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In-situ Investigation of Mars atmosphere and ionizing radiation environment through a distributed network of Tumbleweed Measurement Stations

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Abstract

The state of Mars' present day atmosphere is integral to forming a complete understanding of its climate, including the possible emergence and evolution of biological life. Investigating atmospheric characteristics at various scales is essential for enabling an effective, holistic understanding of the Martian climate, surface environment and habitability. Additionally, the ionizing radiation environment is one of the main factors impacting surface habitability and atmospheric loss. Long-term exposure to ionizing radiation poses concerns for future human exploration. However, given the sparse and incomplete nature of present environmental datasets, creating sufficiently accurate, detailed and complete models of atmospheric processes and interactions is not feasible. Till now, most investigations of Mars' atmosphere have been limited to orbiters and solitary landers or rovers, which leaves a considerable gap in the ability to acquire datasets with satisfactory surface coverage and spatio-temporal resolution. This paper describes various aspects of a novel science & exploration mission equipped with payloads aimed at the acquisition of these much-needed datasets.

The proposed Ultimate Tumbleweed Mission will consist of a swarm of wind-driven mobile impactors with the ability to morph into measurement stations, so as to explore the Martian surface and collect measurements of near-surface meteorological parameters. Following a brief description of the notional mission concept and spacecraft design, we describe the scientific value that can be returned during the mobile and stationary phases of said mission. Datasets from a networked set of Tumbleweed Measurement Stations would enable the refinement of Martian climate and weather models. Through various in-situ measurements, micro- and meso-scale atmospheric phenomena and processes involving interaction between water, dust, and carbon dioxide can be constrained and studied in order to fill existing knowledge gaps. The swarm would help in investigating the ionizing radiation environment on Mars by acquiring direct measurements of flux, absorbed dose, spectral distribution, and angular distribution of various high-energy particles and their secondaries. Atmospheric modulation of incident cosmic rays and solar energetic particles, the nature and abundance of secondary particles, exposures and hazards for electronic and biological systems, and the shielding properties of the Martian regolith as well as natural landscape can be understood further, in order to prepare for future human and robotic exploration missions to the Red Planet. Preliminary formulation of the science case - including a set of candidate instruments - indicates that a network of Tumbleweed Measurement Stations can deliver holistic in-situ characterization of various near-surface atmospheric phenomena as well as the ionizing radiation environment on Mars.

Keywords: Tumbleweed mission, swarm-based Mars exploration, ionizing radiation, atmospheric science, meteorological network

1 Introduction

In its characteristics and effects, the space radiation environment is substantially different from what is experienced on Earth's surface [1]. Ionizing radiation in space consists of a mixed field of electrons, protons, gamma rays, and high mass and charge (HZE) ions. The flux, angular distribution and intensity of the radiation field varies based on the source and environment of observation. With minimal impedance from the tenuous atmosphere and weak magnetic field, most of the exposure on Mars is attributed to the incidence of Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs) on the planet's surface. The relative impact of these sources varies due to modulation by solar activity, over each 11-year solar cycle. Barring this, cosmic rays are relatively constant in flux and isotropic in angular distribution. SEP incidence depends on the phase of Mars, the distribution of magnetic field lines in the Heliosphere and the occurrence of sporadic events such as flares and Coronal Mass Ejections (CMEs), which constitute Solar Particle Events (SPEs). Depending on whether a spacecraft is solely an orbital probe or involves surface-based operations, the radiation environment and exposures differ accordingly [1].

The interaction mechanisms of ionizing radiation with matter give rise to undesirable effects in electronic circuits, biological tissue and materials in general. Energetic particles can cause shifts in the behaviour of transistors and integrated circuits, alter component functioning and deliver permanent physical damage to the structure of microelectronic devices. Exposure to radiation in space is recognized as one of the major flight stressors on the physique of astronauts [1]. Acute effects such as radiation sickness (ARS) can be caused by strong SPEs. Cosmic ray exposure can cause harmful effects such as cataract formation, tissue degeneration, carcinogenesis, damage to the central nervous system, accelerated ageing and digestive as well as cardiovascular diseases [1]. Hence, the radiation environment on Mars and its effects need to be comprehensively understood. This would enable effective risk management and mitigation for long duration human exploration missions.

Investigations to date have revealed that the atmosphere of Mars is similar to that of the Earth in multiple ways. Studies suggest that the similarities had been significantly greater in the past. However, multiple factors including the loss of thermodynamic heat on a planetary scale and sputtering loss led to alterations, resulting in the present frigid, shrunken and tenuous state of the atmosphere. Nevertheless, the dynamic nature of the atmosphere and dramatic variations over numerous time scales, added to the possibility that life may have emerged and evolved on Mars, make it a fascinating climate system[2]. Moreover, it is thought that studying the Martian climate can lead to important advances in the general understanding of climate formation and evolution on similarly sized rocky planets. As such, the modern day climate of Mars can be seen as a uniquely accessible physical laboratory.

To gain a comprehensive understanding of Mars' atmosphere and ionizing radiation environment, it is necessary to collect in-situ observations over large distances and time scales. Current Mars surface missions are carried out using large, infrequent, risky, and relatively high-cost spacecraft platforms that gather localized data. Mars orbiters provide global scale coverage but are limited by inherent limitations in resolution and the inability to perform long-duration measurements of specific targets. Due to various factors such as irregular sampling, mechanical and thermal contamination, calibration problems and lack of appropriate resolution, the meteorological observations collected by terrain-based spacecrafts have been limited [3]. To address this problem, a decentralized surface-based solution, which constitutes a swarm of Tumbleweed-styled impactors/rovers to study the Martian atmosphere and radiation environment over large areas and extended periods of time, has been proposed. Such a rover is shown in Figure 1. This is in the form of an innovative, cost-effective science and exploration mission called the Ultimate Tumbleweed Mission (UTM). The main objective of this paper is to establish the initial feasibility of the UTM, and its utility in carrying out investigations pertaining to atmospheric science and ionizing radiation on Mars.

