

# MEDA HS: Relative humidity sensor for the Mars 2020 Perseverance rover

Maria Hieta<sup>a,\*</sup>, Maria Genzer<sup>a</sup>, Jouni Polkko<sup>a</sup>, Iina Jaakonaho<sup>a</sup>, Shahin Tabandeh<sup>b</sup>, Andreas Lorek<sup>c</sup>, Stephen Garland<sup>c</sup>, Jean-Pierre de Vera<sup>c,d</sup>, Erik Fischer<sup>e</sup>, Germán M. Martínez<sup>e,f</sup>, Ari-Matti Harri<sup>a</sup>, Leslie Tamppari<sup>g</sup>, Harri Haukka<sup>a</sup>, Matias Meskanen<sup>a</sup>, Manuel de la Torre Juárez<sup>g</sup>, José Antonio Rodríguez Manfredi<sup>h</sup>

<sup>a</sup>*Finnish Meteorological Institute, Erik Palmenin aukio 1, 00560 Helsinki, Finland*

<sup>b</sup>*VTT Technical Research Centre of Finland Ltd, National Metrology Institute VTT MIKES, P.O. Box 1000, FI-02044 VTT, Finland*

<sup>c</sup>*Planetary Analog Simulation Laboratory (PASLAB), Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Rutherfordstraße 2, 12489 Berlin*

<sup>d</sup>*Space Operations and Astronaut Training, Microgravity User Support Center (MUSC), Geb. 29, Linder Höhe, 51147 Köln, Germany*

<sup>e</sup>*University of Michigan, 500 S State St, Ann Arbor, MI 48109, USA*

<sup>f</sup>*Lunar and Planetary Institute/USRA, 3600 Bay Area Blvd., Houston, Texas, USA*

<sup>g</sup>*Jet Propulsion Laboratory-California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA*

<sup>h</sup>*Centro de Astrobiología (INTA-CSIC), Ctra de Torrejón a Ajalvir, km 4 28850 Torrejón de Ardoz, Madrid Spain*

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## Abstract

The Finnish Meteorological Institute (FMI) provides a relative humidity measurement sensor (HS) for NASA's Mars 2020 rover. The sensor is a part of the Mars Environmental Dynamic Analyzer (MEDA), a suite of environmental sensors provided by Spain's Centro de Astrobiología. The main scientific goal of the humidity sensor is to measure the relative humidity of the Martian atmosphere near the surface and to complement previous Mars mission atmospheric measurements for a better understanding of Martian atmospheric conditions and the hydrological cycle. Relative humidity has been measured from the surface of Mars previously by Phoenix and Curiosity. Compared to the relative humidity sensor on board Curiosity, the MEDA HS is based on a new version of the polymeric capacitive humidity sensor heads developed by Vaisala. Cali-

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\*Corresponding author

Email address: [maria.hieta@fmi.fi](mailto:maria.hieta@fmi.fi) (Maria Hieta)

bration of humidity devices for Mars conditions is challenging and new methods have been developed for MEDA HS. Calibration and test campaigns have been performed at the FMI, at University of Michigan and the German Aerospace Center (DLR) in Berlin to achieve the best possible calibration. The accuracy of HS and uncertainty of the calibration has been also analysed in detail with VTT Technical Research Centre of Finland. Assessment of sensor performance after landing on Mars confirms that the calibration has been successful, and the HS is delivering high quality data for the science community.

*Keywords:* Mars, humidity sensor, atmosphere, relative humidity, calibration

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## 1. Introduction

MEDA HS is a relative humidity sensor for Mars 2020 Perseverance rover [1] provided by the Finnish Meteorological Institute (FMI). The main outputs of the MEDA HS are the atmospheric relative humidity (RH) at sensor and derived water vapour volume mixing ratio. This paper describes the MEDA HS calibration, data processing and measurement performance confirmed with the first measurements from the surface of Mars. MEDA HS is a part of the Mars Environmental Dynamic Analyzer (MEDA), a set of environmental sensors provided to NASA by the Centro de Astrobiología (CAB) at the Instituto Nacional de Técnica Aeroespacial in Madrid, Spain [2]. MEDA's principal goals are to provide continuous measurements that characterize the diurnal to seasonal cycles of near-surface environment and local environmental dust properties. This work presents additional calibration results to those presented in the MEDA instrument paper [2] that characterised the sensor behaviour between the dry and saturation conditions in Martian environment, and in changing humidity. In addition to this paper, there is a companion paper focusing on the first results of the HS *"Initial results of the relative humidity observations by MEDA instrument onboard the Mars 2020 Perseverance Rover"* submitted to JGR Planets by J. Polkko et al. The remainder of this paper is structured as follows: Section 2 provides the scientific background and objectives of humidity measurements

on Mars, Section 3 presents the MEDA HS sensor, Section 4 describes the calibration tests of the HS, Section 5 presents the flight calibration formulation for the HS and Section 6 presents first observations from the surface. Conclusions and discussion are in Section 7.

## 2. Background

The atmospheric water vapor in the Martian atmosphere was firstly observed through ground-based measurements in 1950-1960 and later on through several Mariner spacecraft giving the first actual observations of the Martian atmosphere [e.g. 3, 4, 5]. Based on the Viking mission results the precipitable amount of water (integrated amount of water in the air column) in the Martian atmosphere seems to be varying between 0 to 100 micrometers depending on location and season [6]. Hence the Martian atmosphere contains roughly one thousand times less water than the terrestrial atmosphere. Large amount of water exists in the form of ice in the polar caps and within the soil providing reservoirs for planetary scale water cycle between the atmosphere and the polar cap areas. In addition, an active adsorption-desorption process seems to be adsorbing water from the Martian atmosphere into the surface regolith during nighttime and releasing the water back to the atmosphere as investigated by, e.g., [6, 7].

In situ humidity measurements are important for understanding the Martian water cycle and for the classification of Mars' habitability. Water is essential for life. Besides the existence of an energy source, the presence of water in solid, gaseous or liquid form is one of the main characteristics for habitability. It is known that a number of organisms are able to be physiologically active in presence of the different states of water's aggregation ([8], [9], [10]) and particular at values of relative humidity between 60% and 100%. But even largely below 60% relative humidity also some bacteria and archaea are even able to grow [10]. In this reference measurements on relative humidity are important to be monitored.

The first long term data set of Martian atmospheric water was generated by the Mars Science Laboratory (MSL) rover Curiosity that landed at the Gale Crater (4.6°S, 137.5°E) in 2012 and has been producing atmospheric humidity observations since then and has proved to be a treasure trove for Martian investigations. The humidity measurements were made by the Rover Environmental Monitoring Station (REMS) instrument, which included an RH measurement device REMS-H [11]. The REMS humidity results have confirmed that the Martian atmosphere is as dry as measured by the Viking mission. The relative humidity is about 0% during daytime [e.g. 12, 13]. The humidity observations have also detected the increased atmospheric humidity with the season advancing toward late Northern Summer and decreasing humidity during the Northern winter and springtime [e.g. 12].

Before the MSL mission, the Phoenix lander reached Martian surface in May 2008 in the Northern part of Mars at the Green valley (68°N, 127°W), and was probing for atmospheric humidity during the 150 sols of its lifetime. Those humidity measurements were made by a thermal and electrical conductivity probe (TECP). These measurements were later on recalibrated and adjusted giving eventually results that also matched with the earlier estimates of the atmospheric humidity at the Northern latitudes [14, 15, 16]. A review of in situ meteorological data obtained from the Viking landers to Curiosity rover can be found in [17].

The value of Martian atmospheric humidity measurement have been extended through modeling activity by [e.g. 18]. Using modeling tools together with actual humidity observations have shown that the Martian atmospheric humidity levels vary between few precipitable micrometers up to more than 10 micrometers with higher humidity levels at the high latitudes (Phoenix site) than at lower latitudes of the MSL rover at Gale crater. The current MEDA observations are now producing a third data set of the Martian atmospheric humidity thereby enhancing our understanding of the Martian atmosphere.

