Calibration of radiosonde humidity sensors using upper air simulator and applications to soundings

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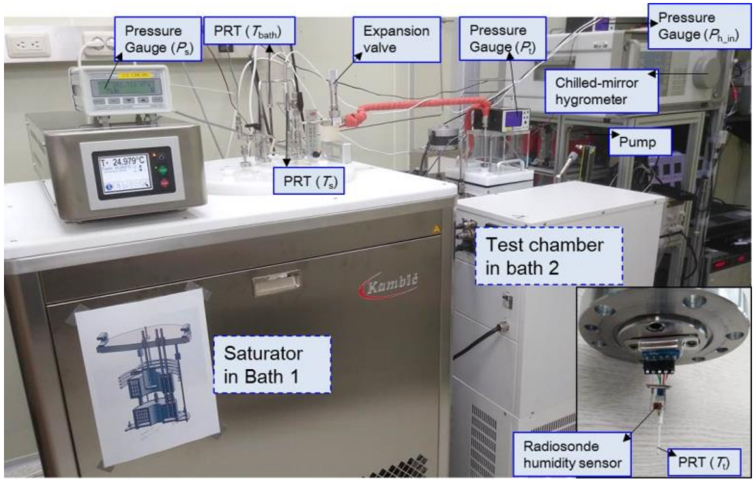
Calibration facilities for radiosonde humidity sensors

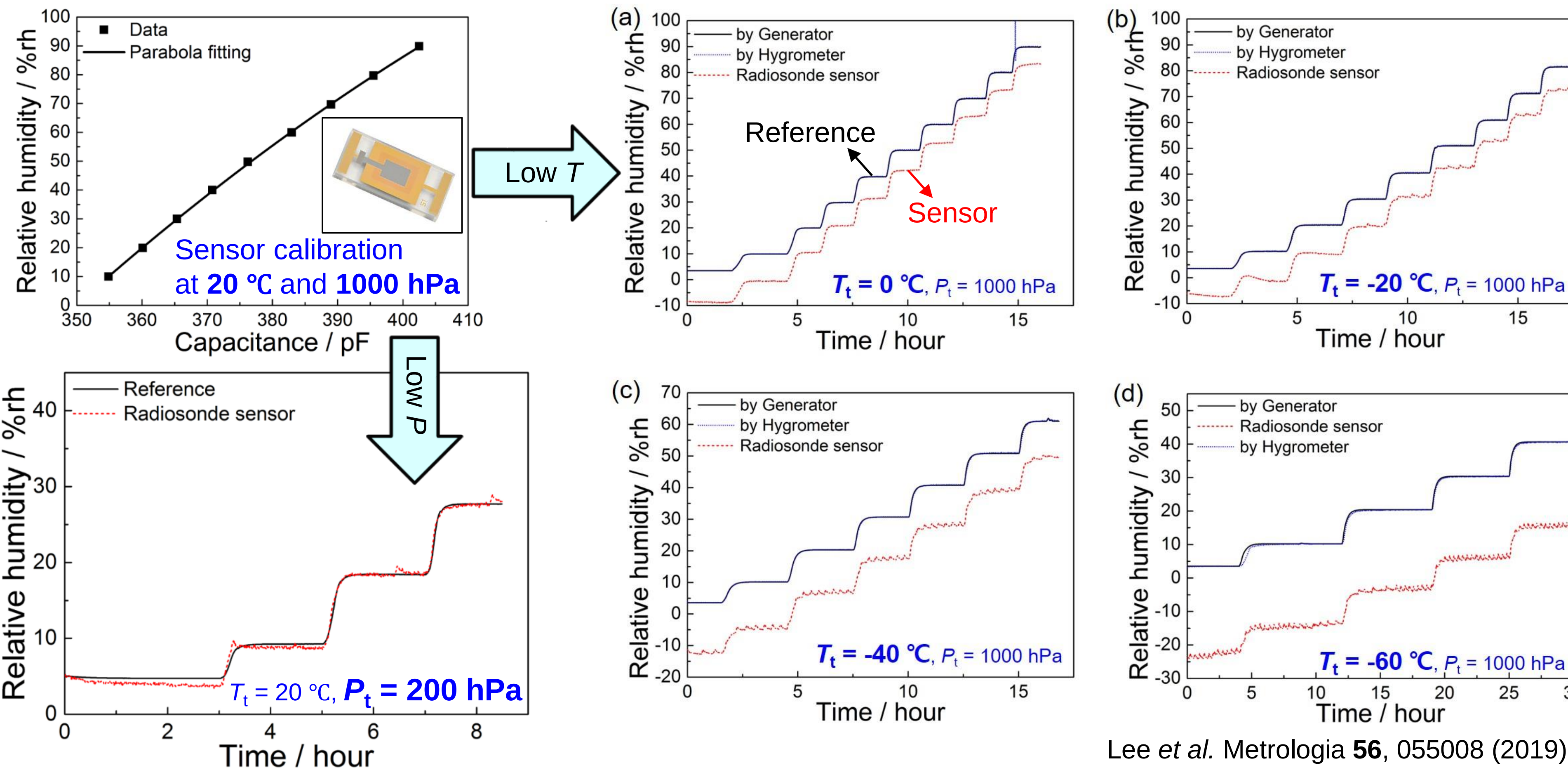
- Humidity measurement conditions in upper air
  - Temperature (< -80 ^{o}C)
  - Pressure (< 10 hPa)
  - Frost-point temperature (< -90 ^{o}C)
- Quality control of humidity measurements
  - SI-traceable calibration of humidity sensors using ground facilities
  - Low-pressure low-temperature humidity generators
- KRISS calibration setup
  - Humidity sensors meets
    - Temperature: (-70 – 30) ^{o}C
    - Pressure: (50 – 1000) hPa
    - Dew/frost point temperature: (-90 – 20) ^{o}Cdp/fp
    - Relative humidity: (2 – 100) %rh



Lee *et al.* Metrologia **56**, 025009 (2019)

Effect of low-temperature and low-pressure

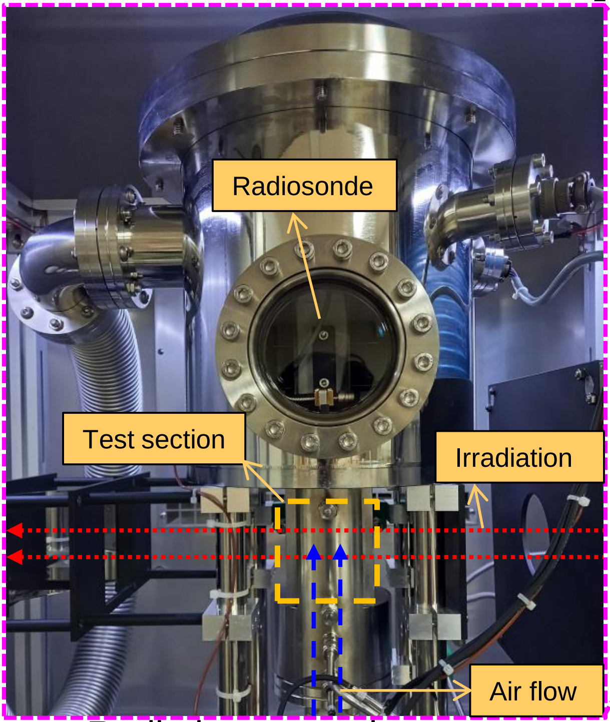
- Low T effect → water adsorption capacity ↑ but absolute humidity ↓
- Low P effect → Sensor responds to partial vapour pressure only



Lee *et al.* Metrologia **56**, 055008 (2019)

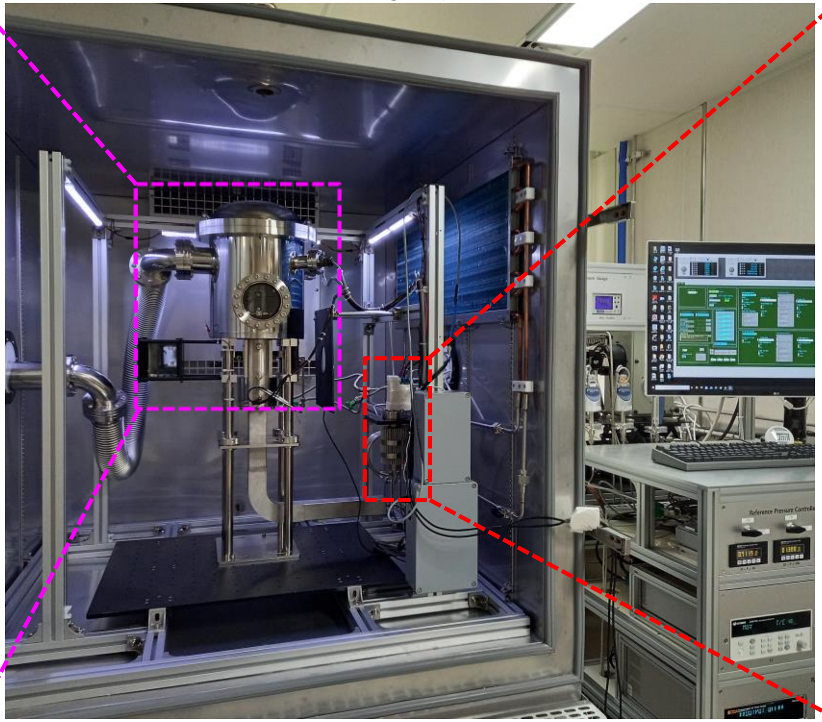
Upper air simulator (UAS) at KRISS

- Radiation correction of temperature sensors
  - Control of temperature, pressure, ventilation, and irradiance (using dry air)
- Calibration of humidity sensors
  - Control of temperature and humidity (1000 hPa & low ventilation speed)

