Advancing atmospheric humidity measurements on Mars through improved calibration methods

Maria Hieta

Aalto University

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ABSTRACT

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Although Mars is an extremely dry planet with a thin atmosphere dominated by carbon dioxide, water vapor is one of the central components of its climate system, alongside dust. Therefore, understanding the behavior of water vapor is essential for characterizing the Martian water cycle, the regolith–atmosphere exchange processes, assessing whether liquid water could briefly exist at the surface, and improving Mars climate models. Accurate near-surface humidity measurements obtained directly at the surface are therefore indispensable as the lowest atmospheric layers cannot be reliably characterized from orbit.

This dissertation focuses on improving measurements from the humidity sensors flown on NASA's Mars missions, specifically the Curiosity and Perseverance rovers. It presents new laboratory calibrations and an improved calibration methodology in order to obtain near-surface relative humidity measurements that are more accurate than previously possible. The flight calibration of the MEDA HS humidity sensor onboard the Perseverance rover was planned and executed, consisting of extensive calibration measurements at multiple test facilities. The previous calibration of REMS-H, the humidity sensor onboard the Curiosity rover, was re-evaluated using the same methodology, improving the quality of the dataset.

The results cover the MEDA HS flight calibration and its assessment after landing, as well as the revised calibration of REMS-H. The MEDA HS calibration resulted in reduced uncertainty and demonstrated a robust instrument performance on Mars. These calibrations revealed the way extremely low temperatures, low pressures and the atmospheric composition of Mars influence sensor behavior, highlighting the importance of testing under a representative environment. The reprocessed REMS-H dataset now provides a revised and more accurate long-term record covering 13 years of observations. Together, the two resulting datasets constitute the most comprehensive and intercomparable near-surface humidity records obtained from Mars to date, supporting studies of the Martian water cycle and surface–atmosphere exchange phenomena.

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Avainsanat Mars, kosteusanturi, suhteellinen kosteus, ilmakehä, kalibrointi

Vaikka Mars on äärimmäisen kuiva planeetta, vesihöyry vaikuttaa silti olennaisesti sen nykyilmastoon hiilidioksidin ja pölyn ohella. Vesihöyryn käyttäytymisen ymmärtäminen on keskeistä Marsin veden kiertokulun ja kaasukehän sekä pinnan välisen vuorovaikutuksen tutkimuksessa. Lisäksi se on olennaista nestemäisen veden esiintyvyyden arvioinnissa sekä Marsin ilmastomallien kehittämisessä. Suoraan pinnalla käsin tehdyt kaasukehän kosteuden mittaukset ovat erityisen arvokkaita, sillä ilmakehän alimpia kerroksia ei voida luotettavasti havainnoida kiertoradalta käsin.

Tässä väitöskirjatyössä on kehitetty ja parannettu kalibrointimenetelmiä, joiden avulla voidaan tuottaa luotettavampia suhteellisen kosteuden mittauksia Marsin pinnalta. Keskeisessä osassa ovat uudet laboratoriokalibrointitulokset, joiden avulla on pystytty parantamaan myös historiallisia mittaussarjoja.

Työn tuloksena suunniteltiin ja toteutettiin Nasan Perseverance-kulkijassa olevan MEDA HS-kosteusinstrumentin kalibrointi, sekä Nasan Curiosity-kulkijan REMS-H-instrumentin aiemman kalibroinnin uudelleenanalysointi. MEDA HS -instrumentin mittausepävarmuutta voitiin pienentää aiempaan verrattuna, ja instrumentin suorituskyky osoittautui Marsissa erittäin vakaaksi. Kalibrointitestit osoittivat, miten Marsin äärimmäisen matalat lämpötilat, alhainen paine ja hiilidioksidipitoinen kaasukehä vaikuttavat kosteusanturin käyttäytymiseen, ja korostavat tarvetta suorittaa myös kalibroinnit Marsin olosuhteita riittävästi vastaavassa ympäristössä. Uudelleenprosessoitu REMS-H:n mittausaineisto tarjoaa aiempaa luotettavamman kuvan kaasukehän suhteellisen kosteuden vaihteluista. Nämä kaksi aineistoa muodostavat yhdessä tähän mennessä kattavimman ja keskenään vertailukelpoisimman Marsin pinnalta mitatun suhteellisen kosteuden kokonaisuuden. Nämä havainnot tukevat laajasti Marsin ilmaston tutkimusta ja mallinnusta.

Preface

This research was conducted during my time at the Finnish Meteorological Institute (FMI) in Helsinki, where I had the privilege of contributing to many exciting space instrumentation projects. More often than not, the demanding schedules of flight hardware delivery took priority over my thesis work. I never declined a new space mission project. These experiences have been invaluable, and I look back on them with no regrets.

I would like to thank my thesis supervisor, Professor Esa Kallio, for his support and understanding throughout my prolonged doctoral studies. I am also deeply grateful to my thesis advisor, Professor Ari-Matti Harri, whose unwavering belief in my ability to complete this thesis often surpassed my own and who has provided me with invaluable opportunities throughout my career. I thank Professor Axel Hagermann for serving as my opponent and pre-examiner at the thesis defense, and Dr. Andrew Ball for valuable feedback as a pre-examiner. My heartfelt thanks to Professor Jaan Praks for inspiring space engineers like myself to believe in themselves and that anything is possible.

This work is the result of the efforts of numerous people, as well as earlier work that laid the foundation for the research presented here. A particularly important role was played by Maria Genzer, my research group supervisor and project manager in many of our shared projects. I am forever grateful for our adventures. I would also like to express my sincere thanks to my co-author Iina Jaakonaho, whose contribution has been essential not only to this work but also to the broader scientific community using the resulting data. I would like to thank our FMI Mars science team Jouni Polkko, Hannu Savijärvi, Joonas Leino and Mark Paton for interesting discussions and their support.

Special thanks to all my fellow lab dwellers who have spent countless long hours in various laboratories recreating Martian conditions on Earth: Martti Heinonen, Hannu Sairanen, Erik Fischer, Germán Martínez, Andreas Lorek and Stephen Garland. I learned a great deal from working alongside you.

Being part of NASA's MEDA and REMS science teams has shown me the dedication of the many scientists and engineers who have worked tirelessly to provide the scientific community with the best possible data from another planet, and it has taught me what perseverance truly means. I would like to specifically acknowledge José Antonio Rodríguez-Manfredi, Manuel de la Torre Juárez, Leslie Tamppari, Timothy McConnochie, Verónica Peinado González and Luis Mora Sotomayor for their work and support.

A huge thanks goes out to all my colleagues at FMI, past and present, who have shared this journey with me over the years. I would especially like to thank Henrik Kahanpää, Harri Haukka, Matias Meskanen, Markku Mäkelä, Pekka Riihelä, Walter Schmidt, Jouni Rynö, Timo Nikkanen, Osku Kemppinen, the inhabitants of our ”space nest” office, and the coffee break crew for their support, good advice, and good times. I would also like to thank Pekka Salminen for his amazing craftsmanship, and Shahin Tabandeh, Richard Högström and Henrik Söderblom for their work on improving the calibration uncertainty analysis.

I couldn't have done this without my husband. While this thesis took me on research trips and to calibration laboratories, he stayed at home performing the far more demanding experiment of caring for our three young children (for a while, all under three). Let the record show that he held the fort with patience and resilience. To Henrik, Leevi, Veeti and Eetu: you are the most important to me.

Helsinki, March 9, 2026,

Maria Hieta

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Maria Hieta, Maria Genzer, Jouni Polkko, Iina Jaakonaho, Shahin Tabandeh, Andreas Lorek, Stephen Garland, Jean-Pierre de Vera, Erik Fischer, Germán M. Martínez, Ari-Matti Harri, Leslie Tamppari, Harri Haukka, Matias Meskanen, Manuel de la Torre Juárez, and José Antonio Rodriguez Manfredi. MEDA HS: Relative humidity sensor for the Mars 2020 Perseverance rover. *Planetary and Space Science*, Volume 223, pp. 105590, https://doi.org/10.1016/j.pss.2022.105590, October 2022.

II Maria Hieta, Iina Jaakonaho, Jouni Polkko, Andreas Lorek, Stephen Garland, Jean-Pierre de Vera, Maria Genzer, and Ari-Matti Harri. Improving relative humidity measurements on Mars: New laboratory calibration measurements. *Geoscientific Instrumentation, Methods and Data Systems*, Volume 13, pp. 337–351, https://doi.org/10.5194/gi-13-337-2024, November 2024.

III Maria Hieta, Iina Jaakonaho, Jouni Polkko, Hannu Savijärvi, Maria Genzer, Ari-Matti Harri, Andreas Lorek, Stephen Garland, Jean-Pierre de Vera, Germán Martínez, Erik Fischer, Eduardo Sebastián Martínez, José Antonio Rodríguez-Manfredi, Leslie Tamppari, Manuel de la Torre Juárez, and Timothy McConnochie. REMS-H Revisited: Updated calibration and results of the humidity sensor of the MSL Curiosity. *Space Science Reviews*, Volume 221, article number 58, https://doi.org/10.1007/s11214-025-01187-1, June 2025.

Author’s contributions

Publication I: “MEDA HS: Relative humidity sensor for the Mars 2020 Perseverance rover”

The author was part of the team at Finnish Meteorological Institute developing the relative humidity sensor for the Perseverance rover. The author planned the environmental and calibration tests, conducted the majority of the measurements, and managed the uncertainty analysis. The author wrote the manuscript with input from the co-authors.

Publication II: “Improving relative humidity measurements on Mars: New laboratory calibration measurements”

The author initiated the project and designed the experiments with the support of the co-authors. The author planned and coordinated the data analysis and wrote the manuscript with input from the co-authors.

Publication III: “REMS-H Revisited: Updated calibration and results of the humidity sensor of the MSL Curiosity”

The author initiated and led the calibration improvement process, which was conducted in close collaboration with all co-authors. The author wrote the majority of the manuscript with input from the co-authors.

