INTERNATIONAL MARS ICE MAPPER MISSION

Reconnaissance / Science Measurement Definition Team

ADDENDUM

INSTRUMENT DEFINITION TEAMS

VHF SOUNDER HIGH-RESOLUTION IMAGER SUBMILLIMETER SOUNDER

SUBMITTED TO
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1 FORWARD

> This report is an addendum to the I-MIM Reconnaissance/Science Measurement Definition Team (2022).

1.1 OVERVIEW FROM THE I-MIM PARTNER AGENCIES

Under a joint Statement of Intent (January, 2021), the Agenzia Spaziale Italiana (ASI), the Canadian Space Agency (CSA), the Japan Aerospace Exploration Agency (JAXA), and the National Aeronautics and Space Administration (NASA), hereinafter "the Agencies," formed a Concept Team to assess the potential of an International Mars Ice Mapper (I-MIM) mission. As part of this collaboration, the Agencies competitively selected an international, multidisciplinary Measurement Definition Team (MDT). The MDT produced a final report (2022), which can be accessed at: https://go.nasa.gov/imim_mdt

Based on the MDT findings, the release of the US Planetary Science and Astrobiology Decadal Survey (2022), and evolving partner Agency strategies, the Agency partners agreed to continue their collaboration through a follow-on I-MIM Concept Study Phase 2 (CS2). To follow up on the MDT recommendations, the Agencies asked a number of MDT members to engage in a brief, fast-paced ~6-week activity to complete traceability matrices for the three highest MDT-recommended payloads for potential augmentation on the mission. Complementary to the mission's anchor payload, an L-band Synthetic Aperture Radar (SAR)/SAR Sounder, the three prioritized instruments are:

- a Very High Frequency (VHF) Sounder;
- a High-resolution Optical Imager; and,
- a Submillimeter Sounder.

In alignment with the Agency partners' expressed intent to maximize dual benefits (science for human exploration and fundamental Mars science), the Agency partners provided revised mission concept goals and objectives similar to the original given to the MDT, but updated based on MDT language, as relevant to completing the IDT task:

GOAL 1: Map and characterize accessible, near-surface (uppermost 0-10 m) water ice and its overburden in mid-to-low latitudes to support planning for the first potential human surface missions to Mars.

O1.1 In the Reconnaissance Zone, detect, map, and inventory the spatial distribution and depth-to-ice of water-ice resources in the near surface (top 0 –10 m).

O1.2 In the Reconnaissance Zone, detect, characterize, and map surface/near-surface geotechnical properties (roughness, compactness) to provide a fundamental understanding of the accessibility of water-ice resources (where accessibility includes characterization of the overburden for drilling/ISRU and the structural stability of the terrain for landing/launch, construction, trafficability, and other human-related surface operations).

O1.3 Based on analyses of the above surveys of the Reconnaissance Zone, provide detailed high-resolution maps of targeted areas of interest (TAI) that: have adequate (RO-1) and accessible (RO-2) water ice, are as equatorward as possible, and model the potential for human-led surface science and human-class landing and ascent, ISRU, and civil engineering.

O1.4: Measure atmospheric density, winds, and volatiles to predict extreme events, enable safe human landings, and determine atmospheric ISRU potential.

GOAL 2: Analyze evidence of ice-related subsurface, surface, and atmospheric interactions planetwide and their relation to geologic and climatological processes and potential habitable environments on Mars.

O2.1 Evaluate depths to buried ice at a global scale to assess Mars's inventory of subsurface volatiles.

O2.2 Detect and monitor seasonal ice-related changes to understand active geologic and climatological processes on Mars and their implications for habitability.

O2.3 Identify candidate subsurface environments that could potentially support active microbial ecosystems and/or contain biosignature remnants of past micro-organisms for potential study by future landed missions and for related planetary protection planning.

O2.4 Generate 3D maps of temperature, water vapor, aerosols, and vector wind to understand past and present atmospheric processes and dynamics, surface-atmosphere cycling of volatiles, and ionospheric phenomena.

For continuity and cohesion, the MDT Co-chairs reviewed the IDT outcomes and finalized this document as an addendum to the full MDT report. The Agencies intend to use both the MDT and the IDT Addendum to finalize their joint concept study. ASI, CSA, JAXA and NASA extend gratitude to those who generously volunteered more of their time, as well as to the entire MDT whose initial in-depth work was highly leveraged for this exercise.

1.2 OVERVIEW FROM THE I-MIM MDT CO-CHAIRS

The MDT co-chairs commend the work done by the IDT teams that expands upon the work done for the original MDT report. The results contained in this report provide crucial additional inputs that can be considered for decisions on additional payloads that would aid in addressing the reconnaissance objectives posed by the I-MIM concept team and the science priorities determined by the MDT.

The work enhances and fills crucial gaps that the anchor payload could have in addressing the reconnaissance objectives, and would expand the science capabilities of the mission. VHF sounding would enhance the sensing depth to an ice table and bridge the L-band anchor payload with current radar sounding assets like SHARAD. The imager would provide crucial high resolution and compositional details of the terrain, as well as stereo topography that could aid in interpretation of the L-band data, especially in areas of scattering. Submillimeter sounding would provide climatological details, including the water cycle, wind fields, and temperature and pressure of the atmosphere. These measurements would complement the anchor payload and provide additional weather predictions that could aid in landings, launches, and EVAs during human missions.

Overall, the work contained in this report provides an important addendum to the original MDT Report. We recommend its contents be considered during future I-MIM concept development, and, in particular, for decisions regarding additional payloads that could be onboard.

HiRISE Image of Candor Chasma Layered Deposits

Credit: Artwork by S.G.C.Salmon, FBIS, MIAAA, based on PSP_000597_1740 (NASA/JPL-Caltech/UofA)

2 VHF SOUNDING

2.1 BACKGROUND

The International Mars Ice Mapper (I-MIM) is a mission concept currently being explored by an international team made up of representatives from five different space agencies (ASI, CSA, JAXA, NASA and NSO). Its primary goal is to detect and characterize the ice in the upper 10 m of the Martian regolith for use as a resource by future human explorers, with additional goals for the scientific exploration of Mars. The anchor payload for the mission is an L-Band (930 MHz) Synthetic Aperture Radar (SAR)/SAR Sounder. In 2022, the I-MIM Mission Definition Team (MDT) released a report outlining how the anchor payload addresses the key goal of reconnaissance for future human missions, as well as the ways in which it would also address scientific questions of importance to Martian geology, habitability, and atmospheric science (I-MIM MDT, 2022).

One of the findings of the MDT report was that "additional instruments could expand the capabilities of I-MIM to undertake high-priority science investigations and fill any gaps in meeting reconnaissance objectives." In particular, the MDT considered a sounder in the VHF band (30-300 MHz) to be a high-value complementary instrument. The main rationale for the inclusion of a VHF sounder on I-MIM was that it would help to fill in the gap between the frequency coverages provided by the anchor payload on I-MIM (a 930 MHz combined SAR/sounder instrument) and the SHARAD instrument on the Mars Reconnaissance Orbiter (20 MHz). The VHF sounder would acquire information in the "blind zone" between SHARAD's minimal resolution depth (~20 m) and the upper 5-10 m expected to be accessible by the anchor payload's sounding mode. The lower frequency band of the VHF sounder would allow it to detect reflectors associated with ice deposits buried under materials that are too thick and/or lossy (including scattering) to be penetrated by the anchor payload, resulting in a more complete inventory of buried ice on Mars. It would also expand the measurement of the "depth to ice table" – a high-priority science objective of the mission – in areas where the ice table is deeper than 5-10 m. Used in tandem with the anchor payload, the VHF sounder would also constrain the frequency-dependent dielectric permittivity of subsurface materials, allowing a better determination of their composition.

The inclusion of a VHF sounder would allow the I-MIM mission to achieve a number of scientific and reconnaissance objectives outlined in the I-MIM MDT report, as well as to increase the confidence of all objectives being successfully completed. Namely, it would aid in the characterization of subsurface ice deposits in the Reconnaissance Zone (midlatitude locations where human missions are more operationally viable) and the suitability of these deposits for supporting human exploration. For example, a VHF sounder may be able to see the bottom interface of an ice deposit whose upper interface is detected by the L-Band SAR sounder, or the top interface of an ice deposit that is deeper than the 5 - 10 m penetration of the anchor payload. It would also help advance many I-MIM fundamental science objectives, including investigations of the cryosphere, geosphere, surface-atmosphere interactions, and habitability. For example, a VHF sounder has the potential to measure the thickness and determine the composition of the debris cover over viscous flow features (VFFs) shown by SHARAD (a radar instrument onboard NASA's Mars Reconnaissance Orbiter) to contain massive ice by detection of their bases. It may also resolve internal debris bands within VFFs that are too deep to be imaged by the anchor payload, with implications for recent climate history on Mars and approaches to ISRU. Furthermore, the additional penetration depth may lead to a better understanding of the connections between shallower and deeper ices within the upper few tens of meters. Lastly, given that lower radar frequencies are less susceptible to scattering by rocks, cracks, and voids than an L-Band radar instrument, a VHF sounder would provide a clearer view of the near subsurface. This capability is especially desirable considering that the scattering properties of the Martian subsurface are largely unknown, but could have a strong attenuating impact that limits the maximum penetration depth of the L-band signal. The inclusion of a VHF sounder significantly increases the ability to complement the L-band penetration depth and more fully address the breadth of I-MIM's science and reconnaissance objectives.

In this report, the Instrument Definition Team (IDT) for the VHF sounder outlines the performance requirements for the potential instrument. The team focused specifically on defining measurements needed to address I-MIM reconnaissance and scientific objectives of I-MIM and optimal ways of making those measurements.

2.2 ASSESSMENT OF RECONNAISSANCE & SCIENCE OBJECTIVE

2.2.1 VHF Sounder IDT Process

The IDT started its work by assessing the objectives and measurements defined by the MDT, as laid out in the Reconnaissance and Science Traceability Matrices (RTM and STM) of the I-MIM MDT Final Report (2022). For context, the VHF Sounder IDT reviewed the sounding capabilities established for the SAR anchor payload, which is intended to provide a 1-m freespace range (vertical) resolution and a signal-to-noise ratio (S/N) > 100 dB. The MDT noted that a "VHF sounder could fill a remaining gap between the near-surface (several m) sounding of the L-band sounder mode, and the lower boundary of the so-called 'blind zone' of SHARAD, which extends to about 20 m."

To achieve this goal, the MDT presented some general characteristics of the desired VHF sounder that include a band center near 100 MHz, a large bandwidth that would enable finer range resolution than that of SHARAD, which is 15 m in freespace, and the ability to explore the connections between near-surface ice that may be characterized by the L-band sounder mode (upper 0 -10 m) and ice at depths of up to a few 10s of meters. In general, the idea is for the VHF sounder to provide complementary capabilities, including some overlap, with that of the SAR sounder mode for ensuring that both the Reconnaissance and Science Objectives of the I-MIM mission will be more fully addressed.

2.2.2 VHF Sounder & I-MIM Reconnaissance Objectives

The top-level Reconnaissance Objectives (RO) discussed in the I-MIM MDT report are:

RO-1. Detect, map, and inventory the distribution of and depth to water ice in the 0 to 10 m depth zone.