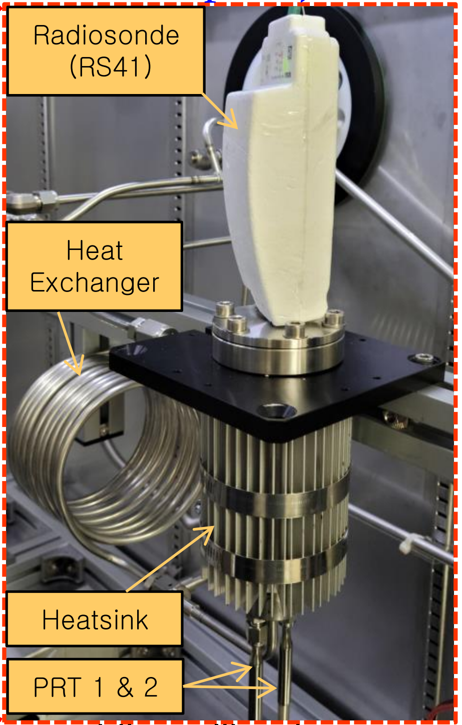


<Radiation correction setup>

Lee *et al.* Meteorol. Appl. **27**, e1855 (2020)



<Upper air simulator>



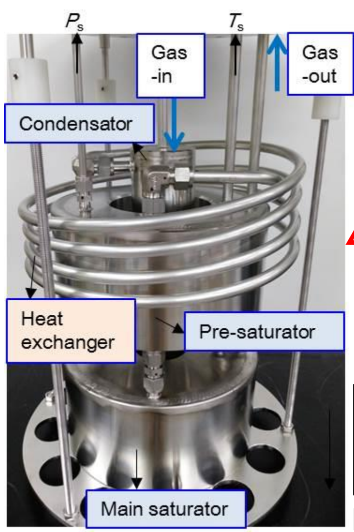
<Humidity calibration setup>

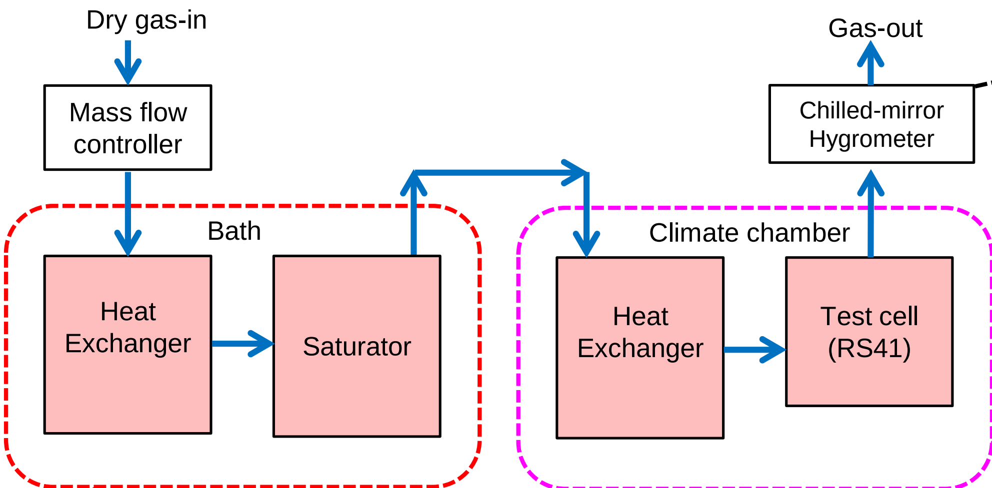
Lee *et al.* Meteorol. Appl. **28**, e2010 (2021)

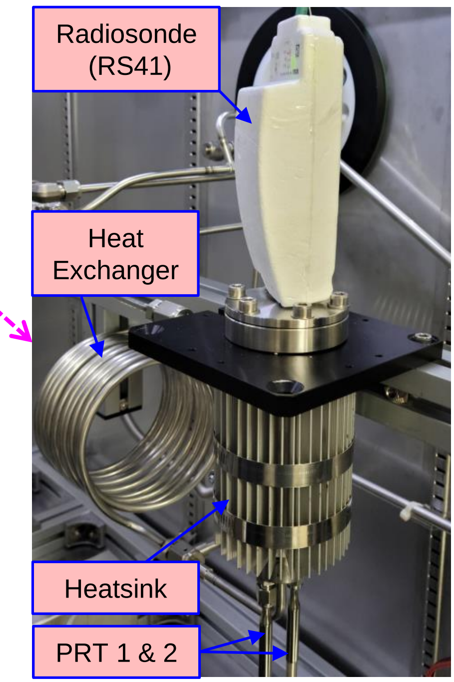
Operation of UAS humidity setup

- Two-temperature type humidity generator
  - $T_{saturator}$ & $T_{test\ cell}$

Hygrometer: Validation







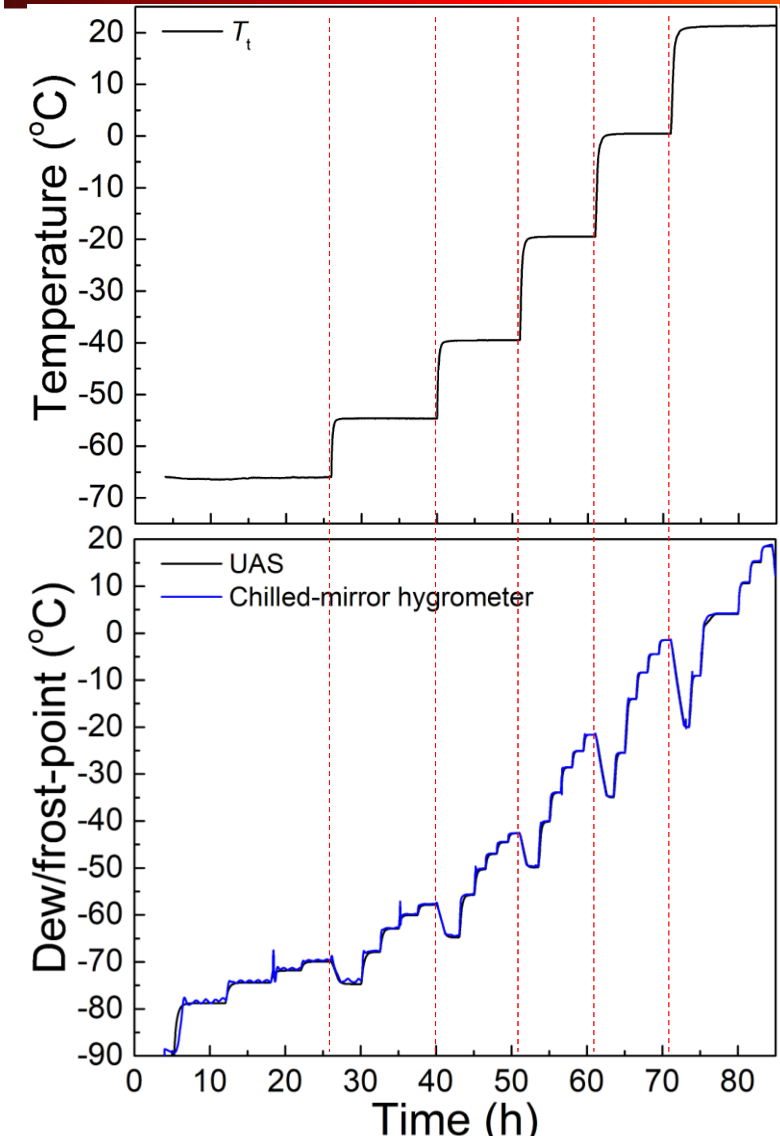
Generation of well-defined vapor pressure

Control of test temperature

A copy of KRISS low frost point generator 2

Lee *et al.* Metrologia **58**, 065002 (2021)

Operation of humidity generator



$$\mathrm{RH} = \frac{e_{ws}(T_s)}{e_{ws}(T_t)} \times \frac{f(T_s, P_s)}{f(T_t, P_t)} \times \frac{P_t}{P_s} \times 100\ (\%\mathrm{rh})$$

T_s = saturator temperature, P_s = saturator pressure

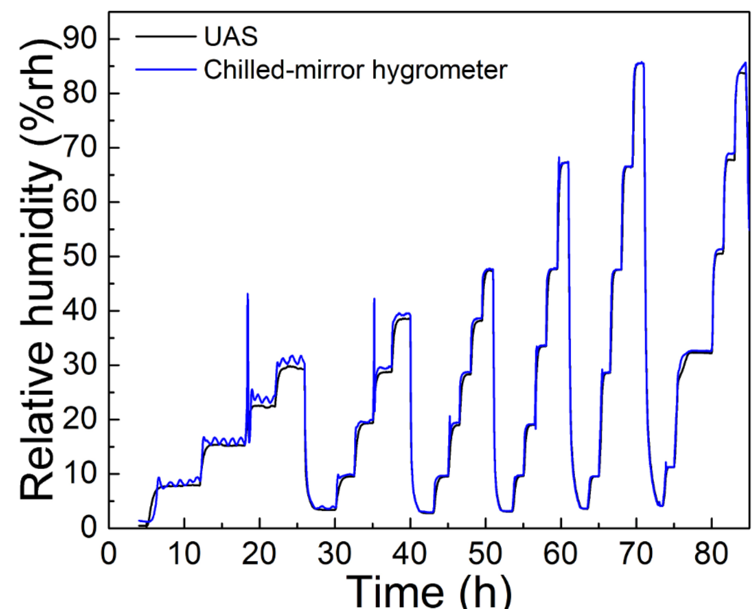
T_t = test chamber temperature, P_t = test chamber pressure

$e_{is}(T_s)$ = saturation vapour pressure over ice in saturator

$e_{ws}(T_t)$ = saturation vapour pressure over water in test chamber

$f(T_s, P_s)$ = enhancement factor in saturator

$f(T_t, P_t)$ = enhancement factor in test chamber



UAS (input humidity) → Radiosonde → CM hygrometer (output humidity)