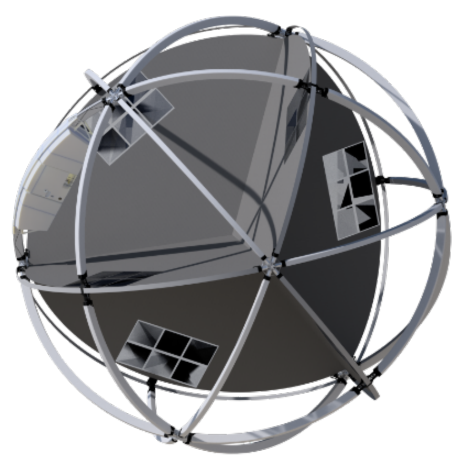

Figure 1: Visualization of TTW Rover Design V3

[1] This is due in part to the shielding or obstruction provided by the planet itself. This 'shadowing' effect varies based on the altitude of the orbit since the amount of incoming radiation that is blocked out depends on the view factor of Mars as seen from the spacecraft. Hence, half of the GCR environment is effectively blocked out for objects on the surface

2 Tumbleweed Rover & Mission

Team Tumbleweed is engaged in the design and development of an autonomous, wind-driven, and solar-powered rover for Mars, called the Team Tumbleweed (TTW) Rover. The basic idea draws from rolling rovers called Tumbleweeds, which have been proposed for the exploration of various planetary bodies with an appreciable atmosphere, such as Mars, Titan, Triton and Earth itself [4, 5, 6].

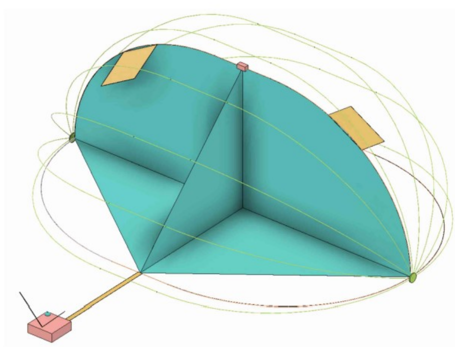

Figure 2: Illustration depicting stationary phase configuration [7]

The TTW Rover is a hybrid impactor/rover, evolved from box-kite styled Tumbleweeds [8]. The rover is made of a nested structure, with the spheroidal outer structure built to absorb dynamic loads due to landing and rolling. The inner structure is similar to an axi-symmetric ellipsoidal squirrelcage, possessing one degree of freedom (DOF) with respect to the outer structure, about the primary rolling axis of the rover. A full-scale TTW Rover would have a primary diameter of 5m and a mass of approximately 20 kg. The payload fraction is aspired to be almost a quarter of the total spacecraft mass, as shown by the payload constraints in Table 1. The rover structure is designed to be deployable with respect to a compact configuration and irreversibly collapsible into a terminal state later on. Figure 1 shows a visualization of the TTW rover's version 4 design. The rover is propelled by virtue of wind forces acting on sails stretched across the interior of the rover, between structural members called 'arcs'. Using limited deliberate control actuation and internal power expenditure, Tumbleweeds can use environmental gradients in an elegant manner to achieve displacement while collecting large amounts of information through the use of a diverse collection of scientific instruments and sensors.

Constraint	Value
Mass	5 kg
Power	20 W (peak) at 100 Wh capacity
Volume	6U

Table 1: Baseline Tumbleweed Payload Constraints [9]

2.1 Ultimate Mission Concept

Leveraging the unique capabilities presented by the TTW Rover's innovative design, Team Tumbleweed is working on a swarm-based mission, hereafter referred to as the Ultimate Tumbleweed Mission (UTM). Initially, all Tumbleweeds will be stowed in a compact, undeployed configuration inside an Entry & Descent capsule. During descent through the atmosphere of Mars, all the rovers will be ejected and deployed mid-air (as shown by the schematic in Figure 3, points 5-6) and impact the ground at terminal velocity. Hereafter, the mission is bifurcated into a post-impact mobile phase and a terminal stationary phase. The mobile phase will run through an arbitrary fraction of a Martian year, with the TTW Rovers being driven by wind and gradients in topography while conducting surface exploration and science operations in a semi-autonomous manner (points 7-9). Based on ebbs and flows in wind patterns and velocity magnitudes, the rovers will experience diurnal static periods. After the culmination of the mobile phase, the rovers will be collapsed in order to function as Measurement Stations until the end of life (point 10). The number of rovers in the swarm was taken to be 90-100 as a baseline, however the actual swarm strength will be decided based on a multitude of factors such as launch vehicle, descent capsule sizing, analysis of surface wind patterns, exploration targets, desired coverage etc.

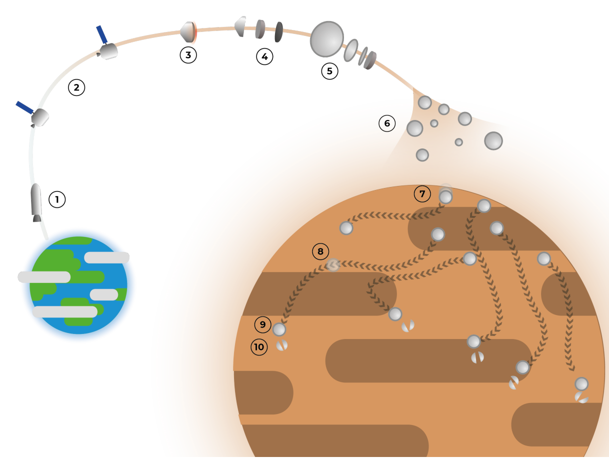

Figure 3: Ultimate Mission ConOps [10]

Figure 2 shows a schematic view of the TTW Rover during the stationary phase of the mission, when each rover will effectively be utilized as a node in a large network of Mars Weather Stations, called the Tumbleweed Network. The UTM's swarm-based architecture is intended to multiply the advantages of each individual TTW Rover and to channel it into the unparalleled ability of distributed sensor arrays to conduct investigations over local to global distance scales, over time periods ranging from seconds to years.

3 Mars Climate & Atmosphere: Background Information

The Martian atmosphere can be segmented into three vertical layers. The upper atmosphere exhibits very high temperatures and weak mixing, such that scale heights between different gases start to differentiate. The middle or "mixed" atmosphere has a strong winter polar jet stream. The lower atmosphere is dominated by turbulent interactions of the ground with air, and strong mesoscale circulations forced by topography and horizontal contrasts in temperature. The Planetary Boundary Layer (PBL) is the dynamic zone of the lower atmosphere where water, momentum, heat, dust and other trace species are directly exchanged by turbulent mixing between the atmosphere and the surface. On Mars, the PBL varies substantially in depth and properties depending strongly on the local time, but also on location, season, and the atmospheric dust and water ice opacity. During the day, intense convection may take place, with plumes and vortices rising to heights in excess of 10 km. At night, convection is inhibited and radiative cooling produces a stably stratified layer at the surface, and the PBL reduces to a shallow layer (as little as several 10's of meters in altitude) forced by mechanical turbulence at the bottom of the stable layer [11].