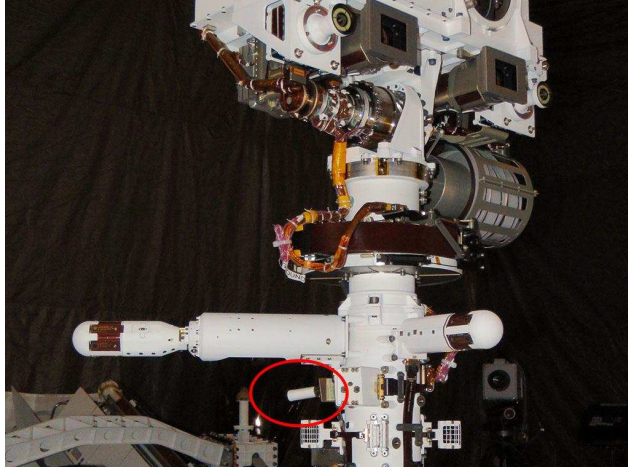


Figure 1: Location of the MEDA HS sensor in Perseverance’s Remote Sensing Mast (RSM) below the deployable wind sensor (WS2) and above the air temperature sensor (ATS2). Credit: NASA/JPL-Caltech

### 3. MEDA HS description

The MEDA HS measures near-surface relative humidity with capacitive humidity sensor heads which react to relative humidity of the ambient air. The HS is located on the Remote Sensing Mast (RSM) of NASA’s Perseverance Mars rover at 1.5m height from the ground. It is therefore well exposed to the Martian atmosphere but at the same time experiences extreme temperature variations.

The relative humidity (RH) is normally expressed as a percentage, representing the amount of water vapor in the air at a given temperature compared to the water vapour saturation pressure at that same temperature:

$$RH = \frac{e}{e_s} * 100\% \quad (1)$$

where  $e$  is the water vapor content of the gas (water vapor pressure) and  $e_s$  is the maximum possible water vapor content of the gas at that same temperature (saturation vapor pressure over ice). Relative humidity in this paper is mostly calculated with respect to ice.

Water vapour volume mixing ratio (VMR) is used in the this paper to express

absolute humidity. It can be derived from RH using pressure readings from MEDA pressure sensor [2] as will be shown in Section 5.1.

### *3.1. MEDA HS hardware description*

MEDA HS is built around the capacitive HUMICAP® sensor technology by a private company Vaisala Oyj [19] and the reading electronics are based on an oscillator transducer that converts the output of the capacitive sensors into frequency. The HS transducer contains 8 measurement channels in total: 2 HUMICAP sensor heads, 2 capacitive THERMOCAP® temperature sensors and 4 reference and housekeeping capacitors. Each sensor head is individually characterised, and they can have slightly different behaviour. Thanks to two sensor heads, the humidity measurement has dual redundancy and when using two sensor heads the average is used as the derived relative humidity. The transducer active components and the multiplexer are implemented into a Vaisala proprietary ASIC (Application Specific Integrated Circuit). The capacitance of the channel is calculated with the constant reference channels. The algorithm for calculating the capacitance from the raw frequencies of the channels is proprietary information of Vaisala. Some of the constant channels are used as housekeeping references to monitor the condition and drift of the transducer. The transducer electronics and the sensor heads are placed on a single multi-layer printed circuit board (PCB) of a  $63 \times 15$  mm size. The HUMICAP sensor heads are electrically connected to the PCB with manually solder-bonded 50  $\mu\text{m}$  silver wire and mechanically secured with a small amount of epoxy to allow thermal expansion and contraction.

Each HUMICAP sensor head has its own temperature sensor: on-chip platinum Pt1000 platinum resistance thermometer (PRT). Pt1000 sensors are used for two purposes, and they are read by the MEDA Instrument Control Unit (ICU). Pt1000<sub>1</sub> with 2-wire measurement is used for monitoring regeneration or defrosting temperature (see Section 3.4), and Pt1000<sub>2</sub> with 4-wire measurement is used for scientific temperature measurement during nominal operation. The 4-wire connection eliminates the influence of the connection leads on the

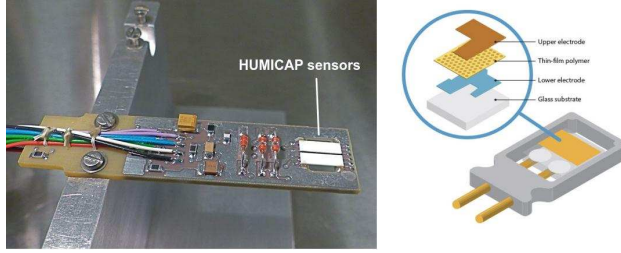


Figure 2: MEDA HS sensor PCB on the left (HUMICAP® sensor heads facing down) and the basic structure of HUMICAP sensor head on the right [19]. HUMICAP consists of a substrate on which a thin film of polymer is deposited between two conductive electrodes.

measuring result by compensating for the effect of lead resistance. Having the reference temperature measurement in the actual HUMICAP sensor head is a major improvement compared to previous-generation sensors. The capacitive THERMOCAP sensors also give an independent temperature reading from the PCB. This gives an advantage in estimating temperature measurement accuracy and calibration stability after landing.

The MEDA HS assembly consists of the PCB containing all the electronics, a cylindrical stainless steel Faraday cage around the PCB and a sensor housing. The Faraday cage is perforated to allow sufficient ventilation and covered with a polytetrafluoroethylene (PTFE) membrane filter (pore size  $0.2 \mu\text{m}$ ) to protect the sensor heads from dust. The size of the complete sensor is  $55 \times 25 \times 90 \text{ mm}$  and the total mass is 45 g. The HS operating power is supplied from the ICU. ICU power circuitry regulates power input voltage to HS according to in-line sensing resistor on the HS PCB so that at the ASIC input the operating voltage is always +5 V. Power input to the HS PCB measured during testing was +6.9 V at  $-70^\circ\text{C}$  and total power consumption during measurement mode was 21 mW.

### 3.2. Operational modes

Humidity sensor operations are controlled by the ICU's flight software. At the beginning of the mission MEDA nominal operational cadence was to measure autonomously around the clock, 1 hour on and 1 hour off alternating between

even and odd hours. The nominal acquisition of HS is to read all transducer channels at a rate of 1 Hz, but 0.5 Hz is also possible to configure. The HUMICAP sensor heads react to the surrounding relative humidity even when the sensor is off so after powering on, the relative humidity can be read almost instantly. After 1 s the readings are considered reliable and during HS calibration, seconds 2-5 from 1 Hz acquisition were averaged to get the most accurate reading of the sensor. Self-heating starts to affect the readings after few seconds.

The HS has two operational modes: *high-resolution interval mode (HRIM)* and *continuous mode*. Both HRIM and continuous mode can be used in HS operations considering the advantages and limitations of each mode (see Table 1).

In HRIM the HS is powered on only for 10 seconds and then powered off to avoid self-heating. HRIM can be used with different intervals and 15-minute and 5-minute intervals are currently configured in MEDA. The HS has been calibrated using HRIM and that measurement mode provides the highest accuracy.

In continuous mode the sensor stays powered on for long periods. A cool-down period of 30 minutes has been used after long continuous measurements before high accuracy measurements in laboratory conditions, but a shorter cooling time can also be sufficient in real Mars conditions. During continuous measurement the sensor self-heating is prominent for about 15-20 minutes from the start of the continuous measurement block. After the self-heating period, the sensor temperature stabilises.

### 3.3. Data products

The main data products of the MEDA HS are the local relative humidity, local sensor temperature and derived water vapour volume mixing ratio (VMR). Local temperature is the sensor internal temperature and measured from Pt1000<sub>2</sub> sensor on HUMICAP 2. The sensor temperature is not the same as the local atmospheric temperature so it needs to be taken into account when using the relative humidity data.



Table 1: The HS operational modes and their use cases

HRIM	Continuous mode
Seasonal measurements	Diurnal variability
Diurnal comparison measurements	Short scale changes
Best accuracy	Absolute accuracy not essential
Operations more resource heavy	Highest temporal coverage
Comparison to models	Environmental dynamics combined with other sensors
Comparison to other RH/VMR instruments	

The HS data is archived and published in the Planetary Data System (PDS) for further use by the scientific community [20]. Four datasets with different levels of data handling are available:

- *Raw data*: Pulse count readings of each HS channel read by MEDA ICU and measurement configuration information. Raw data is not useful for a general user since the calculation of channel capacitances from raw data is Vaisala proprietary information.
- *Partially processed data*: HUMICAP and THERMOCAP capacitances. Not useful for a general user.
- *Calibrated data*: Calibrated relative humidity for individual HUMICAPs in %rh, calibrated Pt1000<sub>2</sub> temperature in Kelvin and calibrated THERMOCAP temperatures in Kelvin without uncertainties.
- *Derived data*: Calibrated local relative humidity (average of the two HUMICAPs) in %rh, uncertainty of local relative humidity in %rh, calibrated local temperature (Pt1000<sub>2</sub>) in Kelvin, uncertainty of local temperature in Kelvin, and volume mixing ratio in ppm (only when RH > 2.5 %rh). The recommended dataset to use for scientific analysis.