Uncertainty of UAS humidity generator

$$\mathrm{RH} = \frac{e_{ws}(T_s)}{e_{ws}(T_t)} \times \frac{f(T_s, P_s)}{f(T_t, P_t)} \times \frac{P_t}{P_s} \times 100\ (\%\mathrm{rh})$$

$u(T_s) \times \{\partial e_s(T)/\partial T\}|_{Ts} \times [\ ] \times 100$

$u(P_s) \times \{-1/P_s^2\} \times [\ ] \times 100$

$u_r(e_s(T_s)) \times [\ ] \times 100$

$u_r(f(P_s,T_s)) \times [\ ] \times 100$

$u(T_t) \times (-1/e_s^2(T_t)) \times \{\partial e_s(T)/\partial T\}|T_t \times [\ ] \times 100$

$u(P_t) \times [\ ] \times 100$

$u_r(e_s(T_t)) \times (-1/e_s^2(T_t)) \times [\ ] \times 100$

$u_r(f(T_t,P_t)) \times (-1/f(T_t,P_t)^2) \times [\ ] \times 100$

u (Efficiency)

u(Adsorption/Desorption)

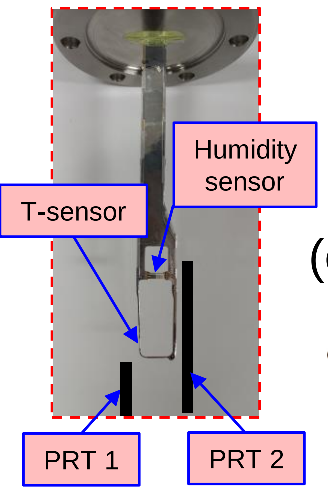
Table 2. Uncertainty budget on relative humidity of UAS at T_t = -67.8 °C.

Relative humidity at T_t = -67.8 °C	%rh	9.5	19.0	28.3	37.4	9.5	19.0	28.3	37.4	9.5	19.0	28.3	37.4
Uncertainty component	**Unit**	**Standard uncertainty**				**Sensitivity coefficient**				**Contribution to uncertainty**			
Saturator temperature, $u(T_s)$	°C	0.027	0.027	0.027	0.027	1.549	2.958	4.289	5.565	0.042	0.080	0.116	0.150
Saturator pressure, $u(P_s)$	kPa	0.177	0.177	0.177	0.177	0.093	0.185	0.275	0.363	0.016	0.033	0.049	0.064
Saturation vapour pressure in saturator, $u_r(e_{is}(T_s))$	Pa	0.00014	0.00025	0.00036	0.00046	139.823	139.527	139.689	139.116	0.019	0.036	0.050	0.064
Enhancement factor in saturator, $u_r(f(P_s,T_s))$		0.00049	0.00046	0.00044	0.00043	9.474	18.911	28.130	37.185	0.005	0.009	0.012	0.016
Test chamber temperature, $u(T_t)$	K	0.063	0.063	0.063	0.063	-1.301	-2.596	-3.861	-5.102	-0.082	-0.164	-0.243	-0.321
Test chamber pressure, $u(P_t)$	kPa	0.182	0.182	0.182	0.182	0.095	0.189	0.281	0.371	0.017	0.034	0.051	0.068
Saturation vapour pressure in test chamber, $u_r(e_{ws}(T_t))$	Pa	0.002	0.002	0.002	0.002	13.623	27.138	40.411	53.200	0.032	0.063	0.094	0.124
Enhancement factor in test chamber, $u_r(f(T_t,P_t))$		0.00081	0.00081	0.00081	0.00081	-9.485	-18.928	-27.975	-37.207	-0.008	-0.015	-0.023	-0.030
Saturator efficiency, u (Efficiency)	°C	0.006	0.006	0.006	0.006	1.547	2.955	4.285	5.562	0.010	0.019	0.027	0.036
Adsorption/desorption, u(Ads./Des.)	°C	0.100	0.100	0.060	0.060	1.547	2.955	4.285	5.562	0.155	0.296	0.257	0.334
Combined standard uncertainty, $u_c(RH)$ (k=1)	%rh									0.2	0.4	0.4	0.5
Expanded uncertainty, $u(RH)$ (k=2)	%rh									**0.4**	**0.7**	**0.8**	**1.0**

