73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.

IAC-22,A3,IPB,35,x72466

Martian Interior Investigation Using Distributed Geodetic Sensor Network in the Tharsis Region of Mars

Julian Rothenbuchner[a]*, Onė Mikulskytė[a], Bart Root [b]
[a] *Team Tumbleweed, Delft, The Netherlands*
[b] *Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, Delft, The Netherlands*
* Corresponding Author, julian@teamtumbleweed.eu

Abstract

Mars can provide unique insights into the mechanisms of planetary formation, thereby offering valuable clues to the early history of Earth and other rocky bodies. Currently, the internal structure of Mars is investigated using the instruments of the InSight lander, offering clues to its internal structure and formation. However, many questions remain unanswered, such as the existence and strength of convective mantle plumes. One major limitation of current experiments is that they provide measurements from only one point on the Martian surface.

We propose the **I**n-situ **MA**rs **G**eodetic **I**nstrument **NE**twork (IMAGINE) instrument - a network of combined radiobeacon and laser retro-reflector instruments to be deployed on Martian surface using a swarm of wind-driven Mars Rovers. After being deployed on Mars, the instruments will be spread to cover significant portions of the Martian surface, such as the Tharsis region. They take advantage of already-existing ranging capabilities on orbital spacecraft used on legacy surface missions and can provide geodetic data over long periods up to several decades.

The Tharsis region on Mars is uniquely suited to provide insights into the interior structure of Mars by investigating volcanic and tectonic activity. Gathering geodetic data and measuring potential ground deformation will offer vital clues on the mechanisms supporting the region. Moreover, it is possible to measure tidal deformations, providing more exact constraints on the Love number k_2 which can give further insight into the size of the planetary core and mantle properties. Next to that, the proposed network augments gravimetry of Mars through tracking orbiters. The radio beacon network also allows for the precise determination of Martian rotation, precession and nutation to gain insights into polar ice cap evolution and Martian interior structure.

We have also identified numerous secondary applications for this network, namely long-term atmospheric studies using optical sensing. Using proven instruments and methods, it is possible to make measurements of the optical density and absorption characteristics of the atmosphere using the retro-reflector. The same instrument can also be used in fundamental science, validating aspects of general relativity. Lastly, the technical feasibility of the instrument is evaluated - while there is a laser retro-reflector with flight heritage fitting the requirements, creating a radio beacon and transmitter that is sufficiently light will require further development.

Keywords: Geodetic Network, Mars, Radio Beacon, Laser Retro-reflector, Tharsis Region, Tumbleweed Mission

1 Introduction

Mars, with its intermediate size between the Moon and Earth, can provide invaluable insights into planet formation. The surface of Mars is affected by processes much akin to the other rocky planets in our solar system (e.g. volcanism, erosion, impact craters). At the same time, its surface seems to be arrested in its arguably original state, as it has cooled down more quickly due to its relatively smaller size [1]. Nevertheless, the Insight mission determined that the iron core is at least partially liquid [2], suggesting some thermal activity within Mars' interior. Therefore, understanding the Martian interior and its evolution is key to understanding the formation of planets in general.

Most Martian missions are focusing on in-depth measurements in a relatively small area using landers, rovers, or, recently, aerial vehicles, but to get a global picture of the planet larger regions should be studied. Currently, the Martian interior is being investigated with SEIS (Seismic Experiment for Interior Structure), HP^3 (Heat Flow and Physical Properties Package) and RISE (Rotation and Interior Structure Experiment) experiments on the InSight lander, which will soon be decommissioned [3, 4]. This singular point of measurement is not enough to gather 3D data on a planet's interior. The next step in Martian exploration is a distributed network of landers. In the past, two ground network-based missions have been proposed, providing multiple landers on the Martian surface: the NetLander [5] and Mars MetNet[6]. The NetLander mission proposed a combination of four identical landers that would perform geodetic measurements for at least one Martian year. NEIGE [7], its main instrument for geodesy experiments using a radio system, was shown to hold potential for investigating the Martian interior. Unfortunately, the mission was canceled due to its high cost. The NetLander's successor, Mars MetNet, has been proposed and developed in the early 21st century. While its launch date is still to be determined, the expected science goals only cover the atmospheric and meteorologic measurements. This leaves a research gap in the network-based ground mission to Mars with the purpose of investigating its interior properties.

In this paper, we propose the **I**n-situ **MA**rs **G**eodetic **I**nstrument **NE**twork (IMAGINE) instrument - an array of up to 90 combined radio-beacon and retro-reflector installations dispersed over Mars and, most importantly, the currently unexplored Tharsis region. A distributed radio beacon system allows for the generation of exact geodetic information as well as subsequent orbit determination of orbiters using well-established Doppler measurement techniques. The retro-reflector will provide similar measurements, using laser time-of-flight measurements from Mars orbiters, and continue to do so even after the end of the mission. Combining these two instruments, IMAGINE will be able to provide geodetic information in the long term. Furthermore, its global coverage will offer a completely novel data set enabling more exact constraints within ongoing studies of the planet's interior and atmosphere, as well as enable novel science cases such as the direct measurement of polar motion. The instrument's further scientific potential is explored in subsection 2.1.

IMAGINE will be deployed using a swarm of fast-moving wind-driven Mars rovers: the Tumbleweed mission (see Figure 1), a mission concept offering low-cost access to network science on Mars. The scaleable mission architecture consists of up to 90 rovers deployed at the Martian poles, dispersing over the Martian surface towards the equator using its spherical shape and sails. The mission's scientific opportunities span a variety of areas: from the Martian climate, water and dust cycle to its surface geology and investigations into its internal structure, to name but a few. Crucially, the mission allows for the coverage on the order of 1/10th of the Martian surface, with the rovers being in motion for 90 days. It is followed by an arresting of the rover's motion and a stationary phase of at least one Martian year [8]. The spheroidal rovers (Figure 1) can carry a scientific payload of up to 5 kg each for a rover with a diameter of 5 meters, and provide location information and in-situ data processing as well as electrical power to the instruments. The Tumbleweed rover is suitable for small, simple instruments which pose few requirements with respect to positioning accuracy or available budgets. When it comes to geophysical measurements, the main strength of the mission is the large spread of instruments it can achieve over the surface. This allows for the mapping of large areas, for example with respect to their magnetic field, and the delivery of an array of a large number of sensors over the entire area.