RO-2. Detect, characterize, and map the geotechnical properties of the overburden above buried water ice.

RO-3. Characterize locations with adequate and accessible water ice in terms of their potential for surface science, human-class entry, descent, and landing, in situ resource utilization, and civil engineering.

The VHF sounder would contribute directly to the first two of these Reconnaissance Objectives, each of which has a detailed list of associated parameters as described in the I-MIM MDT Final Report (2022). Relative to the SAR, the VHF sounder will be less susceptible to attenuation and capable of achieving greater depth of penetration. Thus, it will contribute significantly to the RO-1 parameters concerning ice presence and concentration vs. depth and non-ice component properties, including that of the overburden. Given a coarser footprint relative to the SAR, the VHF sounder would only contribute to parameters concerning the lateral extent and continuity of ice when detecting ice where the SAR does not and for locations where the SAR is not used.

RO-2 parameters fall into three categories concerning the nature of the surface, the thickness of overburden, and the stratigraphy and structure of the overburden, and they inform geotechnical characteristics, notably the surface roughness and the compactness of overburden materials. While the SAR is well suited to assessing many of these parameters on its own and at finer resolution than the VHF sounder, the latter's lower susceptibility to attenuation means that it can extend the vertical extent of an assessment of these parameters, most critically in areas where the overburden is especially attenuating at SAR frequencies or is of a great enough thickness to attenuate fully the SAR signals.

2.2.3 VHF Sounder & I-MIM Science Objectives

The top-level Science Objectives discussed in the I-MIM MDT report include investigations of:

- Past and present atmospheric processes, including interactions with the surface and ionosphere;
- Past and present geologic processes, including climate records; and,
- Past and present habitable environments.

The VHF sounder would contribute to investigations in all three of these areas. As noted in the I-MIM MDT report, it would provide deeper penetration than the SAR sounder mode for the polar layered deposits, which are critical records of surface-atmosphere interactions over time and constitute records of past climate. In addition, the VHF sounder could provide complementary information to that from the SAR by providing an additional frequency band in which to assess the total electron content of the ionosphere.

As noted for the Reconnaissance Objectives, the VHF sounder's greater penetration depth would enable the characterization of ice and overburden to greater depths, which also has significant benefits to scientific studies. This same capability would also benefit studies of volcanic and regolith processes that have occurred in the recent geologic past. The I-MIM MDT Final Report (2022) also points out that the SAR sounding mode could be used in combination with the VHF sounder to measure emitted microwave energy and thereby sense temperature gradients and changes to depths of 50 m, yielding insights into variations in subsurface composition and density.

In seeking habitable environments, any putative detection of near-surface brines by the SAR sounder mode could be tested by the VHF sounder, given the frequency-dependent nature of radar signals associated with brines. As habitable conditions are thought to be more likely at greater depth and in association with ground water or ice, the I-MIM MDT Final Report (2022) notes that the greater penetration depth afforded by the VHF sounder is critical to assessing habitability below 10 m depth, not only in terrains with buried ice, but also in fluvial environments where understanding the deeper stratigraphy and nature of sedimentary deposits is needed. Subsurface void spaces also constitute habitable environments at both microbe and human scales. In the latter case, they offer potential zones for human exploration and habitation. For these larger-scale features, the greater penetration depth of the VHF sounder would greatly enable their detection.

With regard to both Reconnaissance and Science Objectives, the I-MIM VHF Sounder IDT generally concurs with the I-MIM MDT conclusions concerning the importance and potential enhancements afforded by the inclusion of a VHF sounder. The team's high-level recommendations for scale, resolution, and accuracy apply to both Reconnaissance and Science Objectives. These recommendations are that the VHF sounder should have:

1) a bandwidth (and thus vertical resolution) comparable to the SAR sounding mode;

2) a frequency that enables a penetration capability significantly higher than that of the SAR sounding mode; and,

3) a horizontal resolution on the order of several hundred meters (see Fig. 2), which will be limited by an expected lack of antenna directivity and defined by the pulse bandwidth and processing.

In addition, the VHF sounder can contribute to the same science investigations that are intended for the SAR sounding mode. More details can be found in the updated RTM and STM for the VHF Sounder.

2.3 MODELING THE PERFORMANCE OF THE VHF SOUNDER

Orbital radar sounding is based on the same principle as radioglaciology, a well-established geophysical technique employed since the mid-20th century to probe the interior of ice sheets and glaciers in Antarctica, Greenland, and the Arctic (Bogorodsky et al., 1985). It is based on the transmission of radar pulses at frequencies in the MF, HF and VHF range into the surface. It can detect signals reflected from dielectric discontinuities associated with compositional and/or structural changes in the subsurface. Radar sounders have been successfully employed in planetary exploration since the times of the Apollo program (e.g., Phillips et al., 1973; Picardi et al., 2005; Seu et al., 2007; Ono et al., 2009; Kofman et al., 2015). They are still the only remote-sensing instruments allowing the study of the subsurface of a planet from orbit.

An electromagnetic wave encountering a discontinuity in the medium through which it is propagating is partially reflected, while the remainder is transmitted into the subsurface and can be reflected by any dielectric discontinuity in the subsurface. The depth at which a radar sounder can detect subsurface interfaces depends on the nature of the material being probed. Other factors such as topographic roughness, as well as the presence of inhomogeneities in the material through which the radar pulse propagates, further reduce penetration by scattering the radar pulse.

In the ideal case of a plane parallel geometry in which the wave is perpendicular to the discontinuity, the partition between reflected and transmitted power is described by the reflectance (or reflectivity, or power reflection coefficient) R, and the transmittance (or transmissivity, or power transmission coefficient) T at normal incidence (Stratton, 1941):

$$\mathrm{R} = \left| \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \right|^2 \tag{1}$$

$$\mathrm{T} = 1 - \mathrm{R} \tag{2}$$

where $\varepsilon 1$ is the complex relative permittivity in the medium from which the electromagnetic wave propagates and $\varepsilon 2$ is the same parameter for the medium past the discontinuity. It can be seen from Equation (1) that the greater the difference between $\varepsilon 1$ and $\varepsilon 2$, the more energy is backscattered towards the radar transmitting the electromagnetic wave.

$$P_s = P_t \cdot \left(\frac{G\lambda}{8\pi H} \right)^2 \cdot \mathrm{R}_s \tag{3}$$

where *Ps* is the power of the surface echo received by the radar, *Pt* is the power of the transmitted pulse, *G* is the radar antenna gain, λ the pulse wavelength, *H* the spacecraft altitude and *Rs* the Fresnel reflection coefficient at normal incidence for the surface. The term *Rs* in Equation (3) implies that part of the radar pulse energy propagates into the subsurface and can be reflected back to the radar in the presence of a subsurface dielectric discontinuity. In this case, the subsurface echo power *Pss* received by the radar can be computed through the following expression (Porcello et al., 1974):

$$P_{ss} = P_t \cdot \left(\frac{G\lambda}{8\pi(H+z)} \right)^2 \cdot \mathrm{T}_s^2 \cdot \mathrm{R}_{ss} \cdot \exp\left(-2\pi f \tan\delta\, \tau\right) \tag{4}$$

where *z* is the depth of the subsurface dielectric discontinuity, *Ts* the surface transmission coefficient, *Rss* the subsurface Fresnel reflection coefficient at normal incidence, *f* the radar frequency, tan δ the loss tangent of the medium between the surface and the subsurface discontinuity, while τ is the time delay between the reception of the surface and subsurface echoes. The loss tangent is the ratio between the imaginary and the real parts of the complex relative permittivity, and the term exp(-2π*f* tanδ τ) expresses the attenuation of the radar signal because of dielectric losses as it propagates through the subsurface. Depth *z* and subsurface echo delay *ε* are related through the following expression:

$$z = \frac{c\,\tau}{2\sqrt{\varepsilon'_s}} \qquad (5)$$

where *c* is the speed of light in vacuo and ε'_s is the real part of the relative permittivity of the medium between the surface and the subsurface interface.

Materials expected to be found in the first meters to hundred of meters of the Martian subsurface can generally be classified as rocks, regolith, sediments, and ices. Their dielectric properties at MHz to GHz frequencies have been measured in the laboratory, and sometimes retrieved from observations by the MARSIS and SHARAD radar sounders. In modeling the capability of the VHF sounder to detect a subsurface echo, this IDT assigned to each general category of material a range of values for both the dielectric permittivity and the loss tangent, encompassing individual measurements found in the literature. Such values are reported in Table 1.

Table 1. Values of Dielectric Properties for Different Categories of Materials Expected to be Found on Mars

MATERIAL CATEGORY	RELATIVE PERMITTIVITY	LOSS TANGENT
Pure or dust-contaminated ice	3 - 3.5	$3\cdot10^{-4}$ - $3\cdot10^{-3}$
Regolith	4 - 5	10^{-3} - $5\cdot10^{-3}$
Basalts	5 - 10	$5\cdot10^{-3}$ - 10^{-2}
Sediments	4 - 6	$5\cdot10^{-3}$ - $5\cdot10^{-2}$

Values in Table 1 have been used in Equations (3) and (4) to produce estimates of surface and subsurface echo power. The choice of materials constituting surface and subsurface layers is based on the analysis of Reconnaissance and Scientific Objectives listed in the I-MIM Measurement Definition Team Final Report (2022): four combinations of surface and subsurface dielectric properties, called simulation scenarios, can be used to represent all types of observations to be performed by the VHF sounder. The simulation scenarios are listed in Table 2 below, together with the reference to their corresponding Reconnaissance and Science Objectives.

Table 2. Scenarios For Estimating the Depth of Penetration through Equations (3) and (4), with their Corresponding Objectives

SIMULATION SCENARIO	RECONNAISSANCE OBJECTIVES	SCIENCE OBJECTIVES
Regolith over Ice	1, 2.1A, 2.3, 2.4, 2.5, 2.6, 3.1, 3.2, 4.1A, 4.1B, 4.2, 4.3, 5.3B, 5.4	ATMO 1.1, GEO 2.2, HAB 1.2, HAB 2.1, HAB 2.2
Ice over Basalt	2.2, 5.5	ATMO 1.1, GEO 2.1, GEO 3.4
Basalt over Void	5.3A, C, E	HAB 1.4
Sediment over Basalt	5.3A, C, E	GEO 2.3, GEO 3.1, GEO 3.2, HAB 1.1, HAB 1.3, HAB 1.5

The depth of penetration has been estimated by computing the ratio of surface to subsurface echo power. This ratio has been set to 40 dB as representative of the dynamic range that instruments such as MARSIS and SHARAD can achieve. Different material categories consist in ranges of values for dielectric parameters, representing the uncertainty in the actual properties of a specific site. Depths of penetration for a given scenario were thus computed by generating 10000 linearly distributed random combinations of dielectric parameters. A range for penetration depth was then computed as the mean value of the resulting distribution plus or minus one standard deviation. The resulting ranges for penetration depth at different frequencies for different scenarios are shown in Figure 1. Consistent with the analysis reported in the I-MIM MDT Final Report (2022), the VHF Sounder IDT only considered a frequency range between 100 and 200 MHz.

