European Space Research_and Technology Centre
Keplerlaan 1_2201 AZ Noordwijk_The Netherlands
Tel. (31) 71 5656565_Fax (31) 71 5656040_www.esa.int

DOCUMENT

LightShip-1
Passenger S/C
“SpotLight”

Measurement Definition Team, Final Report

V1.1 – Release date 12/12/2024

APPROVAL

Title : LightShip-1 Passenger S/C “SpotLight”, Measurement Definition Team, Final Report
Ref : ESA-E3P-LS1-RP-001.1

Issue: 1	**Revision 1**
Authors: MDT Team, H. Svedhem	**Date 2024-12-12**
Approved by	**Date**

CHANGE LOG

Reason for change	Issue	Revision	Date

CHANGE RECORD

Issue 0	**Revision**		
Reason for change	**Date**	**Pages**	**Paragraph(s)**
Minor update of paragraph 5.3	12/12/2024		5.3

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1. SCOPE AND CONTENT

This Document describes the science requirements of the Passenger spacecraft, called SpotLight, of the LightShip-1 mission. It also lists the instruments of a SpotLight strawman payload, and their characteristics. It further defines the requirements on these instruments and the requirements that these instruments imply on the spacecraft and the mission overall. The objective is to enable a well-defined specification to be written for the Invitation To Tender (ITT) for industry for a Phase A/B1 study and to act as a guideline throughout these industrial studies.

2. EXECUTIVE SUMMARY

ESA is studying a new Mars mission concept providing essential infrastructure to support its future programme of Mars exploration. The concept includes a series of electric propulsion-powered tugs (EP-Tugs) to transport space elements to Mars orbit and establish a high-altitude communications and navigation network. Each tug, named LightShip, will carry a small scientific instrument payload to study the atmosphere and space environment, and transport one or multiple 'passenger' spacecraft to Mars orbit. The first passenger spacecraft, a low-altitude orbiter named 'SpotLight', is the focus of this report. ESA has determined that SpotLight will perform high-resolution (25 cm/pixel) and context imaging at Mars, to secure safe landings for robotic and human missions. SpotLight will enable a new era of world-class scientific discovery through European experience and leadership and ensure ESA self-sufficiency in orbital support for its next-generation robotic and human surface missions. Higher Mars-Earth data transfer rates enabled by LightShip-1 will allow faster data return, and hence potentially more rapid data coverage than currently possible.

An ESA-appointed Measurement Definition Team (MDT) was tasked to perform a study of SpotLight to define a *strawman payload* for SpotLight, including *instrument parameters and requirements,* and provide *science objectives and measurement requirements* as well as *spacecraft and mission requirements*. This is based on ESA-assigned primary mission objectives, which are to enable landing site selection and characterisation for future robotic and human missions, and to support and/or complement ongoing and future missions and their investigations. In addition to these exploration-focused objectives, numerous high-priority science questions can be addressed by SpotLight as exploration-enabled objectives. This document is the MDT's final report. It shall serve as a source of information for the Invitation To Tender (ITT) for industry for a Phase A/B1 study, and act as a guideline throughout the industrial studies. If the instrument development will become part of an industrial contract, the MDT recommends that the industrial study be accompanied by a science advisory group to support activities related to the use and performance of the payload.

Science Objectives for SpotLight, and examples of investigations to address them, have been derived and modified and elaborated from the MEPAG 2020 Goals document compiled by the international Mars science community, together with other sources, including ESA's Terrae Novae Roadmap (2022) and NASA's Moon2Mars Objectives (2022).
The identified ***strawman payload*** comprises four instruments: a ***High-Resolution Multispectral Imager (HRMI)*** and a ***Colour Context Imager (CCI)***; and, if sufficient mass is available, an ***Imaging Spectrometer*** and a ***Doppler LiDAR*** for wind measurements. Individually, these instruments address numerous high-priority science objectives relating to the martian surface, subsurface and atmosphere. When combined, they provide a powerful suite of instruments addressing science objectives at a range of spatial and spectral resolutions, over a range of spatial extents, and connecting surface and atmospheric processes.

The HRMI will be the first orbital imager at Mars capable of obtaining high-value, decimetre-scale (25 cm/pixel) multispectral information for Mars over a full image swath-width of no less than 7 km, and with no fewer than 4 colour filters. Stereo imaging will enable the generation of digital terrain models with spatial resolutions of 1 m/pixel, required for ESA's ambition to achieve autonomous landing on Mars and for landing site characterisation, and enabling detailed 3D analyses of the martian surface. The HRMI will empower Europe to independently shape its Mars exploration program, reducing dependence on NASA's MRO/HiRISE, which is nearing the end of its operational life. HiRISE - which has covered ~3% of Mars surface with predominantly panchromatic images and much smaller areas with 3-band colour - has been vital for high-resolution imaging for landing site identification and certification (including ESA's Rosalind

Franklin rover) as well as supporting entry, descent and landing and surface science operations. ESA's HRMI not only builds on the monumental legacy of HiRISE but also significantly advances on its capabilities, facilitating future ESA missions and enabling a new era of scientific discovery on Mars's environment, geology, climate history, and habitability.

HRMI will be complemented by, and co-aligned with, the Colour Context imager (CCI). The CCI will be the highest-resolution context imager at Mars to date (2.5 m/pixel) and provide multispectral information over a swath width of at least 22 km, with at least six bands at visible and near-infrared wavelengths. With time, the CCI has potential to provide near-global multispectral image coverage of Mars. Coordinated observations with the HRMI will enable next-generation science at a combined spectral and spatial resolution, and over spatial extents not previously achieved for Mars. The CCI will provide context-level information required for the identification and certification of safe landing sites and surface exploration zones. It will acquire stereo-pair images in a single orbital pass, enabling the generation of spatially extensive digital elevation models at 5–10 m/pixel, providing the information ESA requires for autonomous landing technologies and enabling extensive 3D analyses of the martian surface at higher resolutions than previously possible.

The new scientific insights from the HRMI and CCI will be greatly enhanced by integrating hyperspectral data from an **Imaging Spectrometer**, potentially with a spectral range extending to 6 µm. This will enable SpotLight to identify specific mineral groups and unveil deeper insights into the geological and climate processes they record. Importantly, it could enable high-priority mapping of key minerals for understanding the aqueous and alteration history of Mars, such as carbonates, phyllosilicates and serpentine. It would also permit high-confidence distinctions of water and CO2 ices (both frosts and perennial deposits) and provide surface temperature maps to support the detection of subsurface ice as a potential in situ resource. These surface temperature maps will also greatly advance modern climatology, particularly when combined with a **Doppler LiDAR**, which would enable the first direct orbital measurements martian winds, including near to the surface. Such measurements are widely recognised as of high priority for ensuring safe entry, descent, landing, and operations of surface missions, and for advancing martian climatology. Coordinated observations with SpotLight's imaging instruments will unlock new and exciting opportunities to connect surface observations (including of landforms and dynamic processes such as dust devils, frosts, dune migration and slope mass movements) with a detailed understanding of the contemporary atmospheric regime and its spatiotemporal variability.

The MDT carefully considered the pros and cons of a Sun-synchronous orbit (SSO) versus a non-Sun-synchronous orbit (non-SSO), weighing their potential impacts on both exploration-focused and exploration-enabled objectives. Ideally, SpotLight could operate in either SSO or non-SSO, with the possibility of switching between the two during the mission. Operating in non-SSO would allow SpotLight to capture novel information on Martian surface and atmospheric conditions at various times of the day, which ESA requests to improve the detectability of landing site hazards under different illumination conditions. However, non-SSO could have implications for stereo imaging. The MDT recommends conducting a more detailed study to evaluate how each orbit configuration could affect science objectives. The reader is directed to the full discussion in Chapter 5 for the MDT's full recommendations on SSO versus non-SSO. The MDT recommends a polar orbit.

The estimated total mass (including margin) of the strawman payload is 164kg, of which the HRMI and CCI together account for 80kg.

3. INTRODUCTION

The information contained in this report has been collected and discussed by the members of the Measurement Definition Team during a workshop in ESTEC 13-15 May 2024 and during several subsequent on-line meetings (MS Teams). The members of the team are:

Francesca Altieri, INAF, Rome, IT
Frances Butcher, University of Sheffield, UK
Peter Grindrod, Natural History Museum, London, UK
Ernst Hauber, German Aerospace Center (DLR), Berlin, DE
Daniel Mège, Space Research Centre, Polish Academy of Sciences, Wroclaw, PL
Yoanna-Reine Nowicki-Bringuier, SAT4SPACE, Arcachon, FR
Nicole Schmitz, German Aerospace Center (DLR), Berlin, DE
Nicolas Thomas, Physikalisches Institut, Uni Bern, CH
Livio Tornabene, Univ. of West. Ontario (UWO), London, CA
Håkan Svedhem, ESA Consultant, Noordwijk, NL

Assistance to the team has been provided by several experts at ESTEC, Noordwijk, especially by Daniel Paardekooper, Andrew Ball and Colin Wilson (LightShip-1 IDT liaison)

3.1. Context

ESA is studying a new Mars mission concept providing essential infrastructure to support the future programme. It includes a series of electric propulsion-powered tugs (EP-Tugs) to transport space elements to Mars orbit. Each EP-Tug will be capable of transporting an orbital spacecraft to Mars as a ‘passenger’. Once passengers are delivered, the tugs will remain in a high (~5700 km altitude) orbit where they will serve as part of a communication network, to provide relay communication between landers and rovers on the surface and s/c in orbit, and the Earth. The tugs will also provide navigation support to landers and rovers on the surface (and to s/c in orbit). Each tug, named LightShip, will, in addition to its communication and navigation payload, carry a small scientific instrument payload primarily focussing on the atmosphere and the environment around the planet. LightShip-1 will deliver the first passenger s/c (SpotLight) into a low-altitude polar, mapping, orbit. SpotLight will carry a very High-Resolution Multispectral Imager (similar in scale to MRO/HiRISE), which is tasked with characterising candidate future landing sites and monitoring presently active ones, in full multi-band colour and in stereo. Stereo images enable the production of high-resolution Digital Elevation Models (DEMs) required for safety, exploration and science. In addition, SpotLight will carry a Colour Context Imager, to support the High-Resolution Imager. The Colour Context Imager will also acquire stereo images, but over a larger region at a reduced resolution. If sufficient mass is available on the spacecraft additional scientific instruments will be considered and accommodated.

The Measurement Definition Team, MDT, has had the task to define the objectives and the related measurements needed to fulfil the objectives. Inputs for the Exploration-focussed Requirements have been provided by ESA, based on the needs for safe autonomous landing. In addition, extensive elaborations have been held by the team to define the Exploration-enabled science and related requirements for the complementary payloads. The team has taken an open-minded approach but has used the MEPAG 2020 Goals document as a starting point when deriving the science objectives. MEPAG is community-based and is organised by large group of scientists with a very solid combined expertise in all aspects of Mars sciences. The MEPAG 2020 Goals document (and its predecessors, dating back to 2001) has been refined by the international Mars science community and has for a long period been a guide for the exploration of Mars. In addition, the MDT has considered information from several other sources, including ESA's Terra Novae Roadmap (2022) and NASA's Moon2Mars Objectives (2022), see list of references in chapter 9.

3.2. Strawman Payload

Two instruments are pre-assigned by ESA as part of the strawman payload, a High-Resolution Camera, and a Context Camera. These instruments will provide essential information for ESA's future Mars Exploration programme. In addition, they will enable a new level of advanced science for the Martian surface and subsurface, and to some extent for the Martian atmosphere. The MDT has carefully considered the potential performance of two such instruments and refined the requirements in order to maximise their value for characterising landing sites and surface exploration zones, preparing for human exploration (including in situ resource mapping), and advancing high-priority science. To better reflect the specific capabilities identified by the MDT, these instruments are herein named the High-Resolution Multispectral Imager (HRMI), and the Colour Context Imager (CCI).

Should sufficient mass be available, two additional instruments are recommended by the MDT to be included in the strawman payload, to enhance the pre-assigned or "primary" payload: an Imaging Spectrometer, for surface composition, mineralogical studies and coarse surface temperature; and a Doppler LiDAR, for studies of low altitude winds and aerosols including atmospheric dust.

Additional instruments have been discussed that potentially could be included if sufficient resources are available on the spacecraft, including a VHF sounder (for sub-surface sounding) and a Laser Altimeter (for surface topography).

Any additional instrument should not compromise the operation of the strawman payload. In defining/selecting additional instruments, careful assessment of any influence on the operation and performance of the strawman payload should be made.

4. SCIENCE OBJECTIVES

Science Objectives for SpotLight, and examples of investigations to address them, have been derived, modified and elaborated from the MEPAG 2020 Goals document compiled by the international Mars science community, together with other sources, including ESA's Terrae Novae Roadmap (2022) and NASA's Moon2Mars Objectives (2022).The science objectives listed below are not intended to be exhaustive and are not given in order of priority.

Exploration-focused Objectives

Themes	Number	Objective
Preparing for robotic and human exploration	OBJ-SCI-SP-01	Assess landing-site characteristics and environment related to safe landing.
	OBJ-SCI-SP-02	Assess landing-site characteristics and environment related to safe operations and trafficability within the possible exploration zones to be accessed by rovers or human missions.
	OBJ-SCI-SP-03	Characterise potentially extractable water and geological resources to support in situ resource utilisation.
	OBJ-SCI-SP-04	Determine the martian environmental niches that meet the definition of "Special Region" at potential landing sites and inside of exploration zones for surface missions.

Exploration-enabled Objectives

Themes	Number	Objectives
Investigating the evolution of Mars as a geological system.	OBJ-SCI-SP-05	Identify and characterise past and present water and other volatile reservoirs.
	OBJ-SCI-SP-06	Document the geologic record preserved in sediments and sedimentary deposits.
	OBJ-SCI-SP-07	Constrain the magnitude, nature, timing, and origin of ancient environmental transitions.
	OBJ-SCI-SP-08	Determine the nature, composition and modification history of the crust.
Investigating past and present climate and related processes on Mars	OBJ-SCI-SP-09	Characterise the dynamics, thermal structure, and distributions of dust, water, and carbon dioxide in the lower atmosphere.
	OBJ-SCI-SP-10	Constrain processes by which volatiles and dust exchange between surface and atmospheric reservoirs.
	OBJ-SCI-SP-11	Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions.
	OBJ-SCI-SP-12	Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of low- and mid-latitudes.
	OBJ-SCI-SP-13	Investigate how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.
	OBJ-SCI-SP-14	Find and interpret surface records of past climates and factors that affect climate.
Investigating past and present habitability on Mars.	OBJ-SCI-SP-15	Investigate the nature and evolution of habitable environments near the surface and in the subsurface, both past and present.
	OBJ-SCI-SP-16	Assess the preservation potential of biosignatures near the surface.
	OBJ-SCI-SP-17	Constrain the surface, atmosphere, and subsurface processes through which organic molecules could have formed and evolved over martian history.