The aim of this paper is to show the compatibility of the IMAGINE instrument with the Tumbleweed mission, and present its scientific value. First, we derive technical requirements and scientific capabilities, followed by an elaborate description of the proposed instrument. Then, its suitability for the Tumbleweed mission is examined and scientific implications are further discussed.

2 Required Capabilities and Constraints

In order to investigate the fitness of the IMAGINE radio beacon concept for its intended scientific and other use cases and its compatibility, we analyze both the required capabilities for the science case as well as the applied constraints from the Tumbleweed rover. Considered as capabilities are the functions and the performance at which they are to be performed by the instrument, whereas the constraints are the technical limitations imposed onto the system by its intended application in a Tumbleweed rover.

Figure 1: Visualizations of the Tumbleweed rover, which would host the IMAGINE instrument. a) A rendering of the Tumbleweed Rover. b) The Tumbleweed rover prototype V3, currently under development by Team Tumbleweed.

We do this by first establishing the scientific aims, capabilities and constraints of the instrument and then reviewing the status quo of relevant technologies, focusing on the ability of the instrument to provide geodetic information. Ultimately, the goal is to show that a system can in principle be devised which fulfills all capabilities within the constraints.

2.1 Scientific aims and their system requirements

A network of IMAGINE instruments deployed on Mars will be able to collect valuable information on its subsurface and internal structure, geology of the surface, as well as its atmospheric properties. We will present the identified use cases with their relevant references for further reading.

Continued and accurate tracking of radiobeacons enables the precise determination of Martian rotation, precession and nutation. The planetary precession of Mars can give indications of the high-level mass distribution of the planet, giving insight into its internal structure, while nutation can give insight into the response of the planet to rotational variations. Although extremely small (500 milliarcseconds), nutations can be used to infer properties of the Martian interior [9]. Although both measures have been investigated with the recent orbital and ground missions to Mars, the accuracy could be improved due to a large area coverage with IMAGINE.

Moreover, one of the most significant applications is the distributed network for orbit determination of satellites. The IMAGINE network allows for accurate measurement of the global gravity field by allowing the precise tracking of orbiter position, a method that has been employed previously in order to indirectly observe deformations of the Martian crusts. The same instrument can also be used in fundamental science, validating aspects of general relativity [10]. Through tracking orbital spacecraft, highly precise gravimetric data can be gathered regularly. While the parameters are currently well determined, their temporal evolution is not [1]. The data can also be used to improve the ephemeris of Mars and its moons.

It has recently been proposed that Tharsis could be rising in elevation [11]. The origin of the Tharsis region and other volcanically active regions is not clear, as are the mechanisms supporting their elevation. IMAGINE is the only way to directly measure the potential rise of the Tharsis region due to the high altitude of the landing site and the required surface-level measurements. This would offer vital clues on the mechanisms affecting this region. As it cannot be supported through isostatic buoyancy force on the mantle, understanding the mechanism that led to its formation and continued evolution provides insights into planetary formation as well as the Martian interior and mantle dynamics [1, 11]. Further, this could be helped by precise gravimetry data over time.

The deformation of Mars due to Solar tides allows for an exact constraint of the Love number k_2, which gives accurate constraints on the size of a liquid core and the state of the mantle, and can be directly measured [12]. This measure of the response of Mars to solar tides is both determined through the direct deformation of the planet and through measuring induced orbit precession of orbiting spacecraft [13, 1]. A global network of beacons can give better insight in shorter spatial-scale deformations.

Various secondary objectives are also achievable using this system, namely long-term ionosphere and atmosphere measurements studies using optical sensing and radiometric methods. Perturbations of signal can be used to study the ionosphere and density of the atmosphere. This further allows the study of material and mass exchange between the atmosphere and the poles ([9]. Atmospheric measurements can also be performed with the proposed retro-reflector. The reflected laser signal can be used to measure atmospheric optical depth and infer chemical abundances and absorption characteristics, dust concentrations, and more [10]. These measurements can be then used to improve the atmospheric density model of Mars.

While the Tumbleweed mission aims to achieve a similar level precision to older missions (position accuracy up to the centimeter level in all directions, as per InSight mission), the identical rovers would be spread over the surface of Mars, providing multiple-point measurements. As a result, we do not expect to improve the position accuracy, rather, provide a large coverage of the surface. Table 1 presents the relevant requirements for each science case.

Table 1: Scientific use cases

ID	Science Use Case	Accuracy	Location
SCI-1	Planetary Precession	cm	baseline only
SCI-2	Planetary Nutation	cm	baseline only
SCI-4	Length-of-day	cm	low latitude
SCI-5	Planetary love number k_2	mm	high latitude
SCI-6	Planetary Gravimetry	N/A	baseline only
SCI-7	Mantle Plume Strength & Surface Support Mechanisms	mm	Tharsis region

As can be seen, the for most science goals a centimeter-level accuracy is sufficient, as evidenced by legacy missions [13]. However, to determine the love number through polar motion, we argue that millimeter-level position accuracy is required as polar motion is estimated to be no more than 10 cm, in order to get accurate constraints (accuracy < 10 % of the expected observation). Lastly, if present, surface deformation in the Tharsis region is very small, therefore, we assume that millimeter-level accuracy will be required. For position, several science cases are only affected by the distribution of the network. Instead, the ideal location will be determined by the geometry of the network with the orbiting spacecraft, which is not analyzed in this paper. However, for length-of-day measurements a large distance between the rotation axis of Mars and the station, and therefore low latitude is desired. Conversely, high latitudes are required for polar motion, while measuring Tharsis region movement requires stations within Tharsis.