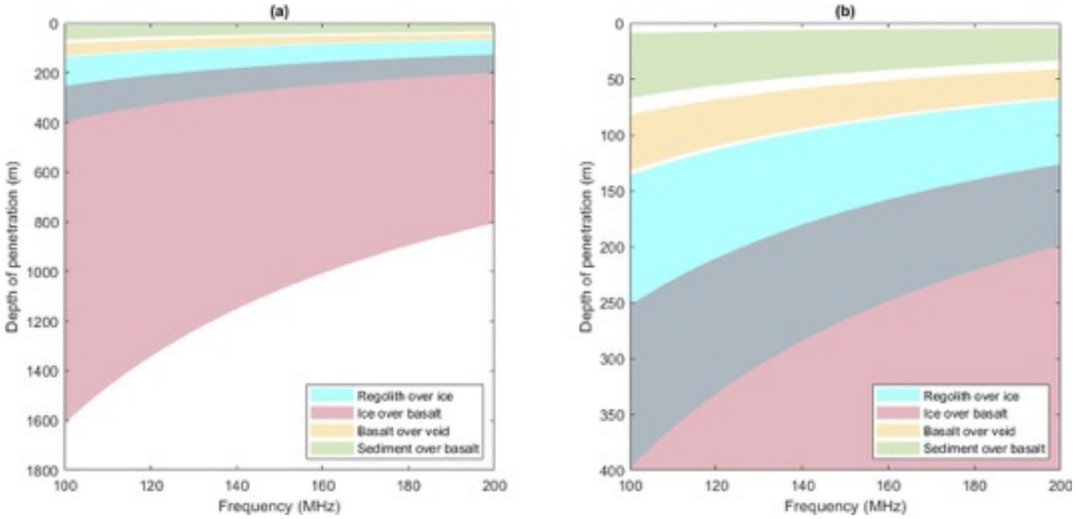


Figure 1: Estimated ranges of penetration depths for the different observation scenarios listed in Table 2 as a function of the central frequency of the VHF sounder; (b) is a zoomed-in version of the plot shown in (a).

Figure 1 shows that the penetration is the greatest at the lowest frequency used. Thus, a requirement to achieve deep penetration will translate into the selection of the lowest frequency possible. Another fundamental requirement for the performance of the VHF sounder is its resolution, both vertical (range) and horizontal. These two parameters are both a function of the transmitted bandwidth: the greater the bandwidth, the lower (better) are both resolutions. As the bandwidth cannot exceed the maximum transmitted frequency of the sounder, it becomes evident that penetration and resolution are conflicting requirements in the definition of the functional parameters of a sounding radar.

To help visualize possible trade-offs, Figure 2 shows both vertical and horizontal resolutions as a function of the selected bandwidth. For technical reasons, it is difficult to transmit efficiently a fractional bandwidth exceeding 50% of the central frequency, so resolution has been computed for a bandwidth ranging from 50 MHz to 100 MHz.

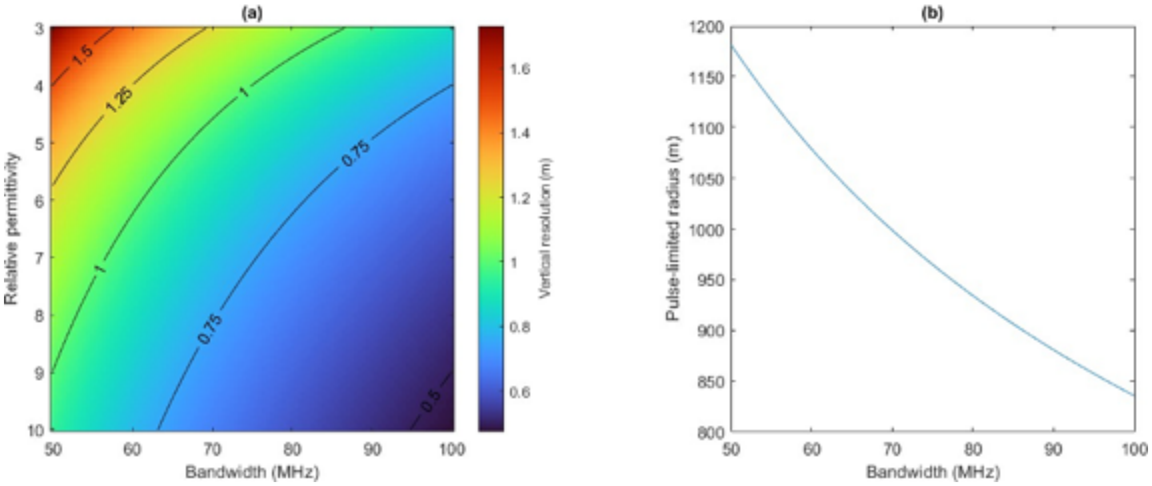


Figure 2: (a) vertical resolution of the sounder as a function of bandwidth and permittivity; (b) horizontal resolution of the sounder as a function of bandwidth computed as the pulse-limited footprint radius.

Vertical resolution has been computed as the round-trip distance corresponding to a time equal to the duration of the ideally compressed chirp, which in turn equals the inverse of the bandwidth. Because the speed of propagation of an electromagnetic wave in a medium is equal to the speed of light in vacuo divided by the square root of the permittivity [see Equation (5)], then the vertical resolution is also a function of the material through which the pulse is propagating.

Figure 2a thus shows resolution as a function of both frequency and permittivity for values of permittivity between 3 and 10. The correspondence between a given value of permittivity and a material category can be traced through Table 1.

At MARSIS and SHARAD frequencies (MHz to tens of MHz), the only efficient antennas that can be accommodated on a spacecraft are dipoles, which possess negligible directivity. Although a VHF sounder could use a Yagi antenna, its beam is still very wide. Thus, the size of the radar footprint is determined by the characteristics of the transmitted pulse.

For very flat areas, the radar footprint is assumed to correspond to the Fresnel zone; that is, to the size of the area contributing to coherent backscattering. For rougher surfaces, however, the radar footprint size is assumed to be defined as the area that is simultaneously illuminated by a pulse; that is, the area whose echo time delay difference corresponds to pulse duration (the so-called pulse-limited footprint). Figure 2b shows the value of the pulse-limited footprint radius as a function of frequency for a set altitude of 250 km. Horizontal resolution is usually assumed to correspond to the pulse-limited radius rather than to the diameter.

2.4 IMPLICATIONS FOR INSTRUMENT DESIGN

Results from the previous section illustrate how both penetration and resolution are not linear functions of frequency or bandwidth. The loss of penetration with increasing frequency is faster at the lower end of the frequency interval considered, so that increasing the central frequency by 10 MHz from a baseline of 100 MHz has a greater impact on instrument performance than changing it from, for example, 150 MHz to 160 MHz. On the other hand, resolution improves more quickly when increasing the bandwidth at the lower end of the interval of values considered, while a continued increase of the bandwidth results in an increasingly smaller improvement on resolution.

Another consideration in evaluating the results in the previous section is that they are based on an idealized geometry, that of plane parallel interfaces between different materials. Roughness can disrupt an impinging wavefront, and thus significantly reduce the power of the echo backscattered towards the radar. This case is also true for subsurface echoes, which are affected both by surface and subsurface interface roughness. Scattering by topographic roughness depends on the ratio between it and the wavelength, rather than on its value alone. It is generally assumed that a surface can be considered specular when its roughness is a small fraction of the wavelength (1/8 to 1/10, depending on the criteria applied). For a wavelength of about 3 m at 100 MHz, this implies that the surface should have a rms height of about 30 cm over an area several hundred meters across. Although not prohibitive, this criterion will not be satisfied everywhere, and is likely to be violated on areas of particular interest for I-MIM such as viscous flow features.

For this reason, it is necessary to assume that the depths of penetration estimated in the previous section represent an upper bound on the real performance of the radar, and that sounding over complex features such as the VFF will achieve a lower penetration. As the effect of roughness scales with wavelength, increasing the VHF sounder frequency will also increase the extent of surface and subsurface scattering over a given area.

The loss tangent of Martian materials can vary by at least 2 orders of magnitude (see Table 1) and penetration depth is inversely proportional to that (Chyba et al., 1998). One of the major lessons learned with SHARAD is that although shallow, widespread, thick, and relatively clean water ice exists at high latitudes (e.g., the Mars Phoenix lander site; ice-exposing impacts) and mid latitudes (ice-exposing impacts, ice-exposing scarps, debris-covered glaciers, etc.), it often cannot be detected with current radars, likely due to high loss of the overburden (e.g., Stillman and Grimm, 2011) and insufficient vertical resolution. In some cases, relatively pure polar-cap ice was also found to be lossy, such as in portions of the SPLD (e.g., Abu Hasmeh et al., 2022). Thus, although penetrating hundreds of meters into clean ice (a very low loss material) may appear to be an overachievement, it also means only penetrating ~10 m in very lossy sediments and ice mixtures commonly found on Mars.

Based on these considerations, and because the VHF sounder is required to penetrate deeper and through more lossy materials than the L-band sounder, this IDT recommends that **the VHF sounder should be designed to keep the operating frequency as low as possible (ideally 100 MHz) with a bandwidth that is sufficient to achieve a resolution comparable to that of the L-band sounder (60 MHz)**, which ensures a depth resolution below 1.5 m in all materials considered in the simulation scenarios in Table 2).

2.5 PRELIMINARY INSTRUMENT DESIGN

2.5.1 Instrument Architecture

The VHF sounder baseline architecture would likely follow very closely with that of SHARAD, a single-string instrument composed of:

- a power supply;
- a digital section (fully implemented in FPGA);
- a single baseband receiver chain with anti-aliasing filtering and programmable gain;
- a transmitter; and,
- an antenna.

The digital section would contain both the acquisition electronics: an ADC (Analog to Digital Converter), directly connected to the receiver chain and the Digital Chirp generator DAC (Digital to Analog Converter). Spacecraft electrical interfaces would be concentrated in the power supply and in the digital section. The latter would also have a high-speed data link toward the on-board mass memory.The proposed antenna would be a Log Periodic Dipole Antenna (LPDA); some tradeoffs can be analyzed. The size of the antenna is not considered a particular issue, as it is a design that can also be easily collapsed.

The entire VHF Sounder design would be based architecturally on SHARAD experience: high Technology Readiness Level (TRL) in terms of obtainable performances, overall architecture, and operations. With regards to specific technologies, noteworthy ones involved are all high TRL.

2.5.2 Instrument Parameters

The design inputs provided by science to assist in the correct configuration of the radar sounder suggests, as a baseline for the VHF Sounder, a set of engineering parameters and some optional considerations (Table 3).

2.5.3 Data Volume/Rates vs. Acquisition Scenarios

The data volume produced by the VHF Sounder depends on the chosen Pulse Repetition Frequency (PRF), and the size of the Receive Window (RxWin). Differently from SHARAD on MRO, we are proposing an instrument in which both parameters can be changed in flight and therefore the data volume can also be optimized according to the sounding results needed for specific observations.

The following data are relevant to two very basic scenarios, with a nominal operational configuration, for both a RZ acquisition (5 minutes long) and a Targeted Area of Interest (TAI) acquisition (100Km -> 53s), as defined in the MDT Final Report (2022).