Abbreviations

ASIC	Application Specific Integrated Circuit
ATS	Air Temperature Sensor
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ESA	European Space Agency
FM	Flight Model
FMI	Finnish Meteorological Institute
GCM	Global Circulation Model
GDS	Global Dust Storm
HRIM	High-Resolution Interval Mode
HS	Humidity Sensor
ICU	Instrument Control Unit
LMST	Local Mean Solar Time
LTST	Local True Solar Time
MCD	Mars Climate Database
MEDA	Mars Environmental Dynamic Analyzer
MMEC	Michigan Mars Environmental Chamber
MSL	Mars Science Laboratory
MY	Mars Year
NASA	National Aeronautics and Space Administration
PASLAB	Planetary Analog Simulation Laboratory

PCB	Printed Circuit Board
PDS	Planetary Data System
PQV	Packaging Qualification and Verification
PRT	Platinum Resistance Thermometer
REMS	Rover Environmental Monitoring Station
RH	Relative Humidity
RSM	Remote Sensing Mast
RTG	Radioisotope Thermal Generator
SCM	Single-Column Model
VM	Validation Model
VMR	Volume Mixing Ratio

Symbols

C capacitance

e water vapor partial pressure

e_s saturation vapor pressure

k coverage factor

L_s solar longitude

p atmospheric pressure

T temperature

τ time constant

T_f frost point temperature

T_g ground temperature

u standard uncertainty

u_T standard uncertainty of temperature

u_P standard uncertainty of pressure

1. Introduction

The research work presented in this dissertation focuses on increasing the scientific return of in situ humidity measurements on Mars. Atmospheric analysis and prediction rely on accurate observations to test and improve models that describe how atmospheric variables change over space and time. On Mars, surface-based measurements provide the high-precision data needed for this purpose, while orbital observations complement them by offering broad spatial coverage. To achieve this, the dissertation improves calibration and measurement analysis methods for humidity sensors, using the MEDA HS instrument onboard Perseverance and the REMS-H instrument onboard Curiosity.

This introductory section begins by outlining the scientific background that demonstrates the significance of accurate humidity measurements on the surface of Mars (Section 1.1). It then reviews the history of water detection on the planet, summarizing key observations, missions, and measurement techniques that have shaped the current understanding and influenced the design of the instruments used in this study (Section 1.2). Finally, Section 1.3 describes the focus and objectives of the dissertation, defining the scope of this research work and the central research questions it seeks to address.

1.1 Background of water on Mars

Mars, the fourth planet from the Sun, is a rocky world smaller than Earth characterized by a thin atmosphere and a predominantly cold, arid surface with an average temperature of around -60°C. Geological evidence suggests that Mars once harbored substantial quantities of surface water, possibly in the form of ancient oceans. Traces of water-related erosion are still visible across the planet's landscape. Today, however, most of the water is gone, and the surface is mostly covered by regolith, a mixture of dust, sand and broken rock.

The atmosphere of Mars consists primarily of carbon dioxide (95%) with smaller fractions of molecular nitrogen (2.6%), argon (1.9%), molecular oxygen (0.16%), carbon monoxide (0.06%) and water vapor (0.02%) [63, 28]. The surface pressure on Mars is only about 6 hPa, which is less than 1% of Earth's surface pressure. Although significantly drier than Earth's, the Martian atmosphere still contains water in several forms, including ice within the polar caps, subsurface deposits and atmospheric vapor. The remaining water creates the Martian water cycle, which involves exchanging water between the atmosphere, surface, and the subsurface, and is further redistributed by atmospheric circulation. Together with carbon dioxide and dust, water is among the key dynamic components governing Martian atmospheric processes. Due to Mars's axial tilt similar to that of Earth, the planet experiences seasons, and its water cycle undergoes pronounced seasonal variations [26, 59]. A Mars year, which is approximately 687 Earth days, defines a full orbit of Mars around the Sun and serves as the basis for describing seasonal changes on the planet. Martian seasons are often expressed using solar longitude (L_s), which measures the planet's position in its orbit relative to the northern spring equinox, with $L_s = 0°$ marking the northern spring equinox, 90° the northern summer solstice, 180° the northern autumn equinox, and 270° the northern winter solstice. During the northern summer, water sublimates from the northern polar cap and produces an annual peak in atmospheric water vapor at high northern latitudes. The vapor is subsequently transported equatorward by atmospheric circulation, spreading across much of the planet. In the southern summer, sublimation from the smaller seasonal southern polar cap provides an additional, though generally weaker, source of atmospheric water vapor.

Investigations of the behavior of water vapor are essential for understanding atmospheric phenomena and constraining surface–atmosphere exchange processes, such as the adsorption of vapor molecules onto regolith particles and their subsequent desorption. The extent of regolith–atmosphere interactions in terms of water vapor exchange is not yet fully understood. Such knowledge is also crucial for assessing the potential occurrence of transient liquid phases and for improving global circulation models. Accurate near-surface humidity measurements are therefore highly important. Observations made directly at the surface, in situ, provide unique advantages over remote-sensing techniques, as the lowest few kilometers of the atmosphere cannot be accurately characterized from orbit. Consequently, both in situ and remote-sensing observations are needed to investigate the near-surface environment. Surface measurements also provide high-resolution temporal data and enable direct observations under the exact environmental conditions present at the surface. This facilitates the characterization of diurnal variability, nighttime condensation processes, and localized interactions with the regolith.

The presence of water on Mars also holds astrobiological interest, as water is an essential component for life as we know it. Understanding the behavior of water, particularly the interaction between atmospheric water and the regolith and its implications, for example, for the potential occurrence of liquid brines [39], is also fundamental for astrobiological investigations. These biological implications, however, are beyond the scope of this thesis, which focuses on measuring the atmospheric water.

1.2 History of water detection on Mars

Water vapor on Mars was first detected through ground-based observations in 1963 [61]. This discovery was followed by several Mariner spacecraft missions, which provided the first direct measurements of the Martian atmosphere. The first spacecraft to successfully orbit Mars was Mariner 9 in 1971, which mapped approximately 70% of the Martian surface and investigated temporal variations in the atmosphere and surface [4].

The first successful landing on Mars was achieved by the Viking program in 1976, which included two landers and two orbiters. The Viking Landers, VL1 and VL2, provided the first in situ meteorological measurements from the Martian surface [24], revealing the large diurnal temperature cycle and its repetitive nature. Data from the Mars Atmospheric Water Detector (MAWD) onboard the Viking orbiters indicated that the precipitable water content in the Martian atmosphere (the integrated column of water vapor) varied from nearly zero to about 100 micrometers, depending on season and location [27]. This corresponds to an atmospheric water abundance roughly one thousand times lower than that of Earth. Viking orbiter measurements also provided evidence that the northern polar cap is the primary source of atmospheric water and revealed a north–south asymmetry in its distribution [27, 26].

The main goal of the Viking lander missions was to find life on Mars. However, no definitive evidence was found, leading to a pause in major missions until the arrival of Mars Global Surveyor in 1997. The modern understanding of Martian water climatology is largely based on data collected by its Thermal Emission Spectrometer (TES) instrument, which operated from 1997 until 2006 [59].

Despite decades of study, surface-based measurements of atmospheric humidity remain scarce. The first such observations were made by the Imager for Mars Pathfinder (IMP) in 1997, which recorded water vapor on four sols (Martian days) [60]. In 2008, the Thermal and Electrical Conductivity Probe (TECP) mounted on the robotic arm of the Phoenix lander measured relative humidity near the northern polar cap for 150 sols [67]. However, it was not until the Curiosity rover that the first long-term dataset of surface measurements of atmospheric water was collected, providing the continuous records needed to capture seasonal cycles and interannual variability that short missions cannot resolve.

It should also be noted that the history of attempts to measure Martian water includes a number of missions and payloads that never reached the Martian surface or returned data, or were ultimately not flown. Among these are the Mars 96 [20], the Mars Polar Lander [41], the ExoMars 2016 Schiaparelli [7], the ExoMars Kazachok surface platform [30] and the ExoMars Humboldt package [29]. These efforts, though unrealized, represent important steps toward successful surface-based humidity measurements.

The Curiosity rover landed in Gale Crater in 2012 and has been collecting atmospheric humidity observations ever since, continuing to operate and provide data even today. The humidity measurements are made by the Rover Environmental Monitoring Station (REMS) [17], which includes the relative humidity (RH) sensor REMS-H [19]. The calibration of REMS-H has been reassessed and updated in this thesis. Results from REMS confirmed that the Martian atmosphere is extremely dry, with daytime relative humidity approaching 0%. The observations also showed seasonal variations, with humidity increasing during the northern summer and declining throughout northern winter and spring.

NASA's Mars 2020 mission continued this line of investigation. The Perseverance rover, which landed in 2021, carries MEDA HS, a direct successor to Curiosity's REMS-H sensor [50]. Therefore, the calibration of MEDA HS is a key topic addressed in this thesis. Like its predecessor, MEDA HS measures atmospheric humidity and provides long-term surface records, enabling continuity in the study of Martian water vapor.

In addition to REMS-H and MEDA HS, both Curiosity's ChemCam and Perseverance's SuperCam contribute valuable atmospheric water vapor measurements. These remote-sensing instruments use passive sky spectroscopy to assess the column abundance of water vapor. ChemCam has conducted 113 passive sky observations over three Martian years, providing insight into the water vapor variability and aerosol properties above Gale Crater [42]. SuperCam has performed similar observations since Perseverance's landing [44]. Although less frequent, these measurements are particularly valuable as they complement the nocturnal data provided by REMS-H and MEDA HS by expanding temporal coverage to other times of day, improving the reconstruction of daily and seasonal cycles.

The data from REMS-H and MEDA HS have been analyzed and used in a number of scientific publications. First examples include: Gómez-Elvira et al. [16], which presented an overview of the first 100 sols of REMS-H observations; Harri et al. [19], which conducted an initial analysis of REMS-H data; and Savijärvi et al. [52], which examined Curiosity's diurnal moisture measurements using column modeling. REMS-H observations also inspired the modeling study by Martín-Torres et al. [37], which claimed indirect evidence of transient liquid water tens of centimeters below the Martian surface, an interpretation that has yet to be confirmed by independent analyses. Moreover, the exchange of water between the atmosphere and the surface was investigated by Savijärvi et al. [52] through modeling the diurnal water cycle and fitting nighttime REMS-H data into the model. REMS-H measurements were further used in the review by Martínez et al. [38], which synthesized in situ Martian meteorological data from Viking to Curiosity. Additionally, McConnochie et al. [42] integrated REMS-H observations into their retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy.

Several additional studies utilizing REMS-H data were published between 2019 and 2020. These include investigations of the annual and diurnal water cycles [54], water vapor mixing ratios and air temperatures over three Martian years [55], the effects of the MY34/2018 Global Dust Storm [65], and column model integrations during a global dust event [53]. The REMS-H observations also provided key input for the physical formulation of water vapor adsorption within the Martian regolith by Savijärvi and Harri [57].