2.2 Technical constraints of the Tumbleweed mission

The technical constraints on which the instrument shall operate are based on specifications of the Tumbleweed rover currently under development [8]. The resulting major constraints are listed below in Table 2.

Table 2: Constraints of the IMAGINE

ID	Description	Rationale
CON-1	Total radio beacon equipment mass shall not exceed 1.03 kg.	Derived from modified mass model outlined in [8], limit to mass in order to comply with 10 kg mass restriction of mission. Mass margins applied in accordance with ECSS-E-TM-25A recommendations.
CON-2	Total retroreflector mass shall not exceed 0.025 kg.	Derived from payload mass budgets of the Tumbleweed demonstrator mission [8]
CON-3	The instrument shall fit within a footprint no larger than 10×10 cm, not including externally mounted hardware.	The electronics box of the Tumbleweed rover is sized to support CubeSat hardware with this approximate footprint.
CON-4	The instrument shall have a peak power consumption of no more than 43 W.	Assumed power consumption based on 30% amplifier efficiency and 12.8 W transmitter power [14, 15].

As can be seen, the instrument is subject to tight mass constraints, with an allowable mass significantly lower than legacy instruments such as RISE, which had an overall mass of $7.6kg$ [16]. Furthermore, the footprint requirement is imposed due to packaging constraints within the pod that houses the payload of the Tumbleweed rover. Lastly, the power requirement is considered non-critical. However, this comes with the likely caveat that it will require instrument-internal power regulation to stay within the limitations of the PCDU (Power Conditioning and Distribution Unit) of the Tumbleweed.

3 IMAGINE Instrument Overview

In order to utilize the opportunity to deploy in geodetic instruments to Mars in unprecedented numbers with the Tumbleweed Mission, we propose a combined laser retro-reflector and radio beacon payload. This combination of instruments has flight heritage on several different missions, the latest one being the InSight mission [13]. It allows for the generation of geodetic information using both established radio ranging techniques, primarily two-way Doppler measurements, as well as the use of satellite laser ranging to complement these measurements. Doppler tracking has been used to determine the position of instruments on the Martian surface to within 2 cm [2]. Meanwhile, retro-reflectors allow complemen-

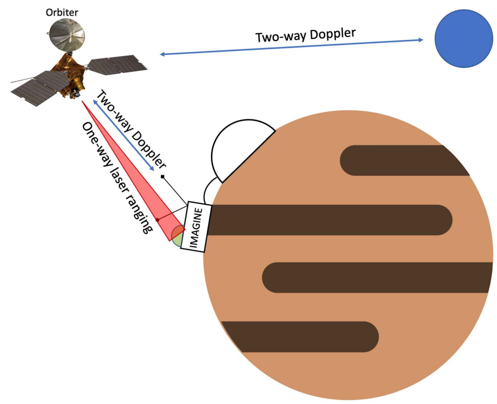


Figure 2: Concept of operations for the IMAGINE instrument, showing both radio and laser ranging.

tary measurements from orbiters and ground-based stations also contributing to a long-lived Mars geodetic network [17]. The lifetime of such a retro-reflector has been shown to be on the order of decades [10]. This means that the IMAGINE instrument supports both ground-based and relay-based range or range rate measurements, maximizing the number of measurements that IMAGINE can provide. Figure 2 shows the concept of operations for the IMAGINE instrument.

As shown, the position of an IMAGINE station relative to an orbiting spacecraft is determined using either two-way Doppler ranging using the radio beacon or using laser ranging with the retro-reflector, or both. The position of the orbiter is determined using ranging from Earth, or, in alternate use cases, using the known position of the IMAGINE station and network.

3.1 Integration with Tumbleweed mission

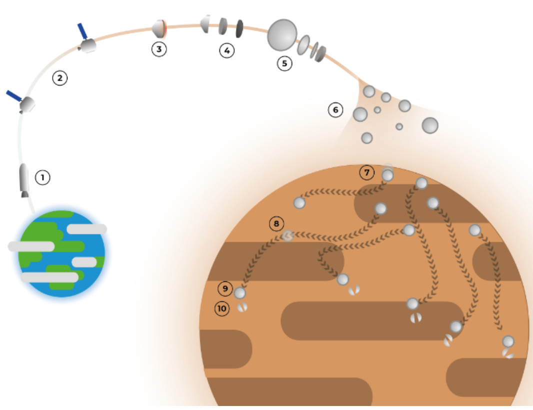


Figure 3: Concept of operations diagram showing landing, rolling and deployment of IMAGINE using wind-driven rovers.

As previously discussed, the instrument is proposed to be deployed using a swarm of wind-driven Tumbleweed rovers. These rovers impact the Martian surface in close proximity to each other and subsequently spread out by utilizing the Martian winds, generating science data during the mobile phase as shown above in **??**. Figure 4 shows a computer image of the next-generation Tumbleweed rover, highlighting its various parts.

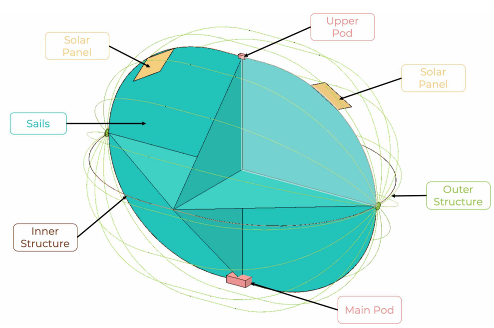
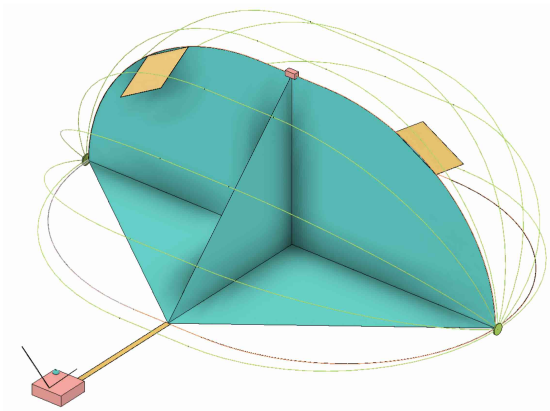


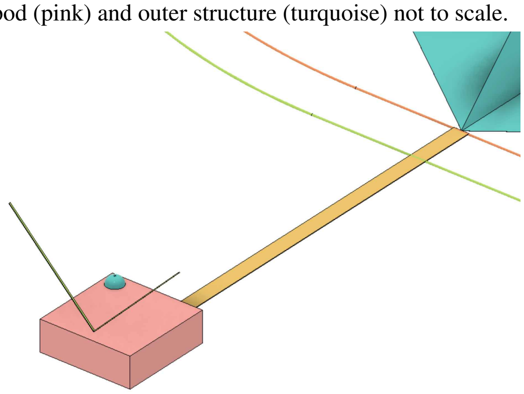
Figure 4: The next-generation Tumbleweed rover featuring the inner structure with pods and outer structure [8].