Instrument Configuration

PRF	700 Hz
RxWindow	135 µs
Data Block Size (one echo)	21060 samples
Sample Size	8 bits
Resulting Data Rate	112.5 Mb/s*

*has impact on the link to the mass memory

Single Observation DV – for RZ Scenario (300s)

Data Volume, presumming 1	4.12 GBytes
Data Volume, presumming 2	2.06 GBytes
Data Volume, presumming 4	1.03 GBytes

Single Observation DV – for TAI Scenarios (53s)

Data Volume, presumming 1	745.1 MBytes
Data Volume, presumming 2	372.6 MBytes
Data Volume, presumming 4	186.3 MBytes

Table 3. VHF Sounder Engineering Parameters and Options

DESIGN PARAMETER	NOMINAL VALUE(S)	OPTIONS	NOTES
Operational Frequency	120 to 180MHz (Center Freq: 150MHz)	70 to 130MHz (Center Freq: 100MHz)	The center frequency can be revised: lower value 100, maximum value + ½ BW < 200MHz
Bandwidth	60MHz (fixed)	80MHz (fixed)	The option would change the Operational Frequency range.
Chirp Duration (nominal)	85µs	Variable 40 to 150µs	Chirp duration variability (fixed values or continuous) is added for flexibility.
Rx Window Duration (nominal)	135µs	Variable according to chirp duration.	Rx Window duration variability (fixed or continuous) derives from chirp duration variability; can also be used to reduce the data volume.
Duty Cycle (nominal)	~ 5%	<10% always	
SNR	60dB required		Tempant ~800K 20W TX output power min. +5dBi antenna gain (one way), including matching losses
Orbital Range	Assumed MRO-like (316 by 252 km)	Mission dependent.	MDT is not clear if the reference orbit is 300 or 250 km
PRF (Note)	Nominal: ~700Hz Alternate1: ~1400Hz Alternate2: ~350Hz	Fully controllable PRF from 250 to 1600Hz.	High PRF cases needed for high- slope conditions.
Sampling Rate	156Ms/s @60MHz	208Ms/s @80MHz	Basic approach: SHARAD-like (I/Q alternative could be considered).
Sample Resolution	8 bits	4, 2 bits	6 bits has issues with PDS4 archiving

Note: PRF values depend on orbital altitude and orbital altitude variation, if not circular. It is not a critical value, but it affects the data rate and therefore the data volume.

2.5.4 Systems Requirements

The VFH Sounder IDT based all requirements on the current VHF Sounder reference design and the fact that the design is based on a well-known architecture and very high TRL components.

Mass Requirements

- Total Instrument (Less Antenna) < 40 Kg

Power Requirements

- Maximum Power Consumption < 70 W
- The VHF Sounder will always be kept active in a stand-by condition.

Installation Requirements

- The preliminary design of the VHF Sounder foresees that the antenna system feed-point is at a fixed impedance. For this reason, the instrument electronics could be allocated at a certain distance from the antenna.
- The antenna itself, in its reference design, should be Nadir-pointing, with disturbances to its radiation pattern in the Nadir-direction minimized.
- The cross-section of the pattern can be approximated with an ellipse and the major axis of the ellipse should be parallel with the ground track.

Pointing Requirements

- All observations would be performed with the VHF Souder antenna pointed at Nadir (the main axis of the antenna directional lobe is the reference).
- Required pointing accuracy (according to the antenna reference design for a center frequency of 150 MHz):
    - Preferred Nadir Pointing Accuracy:
      Radius of 2.5° around the maximum gain direction.
    - Acceptable Nadir Pointing Accuracy:
      Radius of 5.0° around the maximum gain direction

Other Requirements

- Orbital Requirements:
  None; however, the total expected variations in orbital altitude will drive the selectable range of PRF values.
- Instrument Duty Cycle:
  Not a factor. The instrument is expected to be well balanced thermally. Therefore, no usage limitations are foreseen. Spacecraft accommodation may, however, induce some limitations.

2.5.5 Operational Constraints Scenarios

Operational constraints for the VHF Sounder derive from direct experience after more than 15 years of SHARAD operations. In the specific case of SHARAD, the antenna mounting position was very challenging and imposed a number of operations issues and costs that would not be present in the VHF Sounder.

Setup Before Acquisition

- Transmitter and receiver electronics may need a few minutes (<3) of warm-up: this is design-dependent and may not even be necessary.

Observations Programming

- A programming model similar to SHARAD would be implemented:
    - each observation would have a start time and a duration in PRIs (the spacecraft onboard computer can handle the conversion of the overfly latitude to the start time)
    - each observation would also program in the instrument the necessary geometry information for the open-loop positioning of the RX Windows opening time (with regard to the surface)

Daylight/Nightside Observations

- No impact is foreseen (ionospheric impact considered minimal).

Simultaneous Operations with Other Instruments

- Not a factor, unless radiated disturbances by other instruments affect the sounder band in a considerable way.

Monitoring requirements

- Basic monitoring and failure detection would be implemented on the spacecraft for a few observables produced by the radar.

2.6 SUMMARY

The VHF sounder is considered a high-priority complement to the anchor payload of the I-MIM mission. The main MDT rationale for the inclusion of a VHF sounder on I-MIM was that it would help to fill in the gap between the frequency coverage provided by the anchor payload on I-MIM and the SHARAD instrument on the Mars Reconnaissance Orbiter (20 MHz). It would also expand the measurement of “depth-to-ice-table” – a high-priority science objective of the mission – to areas where the ice table is deeper than 5 -10 m.

The VHF Sounder Instrument Definition Team analyzed instrument performance over different observation scenarios by means of simulations based on plane parallel geometry and a range of values for the dielectric properties of materials thought to be representative of the Martian surface and subsurface composition. The modeling effort that was possible within the constraints of the IDT charter could not account for the effect of topographic roughness, and can thus underestimate the depth of penetration of the sounder over complex topography.

That leads the VHF Sounder IDT to recommend a low central frequency within the interval 100-200 MHz and a 60 MHz bandwidth, which is considered sufficient for achieving the resolution required by the Reconnaissance and Science Traceability Matrices found in the MDT Final Report (2022).

The VHF Sounder IDT presented a potential design based on these recommendations, with a few options that can be considered for possible trade-offs required by I-MIM’s mass, power, or data-rate constraints. However, the VHF sounder design can still accommodate options beyond those presented here, if necessary. One important issue that the IDT could not address is antenna design. Not enough information about the spacecraft structure and materials is available to assess a possible allocation of the VHF Sounder and its antenna. This very basic information is needed not only to evaluate the sounder antenna fitting, but also to provide preliminarily estimates of the EM behavior and the impact of spacecraft structures on the antenna pattern. This consideration was beyond the scope of this IDT.

2.7 VHF SOUNDER TRACEABILITY MATRIX

VHF SOUNDER TRACEABILITY MATRIX

SCIENCE FOR HUMAN EXPLORATION:
TOPIC 1. WHERE IS THE HUMAN-ACCESSIBLE ICE ON MARS?

1 ICE PRESENCE

MEASURABLE PARAMETER(S)	MEASURABLE SUBPARAMETER(S)	SCALE OF MEASUREMENTS FOR HUMAN MISSION PLANNING	SCALE / RESOLUTION / ACCURACY	MODELS NEEDED
1 Ice Presence	-	-	Vertical Penetration: Top 10 m to 100 meters Horizontal Resolution: 100s of meters to kilometers Vertical resolution: Meter scale	Assumptions about overburden (if present) ε' and scattering (surface & volume)
2 ICE CONCENTRATION				
2.1 **Depth to Top of Ice Table**	2.1A Overburden/Ice Transition Depth Below 1.5* m * Had to change original SAR depth for the VHF sounder	ICE SCI: 1.5 m Vertical Resolution H-C L/L: N/A ISRU: within +/- 1.5 m CE: +/- 200cm	Vertical Penetration: 10m to 10s of m Horizontal Resolution: 100s of meters to kilometers Vertical Resolution: Meter scale	Assumptions about Overburden ε' & Scattering (Surface & Volume)
2.2 **Thickness of Ice in Upper 10 m**	-	Same as above.	Same as above.	Same as above.
2.3 **Nature of Ice/Overburden Transition** High-priority reconnaissance goal; 2.3 should drive instrument design	-	Same as above.	Same as above.	- Same as above.
2.4 **Integrated Ice Mass in Column of top 100 m*** * Had to change original SAR depth for the VHF sounder	-	Same as above.	Same as above.	Would be up to ~100 m for VHF; will not necessarily address top 5 m for landing/human-class recon goals. 100 m is a reasonable order of magnitude -- it should not be considered a hard requirement for this recon parameter.
2.5 **Ice Porosity**	-	Same as above.	Same as above.	Dielectric permittivity mixing models at VHF frequencies and material properties
2.6 **Ice Lenses in Overburden**	-	Same as above.	Vertical Penetration: Top 20 m Horizontal Resolution: 100s of meters to kilometers Vertical Resolution: Meter scale (Depends on spatial scale of ice lenses;100s of meters scale may not be realistic for ice lenses.)	Assumptions about overburden ε' and scattering (surface & volume)

ICE SCI = Human-led Ice Science. H-C L/L = Human-class Landing/Launch. ISRU=In Situ Resource Utilization. CE = Civil Engineering for human exploration.

VHF SOUNDER TRACEABILITY MATRIX

SCIENCE FOR HUMAN EXPLORATION:
TOPIC 1. WHERE IS THE HUMAN-ACCESSIBLE ICE ON MARS?

3 LATERAL EXTENT & CONTINUITY OF ICE

MEASURABLE PARAMETER(S)	MEASURABLE SUBPARAMETER(S)	SCALE OF MEASUREMENTS FOR HUMAN MISSION PLANNING	SCALE / RESOLUTION / ACCURACY	MODELS NEEDED
3.1 **Spatial Continuity of Ice (Patchiness)**	-	ICE SCI 1.5 m Vertical Resolution H-C L/L N/A ISRU within +/- 1.5 m CE +/- 200cm	Vertical Penetration Top 10 m to 100 meters Horizontal Resolution 100s of meters to kilometers Vertical resolution Meter scale (PRF considerations if ice patches and lenses are thought to have steep slopes)	Same as STM - ATMO 1.1 Near-surface Ice abundance & HAB 1.2 Global Distribution & Nature of Ice
3.2 **Horizontal Extent of Ice**	-	Same as above.	Same as STM - ATMO 1.1 Near-surface Ice abundance & HAB 1.2 Global Distribution & Nature of Ice	Same as STM - ATMO 1.1 Near-surface Ice abundance & HAB 1.2 Global Distribution & Nature of Ice

4 NON-ICE CONSTITUENTS IN THE MATRIX

MEASURABLE PARAMETER(S)	MEASURABLE SUBPARAMETER(S)	SCALE OF MEASUREMENTS FOR HUMAN MISSION PLANNING	SCALE / RESOLUTION / ACCURACY	MODELS NEEDED
4.1 **Rocks in Ice or Ice Matrix**	4.1A Ice/Rock Mixing Ratio	ICE SCI 1.5 m Vertical Resolution H-C L/L N/A ISRU within +/- 1.5 m CE +/- 200cm	Same as STM - ATMO 1.1 Presence of & Depth to Ice Table Vertical Penetration 10m to 10s of m Horizontal Resolution 100s of meters to kilometers Vertical Resolution Meter scale	Dielectric permittivity mixing models at VHF frequencies and material properties
	4.1B Layering of Lithics in Ice - Thickness & Frequency (Drives vertical resolution/bandwidth)	Same as above.	Same as above.	Assumptions about overburden; internal layering ε' and scattering (Surface & Volume)
4.2 **Solutes in Ice or Ice Matrix** **(Marginal; only for certain materials)**	-	Same as above.	Vertical Penetration: 10 m to 10s of meters Horizontal Resolution: 100s of meters to kilometers Vertical Resolution: Meter scale	Assumptions about bulk & overburden ε' and scattering (Surface & Volume) Dielectric permittivity mixing models at VHF frequencies and material properties
4.3 **Presence of Liquids**	-	Same as above.	Same as STM - HAB 1.1 Presence of Liquid Brines	Same as STM - HAB 1.1 Presence of Liquid Brines

ICE SCI = Human-led Ice Science. H-C L/L = Human-class Landing/Launch. ISRU=In Situ Resource Utilization. CE = Civil Engineering for human exploration.