The first analysis of in situ humidity measurements from the MEDA HS was presented by Polkko et al. [46], followed by Martínez et al. [40], who examined the surface energy budget, albedo, and thermal inertia using MEDA HS and other MEDA sensor data. The annual and diurnal water cycle analysis continued in [47]. Savijärvi et al. [56] modeled the Martian wintertime water cycle in Jezero Crater during periods of near-fog and a dust event based on MEDA HS observations. Column modeling has been widely employed to enhance the scientific interpretation of in situ humidity data from both REMS-H and MEDA HS. The model's sensitivity to ambient conditions was assessed using REMS data by Leino et al. [31]. Furthermore, Zorzano et al. [69] used MEDA HS data to characterize the water content of samples collected and sealed in the sample tubes by the Perseverance rover for future return to Earth.

The author of this dissertation has participated in the Martian water detection and analysis process by leading the humidity instruments' calibration activity, coauthoring several of the investigations mentioned above [31, 40, 46, 47, 56] and through the Publications I, II and III of this dissertation.

> *"Do what you can, where you are, with what you have."*
> —Roosevelt's Law of Task Planning

1.3 Focus and objectives of the dissertation

This dissertation focuses on improving the calibration methodology for capacitive relative humidity sensors operating under Martian environmental conditions. The work is motivated by the need to maximize the scientific value of in situ humidity measurements that are available for the atmosphere on Mars, which depends fundamentally on the quality, traceability and stability of the calibration of the flight instruments.

The first objective is to develop, implement, and validate calibration methods that achieve accurate and robust calibration of the MEDA HS humidity instrument onboard NASA's Perseverance rover. A second objective is to re-evaluate, and improve where possible, the calibration of the earlier REMS-H humidity instrument onboard NASA's Curiosity rover, in order to enable more effective scientific use of its long operational dataset.

Overall, the focus is to increase the scientific value of in situ humidity measurements on Mars by improving the calibration and analysis methods used for the two humidity sensor systems that are existent on Mars.

This dissertation addresses the following research questions:

1. How can relative humidity sensors be accurately and reliably calibrated for the extreme conditions of the Martian atmosphere?

2. To what extent does the pre-flight calibration of the MEDA HS instrument translate to accurate in situ measurements on Mars?

3. How do the revised calibration methodologies improve the scientific value and reliability of the MSL/REMS-H dataset from Mars?

2. Methodology and instrumentation

This section presents the relative humidity (RH) instruments operating on Mars that are studied in this work, the developed calibration methods and the improved observational data sets, which form the central part of this dissertation. Section 2.1 introduces the Mars-based relative humidity instruments produced by the Finnish Meteorological Institute, which are central to Publications I–III. Section 2.2 describes the overall calibration methodology, while Section 2.2.1 provides more detail on the test facilities used in the work, focusing on the Martian simulation facility involved in Publication II. Section 2.2.2 summarizes the data processing and analysis methods applied in Publications I–III.

2.1 Martian relative humidity instruments

Observations from Mars orbiters have provided valuable information on the Martian water cycle. However, they lack the observational accuracy, as well as the spatial and temporal resolution needed to capture near-surface humidity variations at local scales. In situ measurements by landers and rovers allow these variations to be characterized directly at the surface, providing ground truth for orbital data and helping to refine climate model predictions.

The harsh environment on Mars, combined with the mechanical stresses of launch and landing, requires instruments to be robust and maintain their calibration over long periods, while still providing the accuracy and sensitivity needed for scientific measurements. The Finnish Meteorological Institute has been involved in developing meteorological instruments for planetary missions since the 1980s. Initially, the focus was on finding sensor technologies that are both reliable and accurate, capable of withstanding the extreme conditions on Mars as well as on other planetary bodies such as Titan [23]. A suitable technology was provided by the Finnish company Vaisala, which has invented sensor families for measuring pressure (BAROCAP®), relative humidity (HUMICAP®) and temperature (THERMOCAP®).

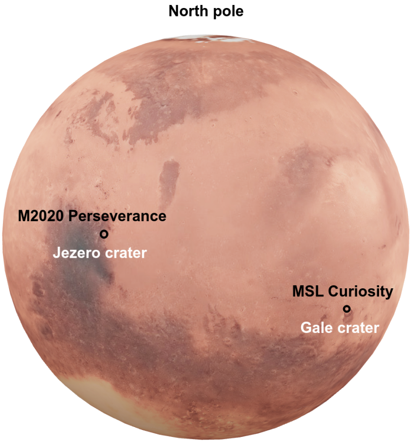

Figure 2.1. The approximate locations of the Perseverance and Curiosity rovers on Mars. Perseverance landed in Jezero crater in the Northern Hemisphere (18.4° N, 77.5° E), and Curiosity in Gale crater in the Southern Hemisphere (4.6° S, 137.4° E). Credit: NASA, adapted by the author.

These sensor families operate by measuring capacitance, which changes in response to variations in the specific meteorological parameter. The sensor heads are miniature in size and mass, and the associated electronics consume very little power, making this technology an excellent candidate for planetary missions. The HUMICAPs are thin-film polymer sensor heads that respond to the surrounding relative humidity even when powered off, allowing near-instant readings after activation. The sensing polymer either absorbs or releases water vapor as the relative humidity of the atmosphere changes. The HUMICAP sensor heads have good long-term stability as well as robust tolerance to chemical exposure and dust. In ambient pressure air, at constant temperature, the sensor response is very close to linear. Notably, the only other relative humidity sensor operating on Mars, besides those developed by FMI based on Vaisala sensors, is the TECP on the Phoenix lander, which also employed a capacitive sensing principle [67].

While polymer capacitive humidity sensor technology has many advantages as described above, the sensors are typically most accurate between 5% and 95% relative humidity with a typical accuracy of 2%–5% RH [6, 36, 33, 68]. Outside this range, the sensors tend to have larger uncertainty and performance degradation. Below about 5% RH, the capacitive response can become weak relative to noise, drift and offsets, and above 95% RH there is a risk of condensation, high hysteresis and saturation effects. Nevertheless, on Mars, such very low and very high relative humidities are actually expected due to the planet's strong diurnal temperature cycle and extremely low absolute water content. Daytime conditions often correspond to near-zero relative humidity as the atmosphere warms, while during the cold nighttime hours the relative humidity can reach saturation [19, 12].

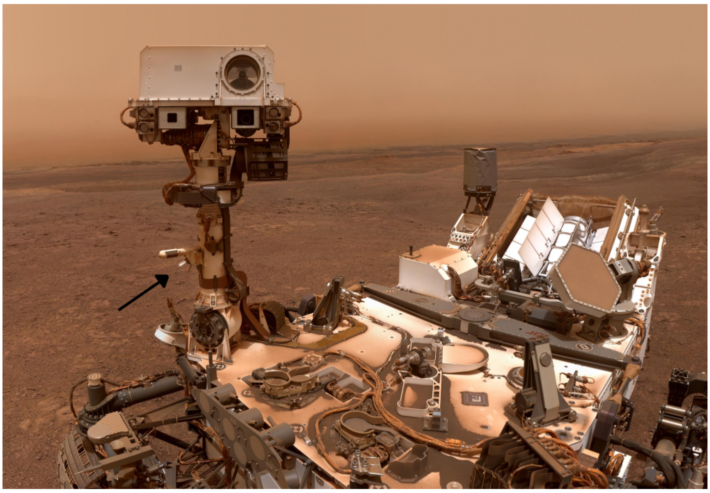

Figure 2.2. REMS-H sensor is located on Curiosity's mast. The arrow marks the humidity sensor, with one of the two wind sensors positioned above it and the air temperature sensor below it. Credit: NASA/JPL-Caltech/MSSS

The first batches of Vaisala sensor heads were qualified for the Mars-96 mission between 1989 and 1993, achieving excellent results [23, 20]. Although the Mars-96 mission ultimately failed to reach Mars, development, collaboration and testing of these sensors have continued ever since that time. The following sections present the Mars instrumentation relevant to this work, including some instruments that never reached Mars but nonetheless contributed valuable data and experience.

> *"You can't make it better until you make it work."*
> —Akin's Laws of Spacecraft Design (McBryan's Law)

2.1.1 REMS-H onboard Curiosity rover

REMS-H (shown in Figure 2.3, left) is a relative humidity instrument that is part of the REMS suite (Rover Environmental Monitoring System) onboard the Mars Science Laboratory (MSL) rover, Curiosity. The humidity sensor is mounted on a remote sensing boom attached to the rover mast. The "head" of the rover is located atop that mast and contains the navigation and science cameras, as well as other instruments. The MSL successfully landed on 6 August 2012 in the floor of Gale crater close to the equator (Figure 2.1). The instrument with its initial calibration and performance are described in [19, 17].

The REMS-H instrument includes three HUMICAP sensor heads and one THERMOCAP sensor head. An integrated heating resistor is used to regenerate HUMICAP sensors 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 instrument contains a total of eight channels, each corresponding to a capacitor, including constant reference channels and housekeeping channels. The read-out electronics are based on an oscillator transducer that converts the output of the capacitive sensors into frequency. The capacitance of each humidity and temperature channel is then calculated using the constant reference capacitors and a proprietary algorithm developed by Vaisala. The transducer electronics and sensor heads are placed on a single multi-layer printed circuit board (PCB) of 36 mm × 15 mm, protected by a metallic Faraday cage with ventilation cutouts. The Faraday shield is additionally covered with a white polytetrafluoroethylene (PTFE) filter to protect the electronics from dust. The total mass of the sensor is only about 15 g. After powering on the sensor, the channel capacitances can be read almost instantaneously. However, after a few seconds, self-heating begins to influence the measurements. Self-heating refers to the increase in a sensor's temperature caused by the electrical current flowing through its circuitry. This temperature rise elevates the sensor's temperature usually a couple of degrees above the ambient environment, thereby affecting relative humidity measurements, since relative humidity is inherently dependent on temperature. Calibration data is typically obtained before the self-heating starts to affect the sensor.

