# Antenna placement and architecture for a wind-driven, spheroid Tumbleweed rover on Mars

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**Abstract —** Interest in Mars exploration has seen stark growth in recent years. Advances in distributed systems, miniaturization and commoditization of space electronics, and innovations in communications permit the rise of innovative concepts such as the Tumbleweed Mission - a low-cost Mars surface mission using a swarm of wind-driven mobile impactors. The antenna accommodation proves challenging for this mission, primarily due to the semi-controlled tumbling motion of the rovers and the fact that the structure is subject to abrasive contact with the Martian surface.

Insufficient realized antenna gain, potential interference with structural elements and mechanical damage could prevent the rover from successfully transmitting its data to the data relay orbiter in Mars orbit.

In prior work on the communications architecture for the Tumbleweed Mission, antenna integration was identified as an issue to be addressed for exploration vehicles with semi-random movement. The data downlink is a crucial aspect of every exploration mission, for without it, the mission has no purpose. Therefore, the objective of this paper is to find suitable antenna architectures and identify at least one solution meeting the system and performance requirements of the mission. We propose three antenna architectures and conduct a qualitative trade-off taking into account the communication performance and effects on the rover as a hosting platform accommodating the antenna needs.

We examine three antenna architectures. First, we consider a fixed-mounted, single-element omnidirectional antenna, which is low-mass, simple to mount, and requires no electronic or mechanical control.

However, it features the worst antenna gain out of all options and could be subject to harmful interference with the rovers' structure and suffer from multipath effects. We also study a single-element antenna, which employs passive mechanical steering to achieve zenith-pointing and features improved gain. While this stabilization is already technically realized in Tumbleweed Rovers requiring controllability, questions of antenna placement remain. Furthermore, the remaining pointing uncertainty raises concerns for the link availability given undesirable pointing states. Third, an electronically steered phased array antenna with elements integrated into the rovers' outer structure is examined. It features improved gain without moving parts, yet it requires a large number of antennas that come with complex electronics to drive it and could be subject to harmful contact with the Martian surface. In the paper, we present an antenna architecture fulfilling the requirements of the Tumbleweed Missions and recommend further steps to mature and validate its design.

**Keywords:** Tumbleweed mission, Mars exploration, rover, swarm, antenna, communication

## 1 Introduction

Over the past few decades, the space industry has seen the rise of the distributed space systems, along with the benefits these systems come with. This swarm concept, when brought to the realm of interplanetary exploration, results in a significant increase in scientific data gathering, in various areas [1] [2]. Furthermore, the rising interest in Mars and its exploration make a good case for a deployment of a distributed space system - that could result in an unprecedented expansion of our knowledge of the Red Planet.

The Tumbleweed Mission aims to widen our knowledge of Mars, through the usage of a swarm of wind-driven mobile impactors, to be deployed on the surface of the planet as described in [3]. These rovers - equipped with a plethora of scientific instruments - will be able to gather plenty of data throughout the mission's lifetime. This necessitates the transmission of vast amounts of data back to Earth, which is handled by the Transmit-Receive-Module (TRM) of each one of the Tumbleweed rovers.

During the operation of the TRM, an antenna composed of one or multiple antenna elements will exchange information with a set of relays - as proposed in [4]. This poses a challenge, as the motion by which the rover moves across the Martian surface and the proximity of the rover to the Martian ground may become problematic, with respect to the antenna's performance. Therefore it is of great importance to optimize the antenna architecture and choose a suitable type of antenna. While in previous research, we have assumed an isotropic radiator in modelling the communications link of the Tumbleweed mission, the goal of this research is to perform a trade-off analysis between the different antenna architectures. In order to do so, we will first present and aggregate the unique antenna requirements the Tumbleweed mission poses. Secondly, three antenna architecture design options will be shown. Lastly, a recommendation will be given with regards to the antenna architecture suitable for our requirements, as well as the steps to further develop this design.

