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REMS-H Revisited: Updated Calibration and Results of the Humidity Sensor of the MSL Curiosity

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Abstract
The Mars Science Laboratory (MSL) Curiosity rover landed on 6 August 2012 in Gale crater carrying the Rover Environmental Monitoring Station (REMS). REMS measures various atmospheric and surface parameters, and among its instruments is a relative humidity sensor, REMS-H, provided by the Finnish Meteorological Institute. REMS-H has been operating successfully for more than 12 years since the landing, providing the longest dataset on near-surface humidity conditions on Mars. New calibration measurements performed under a Martian analogue environment at the Planetary Analogue Simulation Laboratory of the German Aerospace Center have been used to evaluate the current calibration of REMS-H, and based on the findings a revised calibration has been developed for REMS-H. This paper describes the revised calibration, presents the corresponding updated results up to sol 3965 of the MSL mission, and analyzes the revised interannual, seasonal, and diurnal variations in relative humidity and derived water vapor mixing ratio. Comparisons with results from the previous calibration, modeling, and the Mars 2020 mission are also discussed. In general, the new calibration resulted in lower relative humidity values, although the difference varies without a clear diurnal or seasonal pattern. The water vapor volume mixing ratio derived from the new relative humidity values shows larger changes between the old and the revised data, especially during early night. The recalibration effort has improved the accuracy and reliability of REMS-H data, aligning the results with orbital observations and simulation runs. Results from this recalibration will be uploaded to NASA's Planetary Data System, replacing the values available to date.

Keywords Mars · Atmosphere · Relative humidity · Calibration

1 Introduction

The Mars Science Laboratory (MSL) Curiosity rover landed in Gale crater (4.6°S, 137.4°E) on 6 August 2012 at a solar longitude (Ls) of ≈ 151° in Mars Year (MY) 31, carrying the

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Rover Environmental Monitoring Station (REMS) for the measurement of several atmospheric and surface parameters (Gomez-Elvira et al. 2012). REMS includes a relative humidity sensor, REMS-H, which was provided by the Finnish Meteorological Institute (FMI). As of September 2024, REMS-H has operated for a little over 4300 sols; almost 12 Earth years, providing the longest relative humidity record from the surface of Mars.

Mars has been known to have an atmosphere since the early 19th century (Zurek 1992). The first definitive detection of water vapor on Mars was made by Spinrad et al. (1963) using ground-based spectroscopic observations. They estimated the globally averaged column abundance — representing the thickness of liquid water if all the atmospheric water vapor were condensed onto the surface — to be approximately 10 precipitable micrometers (pr μm). In comparison, the corresponding value for Earth's atmosphere is several centimeters (e.g., James et al. (1992)), highlighting that Mars's atmosphere is extremely dry in absolute terms.

In situ observations of water on Mars began with the Viking Landers. Their imaging systems captured the condensation and sublimation of ground frost (Wall 1981), while their mass spectrometers measured the water content in the regolith (Biemann et al. 1977). The Viking Orbiters' Infrared Thermal Mapper identified the northern polar cap as being composed of water ice (Kieffer et al. 1977). The Mars Atmospheric Water Detector (MAWD) spectrometers provided the first spatially and seasonally comprehensive observations of atmospheric water vapor, confirming that the exposed northern polar cap consisted of water ice (Farmer et al. 1977). The relative humidity of the near-surface atmosphere was measured only by the Thermal and Electrical Conductivity Probe (TECP) onboard the Phoenix lander (Zent et al. 2009), which landed in Mars' north polar region in 2008, prior to the arrival of the Curiosity rover.

Measurements from REMS-H have been used to characterize the relative humidity environment at Gale (Harri et al. 2014a; Martinez et al. 2017; Savijärvi et al. 2019a; Guzewich et al. 2019; Savijärvi et al. 2020). More specifically, these measurements have been used to assess the potential formation of liquid brine (Martínez and Renno 2013; Martín-Torres et al. 2015; Rivera-Valentín et al. 2018; Gough et al. 2023) and frost (Martínez et al. 2016), the exchange of H_2O between the regolith and the atmosphere (Savijärvi et al. 2016), and water uptake by salts (Rapin et al. 2016; Vaniman et al. 2018; Primm et al. 2018; Gough et al. 2019; Chipera et al. 2023). In addition, REMS-H measurements have supported investigations from other MSL instruments (McConnochie et al. 2018; Hallet et al. 2022), have enabled comparisons between Mars missions (Martinez et al. 2017; Battalio et al. 2022), and have been applied in pioneering machine learning studies on Mars (Abdelmoneim et al. 2024).

The main motivation for the recalibration work is the new laboratory calibration dataset measured in the Planetary Analogue Simulation Laboratory (PASLAB) of the German Aerospace Center (DLR) under representative Martian conditions using a ground calibration reference model of REMS-H (Hieta et al. 2024a). This new dataset allows two aspects of the previous calibration, which was based on less representative data, to be corrected: the relative humidity (RH) response function between 0% and 100% and the dynamic range of the sensor in CO_2. However, upon application to Mars in-situ data, corrections were required to account for drift and variability observed in the sensor response under actual Martian conditions. The calibration of the REMS-H was then revised using a combination of laboratory and Martian in-situ measurements.

In this work, the revised calibration and its corrections based on flight data are presented, and compared to results from the old calibration and modeling. Additionally, the humidity observations made by Perseverance and Curiosity during the same time period are compared and discussed, also reflecting orbital observations of these locations.

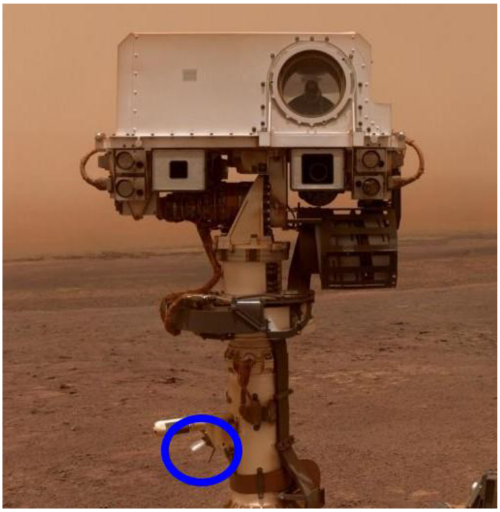


Fig. 1 Location of the REMS-H sensor on Curiosity's mast, highlighted with a blue circle. Above the humidity sensor is one of the two wind sensors, and below is the air temperature sensor. Credit: NASA/JPL-Caltech/MSSS

2 Background

2.1 REMS-H Instrument and the Pre-Flight Calibration

REMS-H is a relative humidity measurement device based on capacitive sensor heads which react to relative humidity of the surrounding environment. The sensor is accommodated on REMS Boom 2 attached to the mast of Curiosity (Fig. 1).

Relative humidity (RH) is defined as $RH(\%) = \frac{e}{e_s(T)} \times 100$, where e represents the water vapor pressure over ice, and $e_s(T)$ is the saturation vapor pressure over ice at the temperature T, which is also measured by REMS-H. In this paper, RH is primarily calculated with respect to ice.

The water vapor volume mixing ratio (VMR) is used to express absolute humidity. It can be derived as VMR $= e/P = (RH \times e_s(T))/P$, where P is the surface atmospheric pressure measured from the REMS-P pressure sensor (Harri et al. 2014b). The saturation water vapor pressure over ice at temperature T is calculated using the 1996 revision of the Arden Buck equation (Buck 1981). The equation is more accurate in the range −80 °C to +50 °C than the previously used Goff–Gratch equation (Goff and Gratch 1946).

The instrument features three capacitive HUMICAP® sensor heads manufactured by Vaisala (Vaisala Oyj 2020). The readout electronics are placed on the same small 36 × 15 mm multilayer printed circuit board (PCB). Sensor temperature is measured with capacitive THERMOCAP® sensor heads mounted to the PCB. This is an important difference to the newer instrument MEDA HS onboard Perseverance rover, which has a temperature measurement from the HUMICAP chip itself (Hieta et al. 2022). Capacitances of HUMICAP and THERMOCAP sensor heads are calculated from raw data with help of constant reference channels using a proprietary algorithm by Vaisala. The PCB is surrounded by a metallic Faraday cage and covered with a perforated PTFE (polytetrafluoroethylene) sheet filter. The instrument is described in more detail by Harri et al. (2014a).

The REMS-H has two operational modes: high-resolution interval mode (HRIM) and continuous mode. The HUMICAP sensor heads react to humidity changes even when the instrument is not powered, meaning that the RH can be read almost immediately after powering on the sensor. In HRIM, the sensor is powered on only for 5 seconds and then powered

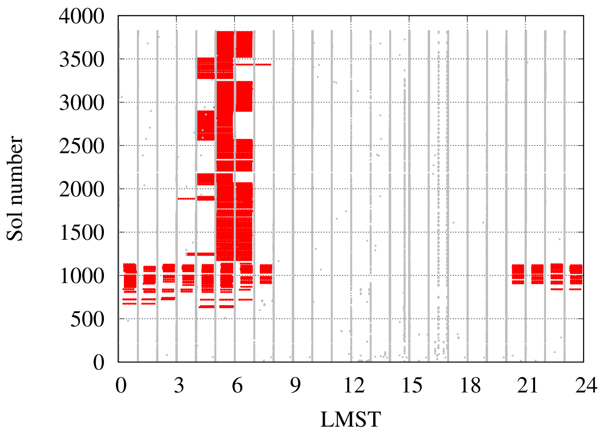


Fig. 2 REMS-H operational modes up to sol 3992. Red data points show high-resolution interval mode observations and gray points show the continuous mode start times

off to avoid self-heating. During continuous operation the sensor heats up a couple of degrees, which correspondingly causes the relative humidity (RH) to decrease. In the ideal case, the absolute humidity should be the same before and after self-heating, but in reality an offset has been observed in stable laboratory conditions with MEDA HS instrument. With good reason the same can be assumed to be the case also with REMS-H. For this reason the HRIM measurements are considered to be most accurate.