The exact contents of the datasets can evolve over time so the reader is always referred to the latest information, like the release notes, in the PDS.

The recommended dataset for almost all users is the derived data. The calculation of the calibrated RH from the channel capacitance is presented in Section 5. The dataset includes both continuous measurements and HRIM measurements, but the measurement uncertainty is at the moment provided only for the HRIM data because the uncertainty during continuous measurement after sensor self-heating is currently undefined. In some cases the daytime RH goes slightly below zero in one or both HUMICAPs and in that case the derived value is rounded to zero. Volume mixing ratio is calculated from the RH, the local temperature and the MEDA PS pressure only when the  $RH > 2.5$  %rh. In very low humidities the uncertainty becomes larger than the actual measured value and this has been selected as the practical lower limit at this point. VMR uncertainty is not yet included in the PDS but it will be added in the future.

The current datasets do not include any corrections to the HS readings other than the RH compensation presented in the in Section 5.2.

### *3.4. HUMICAP technology description*

HUMICAP® is a miniature capacitive thin-film polymer sensor head for sensing relative humidity by Vaisala Oyj [19]. HUMICAP sensor heads have good long-term stability and good tolerance against chemical exposure and dust. The sensor head consists of an alumina substrate on which a thin film of polymer is deposited between two conductive electrodes. The polymer either absorbs or releases water vapor as the relative humidity of the atmosphere changes. The sensing surface is coated with a porous metal electrode to protect it from contamination and exposure to condensation. HUMICAP has a full measurement range from 0 to 100 %rh and an accuracy down to  $\pm 0.8$  %rh. The surface area of the HUMICAP sensor head is approximately 8 x 3 mm and the thickness is less than 1 mm.

The new HUMICAP sensor head has the same polymer and operating principle as the one used in REMS-H/Curiosity [12], but with several advantages:

higher capacitance (45 pF in room temperature), considerably larger dynamic range (2.5-3 pF at -70 °C (203 K) compared to 0.3 pF of REMS-H), and an integrated resistive temperature sensor and a heating resistor. The integrated temperature sensor allows calculation of humidity values with respect to the actual temperature of the sensor head. The heating resistor is used to regenerate HUMICAPs in order to remove possible contaminants that can affect the capacitance, to restore the sensor head performance and to correct possible long-term drifts. The regeneration is done by heating the resistors to +160...+170°C for a few minutes. Regeneration heating removes also absorbed CO<sub>2</sub> from the HUMICAPs and it takes some time to return to normal readings after regeneration, depending of the surrounding conditions.

At a given temperature in ambient pressure air, the response between 0 and 100 %rh is very close to linear. The dynamic range of the HUMICAP decreases at lower temperatures and the response time grows with decreasing temperature. During the MEDA HS calibration project the HUMICAP sensor has been characterised in Mars-like conditions instead of ambient pressure air, and while the sensor also functions in carbon dioxide it is affected by these conditions.

#### **4. Sensor calibration tests**

Relative humidity instruments on both Phoenix and Curiosity had incomplete calibration in the original flight models and the instrument calibration had to be corrected retroactively [12],[16]. Supplementary tests with representative ground test models have been valuable in both cases. Therefore, the calibration flow developed for MEDA HS included manufacturing of an identical ground reference model of the HS which accompanied the flight model in all calibration tests and was subjected to supplementary tests after flight model delivery. Another important principle in MEDA HS calibration was to subject the actual flight model to as representative a calibration environment as possible (including the low temperatures, low pressure and carbon dioxide (CO<sub>2</sub>) environment)

and to cover a large operational range of temperatures and relative humidity.

The MEDA HS flight model (FM) has been tested and calibrated at the FMI together with the spare model (FS) and the ground reference model (REF). All three flight quality models of the HS were manufactured at the same time and the only difference between the REF model compared to FM and FS is that the housing box was never installed on the REF model for practical reasons (in humidity tests all extra surface area should be minimized and the extra housing has no effect on the performance). During calibration tests the configuration of the models was the same. The three flight equivalent instruments went through multiple different tests in ambient pressure, Martian pressure and high vacuum. Both air and CO<sub>2</sub> gas have been used as a test medium when applicable. FM and FS also underwent random vibration tests and a thermal vacuum test (see Section 4.4). All three models were found to be very similar and the difference is mainly the slightly different capacitance range of each model.

After the test and calibration campaign at the FMI, the FM and the FS were delivered to M2020 and REF was kept at the FMI. This made possible the additional testing at other laboratories which was not possible with the flight models due, for example, to cleanliness requirements, availability, transportation risks and schedule. Additional tests were performed with the ground reference model at the University of Michigan and at the DLR Planetary Analogue Simulation Laboratory (PASLAB). Although the calibration performed at the FMI was sufficient to fulfill the instrument performance requirements, the additional tests improved the calibration significantly.

#### *4.1. Calibration performed at the Finnish Meteorological Institute*

The FMI has a dedicated test laboratory developed for humidity sensor calibration purposes. The sensors under test are placed inside a measurement chamber using support brackets and connected to cable feedthroughs in the chamber. The measurement chamber is closed inside a cleanroom and transported to a climate test station to control the temperature. The pressure vessel provides a stable temperature environment for the instruments and it can be



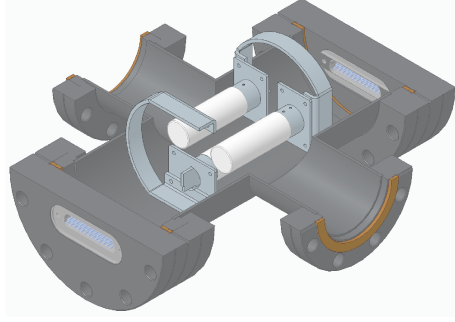


Figure 4: Three MEDA HS models inside the measurement chamber with cable feedthroughs in both ends. The models are attached to U-shape support brackets and located so that all are facing the center of the chamber. Cable feedthroughs are on both ends of the chamber. The gas flow is through the smaller flanges perpendicular to the HS instruments. The same measurement chamber was used also at the DLR.

health, though the vacuum point cannot be used for calibration check purposes.

Calibration tests include temperature calibration and humidity calibration tests. Temperature calibration was performed for THERMOCAP capacitive sensors, heating resistors and Pt1000 sensors against a reference temperature sensor in stable conditions between  $+100^{\circ}\text{C}$  (373 K) and  $-70^{\circ}\text{C}$  (203 K) in ambient pressure air. Humidity calibration was performed in  $\text{CO}_2$  gas at pressures of 5.5 hPa, 7.0 hPa and 8.5 hPa. Calibration consisted of two humidity points: dry and saturated gas. Dry gas was measured at the temperatures  $-70^{\circ}\text{C}$ ,  $-55^{\circ}\text{C}$ ,  $-40^{\circ}\text{C}$ ,  $-25^{\circ}\text{C}$ ,  $-10^{\circ}\text{C}$ ,  $+5^{\circ}\text{C}$ ,  $+22^{\circ}\text{C}$ , and saturated gas at  $-70^{\circ}\text{C}$ ,  $-60^{\circ}\text{C}$ ,  $-50^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$ . Saturation points were achieved by routing the  $\text{CO}_2$  to the measurement chamber through a sterile water container (see Figure ??). The routing was done by manually operating the array of control valves. The humidified  $\text{CO}_2$  flow was kept going through the test and the relative humidity slowly rose inside the vessel. No reference was used to measure the input gas. The HS sensors were monitored every 15 minutes during the saturation period at one temperature until the HS reading stabilized. Dry and saturation points are generally not ideal calibration points and especially in high relative humidity condensation can affect the RH sensor head performance and stability.

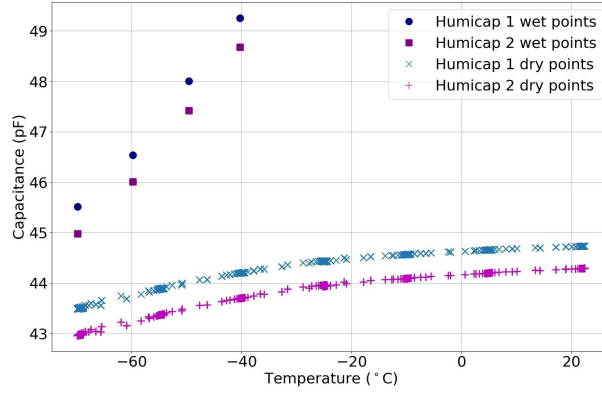


Figure 5: Dry and saturation calibration curves of both of MEDA HS FM sensor heads show the behaviour and dynamic range in temperature scale in Martian pressure. The curves are very similar for FS and REF sensor heads.