The IMAGINE instrument is envisioned to be mounted both inside the main pod (radio beacon electronics) and externally (antennas and retro-reflector). However, IMAGINE is only deployed once the subsequent stationary phase of the mission is reached, where the rovers permanently arrest their movement once the desired spread is reached. The deployed configuration is shown in Figure 5.

As can be seen in Figure 5a, the Tumbleweed rover collapses and deploys the pod to the side of the collapsed outer structure. This allows IMAGINE to have line-of-sight with the passing orbiters. Alternatively, mounting of the retro-reflector and antennas to the top of the inner structure (on the upper pod) could be considered, enabling operating before the stationary phase is reached, increasing ground separation and potentially simplifying deployment at the cost of lengthened antenna wires. Overall, no final decision on the preferable mounting point can be made at this time.



(a) Schematic of the stationary Tumbleweed. Distance between main pod (pink) and outer structure (turquoise) not to scale.



(b) Detailed view of deployed IMAGINE with retro-reflector (turquoise) and antenna (green). Antenna design is for illustrative purposes only.

Figure 5: Rendering showing the stationary Tumbleweed rover with deployed IMAGINE.

3.2 Achievable sensor baselines

Next, we consider three critical aspects of the Tumbleweed mission to establish its suitability for deploying the proposed instrument network.

In order to achieve an instrument baseline of 1760 ± 5km as discussed in [7], the Tumbleweed rovers will have to cover at least this distance in order to deploy two sensors with this baseline - one at the landing site, and one after rolling the required distance. In this case one Tumbleweed rover will arrest its motion almost immediately, while the other will continue until the distance is reached. It has been estimated that a Tumbleweed rover, using Martian winds, can travel up to 185km downwind at Martian vertical datum [8]. This suggests that the desired distance can be reached as early as 9.5 days after landing. This number most certainly underestimates the time required to reach the final distribution as it does not account for undesirable wind directions, the lower density at the Tharsis region resulting in reduced performance and the actual terrain.

Still, it is important to note that even a ten-fold decrease in performance, leading to a deployment time of 95 days, is still roughly 7 times smaller than the required time of operation of the IMAGINE instrument of at least 100 weeks or approximately one Martian year as discussed in [18] and also significantly smaller than the transfer time between Earth and Mars. Therefore, we deem the Tumbleweed rover a viable option to deploy the IMAGINE network from a distance performance perspective.

3.3 Tharsis region landing

Next, we consider the Tumbleweed mission's ability to deploy rovers to the Tharsis region, where the atmosphere is significantly thinner than at the Martian vertical datum and therefore impact velocity is increased.

To do this, we investigate the impact acceleration that will be experienced at a landing at 5km, as it would be found at the outer parts of the Tharsis highlands. Here, we model the terminal phase of the Tumbleweed rover descent, where it falls at terminal velocity, slowed by its aerodynamic properties. To model the aerodynamic properties of the rover, they are considered equal to those of a finite flat plate, neglecting the drag contribution from the other sails and structure. Furthermore, lacking exact knowledge of the structural characteristics, the impact is modeled in two ways: as an upper bound for impact loading, a linear deformation-force relationship is assumed, and assuming a point mass and a mass-less spring/decelerator. For the lower bound, a constant-force impact is taken. The model applied is discussed in more detail in [19]. There, it was shown that the worst-case impact acceleration, assuming a deformation of the structure of 20%, would be approximately 40g, while the best case would be 21g. These numbers are likely quite conservative, as the outer structure, consisting of thin rods and wires, contributes a significant portion of the drag force. Moreover, the assumption of a single mass and mass-less spring/decelerator means that it underestimates the load factors experienced by some parts, while it overestimates those of other parts. The pod, with it being supported in tension by the upper arc of the inner structure, could therefore be designed to experience significantly less load.

Even taking the estimations at face value, however, they do not fall outside the range of impact loads commonly experienced by space hardware in the launch environment. Therefore, the impact load experienced by IMAGINE during a landing at will likely not drive the mechanical design in a significant way, underscoring the overall feasibility of deploying to the Tharsis region.

3.4 Mission Cost

Moreover, the deployment of instrument network using a Tumbleweed mission has the key advantage of low cost per station delivered. Whereas the legacy NetLander mission delivered four stations for $350 million ($87.5 million per station) and the InSight mission delivered one station for $814 million, the Tumbleweed mission is estimated to deliver 90 stations for a cost of $460 million ($5.1 million per station), while also being scaleable to suit varying mission budgets [8].

Next, we present both parts of the IMAGINE instrument in detail and review the status quo of work done in both fields This is done with the goal of finding legacy systems which have a good fit with the applied requirements and determining how well they perform within the IMAGINE instrument.

3.5 Laser retro-reflector

The fundamental principle of a retro-reflector of using three adjacent, mutually orthogonal planes to return a beam of light to its origin is well established both in terrestrial use and in space. On Mars, range measurements with millimeter-level accuracy using orbiting spacecraft and laser retro-reflectors have been shown to be feasible [10]. The first retro-reflector with such capability was supposed to be sent to Mars on the ExoMars EDM as the INRRI [10], which was scheduled to land on Mars in 2016. An identical unit was successfully delivered to Mars two years later aboard the Mars InSight lander [20] and later on the Perseverance rover. These instruments consist of a set of 8 15.7mm corner cube reflectors mounted in a dome-shaped housing, designed to be mounted on zenith-pointing surfaces of Mars landers and rovers. Figure 6 shows the INRRI laser retro-reflector.