The REMS-H has provided almost daily coverage of relative humidity scattered around the sol (Fig. 2). HRIM mode was first used on sol 739, and it has predominantly been used between 04:00 and 07:00 LMST (Local Mean Solar Time) to capture the diurnal maximum.

REMS-H has one maintenance operation that has to be performed periodically: regeneration heating of the sensor heads. Heating resistors located at the sensor heads are used to heat the sensor heads to high temperature (the target is between + 135 °C and + 150 °C) to eliminate possible contaminants that can affect capacitance. Regeneration is generally performed during daylight hours and has a typical duration of 15 minutes. Since the beginning of the mission, regeneration was performed roughly every 10 sols - named frequent regeneration mode. Regeneration was observed to affect the capacitances immediately after the regeneration, elevating the daytime dry values about 1–2% RH. The mode of frequent regenerations was stopped after sol 3267 following good experience with very sparse regeneration only once every 180 sols with MEDA HS. The regeneration and its effect on the RH values is discussed more in Sect. 3.3.

The description of the original calibration of the REMS-H is provided by Harri et al. (2014a) and only a summary is presented here. Three pieces of REMS-H devices were manufactured and calibrated simultaneously: the flight model (FM), the spare model (SM), and the ground reference model (RM). The spare model is the one that was finally integrated to Curiosity and landed on Mars. The purpose of the reference model was to study the aging of REMS-H and to make reference measurements on-ground when needed. The RM has been a highly valuable instrument and it has been subjected to numerous measurement campaigns over the years. To date, it has also shown remarkable reliability without any functional or calibration issues despite having been manufactured in 2008.

The three REMS-H models were calibrated through a two-step process. First, a basic calibration was performed at six humidity levels with air at ambient pressure and room temperature from nearly dry to nearly wet conditions to establish a calibration function. Then, a two-point calibration was conducted at approximately 0% RH (dry) and 100%RH (wet) at six to eight temperature points. Dry conditions were created in a vacuum chamber pumped to high vacuum, and wet conditions in a closed vessel cooled to the dew/frost point at ambient atmospheric pressure. The calibration was finally validated by measuring humidity at various temperatures and comparing results above −40 °C with Vaisala humidity and temperature transmitters, with −40 °C serving as the lower limit due to the calibration constraints of the transmitters.

All original calibration measurements were performed either in air at ambient pressure or in vacuum, and not under a representative Martian environment. A final rover-level end-to-end test was performed in CO_2, but only at room temperature. As a result, it was not discovered that the extremely cold, low pressure CO_2 environment would considerably affect sensor calibration.

2.2 Anomaly Investigation and Capacitance Correction

This section summarizes the REMS-H flight model anomaly investigation and resulting correction as detailed in Harri et al. (2014a), providing a retrospective view.

One of the constant reference channels of REMS-H showed unexpected behaviour during the integrated tests with the Curiosity rover. The temperature dependency of the channel had permanently changed so that it was prominently divergent at low temperatures. This resulted in distorted humidity readings if the channel in question was used for calculating the relative humidity. Despite extensive investigation, the root cause of this anomaly has never been discovered. The misbehaving channel was disregarded and a spare housekeeping channel has been used for capacitance calculation. The resulting humidity readings matched the dry conditions measured during the prelaunch test, and also the measurements taken after launch during cruise checkouts were consistent with the prelaunch tests.

The first nighttime measurements on Mars at low temperatures revealed another issue with the humidity measurements. The capacitances of the humidity sensor heads were outside the calibration range, with the difference to dry calibration increasing towards lower temperatures. All three sensor heads behaved in a similar fashion and reacted to regeneration, so it was concluded that the sensor heads themselves were intact. Lacking better explanation, the effect was called an unknown transducer electronics artifact. Since the sensor had experienced already an anomaly with a reference channel, a calibration issue was not considered the most likely reason. Now it is known that this exact effect is caused by the low pressure carbon dioxide environment of the Martian atmosphere (Hieta et al. 2024a; Lorek and Majewski 2018).

Originally, to compensate for this "transducer artifact", seemingly causing too low capacitances in humidity channels, a method based on natural system calibration was developed. No new laboratory calibration measurements were performed. First it was assumed that RH in Gale crater is near 0% during daytime down to −30 °C given the very low values of near-surface water content on Mars (Martinez et al. 2017; Fischer et al. 2019). A second-order polynomial curve was fitted to both the dry calibration measurements and the Gale capacitances for temperatures down to −30 °C (later down to −40 °C). The difference of these two curves was the compensation curve, which was added to the raw capacitances. The correction has been in use ever since and it is recalculated every 30 sols to be used for the next 30 sols.

The calibration has since been further adjusted, but the underlying issue of not having calibration data measured in a representative environment persisted until the new laboratory measurements, presented in Sect. 3.1, were obtained.

3 Methods

3.1 New Laboratory Measurements

The ground reference model (RM) of REMS-H has been extensively used at different laboratories to investigate the anomaly of REMS-H flight model, and to improve the calibration and understanding of the sensor's behavior in various situations. Measurements have been performed at FMI's own calibration laboratory (Genzer et al. 2017), at the VTT MIKES National Metrology Institute of Finland, Michigan Mars Environmental Chamber (MMEC) at the University of Michigan (Fischer et al. 2019), and the DLR's PASLAB (Lorek and Koncz 2013). Ensuring the representativeness of these measurements has been a persistent challenge, as creating the Martian analogous environment requires a unique environment including low temperature, low pressure and CO_2 composition. Additionally, obtaining calibration reference measurements of ambient humidity for calibration purposes has been difficult due to variations in water vapor distribution or large temperature gradients within the measurement system. The calibration reference may not accurately measure the same humidity environment if its location differs from that of the measured sensor or if the water vapor distribution is inhomogeneous.

Due to the aforementioned challenges, part of the earlier calibration measurements have later been deemed unrepresentative of the real environment. Successful and comprehensive calibration measurements of the RM of REMS-H were finally obtained during a combined calibration campaign with MEDA HS (M2020) and METEO-H (ExoMars 2022) instruments at DLR PASLAB reported in Hieta et al. (2024a). Calibration measurements were obtained from all three instruments under stable humidity and temperature conditions. The temperature range covered was from −30 °C to −70 °C, with relative humidity varying from near zero to almost 100%. At −70 °C, the lowest humidities recorded were approximately 0.3%, while at −40 °C, the humidity levels ranged between 0.01 and 0.02%RH. At all temperatures, RH values exceeding 80% were reached, with the highest RH recorded at 97%. Measurements were performed at different Martian pressure ranges from 5.5 to 9.8 hPa, all in CO_2 gas.

In addition to the PASLAB campaign, one important result from the MMEC shall be noted. The MMEC campaign (Hieta et al. 2022) aimed to replicate relative humidity measurements for the FMI's sensors in a different system to confirm FMI results for MEDA HS, REMS-H, and METEO-H. Calibration efforts were challenged by inadequate thermal conductivity between the sensors and the cooling plate, leading to temperature discrepancies. Despite these issues, an important measurement of the time response of the sensors was obtained (see Sect. 3.3.1).

3.2 Revised Calibration Functions

Based on the calibration data obtained from the PASLAB measurement campaign, a calibration was determined for the REMS-H reference model following the same method as presented for MEDA HS in Hieta et al. (2022) with only very minor changes. The calibration information was then transferred to the flight model using the measured, slightly temperature dependent offset difference between the instruments in vacuum. Different REMS-H models have slightly different capacitances due to small variability in the component values in readout electronics. Figure 3 shows measurements of both instruments at FMI's calibration laboratory in vacuum and in saturated air. The similarity between the different HUMICAP sensor heads is clearly evident, as is the difference in capacitance range between the two instruments.

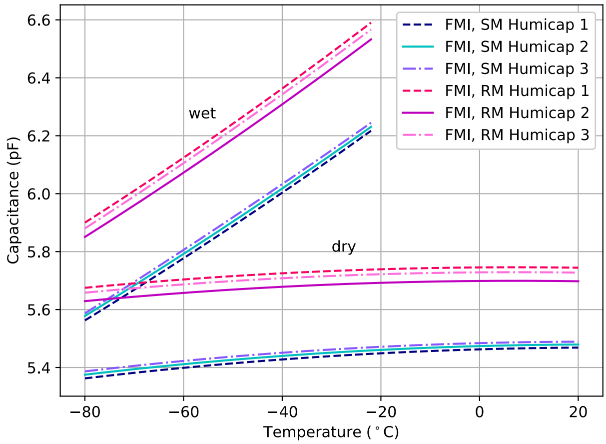


Fig. 3 The dry and wet curves of the flight spare model (SM) and the reference model (RM) used in the old calibration. This plot shows the difference between the SM and reference model RM sensor heads when the models were measured at the same time at FMI. The measurements were performed in vacuum and in saturated air. The difference in vacuum measurements was used to transfer the new calibration functions from RM to SM

The calibration was calculated from data measured at 7–8 hPa, and is therefore optimized for this range. Only the average values of the first 2–5 s of each measurement were used in the calibration in order to avoid self-heating. First a second-degree polynomial curve was fitted to all measurements taken at each temperature. Some temperatures were measured twice and some only once. Using the intersection points, sensor head specific dry (0%) and wet (100%) curves were calculated as a function of HUMICAP capacitance readings (in pF) and the sensor temperature (in °C).

The following function is fitted to the interpolated dry points:

$$C_{\text{dry}}(T_{TC}) = a_d T_{TC}^2 + b_d T_{TC} + c_d \tag{1}$$

where T_{TC} is the sensor temperature in °C, and a_d, b_d and c_d are calibration coefficients.