For MEDA HS the two-point calibration provided preliminary RH calibration and the full-scale range for each sensor head. Two-point calibration points for the FM are shown in Figure 5. The effect of Mars pressure CO<sub>2</sub> compared to vacuum measurements can be seen in Figure 6.

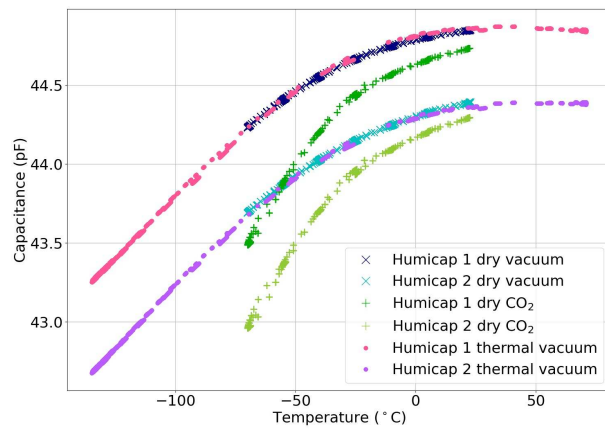


Figure 6: Dry curves in vacuum during characterization tests, thermal vacuum test and in dry CO<sub>2</sub> for MEDA HS FM sensor heads.



#### *4.2. Additional characterization performed at University of Michigan*

Two measurement campaigns were performed at the University of Michigan with the MEDA HS ground reference model (REF): the first one in 2017 just after manufacturing the MEDA HS models and the second in 2019 after flight model delivery. The campaign goals were to replicate RH measurements for HS in a different measurement system to confirm the FMI measurements and to determine the calibration coefficients under dry and saturated Martian conditions. In addition to MEDA HS also REMS-H (MSL/Curiosity) and METEO-H (ExoMars 2022) ground reference models were included in the tests.

The Michigan Mars Environmental Chamber (MMEC) [21] is a cylindrical chamber with an internal diameter of 64 cm and length of 160 cm. It has a thermal plate with embedded heaters and a liquid nitrogen cooling loop to control the temperature of the plate. The surrounding shroud is not thermally controlled. Water vapor is added to the chamber through a temperature and pressure-controlled H<sub>2</sub>O bath. The MMEC is capable of simulating temperatures ranging from 145 K to 500 K, CO<sub>2</sub> pressures ranging from 10 to 10<sup>5</sup> Pa, and relative humidity ranging from nearly 0 to 100 %rh. MMEC has been successfully used for example in Phoenix Thermal and Electrical Conductivity Probe (TECP) sensor recalibration [16]. Compared to the FMI calibration chamber the volume of MMEC is significantly larger, which has some advantages for certain type of measurements. The sensors themselves do not affect the surrounding environment on the same scale as in a smaller chamber and therefore it was possible to monitor the self-heating and final stabilization temperature of the HS. Another advantage of the MMEC is that the water vapour can be released almost instantaneously inside the chamber which allows time response measurements of the HUMICAP sensor heads to be performed.

Thermal conductivity between the HS and the cooling plate turned out to be problematic and the HS did not reach the temperature that was set. Improvements were introduced in the 2019 setup to provide better thermal conductance but still a large temperature difference remained between the sensors, the cooling plate and the Buck inlet tube. Ultimately we were not confident that the Buck

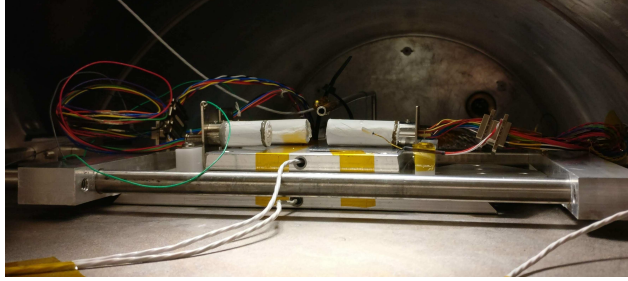


Figure 7: MEDA HS, REMS-H and METEO-H ground reference models inside the Michigan Mars Environmental chamber. The instruments rest on the temperature-controlled plate of the chamber that is cooled with liquid nitrogen. The inlet tube of the Buck hygrometer can be seen right above the instruments. Temperature sensors were placed on the Buck tube, inside the HS support structure and next to the MEDA HS sensor at the same height.

was measuring the same conditions as the HS. That said, the test campaigns provided important information about MEDA HS calibration and characteristics. The HS was measured in temperatures ranging from  $-67^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$  (206 K to 233 K) and in 850-1000 Pa but most importantly the time response of the HS was successfully measured at  $-51^{\circ}\text{C}$  (222 K) by causing a small, almost stepwise, change in chamber humidity by releasing a small amount of water vapour in the chamber using a manual valve (Figure 8 [a]). The time constant  $\tau$  is defined as the time required for the sensor reading to reach to 63.2% of its total step change and it was determined from the test and  $\tau = 77$  s. Repeating the test was not successful (see Figure 8 [b]) and the measurement in Figure 8 [a] is the only test that could be used to measure the time constant distinctly. This result can be applied to Mars data with some caution. The HS configuration in this test is lacking the housing box that is used to attach the HS to the RSM so there remains a small opening in the back of the sensor mechanics which was closed on Mars. If the PTFE filter is causing additional time lag on top of HUMICAP sensor head time lag the opening in the back could result in overly optimistic results. In lower temperatures the time lag is larger but according to our estimate it is still less than 30 minutes at  $-70^{\circ}\text{C}$  (203 K). Time response tests in different temperatures and configurations are still needed in

the future to determine the sensor behaviour especially in changing conditions more precisely and to possibly develop a time-lag correction for MEDA HS.

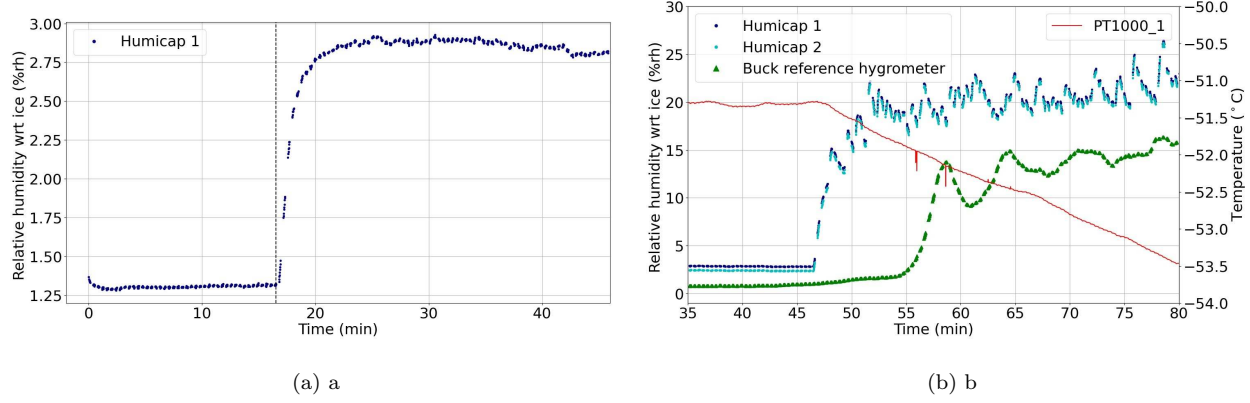


Figure 8: MEDA HS time response tests in  $-51^{\circ}\text{C}$  (222 K). Pt1000.1 is the temperature of the HUMICAP sensor head. In Figure [a] water was released into the chamber at  $T=16$  min and the HS reacts in approximately 15 seconds from opening the valve. The reference dew point mirror has slower reaction time and therefore the reference RH is not comparable. In Figure [b] the test was repeated in water was released in the chamber at  $T=46$  min. This leads to a large change in the HS, but because of the turbulence in the chamber and also temperature decreasing at the same time, time response is more difficult to define. From Figure [b] it can also be seen that the Buck reference hygrometer reaction is much slower than the HS response.

#### 4.3. Additional calibration performed at DLR PASLAB

An additional calibration campaign was performed at the DLR Institute of Planetary Research PASLAB (Planetary Analog Simulation Laboratory), Berlin. The laboratory is used for habitability-related experiments under Martian conditions as well as humidity sensor studies. Similar sensor studies have been performed previously [22],[23]. The Mars simulation facility in the DLR PASLAB is described in detail in [24]. The HS was enclosed in the same measurement chamber as was used for the FMI tests but this time the chamber was connected to the Mars simulation facility environmental control system of the PASLAB. Figure 9 shows the measurement configuration.