The following are examples of investigations that could be undertaken with the strawman payload to address each of the above objectives. This list is not meant to be exhaustive, but rather illustrates the diversity of high-priority scientific investigations that could be undertaken. Some investigations, particularly those requiring observations at different times of day will require a non-Sun-synchronous orbit (non-SSO), while others may be achieved in either SSO (sun-synchronous orbit) or non-SSO. Some investigations, while achievable in either orbit, would be enhanced by one or other orbit configuration. The advantages and disadvantages of these orbits are outlined in Section 5. A non-SSO orbit brings many opportunities for both exploration-focused and exploration-enabled science objectives, including the opportunity to characterise Mars at different times of day, and with different illumination angles (for example, enhancing insights from multispectral imaging). SSO, and specifically one which matches the orbital parameters of MRO would maximise opportunities to extend the baseline of time-series imaging and change-detection initiated by HiRISE, though this could also be achieved (albeit less frequently) in non-SSO when the orbit allows 3pm imaging. If single-pass stereo imaging approaches are adopted, images required for DEM generation can be acquired in a single orbital pass in either non-SSO or SSO. If a repeat-pass stereo imaging approach is adopted (with images acquired on separate orbits as with MRO), it may be harder to complete stereo pairs in a timely manner with non-SSO than SSO. However, the specific advantages and disadvantages of SSO/non-SSO (including those outlined in Section 5) will depend on factors such as the specific orbital parameters selected, the capabilities of the instruments and spacecraft, and the approach to mission operations. For example, the ability to acquire timely stereo pairs with repeat-pass imaging is influenced by the size of the image footprint on the surface, s/c roll capabilities, and spacecraft pointing accuracy. These attributes not only affect the “reach” or repeatability for imaging, especially where orbital tracks are spaced furthest-apart (e.g., the near-equatorial regions in a polar/mapping orbit), but are also important for obtaining adequate convergence angles for stereo pair imaging, which depends on the wavelength scale variation the topography of the surface. For example, large s/c rolls are critical for stereo imaging of landing sites due to their often-subtle topography requiring convergence angles of ~20-30º. As such, in the event that a non-SSO orbit and repeat-pass stereo imaging approach is chosen for SpotLight, a thorough investigation into the impacts on repeat-pass stereo imaging should be undertaken.

OBJ-SCI-SP-01 **Assess landing-site characteristics and environment related to safe landing.**
Exploration-focused investigation required by ESA:

- Generate the data required for Digital Elevation Models of potential landing sites to be produced with Ground Sampling Distance (GSD) of 1 m for an area of radius 5 km, and a GSD of 10 m in an area of radius 30 km.
- Image potential landing sites at scale of 25 cm per pixel over an area of 5 km radius and potential exploration zones at a scale of 2.5 m per pixel.
- The high-resolution imager suite shall be able to make observations at multiple local solar time with 0.25 m/pixel (minimum) in order to generate a-priori hazard maps for a future lander.

Example investigations:

- Characterise and monitor candidate and current landing sites, respectively, to sufficient resolution to detect and identify hazards for landing of landers, rovers, and human-scale systems.
- Determine rock sizes and rock size distribution of candidate landing sites.
- Determine physical and mechanical properties and structure and the chemistry and mineralogy of the regolith, including ice contents.
- Monitor dynamic processes (e.g., frosts, dust devil activity, atmospheric opacity) which could affect operations of surface missions, potentially including different times of the day.

Profile the near-surface winds (<15 km altitude) with a precision ≤2.5 m/s in representative locales (e.g., plains, up/down wind of topography, canyons). The boundary layer winds would need a vertical resolution of ≤1 km and a horizontal resolution of ≤100 m.

- Measure surface winds for several local times throughout the diurnal cycle (during daytime at one hour interval), but not necessarily during the same cycle.

OBJ-SCI-SP-02 **Assess landing-site characteristics and environment related to safe operations and trafficability within the possible exploration zones to be accessed by rovers or human missions.**

Example investigations:

- Characterise selected potential landing sites and wider exploration zones to sufficient resolution to detect and characterise hazards to trafficability at the scale of the relevant systems.
- Map potential science targets for surface missions and characterise their topographic, geologic, and environmental contexts.
- Determine physical properties and structure of surface materials to infer mechanical parameters such as particle size distribution, cohesion, and gas permeability; and chemistry and mineralogy of the regolith, including ice contents.

OBJ-SCI-SP-03 **Characterise potentially extractable water and geological resources to support in situ resource utilisation.**

Example investigations:

- Identify candidate water resource deposits that have the potential to be relevant for future human exploration, including those which have the greatest potential to drive scientific advances from surface missions.
- Prepare high spatial resolution maps of sites with water bound in regolith materials and sites with water ice at or within a few metres of the surface.
- Prepare maps of the composition of surface and near-surface materials, and their diversity, to identify geological materials with potential for in situ resource utilisation.
- Characterise the materials which cover or contain potential in situ resources.

OBJ-SCI-SP-04 **Determine the martian environmental niches that meet the definition of "Special Region" * at potential landing sites and inside of exploration zones for surface missions.**

** 'A Special Region is defined as a region within which terrestrial organisms are likely to replicate. Any region which is interpreted to have a high potential for the existence of extant Martian life forms is also defined as a Special Region.' (COSPAR, 2024, p. 33).*

Example investigations:

- Identify the locations and characteristics of naturally occurring Special Regions, and regions with the potential for spacecraft-induced Special Regions.

OBJ-SCI-SP-05 **Identify and characterise past and present water and other volatile reservoirs.**

Example investigations:

- Determine the modern extent and volume of water and hydrous minerals within the crust.
- Identify the geologic evidence for the location, volume, and timing of water reservoirs through martian history.
- Determine how the vertical and lateral distribution of surface ice, ground ice, and buried ice has changed over time.

- Determine the role of volatiles in modern dynamic surface processes on diurnal, seasonal, interannual, and decadal timescales, correlate with records of recent climate change, and link to past processes and landforms.

OBJ-SCI-SP-06 **Document the geologic record preserved in sediments and sedimentary deposits.**
Example investigations:

- Constrain the location, timing, and duration of past hydrologic activity, the volumes of water involved, and the nature of hydrological cycles that contributed to the sedimentary and geomorphic record.
- Constrain the location, composition and timing of diagenesis of sedimentary deposits and other types of alteration.
- Identify the intervals of the sedimentary record conducive to habitability and biosignature preservation.
- Determine the sources and fluxes of modern aeolian sediments.
- Constrain the role of winds in forming, modifying, and eroding sedimentary records and deposits in the geologic record and in the present day.
- Determine the origin and timing of dust genesis, lofting mechanisms, and circulation pathways.

OBJ-SCI-SP-07 **Constrain the magnitude, nature, timing, and causes of ancient environmental transitions.**
Example investigations:

- Link geologic evidence for local environmental transitions to global-scale planetary evolution.
- Determine the relative and absolute age, durations, and intermittency of ancient and more recent environmental transitions.
- Document the nature and diversity of ancient environments and their implications for surface temperature, geochemistry, and aridity.
- Determine the history and fate of sulphur and carbon throughout the Mars system.

OBJ-SCI-SP-08 **Determine the nature, composition, and modification history of the crust.**
Example investigations:

- Determine the absolute and relative ages of geologic units and events through martian history.
- Search for and characterise surface exposures of the oldest (i.e. pre-Noachian) rocks.
- Characterise modern surface processes and their rates of change and assess their origin.
- Constrain the effect of impact processes on the martian crust and determine the martian crater production rate now and in the past.
- Determine the surface manifestation of volcanic and tectonic processes through time and their implications for surface conditions.
- Determine the role of glacial and other cryospheric processes in modifying the martian surface through time, and their implications for surface conditions.
- Develop a planet-wide model of Mars evolution through global and regional mapping efforts.

OBJ-SCI-SP-09 **Characterise the dynamics, thermal structure, and distributions of dust, water, and carbon dioxide in the lower atmosphere.**
Example Investigations:

- Characterise the dynamical and thermal state of the lower atmosphere and their controlling processes on local to global scales.

- Monitor dust-devil activity and other dust-lifting processes, and measure atmospheric dust activity and its variability.
- Monitor clouds in the lower atmosphere and characterise their evolution and variability.

OBJ-SCI-SP-10 **Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.**
Example investigations:

- Characterise the fluxes and sources of dust and volatiles between surface and atmospheric reservoirs.
- Determine how the processes exchanging volatiles and dust between surface and atmospheric reservoirs affect the present distribution and short-term variability of surface and subsurface water and CO_2 ice.

OBJ-SCI-SP-11 **Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions.**
Example investigations:

- Determine how atmospheric and surface processes, and orbital parameters, influence layer formation and properties in the polar regions.
- Determine the vertical and horizontal variations in composition and physical properties of the materials forming the Polar Layered Deposits.

OBJ-SCI-SP-12 **Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of low- and mid-latitudes.**
Example investigations:

- Characterise the locations, composition, and structure of low and mid-latitude ice and volatile reservoirs at the surface and near-surface.
- Determine the conditions under which low- and mid-latitude volatile reservoirs accumulated, evolved, and persisted until the present day and ascertain their relative and absolute ages.
- Characterise the physical and chemical properties and modification histories of the materials which cover or contain mid to low latitude ice (the overburden) and determine their influence on the stability of near-surface ice.

OBJ-SCI-SP-13 **Investigate how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.**
Example investigations:

- Characterise mineral and volatile deposits to determine sinks of key atmospheric species.
- Determine sources of gases to the atmosphere over time by characterising rates of volcanism, tectonism, crustal alteration, and bolide impact delivery.

OBJ-SCI-SP-14 **Find and interpret surface records of past climates and factors that affect climate.**
Example investigations:

- Constrain the history of the water cycle on ancient and recent Mars by determining the spatial extent, age, duration, and formation conditions (including water volumes) of ancient water and ice-related features.
- Provide data to inform modelling of past and present climate.

OBJ-SCI-SP-15 **Investigate the nature and evolution of habitable environments near the surface and in the subsurface, both past and present.**
Example investigations:

- Constrain the availability of liquid water with respect to duration, extent, volume, and chemical activity.
- Identify and characterise possible energy sources required for life.
- Characterise the physical and chemical environment, particularly with respect to parameters that affect the stability of organic covalent bonds.
- Constrain the abundance and characterise potential sources of bioessential elements.
- Provide overall geologic context.

OBJ-SCI-SP-16 **Assess the preservation potential of biosignatures near the surface**.
Example investigations:

- Evaluate conditions and processes that would have aided preservation and/or degradation of complex organic compounds.
- Evaluate the conditions and processes that would have aided preservation and/or degradation of biosignatures.

OBJ-SCI-SP-17 **Constrain the surface, atmosphere, and subsurface processes through which organic molecules could have formed and evolved over martian history.**
Example investigations:

- Investigate surface and subsurface processes, such as mineral catalysis, that play a role in organic evolution.
- Investigate the role of subsurface processes (e.g. hydrothermalism, serpentinization) in driving organic evolution.

5. INSTRUMENT SCIENCE CASES

The strawman payload comprises four instruments which individually address numerous high-priority science objectives relating to the martian surface, subsurface and atmosphere. When combined, they provide a powerful suite of instruments addressing science objectives at a range of spatial and spectral resolutions and over a range of spatial extents (from targeted high-resolution imaging to – with time – potentially near-global colour context coverage) and connect surface and atmospheric processes. Coordinated observations with multiple instruments in the strawman payload will provide opportunities to greatly enhance the potential scientific insights that can be gained from any individual instrument. For example, while multispectral imagers are of significant value for understanding compositional diversity over large areas, the unique identification of specific minerals or rocks is more readily achieved by the addition of hyperspectral imaging capabilities. However, hyperspectral imaging invariably comes at the cost of pixel resolution, which has historically been acquired at 10s of metres in scale, when permitted to gimbal, to achieve sufficient SNR. A powerful means of mapping of unique minerals and spectral signatures, and ascertaining detailed morphologies, unit associations (e.g., stratigraphic relationships) and geologic context, will be achieved by coordinated observations, and subsequent co-analysis of the High-Resolution Multispectral Imager and Colour Context Imager datasets with the hyperspectral Imaging Spectrometer data. This synthesis of the datasets will greatly enhance our ability to understand the origin and evolution of crustal surface materials on Mars, dynamic processes such as seasonal and diurnal frosts, and ices linked to the past and present climate of Mars. The addition of a Doppler LiDAR will allow coordinated observations of near-surface winds with surface imaging, for example to understand contemporary dust-lifting and volatile-cycling processes (e.g. dust devils and frosts, both throughout the year and at different times of day) which exert critical controls on the weather and longer-term climate evolution of Mars. It would unlock new and exciting opportunities to connect surface observations (including of landforms and dynamic processes such as dust devils, frosts, dune migration and slope mass movements) with a detailed understanding of the contemporary atmospheric regime and its spatiotemporal variability.

5.1. High-Resolution Multispectral Imager (HRMI)

The proposed ESA High-Resolution Multispectral Imager provides a unique opportunity for ESA to lead next-generation high-resolution orbital imaging of Mars. Building upon the success and legacy of NASA's MRO/HiRISE, and advancing on its capabilities, HRMI will produce inspiring world-class scientific discoveries and ensure European self-sufficiency and leadership in obtaining critical information for the identification and certification of safe and scientifically valuable landing sites for landers, rovers, and human missions (Figure 1). HRMI will obtain unprecedented full-colour high-resolution images at 25 cm/pixel or better, with a swath-width of no less than 7 km and no fewer than 4 colour filters. Higher Mars-Earth data transfer rates enabled by LightShip-1 would allow faster rates of surface coverage than previous high-resolution imaging by HiRISE, which has been predominantly panchromatic (greyscale), with more spatially limited 3-band colour coverage (~20% or less of the swath width; see Figures 4 and 7). If chosen, a non-sun-synchronous orbit for the SpotLight s/c would permit, for the first time, decimetre-scale imaging at different times of day, allowing observations of surface and atmospheric conditions through diurnal cycles and under a range of illumination