The wet curve is accordingly:

$$C_{\text{wet}}(T_{TC}) = a_w T_{TC}^2 + b_w T_{TC} + c_w \tag{2}$$

where a_w and b_w are calibration coefficients.

Figure 4 shows the differences between the dry and wet curves used in the old calibration compared to the new curves, representing one of the main results of the new calibration campaign: both the capacitance and the dynamic range are affected by Martian atmospheric conditions. No calibration data exists below −70 °C so the curves are slightly extrapolated. One sensor head is shown as an example, but the others have very similar behavior. The new curves show that the dry capacitances are lower in dry Martian conditions than in dry vacuum, starting at approximately −40 °C and diverging further as the temperature decreases. This confirms that the very low capacitances returned by the REMS-H flight model are due to this calibration error. At high humidities, the capacitances also are lower than previously, and the difference to the old calibration grows with decreasing temperature. It shall be noted that above −40 °C, no high-humidity calibration measurements are available, and the wet curves in 4 for temperatures above this range might be inaccurate. The dynamic range of the sensor is smaller than previously assumed, especially below −40 °C, and appears to shrink further at lower temperatures.

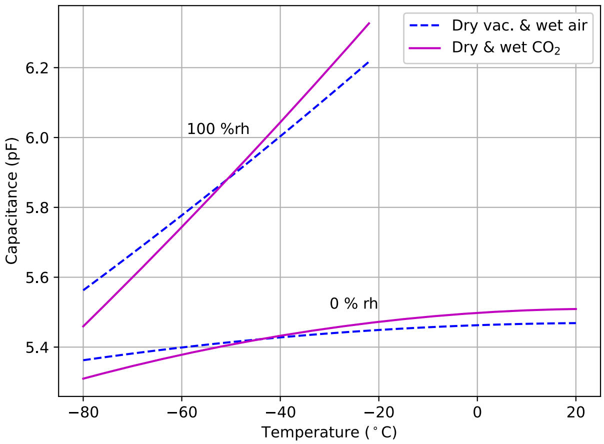


Fig. 4 The old (blue) and revised (purple) dry and wet calibration curves for one of the SM sensor heads, extrapolated down to -80 °C. The old curves are measured in vacuum and in normal pressure air, and the new curves have been transferred from the reference model measurements in Martian pressure CO_2. This shows a key result of the new calibration: capacitance and dynamic range are influenced by Martian conditions

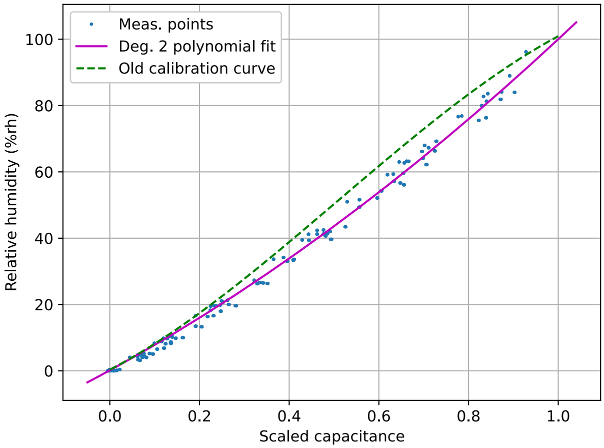


Fig. 5 New calibration measurement points and the old (green) and revised (purple) calibration curves for calculating the final relative humidity from the scaled capacitance. Here it can be seen that using the old response function could cause large errors especially at mid-range humidities

A scaled capacitance (a dimensionless value between 0 and 1) is then calculated using 100% and 0% RH curves to represent the range of the capacitance in each temperature:

$$C_{\text{scaled}}(T_{TC}) = \frac{C - C_{\text{dry}}(T_{TC})}{C_{\text{wet}}(T_{TC}) - C_{\text{dry}}(T_{TC})} \tag{3}$$

The scaled capacitance is used to determine the RH response of the sensor heads between dry and wet. At ambient room conditions the response would be very close to linear, but the Martian environment changes the behavior. The calibration curve was determined using all three sensor heads of the REMS-H ground reference model measured at PASLAB at temperatures from −30 to −70 °C (243 K to 203 K). The behavior of different sensor heads is very similar and this averaging is not believed to cause a significant error in the calibration. The determined calibration curve was then transferred to the flight sensor. The resulting response curve is shown in Fig. 5 together with the old curve for comparison. The calibration curve is the same for the whole temperature range. The old and new response functions diverge most in the range from 40 to 80% RH where the old function would give up to 8% RH higher relative humidities.

Table 1 REMS-H flight model sensor head calibration parameters

Parameter	HUMICAP 1	HUMICAP 2	HUMICAP 3
a_d	−1.792522784e−05	−1.805641172e−05	−1.814775436e−05
b_d	9.186794694e−04	8.906352073e−04	8.673998509e−04
c_d	5.497857938	5.509145192	5.519334320
a_w	1.939039144e−05	1.925920756e−05	1.916786492e−05
b_w	1.693199698e−02	1.690395272e−02	1.688071736e−02
c_w	6.689867153	6.701154406	6.711343534
a_f	25.84501912	25.84501912	25.84501912
b_f	74.02101412	74.02101412	74.02101412
c_f	0.146477172	0.146477172	0.146477172

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

$$RH = a_f C_{\text{scaled}}^2 + b_f C_{\text{scaled}} + c_f \quad (4)$$

The calibration coefficients a_f, b_f and c_f are common to all REMS-H sensor heads. Finally, all the coefficients for the REMS-H flight model are listed in Table 1.

3.3 Corrections Based on Flight Data

The revised calibration should be directly applicable to Mars data, since it has already been adjusted specifically for the flight model. In an ideal case no further corrections would be necessary, as was the case with MEDA HS (Hieta et al. 2022). However, REMS-H capacitances from Mars did not immediately fall within the expected range between dry and wet calibration curves. Already directly after landing and starting operations, the measured capacitances were lower than expected. Signs of this behavior might have been present already at prelaunch tests when the instrument returned lower capacitances than at dry calibration (Harri et al. 2014a), but at the time the reason was believed to be lack of regeneration. Furthermore, the measured capacitances seem to be drifting slowly further away from the dry calibration curve over time. The measured capacitances do follow the overall curvature of the calibration curve better than before, but a correction is obviously necessary.

The behavior of Mars data was investigated using a so called dry capacitance fit to sol data. A second degree polynomial is fitted to data points of one or more sols measured above −40 °C where it is assumed to be dry (very close to 0%RH). This gives a way to compare the behavior of the instrument to the dry calibration curve. This kind of fit is demonstrated in Fig. 6. In the example case, capacitances from 10 consecutive sols were plotted on the same graph, and a second degree polynomial was fitted to the combined data above −40 °C. As it can be seen, the capacitances measured in typical daytime temperatures are very similar and variation is small. In colder temperatures the relative humidity is usually no longer close to 0% and the measured capacitances start to rise higher towards the wet curve (not shown in the figure).

Through detailed investigation, it was found that the capacitance drift over shorter timescales was irregular. Furthermore, there were also changes in the slope of the dry capacitance curves measured at different time periods. It is known that regeneration causes immediate effect or rising daytime capacitances, so the regeneration sols and one sol right

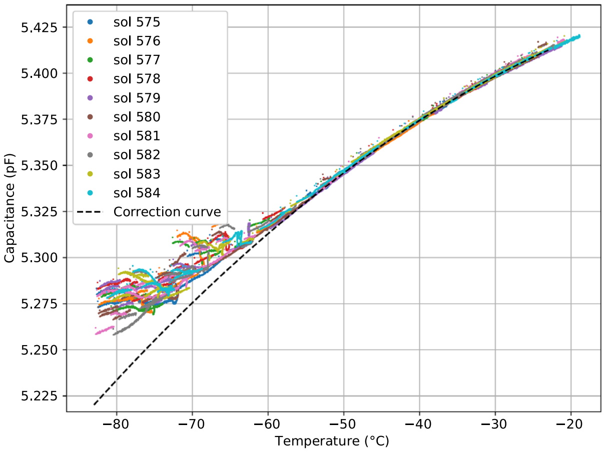


Fig. 6 An example of dry capacitance fit to REMS-H flight data. A second degree polynomial is fitted to the combined capacitance data of 10 consecutive sols from 575 to 584 above -40 °C. This fitted curve represents dry (0% RH) conditions at that time period

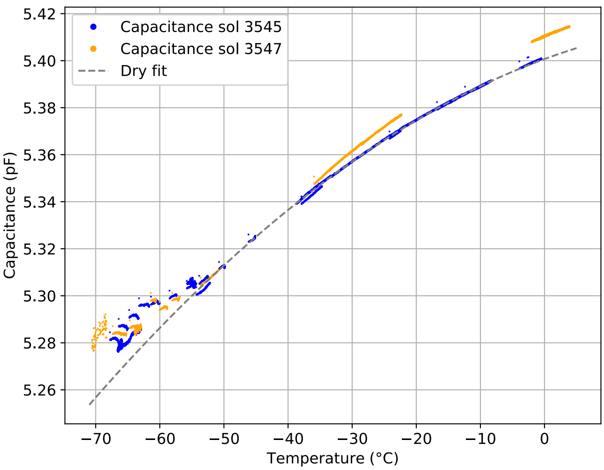


Fig. 7 An example of how the regeneration of REMS-H affects the measured capacitances on Mars. The regeneration in this example was performed after a long recovery time. The blue points represent measurements taken before regeneration, the dashed line is the dry fit to that data, and the orange markers indicate measurements from a sol after regeneration. The impact is clear at higher temperatures, but it is more difficult to see what it is at lower temperatures due to larger RH variation

after regeneration are at least compromised. An example of capacitances before and after regeneration is shown in Fig. 7. After regeneration the capacitances measured above −40 °C are higher than before regeneration. The daytime capacitances should all be very similar, because there is no significant variability in the relative humidity. The effect is clear during the dry part of the sol, but it is more difficult to determine what the impact is at lower temperatures due to greater variation in relative humidity. The daytime difference is also more prominent because of the larger dynamic range at higher temperatures. From MEDA HS observations we have seen that the recovery after regeneration can take more than 10 sols while most of the change happens already a few sols after regeneration (Hieta et al. 2022). With a 10-sol regeneration interval it is possible that REMS-H has not had time to completely recover between the regenerations, causing the irregular behavior. We have also observed possible pressure dependency in the slope changes, but it does not account for all the variation.