The attainable millimeter-level ranging accuracy is, in principle, able to fulfill even the most demanding science use case. However, this is contingent on generating sufficient knowledge of the relay orbiter's position with respect to the Martian frame of reference. Here, it is noteworthy that using more than three retro-reflectors allows for triangulation of satellite position, alleviating the concern of satellite position uncertainty [21]. In order to establish the compliance of the instruments with the constraints of the Tumbleweed carrier, we consider the instrument's physical parameters. The characteristics of both instruments are listed below in Table 3.

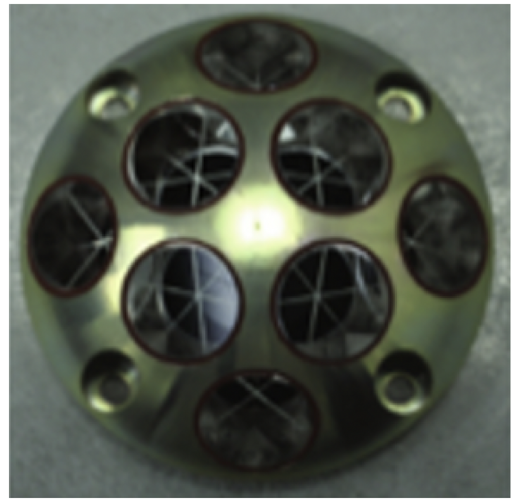


Figure 6: The INRRI flight instrument [10].

Considering the key parameters of the INRRI/LaRRI instruments, it is apparent that they fit the applied constraints without further modification. As they do not require electrical energy, power consumption is omitted, and therefore, it is compliant with CON-4 by default. For the mass, they fit within the overall mass budget set out by CON-2 - in fact, the retro-reflector mass budget of the demonstrator mission has been created with this exact instrument in mind. The footprint constraint CON-3 does not apply to this instrument as it is externally mounted as discussed above. It is expected that due to the instrument's small size and low profile, mounting will present little issues. The zenith-pointing requirement of the retro-reflector can be fulfilled mounting on the rover inner structure or on top of the pod, which will retain an upright orientation throughout the mission. However, its packaging and size limitations must be investigated in more detail once exact information on the folding process of the Tumbleweed is available.

3.6 Radio Beacon

In general, the principle of two-way time-of-flight and Doppler shift measurements in space is well established and has been one of the main methods of spacecraft navigation for decades. Furthermore, the capability of radio-based location determination between Mars surface craft and orbiters has significant heritage as well, with legacy missions successfully using this technique to determine their position on the Martian surface to within several meters [22]. Furthermore, various radio science experiments such as the MER radio science experiment and the RISE instrument carried aboard Insight have been used to provide geodetic information using radio links between Mars and Earth, the latter being a five-fold improvement of positional uncertainty over previous efforts [2]. Additionally,

Table 3: As-built characteristics of the INRRI/LaRRI/LaRa instrument [21].

Mass	$0.025kg$
Size	$5.5x2.0cm$

significant development effort has been made on NEIGE, a relay - Mars surface geodetic payload which was to be sent on the NetLander mission. Another similarity between NEIGE and IMAGINE is that NEIGE was designed to be deployed in a network, albeit in much smaller quantities (4 instead of 10s or even 100s of stations) [7]. Lastly, it is important to mention the IRIS series of deep space transponders, which have capabilities to support radio science as proposed for IMAGINE, while also being notable for being highly compact and light-weight [23].

The performance of the NEIGE instrument network has been the subject of significant study. It consists of a combination of a UHF coherent turnaround radio which doubles as a TM/TC system, and a phase-linked X-Band transmitter transmitting a pure carrier signal. This is done in order to correct for influences of the Martian ionosphere [7]. In performance analysis of this system, it has been shown that even with comparatively low numbers of passes with limited integration time, leading to a measurement time of 15-20 minutes per week [18], is sufficient to determine the position of each station with an uncertainty of a few centimeters [24]. Furthermore, the ability to address science cases pertaining to nutation, polar motion and length-of-day measurements has also been shown [25]. Moreover, a positioning instruments at higher latitudes, such as the Northern or Southern flanks of the Tharsis region could also allow to further constrain the polar motion of the planet. Given the track record of the IRIS radio, its performance applied within the IMAGINE instrument would likely be similar if UHF transmission and concurrent X-Band and UHF transmission capabilities can be integrated. The IRIS transponder, including SSPA and LNA is shown in Figure 7.

Compared to the NEIGE instrument, the higher number of stations will allow for more overpasses resulting in more measurements being taken and triangulation between stations, leading to a higher number of observables with subsequently increased accuracy and reduced convergence time. Furthermore, determining geodetic information at a higher number of points could offer benefits in determining rotational characteristics, polar motion and solar tides. Lastly, through deployment in the Tharsis region, direct measurements in this area are possible for the first time ever.

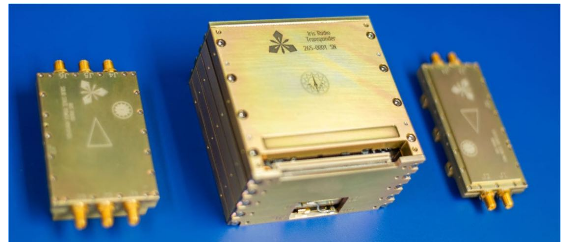


Figure 7: The IRIS transponder [23].

With peak positional accuracy on the order of centimeters, NEIGE (and, given that the above conditions are met, also IRIS) can address science goals requiring centimeter-level accuracy, such as precession, nutation and length-of-day measurements. However, on their own, they are ill-equipped to address the most demanding of geodesy science goals such as measuring potential tectonic activities within the Tharsis region and measuring polar motion.