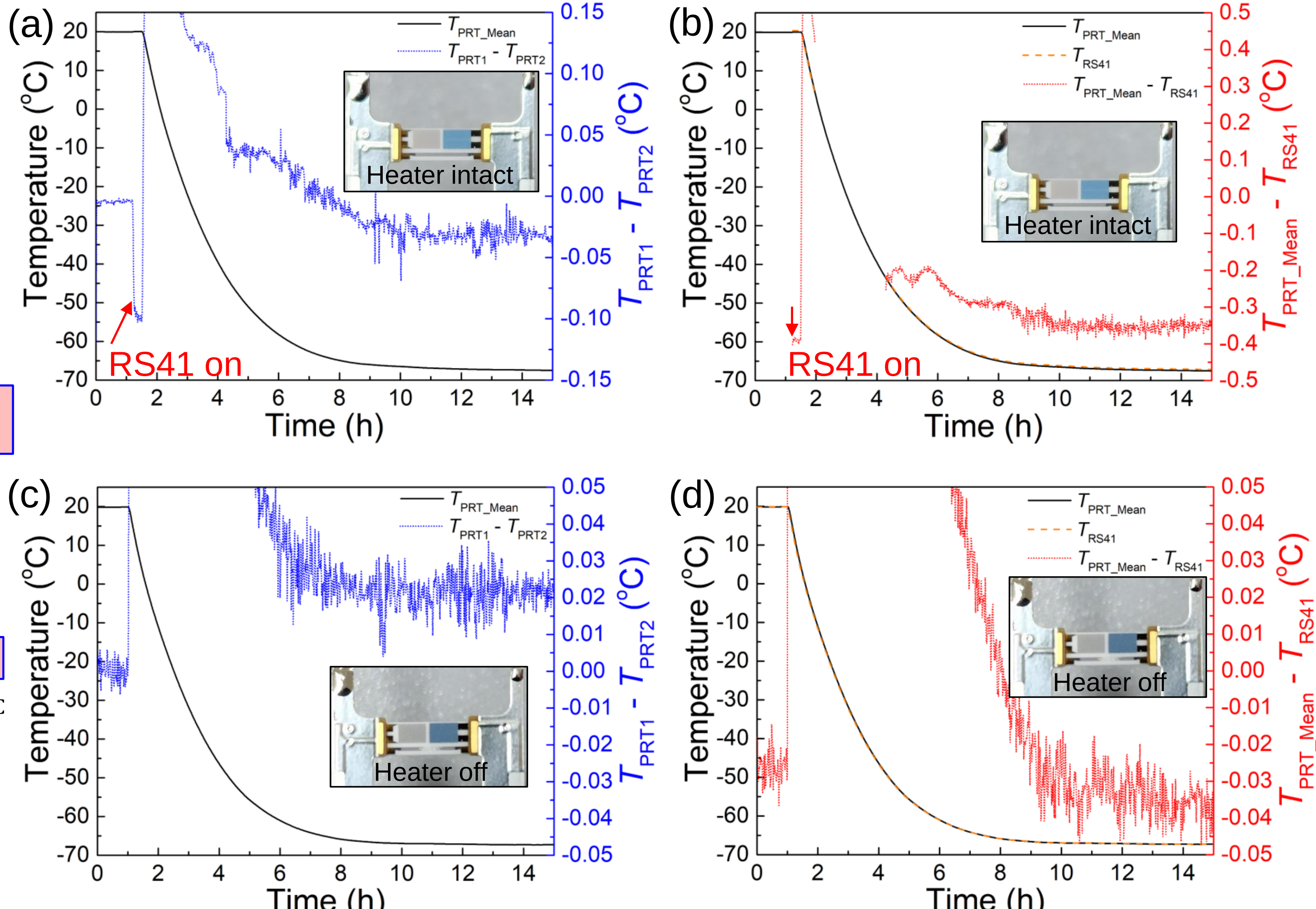
%rh

Reference temperature for RH of RS41

RH test cell



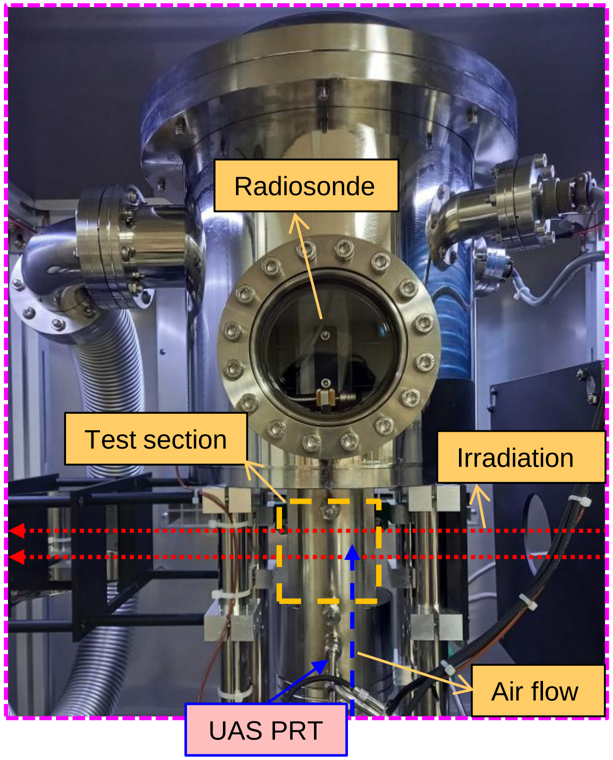
PRT uncertainty = 0.05 ℃

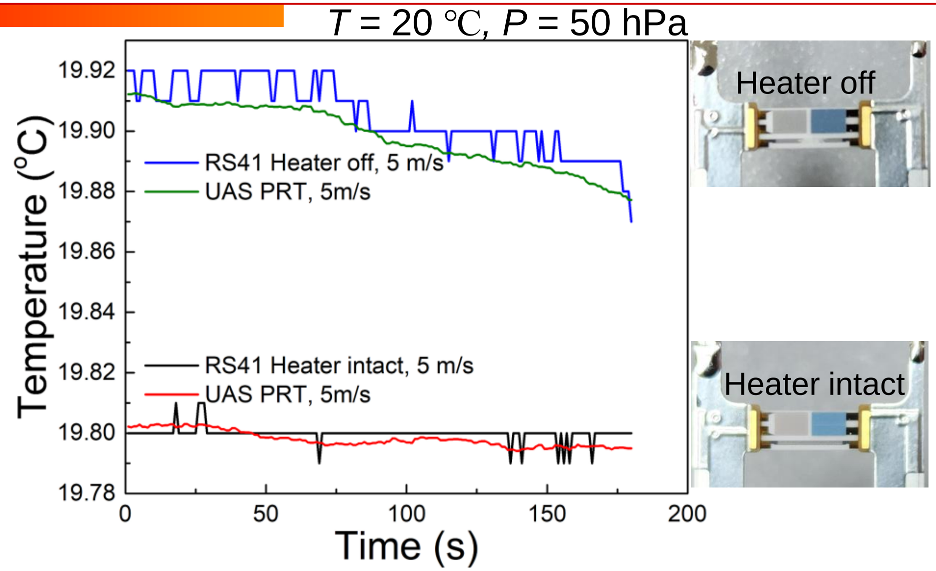


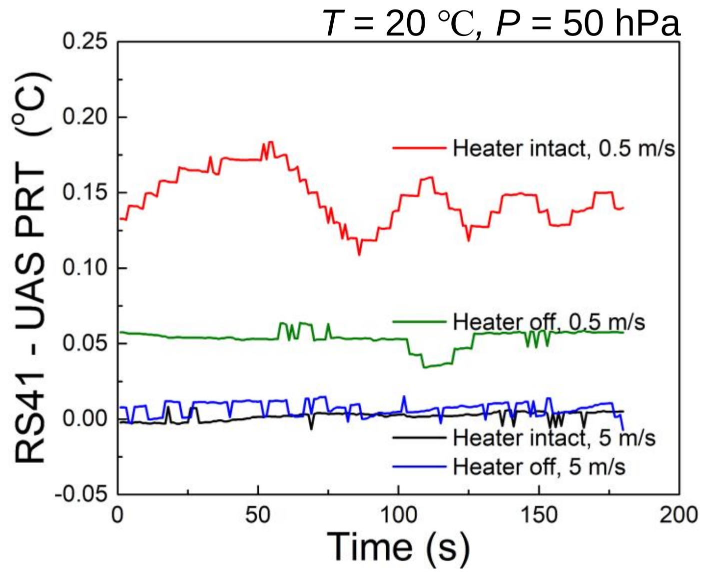
However, the ventilation speed in the test cell was 0.02 m/s (max. 0.6 m/s possible)

Reference temperature for RH of RS41

<Radiation correction setup>

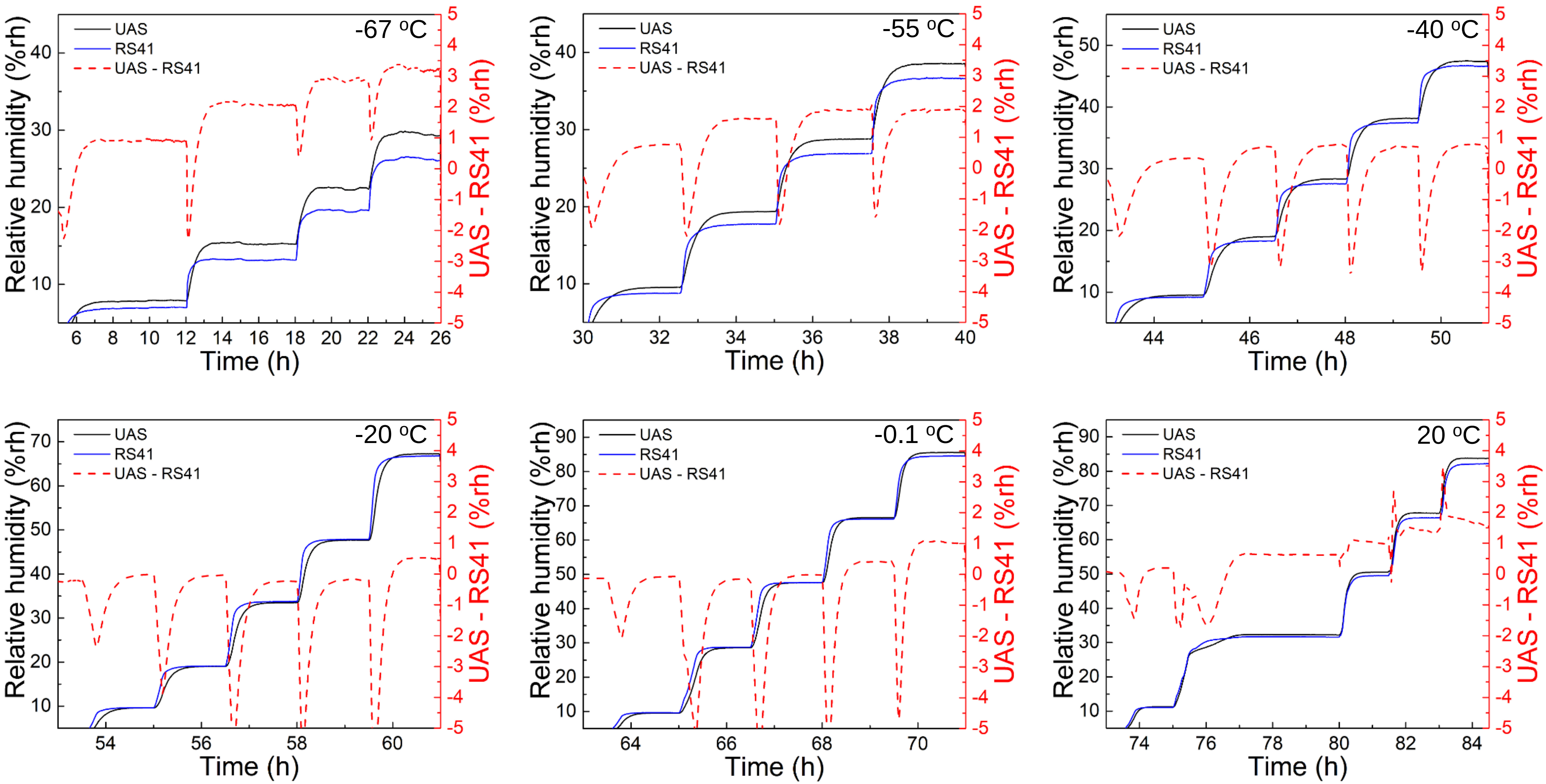






Calibration of RS41 humidity sensor using UAS

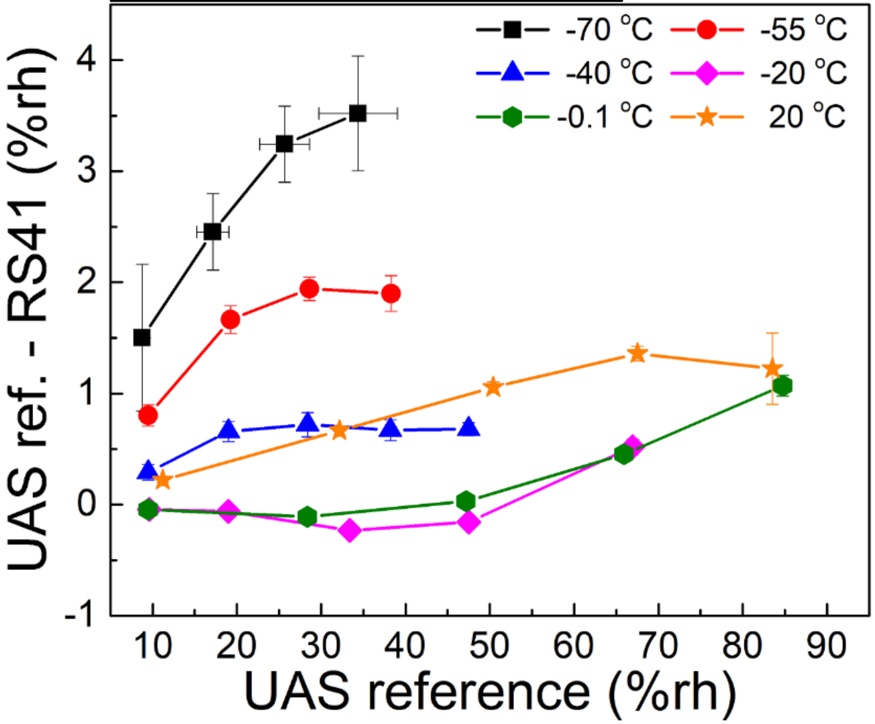
- RS41 T-sensor → Reference T → Reference RH of UAS