A simple offset change could not correct the difference to the laboratory calibration during the time period when frequent regenerations were performed. Instead, the previously used capacitance correction method had to be reintroduced. This time the correction is

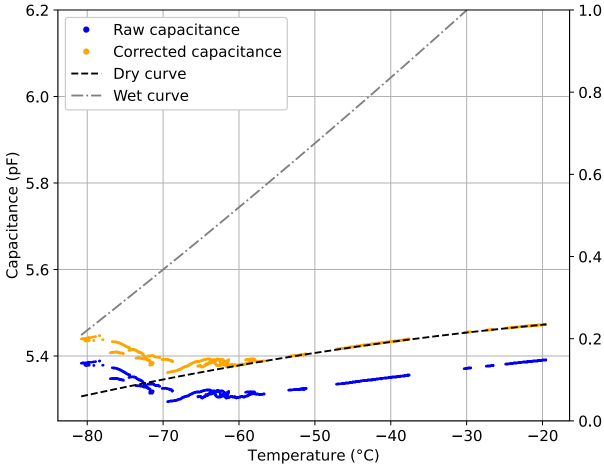


Fig. 8 An example of the capacitance correction of one sensor head at sol 2530. The measured raw capacitances are shown in blue and the dry laboratory calibration curve is shown as a dashed line. A second-order polynomial curve is fitted to both the dry calibration measurements and the Gale capacitances for down to -40 °C. The difference of these two curves is the compensation curve, which is added to the raw capacitances. The resulting reconstructed capacitances are shown in orange

smaller and it is calculated from the same data that it is applied to. Capacitance correction is done to 10 sols at a time by finding the dry capacitance curve of the sols in questions, as already shown in Fig. 6. A difference between the obtained curve and the dry calibration curve is then used to correct the Martian capacitances as shown in Fig. 8. Regeneration sols and one sol after are left out from the calculation process, but not from the data.

After the frequent regenerations were stopped and REMS-H moved to a 180-sol regeneration interval instead of a 10-sol interval, the slope variability of the dry capacitance fits stabilized to follow the calibration curve. There is still drift, but it can be corrected with a sol-specific offset calculated at a specific temperature. −40 °C was selected as the correction temperature, but a nearly identical correction could have been obtained using, for example, −50 °C. These sol-specific offset corrections applied to the Mars data are shown in Fig. 9 as a function of sol. The three regenerations during this time period, marked with vertical lines, cause a visible discontinuity in the applied corrections. The offset correction is not linear, and additional time is needed to monitor its behavior over time. However, the offset correction may be at least partially pressure-dependent, which could help adjust the RH calibration to account for pressure variations.

In conclusion, the flight correction consists of two distinct components. For data collected up to sol 3280, a capacitance correction is applied through a dry capacitance fitting conducted every 10 sols during frequent regenerations. After sol 3280, only an offset correction is implemented to correct each individual sol.

3.3.1 Sensor Time Lag and Filter Correction

The REMS-H humidity value output has a time lag, which is strongly temperature dependent. The time lag increases exponentially as the temperature drops. The factors affecting the time lag, when the temperature remains constant, are the HUMICAP sensor thin film membrane time constant, the PTFE dust filter, and the gas exchange. If also temperature changes simultaneously, the relative humidity measurement will not be correct until the sensor's temperature has stabilized (Vaisala Oyj 2021). Determining the time lag and separating the effects of different factors has been difficult to achieve, and in many cases the measurement chamber environment changes significantly slower than what the sensor can detect. This is the case with both the FMI calibration chamber and the DLR chamber, they are not

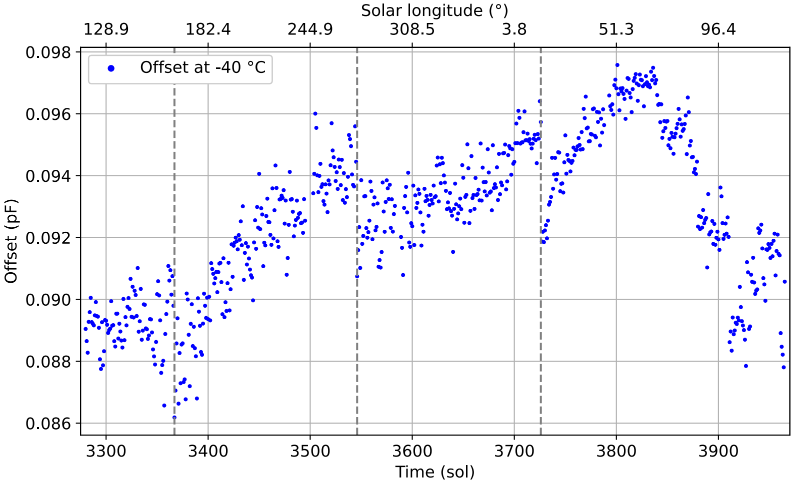


Fig. 9 Magnitude of the offset correction per sol applied to capacitances after frequent regenerations were stopped. The three regenerations during this time period are marked with vertical lines

designed for rapid humidity level changes. While the old dataset includes a time lag correction, new measurements and reanalysis have shown that this correction is not as effective as anticipated. Therefore, it was decided not to apply the same correction to the recalibrated data.

The time lag of the complete REMS-H sensor in a representative Martian environment was finally successfully measured at MMEC with REMS-H ground reference model, although only at one temperature. The MMEC's larger volume and operating principle allowed for almost instantaneous release of water vapour inside the chamber to test the time response. Both REMS-H and MEDA HS were measured at the same time and for MEDA HS the results are reported in Hieta et al. (2022). The single successful test of REMS-H is shown in Fig. 10. The time constant τ is defined as the time required for the sensor reading to reach 63. 2% of its total step change in response to a sudden change in water vapor concentration. At −68 °C, τ was measured to be 500 ± 10 s. The measured delay time for REMS-H was approximately 30 seconds, defined here as the time between the step change in humidity and the point at which the sensor output begins to respond noticeably. These values include the effect of the PTFE filter and the sensor's internal volume. The result aligns well with the estimated time constant of just the HUMICAP sensor head, which is in the order of 0.1 s at +20 °C, increasing to about 30 s at −40 °C and 700 s at −70 °C, following an exponential dependence on temperature (Harri et al. 2014a). In comparison to the REMS-H sensor time lag, it can be concluded that the filter and internal volume do not introduce any observable difference in the time lag. Based on the observed exponential dependence of the time constant on temperature, it can be expected that at temperatures colder than −70 °C, the sensor time lag would increase further. At the temperatures measured during the MSL mission, which typically reached minimum values around −80 °C, the time constant is still estimated to be less than one hour, allowing the diurnal cycle to be resolved.

The revised dataset does not include a separate time lag or a filter correction. If the humidity changes very rapidly, the sensor will lag behind the actual environmental conditions. This means that the recorded humidity readings will not reflect these rapid fluctuations accurately. For slower and gradual changes in humidity, REMS-H will give a more accurate

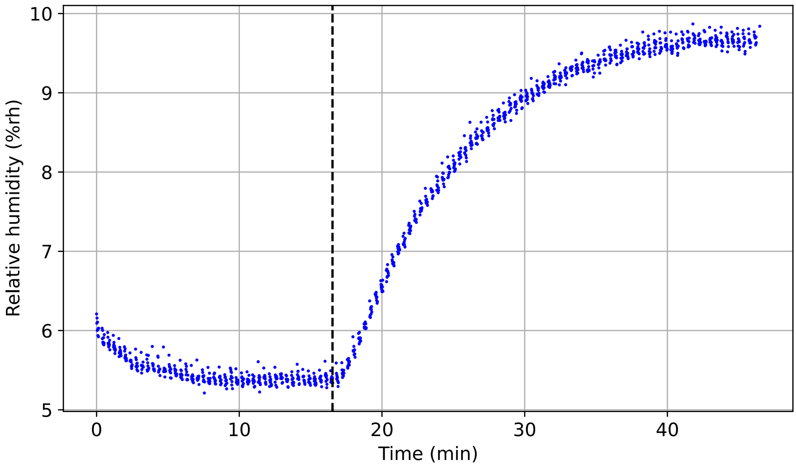
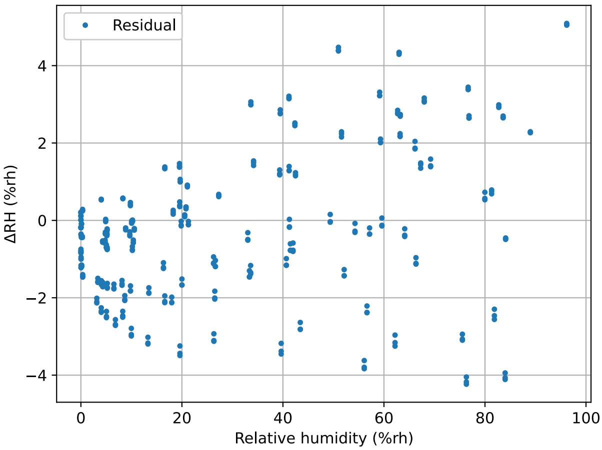


Fig. 10 REMS-H reference model time response tests in MMEC at −68 °C. Water vapour was released into the chamber at t = 16 min (indicated with vertical dashed line) and the instrument reacts in approximately 30 seconds after opening the valve

Fig. 11 This plot illustrates the RH fitting residuals, calculated as the difference between the values obtained from the REMS-H reference model after calibration and the reference dew point hygrometer at PASLAB. Each point represents an individual measurement across a range of relative humidities in temperature range of -30 °C to -70 °C. The plot shows larger residuals at higher relative humidities, while the temperature dependency is not significant



representation. In this context, rapid changes refer to variations occurring on timescales shorter than the sensor time constant τ at the ambient temperature, while slower changes occur over timescales significantly longer than τ.

