operational altitude range: z = 15 km → 24 km

5 Contrast and Operation

optics quality quantified by contrast $\frac{I_s - I_0}{I_0}$



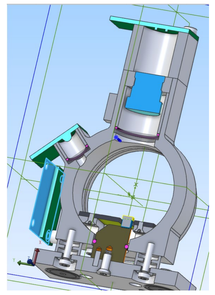
laboratory investigation
→ imaging can improve contrast from 2..3 to > 10

pre-flight contrast measurements
→ setup validation
→ systematic definition of flight operation points

geometric margins for manufacturing tolerance

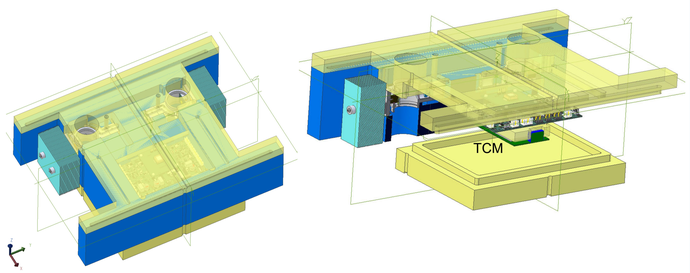
flight deployments:
enhanced sensitivity by new ice formation strategy and operating points

intermediate solution for concurrent electronics development:
hybrid composition of the new optics with the existing electronics

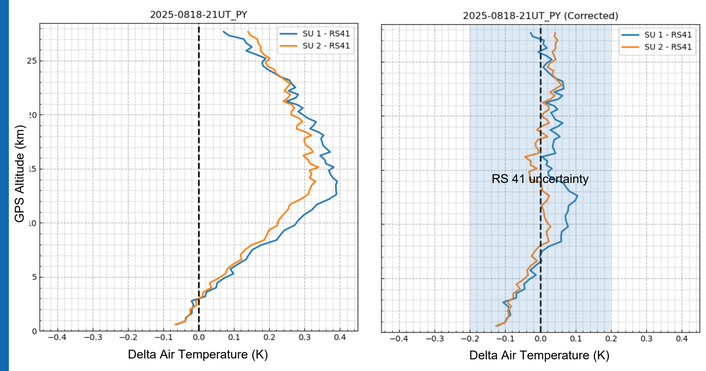


6 Revised Thermal / Mechanical Setup

modular design
improved thermal insulation of the thermocouple module (TCM)



7 Air Temperature Validation and Correction



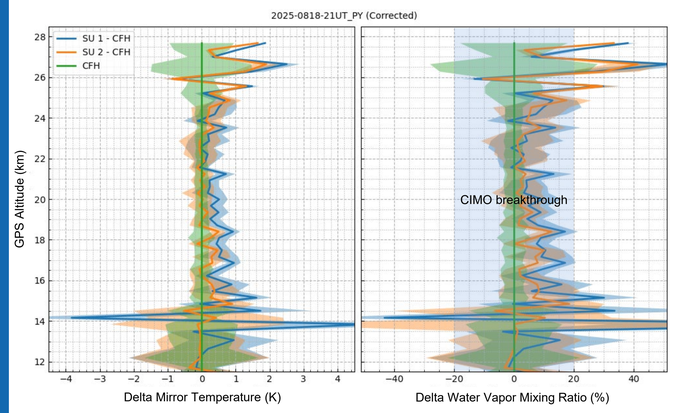
Additional thermocouples on the TCM reveal internal gradients caused by battery supply hotspots.

The TCM thermocouple data correct the PCFH air temperature to the radiosonde measurement by a multiple linear regression.

This improves the agreement to < 0.1 K.

The upcoming design avoids the thermal hotspots and reduces the TCM susceptibility to internal thermal gradients.

8 Frostpoint and Water Vapor Comparison



A flight with exceptional CFH performance is selected as the CFH is taken as reference instrument.

The frostpoint temperature is corrected based on the air temperature regression yielding margins of <1K (2σ) for the frostpoint temperature difference.

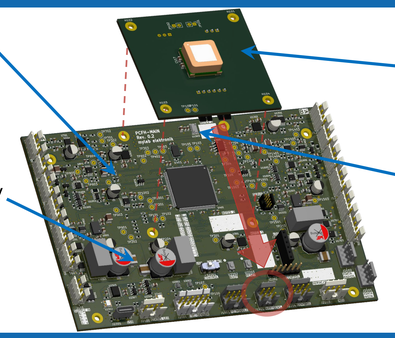
This translates to 1 ppmv in the water vapor mixing ratio.