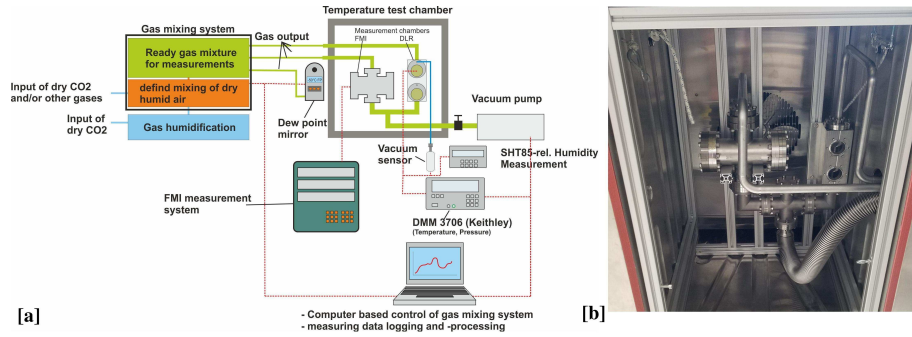


Figure 9: [a] Experimental setup of the DLR humidity tests. [b] A photograph of the chamber setup inside the temperature test station. FMI measurement chamber is on the left side and DLR measurement cell on the right. Humidified gas is routed to the chambers from above and the outlet is below the chambers. Credit: DLR

The long campaign was performed from Autumn 2020 to Spring 2021 with the ground reference models of MEDA HS, REMS-H and METEO-H. During this additional campaign the calibration curve for RH between the dry and saturation points was determined between  $-70^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$  (203 K and 233 K) in low pressure  $\text{CO}_2$  gas. From a control measurement of the dew/frost point of the in-going gas using a dewpoint mirror in conjunction with the measurement chamber pressure and temperature, the relative humidity in the chamber could be accurately determined. Temperatures lower than  $-70^{\circ}\text{C}$  (203 K) were not possible to reach with the temperature test chamber. At  $-30^{\circ}\text{C}$  (243 K) a smaller humidity range, from dry up to about 30% RH, was covered due to limitations in the humidification system, which works at a pressure of 2.5 bar. At each temperature a set of stable pressure and humidity points was programmed to be performed automatically. Generally the points were measured twice: from the driest point to the highest humidity and then back to dry. Different pressures ranging from 5.7 hPa to 9.8 hPa were measured to provide additional information about the pressure dependency of the HS. Some stable humidity points were not achieved as planned and unstable points were left out from the calibration data. MEDA HS was measured at 15-minute intervals for 10 seconds at a time to avoid self-heating. An average over seconds 2-5 was used for the

calibration. Figure 10 shows an example of one measurement series at  $-40^{\circ}\text{C}$  ( $233\text{ K}$ ) and  $8\text{ hPa}$  starting from dry gas and first increasing the humidity in the chamber before decreasing back to dry. From the time labels on the x-axis it can be seen that these measurements took a lot of time (on the order of several days) and at lower temperatures the stabilization times were even longer. Figure 11 shows capacitance measurements from both MEDA HS HUMICAPs at all calibration points. The difference between the temperatures and even pressures can clearly be seen. Each HUMICAP sensor head has its individual capacitance range but otherwise the measurements of both HUMICAPs are very similar.

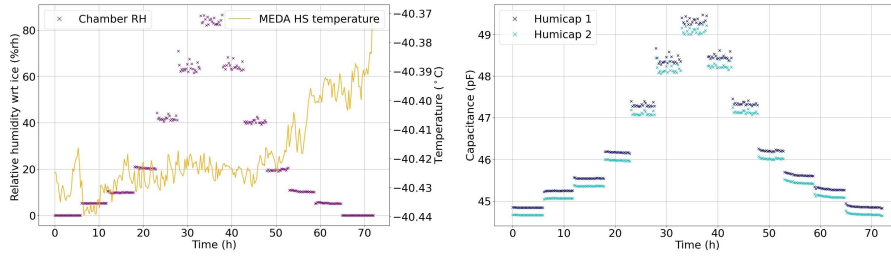


Figure 10: Example of MEDA HS and chamber behaviour during one measurement run at  $-40^{\circ}\text{C}$  ( $233\text{ K}$ ). In the left figure, the orange line represents MEDA HS temperature measured by Pt1000<sub>2</sub>. Purple crosses represent relative humidity calculated from the dewpoint, obtained from the reference mirror, at HS temperature. Each point represents one HS measurement every 15 minutes. HS was on for 10 seconds and the average over seconds 2-5 is used. The temperature can change slightly during the measurements due to fluctuations in the temperature test chamber and the inflow of humidified gas. In the right figure HUMICAP 1 and 2 raw capacitances are shown during the same run as in the figure above.

#### 4.4. Environmental tests and verification

MEDA HS has been thoroughly tested to withstand the environmental conditions during the Mars 2020 mission: the launch, the cruise, the landing and finally the surface operations. A dedicated qualification model (QM) has been subjected to a qualification campaign and the flight model (FM) and flight spare model (FS) have gone through an acceptance test campaign. In addition, 14 validation models (VM) were manufactured for different purposes.

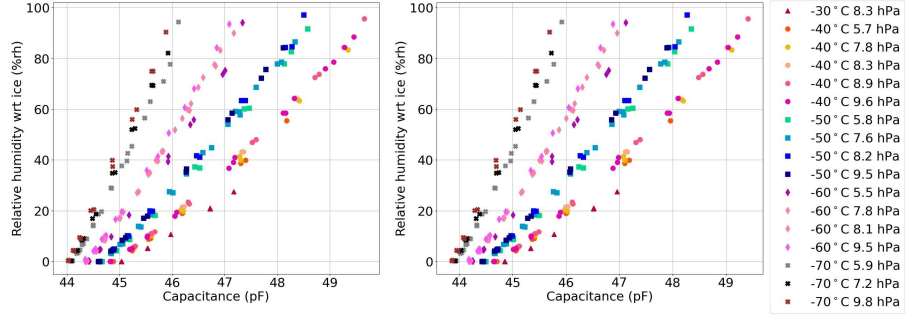


Figure 11: All measurement points that were obtained during the calibration campaign at DLR of HUMICAP 1 (on the left) and HUMICAP 2 (on the right). Different colours represent different temperatures and pressures, each point is averaged over a 4-second period, calculated from the beginning of a stabilized measurement. Capacitance is a raw value calculated from the HS frequencies. Relative humidity, on the y-axis, is calculated from the reference frost point temperature, HS Pt1000-temperature and chamber pressure.

The sensor level qualification campaign run by FMI consisted of full functional testing including calibration, mechanical testing, electromagnetic compatibility (EMC) testing and thermal vacuum cycling. Mechanical qualification tests consisted of quasi-static loads, random vibration and pyroshock tests to all three sensor axes. The quasi-static loads and random vibration tests were performed with an electrodynamic shaker and the pyroshocks with a shock generating table apparatus. The pyroshock test represents the structurally transmitted transients from the explosive devices used to achieve various separations during the mission stages. The purpose of the EMC conducted susceptibility test was to verify that HS measurements are not affected by the expected voltage ripple levels on the MEDA power supply lines. The mechanical acceptance test campaign for the flight model consisted only of random vibration tests at sensor level to avoid over-stressing the hardware. No degradation or any kind of damage was observed during the mechanical tests.

A thermal vacuum test (TVT) was done to the HS QM, FM and FS models at the same time by CAB at INTA facilities. Qualification levels were applied to all sensor models. TVT consisted of 1 non-operational cycle and 3 operational

cycles. In both cases the temperature range was from +70 °C to -135 °C. Dwell time in the first non-operational cycle was 8 hours both in hot and cold temperatures. In the rest of the cycles the cumulative dwell time in hot was 72 hours and in cold 24 hours. The thermal vacuum test served also as a dry point check where the vacuum measurements were compared to previous measurements to ensure the proper functionality of the HS sensor. Comparing the vacuum measurements also gives a good indication that the calibration has not changed even though it is not used as a calibration reference point.

Packaging Qualification and Verification (PQV) was performed for 4 validation models (VM) of MEDA HS to demonstrate durability against cycle fatigue and thermally induced failures of the new HUMICAP sensor head attachment. Validation models were subjected to qualification level shock and vibration tests before starting the thermal cycling. In PQV testing three VM sensors went through a total of 3015 thermal cycles and the fourth VM, that included a slightly enhanced stress relief, experienced 1475 cycles. The test included two types of winter and summer cycles. Winter cycles ranged from -130 °C to +15 °C and from -115 °C to +15 °C. Summer cycles from -80 °C to +50 °C and from -105 °C to +40 °C. The success criteria set for the sensors was that at least one HUMICAP and one temperature channel is working in each model. These criteria were met.