3.3.2 Measurement Uncertainty

The revised dataset includes uncertainties for RH and VMR. The reported uncertainties are expanded uncertainties calculated with a coverage factor k=2, corresponding to a confidence level of approximately 95%. The measurement uncertainty reflects the potential deviation of an instrument's readings from the true values. While the revised calibration adjusts the REMS-H readings to be more accurate, it does not inherently reduce the uncertainty. The uncertainty of REMS-H has contributions from several components. The biggest known contributor is the uncertainty of the RH calibration (Fig. 11), while others include the uncertainty of the temperature sensors, the reference measurements at PASLAB calibration campaign, and the transfer of calibration information from the ground reference model to the flight model. In addition, the REMS-H flight instrument has exhibited anomalous behavior of one channel and capacitance drifting, which may also contribute to uncertainty, but the extent of their impact is difficult to quantify. Comprehensive quantitative analysis cannot be reliably done due to these unknowns, but we can give an estimation based on the MEDA HS uncertainty analysis (Tabandeh and Högström 2021; Polkko et al. 2023) and experience during the REMS-H recalibration process.

The uncertainties of the old REMS-H relative humidity values in PDS are temperature dependent: ±10%RH between −70 °C and −30 °C, ±20%RH below −70 °C and ±2%RH above −30 °C. The new uncertainties remain very similar, but a humidity-dependent gradient has been added to better reflect the expected uncertainty at lower relative humidities. Between −70 °C and −30 °C the uncertainty is gradually rising from ±1% RH at 0% to ±4% RH at 10% and to ±10%RH at 100%. Below −70 °C the uncertainties are larger: ±2% RH at 0% to ±6% RH at 10% and to ±20% RH at 100%. For temperatures above −30 °C, providing uncertainties is not very meaningful because it is outside the range of calibration measurements, and the relative humidity is always assumed to be zero during data processing.

VMR uncertainty is calculated by combining contributing uncertainties of RH, sensor temperature and atmospheric pressure following the same approach as with MEDA HS (Polkko et al. 2023). Standard uncertainty 0.15 °C was used for the sensor temperature. The VMR uncertainty is dominated by the uncertainty of the relative humidity measurement, the effect of pressure uncertainty is negligible. When RH is close to 0%, even small absolute errors in RH measurement translate into very large relative errors. For example, if the RH is 2% the uncertainty is ±1.6%, but the relative uncertainty is ±80%. This large uncertainty propagates directly to the VMR calculation, making it much less precise under low RH conditions. During the season when the RH is typically high, the VMR uncertainties are in the range of 10 ppm. When the RH is very low, the uncertainty of the derived VMR can be many times greater than the obtained VMR value. The nighttime hours LMST 23-06 restriction used in this paper typically results in VMR uncertainties below 40 ppm, though this is highly case-sensitive and should be verified for each specific set of measurements, as temporal conditions can significantly influence the accuracy of the values.

4 Results

4.1 The Revised Dataset

Following the calibration revision, the raw data returned by REMS-H from Gale Crater has been reprocessed up to sol 3965. This new dataset includes revised relative humidity values, updated derived water vapor volume mixing ratios (VMR), and their associated uncertainties, while the sensor temperatures remain unchanged. The reprocessed data are available at FMI's METIS data repository (Hieta et al. 2024b) and will be added to the Planetary Data System (PDS) in a future release. In the following sections, the new dataset is compared with the previous one, with MEDA HS during the same time period, and with the single column model (SCM) runs.

Figure 12 presents the revised minimum and maximum relative humidities and sensor internal temperatures recorded by REMS-H from sol 15 to sol 3965. The relative humidity is

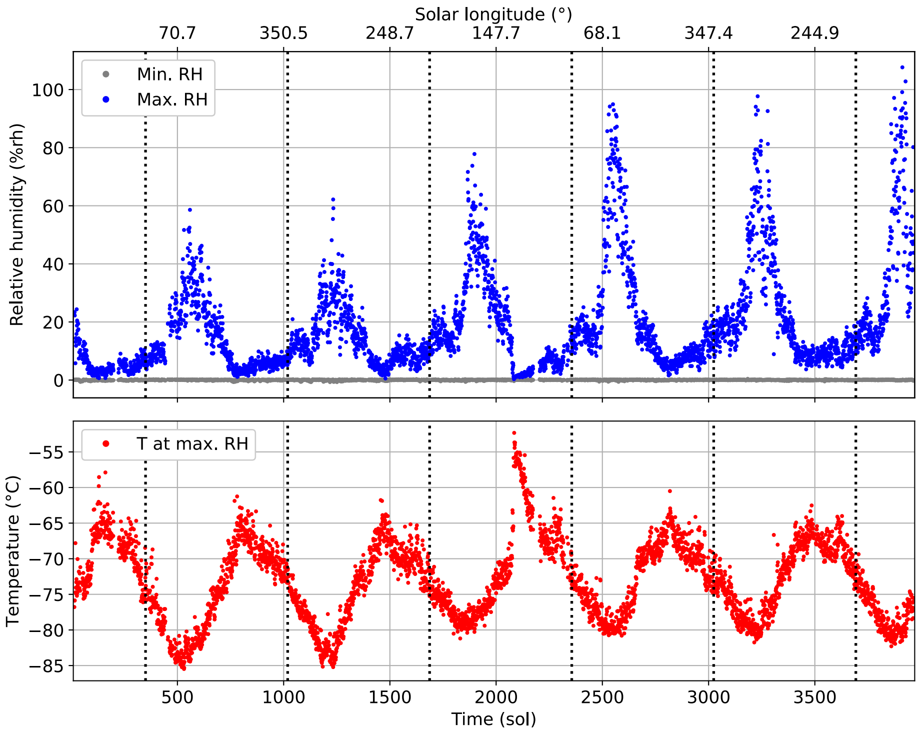


Fig. 12 Top panel: Revised daily minimum and maximum relative humidities, relative to the sensor's internal temperature and not the atmospheric temperature, starting from sol 15 and up to sol 3965. Vertical lines mark the Martian years starting from MY 31 at the time of landing and reaching up to MY 37. Minimum values each sol are close to 0% and the highest relative humidities reach 100%. Bottom panel: Sensor temperature when the maximum RH was measured

related to the sensor's internal temperature and not the atmospheric temperature. The difference between the humidity sensor's internal temperature and the atmospheric temperature varies depending on environmental conditions. Moreover, the atmospheric temperature itself is not easily determined in absolute terms, as it is measured using instruments that have their own limitations, such as time lags and sensitivity to heat plumes from the rover's RTG (Gomez-Elvira et al. 2012). During daylight hours, the sensor's internal temperature is typically several degrees higher than the temperature recorded by the air temperature sensors.

Only data unaffected by sensor self-heating were included, specifically HRIM measurements and the initial seconds of longer measurement blocks. The median values from the three sensor heads were used. The minimum RH of each sol is very close to zero as defined by the calibration process, meaning that the daytime relative humidities are scientifically not useful. There is no set or restricted upper limit for relative humidity in the recalibration process. The relative humidity changes are mostly driven by the atmospheric temperature, and not by the absolute water amount. Notably, the highest annual relative humidities coincide with the coldest time of the year during southern winter (Ls $\sim$ 100°).

Figure 13 presents typical examples of diurnal behavior over seven Martian sols. Only HRIM data and the initial seconds of longer measurements are plotted. Maximum relative humidity readings generally occur in the early morning, when atmospheric temperature is at its lowest. Notably, there are clear variations in nighttime relative humidity (RH) between

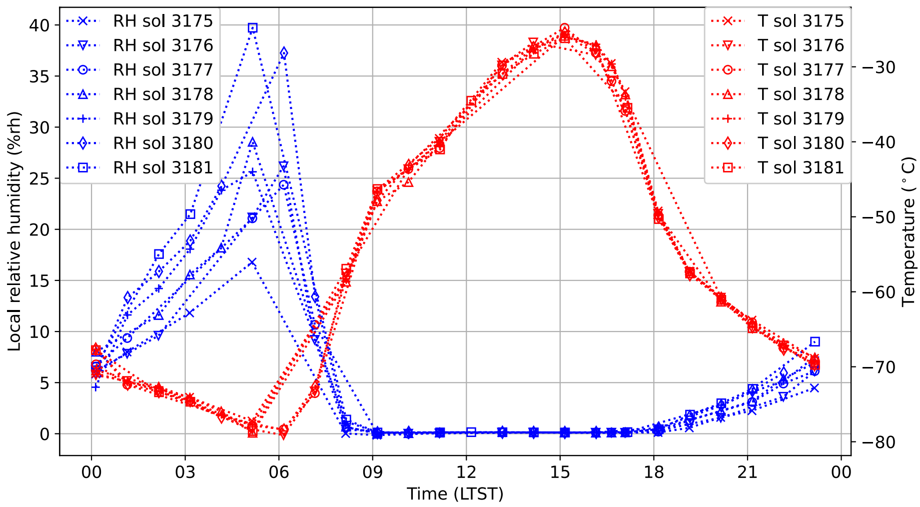


Fig. 13 Diurnal variations in relative humidity (RH) over seven Martian sols, showing typical daily patterns. Maximum RH values generally occur in the early morning when atmospheric temperature is at its lowest. The daytime minimum RH is approximately 0% between 9 and 17 LTST

different sols, even within this short span. During this period, the highest recorded RH was 40%, while the lowest nighttime peak was 17%.