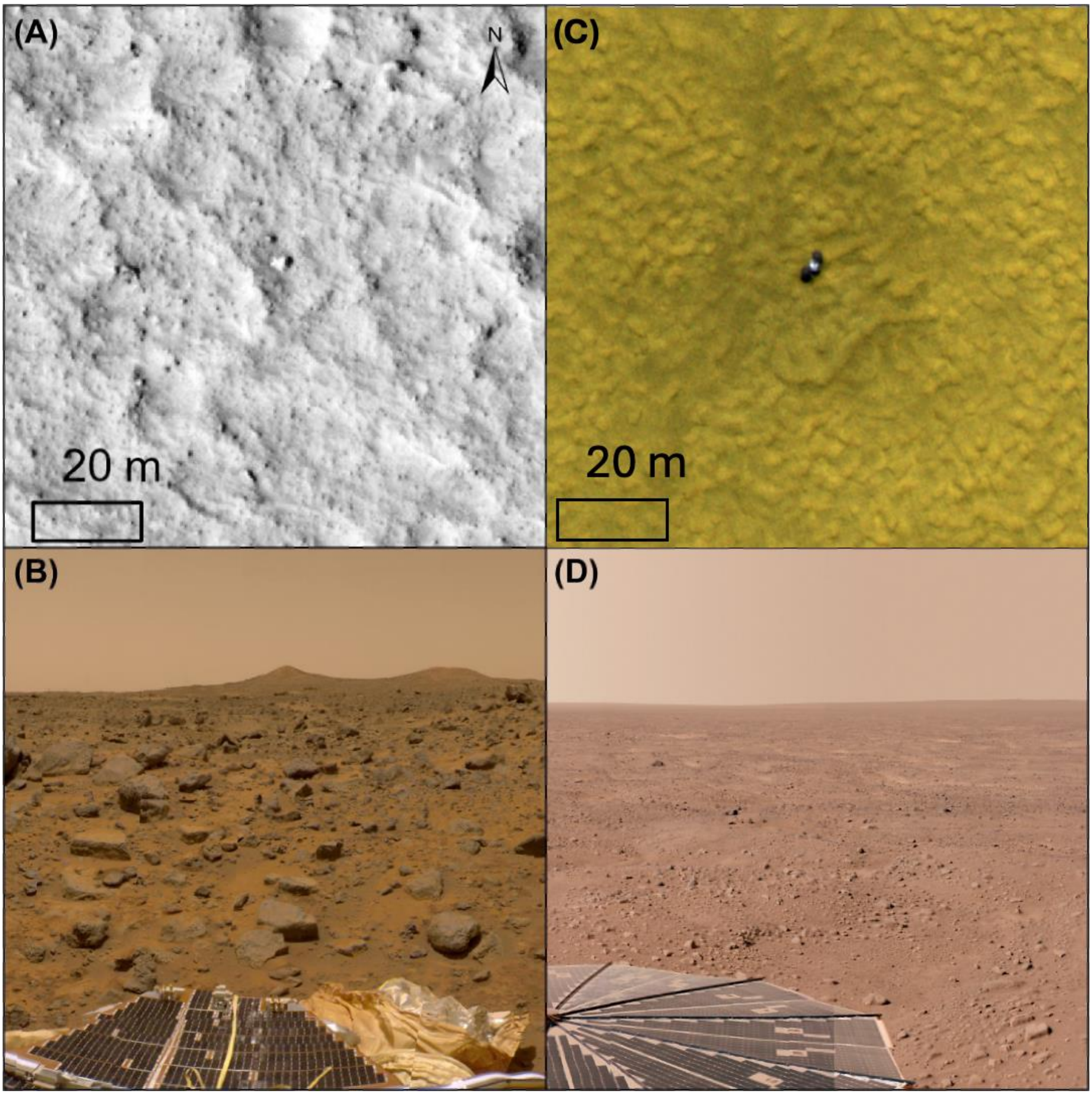
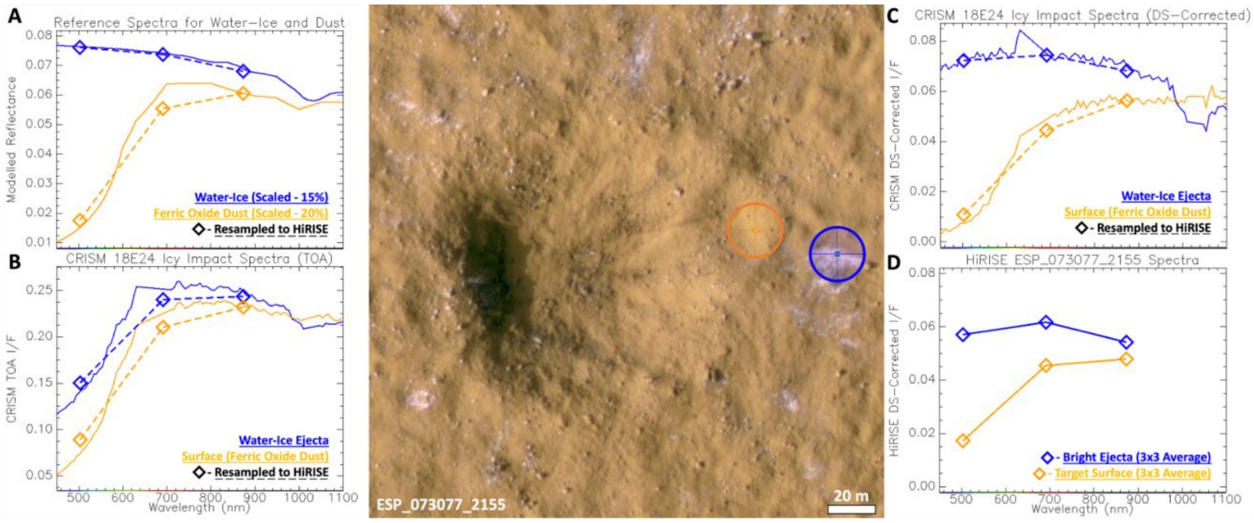


Figure 1. *Examples of the use of high-resolution images of landing sites to assess the occurrence of sub-metre to metre-sized boulder hazards. Left two images show the Pathfinder landing site, selected before sub-metre pixel scale imaging was available; right two images show the Phoenix landing site, selected after sub-metre pixel scale imaging became available. Mars scientists, engineers, and surface mission teams are facing the near-term loss of critical sub-metre pixel scale orbital imaging capabilities at Mars, as the HiRISE instrument approaches the end of its useful lifetime. (A) Sub-region of HiRISE RED image PSP_001890_1995 over the Mars Pathfinder landing site, taken long after the mission landed, which shows numerous metre-scale boulders at full resolution. (B) Part of a surface panorama (PIA00752) taken by the Imager for Mars Pathfinder instrument, looking SW. Metre-scale boulders are apparent, and would be considered a landing hazard if known at the time. For a mobile rover, such features would pose severe traversability issues. (C) Sub-region of HiRISE IRB image PSP_008855_2485 over the Phoenix landing site, which shows no metre-scale boulders at full resolution. HiRISE imaging was a critical dataset for identifying a safe landing site for Phoenix. (D) Part of a surface panorama (PIA11734) taken by the Phoenix Lander Surface Stereo Imager instrument, showing a lack of landing hazards at this location. Credit: NASA/JPL-Caltech/Univ. of Arizona.*

geometries. However, this orbital configuration should not come at the expense of stereo imaging capabilities, which are required for the generation of DEMs at 1 m/pixel. Stereo-pair images could be acquired via single-pass stereo imaging (e.g., with a rotating imager or slewing spacecraft), or via repeat-pass imaging. If the latter, carefully defined orbital parameters should ensure that suitably illuminated stereo pair images can be acquired within less than four weeks of the first image, and with suitable convergence angles to allow Mars scientists to generate high-quality digital terrain models with vertical precisions of tens of centimetres for detailed 3D analyses of the martian surface. A detailed study is required to ensure this can be achieved in non-SSO, else SSO may be required to facilitate and optimise stereo imaging. The spacecraft will need to provide sufficient roll capabilities and a high pointing accuracy to ensure precise image targeting spanning the equatorial region to the highest possible latitudes, including the poles.

Securing the future for safe landings on Mars and providing critical information for human missions to Mars.

High-resolution images are essential for identifying and certifying safe landing sites on Mars because boulders and other decimetre-scale features (e.g., aeolian materials and escarpments) represent critical hazards that can damage, immobilise, or even cause total failure of surface missions (Figure 1). 25-30 cm/pixel imaging has been proven as the ‘sweet spot’ for Mars landing site certification, which maximises information on terrain hazards without imposing unfeasible technological requirements, such as on the size of the optics and the stability of the spacecraft. High-resolution DEMs derived from stereo-pair images additionally reveal the magnitudes and distributions of hazardous surface slopes. ESA’s plans to implement novel automated technologies for guided spacecraft descent (an approach already adopted by NASA) will also require 1 m/pixel elevation information over a 5 km radius around landing targets. Given that the new ESA HRMI will have a swath of no less than 7 km, it would be able to satisfy this requirement in as few as four orbital passes over a target landing site if adopting a repeat-pass stereo approach. If a single-pass stereo imaging approach is adopted, the requirement could be achieved in two orbital passes over the landing site. It will also more rapidly satisfy the requirement to characterise hazards, in three-dimensions, over larger exploration zones across which missions may need to traverse to reach science targets perhaps tens of kilometres (and in future even hundreds of kilometres) from the landing site. The derived DEMs will also enable images to be orthorectified for more accurate geolocation of surface hazards and other features, which in turn could be used to photometrically correct the images for a more accurate surface reflectance representation (notably, only approximations or incomplete photometric corrections at this scale have been accomplished to date with the 3 bands of HiRISE). If a non-sun synchronous orbit is selected, repeat imaging under different illumination angles would maximise the ability to identify terrain complexities with different dominant orientations or aspects, and imaging at different times of day would allow characterisation of potential hazards posed by dynamic diurnal processes (e.g. frosts, atmospheric opacity, mass wasting, and dust devil activity) that pose hazards to surface missions and particularly to humans. Frost cycles are more pronounced and dynamic in the icy mid-latitude regions being targeted for human missions than they are at equatorial latitudes. In addition to hazard characterisation, high-resolution multispectral images and DEMs greatly enhance the ability to plan traverses to scientifically exciting targets within mission exploration regions. The accuracy of the DEM benefits from additional stereo pairs of the same area.



Credits: Livio Tornabene/UWO/SETI & NASA/JPL-Caltech/University of Arizona (see Figs. 3 and 4 in Rangarajan and Tornabene et al. 2024)

Figure 2. *Identification and multispectral characterisation of mid-latitude (35.1ºN, 189.8ºE) water-ice, which was exposed from the subsurface by a recent impact formed on December 24, 2021. This "Christmas Eve" impact was detected seismically by the Insight Lander (seismically) and visually by MARCI on MRO. The ability to detect the impact with context imaging (in this case from MARCI, but in numerous other cases from MRO Context Camera images) allowed rapid-response follow-up imaging of the crater by HiRISE (shown in the centre panel) to confirm that the impact had exposed subsurface ice (bright patches), before the ice sublimated or became obscured by dust. (A) Plot of Hapke-modelled reflectance spectra of 1000 µm water-ice particles (blue) and ferric dust (orange) at an incidence of 40°; this shows the shape of the curves that is expected for these materials – i.e. their 'reference spectra'. (B) Plot of CRISM FRT00018E24 Top Of Atmosphere (TOA) I/F spectra extracted from a site with a previously verified icy impact. (centre) Cropped enhanced-colour image of the Christmas Eve crater from HiRISE IRB image ESP073077_2155. (C) Plot of DS-corrected CRISM spectra extracted from the inside (blue) and outside (orange) the bright white ejecta of the previously verified icy impact crater.(D) Plot of the HiRISE DS-corrected I/F spectra from the locations shown atop the "Christmas Eve" crater (centre); the similarity to the CRISM-verified icy impact in panel C, and the reference spectra in panel A is clear. Credit: NASA/JPL-Caltech/Univ. of Arizona.*

International Mars exploration is on a trajectory towards higher-cadence (and lower-cost) robotic missions. Globally, space agencies and private enterprises alike are also seeking to qualify landing sites for higher-mass and eventual human missions. These ambitions bring new requirements for orbital landing site characterisation, including a higher rate of imaging, improved capabilities to monitor dynamic diurnal processes, and colour coverage which will be especially important towards identifying sites with accessible in situ resources required to support human missions. One such critical resource is water-ice, with the most likely source being shallow subsurface ice in the mid latitudes (e.g. Figure 2). In fact, high-resolution colour images have been identified as the most critical dataset needed to support a long-anticipated ice-mapping radar mission that has gained significant traction amongst the international science community and across several space agencies. High-resolution colour-infrared images will permit the disambiguation of shallow ice from boulder-rich and some mafic materials, which can have similar signatures in radar and multispectral datasets, respectively. These images will also enhance our ability to detect small-scale exposures of ice (for example, excavated by small fresh impacts), which serve as highly valuable orbital 'ground truth' for indirect ice detection methods (e.g., with radar and neutron spectrometers) (Figure 2). They will additionally ensure the continuation of our ability to identify surface morphologies that are only visible in decimetre-scale images, including - for example – spatially-extensive small-scale polygonal patterned ground, which is a key indicator for mapping near-surface ice that will be essential for future human exploration of Mars. While these and many other features appear small-scale in orbital images, such features are at a critical scale that can pose potential hazards for landing and traversing on the surface of Mars (e.g. compare Figures 2A and B).

The value of high-resolution imaging for underpinning the success of surface missions extends well beyond landing site identification and certification. In documenting the descent and landing of surface missions, and monitoring landing sites and hardware after a successful touchdown, or in the event of an unsuccessful landing, high-resolution orbital images provide high-value information for mission engineers developing future missions, see Figure 2. High-resolution images additionally provide high-value orbital context for surface mission operations; they allow for precise geolocation of rovers following traverses across the surface, for augmented geologic context for in situ measurements and/or sampling, and monitoring of dust dynamics that affect the efficiency of solar panels and the ultimate durations of solar-powered missions.