Having established that the relevant capabilities are mature, we must now consider the applied constraints of mass, size and power consumption. In our search, we consider instruments or existing designs which support coherent turnaround ranging primarily using the UHF frequency band. Furthermore, they should be designed for a deep-space environment. We elected to include both proposed concepts as well as heritage hardware in our search. The limitation of using UHF as a frequency band is made as this is the preeminent frequency band used for Mars [26] - Relay communications courtesy of the Electra proximity radio payload which features heavily in past Mars orbiter mission. The limitation of using relayed communication is made due to mass and power considerations. Ultimately, two instruments were found worthy of further consideration: the proposed NEIGE instrument, and the IRIS V2 transponder. Their characteristics are shown in Table 4.

First up, it is important to note that the specifications of both instruments match closely, showing the validity of the parameters generated for the NEIGE instrument. Both instruments exceed the mass limits posed by the Tumbleweed mission by some margin, especially considering the fact that antenna and harness mass are not included in this estimation. This additional hardware can be expected to add around 0.35kg of mass to the system [7]. Using the Tumbleweed rover subsystem-level mass estimation tool used in [8], we estimate overall mission mass for a single rover demonstration mission to increase from 10.0kg to 11.6kg in case of the IRIS V2 transponder and to 11.4kg for the NEIGE instrument, including said antenna mass.

Table 4: Characteristics of IRIS V2 and NEIGE radio systems. Data extracted from [23] and [7].

	IRIS V2	**NEIGE**
Frequency Band	UHF (UHF transmission subject to further development), X-Band	UHF, X-Band
Mass	$1.1kg$ (excl. Antenna)	$1.05kg$ (excl. Antenna)
Size	Transponder: $10.1x10.1x5.6cm$ SSPA: $11.4x4.6x1.6cm$ LNA: $10.3x5.6x2.4cm$	UHF Transponder: $12x12x3cm$ X-Band Transponder: $12x12x2cm$ UHF Diplexer: $12x6x2cm$
Power Consumption	Receive only: $10.3W$ (X-Band) Transmit/Receive: $33.6W$ (X-Band)	Receive only: $2W$ (UHF) Transmit//Receive: $40W$ (UHF and X-Band)
Transmission Power	$8.1dBW$ EIRP	$5.8dBW$ EIRP

The additional mass increase can be explained through revised sizing of the rover structure and locomotion system to account for the added mass, and the increased entry vehicle sizing. This represents an approximate 16% increase in mission mass. On the other hand, reduction of radio beacon mass or reduction in mass margins for the rest of the scientific payload may present an option that warrants further study.

On the other hand, only the NEIGE instrument exceeds the size limitations. This presents two options: either redesign the Tumbleweed platform or repackage the instrument. We argue that the repackaging of the instrument represents the preferable alternative as, in principle, only the aspect ratio of the instrument needs to be changed as opposed to the overall dimensions of the spacecraft bus. Based on the same argument, we argue that the required development of bringing the instrument in agreement with the footprint constraint is relatively minor.

Lastly, while both instruments fit within the power budget as-is, some changes proposed above to improve instrument precision will likely lead to the power limits being exceeded. Furthermore, while energy budgets of 2Wh per day constitute less than 1% of the currently proposed energy budget of the Tumbleweed rover [19], nearly all measures to increase instrument accuracy will significantly increase the required energy, which will warrant further analysis.

4 Discussion

In this paper, we present IMAGINE, a network of combined radio beacons and retro-reflectors deployed by wind-driven Tumbleweed rovers. We show that, first, there are legacy hardware and development efforts which are able to provide centimeter-level position accuracy for each station using the radio beacon and millimeter-level ranging accuracy using the retro-reflector. We also investigate the technical feasibility of deploying a network of IMAGINE using Tumbleweed rovers. To this end, we evaluate the NEIGE instrument concept, the IRIS V2 deep space transponder and the INRRI/LaRRI/LaRA retro-reflector within the constraints of the Tumbleweed platform.

Here, the retro-reflector is found to be fully compliant with respect to mass and size as well as mounting requirements. For the radio beacon, the mass is determined to exceed limitations by 35% for both the NEIGE instrument and the IRIS V2. If the mass of the radio beacon cannot be reduced, we find that this would cause an increase in Tumbleweed mission mass by up to 16%, based on single-rover modeling. Lastly, footprint requirements are met for IRIS V2, whereas the NEIGE instrument would require a change in aspect ratio of the instrument enclosure. Both investigated systems meet power constraints. Lastly, we find that a Tumbleweed rover can achieve instrument baselines of 1760km, as envisioned in the NetLander mission, provide a survivable landing in the Tharsis region and deploy the stations at a cost of 5.1MEUR per station.

We posit that combined measurements, when applied in large numbers, are able to meet a variety of geodesy science goals, such as improving measurements of Martian precession and nutation, polar motion, variations in length-of-day and, being able to deploy to the Tharsis region, recording potential tectonic activity. Moreover, such a network has a host of additional applications in spacecraft navigation and landing, orbiter-based gravimetry, ionosphere and atmosphere science and fundamental sciences. Overall, the high number of stations has the potential to support geodesy-based Martian interior studies requiring more accurate or complete data sets than currently available. Furthermore, the long-lived nature of the retro-reflectors has the potential for unprecedented long-term studies of Mars, with generating consistent datasets over decades becoming a possibility.

IMAGINE is feasible to be deployed using Tumbleweed rovers, using legacy hardware, with relatively minor modification. The major concern is the mass reduction of the radio beacon. Inability to reduce the mass to within the constraints will cause a considerable mass increase of the mission amounting to 16%, whose consequences would have to be further studied. However, in all other areas that were studied, we found good agreement between constraints and the instruments.