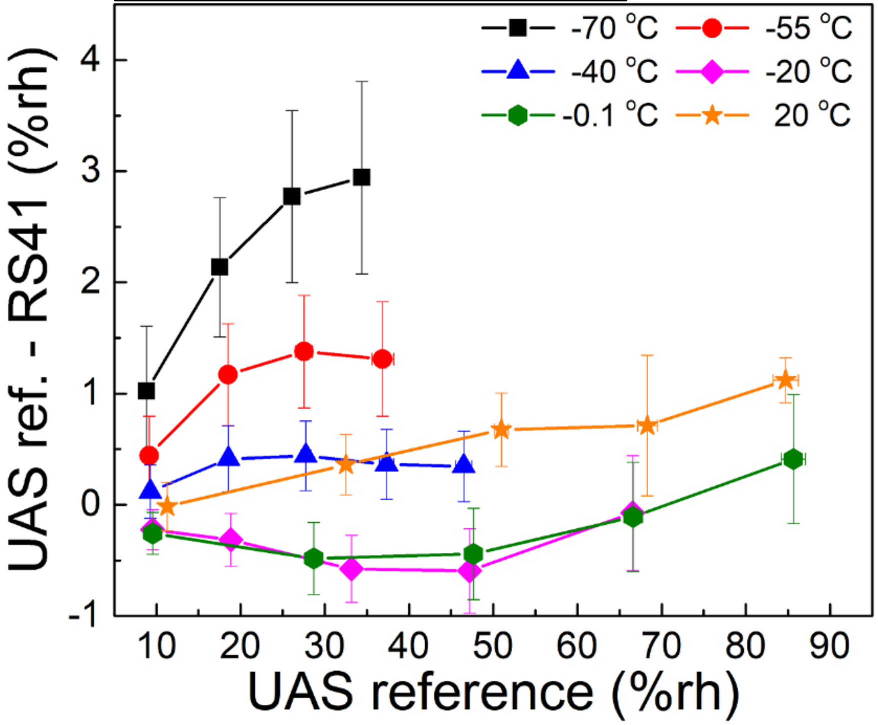
Calibration result; repeatability & reproducibility

- Repeatability and Reproducibility of RS41

Three measurements of a RS41 unit
Mean ± Standard deviation

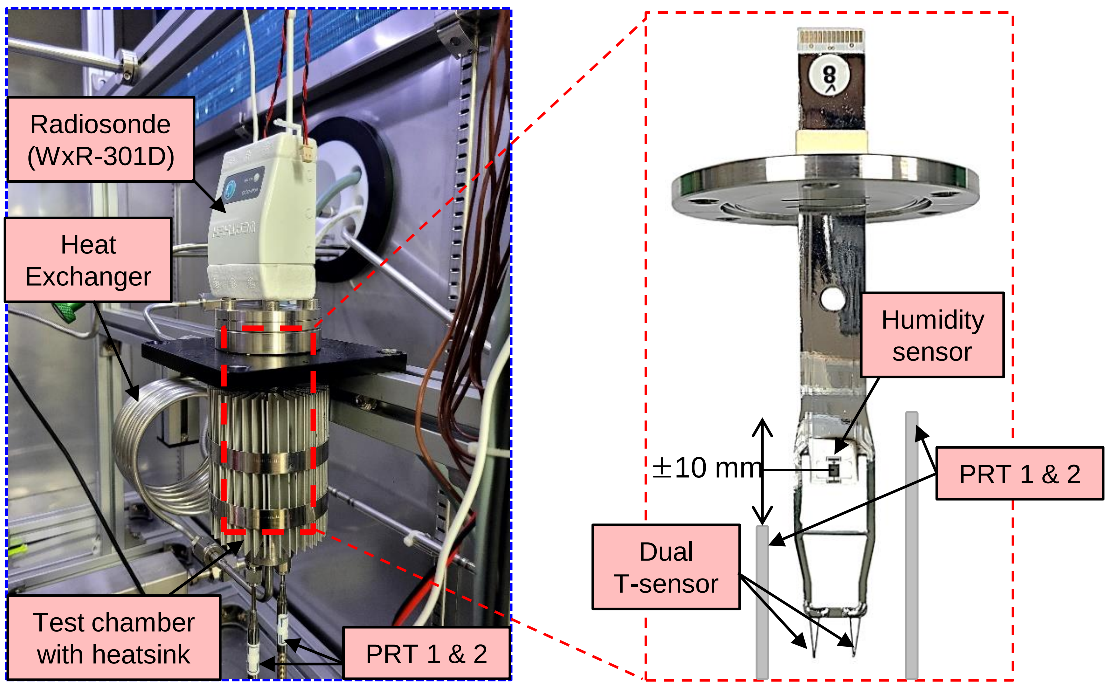


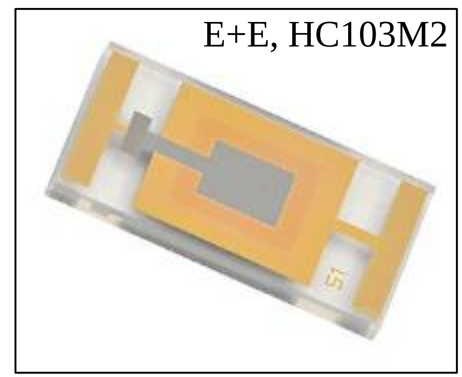
Measurements of three RS41 units
Mean ± Standard deviation



Calibration of DTR humidity sensors using UAS

- Dual thermistor radiosonde (DTR)
  - Black and white sensors for compensation of solar radiation effect.
  - Polymeric thin-film humidity sensors (capacitive sensors)



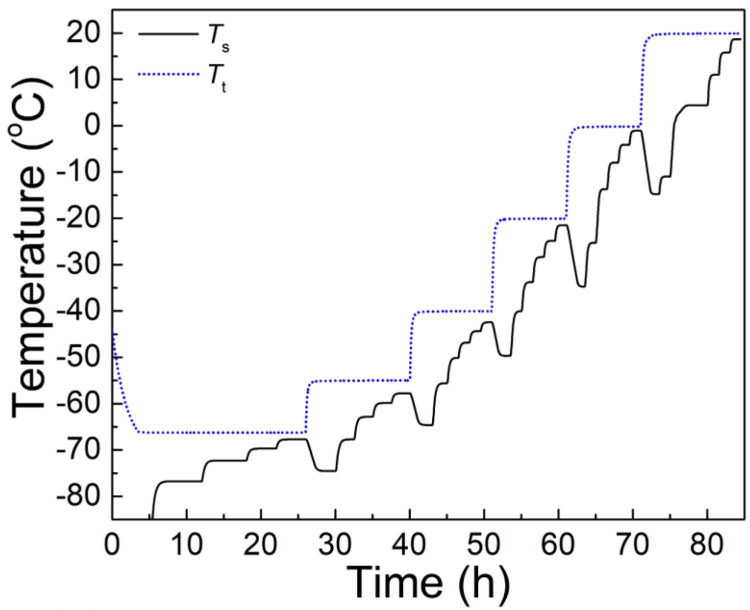


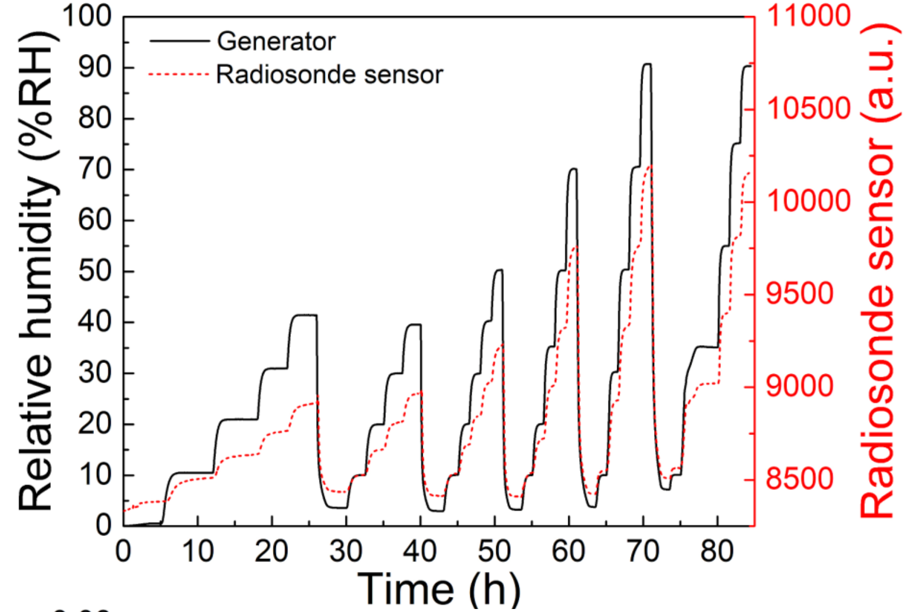
Manufacturer specification

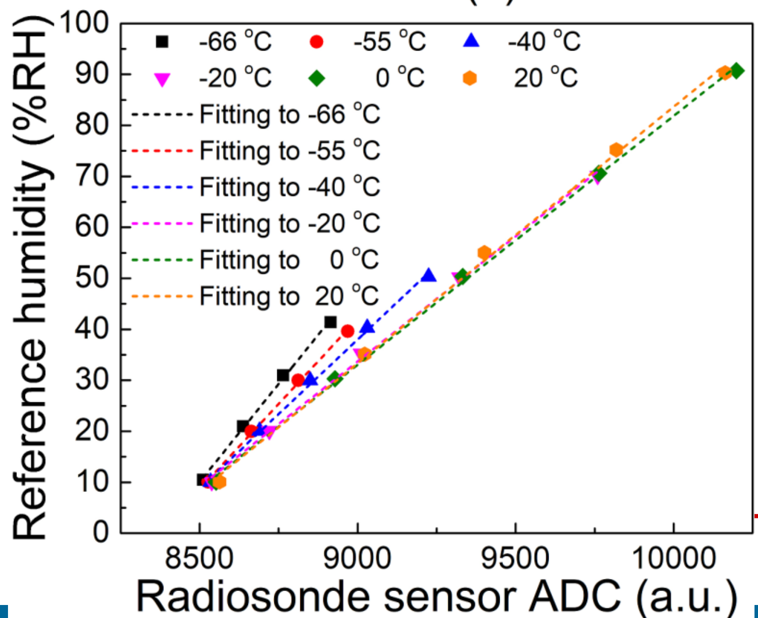
- 160 ± 40 pF
  NOMINAL CAPACITANCE C0 (AT 30°C / 86°F)
- 0...100% RH
  WORKING RANGE HUMIDITY
- < ± 2% RH
  LINEARITY ERROR (0...98% RH)