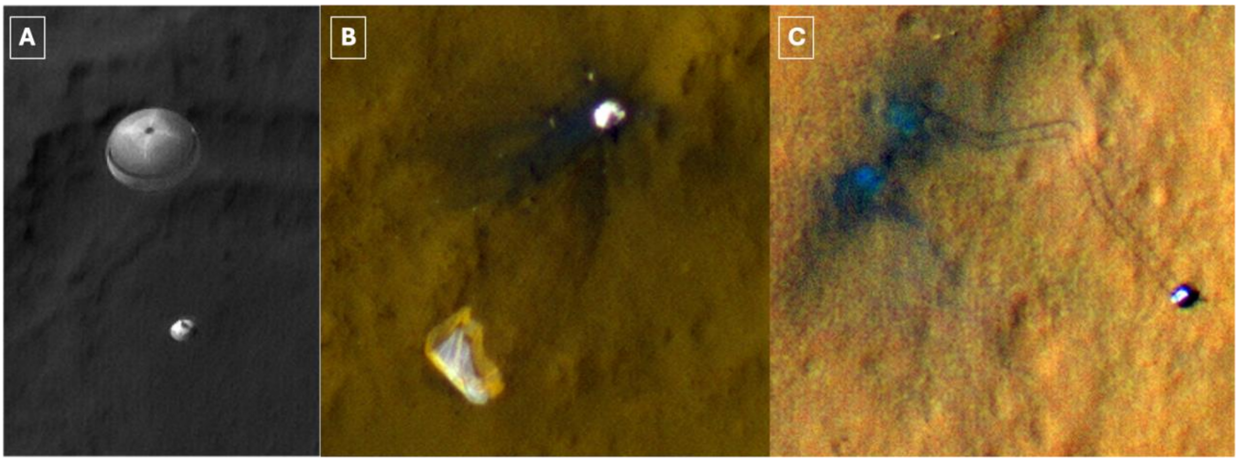


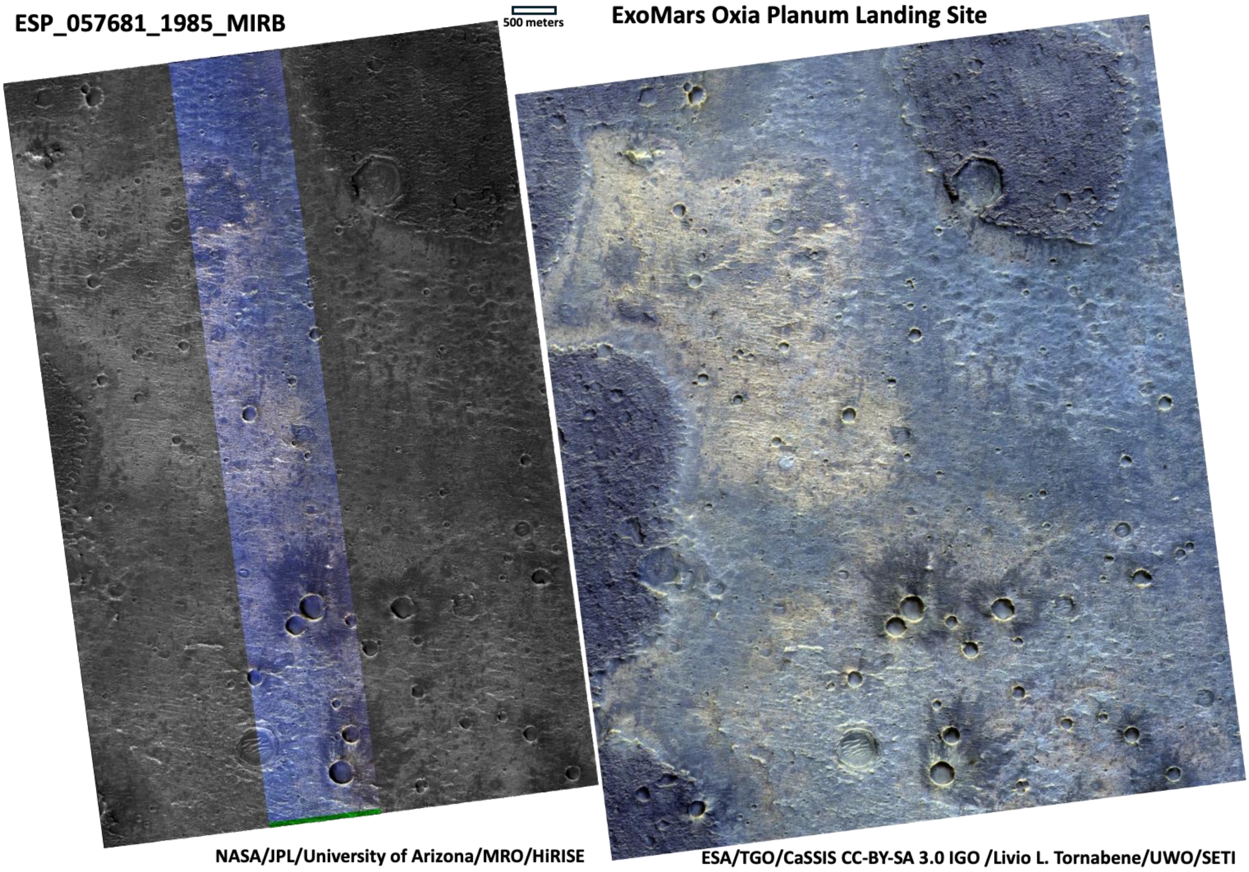
Figure 3. *HiRISE subset images of the Entry Descent and Landing (EDL) and first significant traverse of the Mars Science Laboratory "Curiosity" rover. (A) Shows the encapsulated rover while descending through the atmosphere on the parachute and about a minute before touchdown. The parachute is ~16 m in diameter. The parachute and rover were captured in HiRISE image ESP_028256_9022. The intention was to capture this image in colour, but the descent occurred further downrange than expected. If full-swath colour imaging had been possible (as proposed for HRMI), this image would have been in colour. Notably, this image was taken at a high emission angle and phase (almost 45º and over 90º, respectively). (B) Subregion of HiRISE IRB image ESP_028612_1755 showing the final resting place of the parachute and backshell on the surface. (C) The first extended traverse of the Curiosity rover ~4 weeks after landing. The rover is ~3 m wide. Rover tracks, while smaller than the pixel scale of HIRISE, are resolved due to their high contrast with the surface; likewise, the shadow of the mast and its suite of cameras atop the rover can also just be resolved. Credit: NASA/JPL-Caltech/Univ. of Arizona.*

Cementing ESA's position as an international leader in Mars science and exploration and ensuring European self-sufficiency in orbital support for next-generation surface missions.

The new ESA HRMI will provide unprecedented multispectral high-resolution coverage of the martian surface, enabling detailed characterisation of future landing sites, including for high-cadence, high-mass and eventual human surface missions. It would be the first decimetre-scale imager at Mars capable of obtaining high-value multispectral information – in stereo - over the full image swath. If a non-sun-synchronous orbit is selected, the ESA HRMI would also be the first decimetre-scale imager capable of characterising Mars, including landing sites and surface exploration zones, at different times of day. This will be particularly important for preparing for human exploration, as well as for high-priority science on dynamic surface and climate processes, and would satisfy ESA's request for imaging of landing sites at multiple local times to improve the detectability of hazards under different illumination geometries. The new ESA HRMI will enable European self-sufficiency in determining its future programme of Mars surface exploration, which has until now been heavily reliant on the High Resolution Imaging Science Experiment (HiRISE) on NASA's Mars Reconnaissance Orbiter. Over the last 19 years, HiRISE has cemented high-resolution imaging as indispensable for landing site identification and certification, and for advancing high-priority Mars science. It has supported six successful surface missions, four of which were supported from the landing site selection phase, Entry Descent and Landing (EDL) and throughout the science operations phase (Figure 1 and Figure 2). HiRISE has even aided with diagnosing and troubleshooting the causes of lost surface missions, such as Beagle-2, which, once considered a complete failure, is now considered ESA's first successful EDL on Mars thanks to the evidence subsequently provided in HiRISE imaging (https://www.uahirise.org/ESP_039308_1915). HiRISE continues to provide additional inputs for the landing site characterisation for ESA's upcoming Rosalind Franklin rover mission. HiRISE images have also become a critical dataset for the large and growing community of European Mars scientists who have built extensive expertise in Mars science, landing site analysis, and mission operations (both surface and orbital) required to support ESA's future programme of Mars exploration. Recently, however HiRISE has shown signs of more rapid degradation and may be nearing the end of its useful lifetime. Two charge-coupled devices (CCDs) have been completely lost, including one that was responsible for 50% of the already narrow colour swath, and more losses are anticipated within the next few years. High-resolution stereo imaging at Mars has been repeatedly identified across the scientific community and international space agencies as one of the highest priority scientific capabilities for next-generation orbiters, but no mission has yet been funded to secure high-resolution imaging beyond the impending loss of HiRISE. To date, HiRISE images cover only ~3% of Mars' surface (~4.7% including repeat imaging), and stereo-pairs cover less than 1%. Mars scientists and mission engineers the world over are therefore facing a loss of critical capabilities for addressing diverse science questions and identifying new landing sites that are not yet or insufficiently covered by HiRISE. If we do not secure the future of high-resolution orbital imaging at Mars, the next generation of surface missions to Mars is at significant risk, and the prospect of human missions to Mars will recede into the more distant future. The ESA HRMI, which not only replaces HiRISE but significantly advances on its capabilities, therefore provides an urgent and timely opportunity for Europe to provide international leadership for the future of Mars science and exploration for decades to come and to ensure that its future capabilities for safe exploration of Mars are self-determined.

Enabling world-class science and revealing Mars' colour diversity down to the decimetre scale, over spatial extents never seen before, and potentially providing unprecedented views of dynamic processes throughout the martian day and over seasonal to decadal timescales

The scientific potential of the ESA high-resolution imager is vast. New decimetre-scale coverage of Mars' surface will fuel exciting new scientific discoveries spanning geologic, cryospheric, atmospheric, climatic, and impact processes. This includes processes on contemporary Mars and extending across billions of years of its geologic history. The new imager will be capable of providing new high-resolution full-swath colour images in no less than 4 colour bands, and up to 4 or 5 times the coverage rate of its predecessor, HiRISE (Figure 4). HiRISE has fuelled over 2200 scientific publications despite covering only a small fraction of the surface. Requests for new HiRISE images are received continuously including from the science team, the international Mars science and exploration community, and the public, as current investigations expand, new scientific questions emerge, the next generation of scientists seek data for their research, and the public become ever-



ESP_057681_1985_MIRB

ExoMars Oxia Planum Landing Site

NASA/JPL/University of Arizona/MRO/HiRISE

ESA/TGO/CaSSIS CC-BY-SA 3.0 IGO /Livio L. Tornabene/UWO/SETI

Figure 4. *Comparison of the colour swath of HiRISE and the new ESA HRMI (illustrated here using a lower-resolution ESA Trace Gas Orbiter CaSSIS image) over a clay-bearing portion of the Oxia Planum landing site for the ESA's ExoMars Rosalind Franklin rover. Surfaces with abundant clays - significant targets for the rover's search for signs of ancient life - are represented in both colour-infrared images by a yellow-orange colour. They are consistent with CRISM detections of Fe-bearing smectite type clays. The comparison of the HiRISE MIRB browse image (ESP_057681_1985) shown on the left with a Colour and Stereo Surface Imaging System (CaSSIS) NPB mosaic (credit: ESA/TGO/CaSSIS CC-BY-SA 3.0 IGO/Livio L. Tornabene/UWO/SETI) cropped to a width of 7 km on the left, highlights the limitations of the 20% swath width colour coverage of HiRISE. Notably, HiRISE has recently lost the use of RED4 representing 50% of the IRB colour swath shown here (eastern- or right-most half of the colour strip shown above). ESP_057681_1985 was taken after RED9 failed, as clearly seen here with the greyscale portion of the image appearing narrower on its western- or left-most side. The image was taken in Bin1a mode, at ~25 cm/pixel and set to 30,000 lines providing an image length of ~7.5 km.*

more inspired by Mars science. The enhanced capabilities of the new high-resolution colour imager will inevitably increase the rate of requests for imaging, because of the even greater range of potential scientific investigations that can be undertaken with such an instrument.

High-resolution images reveal small-scale surface features which provide key information on the properties of near-surface materials, including their relationships to Mars' climate evolution, and reveal processes that have no analogue here on Earth. For example, spider-like 'araneiform' features at the south pole reveal the widespread occurrence of explosive CO_2 geysers driven by a greenhouse effect beneath translucent CO_2 slab ice. Aeolian bedforms record changes in wind directions over time. High-resolution images also enable analysis of detailed layer stratigraphies, for example of rock outcrops, the polar caps, and other ice and sedimentary deposits. The capability for metre-scale 3D analysis enabled by stereo-pair DEMs (Figure 5) further enhances such insights, for example allowing for inferences on the subsurface manifestations of layer stratigraphies (e.g., via orbital 'dip and strike' measurements), and advanced geomorphic analyses of terrain features.

Full-swath colour imaging (compared to just 20% of the swath width from HiRISE; Figure 4 - now reduced to 10% due to CCD failure) in at least four bands (thereby increasing the broad-band colour coverage at the highest resolution) will reveal new information regarding surface compositional diversity. It will additionally enable higher-confidence detections of water ice and other potential in situ resources and enhance our ability to identify scientifically exciting targets in landing zones for surface missions. High-resolution VNIR colour sensitivity in the 400-1100 nm range (e.g., HRSC, HiRISE and CaSSIS) has been shown to effectively extend spatially limited mineral/phase identifications provided by hyperspectral OMEGA and CRISM data. The VNIR sensitivity is especially effective for mapping ferrous mafic minerals (olivine, pyroxene, plagioclase) and altered ferric bearing materials (hematite, Fe/Mg clays, jarosite, etc.); however, some Fe-poor minerals (e.g., water-ice, chlorides, Al-clays, etc.) are also noted to have distinctive infrared colour signatures on Mars. High resolution colour images provide detailed views at higher resolutions than orbital spectrometers, combined with geologic context which further enhances compositional interpretations. As such, the ESA high-resolution colour imager will maximise our ability to constrain the origins of diverse surface materials reflecting the formation conditions, geological evolution, and past climate of Mars

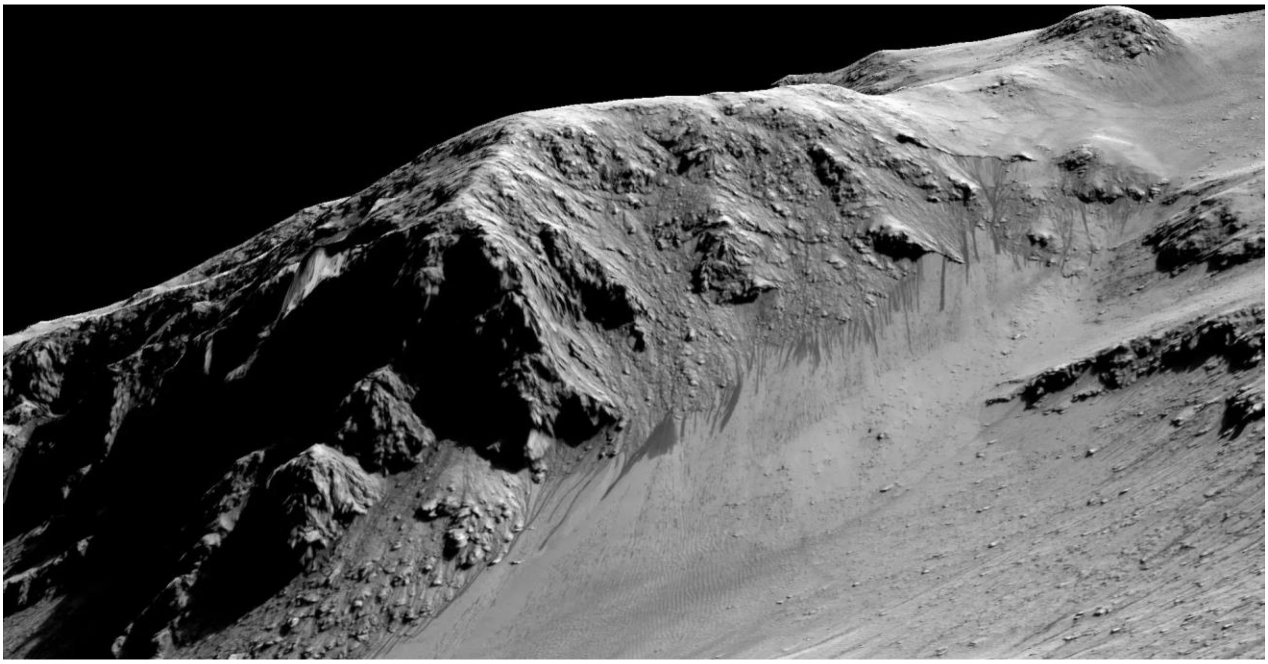


Figure 5. *Recurring Slope Lineae (RSL) in Horowitz Crater. A HiRISE RED orthorectified image (derived from PSP_005787_1475) atop a HiRISE stereo-derived DEM (DTEEC_021689_1475_020832_1475_A01) is shown here as a 3D perspective. Dark, narrow streaks that have been observed to appear and grow incrementally as a function of season and slope appear to emanate from the rubbly bedrock that comprises a small portion of the central uplift of Horowitz Crater. The streaks appear to flow downhill on the smoothest and steepest portions of the slope and have grown to this point up to 100 m in length. The vertical dimension is exaggerated by a factor of 1.5 compared to horizontal dimensions. Such elevation models allow detailed quantitative analyses in three dimensions to address many high-priority science questions; importantly, such information is often critical for connecting surface observations to inferences about the subsurface (e.g. via measurements of dip and strike of outcropping layers, and the geometries of tectonic faults). Credit: NASA/JPL-Caltech/Univ. of Arizona.*

A non-sun-synchronous orbit, one possibility under consideration for SpotLight, would allow imaging at different times of day for the first time at decimetre-scale. Mars is dynamic on diurnal timescales, and observing Mars at high resolution throughout the day would unlock a new understanding that is not possible with HiRISE due to its Sun-synchronous orbit (images taken at ~3 pm). This includes daily frost cycles, for example revealing the distributions of morning frosts, their compositions (H_2O or CO_2), and at what times they are present or absent, and their potential influence upon dynamic changes in surface features such as gullies and dunes. Polar scarp erosion is another time-dependent process for which at present we have little knowledge of behaviours at different times of day.

The new HRMI will also dramatically improve our ability to understand dynamic surface changes on Mars over longer timescales, from seasons to multiple decades. This includes processes such as migrating sand dunes, movements of materials on slopes (e.g., recurring slope lineae like those in Figure 5, mass wasting in gullies, landsliding, rockfalls, etc.) the formation and evolution of features in the polar regions, and recent impact events. In areas with pre-existing HiRISE images, the ESA high-resolution imager will extend the time separation baseline to multiple decades of observation, which is very likely to reveal surface changes that occur at slower rates than have been feasible to detect during the lifetime of HiRISE alone (for example the propagation or new formation of tectonic faults over timescales of decades, which the results of the recent InSight mission suggests could still be occurring). Elsewhere, where high-cadence time series imaging campaigns have been initiated with HiRISE, the longer the delay between the impending loss of HiRISE and next-generation high-resolution imaging, the more the science value of such time series will become compromised; this is just one example that underpins the scientific urgency of the new HRMI.