As a result, the combination of legacy developments and hardware, applied and deployed in a large network using Tumbleweed rovers, can support a whole host of new scientific goals, and improve existing knowledge on the Martian interior. Such a network promises a novel set of network geodesy data that could not only prove highly relevant to a number of Mars interior, ionosphere and atmosphere studies, but could also have huge implications for the operation of orbital and surface missions on Mars. Therefore, this network could form the first piece of Mars surface infrastructure critical to future exploration. Moreover, the Tumbleweed platform has shown to harbor potential to be a cost-effective and scaleable method of deploying IMAGINE and other network science payloads on Mars, such as weather stations.

Accuracy performance is subject to the limitations of NEIGE, as the analysis was largely based on this heritage instrument. The higher number of stations can be expected to increase the accuracy per station due to providing more data points. Additionally, the exact spreading of rovers was not considered, instead, 1D spread was investigated which indicates that the rovers can be controlled to adjust their spread over surface [8]. Next to that, several other constraints were not considered such as energy and thermal considerations. Energy requirements comprise less than 1% of the energy budget of the Tumbleweed rover, but adaptations to improve single-station performance could make this estimation more critical, warranting future investigations. Finally, due to the scope of this paper, the performance of the entire network was not investigated - a detailed analysis will be performed at a later stage.

We recommend that on the side of the Tumbleweed mission development, analysis of spreading performance be improved to include spreading within the Tharsis topography and considering desired spreading patterns for use in the IMAGINE network. Furthermore, energy budgets of the Tumbleweed rover should be reassessed to determine the ability of the Tumbleweed mission to not only support IMAGINE operation within the limited scope of previous missions, but also considering increased measurement time and frequency to improve station accuracy. Moreover, the integration of antennas and the retro-reflector on the outside of the Tumbleweed electronics housing or within the structure should be improved. Lastly, the impact of an increased TM/TC and payload mass budget to fit currently available hardware should be further assessed, especially with regards to the effect of variations in mass margins. For the IMAGINE network, it is necessary to analyze in detail the performance of the network considering various methods of utilizing the network to generate geodetic information. This, together with identifying additional science cases and fully quantifying both the newly identified cases and those already outlined in this paper will be crucial to formally derive performance requirements for the instrument and begin detailed development of the IMAGINE instrument. Also, it is important to, based on the results of this additional analysis, investigate the necessity and effectiveness of additional measures to improve network performance. This includes increasing the per-station transmission time or power. Lastly, the desired position of the individual stations should be investigated for various science cases.

5 Conclusions

In this paper, we show that the potentially paradigm-shifting results of true network science on Mars are within reach using a Tumbleweed mission architecture and a combined retro-reflector and radio beacon instrument called IMAGINE. Geodetic data collected by radio beacons and laser retro-reflectors will provide insight into various aspects of Mars, from its interior and surface to the atmospheric properties. Deployment of this network can be done an order of magnitude more cost-effectively at an estimated cost of $5.1 million per station deployed. IMAGINE can draw from instrument with Mars heritage for the retro-reflector and will require modified versions of existing designs for the radio beacon. Furthermore, previous analysis of the NEIGE instrument has shown that a miniaturized radio beacon is able to provide centimeter-level position accuracy on Mars. We showed this instrument, as well as the IRIS deep space transponder, to be largely compatible with the Tumbleweed mission, with only the mass of both radio instruments, being 35% above the constraint. Lastly, we propose methods for improving the accuracy of the instrument further, including the combination of retro-reflector and radio beacon tracking results, utilizing the high number of deployed instruments to improve position estimates, increasing the signal-to-noise ratio and increasing the number of measurements made per instrument. The relative utility of these measures, while having been partially shown to be effective in previous analyses, must be investigated further. Moreover, efforts to reduce the mass of the radio beacon need to be investigated in detail, and the effect of changes to the operation of the radio beacon instrument on the energy requirements of the instrument need to be assessed.

References

[1] S. E. Smrekar, P. Lognonné, T. Spohn, W. B. Banerdt, D. Breuer, U. Christensen, V. Dehant,

M. Drilleau, W. Folkner, N. Fuji, R. F. Garcia, D. Giardini, M. Golombek, M. Grott, T. Gudkova, C. Johnson, A. Khan, B. Langlais, A. Mittelholz, A. Mocquet, R. Myhill, M. Panning, C. Perrin, T. Pike, A. C. Plesa, A. Rivoldini, H. Samuel, S. C. Stähler, M. van Driel, T. V. Hoolst, O. Verhoeven, R. Weber, and M. Wieczorek, "Pre-mission InSights on the Interior of Mars," 1 2019.

[2] D. S. Kahan, W. M. Folkner, D. R. Buccino, V. Dehant, S. L. Maistre, A. Rivoldini, T. V. Hoolst, M. Yseboodt, and J. C. Marty, "Mars precession rate determined from radiometric tracking of the InSight Lander," *Planetary and Space Science*, vol. 199, 5 2021.

[3] NASA. Mars Curiosity Rover. [Online]. Available: https://mars.nasa.gov/msl/

[4] J. O'Callaghan, "End draws near for lander that mapped the interior of Mars," *Science*, vol. 376, p. 905, 5 2022.

[5] J. L. Counil, F. Ferri, P. Lognonne, O. Marsal, F. Rocard, and R. Bonneville, "The NetLander Mission: a Geophysical Network Aimed at Investigating Mars Atmosphere, Sub-Surface and Deep Interior," 2001.

[6] A.-M. Harri, J. Leinonen, S. Merikallio, M. Paton, H.Haukka, J.Polkko, P. V. Linkin, V. Lipatov, K. Pichkadze, A. Polyakov, M. Uspensky, P. L. Vasquez, D. H. Guerrero, D. Crisp, R. Haberle, S. Calcutt, C. Wilson, P. P. Taylor, P. C. Lange, M.Daly, L. Richter, R. Jaumann, J.-P. Pommereau, F.Forget, P. Lognonne, and J. Zarnecki, "MetNet - In Situ observational network and orbital platform to investigate the Martian environment," 2007.