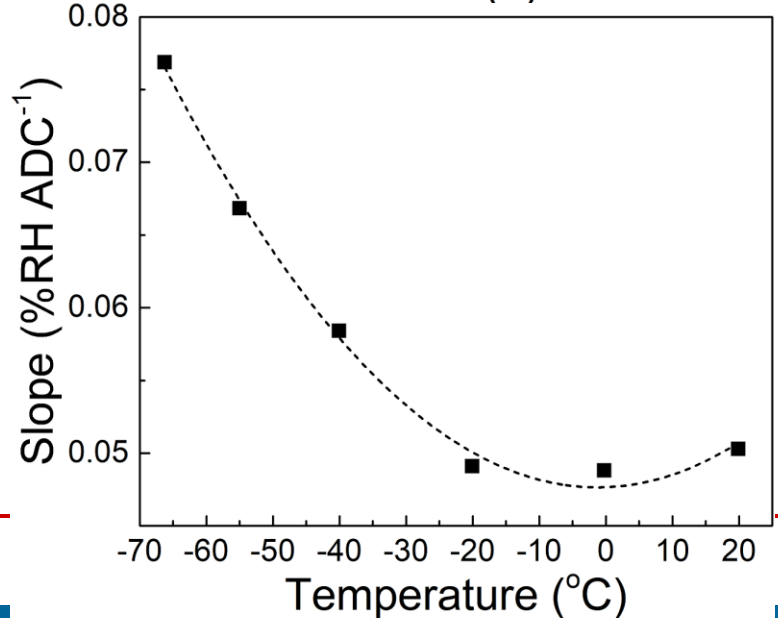
Radiation correction of DTR:
Lee *et al.* Atm. Meas. Tech. **15**, 2531-2545 (2022)