Aeolian processes — dust lifting and sand transport by winds — dominate geological activity on present-day Mars[12]. It also has an active water cycle that exchanges water between the subsurface and atmosphere [13] on seasonal and diurnal timescales, and may move substantial amounts of ground ice with changes in obliquity of the planet. Mars' thin atmosphere, lack of oceans, and widespread coating of low thermal inertia dust favour large seasonal and diurnal temperature variations [14, 15, 16]. Intense horizontal and vertical winds develop near the surface and yield widespread dust devil activity and dust storms that grow to global events.

3.1 Previous Investigations

An eclectic collection of studies including data from orbital and surface-based spacecraft have revealed that Mars has experienced a massive loss of atmosphere, changes in surface pressure and in atmospheric dust flux (including global dust storms), cycling of the distributions of water and dry ice near the surface. These and many other factors have led to climate shifts on many time scales, which have resulted in changes in atmospheric composition, and climate records within rocky and icy landforms and the subsurface. For comprehensively understanding the climate and its impact on Martian life, weather, and geology, understanding of a variety of environmental conditions and process interactions is required [17].

Considering the lower atmosphere and surface based missions, only Viking, Curiosity [18], InSight and Perseverance [19] have collected measurements over a period extending beyond one Martian season. However, this is not always tantamount to continuous and uninterrupted monitoring. Due to thermal and power constraints, most instruments enter a power-saving mode during the night and some parts of the Martian day. Additionally, the intermittent operations of other energy-intensive payloads on the platforms carrying these instruments have necessitated that these environmental monitoring systems be partially or fully shut down in order to redirect available electrical power and data bandwidth resources.

3.2 Knowledge Gap

Data recorded from orbit using remote sensing techniques lack the vertical resolution necessary to discriminate near-surface atmospheric processes from those occurring within the lowest few kilometers of the atmosphere. For instance, the detection of bursts of methane of approx 7 ppbv in the Jezero crater by Curiosity [20] could not be corroborated by either the ExoMars Trace Gas Orbiter (TGO) or Mars Express [21]. Only land based sensors and instruments can record data with the horizontal resolution required on the ground to analyse the local surface properties, especially in those processes of interest where a small resolution scale is required. In general, there are noticeable uncertainties in the surface fluxes of some significant species [17]. The near-surface zone of the atmosphere remains poorly understood. As such, our efforts will be focused on enabling the investigation of various processes in this realm.

There is a lack of understanding of the physics of surface abrasion and particle transport due to aeolian phenomena. This extends to the lack of current capabilities for monitoring the effects of global dust storms near the surface, since dust obstructs orbital imaging. The electrical properties and characteristics of charging of dust and sand grains have not been studied in-situ [17]. From an engineering perspective, dust impact and dust loading can have considerable influence on robotic and crewed missions. This is primarily due to the accumulation of dust on solar panels over time, abrasion of mechanical parts and electrostatic charging. Hence, accurate models that have the ability to predict dust transfer and mobilisation through aeolian processes such as dust devils are highly desirable [2]. An accurate understanding of such processes would inform the design of missions and spacecraft subsystems, for safe landing and surface operations given the hostile nature of the martian environment [19].

4 Ionizing Radiation Environment: Background Information

Mars' sparse atmosphere provides very low shielding against incoming ionizing radiation. Unlike Earth, the lack of an appreciable magnetic field leads to high exposure on the surface. The interaction of primary ionizing radiation with the atmosphere and regolith leads to the generation of secondary particles. Hence, the surface has a complex multi-directional radiation field composed of primary cosmic rays, SEPs and secondaries from the atmosphere and ground. Ionizing radiation from the Sun is recognised as one of the main factors in causing significant loss of the upper atmosphere through sputtering [22, 23].Incident radiation can lead to the formation of complex chemicals and oxidants for life. Conversely, exposure to UV and ionizing radiation over long time intervals has caused the breakdown and destruction of organic species, especially close to the planetary surface. Essential biomolecules such as nucleic acids and proteins can be destroyed or altered by either indirect or direct mechanisms, resulting in disruption to life processes and damage to cells, tissues and organs at different scales. Given the current understanding of the ionizing radiation environment on Mars, it has been estimated that organic species have a survivability of about 300 Myr at a surface depth of about 10 cm [24]. In confluence with other factors, the surface radiation environment implies that it is more likely that microbial life, extant or extinct, is to be found in the subsurface regions where adequate shielding is available. Interestingly, the estimated variation of shielding with depth of regolith implies that some habitable niches could also be found in the shallow subsurface or near surface environment, which may provide relatively sheltered conditions as compared to the bare surface of the planet [25].

4.1 Previous Investigations

NASA's Mars Radiation Environment Experiment (MARIE), on the Mars Odyssey orbiter performed measurements aimed at characterizing the radiation environment in Mars orbit and during interplanetary transit from Earth to Mars [26]. MARIE performed flux and dose measurements, observing average dose rates of about 240 $\mu Gy/day$ in Mars orbit [27]. Other measurements in transit and Mars orbit have been collected by a Liulin MO instrument onboard the ExoMars TGO and the MEPA charged particle telescope manifested on the Tianwen-1 orbiter [28].

The Radiation Assessment Detector (RAD) instrument was flown on-board NASA's Curiosity rover as a part of the Mars Science Laboratory (MSL) mission [29]. RAD collected the first in-situ measurements of ionizing radiation on the Martian surface [30]. Radiation from GCRs and SEPs was measured for different phases of the mission, namely surface operations and the interplanetary transit from Earth to Mars. The average GCR dose rate at the surface was measured to be about 0.21 mGy/day while during cruise it was measured to be more than twice that rate at 0.48 mGy/day [31]. RAD also observed spikes in absorbed dose at the surface due to multiple SPEs. Temporal variations in the dose rate were attributed to a combination of factors, such as the changes in atmospheric pressure, seasonal conditions and variability in the heliospheric structure along with the rotation of Mars [30]. The dose rate on the surface, was found to be anti-correlated with Mars surface atmospheric pressure since higher pressure can lead to an increase in the amount of shielding and higher attenuation of incoming primaries [30].