As is typical for space instrumentation, the development of the REMS-H instrument spanned several years and resulted in the delivery of the flight model (FM) and flight spare (FS) in 2008. The flight model was first assembled into the REMS weather station and then integrated onto the Curiosity rover prior to its launch in 2011. At the same time, a ground reference model (RM) was manufactured from the same material and component batches as the FM and FS, but it was kept at FMI for additional on-ground measurements if needed. The RM has consistently shown reliable performance, without any detected functional or calibration issues to date.

The three REMS-H models were calibrated with a two-step process. Relative humidity response 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, two-point calibration was performed in vacuum for dry conditions and in a closed vessel cooled to the dew/frost point at ambient laboratory pressure for wet conditions. Consequently, all original calibration measurements were conducted either in air at ambient pressure or in vacuum, and not under a representative Martian environment.

The development continued for the DREAMS (Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface) station onboard the Schiaparelli lander in the ExoMars 2016 mission [7]. It included a relative humidity sensor DREAMS-H, which was a direct successor to

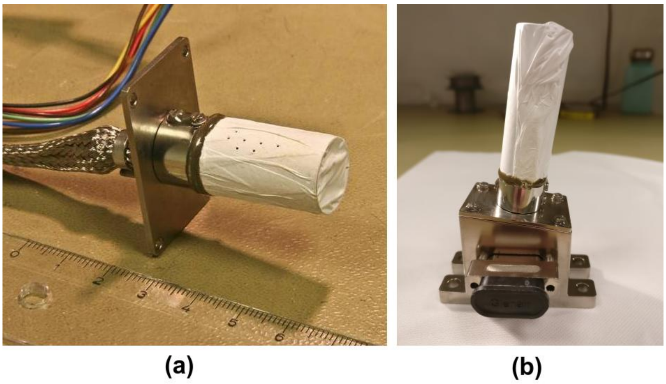

Figure 2.3. (a) REMS-H flight model with a ruler for scale and (b) MEDA HS flight model. The sensors heads have been updated and are mounted on a slightly larger PCB inside the cylindrical shield, with a revised mechanical mounting interface. Credit: FMI

REMS-H with only mechanical changes. The main part of humidity calibration of DREAMS-H flight models was performed at subzero temperatures in a new humidity generator at VTT Technical Research Centre of Finland Ltd, Centre for Metrology MIKES, under ambient-pressure air [14, 51].

2.1.2 MEDA HS onboard Perseverance rover

The MEDA HS instrument (shown in Figure 2.3, right) is a next-generation relative humidity sensor developed for NASA's Mars 2020 Perseverance rover. It is part of the Mars Environmental Dynamic Analyzer (MEDA), a suite of environmental sensors (provided by Spain's Centro de Astrobiología) located on the rover's Remote Sensing Mast (RSM) at a height of 1.5 meters from the ground. Figure 2.4 shows the MEDA HS location on the RSM between the MEDA wind sensor (WS) and the air temperature sensor (ATS). A more detailed description of the HS instrument is given in Publication I.

FMI began developing its next-generation instrument around 2014, eventually leading to the MEDA HS. It uses a new version of HUMICAP sensor heads with the same polymer and operating principle as REMS-H/Curiosity, but with several advantages. It has higher capacitance (45 pF at room temperature) and a considerably larger dynamic range (2.5-3 pF at -70 °C compared to 0.3 pF of REMS-H), improving signal strength and measurement resolution. It also includes an integrated resistive temperature sensor (Pt1000) and a heating resistor. The temperature sensor allows the calculation of humidity values with respect to the actual temperature of each sensing element (approximately 2 x 8 mm^2) instead of the PCB temperature. Similar to REMS-H, MEDA HS also includes a total of eight channels, but this time only two HUMICAP sensor heads instead of three. The mechanical assembly is in general similar to the REMS-H instrument with some modifications to the attachment interface. MEDA HS is slightly

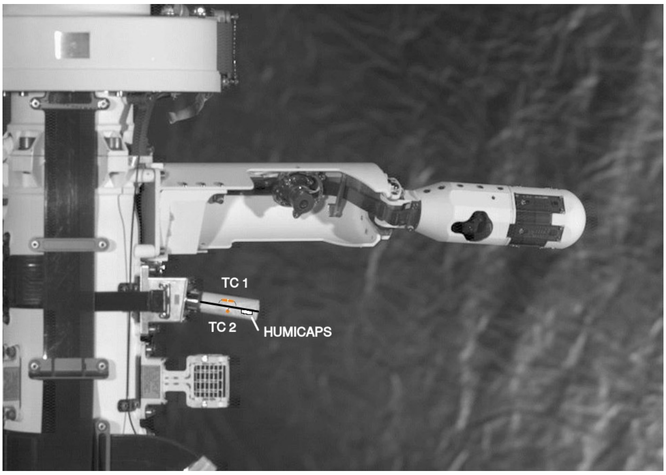

Figure 2.4. MEDA HS mounted on the Remote Sensing Mast of Perseverance. The Figure indicates the PCB orientation inside the cylindrical shield, and the locations of the HUMICAP heads (capacitive humidity sensors that include also platinum resistance thermometers) and the THERMOCAP sensors used to measure PCB temperature. Credit: NASA/JPL-Caltech, adapted by the author.

larger, 55 × 25 × 90 mm^3, with a total mass of 45 g. Power consumption during measurement is around 20 mW.

The model policy of manufacturing the flight model (FM), flight spare (FS), and ground reference model (REF) simultaneously using the same batches of materials and components, was implemented from the beginning. While the FM and FS were delivered for integration in 2018, the REF has remained at FMI and has been used in multiple calibration improvement campaigns since then.

Already before the delivery of the MEDA instruments, a new Martian instrument project, METEO, was launched as part of the ESA–Roscosmos ExoMars 2018 lander. METEO was a meteorological package led by the Space Research Institute of the Russian Academy of Sciences (IKI) and included several European instruments [66]. The mission was first delayed to 2020 and later to 2022, before being suspended and subsequently cancelled by the ESA Council as a result of the Russian invasion of Ukraine, just months before the planned launch. FMI manufactured, calibrated and delivered a humidity instrument called METEO-H, which is an almost identical copy of MEDA HS. The only differences are in the mechanical housing. Also the development and calibration of METEO-H followed the same approach as MEDA HS. Even though METEO-H will not operate on Mars, it has contributed critical information on the characteristics of the new HUMICAP sensor heads, as shown in Publication II.

2.2 Calibration methodology

Calibration of humidity sensors for Martian conditions is a challenging task, and earlier missions Phoenix and Curiosity have shown that incomplete calibration of the flight hardware can lead to significant and difficult post-launch corrections (discussed in [68, 12] and in Publication III). In both cases, additional ground-based testing with reference or engineering models was essential to improve data quality and compensate for limitations in the original calibration. These lessons strongly influenced the approach developed for MEDA HS on the Mars 2020 mission, described more fully in Publication I.

A comprehensive calibration flow (see Figure 2.5) of the MEDA HS instrument incorporated both flight and ground reference models already from the beginning, as had already been proven effective with REMS-H. A central principle of the calibration effort was to subject the flight hardware to test conditions replicating the Martian environment as closely as possible, and supplementing the calibration with more measurement points and additional information by using the REF model as a calibration transfer reference. This extent of calibration measurements of the actual flight model is difficult to obtain due to schedule restrictions, cleanliness requirements, external facility availability and transportation risks.

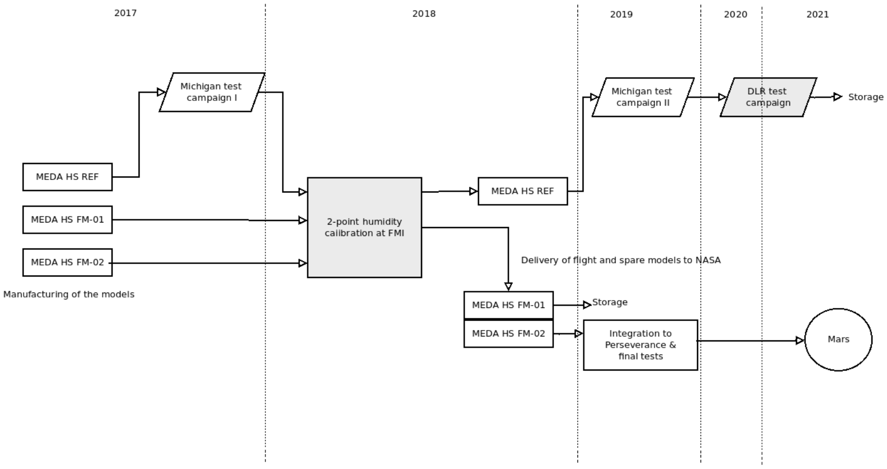

Figure 2.5. Humidity calibration test flow of MEDA HS instruments. The measurements used in the flight calibration are highlighted in grey. The Michigan campaigns yielded important results on sensor time response, but those findings are not directly incorporated into the final data products.

The FM, FS, and REF were tested at FMI simultaneously under various conditions, including Martian pressure and also under high vacuum environments. Both air and CO_2 were used as test gases when appropriate. This initial calibration was limited to dry and saturation humidities resulting in two-point calibration under Martian pressure and the CO_2 environment. A detailed description of the calibration tests is given in Publication I. However, it must be noted that using saturation (100% relative humidity) as a calibration point is not ideal. Near the saturation point, even minor temperature fluctuations can cause condensation on the sensor surface, leading to a nonlinear response, hysteresis and a need for recovery time before reliable results are again achieved.

After the calibration at FMI, the FM and FS were delivered to the Mars 2020 mission for further integration into the MEDA station. The REF was kept at FMI, allowing continued testing in other laboratories, notably the Mars chamber at the University of Michigan and the German Aerospace Center (DLR) in Berlin. The almost identical METEO-H REF was also included in some of the tests to increase the amount of measured sensor heads from the same batch. These additional tests helped improve the calibration, measure the instrument’s time response for the first time, and gather more measurements, including repeated tests and comparisons between different sensor heads.

2.2.1 Test facilities and techniques

Conducting humidity calibration for very low frost-point temperatures is demanding even under standard atmospheric conditions. Specialized facilities are required to simulate Martian conditions, including all relevant environmental parameters that can be accurately controlled and measured: low pressure, low temperature, a carbon dioxide atmosphere, and, in particular, humidity. In fact, one of the main technical contributions of this thesis was the identification of a suitable test facility and technique for calibrating Martian humidity sensors, as detailed in Publication II.