Calibration using the UAS

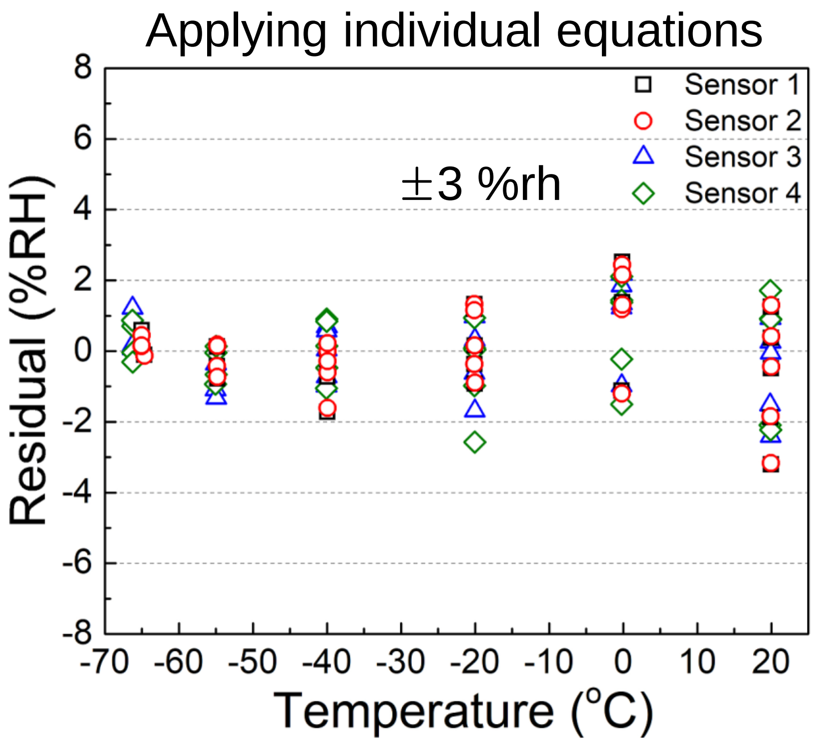


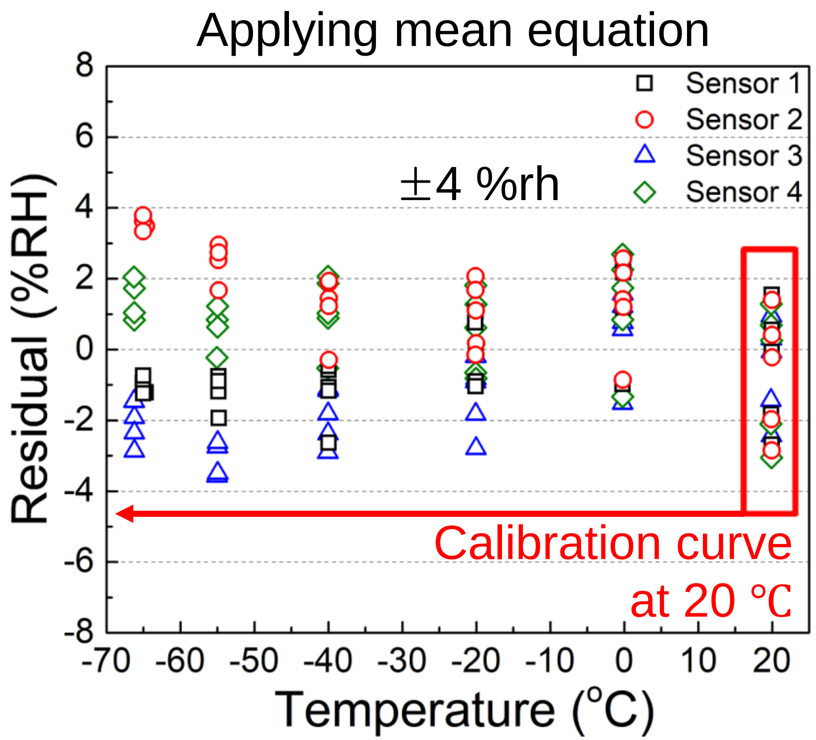






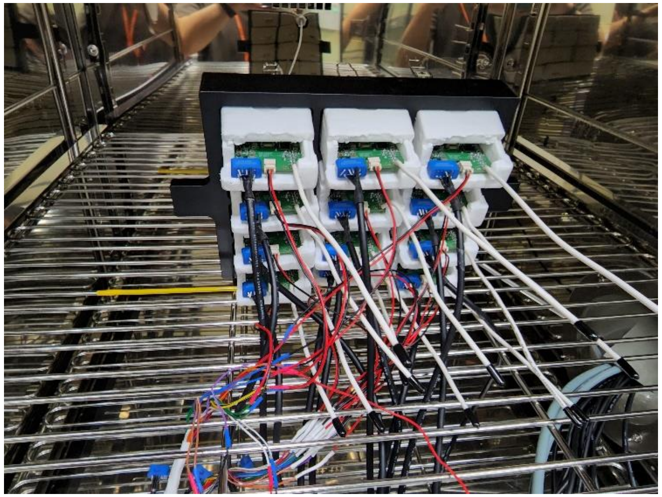
Residuals of calibration curves

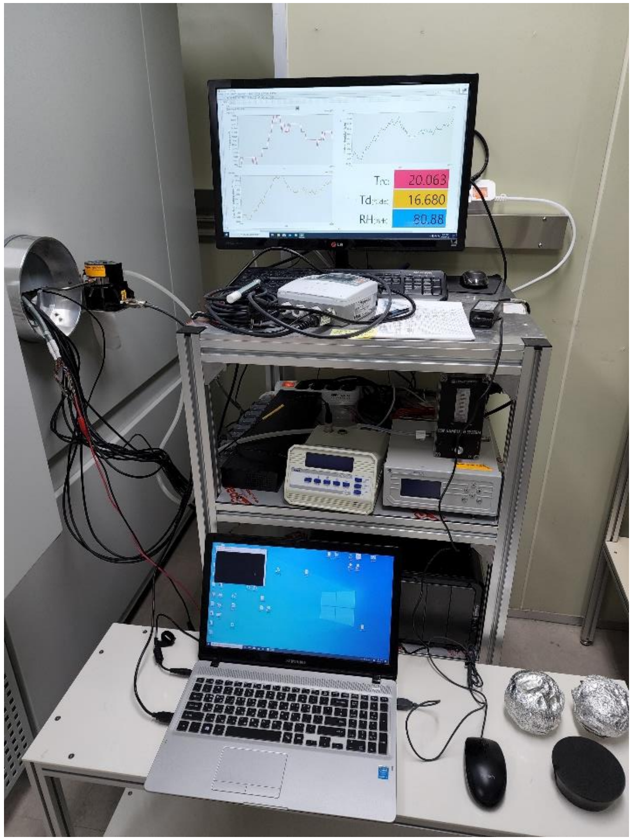




Preparation for sounding

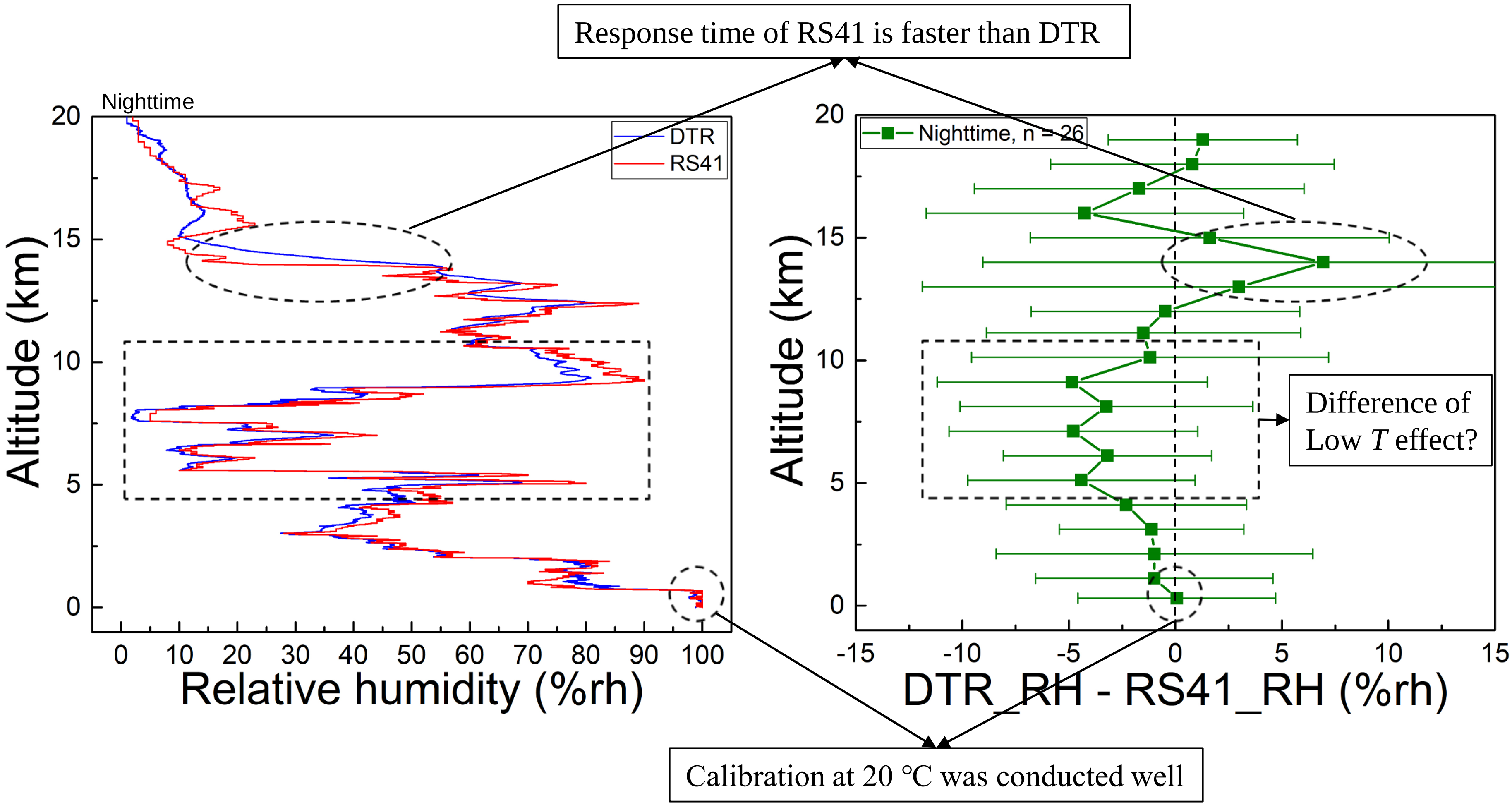
- Calibration of all humidity sensors at 20 °C
  - Climate chamber for controlling T and RH
  - Dew-point hygrometer is used to calculate reference RH