4.2 Knowledge Gap

To date, MSL-RAD is the first and only instrument to make extensive surface-based measurements of the ionizing radiation environment on Mars [30]. As such, many gaps in the current knowledge lie outside the scope of RAD's investigation or correspond to the limitations and drawbacks of this instrument and the spacecraft platform which hosted it. The Curiosity rover has a Radioisotope Thermoelectric Generator (RTG) and Pulsed Neutron Generator (PNG) which act as sources of considerable noise for the RAD instrument [32]. Efforts were made to characterize these sources through an experiment and modelling. Besides the effects of shielding and noise, RAD is restricted to a spectral band of about 10 - 100 MeV/n for certain particles and a 30^o viewing cone about the zenith [33], which poses restrictions on the observation capabilities of this instrument. To account for this, the data corresponding to incident radiation outside these boundaries is sourced from modelling efforts [34]. Based on the comparison of results between RAD data and particle transport model calculations [35], it has been noted that for neutrons below 10 MeV and heavy ions above several hundreds of MeV/n, large deviations were observed in some cases between model predictions and collected data. Hence, measurements conducted in these energy ranges would be highly useful for developing more accurate models in the near future, especially since this range is relevant for heavier shielded environments such as subterranean re-

[2] Curiously, aeolian processes like dust devils are also known to rid the solar panels from dust to a limited extent, thereby acting as a desirable influence.

gions, which are considered of high interest as prospective radiation shelters for human exploration [36].

RAD only collected measurements in Gale crater, hence there isn't any information available regarding spatial variations in the radiation environment over considerable distance and altitude variation. Temporal variations w.r.t diurnal time scales have been studied but for longer time intervals (at the seasonal and annual level), measurements could not always be collected at the same location due to Curiosity's traverse. Important gaps exist in the knowledge of variations in exposure and albedo w.r.t. changes in terrain features, soil composition, altitude, atmospheric composition and dust content. As a proof of principle, the natural shielding experienced by RAD in the vicinity of a butte has been reported [37]. However, there is a lack of data concerning the shielding properties of martian regolith and the attenuation of dose received inside sheltered locations such as lava tubes. In general, the measurements made by RAD during Solar Cycle 24 are hard to generalize given this cycle's very weak nature [28].

The nature of interaction between primary ionizing radiation and the remnant crustal magnetic anomalies of Mars is not known and has not been explored yet. It has been observed that the magnetic field near the crust shows weak, stripe-like features. The interaction of these features with the ionizing radiation field may result in limited and selective shielding of certain local spots in the near-surface environment. As such, these spots could be relatively sheltered from exposure, leading to favorable conditions for preservation of organic molecules, biosignatures and possibly even extant microbial life [38].

These knowledge gaps indicate opportunities to consolidate current models of the ionizing radiation environment on Mars. Despite the important advances in knowledge brought about by previous missions, an important insight is that a limited set of localized observations in a restricted viewing cone and spectral band may not be enough to generalize and infer the richness of the near surface radiation field over the entire planet. Hence, much larger datasets of in-situ measurements are needed to expand on the data acquired by MSL-RAD, and to meet Mars Exploration Program Analysis Group (MEPAG) objectives concerning human exploration and assessment of present-day habitability on Mars [17]. In light of this necessity, the deployment of distributed radiation sensing arrays over large areas of Mars seems to be a promising strategy. In the next section, we describe how this and other science goals can be achieved with the UTM mission, through initial development of a science case aimed at studying various properties of the surface ionizing radiation environment and atmospheric phenomena, in a systematic manner.

5 Science Case Development

Following on from the discussion of previous missions and the knowledge gaps that remain in the domains of ionizing radiation environment and near surface atmospheric phenomena, this section is utilized to delineate a preliminary science case which is dedicated to these topics. Corresponding to the aforementioned knowledge gaps, high-level science goals were formulated. The particulars of the science case are structured and laid out in the form of an abbreviated Science Traceability Matrix (STM), followed by a discussion of the measurements that will be needed to achieve science objectives and the instruments that can be used to acquire these measurements. Lastly, some payload design considerations are brought up to give insights as to how candidate instruments will be integrated into a coherent science payload for the TTW Rover.

5.1 Science Traceability Matrix

The abbreviated STM shown in Table 3 was set up to develop the science case in a systematic manner and to show the natural flow-down of the science goals into measurements. A comprehensive STM which covers the entire multi-disciplinary scope of the UTM is currently under preparation. As such, the abbreviated STM shown here is restricted to the domain of Atmospheric Science (and ionizing radiation). Based on the knowledge gaps and RQs, the following high level science goals were formulated for the UTM. These are decomposed into further sub-goals and objectives, and flowed down into requisite observables in the STM.

1. **SG-1**: Characterize the ionizing radiation environment on Mars and its impact on habitability
2. **SG-2**: Characterize the state of present-day climate and controlling processes in the near-surface environment of Mars

The science goals stated here have a direct connection to NASA's Mars Exploration Program Analysis Group (MEPAG) goals [17] as well as the findings of the Planetary Science Decadal Survey (2023-32) [39]. The relevance of the MEPAG goals is shown via Table 2:

Science Goal	Applicable MEPAG Goals / sub-goals
SG-1	MEPAG I.A2.3/ I.B2.2/ IV.B1.1-2
SG-2	MEPAG II.A1-A3/ IV.B2