The absolute water vapor content of the air is extremely small, and it makes the generation and stabilization of humidity conditions highly sensitive to leaks and adsorption effects on chamber walls and tubing. Localized effects within the calibration system, such as temperature gradients or adsorption and desorption at surfaces, can lead to inhomogeneities in humidity distribution. Another common problem is also slowness in operation due to the time needed to stabilize the calibration system after changing from one setpoint to another. The more tubing that is used between the reference and the device under calibration the longer the stabilization time. A measurement chamber with a relatively large volume causes even longer stabilization time. The main reason for this slowness is adsorption and desorption processes on the internal surfaces of the calibration setup, which delay the stabilization of humidity conditions.

FMI has a dedicated test laboratory developed for Martian sensor calibration purposes. The humidity sensors are placed inside a small pressure vessel which is connected to a pressure control system which allows both high-vacuum and Martian-range pressure operation with CO_2 supply. The chamber is placed inside a climate test station to allow controlling the temperature down to -70°C. Part or all of the inlet gas is possible to route through a water-filled container in order to increase the humidity inside the vessel, but there is no accurate control or reference measurement of the RH available. Therefore the measurements at FMI were limited to high-vacuum, dry-CO_2 and saturation-CO_2 measurements.

Additional tests were performed at University of Michigan and at the DLR Institute of Planetary Research PASLAB (Planetary Analog Simulation Laboratory) in Berlin. The Michigan Mars Environmental Chamber (MMEC) [11] 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 but the surrounding shroud is not thermally controlled. The MMEC is capable of simulating temperatures ranging from 145 K to 500 K, CO_2 pressures from 10 to 105 Pa, and relative humidity from nearly 0 to 100%. Water vapor is added to the chamber through a temperature and pressure-controlled H_2O bath, which enables rapid increases in relative humidity, in contrast to the more slowly changing and stabilizing conditions available at FMI and DLR. Although the large temperature gradients inside the chamber made stable calibration measurements difficult, the setup made it possible to test the humidity sensors' time response under rapidly changing humidity conditions. The results from the MMEC test campaigns are presented in Publication I and Publication III.

The DLR PASLAB is a facility used for humidity sensor studies as well as habitability-related experiments under Martian conditions [32, 34, 36]. The calibration setup consisted of a measurement chamber housed within a temperature test station. The chamber was connected to a gas mixing system and a controllable vacuum pump. All three ground reference models, REMS-H, MEDA HS, and METEO-H, were fitted simultaneously in the calibration chamber. Dry CO_2 gas was mixed with precisely humidified gas using mass flow controllers in the gas mixing system. The resulting gas mixture, with a well-defined water content, was then routed to the measurement chamber and the reference humidity sensor. The reference measurement was performed with a precision dew-point mirror MBW 373LX. The calibration campaign and equipment are described in detail in Publication II. To summarize, calibration data were recorded in CO_2 gas at multiple stable temperatures and across different Martian pressure levels, ranging from 5.5 to 9.8 hPa. 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 obtained, with the highest RH recorded at 97%. The calibration data obtained from the DLR PASLAB campaign were used to supplement the MEDA HS flight calibration and to establish a revised calibration for REMS-H.

2.2.2 Data processing

Relative humidity (RH), the main data product from the sensors in this study, is a measure of how much water vapor is present in the air compared to the maximum amount that the air can hold at a given temperature. A relative humidity of 100% indicates saturation, where condensation or frost may form, while lower values correspond to drier conditions. It is expressed as a percentage:

$$RH = \frac{e}{e_s} * 100\%, \tag{2.1}$$

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 work is mostly calculated with respect to ice, because the temperatures are typically below 0°C.

The humidity sensor electronics are based on an oscillator transducer that converts the capacitive sensor outputs into frequency signals. In the nominal measurement mode, all eight channels are scanned once per second. After powering on, the sensor readings become reliable within approximately one second, so the first measurement cycle data is discarded. During calibration, the raw capacitances are measured under known temperature and relative humidity conditions to establish the relationship between sensor output and environmental conditions. An example of a measured capacitance corresponding to the calibration environment is shown in Figure 2.6.

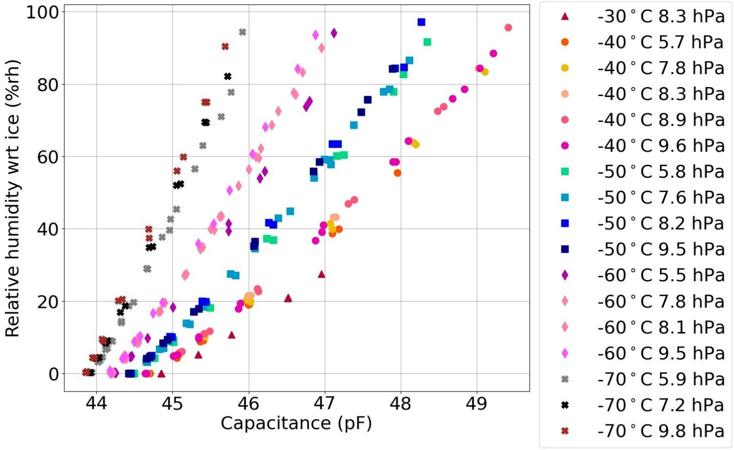

Figure 2.6. Calibration data points that were obtained during the campaign at DLR of one MEDA HS sensor head. Different colors represent different temperatures and pressures, which are also listed in the legend. Capacitance is a raw value calculated from the sensor frequencies. Relative humidity, on the y-axis, is calculated from the reference frost point temperature, sensor temperature and chamber pressure. Created by Iina Jaakonaho.

The strong temperature dependence observed is well known for capacitive polymer sensors and is typically characterized empirically [58]. Both the polymer dielectric properties and water adsorption and desorption kinetics are temperature dependent. The new calibration data also revealed a pressure dependence under Martian conditions, which needs to be addressed in sensor calibration. For MEDA HS, the advanced calibration compensation includes atmospheric pressure (Publication I), whereas REMS-H calibration is currently calculated from calibration data measured at 7-8 hPa, without pressure dependence included. Additional calibration data are required to constrain the pressure cross sensitivity more accurately, without introducing overfitting in the calibration model.

After obtaining the calibration data, the first second of each measurement was discarded, and the data from seconds 2 through 5 were averaged to obtain the most accurate value for each channel. For each temperature, a second-degree polynomial was fitted to the measured values corresponding to relative humidity. From the resulting polynomial, the raw-signal values corresponding to the 0% RH and 100% RH limits were identified. These intersection points were then used to construct the sensor-specific dry (0% RH) and wet (100% RH) reference curves as functions of the HUMICAP capacitance (pF) and sensor temperature (°C).

The following function was fitted to the interpolated dry points:

$$C_{dry}(T_{TC}) = a_d T_{TC}^2 + b_d T_{TC} + c_d, \tag{2.2}$$

where T_{TC} is the sensor temperature in °C, C_{dry} is capacitance at 0% RH and a_d,b_d and c_d are calibration coefficients.

The measurements in very dry conditions typically show lower variance and appear to be more precise, reflecting smaller uncertainty in the sensor response. In contrast, the wet measurements, particularly at very high humidity levels, are sparser and show greater dispersion around the fitted curve. Therefore, determining the optimal fit for the 100% RH curve is more challenging. The best fit for the saturation curve $C_{wet}(T_{TC})$, where C_{wet} is capacitance at 100% RH, differed slightly between the sensor generations. MEDA HS calibration used a linear function and for REMS-H the best fit was found to be a second-degree polynomial curve. The flight model calibration coefficients for MEDA HS are given in Publication I and for REMS-H in Publication III.

A scaled capacitance (C_{scaled}), a dimensionless value between 0 and 1) was then calculated using 100% and 0% curves to represent the range of the capacitance at each temperature:

$$C_{scaled}(T_{TC}) = \frac{C - C_{dry}(T_{TC})}{C_{wet}(T_{TC}) - C_{dry}(T_{TC})} \tag{2.3}$$

The scaled capacitance is used to determine the response of the sensor heads between dry and saturation. Under ambient room conditions the response would be very close to linear, but the Martian environment slightly changes the behavior.

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

$$RH = a_f C_{scaled}^2 + b_f C_{scaled} + c_f \tag{2.4}$$

In addition to relative humidity, water vapor volume mixing ratio (VMR) in ppm can also be derived from relative humidity, the sensor temperature and atmospheric pressure. The VMR tells us how much water vapor there is in the atmosphere compared to other gases, independent of temperature. It is particularly important for comparing water content across locations and times, and for atmospheric modeling. In order to calculate the VMR, first the saturation water vapor pressure over ice e_s (hPa) at temperature T is calculated using equation (2.5), the 1996 revision of the Arden Buck equation [3]:

$$e_{s,ice} = 6.1115 \exp((23.036 - \frac{T}{333.7})(\frac{T}{279.82 + T})) \tag{2.5}$$

The actual water vapor pressure e is obtained from equation (2.1), and finally the VMR in ppm at ambient atmospheric pressure p can be calculated from equation:

$$vmr = e * 10^6/(p - e) \tag{2.6}$$

When relative humidity is very low, even small errors in the RH measurement lead to very large relative errors. For example, if RH is 2%, the uncertainty is ±1.6%, which means a relative error of ±80%. This large error directly affects the calculation of the volume mixing ratio (VMR), making it far less precise at low RH levels. The measurement uncertainty can become larger than the actual measured value. For MEDA HS, the derived VMR is provided when the RH $>$2.5%. In the recalibrated REMS-H dataset, the VMR calculation has been limited to nighttime hours 23 to 06 LMST.

The calibrated data returned from the surface of Mars by both REMS-H and MEDA HS are available in NASA's Planetary Data System (PDS) [49, 15], except for the reprocessed dataset of REMS-H. It will be added in a future PSD release, but it is currently available only in FMI's METIS repository [25]. The PDS is an open-access archive that systematically collects, curates and distributes scientific data from different planetary missions. Several datasets with different levels of data handling are available both of REMS and MEDA data. The recommended MEDA HS dataset for almost all users is the derived data, which includes the calibrated local relative humidity (average of the two sensor heads) in %, the uncertainty of local relative humidity in % RH, the calibrated sensor (HUMICAP) temperature in Kelvin, the uncertainty of local temperature in Kelvin, volume mixing ratio (VMR) in ppm and VMR uncertainty. The recommended REMS-H dataset is the

REMS MODRDR data, which contains similarly the calibrated local relative humidity in %, the sensor PCB temperature in Kelvin, the uncertainty of local relative humidity in % RH, volume mixing ratio (VMR) in ppm and the VMR uncertainty.

”Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time.”
—Akin’s Laws of Spacecraft Design

3. Results and discussion

This section summarizes the main results of the thesis, and is organized into four topics. Section 3.1 presents the assessment of sensor performance after landing on Mars, as reported in Publication I. Section 3.2 summarizes and discusses the recalibration effort and the revised results of the REMS-H instrument, as documented in Publication III. Section 3.3 presents an overview of the performance and uncertainty of both sensors, combining information reported in Publications I—III. Section 3.4 presents simultaneous measurements from different locations on Mars, included in Publication III. These results demonstrate a new aspect enabled by this work, namely the potential for future studies to compare datasets from multiple locations using simultaneous measurements of two instruments with matching observation schemes and comparable calibration.

3.1 Observations and calibration assessment of MEDA HS

On February 18, 2021, the Perseverance rover successfully landed on Mars, carrying the MEDA HS as part of its environmental sensor suite. The landing day is defined as sol 0 of the Perseverance rover mission. The First measurements from MEDA were taken on the day after landing, and regular around-the-clock measurements started around sol 15. Each subsequent sol corresponds to one Martian day. A Martian day, or sol, lasts about 24 hours, 39 minutes and 35 seconds. All measurements are referenced to Local Mean Solar Time (LMST), which is the time at the landing site based on the Sun's mean position in the sky. LMST divides the sol into 24 hours, each slightly longer than an Earth hour. The MEDA instrument suite typically performs sensor measurements in 1-hour blocks, alternating every sol between even and odd hours. This observation strategy provides complete coverage of one full diurnal cycle every other sol. The HS has two operational modes: a high-resolution interval mode (HRIM) and a continuous mode. The HRIM has been developed to avoid the sensor self-heating in order to provide the most accurate measurements. In HRIM the HS is powered on only for 10 seconds and then powered off for 5 or 15 minutes before the next measurement. Switching the instrument on and off requires sending multiple commands from the MEDA instrument control unit, which has a limited number of commands. Therefore, the HRIM cannot be used for all HS measurements but must be alternated with the continuous mode. In continuous mode, the sensor stays powered on for longer periods, typically in 1-hour blocks following the MEDA instrument measurement sequence. At the beginning of a continuous measurement block, the sensor self-heating is prominent for about 15–20 minutes before the sensor temperature reaches equilibrium with the ambient temperature and stabilizes.

Although self-heating inherently influences the relative humidity readings, in an ideal scenario the derived absolute volume mixing ratio (VMR) should remain unchanged before and after self-heating if the ambient conditions are stable. Under such circumstances, the relative humidity sensor data could be used directly after the self-heating phase without corrections to the current calibration. This assumption was evaluated using the MEDA HS ground reference model at the DLR PASLAB, and the results were reported in Publication II. Two tests at -60°C in an 8 hPa CO_2 environment were performed at different relative humidity levels, 9% and 38%. During the self-heating period, the VMR measured by the MEDA HS first rises above the reference level, and then drops below the reference before finally stabilizing slightly above the reference VMR. The most likely explanation for this behavior is small temperature gradients that develop in the PCB electronics during the self-heating. Although clear differences to the reference value were observed, they were negligible compared to the instrument uncertainty, suggesting that the instruments can be operated continuously while relying on the current calibration, with no additional corrections required.

A reduced thermal model could be used to further investigate these self-heating effects and to help identify the physical source of the transient behavior. A model which correctly represents the effect could be used to generalize the behavior when conditions such as airflow or temperature change. Ultimately, the most effective way to mitigate self-heating effects is at the instrument design level: the RH sensing element should ideally be thermally decoupled from heat sources, including power-dissipating electronics.

Finally, since the test was conducted at only one temperature and at two relative humidity levels, the results cannot yet be considered conclusive, and while the continuous mode data is included in the PDS dataset, no uncertainty is provided after the initial 10 seconds of measurements.

Figure 3.1 presents an example of temperature and relative humidity measurements during one Martian day. The maximum relative humidity occurs in the early morning hours when the atmospheric temperature is at its lowest. During the daytime, relative humidity always drops to near zero. Although this confirms very dry conditions, the exact values cannot

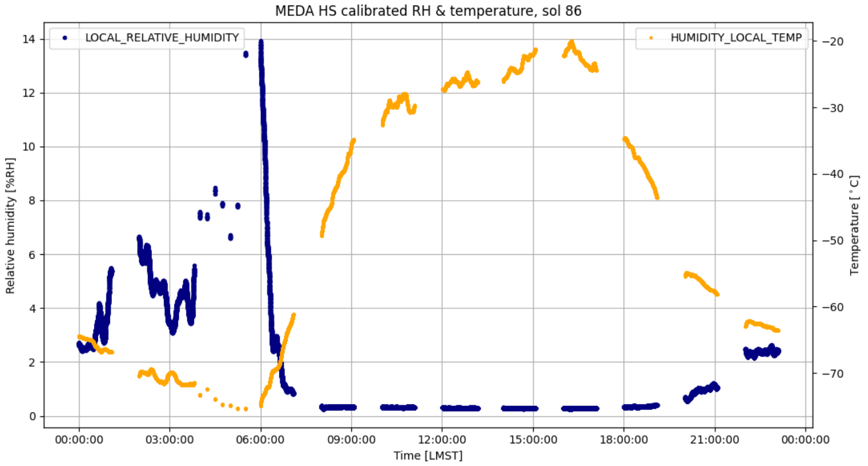

Figure 3.1. MEDA HS measurements of temperature (orange) and relative humidity (blue) over a typical Martian day. During the daytime, relative humidity is close to 0% but starts rising as the temperature drops. In this example, the lowest nighttime temperature was about -75°C, with relative humidity increasing to around 14% before falling again as the Sun rose. The continuous, long measurements show signs of self-heating of the sensor while the point-like measurements have been acquired by powering on the HS for only 10 seconds. Created by Iina Jaakonaho.

be determined reliably, as they fall below the measurement uncertainty. This is an expected result for capacitive humidity sensors and does not indicate a problem with the calibration. Periodic regeneration heating to restore sensor performance and remove any contaminants from the sensor heads was performed successfully on sols 63 and 74, and a clear change in relative humidity values was observed in the data. This change may indicate removal of contaminants or simply a return to the original sensor condition following launch, the lengthy interplanetary cruise and landing phases. Therefore, while the HS data is available from sol 64 onward, the recommendation is to not use the data before sol 80 for scientific purposes.

The first 200 sols of the Perseverance mission at Jezero crater are examined in Publication I, and the work has continued beyond that period. A subsequent publication [46] provides the initial scientific results and operations description up to sol 410, and [47] analyzes the annual and diurnal water cycles during the first 1000 sols. Calibration accuracy has been analysed in detail, but the absolute accuracy of the measurements on Mars cannot be directly determined because there is no independent reference instrument or traceable standard on the Martian surface. Nevertheless, measurements from three independent calibration facilities (FMI, DLR and MMEC) are mutually consistent, no calibration adjustments based on Mars data were required, and the MEDA HS humidity cycle measurements follow the predicted diurnal pattern. Overall, the instrument has provided high-quality data, with performance matching expectations.

3.2 Recalibration of REMS-H and results

Since the landing of the Curiosity rover on 6 August 2012, REMS-H has been collecting the longest-running record of near-surface humidity ever measured on Mars. As of November 2025, the instrument has been operating for more than 13 years. The very first nighttime measurements on Mars after landing however revealed an unexpected issue with the humidity measurements. The measured capacitances of all three humidity sensor heads fell outside the expected calibration range, and the difference to the expected dry values was increasing toward colder temperatures. No explanation was found at the time, and the effect was referred to as an unknown transducer electronics artifact [19]. A correction was developed to eliminate negative relative humidity values, but no physical explanation for the phenomenon was identified. It was only years later that it was discovered that the most likely explanation was the low-pressure carbon dioxide environment of the Martian atmosphere. New calibration measurements, presented in Publication II and performed under a more representative Martian analog environment, enabled a re-evaluation of the current REMS-H calibration, leading to a revised calibration and the updated results reported in Publication III.

This new dataset, obtained using an identical ground reference model of the instrument, allowed correction of two key aspects of the calibration: (i) the relative humidity response function between 0% and 100% and (ii) the dynamic range of the sensor in low-pressure CO_2 environment, compared to previous calibration in ambient-pressure air. The dynamic range of the sensor heads turned out to be smaller than expected, especially below -40°C, and the response curve form is somewhat different than obtained before. Due to the very similar behavior of the flight, the spare and the ground reference models, it is possible to transfer the calibration information to the flight model using the measured offset difference between the instruments under vacuum. The calibration covers the full humidity range at temperatures from -70°C to -40°C, and up to about 30% RH at -30°C. Below -70°C the calibration curves are extrapolated and the calibration uncertainty is larger.

Although the updated calibration was specifically tuned for the REMS-H model on Mars, upon application to Mars in situ data, it was noted that the newly calibrated values did not fall within the expected range. The measured capacitances had been lower than expected since the landing, so this behavior has been present already before, possibly since the prelaunch tests. Further investigation showed that there is also slow drifting in capacitance values over a long time period. The dry daytime capacitances, approximately above -40°C, can quite reliably be used to correct for the offset-type drift in the capacitances because there is no significant variability in the relative humidity. A detailed investigation revealed also another feature

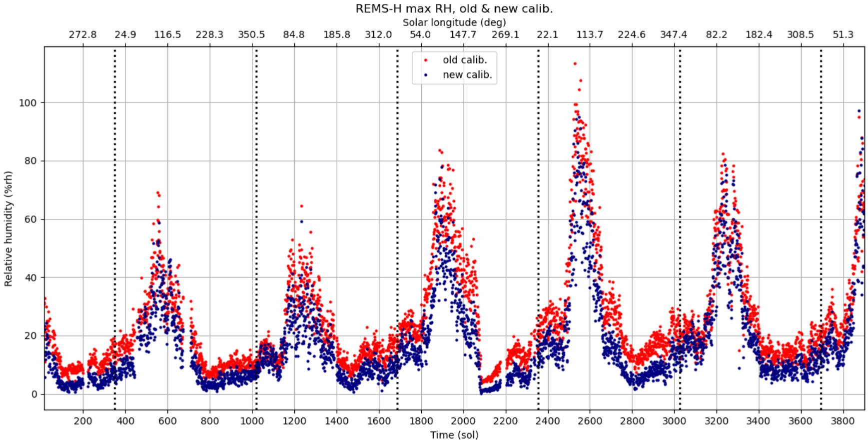

Figure 3.2. Maximum RH of each sol (typically measured during nighttime) with old (red) and new (blue) calibration from sol 15 and up to sol 3900 (relative to the sensor's internal temperature and not the atmospheric temperature). On average the new calibration produces about 10% RH lower relative humidities, although the difference varies. Vertical lines mark the Martian years starting from MY 31 at the time of landing and reaching up to MY 37. Created by Iina Jaakonaho.

in the daytime dry values. The dry capacitance changes over shorter time periods were irregular due to regeneration heating, affecting the sensor heads for at least one sol after the regeneration. REMS-H was regenerated more often than MEDA HS, approximately every 10 sols compared to a 180-sol interval of MEDA HS. The constant regenerations were stopped at sol 3280, after which only a simple offset correction for the drift is enough. Sols prior to 3280 need a more complicated correction averaging every 10 sols to obtain a slope for dry capacitances. Details about the correction are given in Publication III. Eventually, while correction remained necessary for REMS-H despite the revised calibration, it was reduced in magnitude and complexity, and was calculated specifically for each sol.