Daily minimum, maximum and mean values of VMR are plotted between 23 and 05 LMST in Fig. 14. The time span is limited to nighttime hours because calculating the derived VMR is more meaningful when RH is above zero. Although an RH threshold (e.g., 2–3%) could be used in the VMR calculation, a specific time interval was chosen for simplicity in this work. Moving averaging over 6 sols has been used to provide the mean value curve. The seasonal VMR trend reflects the sublimation of the northern polar cap during the northern spring and summer, which releases water vapor into the atmosphere and leads to a peak in absolute humidity levels. The VMR peaks in terms of Solar longitude, Ls, occur at MY32 = 142.1°, MY33 = 163.0°, MY34 = 143.6°–169.4°, MY35 = 174.7°, and MY36 = 151.8°–156.1°.

Along the traverse of the Curiosity rover, one of the most striking environmental changes was the abrupt increase in near-surface, nighttime water content from about sol 1800 (Martian year (MY) 34, Ls $\sim$ 53°) onward, when the Curiosity rover started to climb Mount Sharp (Fig. 14). Savijärvi et al. (2019b) suggested that the observed increase in MY 34 was caused by a change in regolith porosity (fraction of void space in a material), which on average changed from $\sim$30% before sol 1800 (representative of dusty loose material at the landing plane), to 0.3% afterwards (representative of exposed bedrock at the foot of Mt. Sharp). Since a regolith with lower porosity adsorbs less water vapor at night, the near-surface concentration would increase past sol 1800. However, the sub-seasonal evolution of VMR in MY 35 between Ls 50° and 165° was similar to that in MY 34, despite the fact that the rover encountered different types of regolith during its ascent of Mt. Sharp. As a complementary explanation, it was suggested that large scale atmospheric circulations might impact the vertical profile of water vapor, which would be seasonally modulated by the extent to which external air masses could penetrate the stable inversion layer developing from the floor of Gale at night (Rafkin et al. 2016; Steele et al. 2017). Interestingly, Pla-Garcia et al. (2016) showed that mixing between internal and external air masses was especially subdued

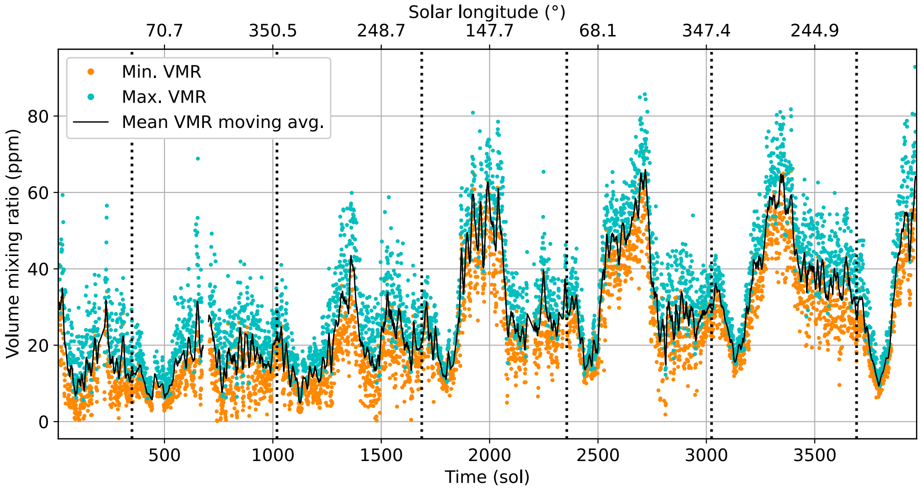


Fig. 14 Revised nighttime (between LMST 23 to 05) minimum and maximum water vapour mixing ratios from sol 15 and up to sol 3965. Daytime VMRs cannot be derived with reasonable uncertainties. Vertical lines mark the Martian years starting from MY 31 at the time of landing and reaching up to MY 37

at around the time VMR abruptly increased in MY 34 and 35 (Ls $\sim 60°$). Therefore, it is plausible that external air masses bringing moister air could only be observed by the rover as it drove away from the crater floor.

4.2 Comparison to the Previous Calibration

The seasonal and interannual behavior in relative humidity is not drastically different with the revised calibration. Figure 15 shows a comparison of new and old RH calibration using the highest daily relative humidities, which usually occur between 04:00 and 06:00 LMST. 10-sol moving averaging has been used in order to smooth out the sol-to-sol variability. Relative humidities are higher in later years in the mission as the rover ascended Mount Sharp, and the global dust storm of MY 34 around sol 2100 is clearly visible in both datasets. On average, the new calibration produces about 10% lower humidities. The largest differences usually occur when the yearly RH is highest, but otherwise there are differences between the years and no clear, repetitive annual trend.

The derived VMR comparison shows relatively larger changes between the old and revised data (Fig. 16). The data from between LMST 23 and 05 has been used in the comparison due to unreliable daytime values, and each hour has been compared separately. Although the differences are small in an absolute sense, usually between 20 and 60 ppm, they are in many occasions larger than the new derived value. Hourly plots in Fig. 16 show that the largest differences occur during early night. The seasonal peaks in years 34 and 35 are strikingly different in both VMR level and shape, with the old values reaching nearly 200 ppm, while the new values peak around 50 ppm and drop more rapidly after the peak to about 25 ppm. Around the coldest time of the night, between 04 and 05 LMST, the difference between the old and new values is much smaller but still approximately equal to the new value itself. Also a specific spike in the difference curve occurs around sol 2100 matching the MY 34 global dust storm.

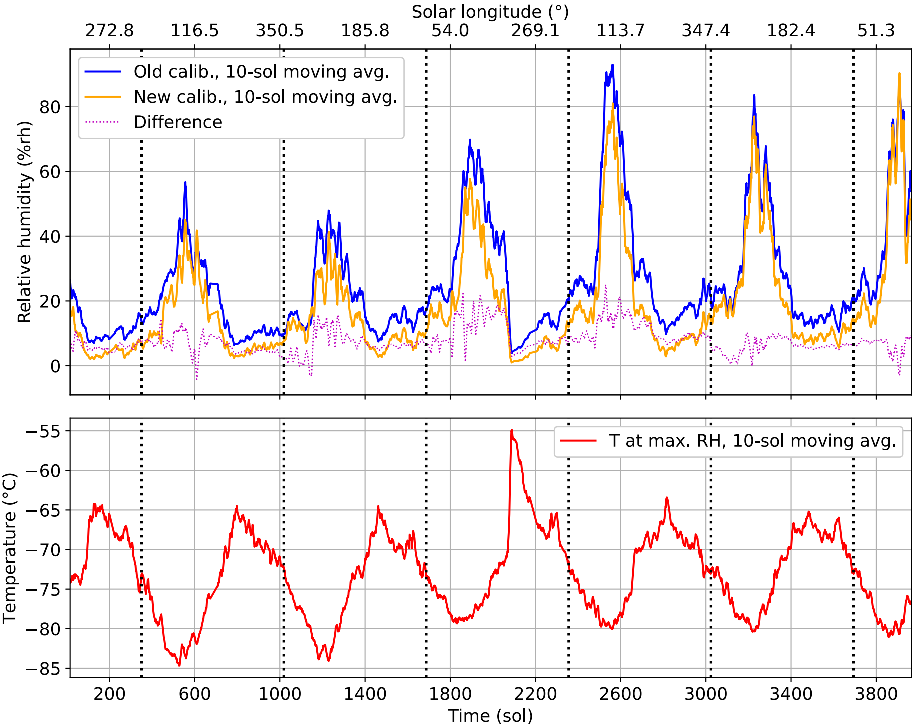


Fig. 15 Top panel: Maximum RH of each sol with old (blue) and new (orange) calibration averaged over 10 sols, relative to the sensor's internal temperature and not the atmospheric temperature. The difference of the two values is also shown with a dashed line. On average the new calibration produces about 10%RH lower relative humidities, but the difference is varying. Bottom panel: Sensor temperature at maximum RH. The sharp spike in temperature coincides with the MY 34 global dust storm

4.3 Comparison to M2020 Perseverance

M2020 Perseverance rover landed on Jezero crater on 18 February 2021 carrying a relative humidity sensor MEDA HS as a part of the Mars Environmental Dynamic Analyzer (MEDA) suite (Rodriguez-Manfredi et al. 2021). MEDA HS is the successor to the REMS-H, representing the next generation of FMI-delivered relative humidity instruments (Hieta et al. 2022). MEDA HS has been typically measuring every other hour, varying between even and odd hours. Similarly to REMS-H, MEDA HS has continuous and HRIM operational modes that can be alternated throughout the sol, and the best accuracy is achieved when using measurements before self-heating.

Due to different locations on the surface, the MEDA HS cannot be used to validate the newly calibrated REMS-H data, but comparisons of the two simultaneously measuring weather stations can still provide useful insights as shown below.