Table 2: Traceability of UTM science goals to MEPAG goals

Table 3: Science Traceability Matrix

Science Goal	Sub-goal	Science Objective	Measurement Observables
Characterize the surface ionizing radiation environment on Mars and its impact on habitability	Characterize spatiotemporal variations in ionizing radiation exposure on the surface	Determine spatial variations in exposure at a scale ranging from [m to 1000 km]	TID and dose rate sampled at one or more locations in equatorial, mid-latitude and polar region
		Determine variations in exposure over hourly, diurnal, monthly, seasonal and annual time scales	Dose rate, flux, angular distribution and spectral distribution
		Determine variation in exposure in the vicinity of geological features such as gullies, lava caves, craters, ancient lakebeds, and boulder fields and identify sheltered zones	Absorbed dose and dose rate of ionizing radiation from primary sources and albedo; UV flux; contextual images to quantify natural shielding
		Determine variation in exposure in relation to remnant crustal magnetic fields	Absorbed dose, dose rate, flux and spectral distribution of ionizing radiation
	Characterize interaction of primary ionizing radiation with the regolith and atmosphere	Determine characteristics of secondary particles, including martian albedo	Absorbed dose and dose rate, LET, flux and spectral distribution; neutron spectra; context images
		Determine the shielding effectiveness of martian regolith	Absorbed dose and dose rate from primary sources and albedo, neutron spectra
		Assess variation in ionizing radiation flux and exposure with changes in ambient temperature, pressure and dust loading near the surface	Ambient pressure, temperature, dust loading, absorbed dose, dose rate and flux
Characterize the state of present-day climate and controlling processes in the near-surface environment of Mars	Characterize the dynamics, thermal structure, and distributions of water, and carbon dioxide in the lower atmosphere	Characterize the dynamical and thermal state of the lower atmosphere and their controlling processes on local to regional scales	Temporal variations in the temperature of the air and ground, ambient pressure, wind velocity, relative humidity and heat and momentum exchange in the PBL at various sites during multiple seasons
		Measure water and CO2 distributions in the lower atmosphere and at polar, mid latitude and equatorial locations	Abundance and concentration of gaseous CO2, water vapor near the surface and their variability over time
	Constrain the processes which govern dust exchange between surface and atmospheric reservoirs	Characterize the fluxes and sources of dust and volatiles between surface and atmospheric reservoirs	Magnitude of dust impact/ loading in conjunction with wind velocity, and its variation over time Electric and magnetic fields within dust devils and charging of grains
	Characterize the chemistry of the atmosphere and surface	Measure spatial and temporal variations of species important for atmospheric chemistry or acting as transport tracers for constraining sources and sinks	Abundance and concentration of [CO2, O2, H2O, CO and CH4] near the surface
		Determine stable isotope ratios of key chemical species relevant to photochemistry and biotic processes in the lower atmosphere	Chemical and isotopic data for a number of extant species, including the D/H, 13C/12C, 15N/14N and 18O/16O ratios
		Determine the small scale temporal variability of the local near surface environment, as context for habitability	Ambient temperature, barometric pressure, wind speed, relative humidity, ionizing radiation exposure, UV exposure, concentration of methane, water vapor, oxygen, CO2
		Detect and characterize shallow subsurface water ice deposits	Spectra of Thermal, Epithermal albedo neutrons (>0.3 eV)

For clarity and convenience, studies of ionizing radiation have been positioned adjacent to meteorological and climate science, but decomposed separately in the STM.

Understanding the ionizing radiation field at the surface involves two main aspects (translated into sub-goals) and is mainly motivated by the need to understand and mitigate risks for sustained human and robotic exploration activities. Another core motivation is to understand the impact on habitability in the near-surface environment, as a means to aid the search for extinct or extant extra-terrestrial life. Firstly, spatio-temporal variations in primary radiation in the form of GCRs and SEPs can be studied. Secondly, the interaction of primary particles with the atmosphere and ground i.e. the nature of scattered secondaries and upward albedo of ionizing radiation is important.

Drawing from MEPAG Goal II.A, the atmospheric science investigation has been forked into three complimentary aspects, described hereon. First, in the lower atmosphere, processes that control the dynamics and distribution of water, dust, carbon dioxide can be understood by direct observations of these species, or through observations of meteorological parameters associated with circulation, atmospheric state and radiative/turbulent forcing over daily, seasonal and annual time scales. Second, the dust cycle on Mars is not understood completely, which has consequences for most robotic spacecraft and planned human missions. To predict the dynamics and impact of dust cycles and dust storms over long time scales, developing an understanding of the lifting processes and source distribution is necessary. Over shorter spans of time i.e. hourly and diurnal intervals, an understanding of the local dynamics and distribution of dust at various locations is needed in order to predict and simulate dust devils. Charging of dust and sand grains due to collisions and the resulting electric and magnetic fields and currents are related to processes such as dust lifting and saltation, especially within dust devils [17]. Third, the chemistry of the lower atmosphere is interlinked with the surface, in terms of exchange of chemical species between these two domains through multiple mechanisms. The possible presence of biological activity, preserved biosignatures from microorganisms, or the presence of environmental niches with habitable conditions could have imprints on near-surface chemistry, which may be probed directly by detecting and tracking CHNOPS-containing compounds for instance. Indirectly, it is possible that fluctuations or small temporal variations in physical and chemical parameters could lead to the identification of biologically relevant zones. The moisture content of the soil and shallow subsurface water ice could also be interesting indicators in this regard. Beyond astrobiology, studies of such chemistry are also important for identifying hazards at candidate landing sites and exploration zones for human exploration, and for estimating the in-situ resource utilization potential in regions of interest (ROIs) [40].

5.2 *Atmospheric measurements & Relevant Instruments*

It has been noted that the simultaneous acquisition of multiple high-quality datasets from networked surface-based weather stations would represent the next major step in climate studies [17], and an important aspect would be to collect these measurements for a variety of topographical contexts and altitudes. The in-situ measurements taken by the Tumbleweed Network in the UTM will result in unique high quality datasets at ; local, regional (microscale and mesoscale) and global/synoptic scales. This would be an indispensable addition to the data collected by conventional missions. The near-surface atmospheric measurements shown in Table 3 will serve to meet the science objectives delineated therein. The Tumbleweed Network will operate mainly in the lower atmosphere, therefore focusing on measurements and processes within the PBL[11]. Tumbleweed Measurement Stations shall provide insights into many aspects of the PBL and atmospheric-surface interactions, such as near-surface PBL turbulence, which can be viably measured with the use of wind and temperature sensors at appropriate frequencies [41].

In addition, the Tumbleweed network can produce novel seasonal data sets to understand Martian climate cycles, including dust, water and CO_2 cycles. Ground-truth data is required to test these theories of surface/atmosphere exchange and to determine the roles of reservoirs [17]. Thus, combined measurements from a plethora of surface based spacecrafts (including the existing landers and rovers) will be useful for studies of dust and volatile cycles. The moisture content of the soil and shallow subsurface deposits will be measured by permittivity sensors and neutron spectrometry, and related to the atmospheric concentration of water vapour periodically. In addition to measurements of electromagnetic fields and ambient sound, dust devils can be studied by virtue of how they perturb closely clustered TTW Rovers, while propagating through a region. In conjunction with global observations from orbiters, local measurements from each node in the Tumbleweed Network would enable studies concerning the effects of synoptic scale processes on the local meteorology, thereby allowing these regimes to be linked through experimental data such that correlations and cause-effect relationships between the dynamics at these adjacent scales can be revealed.