VHF SOUNDER TRACEABILITY MATRIX

SCIENCE FOR HUMAN EXPLORATION:
TOPIC 2: CAN REGIONS OF HUMAN-ACCESSIBLE ICE SUPPORT SURFACE OPERATIONS?

5 SURFACE CHARACTERISTICS

MEASURABLE PARAMETER(S)	MEASURABLE SUBPARAMETER(S)	SCALE OF MEASUREMENTS FOR HUMAN MISSION PLANNING	SCALE / RESOLUTION / ACCURACY	MODELS NEEDED
5.3 Strength of Overburden	5.3B Average/Bulk Porosity of Overburden	ICE SCI 1.5 m Vertical Resolution H-C L/L N/A ISRU within +/- 1.5 m CE +/- 200cm	Vertical Penetration: 10 m to 10s of meters Horizontal Resolution: 100s of meters to kilometers Vertical Resolution: Meter scale	Dielectric permittivity mixing models at VHF frequencies and material properties
5.4 Stratigraphy/ Interbedding	-	Same as above.	Same as above.	Dielectric permittivity and reflectivity models at VHF frequencies and material properties
5.5 Depth to Bedrock	-	H-C L/L 2.5 m Vertical Resolution CE +/- 200cm	Same as above.	Same as above.

ICE SCI = Human-led Ice Science. H-C L/L = Human-class Landing/Launch. ISRU=In Situ Resource Utilization. CE = Civil Engineering for human exploration.

VHF SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL SCIENCE

ATMO 1. SURFACE-ATMOSPHERE INTERACTIONS

ATMO 1.1 SURFACE/SUBSURFACE VOLATILE INVENTORY & VARIABILITY

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY	FUNCTIONAL REQUIREMENTS	MODELS NEEDED
Seasonal Water & CO2 Ice Cap Thickness	Surface Reflectivity	Horizontal Resolution 100s of meters to kilometers Temporal Frequency Ls ~20-degree intervals during the year	≥10 MHz bandwidth	Radar Thin-layer Interference Models
Near-surface Ice Abundance	Echo Time Delay	Vertical Penetration 10m to 10s of m Horizontal Resolution 100s of meters to kilometers Vertical Resolution Meter scale	Bandwidth ≥60 MHz Center Frequency ≤200 MHz Sufficient SNR for the Measurement TBD - Phase A	Assumptions about Overburden ε' & Scattering (Surface & Volume)
Presence of & Depth to Ice Table	Echo Time Delay	Same as above.	Same as above.	Same as above.
Fine Characterization of Polar Layered Deposits	Echo Time Delay	Same as above.	Same as above.	Assumptions about Overburden ε' & Scattering (Surface & Volume) Thin-layer Interference Models

VHF SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL SCIENCE
GEO 2. GEOSPHERE PROCESSES THAT SHAPED THE RECENT PAST

GEO 2.1 POLAR DEPOSITS (PLDs & CO_2)

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY	FUNCTIONAL REQUIREMENTS	MODELS NEEDED
Permittivity Contrast	Echo Time Delay	Vertical Penetration 10m to 10s of m Horizontal Resolution 100s of meters to kilometers Vertical Resolution Meter scale	Bandwidth ≥60 MHz Center Frequency ≤200 MHz Sufficient SNR for the Measurement: TBD - Phase A	Assumptions about Overburden ε' & Scattering (Surface & Volume) Thin-layer Interference Models
Surface Geomorphology	Surface Scattering Characteristics	Horizontal Resolution 100s of meters to kilometers	≥10 MHz bandwidth	Surface Scattering Models at VHF Frequency (Surface & Near-surface)

GEO 2.2 MID-LATITUDE ICE

Permittivity Contrast	Echo Time Delay	Vertical Penetration 10m to 10s of m Horizontal Resolution 100s of meters to kilometers Vertical Resolution Meter scale; Ability to resolve sloping permittivity contrasts	Bandwidth ≥60 MHz Center Frequency ≤200 MHz Sufficient SNR for the Measurement TBD Phase A Sufficient PRF to Resolve Dipping Layers TBD	Assumptions about Overburden ε' & Scattering (Surface & Volume) Stratigraphic & Reflectivity Models for Subsurface Permittivity Contrasts

GEO 2.3 RECENT VOLCANISM (Texture, Stratigraphy & Composition)

Permittivity Contrast	Echo Time Delay	Vertical Penetration 10s of m Vertical Resolution ~0.8 m	Bandwidth ≥60 MHz Center Frequency ≤100 MHz Sufficient SNR for the Measurement TBD-Phase A	Assumptions about Overburden ε' & Scattering (Surface & Volume)

VHF SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL SCIENCE

GEO 3. GEOSPHERE PROCESSES THAT SHAPED THE DISTANT PAST

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY		FUNCTIONAL REQUIREMENTS		MODELS NEEDED
GEO 3.1 CRATER EJECTA EMPLACEMENT & DEGRADATION						
Permittivity Contrast	Echo Time Delay	Vertical Penetration Vertical Resolution	10s of m ~1m	Bandwidth Center Frequency Sufficient SNR for the Measurement	≥60 MHz ≤100 MHz TBD-Phase A	Assumptions about Ejjecta ε' & Scattering (Surface & Volume) Stratigraphic &Reflectivity Models for Subsurface Permittivity Contrasts
GEO 3.2 SEDIMENTATION & STRATEGRAPHY (including Buried Landforms)						
Permittivity Contrast	Echo Time Delay	Same as above.		Same as above.		Assumptions about Sediment ε' Stratigraphic & Reflectivity Models for Subsurface Permittivity Contrasts
GEO 3.3 UNIQUE RADAR TERRAINS (MFF, Stealth Regions, etc.)						
Permittivity Contrast	Echo Time Delay	Vertical Penetration Vertical Resolution	10s – 100s of m ~1 – 1.5m	Same as above.		-
GEO 3.4 NOACHIAN CLIMATE & ICE						
Permittivity Contrast	Echo Time Delay	Same as above.		Same as above, plus: Sufficient PRF to Resolve Dipping Layers	 TBD	-

VHF SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL SCIENCE

HABITABILITY 1. ENABLE THE SEARCH FOR PAST & PRESENT HABITABLE ENVIRONMENTS

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY		FUNCTIONAL REQUIREMENTS		MODELS NEEDED
HAB 1.1 PRESENCE OF LIQUID BRINES						
Brine Depth and Distribution (top 100 m)	Echo Time Delay Reflectivity	Vertical Penetration Horizontal Resolution Vertical Resolution	10 m to 10s of m 100s of m to kms Meter scale	Bandwidth Center Frequency Sufficient SNR for the Measurement	≥60 MHz ≤100 MHz TBD-Phase A	Assumptions about Brine Complex Permittivity Stratigraphic & Reflectivity Models for Ice/Regolith/Brine Permittivity Contrasts
HAB 1.2 GLOBAL DISTRIBUTION & NATURE OF ICE						
Depth to Top of Ice Table (Top 10 m)	Echo Time Delay	Same as above.		Bandwidth Center Frequency Sufficient SNR for the Measurement	≥60 MHz ≤200 MHz TBD Phase A	Assumptions about Overburden ε' & Scattering (Surface & Volume)
Radar Reflectivity as a Function of Depth (top 100 m)	Echo Time Delay	Same as above.		Same as above.		Same as above.
HAB 1.3 PAST FLUVIAL & GLACIOFLUVIAL ACTIVITY						
Subsurface Stratigraphy	Echo Time Delay	Same as above.		Bandwidth Center Frequency Sufficient SNR for the Measurement	≥60 MHz ≤100 MHz TBD-Phase A	Assumptions about Subsurface ε' Stratigraphic & Reflectivity Models for Subsurface Permittivity Contrasts
HAB 1.4 SUBSURFACE VOID DETECTION						
Subsurface Vertical Profile (Top 100 m)	Echo Time Delay Subsurface Scattering	Same as above.		Same as Hab 1.3, plus: Sufficient PRF to resolve scattering due to small voids TBD		Assumptions about Subsurface ε' Subsurface Void Scattering Models

An enigmatic small-scale texture called Brain terrain covers many ice deposits on Mars that have undergone flow and sublimation.

ESP_033165_2195. Credit: NASA/JPL-Caltech/UArizona

3 HIGH-RESOLUTION IMAGING

3.1 BACKGROUND

The I-MIM MDT Final Report (2022) named high-resolution color imaging (and derived stereo topography) as one of the highest priority capabilities that would complement the SAR and better meet mission reconnaissance objectives. As previously stated in that document:

- Direct observations of exposed mid-latitude ice layers and ice-exposing impacts can confirm the presence of icy deposits.
- Measurements of thermal contraction polygons can, in conjunction with models, determine ice depth.
- Blocky surfaces and buried ice may both produce high radar CPR signals that high-resolution images can disambiguate.
- Stereo topography, in conjunction with radar sounding of buried ice interfaces, can constrain bulk dielectric properties.
- Landing-site safety can be determined by roughness and rockiness. Images at decimeter-scale resolutions are required to characterize adequately the abundance of meter-scale boulders, and stereo products (with meter-scale resolution) are necessary to characterize small scale slopes.

For syntergistic fundamental science, a high-resolution imaging capability would also provide:

- important context to radar sounder measurements of polar layered deposits;
- numerous active geolocial processes on Mars such as recurring slope linneae; dune and ripple motions; mass wasting; and new craters; and,
- numerous past geological processes such as lava-flow texture and superposition relationships; impact crater ejecta; impact melts; and fluvial features; glacial meltwater production etc.

The High-resolution Imaging (HIR) IDT considered this potential augmentation further, per the provided updated I-MIM mission concept architecture, in which a freeflying spacecraft would carry a high-resolution imager.