5.2. Colour Context Imager (CCI)

The proposed ESA Colour Context Imager (CCI) provides an opportunity to lead the next generation of scientific discoveries for Mars on a global scale, in addition to providing context-level information required for the identification and certification of landing sites. The CCI will not only provide colour knowledge across the full swath of a wide image (~22 km), but also use a multispectral approach with at least six bands at visible and near-infrared wavelengths, at an image scale of 2.5 m/pixel. A non-SSO orbit under consideration would allow the CCI to detect diurnal features (e.g. morning frosts) that would otherwise be missed, and to maximise the potential colour information with different illumination angles. Co-alignment of the CCI with the High-Resolution Imager will permit coordinated observations and enable science at a combined spectral and spatial resolution, and over spatial extents not previously achieved for Mars. The capability to acquire stereo context images (ideally in a single pass provided that this does not interfere with the HRMI) will allow high-quality digital terrain models to be generated at 5–10 m/pixel (depending on instrument design) for spatially-extensive 3D analyses of the martian surface at higher resolutions than has previously been possible.

Transforming the study of Mars through the use of spatially-extensive colour and stereo imaging.

After almost 20 years of observations, we have global coverage of the surface of Mars at moderate image scales (~5 m/pixel). This set of observations provides global-scale details of the morphology and Visible/Near-infrared (VNIR) brightness of the surface in greyscale (i.e., panchromatic, represented as a single wavelength). The current coverage of Mars in more than one wavelength

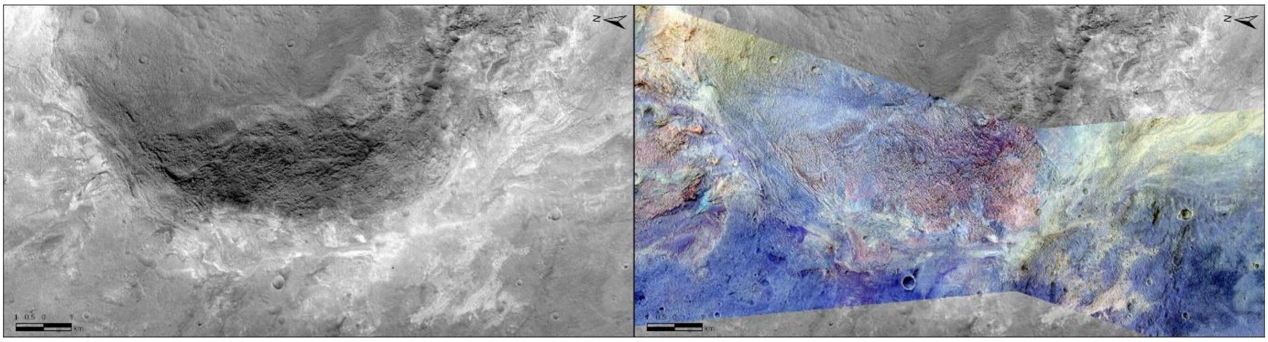


Figure 6. *Example of the advantage of colour imaging. (LEFT) CTX image (B12_014189_1528_XN_27S299W) of an area north of the Hellas impact basin, Mars, taken in a single, panchromatic filter. (RIGHT) CaSSIS false colour (near, pan, and blue filters) two-image mosaic (MY36_021373_333, MY36_022139_208) overlain on the same area. The significant colour differences are due to the presence of different minerals in the bedrock exposed at the surface in this region. The entire frame would be covered in a single CCI image, at a higher spatial resolution and in more wavelengths.*

(multispectral imaging) at the same image scale is less than 5%, and yet offers some of the highest priority scientific returns. The importance of multispectral (colour) imaging of Mars has been demonstrated at medium (e.g. HRSC on Mars Express: typically 25-100 m/pixel), moderate (e.g. CaSSIS on TGO: 4 m/pixel), and high spatial scales (e.g. HiRISE on MRO: 0.25 m/pixel). But crucially, these observations have only had either a large image swath with reduced spatial resolution, or high spatial resolutions with a reduced image swath. The combination of both resolution and swath is required to decipher the detailed geological record of Mars, combining both the compositional (i.e. colour) and geomorphological (i.e. context) aspects.

The ESA CCI will represent a step-change improvement in context imaging, using a minimum of 6 filter wavelengths in contrast to the single wavelength of the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX). The nominal ground sampling distance (GSD) of 2.5 m/pixel offers a factor of two improvement as compared to CTX images despite having a similar large image swath width (~22 km), and through stereo imaging will provide the required 10 m/pixel DEM GSD over a 30 km radius for landing site analysis. Depending on the design of the instrument, it may be possible to exceed this GSD requirement by an approximate factor of two (~5 m/pixel). Ideally, stereo imaging should be performed in a single pass, provided that this does not interfere with the operation or data quality from the High-Resolution Multispectral Imager.

The spatially-extensive surface topographic information provided by stereo context imaging (e.g. Figure 7) will maximise the value of the new colour information from the CCI by enabling better photometric correction. It will also enable scientists to undertake detailed 3D analyses of the martian surface over larger areas than with the HRMI alone, and at higher spatial resolutions than from previous context imagers. This includes by providing topographic information for geologic features on Mars which are larger than the footprint of the HRMI but are smaller than can be adequately resolved with current global-scale elevation information from Mars Orbiter Laser Altimeter (MOLA – hundreds of metres per pixel depending on latitude) or even HRSC stereo DEMs (50-100 m/pixel). CTX images have been used to generate 24 m/pixel digital elevation models for some areas of Mars. Stereo imaging at 2.5 m/pixel will enable spatially-extensive coverage of elevation information at 2.5-10 m/pixel (depending on the design of the instrument), while the higher Mars-Earth data relay rate will enable faster rates of new image coverage than has previously been possible. Hence the new ESA CCI will, with time, provide the highest resolution of spatially-extensive topographic information for Mars to date. Importantly, this will also provide spatially-extensive topographic information at similar spatial resolutions to next-generation very-high-frequency radar instruments which have been deemed of high priority for mapping shallow subsurface ice for potential in situ resource utilisation by human missions; DEMs with resolutions at or below the ground sampling distances of such radars enable robust interpretation of subsurface reflectors detected by orbital radar systems.

At the time of writing (Oct 2024), the CTX instrument has returned ~125,000 images of the surface of Mars, mostly at around 5-6 m/pixel, providing ~99% coverage. CTX has re-imaged ~80% of the surface at least once, with some areas imaged over 25 times, although the time between images varies significantly depending on the region and only a small proportion of these repeat images are suitable for the production of high-quality stereo DEMs at 24 m/pixel. Importantly, CTX images are taken in a single panchromatic filter representing the 500-800 nm wavelength range as one band or wavelength. In comparison, the ESA Trace Gas Orbiter (TGO) Colour and Stereo Surface Imaging System (CaSSIS) instrument has taken >42,000 images of Mars, at 4.5 m/pixel, with <5% cumulative coverage of the surface. However, CaSSIS images are almost always taken in 3-4 different wavelengths in the visible and near-infrared regions (bands at 495, 678, 836, and 939 nm), providing multispectral imaging capabilities. The scientific need for a dedicated context imaging instrument is demonstrated by the near-ubiquitous use of CTX, HRSC and/or CaSSIS images in scientific publications on Mars surface processes. This includes publications exploiting HiRISE data, for which more spatially-extensive context imaging is vital. In a similar way that CTX provides important contextual panchromatic information for HiRISE, the CCI will provide the required multispectral context for HRMI, as well as improving on the spatial and spectral resolutions of both CTX and CaSSIS. Crucially, the overwhelming scientific importance of multispectral observations is demonstrated by the ~150 publications and conference abstracts that are based on CaSSIS observations since reaching orbit in 2016. The new CCI will facilitate the next generation of such scientific advances.

Enabling a new era of scientific discovery through European experience and leadership.

ESA is in a unique position of being able to leverage recent and rapidly growing European experience (e.g. CaSSIS) to open up a new era of scientific discovery. Breakthroughs in our understanding of Mars will be enabled by the new CCI. The science enabled can be split into three main categories: (1) Discovery Potential, (2) Contemporary Science, and (3) Cross-Instrument Synergy. The ‘Discovery Potential’ science of the CCI is, by definition, difficult to quantify, but is based on the logic that a new parameter space is opened up when we are able to look at something in a way not done before. However, observations from current instruments (e.g. CaSSIS, Figure 1) clearly demonstrate that new discoveries will be made with the CCI. The ‘Contemporary Science’ of the CCI includes the more predictable breakthroughs in high priority science goals (e.g. MEPAG Goals), made possible by the ability of the CCI to address specific objectives. Finally, ‘Cross-Instrument Synergy’ science not only includes a joint operational philosophy with the High-Resolution Multispectral Imager and other instruments in the strawman payload, but also with the results from previous, complementary instruments.

Both surface and atmospheric studies can be carried out when using multiple wavelengths. For surface science, multispectral observations allow compositional analyses through colour differentiation of mineral groups that are not possible with a single wavelength. Identifying the diversity of minerals in bedrock allows the compositional stratigraphy to be determined, which informs both the recent and ancient evolution of the surface and subsurface environment. Spectral absorption features in the visible and near-infrared wavelengths are particularly adept at identifying ferrous and ferric compositions, although further intrinsic colour differences can be exploited when overlapping with longer wavelength hyperspectral data at lower spatial resolutions (e.g. OMEGA, CRISM). The use of at least six wavelengths for the CCI will not only allow convergence with previous instruments (i.e. HiRISE, CaSSIS), but also permit the selection of additional filters that specifically target diagnostic absorption features. This includes absorption features of aqueous minerals (e.g. H_2O bands at ~1000 nm), and those which can be used to discriminate between water ice and CO_2 ice to understand dynamic diurnal and seasonal processes and map potential in situ resources for human exploration.

Insights into atmospheric processes such as cloud dynamics, dust storm formation and evolution, dust devil monitoring, and frost formation have all been greatly advanced with spatially-extensive context imaging, though these insights are currently biased towards a single time of day (3pm from MRO/CTX), which is when some dynamic atmospheric processes (e.g. frost formation) are least active The recognition of many of these atmospheric features can be achieved through the use of different wavelengths in order to distinguish atmospheric phenomena from surface features. The CCI will offer the first opportunity to produce a near-global colour view at ~2.5 m/pixel, and at different times of day (if a non-SSO orbit is selected), which highlights compositional differences and is likely to precipitate a step-change in our understanding of the evolution of Mars. The CCI will help to unlock our understanding of the entirety of the history of Mars, from Pre-Noachian processes (e.g., responsible for diverse mineralogies around ancient impact basins), right up to active surface processes on modern Mars.

The large image swath and relatively frequent repeat image opportunities means that a CCI will not only be the main instrument for long-term monitoring of active surface processes on Mars (e.g. aeolian transport, gully activity and recurring slope lineae activity, frost cycles, polar processes), but also serve as the main method for initial identification of stochastic surface changes (e.g. new impact craters, especially ones bearing icy ejecta at the mid- to high latitudes – Figure 2). For example, at present, the vast majority of candidate new impact craters are identified in spatially extensive CTX imaging, before confirmation with targeted HiRISE images, the colour capabilities of which are also used to identify whether an impact exposes ice. However, this method relies on a sufficient albedo, or in this case colour, change occurring and being identified at CTX scale before it fades due to dust deposition. Multispectral observations of new impact craters with CaSSIS have demonstrated that colour differences significantly improve the detectability of such surface changes, including enabling easier identification of smaller impacts than with panchromatic imaging. The largest fresh impacts occasionally reveal patches of high-albedo materials which reach the scale of one or two CTX pixels. Hence, for the larger impact-driven ice exposures, the colour capabilities of the CCI may enable confirmation of ice presence in the same image in which an impact is first detected. The CCI colour capabilities will enhance the ability to identify fresh impacts and extend identifications to smaller crater diameters. This will allow constraints on contemporary martian impact rates – a fundamental new science result with wide-reaching implications for planetary science. Given that any landing site, either robotic or human, will require both short- and long-term monitoring of active surface processes over large areas (e.g. 100 km required for human exploration zones), then the use of a CCI is critical to enable high-cadence, spatially extensive repeat imaging over very large areas. Real-time monitoring of active surface processes is often possible with a colour imager, due to the inherent

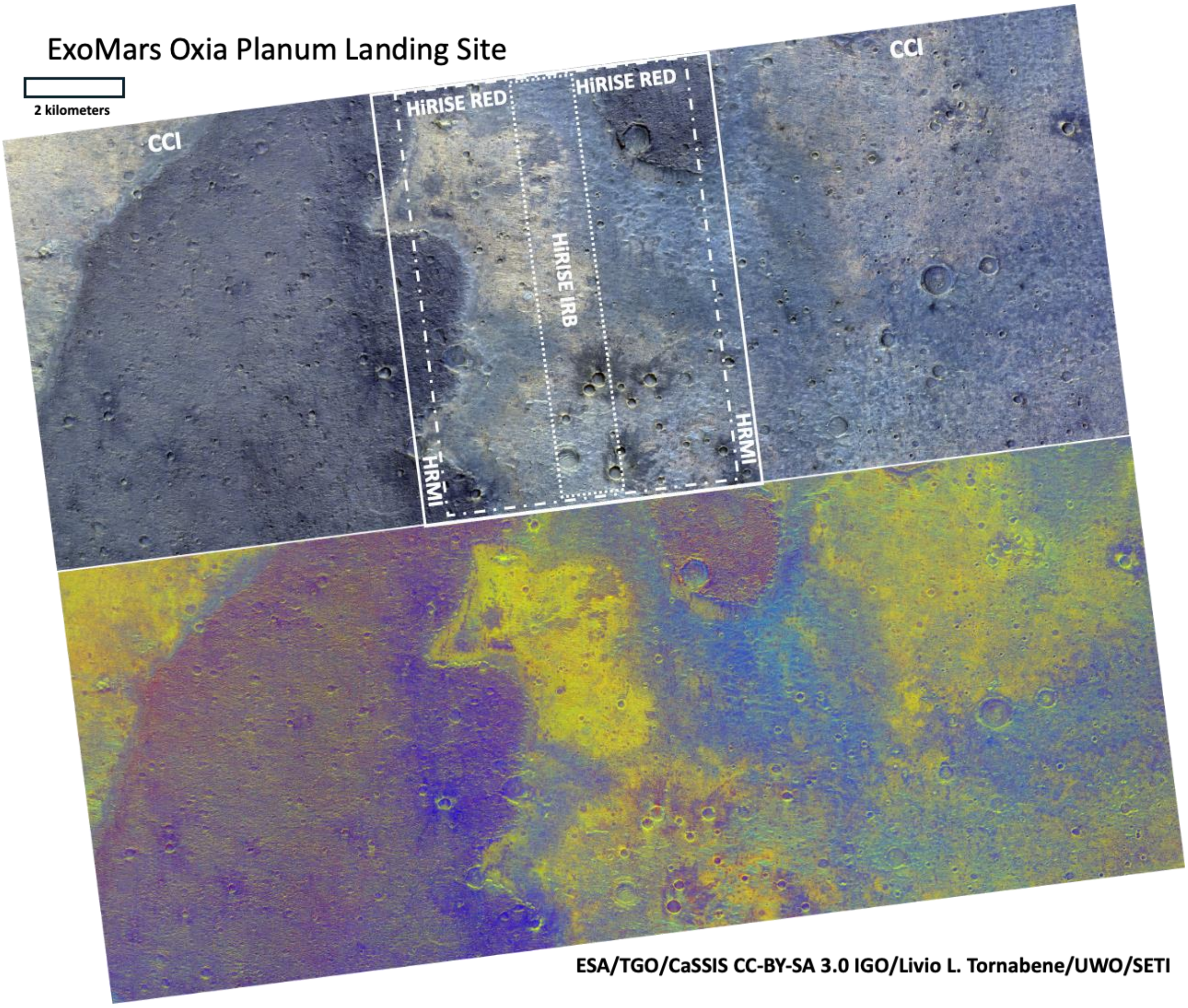


Figure 7. *The improved multispectral coverage of Mars that would be enabled by both the HRMI and the CCI, exemplified with a clay-bearing portion of the Oxia Planum landing site for ESA's ExoMars Rosalind Franklin rover. The suggested CCI swath width of ~22 km is shown here with nominal swath width of HiRSE RED (6 km) and IRB (1.2 km) and the suggested minimum swath width of the HRMI (7 km) for comparison. The top image is sourced from a mosaic of CaSSIS colour-infrared NPB and the bottom image is Colour Band Ratio Composite (CBRC; using RPR-PBR-PNR in R-G-B) image derived from CaSSIS data (credit: ESA/TGO/CaSSIS CC-BY-SA 3.0 IGO/Livio L. Tornabene/UWO/SETI). Comparisons of the two images highlight the colour and spectral mapping capabilities that could be provided by a CCI. CCI will take full colour images that are also suggested to be at least three times the along-track length of ~7.5 km shown here. Surfaces with abundant clays are represented in both images by a yellow-orange colour consistent with CRISM detections of Fe-bearing smectite type clays. Mafic surfaces such as olivine-bearing and basaltic surfaces are shown in blue and purple, respectively.*

instrument design leading to colour fringing (e.g. dust devil tracking revealing direction and velocity with HRSC and CaSSIS images), and a CCI would provide the opportunity for similar studies. The long temporal baseline of repeat imaging offered by the CCI will open new fields of study into slower surface processes, such as sublimation in polar regions, possible slope deformation, and other mass wasting processes that are likely undetectable over the timescale of a single imaging campaign (e.g. CTX, CaSSIS).