In general, temporal resolution and range is to be tailored to the processes and chemical species being investigated. For measurements concerning atmospheric chemistry and transport, the frequency is dependent on reaction rates of the observed species. Slow reacting and well-mixed species can be observed with occasional measurements while highly reactive species would require sampling at higher frequencies i.e. hourly or diurnal. High frequency of observation would enable the study of processes that evolve at a relatively rapid rate, such as dust devils and dust storms. For validation of multi-dimensional models of photochemistry, atmospheric transport and composition (at least in the lower atmosphere), wide-ranging datasets concerning spatiotemporal variations in production and removal rates, abundance and activity are required [17].

Environmental Sensing Suite

Several spacecraft in the past have carried environmental monitoring systems that have enabled them to act as isolated weather stations, such as MEDA and REMS [19, 18]. Most notably, the Beagle 2 lander carried an Environmental Sensing Suite (ESS) [42].This ESS aligns with the technical constraints of the TTW Rover, as shown in Table 1; demonstrated by the mass-limited design, with eight sensor subsystems having a total mass of approximately 100g [42]. The low-cost, low-mass, and modular nature of the ESS onboard the Beagle 2 provides attributes that are suitable for the TTW Rover. Naturally, the TTW Rover will be equipped with an ESS composed of sensors listed in Table 4, to serve as an integral part of the UTM, especially during the stationary phase. Thus, using ESS units on each rover, the Tumbleweed network will enable probing of the near surface atmosphere through acquisition of much needed datasets concerning wind patterns, thermal fluxes, material exchange, gas composition, moisture content, soil characteristics by operating as a cohesive collection of meteorological stations. Locally, the ESS units in the Tumbleweed Network can assess habitability by monitoring volatility and short term variability in atmospheric variables at specific locations. This might indicate dynamics resulting from biologically relevant processes and could lead to the identification of a set of interesting locations containing possible microbial oases / localized hotspots in the near surface environment which are conducive to harboring complex organic species or biosignatures. [43]

5.3 Radiation measurements & Relevant Instruments

At individual locations on the Martian surface, the ionizing radiation environment will be characterised through measurements of quantities such as particle types, absorbed dose in Si/water, angular distribution, flux, LET and energy distribution, collected by each TTW Rover. At the swarm level, these measurements being acquired simultaneously by each rover would result in observations being collected over a vast landmass at the regional scale. To observe spatial and temporal variations in the radiation environment near the surface, measurements will be collected by the swarm in relation to the following influencing factors [28]:

- Heliospheric factors including evolution of the solar cycle and transient events
- Atmospheric variables such as pressure, which vary with daily thermal tides, seasonal CO2 cycle and altitude/ relief
- Shielding provided by local topography and changes in soil properties
- SPEs, which occur sporadically and may intensify within a short time interval

The spectra (especially below 10 KeV and above 100 MeV), and directionality of neutrons near the surface will also be measured, since it is an important aspect of radiation exposure for human exploration [17]. The upward albedo will be studied thoroughly with respect to variations in the terrain and soil composition. Furthermore, the moderation of fast neutrons (generated due to cosmic ray irradiation) to thermal and epithermal neutrons by hydrogen can be used to detect and characterise the water-ice distribution and content in the shallow subsurface zone. Better discrimination between the exposure due to charged as opposed to neutral particles can be performed by the execution of passive neutron spectrometry, dosimetry and LET spectrometry in concert. Measurements from the Tumbleweed Network would provide large amounts of data which would enable modelling of the relative contribution of SEPs, GCRs and neutral particles to dose received near the surface.

As part of the operational infrastructure for future crewed and robotic exploration missions, the forecasting/-monitoring of extreme solar radiation events such as flares and Coronal Mass Ejections (CMEs) would most likely be based on numerical models working in conjunction with observations from space-based warning systems, located in heliocentric or Mars/Earth orbit [17]. To accurately predict the amount of exposure on the surface and the energy deposited into the atmosphere during extreme radiation events, radiation environment models need to be consolidated and constrained with simultaneous, comparable measurements of charged and neutral particle spectra from Mars orbit as well as the surface. Measurements from radiation monitors in the Tumbleweed Network can be combined with data from orbiters to meet such requirements.

	Instrument	Example / sources	Measurements	Measurement characteristics
1	LET Spectrometer / Particle Camera	TimePix based devices [44, 45]	Ionizing radiation field characteristics	LET, Flux, Energy, absorbed dose, particle ID measured at various locations at least every hour
2	Active Dosimeter	FGDOS [46]	Absorbed dose in Si	TID and dose rate at an hourly frequency or higher, for entire mission duration
3	SRAM ThN & HeH Detector	Space RadMon [47]	Fluence of Thermal neutrons and high energy hadrons	Single Event Upset (SEU) and latchup rate in a memory bank
4	Visible/ Multispectral Camera	MastCam-Z [48]	Contextual images of martian landscape and soil	Color images at better than 2 Mpx (aim to be 30 cm/px resolution at 1 km) resolution and 20-40^o FOV
5	Env Sensing Suite (ESS)	Beagle 2 ESS [42]	Atmospheric pressure Temperature Relative humidity Wind speed & direction Dust saltation Ionizing radiation dose UV Flux (and dust loading)	Barometric pressure measured at frequency 1 Hz, with resolution 0.01 mbar Ambient temperature measured at frequency 10 Hz with resolution 0.1 K Relative humidity at resolution 1 % RH , at frequency 1 Hz Wind speed in range [0.3-30] m/s, at frequency 10 Hz Dust impact, momentum and rate at frequency 1 Hz Time resolved absorbed dose and dose rate measured with a resolution 1 uGy/hr. Total Ionizing Dose delivered till Mission End of Life UV flux in 200-400 nm band, measured at least once per minute
6	Ion Trap Mass Spectrometer	Ptolemy Ion Trap MS [49]	Detection of organic and chemical species in the air and soil; isotopic fraction of C,H,O	Mass spectra in range 10 u to 140 u atomic masses, with resolution of 2u or better
7	Neutron Spectrometer	LunaH-Map mini NS [50], HardPix [51]	presence of hydrogen , water ice in the soil	Flux & spectra of thermal and epithermal neutrons (>0.3 eV)

Table 4: List of candidate instruments

Ionizing Radiation Detectors

Recent advancements in semi-conductor technology have led to the development of a variety of ionizing radiation detectors for space applications, which comply with payload constraints for the TTW Rover.