3.2 STARTING IDT ASSUMPTIONS

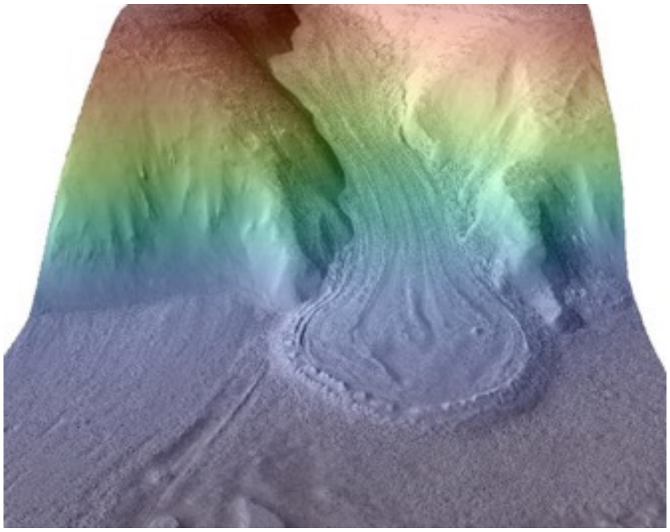
Of central importance to any camera system is the orbit of the spacecraft that carries it. The High-Resolution Imaging (HRI) Instrument Definition Team (IDT) assumed that the high-resolution imager would be carried by a spacecraft in an MRO-like orbit:

- The altitude would vary from 250 km to 300 km from periapse to apoapse, which also fixes the downtrack ground velocity at ~3.2 km/s;
- The inclination would be 93 degrees, making the orbit sun-synchronous, allowing any portion of the planet to be targeted with spacecraft rolls; and,
- The local time at equator-crossing would be ~3 pm, the optimum imaging compromise between signal and incidence angles that highlight terrain variations.

The HRI IDT assumed spacecraft abilities would also be similar to those of MRO:

- Rolls to accommodate off-nadir imaging would be possible in both directions up to 30 degrees;
- The amplitude of high-frequency spacecraft jitter (from moving solar panels, antennae, other instrument parts) would be limited to several microradians; and,
- Pointing stability would result in <0.2 microradians of crosstrack drift over 9.5 msec, which would enable time-delay integration over 128 image lines.

3.3 MEASURED QUANTITIES AND DATA PRODUCTS



A glacier-like feature in Protonilus Mensae flows down valley before spreading out on the lower plain in this perspective view constructed from HiRISE images ESP_018857_2225 and ESP_019358_2225. View is toward the north, contains roughly 1650 m of relief, and is approximately 5 km wide. Credit: NASA/JPL-Caltech/UArizona

Based on the MDT's (2022) findings, the high-resolution imager is required to produce:

- images (in units of calibrated I/F) in up to four color bands; and,
- stereo-derived Digital Terrain Models (DTMs) from two asynchronous images.

3.4 REQUIRED DATA CHARACTERISTICS & INSTRUMENT IMPLICATIONS

For reliable surface feature measurements and DTM production, images must be high-resolution, well-calibrated, low distortion, and have high signal-to-noise (SNR).

3.4.1 Spatial Resolution

Although features as small as one pixel may be detected in ideal conditions, accurate measurement of any feature requires it be multiple pixels in size. The number of pixels needed depends on the contrast of the feature, SNR, and illumination angle, but a useful guideline is that 3 pixels (with >0.1 MTF and high SNR) are needed (Mc Ewen et al., 2007).

The ability fully to resolve meter-sized objects thus requires pixels ~30 cm in size. From an MRO orbit (apoapse 300km), this necessitates an IFOV of one microradian. An IFOV of 1 microradian at visible wavelengths requires a primary mirror 50 cm in diameter, with a focal length 10^6 times the detector pixel pitch. Based on HiRISE experience, aliasing is not expected to be problematic in part because wide filters lead to a range of diffraction-limit resolutions that are averaged and downtrack smear of <1 pixel (due to finite integration time combined with the pushbroom approach) induces some mild smoothing.

The MDT analysis that stereo DTMs should have a resolution of 1 m is also met by this system. Stereo DTMs are created with area-matching algorithms operating on squares 3-5 pixels across. Thus, 1 m/pixel DTMs require image pixel sizes of 20-33 cm and this is met with a 1 microradian IFOV in an MRO-like orbit (generating pixel sizes 25-30 cm). The expected vertical precision of DTMs is given by the product of the image matching error in meters and (H/B), where H is spacecraft height and B is baseline. The (H/B) ratio can be approximated as the reciprocal of the tangent of the stereo convergence angle (typically ~20 degrees). The matching error is typically 0.2 pixels (so 6 cm assuming 30 cm pixels). Thus, vertical precision is expected to be ~16 cm; however, non-ideal spacecraft environments (like jitter) and image noise mean the true vertical precision may be several 10s of cm (Sutton et al., 2022).

3.4.2 Color Bands

Three colors that match those of HiRISE are required in order to perform long-term change detection utilizing the HiRISE dataset as far back as 2006. An additional short-wavelength filter is required to characterize atmospheric scattering and to calibrate surface reflectance.

3.4.3 Signal to Noise

High SNR images are essential for accuracy in identification and measurement of small features, color characterization, and stereo matching for DTMs. SNR is affected by surface insolation (dependent on season and incidence angle), albedo, and the camera filter. For example, the HiRISE camera is an analog of the system described here and can obtain SNR >200 in its RED filter over bright terrain at incidence angles of ~45 degrees at an average Mars-Sun separation. We consider an SNR of 100 to be the minimum needed for high-quality feature measurement and DTM production.

An IFOV of one microradian combined with a groundtrack velocity of 3.2 km/s makes obtaining an SNR of 100 challenging especially in narrower color filters. For the HiRISE BG and IR filters, 2x2 binning is required to achieve the same SNR as the solar-optimized RED filter. HiRISE RED SNRs reach 100 at incidence angles of 65-75 degrees (for dark-bright terrain), which is enough for all locations on Mars at some season. HiRISE achieves this SNR by using Time-Delay-Integration (TDI) of up to 128 image lines, which drives a pointing stability requirement of <0.2 microradians of crosstrack drift over 128 lines (9.5 msec). Other strategies for achieving this SNR have significant drawbacks. For example, a larger primary mirror would steeply escalate the instrument mass; a smaller steerable mirror that effectively slows the groundspeed of the FOV (as utilized by CRISM) would cause resolution and stereo convergence angles to vary throughout each image pair and make DTM production problematic.

3.4.4 Radiometric and Geometric Calibration

Geometric distortions due to the optical system itself must be removed before precision geometry products like DTMs can be created. The high-resolution imager should have post-calibration distortions no greater than one pixel.

Radiometric accuracy of pixels relative to each other in the same image is vital so that terrain appears the same in different images (for DTM production and change detection). The high-resolution imager should have post-calibration relative radiometric errors no greater than 2%. The absolute calibration is typically harder to determine, and images are often compared to each other by scaling the brightnesses of features not expected to be changing. The high-resolution imager should have post-calibration absolute radiometric errors no greater than 20%.

3.4.5 Image Size

Efficiency in data collection require minimizing the number of images and thus maximizing their size. Image width should be >5 km so that Target Areas of Interest (TAIs) can be mosaiced within the mission lifetime (see Section 6.5 of the MDT report for detailed calculations of number of images and data volume involved). The FOV required from an MRO-like orbit is thus > 1.15 degrees.

Similarly, covering target areas efficiently requires making the most of each (predominantly south-north) orbit and acquiring images long enough to cover TAIs (defined to be 100 km across in Section 6 of the MDT report) in one swath. Accordingly, we require the high-resolution imager to be able to image continuously for 32s (100km in an MRO-like orbit).

3.5 HIGH-RESOLUTION IMAGER TRACEABILITY MATRIX

HIGH-LEVEL TRACEABILITY MATRIX			
SYNERGISTIC SCIENCE **(Science for Human Exploration & Fundamental Mars Science)**			
MEASURABLE PARAMETER(S)	**SCALE / RESOLUTION / ACCURACY**	**FUNCTIONAL REQUIREMENTS**	**MODELS REQUIRED**
• Resolved surface reflectance (I/F) from nadir and off-nadir geometries in four visible colors (three to match HiRISE for long-term change detection and one short-wavelength band to improve calibration by characterizing atmospheric scattering). • Surface heights and slopes from DTMs constructed from asynchronous panchromatic filter images acquired with stereo convergence angles from 15 to 30 degrees.	High resolution images shall have: • an image pixel size of 25cm in order to: - resolve fully surface features 1 m in size; - produce Digital Terrain Models at 1m post spacing and 1m vertical precision; • distortions of <1 pixel in order to measure accurately surface features and facilitate stereo topography retrieval; • relative radiometry accurate to 2% and an SNR of > 100 in a panchromatic filter over typical Mars Terrain in order to: - identify surface features; - produce accurate stereo matching in bland terrain; - characterize terrain color after 2x2 binning; and, • a width > 5 km and a length > 100 km in order to obtain representative surface coverage and efficiently cover TAIs.	The instrument shall: • acquire data in multiple spacecraft orientations as stereo images may require off-nadir spacecraft orientations of up to 30 degrees; • have an IFOV of 1 microradian to generate the required 25 cm/pixel images; • be capable of continuous imaging for >32 seconds to fulfill image length requirements; • record data with a cross-track FOV >1 degree to satisfy image width requirements; and, • perform regular calibration updates.	Standard image-processing & stereo-DTM-reconstruction models

High-altitude clouds over Mars, as seen by Mars rover Curiosity.

Credit: NASA/JPL-Caltech

4 SUBMILLIMETER SOUNDING

4.1 SCIENCE & RECONNAISSANCE INVESTIGATIONS

4.1.1 Atmospheric Structure, Dynamics, Vertical Coupling & Loss to Space

It is almost certain that Mars once had a wet and warm climate with the presence of liquid water on the surface. Where/how has such a large amount of water gone? Recent studies show that it is partially lost to space, driven by the short-term variation of the climate in the lower atmosphere (e.g., Chaffin et al., 2021). Thus, coupling between the lower and upper atmosphere (in particular, the vertical transport of water), is important for understanding the water history on Mars.

The Submillimeter Sounding IDT focused on research related to global weather and climate models at planetary scales. When observing the atmosphere from a near-circular orbit allowing multiple orbits per Martian day, submm limb sounding and nadir observations (0.3 – > 1 THz frequency region) would furnish information necessary to create seasonal 3D (altitude, longitude, latitude) maps of winds, temperature, and trace gases, including volume mixing ratios of water vapor, HDO, and O_3.

These daily, globally sampled profiles would supply new and unique information furthering the study of the water cycle, weather and climate, and vertical coupling within the atmosphere. With two observing views of submm sounding (either rapid scanning of the atmosphere for different look angles or two antennas), the native line-of-sight winds can be used to produce vector wind fields, and it is possible to observe the general circulation of zonal winds and meridional circulation in the Martian atmosphere. Recently, models with north-south polar circulation even around altitudes of 80 - 110 km (Clancy et al., 2012) and high-altitude plumes (Sánchez-Lavega et al., 2015) have also been suggested, and such a comprehensive investigation from high to low altitude is expected to reveal the actual vertical coupling in global atmospheric and material circulations in the Martian atmosphere.