WMO Commission for Instruments and Methods (CIMO) asks for
20 % ‘breakthrough’
4 % ‘goal’

9 Current Electronics Development

enhanced reflectivity measurement fully exploiting microcontroller-integrated peripherals
- increased measurement rate
- improved stability
- higher sensitivity

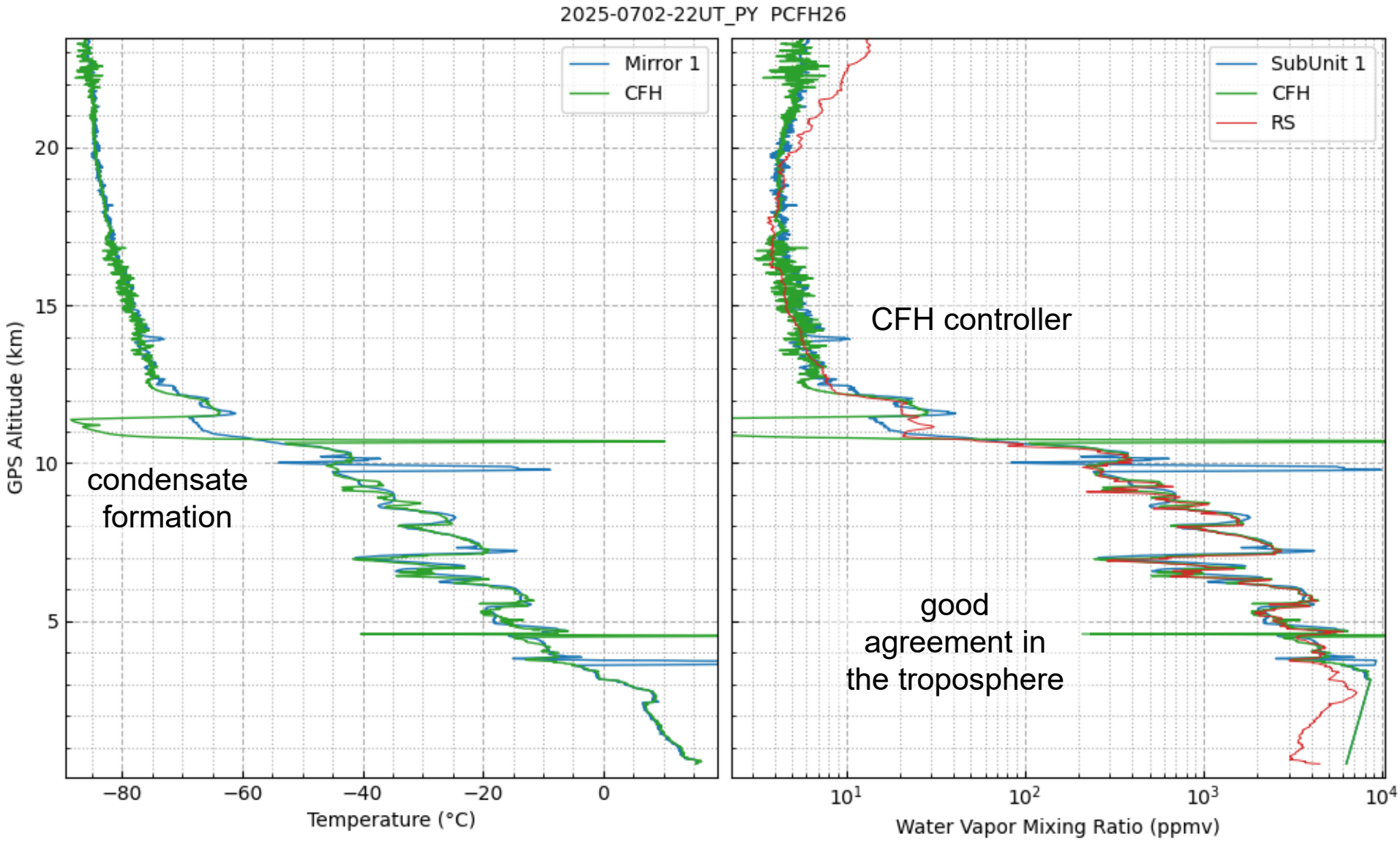
new power supply design for 9…32 V input
- supporting wide range of batteries
- allowing future extensions such as inlet tube heating



interface for additional or optional sensors like GNSS, gyroscope, …

on-board pressure sensor enabling in-flight tuning of control parameters and altitude-based event handling (e.g., detect launch and burst)