FET based detectors (such as RADFETs) have been used abundantly in space [52]. However, these have a relatively coarse resolution and high TID range, which makes them more suitable for use in LEO and Radiation Belts. Floating Gate (FG) MOSFET based dosimeters can be made in very small sizes, with integrated electronics for readout and low required voltage supply [53]. A novel Floating Gate Dosimeter - FGDOS - has been developed for use in space applications, particle accelerators and medical irradiation facilities [54]. The FGDOS provides a redundant pair of sensors with much higher dose resolution than RADFETs. It combines a large TID lifetime with extremely low power consumption and minuscule footprint. As such, several FGDOS chips can be distributed on the exterior and interior of a spacecraft to monitor scattered radiation fields, perform diagnostic measurements of radiation effects on electronics, and estimate the shielding effectiveness of a spacecraft's structure. As such, the FGDOS can be incorporated into the ESS for the TTW Rover. Moreover, it has been incorporated in payloads for several upcoming missions in LEO and beyond [55].

The TimePix is a hybrid active pixel detector that can capture the tracks of incident particles. The sensor consists of a Si detector with a pixelated ASIC for energy readout and interfacing and functions like a 'photon/particle camera'. It can provide high performance radiation measurement capabilities with data products such as track structure images, linear energy transfer, flux and absorbed dose over a wide energy range and dose rate. Moreover, particles can be identified from their tracks in a single detector layer [44]. This reduces the need for and dependence on elaborate multi-layer instruments to a certain extent. The feasibility of using the TimePix for monitoring energetic particles over long time periods in space has been proven through multiple payloads in Earth orbit, on the ISS [56] and on several LEO satellites [57, 58, 59] and beyond [60, 61] . In general, such payloads have shown a trend toward low mass, low size and power consumption while exhibiting high detector performance and radiation tolerant electronics [45].

The extremely low power consumption, high resolution and persistent active dosimetry capabilities of the FG-DOS can be combined with detailed information regarding LET, particle identification and spectral distribution from a TimePix device to obtain comprehensive datasets concerning the characteristics of the ionizing radiation environment. These abilities can be further enhanced by adding an SRAM memory bank in order to measure the fluence of thermal neutrons and high energy hadrons [62]. Addition of a miniaturized neutron spectrometer would allow observation of spectra of albedo neutrons as well as mapping of potential shallow-subsurface water ice deposits [51, 50]. These neutron measurements can be normalized using simultaneously acquired information regarding energy, composition and flux of primary particles from the other detectors. To obtain more detailed and accurate information about directionality of incoming primary and secondary particles, a hodoscope like miniaturized instrument based on multiple layers of Timepix detectors could be utilized [63].

5.4 Science Payload Design Considerations

The TTW Rover will carry science instruments and other payloads in containers called Pods, which will provide thermal, mechanical, electrical and data interfaces. The Pods will be attached to the inner structure such that they are isolated from the bulk motion of the rover while it rolls about the primary axis. A limited set of sensors which acquire measurements through physical contact with the martian soil or air will be mounted on the body of the rover or on the exterior of the Pods. For instance, patch electrodes for sensing electrical permittivity and soil temperature sensors would be integrated on the contact surfaces of the outer structure with the ground. Calibration targets for instruments such as cameras will be attached inside the structure of the rover.

The selection of instruments and sensors to form Pods will be based on the constraints posed by the spacecraft, shown in Table 1. Hence, for the TTW rovers, miniaturized instruments such as those flown on-board CubeSats are the most suitable.The strategy for payload selection is to combine the utilization of miniaturized Semiconductor integrated circuit (IC) package based sensors with more conventional instruments that fit within constraints. This approach is intended to optimize scientific return while achieving a satisfactory balance between spacecraft resource consumption and quality of measurements acquired. To overcome some of the limitations faced by REMS and MEDA, so as to perform environmental measurements at a high frequency for the majority of each sol, the ESS needs to be designed to have extremely low power consumption. The presence of multiple TTW Rovers during the UTM adds some beneficial nuances to payload selection. Across the swarm, the payloads can be homogeneous or heterogeneous in composition. Using a limited set of Pod design variants can add the much-needed capability to study targets using multiple complementary techniques in concert. This would help in overcoming the payload SWaP constraints partially, in addition to raising confidence levels in the measurements acquired. For largely homogeneous pods, there exist opportunities for cross-calibration and comparison of measurements from identical instruments and sensors. Table 4 depicts a list of candidate instruments selected as a result of the review of existing technologies. An additional list shown in Table 5 contains instruments and technologies which can be used onboard the TTW Rover upon further miniaturization or maturation.

#	Instrument	Measurements
1	Dosimetry telescope/ hodoscope	Angular & spectral distribution of ionizing rad.
2	Mini Gas Chromatograph-Mass Spectrometer	Air & soil chemical composition
3	Microspectrometer (UV/Vis/NIR)	Spectra from air, soil, ice at UV, Vis. & IR bands
4	Mini- Tunable Laser Spectrometer	Atmospheric composition: conc. of CO2, CH4, O2
5	Microscintillator/ Si Photomultiplier	Count rate & energy of primary and secondary ionizing radiation
6	Electric field sensor	Electric field
7	Triaxial Flux Gate Magnetometer	Magnetic field
8	Magnetic Field Response Sensors / Patch Electrodes	Electrical permittivity of soil (for water ice detection)

Table 5: Instruments that can be miniaturized/adapted for the TTW Rover

6 Discussion

This section provides a brief discussion of the relevance and applicability of the TTW Rover for conducting science on Mars, followed by some remarks on science operations during the UTM as well as the associated challenges.

At the unit level, a TTW Rover possesses several characteristics that can provide distinctive advantages in the quest for radiation environment characterization and studying the lower atmosphere. First, the advanced mobility and risk tolerance of the platform can enable measurements of scattered radiation fields and environmental parameters in the vicinity of interesting geological features such as lava tubes, steep craters, canyons, gullies etc. In relation to this, the albedo component of the radiation environment and effective shielding provided by Martian regolith can be studied experimentally. By virtue of the large surface area that would be covered by each TTW Rover, unprecedented, large-scale dynamic maps of ionizing radiation exposure could be created from the mission observations. Similarly, dynamic mapping of local weather and environment could be performed along the traverse of each rover. Such monitoring capabilities could help narrow down and verify potential sources and sinks of methane and other biologically relevant species on Mars. The maps from data collected by each rover could be collectivised and juxtaposed to derive information about large-scale spatial variations.