4.1.2 Near-surface & Atmospheric Conditions

Together with radar measurements of the ice-cap thickness and the near-surface ice table, monitoring the surface temperature, dust, ice, water abundances, and winds in the lowest scale height would help quantify the surface-atmosphere cycling of volatiles. Measuring D/H ratios could aid in understanding water exchange between subsurface reservoirs and the atmosphere and the sublimation-condensation process through time (e.g., Aoki et al., 2015; Villanueva et al., 2015). Further, measuring these same quantities above the boundary layer would help reveal the modern-day transport of volatiles and aerosols leading to a better understanding of the timescales for emplacement and preservation of ice around the planet. In surface-atmosphere cycling, dust and water-vapor can extend to an altitude of around 65 km or more, including detached layers, so it is necessary to focus observations from surface to that altitude. Temperature, wind, and HDO/H2O ratio related to the solidification/sublimation of water-vapor varies significantly depending on sunlight conditions. Thus, at a minimum, observations should be made during the typical day and night time (LST:0-3h, 12-15h).

4.1.3 Science for Human Exploration

The development of highly accurate General Circulation Models (GCMs) using novel information on wind fields, temperature, and water vapor holds great potential for advancing weather forecasting and enhancing our understanding of the transport and viable area of potential microbes (either indigenous or emitted by human activity on Mars). For instance, attempts have been made to model weather forecasts incorporating CO_2 cloud/snow (Kuroda et al, 2013.). To achieve progress in such model development, it is crucial to obtain fundamental atmospheric data that can be compared to, and assimilated with, GCMs up to an altitude of about 30 km.

If they become attached to dust particles and shielded from ultraviolet sunlight, microbes possibly introduced by humans from Earth could survive and spread in a state of suspended animation, even at low temperatures and pressures. Instruments on ground-based rovers have revealed significant variations in wind direction, even within a single Martian day (sol), and wind velocities of up to several tens of meters per second. Furthermore, water-bearing dust layers can often extend up to around 65 km in altitude (Villanueva et al., 2021). The latest COSPAR Planetary Protection Policy mentions the potential transport of dust to altitudes of up to 90 km within a few days, particularly in mid to high latitudes. Consequently, obtaining comprehensive atmospheric dynamics data from the surface to an altitude of 80 km across a wide range of latitudes is expected to provide essential insights.

In terms of human exploration, the ability to predict wind patterns and intensity during the descent of spacraft, transport vehicles, and other infrastructure, and the drive to enhance the precision of characterizing candidate sites for human exploration and optimizing human-class EDL and launch operations have assumed paramount importance. For this purpose, the international community strongly endorses research efforts focused on the observation of 2D horizontal wind fields within the altitude range of 0-15 km.

4.2 RATIONALE FOR TRACEABILITY MATRIX

4.2.1 Submillimeter-Wave Sounding

A submillimeter-wave sounder provides diurnal variations in fundamental atmospheric parameters such as temperature, pressure, wind speed, water vapor, D/H ratio, and various other trace gases with latitude, longitude, and altitude resolution. This instrument type has high-frequency resolution, which enables observations of trace molecules in the upper atmosphere, as well as observations of the wind field by Doppler velocity. In addition, because of its longer wavelength compared to infrared, it is less susceptible to absorption and scattering by dust. Therefore, it is possible to observe the target species in the lower altitude, including water vapor, even during dust storms. Also, since it does not need a background light source like the Sun, it can be used for observations at any time, day or night, on Mars. A submillimeter-wave sounder could make significant contributions to research related to the I-MIM mission's objectives, including:

Objective 1.4: Science for Human Exploration

Meteorological forecasting, transport models of microbes relevant to planetary protection, safe human landings associated with Entry, Descent, and Landing (EDL), and safe human-class launches from the Martian surface; and,

Objective 2.4

ATMO 1: Surface-atmosphere Interactions

ATMO 1.3 Near-surface Atmospheric Conditions on Mars

ATMO 2: Atmospheric, Aeronomic Structure, & Processes

ATMO 2.2 Structure, Dynamics, Vertical Coupling, and Loss to Space

4.2.2 Measurable Parameters

The recommended instrument would employ three observation bands:

- Band 1 near 460 GHz;
- Band 2 near 890 GHz; and,
- Band 3 near 980 GHz.

For derivations of wind velocity field, water vapor, temperature and pressure, D/H ratio, and ozone abundance, the Doppler shift of rotational lines of CO and its isotopologues at the band 1 and 2, the spectral lines of H_2O and its isotopologues at the band 2 and 3, the lines of CO and its isotopologues at the band 1 and 2, the lines of H_2O and HDO at band 2 and 3, and the line of O_3 at the band 2 can be observed in limb sounding and/or nadir modes, respectively.

These detectable molecules (those with a dipole moment) as well as the altitude range, vertical resolution, and precision achievable for various frequency regions between 0.3 - ~1 THz are shown in Read et al., 2018. These simulated results depend somewhat on seasons (e.g., abundance of water vapor or dust-induced warming of the atmosphere), tangent altitude, band selection, and integration time.

Since the spectra of molecules distributed at high altitudes have narrow line widths, by selecting optically thick transition lines, the observations are carried out using spectrometers with high-frequency resolution. For the spectra of molecules at low altitudes optically thin lines of their isotopologues are observed using wide-band spectrometers.

The traceability matrix for the submillimeter-wave sounder is shown at the end of this section.

4.3 SUMMARY

The addition of the Submillimeter Sounder would enable the I-MIM mission to address better both reconnaissance and fundamental science objectives of the mission. Daily, globally sampled profiles provided by the submillimeter sounder would supply new and unique information furthering the study of the water cycle, weather and climate, and vertical coupling within the atmosphere.

For reconnaissance objectives, the development of highly accurate General Circulation Models (GCMs) using novel information on wind fields, temperature, and water vapor holds great potential for advancing weather forecasting and enhancing our understanding of the transport and viable area of potential microbes.

For fundamental science objectives, climate science in particular would be significantly advanced. The submillimeter sounder would revolutionize our understanding of atmospheric dynamics through wind measurements that the international science community has long sought, along with making very important measurements of atmospheric temperature, pressure, and water vapor for context.

4.4 SUBMILLIMETER SOUNDER TRACEABILITY MATRIX

SUBMILLIMETER SOUNDER TRACEABILITY MATRIX

SCIENCE FOR HUMAN EXPLORATION:
RECONNAISSANCE

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY	MODELS NEEDED*
WEATHER PREDICTION			
Wind Fields	Doppler Shift of Rotational Lines of CO and its Isotopologues (Limb Sounding)	Altitude Range 5-30+ km Spatial Resolution ~4 deg latitude x 6-8 km vertical (Limb Sounding) Precision 10-15 m/s (parameters tradeable; see text) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg Orientation: Horizontal wind in 2D	-
Water Vapor (Geographic & Altitude Profiles)	Line Profiles of H2O and its Isotopologues (Limb Sounding)	Altitude Range 0-30+ km Spatial Resolution ~4 deg latitude x 2-8 km vertical (Limb Sounding) Precision <10 ppmv (choice of frequency dependent; see text) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg	-
Temperature & Pressure (Geographic & Altitude Profiles)	Line Profiles of CO and its Isotopologues (Limb Sounding)	Altitude Range 0-30+ km Spatial Resolution ~4 deg latitude x <10 km vertical (Limb Sounding) Precision 1-6 K (metrics are altitude- and frequency-dependent; see text) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg	-
TRANSPORT OF POTENTIAL MICROBES			
Wind Fields	Doppler Shift of Rotational Lines of CO and its Isotopologues (Limb Sounding)	Altitude Range 5-80 km Spatial Resolution ~4 deg latitude x 6-8 km vertical (Limb Sounding) Precision 10-15 m/s (parameters tradeable; see text)) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg Orientation: Horizontal wind in 2D	For refining planetary protection requirements for human missions, development and validation of a contamination transport model based on meteorological investigations is required. (Olsson-Francis et al., 2023)
Water Vapor (Geographic & Altitude Profiles)	Line Profiles of H_2O and its Isotopologues (Limb Sounding)	Altitude Range 0-80 km Spatial Resolution ~4 deg latitude x 2-8 km vertical (limb sounding mode) Precision <10 ppmv (choice of frequency dependent; see text) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg	-
Temperature & Pressure (Geographic & Altitude Profiles)	Line Profiles of CO and its Isotopologues (Limb Sounding)	Altitude Range 0-80 km Spatial Resolution ~4 deg latitude x <10 km vertical (limb sounding mode) Precision 1-6 K (metrics are altitude, frequency dependent; see text) Local Solar Time (0-3)h - (12-15)h Latitude >|+/- 75| deg	-

SUBMILLIMETER SOUNDER TRACEABILITY MATRIX

SCIENCE FOR HUMAN EXPLORATION: RECONNAISSANCE

SAFE HUMAN-CLASS LANDING & LAUNCH FROM THE MARTIAN SURFACE

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY		MODELS NEEDED
Wind Fields (Some of the above properties also apply.)	Doppler Shift of Rotational Lines of CO & its Isotopologues (Limb Sounding)	Altitude Range Spatial Resolution Precision Local Solar Time Latitude Orientation	0-15 km ~4 deg latitude x <10 km vertical (limb sounding mode) 10-15 m/s (metrics are altitude-dependent; see text) (0-3)h - (12-15)h >|+/- 75| deg Horizontal Wind in 2D	E-W wind is more important (useful for GCM validation) than N-S wind.

SUBMILLIMETER SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL MARS SCIENCE: ATMO 1. SURFACE ATMOSPHERE INTERACTIONS

ATMO 1.3 NEAR-SURFACE ATMOSPHERIC CONDITIONS

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY		MODELS NEEDED
Water Vapor Abundance	Line Profiles of H_2O and its Isotopologies	Altitude Range Spatial Resolution Precision Local Solar Time Latitude	0-50+ km ~4 deg latitude x 2-8 km vertical (limb sounding) <10 ppmv (choice-of-frequency-dependent; see text) (0-3)h - (12-15)h >|+/- 75| deg	-
D/H Ratio	Line Profiles of H_2O and HDO	Altitude Range Range Precision Local Solar Time Latitude	0-60+ km 0-7000 ‰ δD <500‰ (metrics are altitude-/frequency-dependent; see text) (0-3)h - (12-15)h >|+/- 75| deg	-
Wind Speed	Doppler Shift of Rotational Lines of CO, H_2O, and their Isotopologies	Altitude Range Spatial Resolution Precision Local Solar Time Latitude Orientation:	5-50+ km ~4 deg latitude x 6-8 km vertical (limb sounding) <10 ppmv (parameters tradeable; see text) (0-3)h - (12-15)h >|+/- 75| deg Horizontal wind in 2D	-

SUBMILLIMETER SOUNDER TRACEABILITY MATRIX

FUNDAMENTAL MARS SCIENCE:
ATMO 2. ATMOSPHERIC & AERONOMIC IONS

ATMO 2.2 STRUCTURE, DYNAMICS, VERTICAL COUPLING & LOSS TO SPACE

PROPERTY TO CONSTRAIN	MEASURABLE PARAMETER(S)	SCALE / RESOLUTION / ACCURACY		MODELS NEEDED
Wind Fields	Doppler Shift of Rotational Lines of CO and its Isotopologues	Altitude Range Spatial Resolution Precision Local Solar Time Latitude Orientation:	5-110 km ~4 deg latitude x 6-8 km vertical (limb sounding mode) <10-15 m/s (parameters tradeable; see text) (0-3)h - (12-15)h >|+/- 75| deg Horizontal wind in 2D	-
Water Vapor **(Geographic & Altitude Profiles)**	Line Profiles of H2O and its Isotopologues	Altitude Range Spatial Resolution Precision Local Solar Time Latitude	0-110 km ~4 deg latitude x 2-8 km vertical (limb sounding) <10 ppmv (choice of frequency dependent; see text) (0-3)h - (12-15)h >|+/- 75| deg	-
Temperature & Pressure **(Geographic & Altitude Profiles)**	Line Profiles of CO and its Isotopologues	Altitude Range Spatial Resolution Precision Local Solar Time Latitude	0-110 km ~4 deg latitude x <10 km vertical (limb sounding) 1-6 K (metrics are altitude-/ frequency dependent; see text) (0-3)h - (12-15)h >|+/- 75| deg	-
Ozone Abundance	Line Profile	Altitude Range Spatial Resolution Precision Local Solar Time Latitude	0-60+ km ~8 deg latitude x <8 km vertical 10~100 ppbv (altitude-/frequency-dependent)) (0-3)h - (12-15)h >|+/- 75| deg	-

Note: If the satellite has orbital flexibility, it would be better if it could observe a wider range of LST and latitudes than described above.