The updated calibration produces lower relative humidity values compared to the previous calibration. This can be seen in Figure 3.2, which shows a comparison of the old and revised maximum measured relative humidity of each sol, typically in the early morning. The most notable differences are seen during conditions of high humidity. On average, the new calibration produces about 10% RH lower humidities, but there are variations between sols and the difference is not a simple offset. It is important to note that the relative humidity measured by the sensor is related to the sensor's internal temperature and not the atmospheric temperature. The difference to the temperature of the atmosphere varies depending on current environmental conditions, but it can be several degrees. The temperature difference is not straightforward to determine, because the temperature is measured using instruments that have their own limitations, such as time lags and

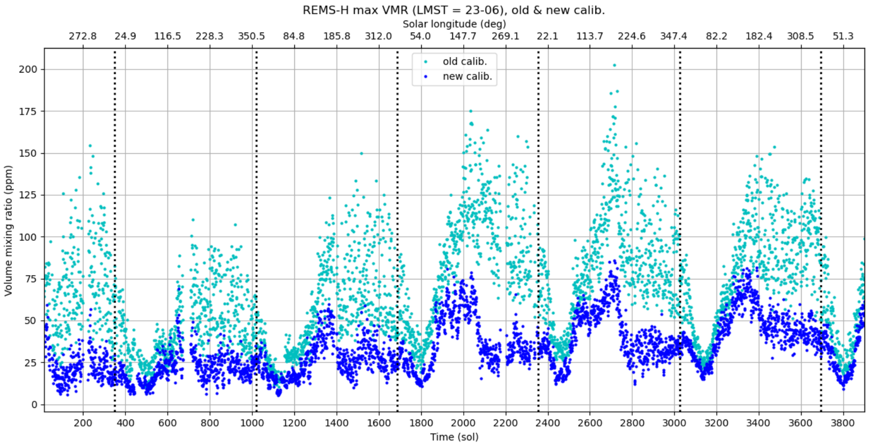

Figure 3.3. Highest daily VMR with old (cyan) and new (blue) calibration between 23 to 06 LMST (Local Mean Solar Time) from sol 15 and up to sol 3900. Daytime VMRs cannot be derived with reasonable uncertainties. Vertical lines mark the Martian years starting from MY 31 at the time of landing and reaching up to MY 37. Created by Iina Jaakonaho.

sensitivity to heat plumes from the rover's Radioisotope Thermal Generator (RTG) [17].

The water vapor mixing ratio often shows larger discrepancies between the old and new calibrations, as can be seen in Figure 3.3. The revised calibration produces lower VMR levels and also alters the shape of the seasonal water maximums. For example, in MY 34 around sol 2100, a sharp drop in the VMR is visible following the global dust storm, whereas the old calibration produces persistently high VMRs during and after the event. The largest difference, about 100 ppm, occurs at the time of the dust storm and may be linked to elevated atmospheric temperatures and larger calibration correction at those conditions. The differences between the old and the new values are small in an absolute sense, usually between 20 and 60 ppm, but on many occasions it is larger than the newly derived value.

The revised data align REMS-H observations more closely with orbital observations and atmospheric modeling, as shown in Publication III, demonstrating that the recalibration was successful. Although uncertainties remain, overall it provides a more accurate characterization of the humidity environment at Gale Crater.

"Sometimes, the fastest way to get to the end is to throw everything out and start over."

—Akin's Laws of Spacecraft Design

3.3 Performance and uncertainty of humidity sensors

The MEDA HS performance was analysed in Publication I. The accuracy requirement for the HS was set at better than ±10% RH for temperatures above -70°C and equal to or better than ±20% RH down to the mission-defined lower limit of -83°C (190 K). A detailed calibration and measurement uncertainty analysis, performed in collaboration with VTT MIKES, identified that the main uncertainty contribution is the non-linearity represented by the residuals of the calibration curve fitting. Other factors include the uncertainty of the temperature sensors, the calibration reference measurements, and the transfer of calibration information from the ground reference model to the flight model. In addition, a compensation model was developed by VTT MIKES [62] to minimize the fitting residuals and further reduce the level of uncertainty. After applying the compensation model, the expanded uncertainty (k=2) in the measurement of relative humidity of the HS is below ±4.5% RH for temperatures above -70°C, and equal to or better than ±6% RH down to -83°C. The uncertainty depends primarily on the measured humidity: lower relative humidities have smaller uncertainties. For example, at a measured humidity of 1%, the associated uncertainty is below ±0.8% RH. Since the calibration data are available only down to -70°C, additional uncertainty propagated by extrapolation below that was quantified using an adaptive Monte Carlo method. Mars data analyses indicate that the sensor exhibits a repeatability of 0.02% RH, based on stable single-day measurements, and a reproducibility of 0.14% RH over ten days under dry daytime conditions with temperatures above -40°C. Hysteresis of the sensor is negligible compared to the other uncertainties. The expanded uncertainties of the temperature measurements (k=2) range from 240 mK at -80°C to 120 mK at -20°C, with cross-checks against THERMOCAP sensors confirming no significant offsets on Mars.

The performance of REMS-H was originally analysed and presented in [19]. Following the calibration revision described in Publication III, the performance of REMS-H was also re-evaluated. While the revised calibration adjusted the REMS-H readings to more accurately represent the real environment, it did not significantly reduce the uncertainty. A comprehensive quantitative analysis, as performed for the MEDA HS instrument, could not be reliably conducted for the REMS-H flight model due to the numerous unknowns associated with its anomalies. The revised 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 gradually rises from ±1% RH at 0% RH to ±4% RH at 10% RH and up to ±10% RH at 100% RH. Below -70°C, the uncertainties are larger, ranging from ±2% RH at 0% RH to ±6% RH at 10% RH and up to ±20% RH at 100% RH.

The calculation of the VMR uncertainty is performed by combining the contributing uncertainties of RH, sensor temperature and the atmospheric pressure as shown in [46]. The VMR uncertainty is dominated by the relative humidity measurement uncertainty, such that when RH approaches 0%, even small absolute errors in RH result in very large relative errors. In such cases, the VMR uncertainty can become so large that the calculated value is no longer scientifically meaningful and must be evaluated on a case-by-case basis. The uncertainties are included in the instrument datasets in the Planetary Data System (PDS).

3.4 Comparison of relative humidity datasets from Gale and Jezero craters

Although located at different sites on the Martian surface, the MEDA HS and REMS-H sensors are operating simultaneously, and comparisons between the two instruments can provide valuable insights. Publication III includes an overall comparison of the simultaneous measurements of MEDA HS and REMS-H from Mars year 36, with further analyses and additional scientific results anticipated in future from these datasets.

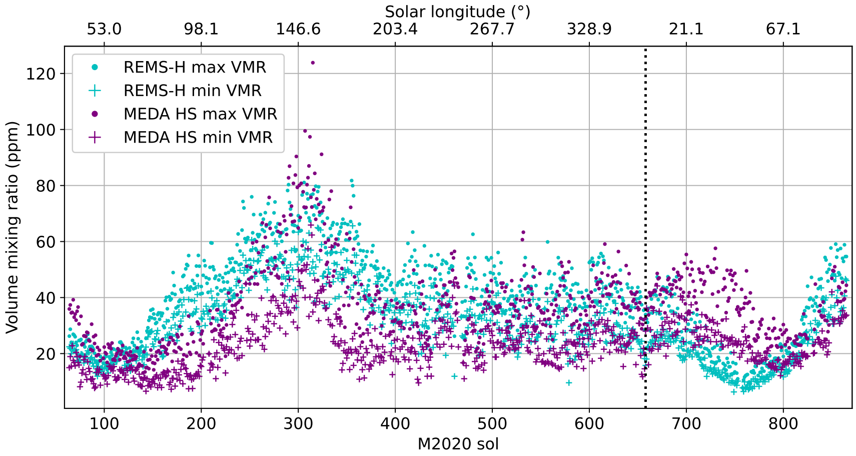

Figure 3.4. Maximum and minimum daily VMR derived from REMS-H (cyan) and MEDA HS (purple) measurements. Created by Iina Jaakonaho.

Both instruments show large seasonal and daily variation in relative humidity ranging from close to 0% and reaching 100% on some occasions. The main difference in the RH data is due to the instruments being located in different hemispheres: MEDA HS onboard Perseverance in Jezero Crater in the northern hemisphere, and REMS-H onboard Curiosity in Gale Crater in the southern hemisphere, although both sites are relatively close to the equator. The seasonal peak in relative humidity does not occur simultaneously at the two sensors since it 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 MY 36 values of the minimum and maximum VMR are instead rather similar as seen in Figure 3.4. Interestingly, the increase toward the VMR peak at around L_s 150° (M2020 sol approx. 300) appears to be stronger at Gale, contrary to the expectation based on Mars Climate Database (MCD) data.

The assessment confirms that the MEDA HS and REMS-H datasets are directly comparable, as the instruments employ the same measurement technology and similar acquisition schemes. This comparability enables future studies to investigate both local differences and similarities between the two landing sites, as well as to explore larger-scale Martian atmospheric phenomena, such as the seasonal moisture peak.