## 2 Antenna Requirements

The inherent complexities in the Tumbleweed rover's dimensions and geometry along with its proximity to the Martian terrain introduce unique challenges concerning the design and placement of the antenna on the rover.

Exact details on the specific dimensions and materials are still under discussion, however a general introduction on the current rover design and the mechanical constraints posed by it are illustrated before presenting the proposed antenna designs.

The Tumbleweed rover is a uniquely designed wind-driven device, distinguished by its ellipsoid-shape and a two-stent structure. This design includes an inner and outer structure connected via a node cap [5]. Designed for deployment on Mars, the rover is initially folded during launch. Once on the Martian surface, it will expand, leveraging an umbrella-like mechanism to assume its ellipsoid shape. The preliminary estimates assume a radius of 1 meter for the outer structure (OS), consisting of 12 arcs. While similar to the OS, the inner structure (IS) has an assumed volume of about one third of the OS. These parameters suggest an approximate 30-centimeter gap between the IS and OS. However, it is essential to note that these are provisional estimates, subject to revision.

One standout feature of the Tumbleweed rover is the capability of its IS to rotate independently of the OS. Both the IS and OS are anticipated to be crafted from a non-metallic composite material.

The design of the rover imposes numerous constraints on the placement and architecture of the antenna it uses for communication with relay satellites.

Considering the rovers' semi-arbitrary wind-driven movement on the Martian surface, it is essential that the antenna's configuration and positioning guarantee stability and proper orientation to consistently uphold a reliable communication link with the relays. The Tumbleweed rover structure and dimensions give strict limitations on the confined space that the antenna, along with its supporting structures and electronics must fit within. These also need to align with the folded pre-deployment structure and the deployment mechanism of the rover. Additionally, it is necessary to ensure that the mass of the antenna does not adversely affect the rover's balance nor prevent its wind-driven motion on the Martian surface. A mass of around 250 grams is targeted.

Even if the rover's OS and IS are made of a composite material, the structure still contains various electrical and metallic components in proximity to the antenna, which in turn can cause interference and negatively affect its performance. As the power supply in Mars is limited, the design of the antenna has to fit within a predetermined power budget. Along with the mechanical constraints posed by the rover structure itself, the antenna also needs to endure potentially harmful Martian environmental effects such as extreme temperature fluctuations and dust accumulation to avoid malfunctioning. The antenna will be subject to further evaluation of their inherent technology readiness level (TRL).

In previous work, it was determined that relay satellites are required for the Tumbleweed mission and that the communication from rover to relay shall be conducted in UHF-band to maintain compatibility with the Electra radio that is used on legacy Mars orbiters and rovers [4].

## 3 Antenna Architecture Design Options

In an effort to tackle these challenges, three antenna design options are proposed. The designs are introduced along with their justifications in the three following chapters.

### 3.1 Single, fixed antenna

The first design option proposes the use of an omnidirectional folded half-wave wire dipole antenna, which would be integrated into the rover's inner structure. The proposed omnidirectional antenna would be horizontally polarized parallel to the axis of the rotation of the rover. While UHF-communications frequently utilize right-handed circular polarization (RHCP), it is deemed unfeasible resulting from the use of a single dipole design. For achieving RHCP, the dipole would need to be paired with another orthogonal dipole, compromising the proposed design.

The omnidirectionality of the antenna guarantees that part of the radiation is always propagating towards zenith and the relays. Additionally, without the need to direct the antenna, no additional controller is required. The design is therefore simple and light, making it easier to fit with the volume and mass constraints. Due to the simple design it further has a financial advantage over the other designs.

While the omnidirectional nature of the antenna has its benefits, it is not devoid of challenges. First of all, the reduced directivity and gain of the antenna results in a lower realized Effective Isotropic Radiated Power (EIRP). To counter this, one might consider amplifying the power supply. Yet, in the Martian setting, where energy resources are scarce, this is not always feasible.

Furthermore, even if the antenna is omnidirectional, it is not immune to positioning challenges. The rover's rotation can sometimes place the antenna in less-than-ideal orientations, compromising the quality of the communication link.