Based on orbital Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) column precipitable water content (PWC; integral of VMR over pressure) maps during MY 25, 26 and 27 in Steele et al. (2017) for Ls 60-80°, 180-200° and 310-330° (and the quite similar Oxford global circulation model (GCM) maps in it), the values of column water over the Gale crater (4.6°S, 137.5°E) and over Jezero (18.4°N, 77.4°E) are nearly the same, despite the difference in location. The values are also similar to each other at the rover

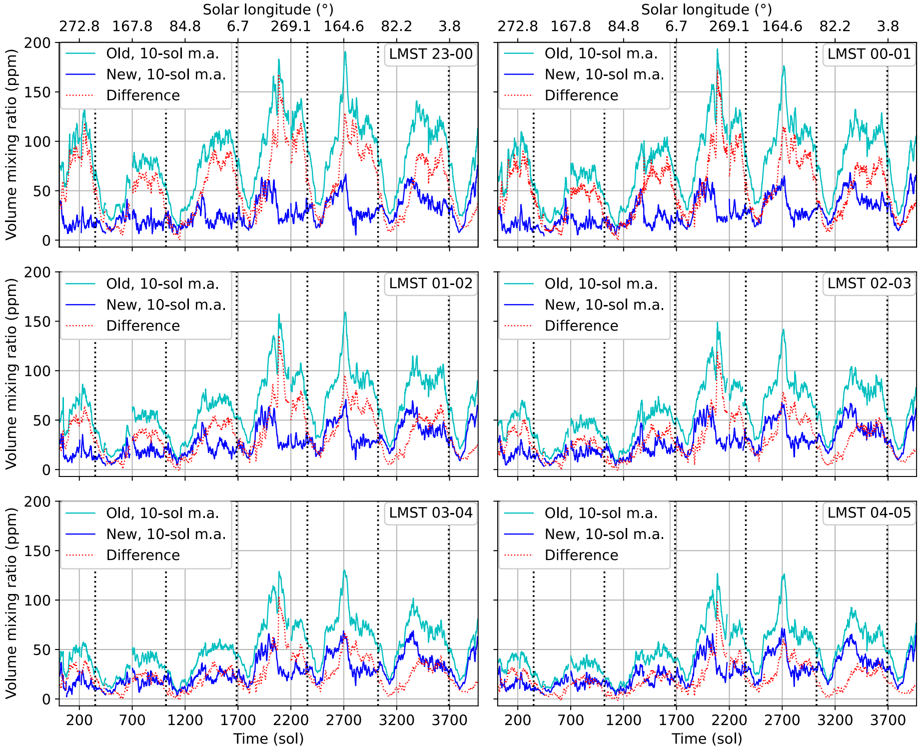


Fig. 16 Hourly plots of highest VMR with old (cyan) and new (blue) calibration from 23 to 05 LMST. The values are averaged over 10 nights. Difference of the two values is shown with dashed red line

landing sites (Curiosity in the Gale crater base and Perseverance at Jezero) in the Mars Climate Database (MCDv6.1), except that the peak in MCD PWC due to transported water vapor from the sublimated northern polar ice is stronger and occurs earlier at the northern Jezero site (28.2 μm, Ls 135°) than at the equatorial Gale (23.3 μm, Ls 165°).

Figure 17 presents data from MY 36, showing relative humidity (RH) in panel (a) and sensor temperature in panel (b), both measured by REMS-H (Gale; blue) and MEDA HS (Jezero; purple), along with the derived VMRs in panel (c). In both cases, the sensor temperature may differ slightly from the air temperature, but overall the trend is the same. The main difference is that the two landers are located in different hemispheres. As seen in the Fig. 17 panel (a), the peak in relative humidity does not occur simultaneously at the two locations and is primarily influenced by air temperature rather than the absolute amount of water. The highest relative humidities at both sensors are reached when the temperature is at its lowest.

The simultaneous MY36 values of minimum and maximum VMR in panel (c) of Fig. 17, derived from the revised REMS-H data and from MEDA HS are also rather similar during the perihelion period (M2020 sols approx. 400-700), but the increase toward the peak of VMR at around Ls 150° (M2020 sol approx. 300) appears to be stronger at Gale, contrary to MCD data. One reason for this may be that by MY 36, Curiosity had climbed from the Gale crater base to the slopes of Aeolis Mons (Mt. Sharp). In the adsorptive mesocale simulations of Steele et al. (2017) the nocturnal water vapor mixing ratios are clearly at their lowest on the cold crater base, increasing upward along the slopes. This is compatible with the revised

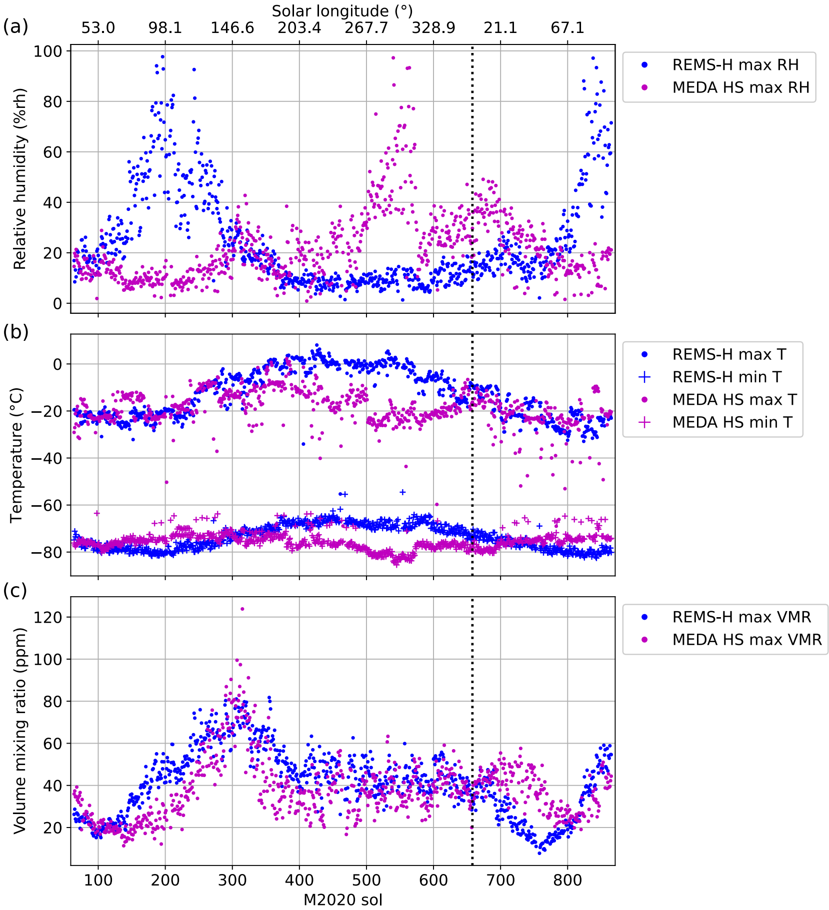


Fig. 17 (a) Maximum daily relative humidities measured by REMS-H (blue) and MEDA HS (purple) during the same time period. The difference in RH is mostly driven by the atmospheric temperature. Sensor temperatures of REMS-H and MEDA HS are shown in (b). The temperature phase difference is due to the rovers being located in different hemispheres. (c) Maximum daily VMR derived from REMS-H (blue) and MEDA HS (purple) measurements

REMS-H maximum VMR values being initially low in Fig. 14 until from approx. sol 1800 onward they do increase, as Curiosity leaves the crater base and starts the upward climb. The MY 36 maximum VMR peak of the revised REMS-H in Fig. 14 (about 80 ppm at Ls 165°, approx. sol 3350) is thus higher than the respective three peaks (about 50 ppm during MY31-33), when the rover was still at the Gale crater base. This relative increase due to altitude is stronger than the MCD-indicated maximum PWC-difference due to location.

4.4 Comparison to the UH/FMI Single Column Model

The revised REMS-H observations are here compared to the Mars Single-Column Model (SCM) from the University of Helsinki and Finnish Meteorological Institute (UH/FMI) – a local adsorptive atmosphere-subsurface model (Savijärvi et al. 2024). This comparison spans MSL sols 13–18 (Ls ∼159°), a period within the moist and warm season at Gale

Crater. The period was selected due to the rover's largely stationary position, which minimized variability between consecutive sols and maintained nighttime relative humidity consistently above ∼10%, thereby minimizing relative uncertainty.

The adsorptive SCM (from Savijärvi et al. 2024) utilizes the MSL-observed surface pressure (p_s) and dust optical depth (τ), taking the ground thermal inertia and surface albedo at each site from Vasavada et al. (2017), their Fig. 2. The resulting diurnal ground surface and 1.6 m air temperatures closely match those observed by REMS Ground Temperature Sensor (GTS) and REMS Air Temperature Sensor (ATS). For model initialization we use well-mixed constant volume mixing ratio (VMR) based on the nearest local CRISM PWC value at 6.1 mbar (McConnochie et al. 2018, Fig. 9). ChemCam local retrievals were not yet available at this time. Soil porosity, controlling adsorption as per Savijärvi and Harri (2021), is set to conserve model PWC from sol to sol during integration, rendering the current SCM simulations fully independent of REMS-H data.

In this investigation, we apply the SCM column model to independently predict the revised relative humidity (RH) and temperature values at a 1.6-meter altitude as provided by REMS-H, utilizing CRISM PWC data and the necessary soil parameters obtained from other sources. It is important to note that previous modeling studies (e.g., Savijärvi et al. 2016) have used older REMS-H data to derive atmospheric PWC and to compare these values with PWC obtained from satellite observations. This modeling work, however, operates without prior knowledge of REMS-H humidity and temperature values, instead independently calculating RH and temperature at 1.6 meters using separate data sources.

The SCM model gives the atmosphere temperature at 1.6 m height. However, temperature sensors at REMS-H electronics board often register higher values than the ambient atmosphere, due not only to heating from the electronics but also to conducted heat from the rover and the mast through the mounting and electrical wires. This thermal difference impacts relative humidity measurements, but the derived VMR (the absolute quantity of water molecules) should remain comparable to the model-predicted VMR.

Figure 18 displays comparisons for MSL sols 13-18 (Ls ∼159°) during the moist and warm season at Gale, with local CRISM PWC being around 10.5 μm at the observed p_s of 7.26 hPa. The REMS-H board temperature at 1.6 m (in red) exceeds model temperatures (dashed line) by 3–4 K during the early evening, with lesser discrepancies observed at night. Consequently, the revised RH values (blue) fall slightly below the model's predictions (thick dashed line). However, the nighttime values of the derived VMR exhibit good agreement with the model's independent predictions. The strong scatter in the observations may indicate effects of nocturnal windshear-driven high-frequency turbulence.

When applying the column model to colder and drier periods within MSL observations, SCM's predictions of RH and air temperature at 1.6 m showed slightly larger deviations from revised REMS-H RH and temperature than on a warm and moist period - still, the VMR values matched relatively well. Further investigation into these differences is needed.