The stationary phase of the UTM will commence when the rovers have dispersed to the desired extent. This would depend on the prior traverse of each rover, the region to be occupied and the required density of distribution of the swarm. This phase is mainly about establishing the Tumbleweed Network of Measurement Stations. On a collective level, this distributed network can provide uniform and repeatable observations. Hence, temporal variations can be studied effectively over a large area. This adds another dimension of capabilities for exploration and environmental sensing, derived from the possibility of network based interactions in a distributed collective of robotic systems. If precise information about positioning, timing and orientation of each rover can be obtained, it would be possible to set up the Tumbleweed Network as a large distributed cosmic ray telescope, aimed at the study of the ionizing radiation environment, atmospheric particle showers and fundamental astrophysical phenomena [64] [3]. Through the use of ESSs distributed throughout the Tumbleweed network, the information acquired could help to constrain models of the lower atmosphere and atmosphere to surface interactions in a highly effective manner. This would allow for the reduction of statistical uncertainties with respect to temporal and spatial variation in various processes observed in the lowest part of the Planetary Boundary Layer (PBL). Consequentially, there would be benefits in the design and evaluation of EDL trajectories, as well as the assessment of the practical implications of dust storms on human exploration infrastructure and land based robotic spacecraft.

Essentially, a network of ionizing radiation monitors and meteorological stations - Tumbleweed Measurement Stations - can be used to perform holistic in-situ characterization of various atmospheric phenomena and the ionizing radiation environment on the surface of Mars. Similar to other sensor arrays, the Tumbleweed Network can serve human and robotic exploration missions in the future by acting as the proof-of-concept and potential nucleus for the establishment of a large, ground based, global-scale distributed environmental sensing infrastructure in the future [3].

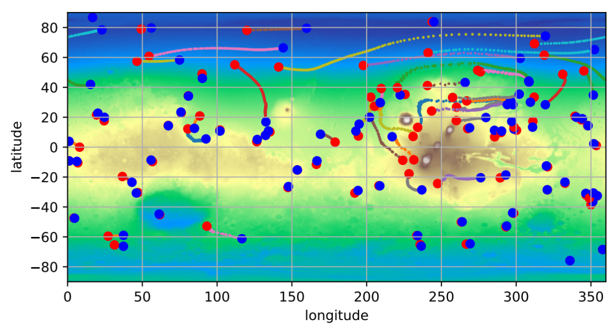

Figure 4: Spreading Simulation of the Tumbleweed swarm over a duration of 80 sols. The initial impact sites were selected randomly. Red & Blue dots represent start & end points respectively [65]

It is apparent that the content and quality of measurements during the UTM would depend on the propagation and spreading of the TTW Rovers to a large extent. For the Tumbleweed Network, the amount of land coverage would be determined by the swarm size and the optimal inter-node distance that is needed to conduct observations. These aspects need to be worked out further as a part of mission design studies for the UTM. A computational tool is being developed by TTW for mission design and analysis of various scenarios of the traverse and spreading of Tumbleweed swarms (of various sizes) based on existing topographical data and climate models [65]. Figure 4 shows a preliminary result from this tool.

6.1 Technical Challenges

Since a Tumbleweed based swarm mission for Mars has no precedent, there exist several technical challenges which need to be overcome in following this approach for

[3] This would be done in a way that's similar to projects such as CREDO, CosmicPi and MuonPi

conducting Mars exploration and science in the foreseeable future.

As the rover is propelled by wind and terrain gradients, the dynamics of rolling will generate bulk motion and vibrations in the pods, which would create a noisy environment for various instruments and sensors. As such, it is planned to use a dynamic system model of the TTW Rover, along with feedback information from inertial sensors in the spacecraft bus and pods, to compensate for noise during post processing of the collected datasets. In the midst of tumbling, it will be difficult to capture high-fidelity information about the angular distribution of incident radiation. This limitation can be partially overcome with the use of accurate attitude determination capabilities. Due to the uncertainty in the amount of shielding that would surround the radiation detecting instruments before deployment of the rovers, it is not known yet whether useful measurements could be acquired during the cruise from Earth orbit to Mars orbit. Invariably, the shielding provided by the pods and rover structure should be pre-characterized by experiment and simulation.

Incidentally, some instruments which can provide detailed information (such as spectrometers), have a tendency to generate large amounts of data (on the order of Mb/s - Gb/s) which might not be downlinked directly given the assumption that radio communication and satellite relays will be used for the TTW mission [66]. As such, a certain amount of on-board processing would be needed to refine the observational data and reduce it to the most essential information to be downlinked. The radiation and meteorology data collected by a subset of rovers in a specific region can be stored, transferred and downlinked back to Earth-based ground stations via smaller sub-networks established temporarily on an ad-hoc basis.

For surface-based investigations, an often overlooked aspect is to account for the effects of accommodation of the weather stations on the fidelity of measurements, as well as inaccuracies arising from thermal and mechanical contamination associated with the spacecraft. To acquire data over a large part of a Mars year in its collapsed configuration, the Tumbleweed Measurement Stations will need to be robust against the effect of dust loading and general wear & tear of components and sensors. Maintaining the scientific instrumentation in calibration for a long time will also be challenging, given extreme temperatures, thermal cycling and abrasion as well as electrostatic charging from dust grains. The avionics will have to withstand long-term exposure to ionizing radiation exposure. As such, the use of radiation-tolerant hardware and software in the TTW Rover might be necessary to deal with radiation effects.

7 Conclusion

Through the TTW Rover, Team Tumbleweed seeks to exploit the inherent robustness and versatility of r-selective spacecraft systems [67] for conducting Mars science and exploration missions. The current approach to Mars surface exploration missions consists of large, infrequent, risky, and relatively high-cost space missions that gather local data only. In order to overcome the drawbacks of this approach, we have proposed a solution that involves using a swarm of wind-driven, relatively inexpensive and lightweight rovers/mobile impactors, which require minimal use of internal stored energy to traverse over large swaths of the Martian surface and collect long term data in an unprecedented manner. The UTM is a promising solution to the trade-off between low-resolution, high-coverage orbital remote sensing, and higher-resolution, low-coverage rovers/landers. The preliminary science case essentially shows how the TTW Rover can be utilized to investigate atmospheric phenomena and characterize the ionizing radiation environment, as part of a broadly scoped mars science and exploration mission. Thus, the UTM holds significant utility concerning MEPAG Goal II (Climate on Mars) and Goal IV (with respect to ionizing radiation exposure), in addition to secondary contributions toward Goal I (concerning habitability) [17]. In general, large high-quality datasets for disciplines such as planetary atmospheric science, surface geology [68], geophysics, astrobiology [43] can be returned, in addition to helping prepare for human exploration [40] of Mars over the next few decades.

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