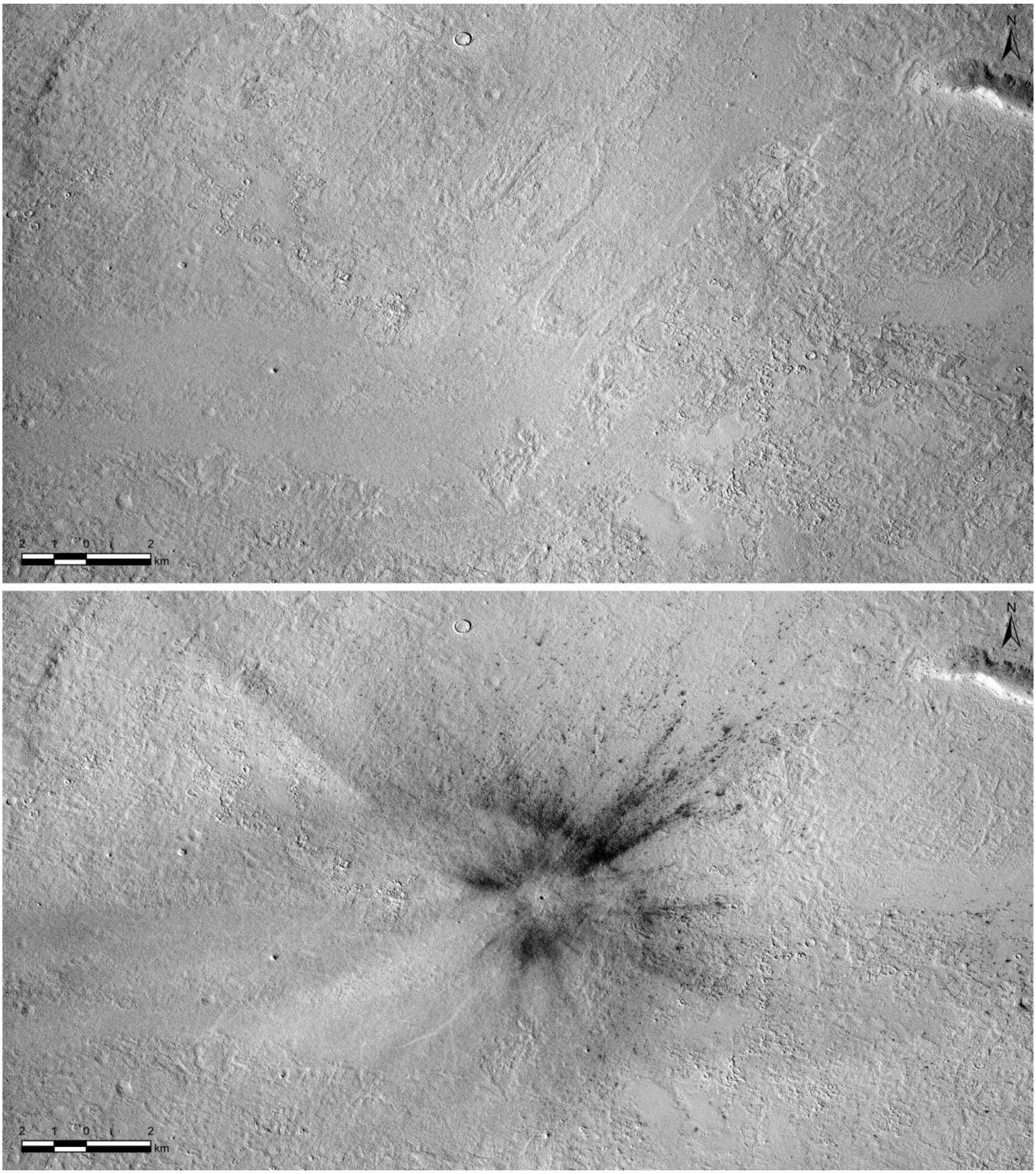


Figure 8. *Example of identification of a fresh, ~150 m diameter impact crater (35.1ºN, 189.8ºE) that was formed on December 24, 2021 (see Figure 2). (TOP) CTX image mosaic taken before the impact event. (BOTTOM) CTX image mosaic of the same region taken after the 24 December 2021 impact. The specific impact shown was first identified by the global MARCI imager, but the vast majority are smaller than this and are first detected by CTX. Coordination between context and high-resolution imaging allows rapid-response follow-up imaging to assess whether a fresh impact exposes ice (Figure 2), before the ice sublimates or is obscured by dust. Long-term monitoring allows the modern impact cratering rate on Mars.*

The recommended co-alignment of the CCI with the high-resolution imager will provide the required colour context for every high-resolution image, if required. Alternatively, reconnaissance imaging of larger areas at moderate resolution can be carried out with the CCI, before deciding whether to target an area with a high-resolution imager. This will greatly enhance the probability of capturing stochastic surface changes, and the capability to reactively target follow-up imaging with the High-Resolution Multispectral Imager and other instruments in the strawman payload. In addition, targeted stereo observations will allow simultaneous DEM production at the two different required GSDs, reducing the time taken to achieve landing site characterisation. Moreover, the stereo CCI digital elevation models will provide the required information on coarser resolution hazard analyses (e.g. slope at longest wavelengths) over a wide area in a single data product.

5.3. Imaging Spectrometer

An imaging spectrometer would greatly enhance the scientific insights that can be gained by SpotLight. The following is an example of an implementation for returning new, high-priority science which complements the HRMI and CCI. There are inherent trade-offs (e.g., spatial resolution, wavelength range, cooling requirements, gimbaling requirements) which must be considered when finalising any specific instrument design, including their potential effects on the HRMI and CCI.

Example instrument
A high spatial resolution imaging spectrometer from about 1 to 6 μ m with a spectral sampling around 10 nm is a key instrument to augment existing instruments and to perform new science on Mars, as well as to continue to assess the availability of resources vital for future human exploration.

Our knowledge of mineral diversity on Mars has rapidly evolved thanks to the data returned by imaging spectrometers such as OMEGA and CRISM. OMEGA (Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité) is the imaging spectrometer onboard the ESA mission 2003 Mars Express (MEX), which started its observations in early 2004. OMEGA covers the 0.4-5.1 µm range with a mean spectral resolution of about 15 nm and a spatial resolution ranging from about 0.4 to 2 km/pixel or more depending on the position on the MEX elliptical orbit at the time of a given acquisition. It has provided near-global maps (with 1-5 km spatial resolution) of martian minerals, surface hydration state and ices (H_2O and CO_2), as well as several atmospheric components. It has targeted selected areas at ~300 m spatial resolution.

OMEGA's most important result has been the first clear detections of aqueous minerals on Mars, including phyllosilicates and sulphates. Aqueous minerals are secondary minerals formed through the interaction between liquid water and the rocks of the crust. They are of primary importance to understand the history of water on Mars and to make inferences regarding the past climate and habitability conditions. Aqueous minerals are also targets of high value as resources for human exploration. CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) was the high spatial resolution imaging spectrometer onboard the NASA mission MRO (2005 Mars Reconnaissance Orbiter). It covered wavelengths from 0.4 to 3.9 µm at 7 nm/spectral channels in small, targeted areas with a spatial resolution between about 18 and 36 m/pixel depending on the observation mode. CRISM began its exploration of Mars in late 2006. It performed the first non-speculative detection of carbonates and other materials, e.g. serpentine, opaline, and a wider variety of phyllosilicates. CRISM unveiled the rich surface compositional diversity in the areas it targeted, providing precious hints to better constrain possible formation scenarios for surface and near-surface materials. The compositional information gained thanks to OMEGA and CRISM has played a crucial role in the selection of the landing sites for the Curiosity, Perseverance and Rosalind Franklin rovers. OMEGA

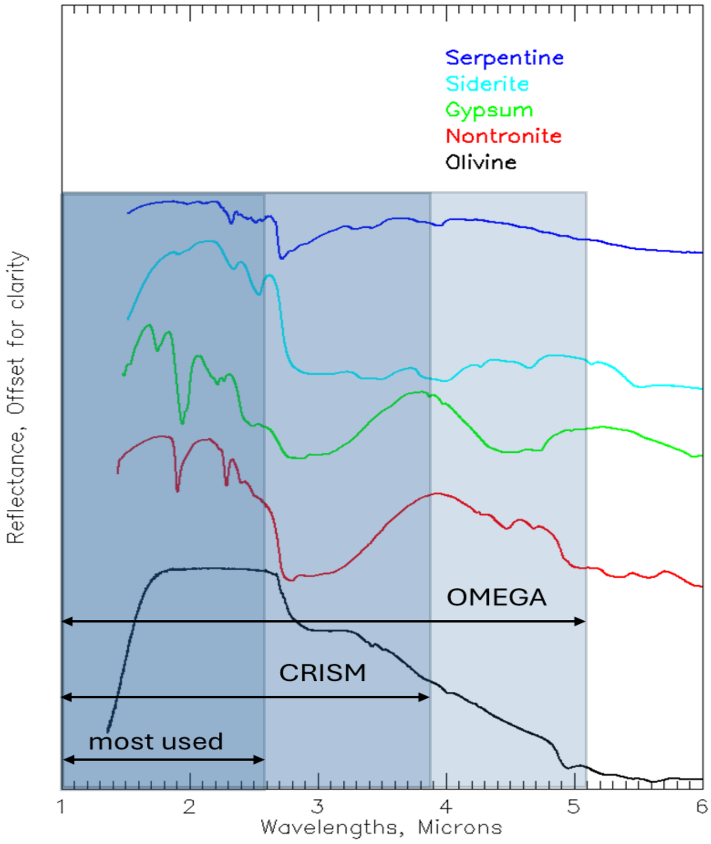


Figure 9. *Example of library spectra of some key minerals identified on Mars: an igneous rock (olivine, in black), two different types of clay (nontronite and serpentine, respectively in red and blue), a sulphate (gypsum, in green) and a carbonate (siderite, in light blue). Spectra are from the ASTER Spectral Library Version 2.0. The OMEGA and CRISM spectral ranges usually used to map hydrated phases on Mars is between 1 and 2.5 µm. Clear detection of carbonates in CRISM spectra was possible only in the first part of the MRO mission, when the CRISM cryocoolers were working properly and it was possible to better study the carbonate diagnostic spectral features in the 3-4 µm range. Though it has a wider spectral range than the CRISM one, OMEGA's spatial resolution is not sufficient to enable detections of carbonates and other key minerals*

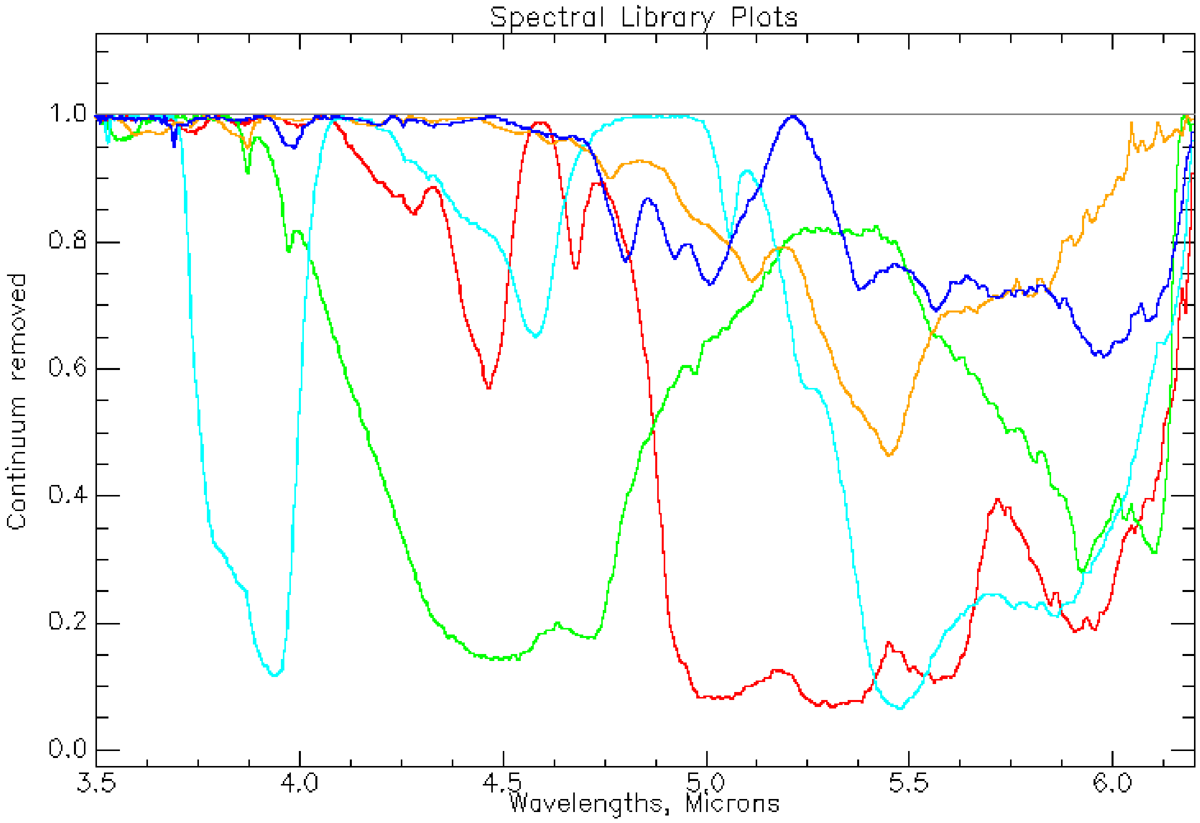


Figure 10. *Here some of the spectra from Figure 9 (clays: red and blue, carbonate: light blue, sulphate: green) are compared to the spectrum of a zeolite (orange). Spectra are from ASTER Spectral Library Version 2.0. These examples are representative for what we can derive thanks to the extended range to 6 micron, in particular when the continuum is removed The continuum has been removed to highlight and better compare diagnostic absorption features.*