## 5. Flight calibration

The MEDA HS flight calibration is based on measurements performed with the HS flight model at the FMI laboratory and supplemented by extensive measurements performed for MEDA HS ground reference model at the DLR PASLAB (Planetary Analog Simulation Laboratory). This way the best possible calibration information can be used also for the FM with some added uncertainty. This is made possible by the very similar and predictable behaviour between the different HS models and also the added statistics of almost identical METEO-H REF model of ExoMars 2022 mission included in the DLR tests.

The flight calibration has been calculated from data measured at 7-8 hPa. A scaled capacitance is used instead of temperature-dependent calibration coefficients to simplify the fitting. The scaled capacitance is calculated using 100 %rh and 0 %rh curves to give the range of the capacitance in each temperature. First, dry and saturation curves are calculated from HUMICAP capacitance readings (in pF) as a function of the Pt1000<sub>2</sub> temperature (in °C). Only the average values of the first 2-5 s of each measurement are used in the calibration. The data from the dry point measurements is approximated as a second-degree polynomial function. The following function is fitted to the dry point data:

$$C_{dry}(T_{Pt2}) = a_d T_{Pt2}^2 + b_d T_{Pt2} + c_d \quad (2)$$

where:

$T_{Pt2}$  is the Pt1000<sub>2</sub> temperature in °C

$a_d, b_d$  and  $c_d$  are calibration coefficients

The saturation point curve is approximated as a linear function, and the following fit is applied:

$$C_{wet}(T) = a_w T_{Pt2} + b_w \quad (3)$$

where:

$a_w$  and  $b_w$  are calibration coefficients



The measured capacitance  $C$  in an arbitrary temperature  $T_{Pt2}$  is then converted to a scaled capacitance, a dimensionless value between 0 and 1:

$$C_{scaled}(T_{Pt2}) = \frac{C - C_{dry}(T_{Pt2})}{C_{wet}(T_{Pt2}) - C_{dry}(T_{Pt2})} \quad (4)$$

The relative humidity reading (in %rh) is then calculated from the scaled capacitance with a second-degree polynomial:

$$RH = a_f C_{scaled}^2 + b_f C_{scaled} + c_f \quad (5)$$

The calibration coefficients  $a_f$ ,  $b_f$  and  $c_f$  were determined from the combined results of the MEDA HS ground reference model and the METEO-H ground reference model measured simultaneously at DLR in temperatures from -30 °C to -70 °C (243 K to 203 K). The coefficients are listed in Table 2. Scaled capacitances of all MEDA HS REF and METEO-H REF sensor heads are presented in Figure 12. This model is the same for both HUMICAP channels.

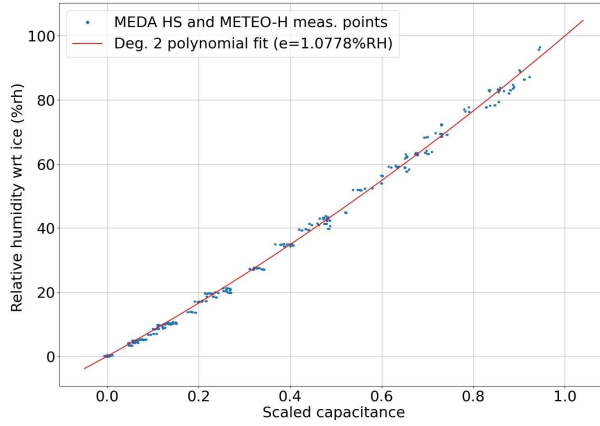


Figure 12: The scaled capacitances of MEDA HS REF and METEO-H REF HUMICAPs (4 pcs in total) measured at DLR in pressures between 7-8 hPa and second degree polynomial fit to the results (e = mean abs. error).

### 5.1. Water vapour volume mixing ratio (VMR)

In addition to relative humidity, also water vapor volume mixing ratio (VMR) derived from the relative humidity, the HS temperature and MEDA PS pressure

Table 2: MEDA HS FM sensor head calibration parameters

Parameter	FM HUMICAP 1	FM HUMICAP 2
$a_d$	-1.79388028997713e-04	-1.78960395709124e-04
$b_d$	4.24066744796165e-03	5.18949319226305e-03
$c_d$	44.6165274289933	44.1548008870084
$a_w$	0.128597377282055	0.126916845708979
$b_w$	54.4673399370933	53.8073124344845
$a_f$	21.223784788589	21.223784788589
$b_f$	78.681340006309	78.681340006309
$c_f$	-6.40600202313e-04	-6.40600202313e-04

will be provided in PDS. First the saturation water vapor pressure over ice at temperature  $T$  is calculated using equation (6), the 1996 revision of the Arden Buck equation [25].

$$P_{ws} = 6.1115 \exp((23.036 - \frac{T}{333.7})(\frac{T}{279.82 + T})) \quad (6)$$

where:

$T$  is the air temperature ( $^{\circ}\text{C}$ )

From equation (7) the partial water vapor pressure  $P_w$  in temperature  $T$  is solved and VMR in ppm is then obtained from equation (8):

$$RH = 100\%(P_w/P_{ws}(T)) \quad (7)$$

$$vmr = p_w \cdot 1000000/(p/100 - p_w) \quad (8)$$

Relative humidity drops when the sensor temperature rises and in the ideal case the calculated VMR should be the same before and after self-heating. In reality this is not the case and an offset in VMR can be observed in stable laboratory conditions. It is speculated to be due to thermal gradients on the PCB between the sensor heads and measurement electronics and for the time

being compensation for the self-heating has not been developed. However, it seems that the VMR offset is smaller than the measurement uncertainty and in the future a compensation might be possible.

## 5.2. The measurement error compensation model and corrected $RH$

The HS calibration compensation model was developed during the uncertainty analysis performed with the national metrology institute VTT MIKES (see Section 5.3) and the calibration uncertainty budget will be reported in a separate article by S. Tabandeh et al. and in which the main uncertainty contribution is governed by the non-linearity represented by the residual of the calibration curve fitting. In this case, the conventional data reduction practice for capacitive humidity sensors exhibits cross-sensitivities to the total pressure and temperature of the humid carbon dioxide. Considering that the contributed standard uncertainty by residuals is as high as 1.38 %rh in the entire range, any compensation model that minimizes the fitting residuals can considerably save the uncertainty budget. Consequently, the best error compensation model is turned to be the first-order Fourier series in which constants depend on temperature, pressure and relative humidity through linear, single exponential and double exponential functions as presented below:

The first part of the compensation has a common equation for both HUMICAPS, defined as

$$\begin{aligned} \bar{C} = & (c_1 + c_2 \cdot T + c_3 \cdot \frac{P}{100} + 0.0181) \cdot RH - 0.08478 \cdot \cos(0.06743 \cdot RH) \\ & - 0.9919 \cdot \sin(0.06743 \cdot RH) + 0.1257 \end{aligned} \quad (9)$$

where:

$RH$  is the relative humidity value of the respective sensor head (%rh)

$T$  is temperature ( $^{\circ}\text{C}$ )

$P$  is pressure (Pa)

Terms  $c_1$ ,  $c_2$  and  $c_3$  are defined as:

$$c_1 = -2.362 \cdot \exp(-0.05704 \cdot RH) - 0.4051 \cdot \exp(0.00369 \cdot RH)$$

$$c_2 = 0.01474 \cdot \exp(c_1) - 0.01095$$

$$c_3 = -0.09237 \cdot c_1 + 0.0004843$$

The second part is a HUMICAP-specific calibration correction compensating for the uncertainty associated with the calibration transfer from the REF model to the FM. The equations for each HUMICAP are:

$$cal_1 = -(0.0073 \cdot (RH_{HC1} + \bar{C}) + 0.05 - 0.0013 \cdot T)$$

$$cal_2 = -(0.0107 \cdot (RH_{HC2} + \bar{C}) + 0.05 - 0.0013 \cdot T)$$

Both parts are finally added to the original RH reading from equation 5 to get the final corrected RH:

$$\begin{aligned} RH_{corr,HC1} &= RH_{HC1} + \bar{C} + cal_1 \\ RH_{corr,HC2} &= RH_{HC2} + \bar{C} + cal_2 \end{aligned} \tag{10}$$

### 5.3. Performance and measurement uncertainty

MEDA HS has a dynamic range from 0 to 100 %rh over the operational temperature range from 190 K (-83 °C) to 270 K (-3 °C). The repeatability and reproducibility of humidity measurements have been analysed based on laboratory measurements and actual Mars data using the definition:

$$repeatability = 2 * \sigma \tag{11}$$

where  $\sigma$  is the standard deviation of the measured value. The repeatability value is based on data during stable conditions in one day and it is 0.02 %rh. The reproducibility has been calculated considering 10 days of data during dry daytime conditions where the temperature is above -43 °C (230 K) and the result is 0.14 %rh. Hysteresis of the HS is negligible [19].