> *”Engineering is done with numbers. Analysis without numbers is only an opinion.”*
>
> —Akin’s Laws of Spacecraft Design

4. Summary and conclusions

This dissertation represents a significant leap forward in our ability to measure, understand and model the near-surface atmospheric humidity on Mars. Fundamentally, atmospheric analysis and prediction rely on complex physical models that describe how atmospheric variables change over space and time. These models require observations that are globally distributed and collected over long periods. On Mars, in-situ surface measurements provide the essential high-accuracy data, supported by orbital observations that offer broad spatial coverage even though they are less precise. Surface measurements are therefore indispensable: they deliver the detailed information needed to test and improve atmospheric models and act as ground truth for interpreting orbital data. A key contribution of this dissertation is the provision of improved surface-level atmospheric humidity observations spanning several Martian years.

The REMS-H and MEDA HS instruments have together provided the most extensive and reliable in situ record of near-surface relative humidity of the Martian atmosphere. REMS-H, operating on the Curiosity rover since 2012, now constitutes the longest-running humidity record from the Martian surface. New calibration measurements were performed using a reference instrument identical to the one flown on Mars. These measurements, conducted under realistic Martian analogue conditions at DLR's Planetary Analogue Simulation Laboratory, has enabled a re-evaluation of the REMS-H calibration. This resulted in a revised dataset of the REMS-H Martian in situ observations, which seems to improve the agreement of modeling results and orbital observations with the ground truth given by in situ surface observations. Based on the experience gained from REMS-H and DREAMS-H development and their previous calibration, the flight calibration for MEDA HS on Perseverance was planned and executed, which resulted in reduced measurement uncertainty and robust performance on Mars. The Martian analog measurements demonstrate that sensor response is affected by the extremely cold, the low-pressure CO_2 atmosphere of Mars and that these effects must be incorporated into future sensor calibration tests. The improved accuracy and reliability of such in situ humidity data provides a robust foundation for future Martian atmospheric and surface research and exploration.

The three principal research questions introduced at the beginning of this dissertation constituted the overarching framework that guided the entire work. Subsequently, the findings of the research investigation can be discussed in relation to these questions as follows:

1. *How can relative humidity sensors be accurately and reliably calibrated for the extreme conditions of the Martian atmosphere?*
   Accurate and reliable calibration of relative humidity sensors for the Martian atmosphere requires that the calibration is performed in an environment that is representative of the Mars operational regime. Only under such conditions can the relevant factors influencing the sensor response be characterized. For relative humidity measurements specifically, the temperatures of the test setup, the reference gauge, and the device under test must all be precisely controlled and recorded. In this work, the relative humidity sensor MEDA HS onboard Perseverance was calibrated under low temperatures, low pressure, and in a carbon dioxide environment. A ground reference model, identical to the flight sensors, allowed extended calibration campaigns beyond the flight schedule. Calibration was performed both at FMI and at DLR PASLAB. The final flight calibration of MEDA HS is based on FMI two-point calibration and extended PASLAB measurements, resulting in more accurate calibration than would have been possible with two-point calibration alone. MEDA HS has been calibrated over the full humidity range at temperatures from -70°C to -40°C, and up to 30% RH at -30°C, with extrapolation down to -83°C. Measurements were performed mainly in Martian-pressure CO_2, however Mars-like gas mixture was also tested. In addition to reproducing the Martian environment during calibration, the calibration methodology must also account for long-term drift, and provide mechanisms to verify performance stability during operations. The near-zero humidities during the Martian day provide a handy reference level to detect any long-term drift, and regeneration can be used as needed to restore the sensor performance.

   Therefore, RH sensors can be accurately and reliably calibrated for Mars by reproducing the relevant Martian environment, by obtaining sufficiently high-density calibration data over that domain to constrain the sensor transfer function, and by implementing validation methods in-flight to detect drift and monitor sensor performance.

2. *To what extent does the pre-flight calibration of the MEDA HS instrument translate to accurate in situ measurements on Mars?*
   The pre-flight calibration of MEDA HS, as described above in relation to the first research question, has effectively resulted in improved accuracy

of the in situ measurements on Mars. Initial surface measurements are consistent with expectations based on the calibration and environmental models, and no post-flight calibration corrections have been required. Verification was performed by examining sensor behavior under near-zero daytime humidities and across the diurnal temperature range, and no unphysical measurement results have been observed. While the full operational range continues to be monitored, these initial results demonstrate that the pre-flight calibration reliably produces physically consistent and accurate measurements under Martian conditions. Therefore, the pre-flight calibration can be considered successful in translating to in situ performance, with ongoing monitoring ensuring that any drift or deviations can be detected and addressed if needed.

3. *How do the revised calibration methodologies improve the scientific value and reliability of the MSL/REMS-H dataset from Mars?*

The revised calibration methodologies significantly improve both the accuracy and reliability of the MSL/REMS-H dataset. By performing laboratory measurements under simulated Martian conditions, the recalibration addresses limitations of the original pre-flight calibration, which was not conducted under fully representative environmental conditions. The updated calibration allowed correction of the sensor response across the full 0–100% relative humidity range and the sensor's dynamic range in CO_2. These improvements also lead to more accurate estimates of the derived water vapor mixing ratio (VMR), particularly during the early night hours, where the original calibration tended to overestimate values. Validation against independent observations and atmospheric modeling shows that the recalibrated dataset aligns more closely with orbital data and model predictions, further confirming its reliability. In summary, the revised calibration enhances the scientific value of the REMS-H dataset by providing more accurate and physically consistent measurements of relative humidity and the VMR, increasing confidence for subsequent scientific analyses.

4.1 Future pathways

Despite the advances in Martian in situ relative humidity measurements presented in this work, measuring accurately the full diurnal humidity cycle remains beyond current capabilities due to limitations in sensor technology. The near-zero humidities present during the Martian daytime are not measurable with typical capacitive humidity sensors, as even high-precision instruments have an accuracy of approximately 1% RH. One possibility to improve the accuracy at very low humidities could be to use Vaisala's DRYCAP® technology which adds an auto-calibration function to the capacitive sensors to optimize the measurements in dry environments [64]. The DRYCAP could be used to measure also during daytime when the RH is below 1%, but most likely the relative errors in RH would still remain large. Preliminary measurements of a DRYCAP-based dew point transmitter have been performed at FMI under vacuum conditions, but further investigation is needed.

The capacitive sensor technology could also be combined with another sensor type to measure also the trace humidity conditions below 3% RH, as was already proposed for the ExoMars mission [29]. A coulometric measurement principle has been investigated for Mars use at DLR Institute for Planetary Research [35, 13]. It works by using diphosphorpentoxide (P_2O_5), a material that strongly absorbs water vapor from the environment. The sensor has two electrodes coated with P_2O_5, and when a small voltage is applied, an electrolysis reaction occurs in the absorbed water. The resulting current is directly proportional to the amount of water present, allowing the sensor to measure very low humidity levels with high sensitivity. These coulometric sensors have so far demonstrated the capability of measuring humidity accurately in the temperature range -20 to 20°C at atmospheric pressure and in CO_2, and Martian pressure range experiments are planned.

A comprehensive understanding of the Martian atmosphere requires simultaneous observations from multiple locations. While the data provided by MEDA and REMS instrument suites have significantly advanced knowledge of Martian near-surface weather including humidity, they represent only two points of measurement on a planet with complex atmospheric dynamics. Many key atmospheric processes, such as circulation patterns, boundary layer dynamics, and seasonal dust and water cycles, operate across spatial and temporal scales that cannot be fully captured by observations from a single station. Because MEDA HS and REMS-H use similar sensor technology and measurement schemes, their datasets are directly comparable. This enables the study of both local atmospheric differences and shared large-scale phenomena, as demonstrated in this work through comparisons between the two landing sites. Such analyses highlight the scientific potential of simultaneous measurements from multiple locations, coordinated to provide a more complete picture of Martian atmospheric

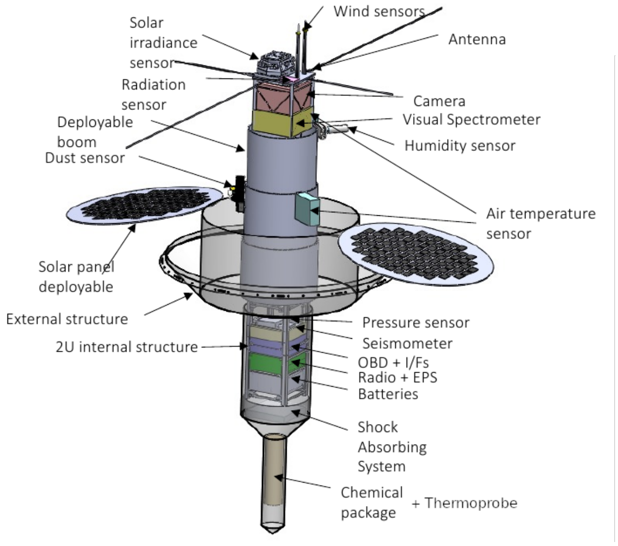

Figure 4.1. Proposed Mars In-Situ Sensors (MINS) lander payload, including also the atmospheric humidity sensor. Credit: AVS/MiniPINS team.

processes.

To resolve the full complexity of Martian atmospheric behavior, a network of surface stations across different latitudes, terrains and elevations has been widely considered by the scientific community [5, 18, 43, 21, 48, 45]. A weather station network was also highlighted in the European Space Agency's Terrae Novae 2030+ Strategy Roadmap [9]. A distributed system of sensors would allow investigations of atmospheric circulation patterns, boundary layer phenomena, and water and dust cycles. Such a network, potentially consisting of several tens of small landers, could be implemented using compact units, allowing many to be delivered to Mars with only a few launches. The Finnish Meteorological Institute has contributed to the design and development of small lander network missions [20, 21, 22], as well as to future mission concepts such as MiniPINS [10]. The MiniPINS Mars lander with its scientific payload is illustrated in Figure 4.1. Similar efforts toward developing a distributed meteorological lander network are ongoing elsewhere [1, 8, 2].

Looking forward, the realization of a Martian weather network would mark a major milestone in planetary exploration. By providing continuous, high-resolution environmental measurements across the planet, such a system would transform our understanding of Mars' atmosphere, climate dynamics, and dust and water cycles. With technological development and coordinated international efforts, the deployment of a Martian meteorological network is becoming increasingly feasible, bringing this long-envisioned scientific goal closer to realization.

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