[7] J.-P. Barriot, V. Dehant, W. Folkner, J.-C. Cerisier, A. Ribes, J. Benoist, T. V. Hoolst, P. Defraigne, R. Wamant, R. A. Preston, L. Romans, S. Wu, and A. W. Wemik, "The NetLander Ionosphere and Geodesy Experiment," pp. 1237–1249, 2001. [Online]. Available: www.elsevier.com/locate/asr

[8] J. Rothenbuchner, L. Cohen, F. Abel, D. Buryak, K. Cuervo, J. Kingsnorth, O. Mikulskytė, L. Oster, A. Phillips, M. Resink, and M. Sandrieser, "The Tumbleweed Mission: Enabling Novel Mars Data Sets through Low-Cost Rover Swarms," 2022. [Online]. Available: https://www.teamtumbleweed.eu

[9] V. Dehant, P. Lognonné, and C. Sotin, "Network science, NetLander: A european mission to study the planet Mars," vol. 52, 9 2004, pp. 977–985.

[10] S. Dell'Agnello, G. D. Monache, L. Porcelli, A. Boni, S. Contessa, E. Ciocci, M. Martini, M. Tibuzzi, N. Intaglietta, L. Salvatori, P. Tuscano, G. Patrizi, C. Mondaini, C. Lops, R. Vittori, M. Maiello, E. Flamini, E. Marchetti, G. Bianco, R. Mugnuolo, and C. Cantone, "INRRI-EDM/2016: the first laser retroreflector on the surface of Mars," *Advances in Space Research*, vol. 59, pp. 645–655, 1 2017.

[11] Y. V. D. Tang, "The Origin of Tharsis-A Deep Mantle Gravity Study MSc. Thesis," 2021. [Online]. Available: http://repository.tudelft.nl/

[12] C. F. Yoder, A. S. Konopliv, D. N. Yuan, E. M. Standish, and W. M. Folkner, "Fluid Core Size of Mars from Detection of the Solar Tide," *Science*, vol. 300, pp. 299–303, 4 2003.

[13] W. M. Folkner, V. Dehant, S. L. Maistre, M. Yseboodt, A. Rivoldini, T. V. Hoolst, S. W. Asmar, and M. P. Golombek, "The Rotation and Interior Structure Experiment on the InSight Mission to Mars," 8 2018.

[14] M. Kobayashi, "Iris deep-space transponder for SLS EM-1 CubeSat missions," 2017.

[15] F. Abel, C. Ferent, P. Sundaramoorthy, and R. T. Rajan, "Communications architecture for Martian surface exploration with a swarm of wind-driven rovers."

[16] "Radio Science Experiment," May 2022. [Online]. Available: https://mars.nasa.gov/insight/spacecraft/instruments/rise/

[17] S. D. G. Delle Monache, L. Porcelli, L. Salvatori, M. Tibuzzi, C. Mondaini, R. Vittori, R. March, M. Muccino, O. Luongo, L. Ioppi *et al.*, "Testing gravity with the moon and mars," *Frascati Physics Series*, vol. 66, no. 2018, 2018.

[18] P. Rosenblatt, J. C. Marty, F. Perosanz, J. P. Barriot, T. V. Hoolst, and V. Dehant, "Numerical simulations of a Mars geodesy network experiment: Effect of orbiter angular momentum desaturation on Mars' rotation estimation," vol. 52, 9 2004, pp. 965–975.

[19] J. Rothenbuchner, J. Kingsnorth, K. Cuervo, M. Renoldner, M. Kapadia, P. Wiesen, S. Harris, and M. Resinck, "Initial Pre-Phase A study of the Tumbleweed Demonstrator Mission," 2022. [Online]. Available: https://www.teamtumbleweed.eu/development/wp-content/uploads/2022/09/Project_1_Deadline_1_Report.pdf

[20] L. Porcelli, M. Tibuzzi, C. Mondaini, L. Salvatori, M. Muccino, M. Petrassi, L. Ioppi, S. Dell'Agnello,

O. Luongo, G. D. Monache *et al.*, "Optical-Performance Testing of the Laser RetroReflector for InSight," *Space Science Reviews*, vol. 215, no. 1, pp. 1–11, 2019.

[21] S. Dell'Agnello, A. Boni, C. Cantone, M. Tibuzzi, R. Vittori, G. Bianco, C. Mondaini, P. Tuscano, E. Ciocci, M. Martini, G. Patrizi, G. D. Monache, D. Currie, N. Intaglietta, L. Salvatori, C. Lops, S. Contessa, L. Porcelli, and M. Maiello, "Next-generation laser retroreflectors for GNSS, solar system exploration, geodesy, gravitational physics and earth observation." SPIE-Intl Soc Optical Eng, 1 2018, p. 172.

[22] C. D. Edwards, K. N. Bruvold, J. K. Erickson, R. E. Gladden, J. R. Guinn, P. A. Ilott, B. Jai, M. D. Johnston, R. P. Kornfeld, T. J. Martin-Mur, G. W. McSmith, R. C. Thomas, P. Varghese, G. Signori, and P. Schmitz, "Telecommunications relay support of the Mars Phoenix lander mission," 2010.

[23] Space Dynamics Laboratory, "Iris Radio For Deep Space Small Satellites Data Sheet." [Online]. Available: https://www.sdl.usu.edu/downloads/pdfs/iris.pdf

[24] J. Vienne, J. Barriot, P. Rosenblatt, M. Yseboodt, J. Duron, and V. Dehant, "Numerical simulations of the Netlander Ionosphere and Geodesy Experiment (NEIGE): Landing site positions determination from Doppler tracking between an orbiter and landers," *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Eur. Space Agency Spec. Publ., ESA-SP*, vol. 544, pp. 351–355, 2004.

[25] M. Yseboodt, P. Rosenblatt, V. Dehant, J. Barriot, and T. Van Hoolst, "Mars Geodesy with NEIGE: Simulation of the Martian orientation parameters estimation," in *Earth-like Planets and Moons*, vol. 514, 2002, pp. 145–149.

[26] C. D. Edwards, T. C. Jedrey, E. Schwartzbaum, A. S. Devereaux, R. Depaula, M. Dapore, and T. W. Fischer, "The Electra Proximity Link Payload for Mars Relay TeIecommunications and Navigation."