Additionally, further analysis is required to examine the observed deviations between REMS-H-measured temperatures and actual ambient temperatures, as the differing thermal properties of the REMS-H sensor often yield warmer readings than those of the surrounding atmosphere, potentially affecting RH measurements. Nonetheless, the VMR – a measure of absolute humidity – appears to remain a directly comparable metric.

5 Discussion

The revised calibration is based on new laboratory measurements in a simulated Martian environment. Although the revised calibration generally results in lower relative humidity

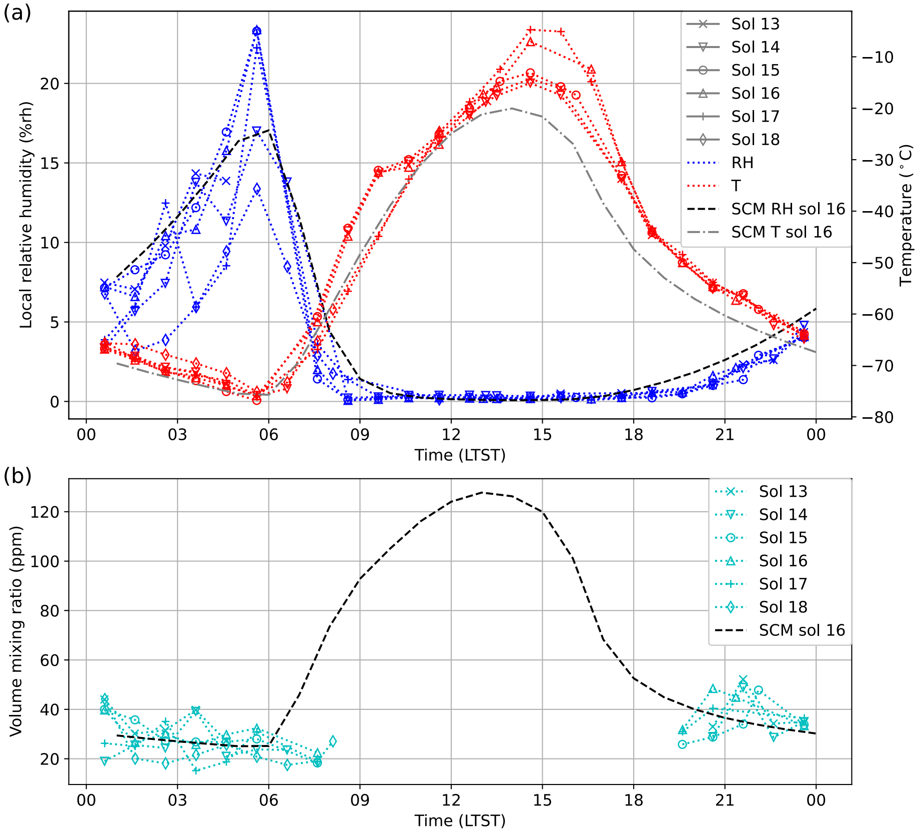


Fig. 18 Single-column model (SCM) results (dashed lines) compared to REMS-H observations (coloured lines and markers) between sols 13 and 18 (Ls 159°). (a) Relative humidity (blue) and sensor temperature (red) measured by REMS-H compared to the model outputs. (b) Derived nighttime VMR compared to the model output

values compared to the previous calibration, there are instances where the difference is significant (more than 20% RH) or even where the new calibration produces slightly higher values. The relationship between the old and new calibrations is influenced by changes in both the capacitance ranges and the dynamic scale of the sensor. One potential contributing factor to the differences that are not fully explained by the calibration itself could be the old filter correction applied to the data. Figure 19 shows two examples of Martian sols where there is a large discrepancy in relative humidity between the calibrations in one case, and almost no difference in the other. This variability highlights the challenges in understanding the precise impact of the revised calibration.

The derived water vapor mixing ratio (VMR) often shows large discrepancies between the old and new calibrations. Not only is the VMR level higher, but the shape of the seasonal maximum can also appear very different. For example, in MY 34, the revised calibration shows a sharp drop in VMR following a global dust storm, whereas the old calibration produces high VMRs during and after the storm. The largest difference, 100 ppm, between the old and revised values occurs at the time of the global dust storm, and could be related to elevated atmospheric temperature. Examining individual sol plots in Fig. 19 reveals that the

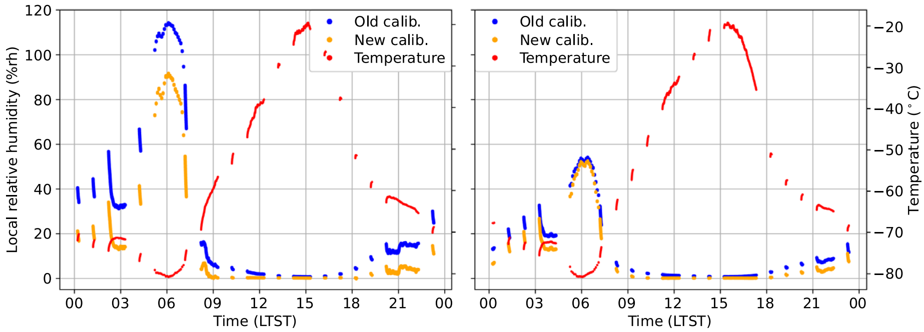


Fig. 19 Example of two individual sols plotted with old (blue) and new (orange) calibration. All RH data is shown, including both the HRIM mode measurements (short, dotted measurement points) and continuous measurements including the self heating period. Sensor temperature (red) has not changed in the calibration revision

old calibration tended to indicate an earlier increase in relative humidity during the evening, which is one reason for much higher VMR values during the early night.

To get reliable and meaningful VMR data, it is important to pay attention to the conditions when the data are collected. Because the RH is low during the day, this causes high uncertainty in RH measurements. It is better to focus on nighttime data, when RH is higher and more stable. Also, setting a minimum RH threshold (for example, $>2\%$) can help get more accurate VMR calculations.

The revised REMS-H data was also compared to the UH/FMI single column model (SCM). While the SCM generally agrees well with the revised VMR values, there are some discrepancies in the predicted relative humidity and air temperature at 1.6 meters. The temperature sensors mounted on the REMS-H board often record warmer temperatures than the surrounding atmosphere, resulting from various reasons including conducted heat from the rover's mast. This temperature difference influences the relative humidity measurements, making it essential to further analyze the observed deviations between the measured and actual atmosphere temperatures.

6 Conclusions

This paper presents the recalibration of the REMS-H relative humidity sensor onboard the Curiosity rover of the Mars Science Laboratory (MSL) mission, based on new laboratory measurements conducted in a Martian analogous environment. The recalibration effort was driven by the need to improve the accuracy and reliability of the REMS-H data, particularly due to the availability of a calibration facility at DLR in Berlin, which outperforms the original calibration facilities.

This study presented the revised calibration and updated results up to sol 3965 of the MSL mission, providing an analysis of the revised interannual, seasonal, and diurnal variations in relative humidity and the derived water vapor mixing ratio. Additionally, comparisons with the previous calibration, modeling efforts, and data from the Mars 2020 mission were discussed.

The new calibration was performed using the REMS-H ground reference model, an exact replica of the flight unit currently aboard the Curiosity rover. These two models were previously tested and calibrated together before the MSL launch, demonstrating similar behavior. As a result, recalibrating the ground reference model allowed for the fine-tuning of the calibration coefficients of the flight model as well.

Overall, the updated calibration results in lower relative humidity values compared to the previous calibration, with the most notable differences observed during high-humidity conditions. However, the recalibration's impact on relative humidity measurements is not uniform. On average, the new calibration yields relative humidity values that are on average 8% RH lower than the original calibration, with a standard deviation of 4% RH. In some cases, the new calibration may actually produce higher humidity readings than the previous version. Hence, it is critical to note that the revised calibration data must be used when working with REMS-H data. The updated dataset is available in FMI's METIS repository and will eventually be available in the PDS system.

The new laboratory calibration measurements facilitated a precise assessment of how Martian atmospheric conditions affect the sensor's capacitance and dynamic range. Specifically, it was observed that REMS-H capacitances in dry Martian conditions are lower than those determined by the original calibration performed in a vacuum, with this difference increasing at lower temperatures. This explains why previous corrections were in the right direction but failed to fully account for the effects of the Martian environment.

Notably, the recalibrated data aligns more closely with orbital observations and atmospheric modeling, further enhancing its reliability. This was achieved by using independent observations and atmospheric modelling tools to discover atmospheric relative humidities and temperatures.

The revised data provides a more accurate characterization of the humidity environment at Gale Crater. Although uncertainties remain, the improved calibration builds confidence for further investigations of the Martian atmosphere. This includes studies on the potential presence of liquid water in the form of brines, frost formation, water exchange between the regolith and atmosphere, and water uptake by salts.

The recalibration of REMS-H represents a significant milestone in advancing our understanding of the Martian humidity environment. The revised dataset not only enhances the scientific value of the long-term REMS-H observations but also provides insights that will inform the design and calibration of future instruments, enabling even more precise and reliable humidity measurements on Mars.

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Data Availability The revised REMS-H dataset is available in the FMI's METIS research data repository (Hieta et al. 2024b). Direct link to the dataset is https://doi.org/10.57707/fmi-b2share.20d2d58e645e4076a7caeb86b5626fd8

Mars Science Laboratory REMS-H instrument raw data used in this work is available in Planetary Data System Atmospheres node (Gomez-Elvira (2013)): https://doi.org/10.17189/z75m-q024

M2020 MEDA HS data used in this work is available in Planetary Data System Atmospheres node (Rodriguez-Manfredi and Torre Juarez (2021)): https://doi.org/10.17189/1522849

Declarations

Competing Interests The authors declare no competing interests.

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