The accuracy requirement for MEDA HS was better than  $\pm 10$  %rh for atmospheric temperatures above 203 K (-70 °C), and equal or better than  $\pm 20$

%rh for the temperature range 190 K (-83 °C) to 200 K (-73 °C). The HS accuracy has been determined by performing a comprehensive measurement uncertainty analysis together with national metrology institute VTT MIKES. It is worth mentioning that a calibration uncertainty budget differs from that of the measurement. The analysis was performed by using calibration data from laboratory measurements although the changing environment on Mars can affect the measurement uncertainty. Thus, the additional uncertainty introduced by rapid changes, e.g. in temperature, can cause more significant *RH* measurement uncertainty levels.

The overall calibration uncertainty of MEDA HS has contributions from several physical terms. The biggest contributors are the uncertainty of the temperature sensors, the reference pressure measurements, the atmospheric reference pressure measurements, the dew/frost point reference temperature measurements, uncertainty contributed by fitting residuals, uncertainty contributed by empirical thermodynamic equations and finally the calibration information transfer from REF to FM. Each of these contributors further consists of several terms and the complete analysis will be published in a separate paper.

The accuracy of the temperature measured by Pt1000<sub>2</sub> in laboratory conditions was also analysed. The accuracy is temperature dependent and the uncertainty is largest in cold temperatures. Expanded uncertainty (k=2) of Pt1000<sub>2</sub> is 240 mK at -80 °C decreasing to 120 mK at -20 °C. On the surface of Mars the Pt1000s are measured by the MEDA ICU but during HS calibration they were measured with a laboratory multimeter so the Pt1000 readings have been checked against the two THERMOCAP sensors on the HS PCB for any changes or offset on Mars due to different reading electronics but no correction was needed.

The HS relative humidity measurement uncertainty is a function of temperature and relative humidity. The uncertainty presented here is defined for the final corrected RH value where the compensation model (section 5.2) has been used.

The combined standard uncertainty  $u$  is defined separately for temperatures

Table 3: MEDA HS performance at the beginning of life (BoL) based on measurements in laboratory conditions.

<b>MEDA HS performance</b>	
RH measurement range	0 to 100 %rh
Operational temperature range	190 K to 270 K (-83 °C to -3 °C)
Survival temperature range	138 K to 398 K (-135 °C to +125 °C)
Time constant $\tau$	2-3 minutes at -50 °C and <30 min. at -70 °C
T accuracy	Better than $\pm 240$ mK above 193 K (-80 °C)
RH accuracy	$\pm 1.0... \pm 4.5$ %rh above 203 K (-70 °C), $\pm 1.8... \pm 6.0$ %rh down to 190 K (-83 °C)
Repeatability	Better than 0.02 %rh
Reproducibility	0.14 %rh

above and below -70 °C as follows:

$$u = \begin{cases} \max(u_1; 0.34), & T \geq -70^\circ\text{C} \\ \max(u_1 + u_2; 0.34), & T < -70^\circ\text{C} \end{cases} \quad (12)$$

where:

$$u_1 = 0.5155 + 0.01501 \cdot RH + 0.008767 \cdot T + 0.00007637 \cdot RH^2 - 0.00016 \cdot RH \cdot T + 0.0001001 \cdot T^2 - 0.000002344 \cdot RH^3 + 0.000001587 \cdot RH^2 \cdot T - 0.000001739 \cdot RH \cdot T^2 + 0.00000002464 \cdot RH^4 + 0.000000008683 \cdot RH^3 \cdot T + 0.00000003676 \cdot RH^2 \cdot T^2 - 0.0000000009476 \cdot RH^5 - 0.0000000007127 \cdot RH^4 \cdot T - 0.0000000009732 \cdot RH^3 \cdot T^2$$

$$u_2 = -1.465 - 0.03362 \cdot RH - 0.02352 \cdot T + 0.0006975 \cdot RH^2 - 0.0005879 \cdot RH \cdot T - 0.00001121 \cdot RH^3 + 0.000008395 \cdot RH^2 \cdot T + 0.00000009395 \cdot RH^4 - 0.00000007038 \cdot RH^3 \cdot T - 0.000000002541 \cdot RH^5 + 0.000000003562 \cdot RH^4 \cdot T$$

$RH$  is the non-compensated RH reading (%RH)

$T$  is the sensor temperature (°C)

The final expanded uncertainty with 95% confidence level ( $k=2$ ) is:

$$U_{RH} = 2 \cdot u \quad (13)$$

As a result the HS uncertainty is smaller than  $\pm 4.5$  %rh in temperatures above  $-70^\circ\text{C}$  (203 K) and equal or better than  $\pm 6$  %rh down to  $-83^\circ\text{C}$  (190 K). Figure 13 presents the RH measurement uncertainty in different temperatures. An adaptive Monte-Carlo method was employed to single out the additional uncertainty levels propagated by a linear extrapolation below  $-70^\circ\text{C}$  (203 K) where we don't have calibration data from that temperature range.

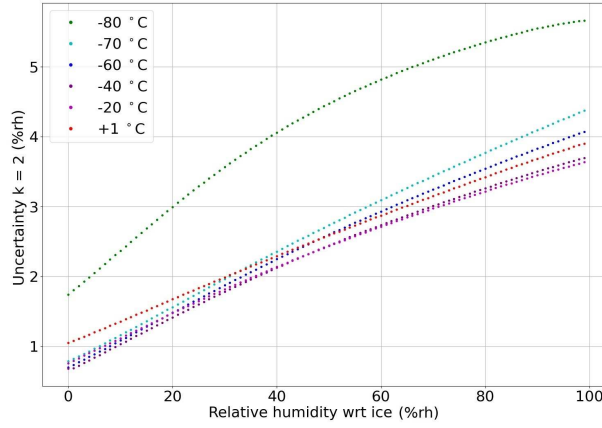


Figure 13: Final compensated uncertainty ( $k = 2$ ) in various temperatures. Uncertainty below  $-70^\circ\text{C}$  (203 K) is larger due to lack of calibration data in such low temperature.

The temperature standard uncertainty (in  $^\circ\text{C}$ ) for the Pt1000<sub>2</sub> sensor temperature  $T$  is calculated as follows:

$$u_{Pt1000} = 8.0 \cdot 10^{-8} \cdot T^3 + 0.0000157 \cdot T^2 - 0.0002142 \cdot T + 0.04663 \quad (14)$$

The expanded temperature uncertainty with 95% confidence level ( $k=2$ ) is then:

$$U_{Pt1000} = 2 \cdot u_{Pt1000} \quad (15)$$

## 6. First observations on Mars

Perseverance rover landed on Mars on Feb. 18 2021 on Mars year 36, at solar longitude  $L_s = 5^\circ$ , close to start of the northern spring. First measurements from MEDA were taken on sol 1 and regular around-the-clock MEDA measurements started around sol 15. During the first months on the surface of Mars the HS has been measured both in HRIM mode and in continuous mode which means that the HS is kept powered on for long periods of time, usually 1 hour. During measurement, frequency signals are read from the capacitive transducer sensor and constant channels by MEDA ICU. The actual calibrated relative humidity readings are obtained through data analysis on the ground. The derived relative humidity in the MEDA HS data product is the average of both sensor heads.

Figure 14 presents a typical example of one Martian sol during the first months of the mission. Within the diurnal cycle the maximum RH occurs in the early morning when the atmospheric temperature is at its lowest. During daytime the relative humidity drops very close to zero and since the RH readings are smaller than the measurement uncertainty, the daytime readings are not scientifically meaningful. The daily humidity cycle measured by HS behaves as expected and so far there has been no need for any calibration corrections based on Mars data.