Frostpoint and Water Vapor Comparison with CFH Issues



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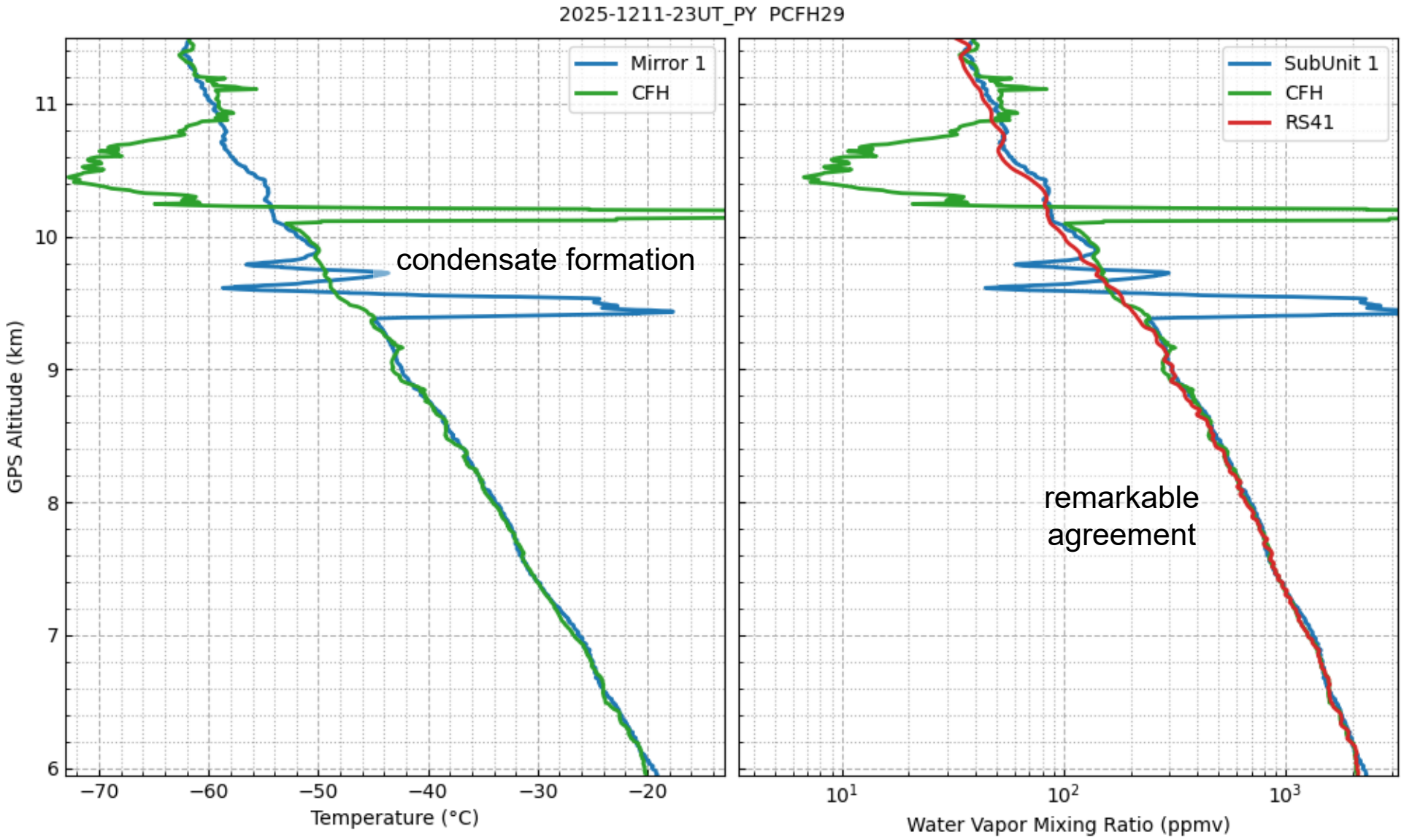

Frostpoint and Water Vapor Comparison with CFH Issues