Radiosondes in climate chamber

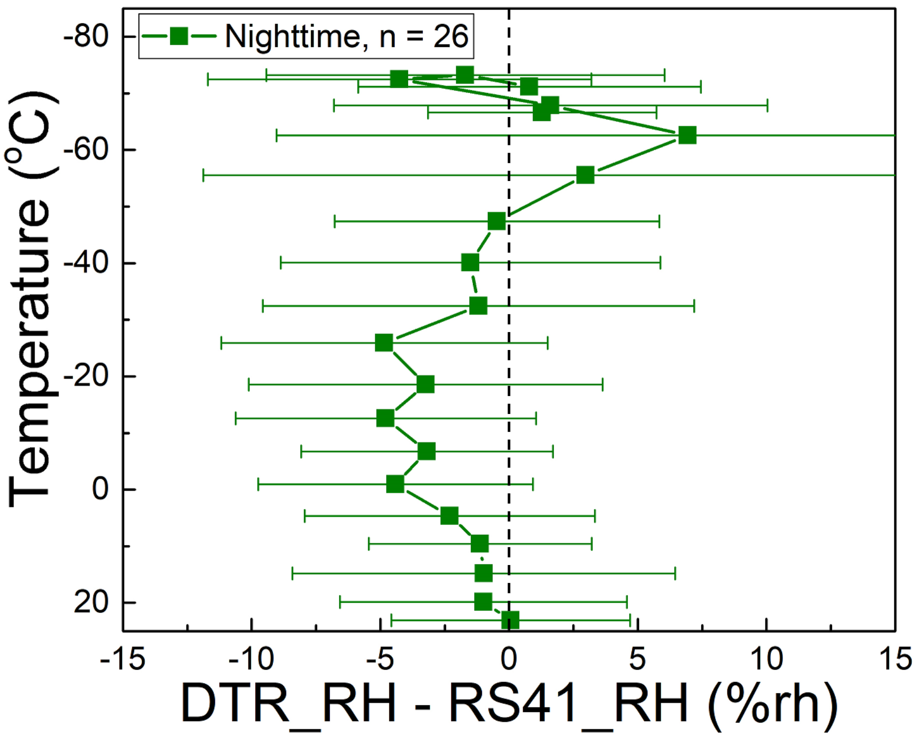


Measurement setup

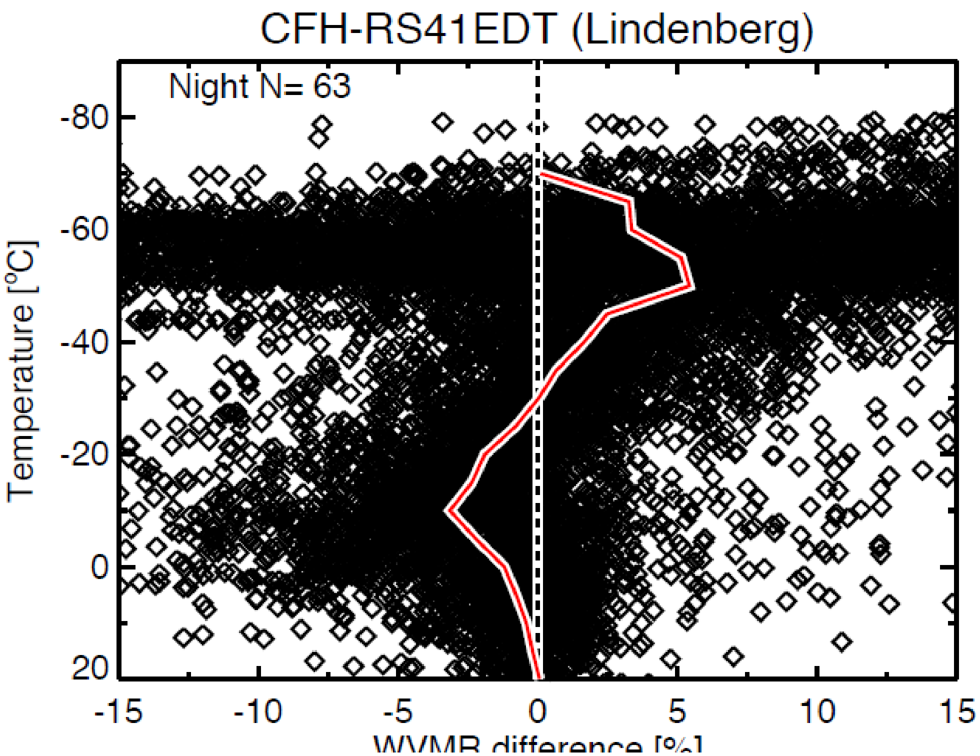
Sounding test; nighttime



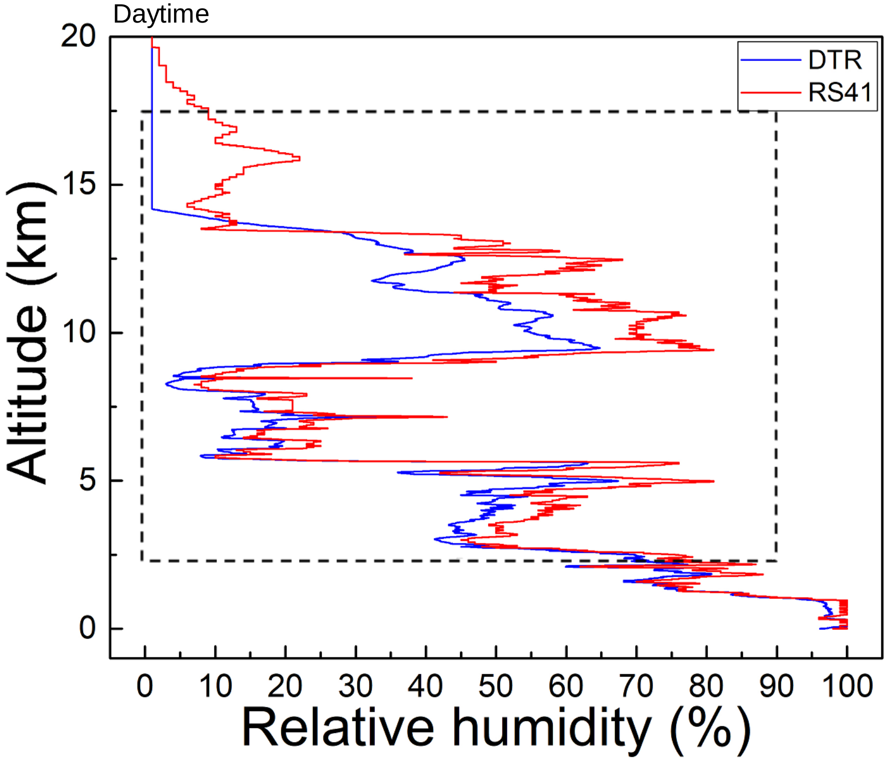
Sounding test; nighttime

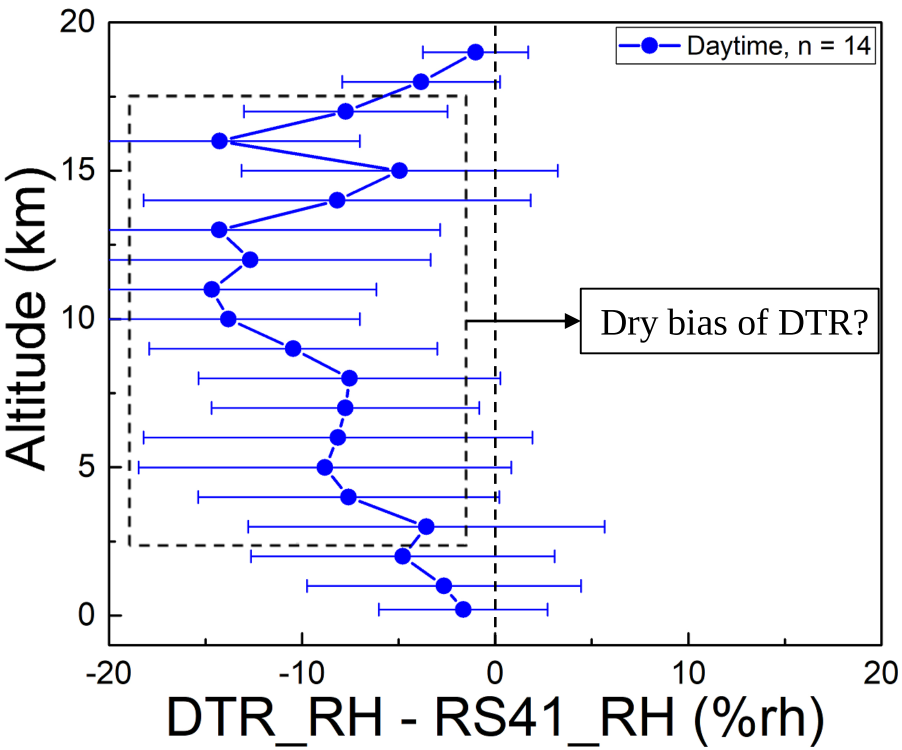


From the GRUAN LC

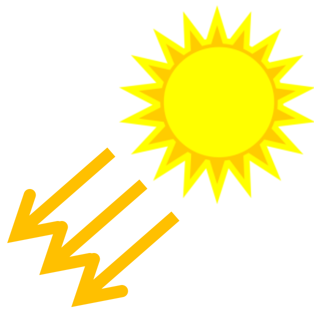


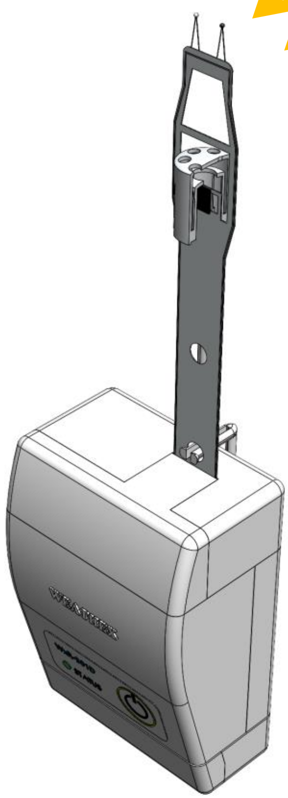
Sounding test; daytime





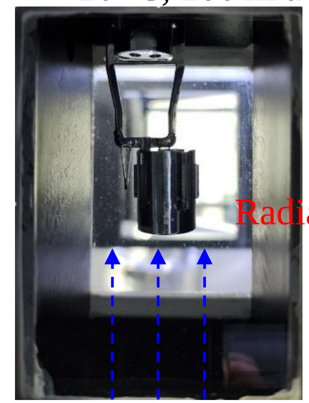
Compensation of dry bias



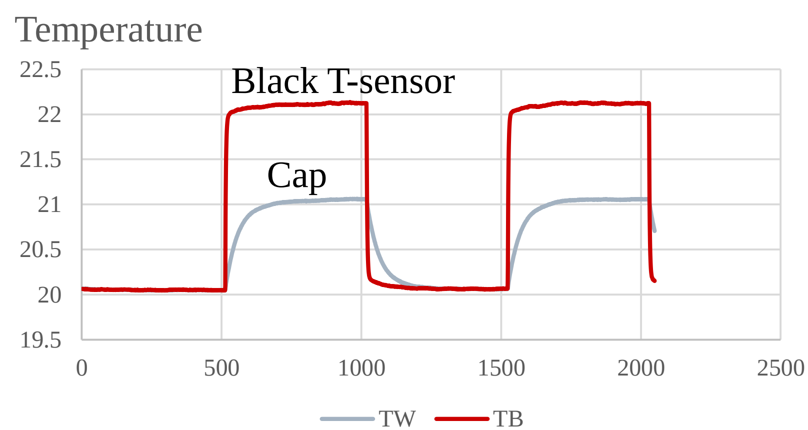


Radiative heating of sensors
↓
Dry bias on humidity measurement

Temperature of humidity sensors
↓
Compensation of the dry bias



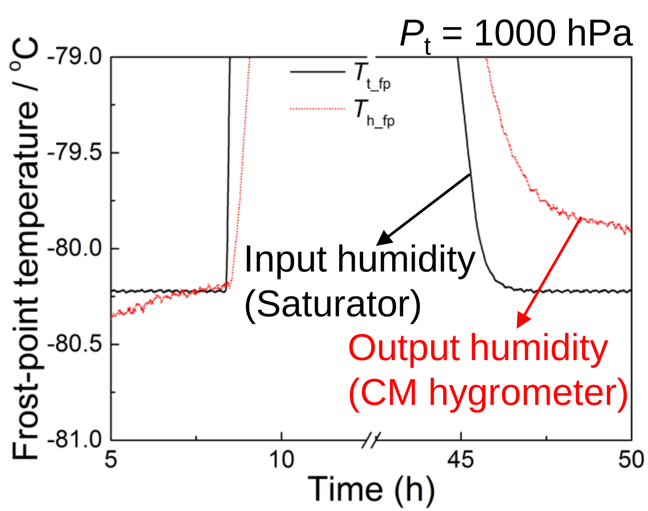
Temperature measurement on the inner side of cap using UAS

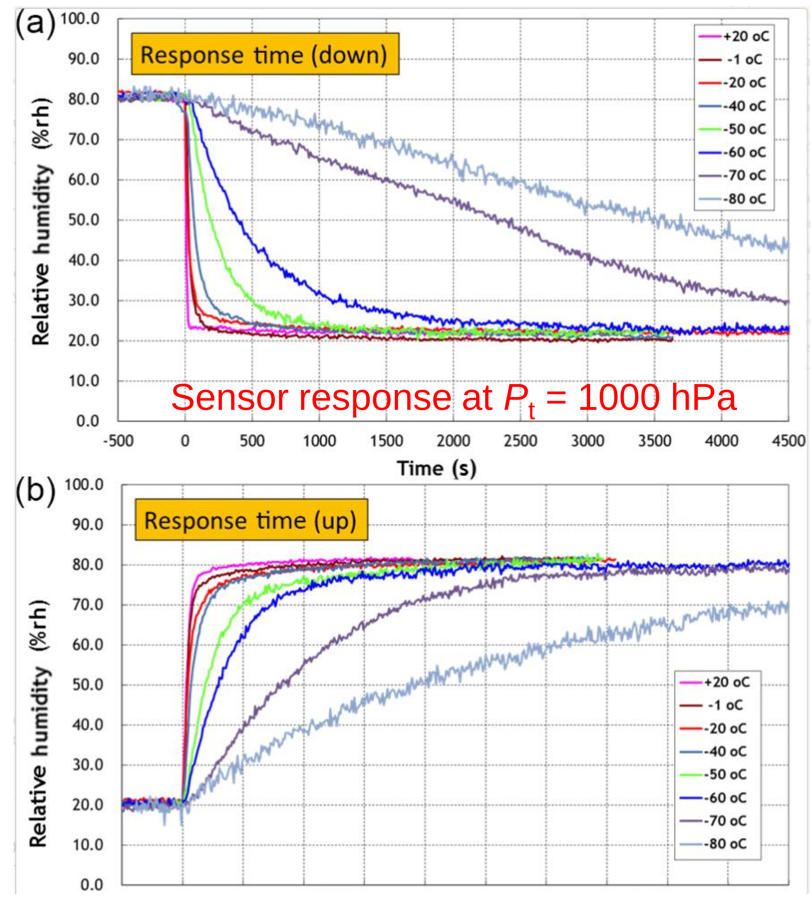


Compensation of dry bias will be further studied.

Response time issue

- Adsorption/desorption of water is slow at low temperatures
  - Temperature of test cell = -70 °C
  - Pressure of test cell = 1000 hPa
  - Frost-point temperature = -80 °C
  - Air flow rate = 0.02 m/s





Air flow rate will be increased for testing response time

Summary

Calibration of radiosonde humidity sensors using the UAS

- Uncertainty of relative humidity generation of the UAS is 1 %rh at -70 °C.
- Calibration of RS41 humidity sensors was conducted using the UAS (Sensor heating & low flow rate → Ref. T → RS41 T-sensor).
- Compensation of low-T effect of DTR having non-heating type humidity sensors was conducted using the UAS.

Sounding test

- Humidity measurements of RS41 and DTR are compared through soundings.
- At nighttime, RS41 and DTR agree within 5 %rh on average.
- At daytime, DTR shows a significant dry bias → Compensation under study.
- DTR shows a slow response time in stratosphere → The setup will be revised to study response time.

Thank you for your attention

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