and CRISM data in combination with morphologies from imagers have greatly improved our understanding of geological, cryospheric, and atmospheric processes (past and present) on Mars and the astrobiological potential of the planet. However, OMEGA and CRISM performances have decreased with time. The OMEGA spectral channel between 1 and 2.6 µm, the most diagnostic spectral range for hydrated mineral detections, is no longer providing data. CRISM, with all cryocoolers failed, is completely switched off now, and only specific locations have been targeted by CRISM at highest spatial resolution. Less than ~3% of the planet has been covered by CRISM at 18-36 m/pixel, so expanding this coverage will inevitably enable new discoveries, and will be essential to prepare for human exploration. Moreover, increased spectral coverage to longer wavelengths than OMEGA and CRISM is required to better assess and remove the Martian thermal contribution to the spectra that begins at ~3 µm and makes the precise identification of the position of absorption features in this range challenging if not accounted for. By extending the spectral coverage up to 6 µm it would not only enable us to derive surface temperature maps with an uncertainty of about 10K, which is the best uncertainty we can reach given the current uncertainty on the emissivity in this spectral range, but permit a thermal correction for a more accurate characterisation of diagnostic features in the > 2.5 µm range. This includes adsorbed water content based on the 3 µm band and better constrain the presence of water ice, carbonates and other key minerals.
The JAXA mission Martian Moons eXploration (MMX) to explore the two moons of Mars, with a planned launch in 2026, will host onboard the MIRS instrument. MIRS (MMX InfraRed Spectrometer) is an imaging spectrometer designed to study Phobos and Deimos in the 0.9-3.6 µm range with spectral resolution better than 20 nm and a spatial resolution better than 20 m/pixel. It will also observe Mars but with a spatial resolution of about 2 km/pixel when nadir pointing. Although this is an excellent instrument to learn more on the martian moons, its spectral range and spatial resolution are not optimal for the study of the surface of Mars. Table 1 below summarises the main characteristics of OMEGA, CRISM and MIRS the here proposed instrument.

The valuable new scientific insights arising from the colour capabilities of the HRMI and CCI would be even further enhanced when combined with hyperspectral information from a new Imaging Spectrometer. Together, they would provide a powerful suite of instruments for understanding the compositional diversity of Mars, via coordinated observations at various spatial scales and over large areas of the surface. Information from the near infrared up to about 6 µm is particularly critical to address high-priority science questions. Key minerals for understanding the aqueous and alteration history of Mars, such as carbonates, show diagnostic bands in the 3 to 6 µm spectral range, see also Figure 9. This extended range for identification of carbonates is particularly important because absorptions around 2.3 and 2.5 are ambiguous and may be caused by a combination or assemblage of minerals such as clays and zeolites. Distinguishing the precise minerals is crucial to constrain the processes that originated a given composition, as minerals form at different conditions of temperatures and pHs, thus allowing a better understanding of the environments that occurred on Mars and available resources. Detecting carbonate minerals is a long-standing goal for Mars science, and it will be important to improve their detections to truly understand their role in the alteration and climate history of the planet. Carbonates are expected weathering products of basalt under the CO_2-rich martian atmosphere under aqueous conditions. Due to the widespread near-surface aqueous alteration in the past, as testified by morphological evidence and the detection of phyllosilicates and sulphates, carbonate deposits are expected to be a dominant record. On the other hand, CRISM investigations have shown that carbonate-bearing rocks appear to be geographically restricted. Thanks to the absorption around 2.5 µm in combination with bands in the 3-4 µm range, carbonates were clearly identified in some specific locations in the first phase of the MRO mission, in particular in Nili Fossae. Unfortunately, the decrease in CRISM performance over time in the 3-4 µm range prevented a better understanding of the distribution of carbonates on Mars. In particular, carbonates have been hypothesised to be present in Oxia Planum, the landing site of the Rosalind Franklin Rover, due to the presence of a weak absorption around 2.5 µm and some indications in the 3-4 µm spectral range in CRISM spectra. However, the martian science community considers the presence of carbonates in Oxia quite speculative because of the lack of clear features in the 3-4 µm spectral range. A future imaging spectrometer able to study the 3-4 µm spectral range but also longer wavelengths is essential to better constrain the presence of carbonates on Mars and their formation scenarios.

Table 1: *A comparison of previous and upcoming imaging spectrometers with the example instrument described here.*

Instrument name/ Mission/ (Starting Observation)	Wavelength range Spectral res	Spatial Resolution pixel size	Used for	Current Status
OMEGA/ MEX (2004), ESA	0.4-5.1µm 15nm	400m to 2km-10km	First detection of clays and sulphates. Global maps of martian mineralogy; surface hydration states, day-time temperature and ices; atmospheric components at local and global scales; retrieval of thermal inertia in some specific locations; possible landing site identification.	1µm to 2.6µm channel not operational anymore
CRISM/MRO (2006), NASA	0.4-3.9µm 7nm	18m / 38m	First detection of carbonates and many other mineralogical phases. Local maps of martian mineralogy; surface ices; atmospheric components at local scale; landing site selection.	No longer operational due to Cryocoolers failure.
MIRS/MMX (2026 TBC), JAXA/CNES	0.9-3.6µm 20nm	2km for Mars observation	Study of Phobos and Deimos, the moons of Mars	To be launched in 2026, science targeting mainly Mars moons
Example instrument	1-6µm 10nm	≤ 20m	Continuing and improving key mineral detections (e.g. carbonates, serpentines, clays, sulphates, igneous rocks, oxides, opals) and their co-occurrence; local maps of surface mineralogy, day-time temperature maps, hydration state and ices; atmospheric components at local scale; possible retrieval of thermal inertia in some specific locations (pending modelling and observational strategy confirmations); landing site selection.	

A spectral range extended to up to 6 µm coupled with a spatial resolution of the order of 20 m/pixel, or better, is also key to better constrain the presence of water ice, particularly at low latitudes, and its availability for human exploration. Water ice shows diagnostic features at 1.03, 1.5, 2 and 3 µm that can enable us to distinguish and H_2O from CO_2 frost. The study of the 3 µm feature is critical to quantitatively evaluate the amount of available water ice through spectral modelling, but for this purpose the contextual estimation of the surface temperature around 5 μm is a fundamental requirement.

Another critical point for extending the spectral range of OMEGA and CRISM is to provide a better understanding of the distribution and formation of serpentine. Serpentine minerals form during hydrothermal alteration of ultramafic rocks at temperatures less than ~400ºC, and under aqueous conditions with high pH and low silica activity. The alteration of olivine-rich rocks to serpentine minerals through a process referred to as serpentinization could have influenced the distribution of habitable environments on early Mars. The influence of serpentinization on martian habitability and early atmospheric evolution is poorly constrained (and likely underestimated) by the available remote sensing data. Moreover, the serpentinization process also produces methane and it has been invoked as one of the possible mechanisms responsible for the enigmatic variability suggested for this trace gas in the martian atmosphere in the last two decades. The origin of possible transient methane in the contemporary Martian atmosphere remains one of the biggest mysteries for atmospheric scientists today. A future imaging spectrometer able to explore the properties of the martian surface in wavelengths up to 6 μm and with a spatial resolution better than 20 m/pixel will shed light also on the science linked to the formation of serpentines and implications for methane.

It should also be noted that imaging spectrometers provide the mineralogical interpretation for higher resolution broad-band colour imaging systems such as the High Resolution and Colour Context imagers. Recent work to extrapolate the spatial coverage of mineralogical identification and to provide higher resolution assessments of observed sites by fusing CRISM data with CaSSIS is proving to be extremely useful and possible to automate using machine learning-based tools. However, to perform this task, high signal to noise and good spatial coverage are needed from the imaging spectrometer to provide clear mineralogical identification.

In summary, a future imaging spectrometer for Mars with comparable CRISM imaging capabilities or even better but with a spectral coverage up to longer wavelengths will improve our understanding of:

- Surface daytime surface temperatures, providing maps for selected areas at a better spatial resolution than the 100m/pixel provided by THEMIS;
- Adsorbed water in the in the upper few microns of the martian regolith;
- The distribution of exposed water ice and frosts and, in combination with thermal maps, ice buried in the shallow subsurface (considered a vital in situ resource for human exploration);
- The distributions of key minerals for high-value science (e.g., carbonates, serpentines, phyllosilicates, sulphates, igneous rock, oxides, opaline); their assessment at a potential landing site is also essential to evaluate in-situ resources for future human exploration, as well as the science targets in the exploration zone;
- The co-occurrence of hydrated phases which form at different pH conditions, such as phyllosilicates and sulphates to better understand formation sequences.

As additional science, an imaging spectrometer at high spatial resolution in the near infrared to wavelengths up to 6 μm and a sampling around 10 nm can also contribute to the study of the Martian atmosphere, e.g.:

- airborne dust monitoring;
- water vapour retrieval;
- detection and monitoring of CO_2 and H_2O ice clouds;
- O_2 airglow at about 1.27 μm and correlation with O_3 is important to better understand martian photochemistry.

OMEGA and CRISM data have trained a wide community of new martian scientists in Europe, gaining wide-ranging expertise in martian science. Maintaining the exploration and study of Mars is crucial to maximise the science returned from in situ exploration by current and forthcoming rovers and landers, as well as to be prepared for sample return, and to pave the way for human exploration.

5.4. Doppler LiDAR for wind measurements

Lower atmosphere wind measurements

The strength and direction of winds throughout the atmosphere of Mars is arguably one of the least measured major parameters in the Martian atmosphere. Except for local measurements on the surface, from a very limited number of locations of landers and rovers, and for some values derived from occasional tracking of cloud motion at higher altitudes, the information on winds come as products of General Circulation Models (GCMs). Even if these data in general are believed to be broadly representative on a global level, they have never been verified by real measurements throughout the atmosphere. In the lower atmosphere and the near-surface region (boundary layer), the surface topography has a major influence on the magnitude and the direction of the winds. A strong diurnal variation is expected and is indeed also observed in the few local measurements existing from the surface. Significant variations with seasons can also be observed. Winds are key to understanding atmospheric transport and answering fundamental questions about the CO_2, H_2O, trace gasses and dust cycles that control the entire Mars climate. Knowledge about local winds is essential when studying the onset of dust storms and predicting when such storms will occur and how they will develop, a process presently by far not fully understood.

Technical and S/C safety related issues

A good understanding of winds, especially near the surface, is essential for planning and execution of safe landing and safe operations on the surface once landed. This is especially true for future human landings and surface expeditions. Assimilation of measured wind data into global or local circulation models will significantly enhance the confidence in these models, both in real time for safety for landed units and for high-priority scientific studies. Accurate wind profiles are essential for safe EDL phases, reducing uncertainties and improving the precision of landing manoeuvres. In future they will also be essential for launches off Mars. Real-time wind data assists in hazard avoidance during landing, ensuring the safety of the spacecraft and instruments. Wind data helps in predicting and managing dust accumulation on solar panels, optimizing power availability for rovers and landers. Understanding wind patterns can improve the reliability of communication systems by mitigating potential signal disruptions caused by atmospheric disturbances.

Atmospheric Dynamics

Accurate wind measurements help refine general circulation models (GCMs) of the Martian atmosphere. Improved models enhance predictions of weather patterns, dust storm formation, diurnal and seasonal changes. Mars experiences global dust storms that can obscure the surface and alter the atmosphere. Understanding wind patterns helps in modelling dust transport and deposition which has impact on the surface geology.

Measurements of wind speeds in the planetary boundary layer, where interactions between the surface and atmosphere are most significant is vital for understanding heat and momentum exchanges between the surface and the atmosphere which control turbulence and surface erosion processes. Measurements over various local times will allow monitoring of diurnal variations in wind patterns, providing insights into how the Martian surface cools and heats over a day, affecting the boundary layer dynamics.

Climate Processes

The Martian climate is influenced by complex interactions between the atmosphere, surface, and subsurface. Wind patterns affect the sublimation and deposition rates of the polar ice caps. Understanding these processes helps in studying seasonal variations in Martian climate. Wind measurements assist in tracking the movement of CO_2 between the poles and the atmosphere, a key component of the Martian seasonal cycle. Wind erosion and sediment transport patterns provide clues about the historical climate on Mars. Identifying current wind erosion features, offers insights into past atmospheric conditions.

Aeolian Processes, Erosion and Deposition

Wind measurements over time can track the movement of sand dunes and other aeolian features, providing data on sediment transport rates and mechanisms. Measuring the wind speeds and patterns associated with dust devils, can help in understanding their formation, structure, and contribution to dust lifting – a key control on contemporary martian weather and a key parameter for modelling long-term climate evolution and volatile cycling. Continuous wind measurements help in studying erosion rates and landform changes over time, contributing to our understanding of the related surface processes and martian climate and geologic evolution.

Instrument and measurement technique

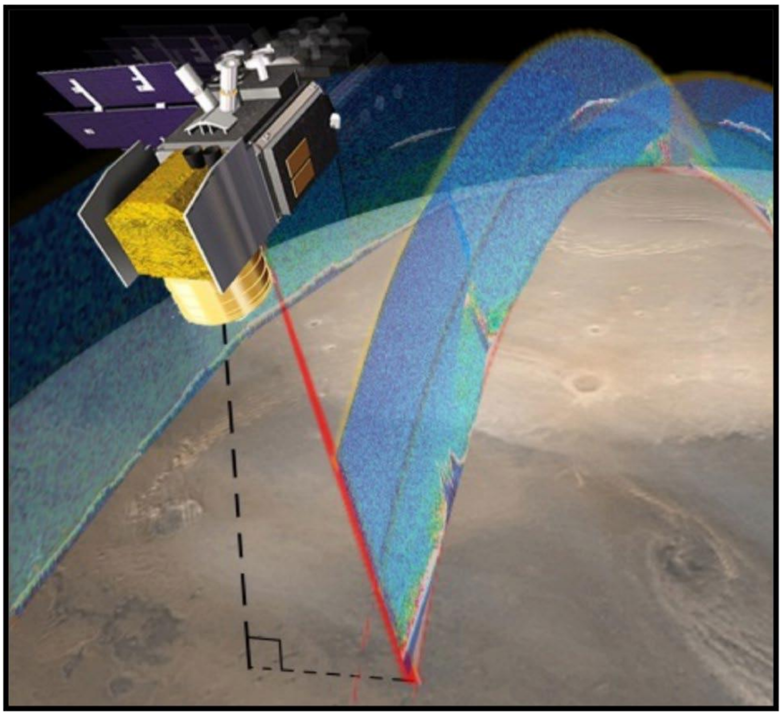


Figure 11 *Artist's impression of MARLI on a spacecraft in low Mars orbit. From Cremons et al., Proc. SPIE 10791, (2018). The laser beam is directed about 30 degrees off Nadir, in a cross-track direction in order to minimise the Doppler shift caused by the Spacecraft velocity. The Horizontal wind speed will be derived from the Line-of-sight vector along the laser beam, in the first approximation by assuming that the horizontal wind is much larger than the vertical winds. In the first instance these data will be assimilated into general circulation models and so improve their confidence, and after many wind profiles have been accumulated, over a representative set of local times and over the seasons a full averaged measured wind field can be assembled.*

Aerosols and atmospheric dust

By the nature of how the winds are measured, through backscattering of a laser beam from dust particles and water and CO_2 ice particles in the atmosphere, these particles and their location and concentrations is mapped in three dimensions, and time, throughout the atmosphere. This provides ample data for analysis of the water and CO_2 balance and its dynamics over short, medium and long timescales. It also allows detailed studies of atmospheric dust, which in combination with the wind measurements will enable a better understanding of the processes related to dust lifting and the onset, persistence, and settling of dust storms both at local, regional and global scales. Data from the on-board Imagers and the IR spectrometer will make additional important contributions to solving this enigma.