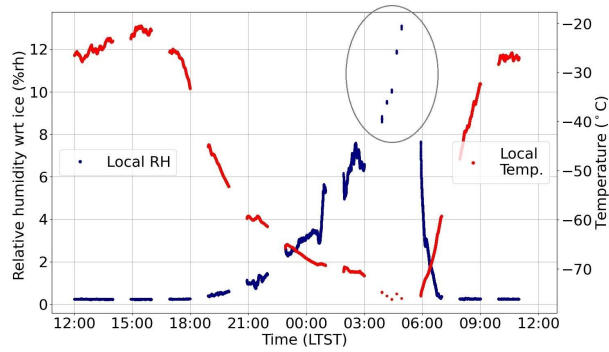


Figure 14: An example of a typical sol during the early months of the mission. MEDA HS temperature (red) and relative humidity (blue) have been measured around the sol with HRIM and continuous mode alternating. HRIM measurements are circled in the figure.



In continuous mode the self-heating is prominent: the temperature of HS rises and the RH decreases correspondingly over about 15 minutes from the beginning of the measurement. After that an equilibrium is reached but an offset remains in VMR. An example of self-heating is shown in Figure 15. The data affected by the self-heating is included in the derived dataset and the sensor self-heating is so far not corrected. The data can be useful for observing short time scale changes and environmental dynamics even though the absolute accuracy of the measurements is lower than in the case of HRIM-like measurements.

An example of measurement uncertainty for relative humidity is presented in Figure 16. The true value of RH is within the range of this uncertainty and short-scale repeatability is better than the absolute measurement uncertainty.

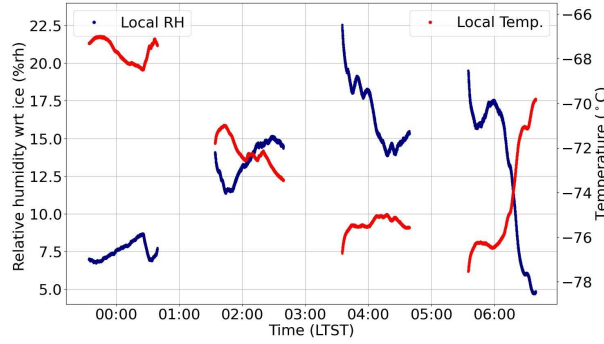


Figure 15: An example of MEDA HS temperature and relative humidity during the continuous mode. The temperature of HS rises and the RH decreases correspondingly over about 15 minutes from the beginning of the measurement. After that an equilibrium is reached.

### 6.1. Maintenance regeneration heating

Humicap sensor head regeneration heating has been performed three times in the first 200 sols to remove any volatile contamination on the sensors heads that might have accumulated during rover assembly, integration and testing phase or during the long cruise. Regeneration also helps to correct possible long-term drifts and restores the performance of the sensors heads.

The first regeneration was performed on sol 63 and was followed by a second

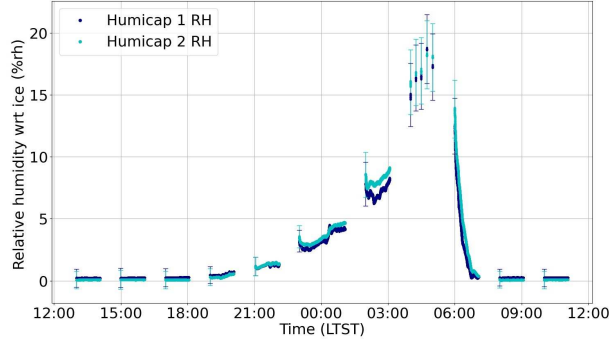


Figure 16: An example of RH measurement uncertainty during one sol. The uncertainty is applicable to HRIM measurements and first seconds of continuous measurement blocks.

regeneration on sol 74 to make sure that a high enough temperature had been reached and the sensors were sufficiently regenerated. A clear change in relative humidity values can be seen in the data especially after the first regeneration (Figure 17). While the HS data is available in derived dataset from sol 64 onwards, our recommendation is to not use the data before sol 80 for scientific purposes. Regeneration heating also removes absorbed  $\text{CO}_2$  from the HUMICAPS and that most likely causes the immediate effect of higher RH measured during daytime in warmer temperatures. The effect seems to be the opposite at the coldest temperatures. The recovery after regeneration was closely monitored since it was known from MSL already that it might take several sols. It was found that while most of the recovery happens after a few sols, the following 10 sols are recommended to be used only with increased uncertainty. The regeneration interval to be used in the mission will be determined after monitoring the sensor behaviour and regeneration recovery over longer time period.

## 7. Conclusions and discussion

MEDA HS is the relative humidity sensor on the Mars 2020 Perseverance rover provided by the Finnish Meteorological Institute. The sensor is a part of the MEDA instrument, a suite of environmental sensors, on board the Per-

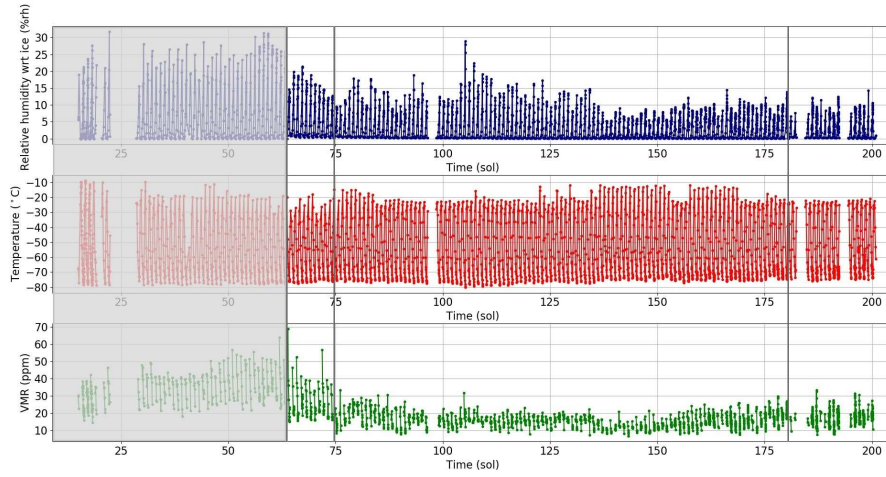


Figure 17: MEDA HS relative humidity, sensor temperature and VMR observations for the first 200 sols of the mission. Regenerations are marked in the plots and the impact of the first regeneration to RH readings is clear in both RH and VMR. Sols before the first regeneration are marked with a grey box. Also following regenerations affect the RH readings and the effect is visible in the near-zero relative humidities.

severance rover that landed successfully on Mars on 18th of February 2021. This paper has presented the humidity sensor design, operation, testing and flight calibration, expanding the calibration results given in MEDA instrument manuscript [2].

MEDA HS is a successor of the previous FMI delivered instruments REMS-H/Curiosity and DREAMS-H/ExoMars 2016 and represents the new generation of relative humidity instruments. Improvements include new HUMICAP® sensor heads by Vaisala with a larger dynamic range, faster response time and on-chip temperature measurement. New calibration methods have also been developed and the MEDA HS has been tested and calibrated in Mars equivalent conditions in low-pressure CO<sub>2</sub> gas from +22 °C to -70 °C (295 K to 203 K). In addition to calibration at the FMI, the MEDA HS ground reference model has been tested in the Michigan Mars Environmental Chamber and at the DLR Planetary Analog Simulation Laboratory.

The flight calibration of MEDA HS is based on two-point calibration per-

formed at FMI in dry and saturation conditions and is supplemented by the calibration data transferred from an identical ground reference model which has gone through rigorous testing after the flight model delivery. During the test campaign at the DLR PASLAB, MEDA HS has been calibrated over the full relative humidity range between  $-70^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$  (203 K to 233 K) in  $\text{CO}_2$  in the pressure ranges from 5.5 to 9.5 hPa, representative of Martian surface atmospheric pressure. The results have been incorporated into the flight model calibration due to the similarity of the instruments and the HUMICAP sensor heads.

MEDA HS has operated flawlessly after integration to Perseverance rover, during the cruise and finally after landing. The first measurements from the surface of Mars were as expected and the first regeneration cycles of the sensor heads have been performed successfully. Accurately calibrated data and a known measurement uncertainty is essential when doing scientific interpretation of the data. If the accuracy of the data is not known it can't be used to draw any conclusions. Combining and comparing the data from different sensors also relies on knowing the calibration and uncertainty of the sensors. Therefore a comprehensive measurement uncertainty analysis has been performed for the HS and it has been found that the sensor exceeds the design requirements and will deliver high accuracy relative humidity measurements from the Martian surface to provide important meteorological observations and to support MEDA and other M2020 investigations.

### **Data availability**

MEDA instrument data from Perseverance mission is publicly available via the Planetary Data System [20].

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