The beam size (FWHM) of a submm sounder with an antenna of aperture D[m] is expressed as ~1.1×λ/D [rad].

When the aperture size is 0.45 m and the altitude of the satellite is 250 km, the beam size is about 0.09 deg for 460 GHz.

This corresponds to about 2 km, which is the spatial resolution in the direction orthogonal and horizontal to the line-of-sight direction of the limb sounding and about 0.4 km on the ground surface in a nadir mode.

APPENDIX A. ACRONYMS

ADC	Analog to Digital Converter
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
C	Carbon
COSPAR	Committee on Space Research
DAC	Digital to Analog Converter
D/H	Deuterium/Hydrogen
DTM	Digital Terrain Model
EM	Electromagnetic
FOV	Field of View
GCM	General Circulation Model
H/B	Height/Baseline
HF	High Frequency
HiRISE	High Resolution Imaging Science Experiment
IDT	Instrument Definition Team
I/F	Intensity/Flux
IFOV	Instantaneous Field of View
I-MIM	International Mars Ice Mapper
IUVS	Imaging Ultraviolet Spectrograph
JAXA	Japan Aerospace Exploration Agency
kR	kilo-Rayleighs
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVEN	Mars Atmospheric and Volatile EvolutioN
MDT	Measurement Definition Team
MF	Medium Frequency
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
nm	Nanometer
NOMAD	Nadir and Occultation for Mars Discovery
NSO	Netherlands Space Office
O	Oxygen
PDS	Planetary Data System
PRF	Pulse Repetition Frequency
PPMV	Parts Per Million by Volume
R	Reflectance
RO	Reconnaissance Objective
SAR	Synthetic Aperture Radar
SHARAD	Shallow Subsurface Radar
SNR	Signal to Noise
SPLD	South Polar Layered Deposits
TDI	Time Delay Integration
TGO	Trace Gas Orbiter
TRL	Technology Readiness Level
UV/VIS	UltraViolet/Visible
UVD	Ultraviolet D
VFF	Viscous Flow Feature
VHF	Very High Frequency

APPENDIX B. ADDITIONAL SUBMILLIMETER SOUNDER IDT INPUT

In a request to the I-MIM Multilateral Science Leadership Team, the Chair of the Submillimeter Sounder Instrument Definition Team made a case for expanding on information regarding the UV/Visible Spectrum Imager, listed as priority 2B in the Atmosphere Subteam's findings in the MDT Final Report (2022). While not precluding additional inputs, the mission's science leadership team maintained the partner Agencies' initial plan to focus on the highest priority MDT-recommended instruments in the main body of the Addendum to the IDT.

The additional information supplied by the Submillimeter Sounder IDT is as follows:

UV/VIS IMAGER: Relevance to Science and Reconnaissance Investigations

Ionospheric irregularities cause distortions of L-band SAR images on Earth. In order to remove ionospheric noise from SAR images, it is necessary to understand and characterize ionospheric irregularities. These irregularities cause disruptions to surface-orbit communications including future potential global positioning (GPS) systems that might be envisioned for Mars. A 2D UV/Visible image of the Martian aurora could be used to visualize the distribution of penetrating energetic particles. Continuous observations at the same altitude would unambiguously differentiate the effects of lower atmospheric activities such as dust storms and gravity waves; solar activities including solar extreme events; and, crustal magnetic fields mainly localized in the southern hemisphere. A dayglow imager (limb and nadir imaging at 289 nm and/or 557.7 nm) could provide the 2D structure of the atmospheric wave activities independently from the SAR and might help calibrate out ionospheric interference in SAR data. Observations at 557.7 nm will also enable measurements of lower atmospheric dust activity on the dayside. Their mapping will advance climate science together along with the submillimeter sounder data.

Human exploration of the Moon and Mars introduces new challenges for space-weather research and operations. Enhancement of capabilities for the characterization and forecasting of the space-radiation environment outside of the protection of Earth's atmosphere and intrinsic magnetic field is a timely and important research subject, as it will be vital to protect astronauts exploring Mars. Understanding the magnetic structure and variations around the planet would provide essential information to assess the space-radiation environment. To infer the radiation environments on the surface of Mars, critical knowledge includes: the distribution of open magnetic field lines connected to the surface and the portion of these open field regions over the entire surface of Mars. These parameters directly determine the peak altitude and geographic distribution of auroral emission that arises from the penetration of energetic particles. By taking a 2D image of the Martian aurora (e.g., Schneider et al., 2021), it is possible to visualize the distribution of the penetrating energetic particles. The I-MIM orbiter is suited to new measurements of spatial distributions of TEC, atmospheric wave activities, and energy inputs from space.

Rationale for UV/Vis Imager Traceability Matrix

A UV/ VIS atmospheric imager would provide 2D maps of the airglow, aurora and dust, and provide essential information relevant to O1.4 and O2.4. The investigation for the instrument includes ionospheric irregularities, space weather & crustal magnetic field effects on the upper atmosphere as well as the atmospheric structure, dynamics, vertical coupling & loss to space.

UV/VIS Atmospheric Imager: Measurable Parameters

Radiance (Brightness) of CO_2^+ UVD emission line at 289 nm and O emission line at 557 nm are measured for airglow and aurora. Radiance at 557 nm with a narrow bandpass filter (10 nm TBD) is measured for the dust reflectance.

AURORA.

To understand penetrating energetic particles from space, imaging of the CO_2^+ UVD emission line at 289 nm and O emission line at 557 nm with nadir and limb geometries by UV and VIS imager should constrain the Aurora Distribution and Space Radiation Environment.

Horizontal Resolution: ~ 10 km To resolve the fine structure rather than previous studies (~50-100 km by MAVEN and EMM) (Schneider et al., 2018; Lillis et al., 2022).

Horizontal Coverage: ~200 km To cover the typical spatial scale of the crustal magnetic field.

Spectral Resolution: 1 nm at 289 nm and 10 nm at 557 nm To contrast better the emission intensity.

Solar Zenith Angle: >100 degrees To avoid the daylight contamination for aurora observation.

Latitude: 50S-50N degrees To measure aurora distribution quasi-simultaneously in both hemispheres up to 50 degrees in latitudes with and without crustal magnetic field. Orbital motion increases spatial coverage and therefore frequency of observation of the regions of interest with and without crustal magnetic field to track the variability.

Sensitivity: 10-20,000 Rayleigh (R) at 289 nm and 557 nm
CO_2^+ UVD line at 289 nm is well confirmed as the UV aurora by IUVS onboard MAVEN. Although green aurora emission at 557 nm has not been yet confirmed, the recent airglow discovery at green line by NOMAD onboard TGO (Gérard et al., 2020) and the combination of UV emission at O297.2 nm by IUVS suggest a bright intensity at green line aurora on Mars. Also, we propose a visible emission line because this could provide us to have a super-compact and light-weight system for aurora imager (18.5 kg to 1.5 kg by changing from UV range to VIS range observations with negligible loss of science). Aurora emission intensity at 289 and 557 nm is expected in the range between <1 and ~7 kR (Soret et al., 2021). We set the minimum detection limit at ~10 R to increase our capability to resolve more aurora events than MAVEN (cf, 50-100 R by MAVEN) (Schneider et al., 2018). The upper limit of the UV aurora emission intensity is set according to the IUVS (Schneider et al., 2018). We detect faint aurora emission on the nightside and bright dayglow emission on the dayside.

AIRGLOW.

To understand energetic transport from the lower atmosphere, dayglow imaging at CO2+ UVD (and/or O5577) emission with nadir and limb geometries by UV and VIS imager should constrain Atmospheric Waves (Airglow Distribution).

Horizontal Resolution: ~ 10-20 km To resolve the fine structure and wavelike signature rather than previous studies (~50-100 km by MAVEN and EMM) (Schneider et al., 2018; Lillis et al., 2022).

Horizontal Coverage: ~200 km To cover the typical spatial scale of the crustal magnetic field.

Spectral Resolution: 1 nm at 289 nm and 10 nm at 557 nm To contrast better the emission intensity.

Solar Zenith Angle: <90 degrees. To focus on the day side.

Sensitivity: < 300 kR with accuracy 10% at 289 nm and 557 nm
The 557 nm peak dayglow intensity is 245 kR (Gérard et al., 2020). The wavelike perturbations of the dayglow should be detected with the accuracy of 10%(TBD).

DUST.

To understand energetic transport from the lower atmosphere, dayglow imaging at CO2+ UVD (and/or O5577) emission with nadir and limb geometries by the UV/VIS imager should constrain Atmospheric Waves (Airglow Distribution).

Horizontal Resolution: ~ 10-20 km Same as THz water vapor, wind observations.

Spectral Range: 557 nm Dust reflectivity in the green channel with MRO/MARCI demonstrates a single channel at 557 nm can work for dust monitoring.

Spectral Resolution: 10 nm To contrast better.

Range: ~1000 MR (/10 nm) at 557 nm. Based on a preliminary study using TGO/NOMAD UVIS, several 100 MR/nm on the dayside, so that ~1000 MR with 10 nm band width filter at 557 nm. High dynamic range to detect both faint aurora emission and bright dayglow emission by the same imaging system.

Accuracy: 10% (TBD)

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INTERNATIONAL MARS ICE MAPPER MISSION

The International Mars Ice Mapper (I-MIM) mission concept is being developed by a multilateral team of space agencies from five countries: Canada, Italy, Japan, the Netherlands, and the United States. I-MIM's primary goal is to map and to characterize accessible, near-surface (uppermost 10 m) water ice and its overburden in mid-to-low latitudes to support planning for the first potential human surface missions to Mars. To maximize return on investment in the mission, the Agencies are committed to additional scientific investigations planetwide, with priorities guided by the participating international scientific community, including this MDT.