Measurements of winds will benefit strongly from measurements taken at different local times, as there are strong variations in both the direction of the wind and of the windspeed throughout the day, with very low windspeeds during the night but with a notable increase soon after sunrise. The low altitude wind patterns are strongly dependent on the local topography and therefore will be distinctly different for each location on the surface.

Winds have so far not been measured from orbit on any planet except the Earth. The Aeolus mission in Earth orbit provided excellent data on winds in the Earth atmosphere, but this instrument is far too massive and complex to fly to Mars. Aeolus used Rayleigh scattering from air molecules as its main measurement principle, and therefore required to operate at UV wavelength. At Mars, in the altitude range concerned here, there are sufficient amounts of dust and one can rely on Mie scattering, and thus can operate at visible or near IR wavelengths. This allows for a significantly easier implementation. The receiver on board will derive the Doppler shift along the line of sight from the returned laser pulse where the distance is measured by time of flight of the laser pulse. The laser beam is oriented cross track of the satellite ground track and 30° from Nadir direction, see Figure 11.

An advanced Doppler Lidar design for planetary space flight is being developed and tested by NASA/Goddard, the Mars Lidar (MARLI). A similar development has been taking place in LATMOS (France) that was funded by CNES, the Mars Orbital Wind Lidar (MOWL). A different, completely new, approach is taken by a German-Latvian consortium, funded by ESA, using a non-Doppler based Lidar technique, employing a Cross-Correlating method to derive similar results as from the Doppler Lidar. This technique allows significant simplifications in the hardware and a less massive instrument, however the TRL level is still lagging the Doppler Lidar based instruments.

6. ORBIT DISCUSSION

The MDT considered the advantages and disadvantages of Sun-synchronous and non-Sun-synchronous orbits (SSO and non-SSO, respectively) for achieving the exploration-focused and exploration-enabled objectives in Chapter 3. These are summarised in Table 2, noting that specific differences are dependent on the specific orbit selected, the capabilities of the s/c (e.g., roll capabilities) and the approach to s/c operations. Some of these nuances are explained in the footnotes to Table 2. See also Chapter 4 (Instrument Science Cases). Some science objectives in Chapter 3 (particularly those requiring imaging at different local times) require a non-sun-synchronous orbit. Others could be achieved in either SSO or non-SSO, though one or other orbit may be better optimised for achieving specific objectives or investigations.

It should be noted that current surface missions benefit from predictable overpasses from orbital spacecraft at particular times of day for data relay. However, in this case LightShip would provide data relay, reducing this requirement on SpotLight.

***Table 2**: Summary of advantages and disadvantages of Sun-synchronous and non-Sun-synchronous orbits. Items in blue are those that benefit exploration-focused objectives, while those in orange could raise challenges for exploration-focused objectives.*

SSO advantages	**Non-SSO advantages**

Consistent local time of imaging [1, 2, 3, 4, 5]
• More frequent opportunities for repeat imaging with similar lighting conditions[1]
  • For timely stereo-pair completion (for DEM generation), if repeat-pass stereo imaging approach adopted [2,3]
  • For ease of detecting changes between images, and performing time-series analyses[4]
  • Facilitates easier construction of seamless image mosaics with consistent illumination[3, 4]
  • If local time of imaging is 3pm like MRO/HiRISE, more frequent opportunities to extend time-series imaging and change-detection over a wider range of Mars years (up to several decades).[3]
• The local time can be selected to reduce the effect of diurnal processes such as frosts, fogs, dust and clouds on views of the surface[5].
	Imaging possible at a variety of local times [5, 6]
	• Allows characterisation of conditions at different times of day, and at times not observed by HiRISE[5,6].
	  • Some images could be taken to match HiRISE local time (extending time-series imaging from HiRISE), while others could be taken at different times.
	  • Images can be acquired at times of day when diurnal processes such as frosts, fogs, dust and clouds have minimal effects on the ability to view the surface, as well as at times of day when these processes are more active (valuable for environmental monitoring and science).
	• Imaging possible under a greater diversity of illumination conditions.
	  o Creates opportunities to enhance SNR for filters with low response from the surface (Blue-green, NIR etc.).
	  o Enables characterisation of the opposition surge effect, providing additional constraints on surface physical properties.
	  o Reveals linear features that may be obscured where they align with an unvarying solar azimuth in SSO; provides opportunities to characterise hazards and terrain features with different geometries and aspects.
	  o Provides opportunities to image surfaces with a range of aspects when they are well-illuminated, including slopes that would be consistently shadowed when taken in SSO.
	  o Provides opportunities to image near-equatorial surfaces at high incidence/phase angles, providing better information on surface texture.

SSO disadvantages	**Non-SSO disadvantages**
Consistent illumination conditions mean that some terrain features may not be clearly seen, particularly linear features aligned with the solar azimuth.	Fewer opportunities for repeat imaging with similar lighting conditions [1,2,3,4] • If a repeat-pass stereo imaging approach is adopted, fewer opportunities for completion of stereo-pairs[2, 3] • Change detection and time-series analysis is more challenging if illumination conditions change between images[4]. Repeat imaging with similar lighting conditions will be possible, but the number of opportunities likely fewer than in SSO. • Harder (or likely to take longer) to construct seamless image and DEM mosaics, or mosaics in which the illumination conditions are spatially consistent[3,4].
Only allows characterisation of Mars at a single local time [5] • Some near-equatorial surfaces remain in shadow (e.g, 3pm images show east-facing slopes in shadow). • It is not possible to characterise surface and atmospheric conditions at different times of day, including those which may pose hazards to surface missions.	
Inability to image at very different incidence/phase angles: • Inability to image surfaces at very low incidence/phase angles reduces ability to characterise surface properties such as composition and colour diversity • Inability to image surfaces at high incidence/phase angles reduces ability to characterise properties such as surface texture	
Less flexibility in the selected orbital inclination[7] • Spacecraft must be in a polar orbit	More flexibility to select orbital inclination [7] • Could select an orbital inclination that is required for particular kinds of observations, and/or to decrease spacing of successive orbital passes over a particular part of the planet[7]

Footnotes:

1. The specific difference in the number of opportunities for repeat imaging with similar lighting conditions is dependent on specific orbit parameters of the spacecraft and how it is operated, including e.g. roll angle, footprint size (altitude) and whether the orbit is allowed to drift. Note that specific lighting conditions do change seasonally in SSO.
2. If stereo completion can be achieved within a single pass, then challenges of changing illumination between images in a given stereo-pair do not apply. However, they remain relevant if constructing DEMs from multiple stereo pairs.
3. While individual DEMs can be mosaicked together to cover larger regions, a different approach is to bundle-adjust several stereo pairs together (generating stereo-pair mosaics of larger areas) to generate a single continuous DEM from multiple stereo-pairs. This is better achieved if adjacent images in each stereo pair have similar illumination conditions.
4. Automated procedures could allow images to be systematically acquired when viewing/illumination conditions are appropriate for a given objective. This could allow image mosaics of quality similar to those obtainable in SSO to be generated in non-SSO – an approach that has been successfully implemented with CaSSIS. A similar approach could be adopted for change detection and time-series imaging if the area is large, or by an easily implemented highest priority acquisition policy for individual images if the area of interest may be covered by a single image. Regardless, generating seamless image mosaics is generally easier in SSO.
5. HiRISE has a local time of imaging of 3pm, which may be optimal to reduce the effects of diurnal frosts, fogs and dust cycles on the ability to view the surface. A local time of imaging that is different to 3pm HiRISE imaging could be selected. However, this is not recommended if imaging is only possible at a single local time. While diurnal processes are scientifically interesting in their own right, imaging only at e.g., 9am would likely compromise the other surface science that could be achieved if imaging at a different time of day was not an option.
6. While non-SSO allows views of the surface at different times of day, with a single spacecraft it still poses challenges for distinguishing dynamic diurnal processes (e.g., slope mass-wasting) from seasonal or stochastic processes. This is because due to insufficient frequency of repeat coverage at sub-diurnal timescales. Generating time series through a single martian day would require multiple spacecraft with the ability to perform coordinated observations of the same site on the same day. Nonetheless, images taken at different times on different days would allow for characterisation of conditions at different times of day (e.g. presence/absence of frosts, number of dust devils) taking account of seasons, and provide new high-value scientific insights.
7. A sun-synchronous orbit requires a particular (polar) orbital inclination. A non-SSO can have a different inclination, as with ExoMars Trace Gas Orbiter (TGO), where an orbital inclination of 74° was selected to enable science to be performed with solar occultations with the NOMAD and ACS instruments. For a surfacing imaging-focused mission such as SpotLight, a polar orbit similar to that required for SSO is likely to be optimal, as this would enable imaging of all regions of the planet, including the poles.

In view of the above, the MDT recommends a non-Sun synchronous polar orbit if both HRMI images of any stereo pair can be acquired in the same orbit, or if stereo-pair images can be acquired in different orbital passes but sufficiently close in time that changes in illumination and surface conditions (e.g., seasonal processes) do not significantly affect the quality of the resulting DEMs. If single-pass stereo imaging is not possible a detailed study should be carried out to investigate if sufficient stereo pairs can be acquired in different orbital passes but with conditions (e.g. illumination and convergence angles) good enough to construct DEMs of sufficient quality for fulfilling the requirements on preparation for future landings. It would be beneficial if the s/c can be designed to be able to operate in both SSO and non-SSO, and possibly also be able to change between the two during the mission.

7. INSTRUMENT PARAMETERS AND REQUIREMENTS

7.1. High-Resolution Multispectral Imager (HRMI)

Instrument parameters and requirements		
Operations philosophy	Push broom line scan	Minimum 4 colours
Stereo imaging at subsequent orbit or in same orbit		Difference in phase angle between the two images linearly varying from +/- 5° at 20° phase to +/-20° at 70° phase angle and above.
Wavelength range	400 nm – 1100 nm	Minimum
SNR	≥ 100	@ 1.52 AU, 45° phase angle, bright Mars spectrum for all colours
Absolute radiometric accuracy	4%	
Relative radiometric accuracy	2%	
Phase angle diff.	≤1°	Max. difference between any filter for the same scene
FOV cross track	≥ 1.6°	All colours (= Swath width 7 km at Nadir from 250 km)
Resolution	≤1.5 µrad	at 600 nm, Diffraction limited
Angular pixel scale	≤1 µrad	
Swath length	≥ 24 km	
Maximum slant range difference	60 km	Between individual images in any stereo pair
Surface coverage	2%	of Martian surface per Mars Year
Calibration req.	once per month	stellar and planetary
System Requirements		
Mass	60 kg	including margin
Volume	1x1x1.8 m	Long dimension along optical axis. Electronics included in over-all dimensions.
Power	45 W operating	25 W standby
Data rate to s/c	100 Mb/s	4 images per orbit 12 orbits per day 3 colours 16000×50000px 4 bits per pixel (SpaceWire assumed)
Data volume	500 Gbit/sol	assumed compression: 3-12
Thermal ref. point	<250K	@20 W heat load

7.2. Colour Context Imager (CCI)

Instrument parameters and requirements		
Operations philosophy	Push frame or push broom line scan	Minimum 6 colours
Single pointing, aligned with main telescope		In-orbit stereo imaging if it can be demonstrated that it is not disturbing the HRMI
Wavelength range	400 nm to 1100 nm	minimum, possible extension to 2000 nm
SNR	≥100	@ 1.52 AU, 45° phase angle, bright Mars spectrum, for all colours
Absolute radiometric accuracy	4%	
Relative radiometric accuracy	2%	
Phase angle diff.	≤3°	Max. difference between any filter for the same scene
FOV cross track	≥5°	~22 km swath width at nadir from 250 km
Optical resolution	≤15 µrad	FWHM
Angular pixel scale	≤10 µrad	
Maximum slant range difference	60 km	Between individual images in any stereo pair
Calibration req.	Joint with main imager	aligned with High-Res Imager
System Requirements		
Mass	20 kg	including margin
Volume	80x50x25cm	Long dimension along optical axis
Power	25 W operating	
Data rate to s/c	100 Mb/s	SpaceWire assumed
Data volume per day	100 Gbit/sol	assumed compression 3-12
Thermal reference point	≤200K	@5 W heat load

7.3. Complementary instrument (1): Imaging Spectrometer

Instrument parameters and requirements		
Operations philosophy	Push broom	
Wavelength range	1-6 µm	minimum
Calibration req.	Phobos, stellar	
System Requirements		
Mass	48 kg	including margin
Volume	90x80x40cm	upper limit tbc
Power	30 W	Peak
Data rate	100 Mb/s	
Data volume per day	50 Gbit/sol	170 MByte per cube
Thermal reference mounting point	TBD	

7.4. Complementary instrument (2): Wind LiDAR

Instrument parameters and requirements		
Operations philosophy	Side looking Laser, Doppler velocity	
Viewing Direction	30° off Nadir, cross track	
Horizontal wind measurement precision	+/- 2.5 m/s	0-15 km
Calibration req.	Internal only	
System Requirements		
Mass	36 kg	
Volume	80 x 80 x 70 cm	
Power	81 W	
Data rate	50 kbit/s	
Data volume per day	2 Gbit/sol	
Thermal reference mounting point	Not required	

8. SPACECRAFT AND MISSION REQUIREMENTS

Orbit	250 km circular	250-280 km acceptable
Inclination	90°	85° – 95° acceptable
Type	Non-Sun-sync preferred	
Ground track repetition rate	Non-repetitive preferred	
Pointing stability	≤0.5 µrad in 10 ms	
	≤10 µrad in 10 s	
Pointing accuracy, Absolute	≤200 µrad	
Pointing accuracy, Relative	n/a	
Off Nadir pointing capability Roll	≥+/-30°	
Off Nadir pointing capability Pitch	≥+/-3°	
Fixed Yaw operation capability, duration	yes, ≥1 minute	
Slew rate	≥10° per minute	
Settling time	≤5 minutes	

9. NOTES

In the requirement specifications in sections 7 and 8 above, relevant parameters are generally expressed in angular size, assuming the specified orbit parameters, with the altitude assumed to be 250 km. They may be translated into corresponding dimensions on the surface of the planet to allow freedom for choice of orbit. If, however, the orbit would be higher than 250 km, the angular sizes will need to be adjusted accordingly. The orbit altitude should however not exceed 400 km as that will require more power for the laser and/or a larger telescope for the receiver and force the LiDAR to be modified.

At the time of the writing of this report it was not known if ESA will ask industry to provide the High-Resolution imager and the Context Imager, or if there will be an Announcement of Opportunity opened to the scientific community to propose to provide these instruments. If these instruments will become part of an industrial contract, the MDT strongly recommends to ESA to establish a scientific advisory group that will follow the development of these instruments, from the early development to the final testing and in-orbit commissioning. The setup should be such that the advisory group is sufficiently informed at all stages and that there is an agreed procedure for how recommendations from the advisory group are taken into account and implemented.

10. DOCUMENTATION AND REFERENCES

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