Additionally, while broadcasting upwards, another point of concern is the antenna's inherent radiation towards the Martian ground. This radiation can introduce interference, with noise and phase offset being primary concerns. Addressing these issues justifies the need for enhanced signal processing capabilities in the receivers of both the rover and relay antennas.

The directivity pattern of the $\frac{\lambda}{2}$ dipole is independent of azimuth $\phi$ and only depends on $\theta$ as [6, ch 17.4]

$$d(\theta) = 1.64 \frac{\cos^2(0.5\pi\cos(\theta))}{\sin^2(\theta)} \tag{1}$$

### 3.2 Mechanically steered zenith pointing antenna

The second antenna design proposed is the mechanically steered zenith pointing antenna. Similar to the first design, this option considers the use of a single element antenna. However, to solve the challenge of maintaining a reliable availability between the rover-relay link, unlike the omnidirectional approach, this design aims to mechanically steer the antenna directly towards the zenith, allowing for consistent orientation towards the relay satellites.

This configuration ensures an enhanced directivity and gain, thereby resulting in optimized power utilization, higher data rates and EIRP. In addition, by directing the majority of the radiation towards the zenith, interference due to multipath effects is substantially diminished, avoiding the need for enhanced signal processing.

However, the introduction of mechanical steering includes certain design complexities. The requisite mechanical controller introduces additional weight and volume to the antenna design. Considering the strict weight and spatial constraints inherent to the rover's operational design, these necessitate optimization. Furthermore, the increased energy consumption of the controller must also fit within the rover's power budget.

Although advantageous in several aspects, the ability for mechanical steering brings along potential vulnerabilities. With the limited field of view, a malfunction in the steering mechanism or latency in the controller's adaptability can jeopardize the communication link. Hence, it is imperative to integrate a controller distinguished by its reliability in order to ensure link availability.

The directivity of a patch antenna is given as [6, ch 21.6]

$$d(\theta,\phi) = 5.02 \left(\cos^2\theta \, \sin^2\phi + \cos^2\theta\right) |F(\theta,\phi)|, \tag{2}$$

where [6, ch 21.6]

$$F(\theta,\phi) = \cos(\pi\nu_x) \frac{\sin(\pi\nu_y)}{\pi\nu_y}, \tag{3}$$

with [6, ch 21.6]

$$\nu_x = \frac{L}{\lambda}\sin\theta, \qquad \nu_y = \frac{W}{\lambda}\sin\theta. \tag{4}$$

The length $L$ and width $W$ of the patch array are chosen such that $\frac{L}{\lambda} = \frac{W}{\lambda} = 2$.

### 3.3 Antenna array integrated into rover structure

The third design option diverges fundamentally from the first two designs by employing an electrically steered phased antenna array, arranged circumferentially around the rover. In contrast to the two other designs that both employ single-element antennas, this approach utilizes multiple antennas positioned strategically on the rover's outer structure. Each of the individual antennas are interfaced with an RF switching module, granting the capability to activate or deactivate them respectively.

This approach holds the benefit of being able to ensure consistent availability with relay satellites while concurrently achieving high directivity and gain for each of the individual antennas. The configuration thereby results in highly elevated data rates and a notably improved EIRP.

The design incorporates a distinct advantage in its ability to electronically steer the direction of the signal without the need to physically move the antennas. This electrical steering not only ensures rapid beam re-orientation, but also increases reliability by removing wear-prone mechanical parts. Furthermore, the capability enables the formation of multiple beams simultaneously, offering the possibility for simultaneous communication with multiple relay satellites. Such a system is generally more power-efficient compared to its mechanical counterpart, essential for the Martian environment with limited power resources. Moreover, without the burden of excess mechanical components, the design becomes lighter, more compact, and less susceptible to the challenging Martian environmental conditions, which can hinder mechanical precision.

In opposition to the vast advantages of the design, the configuration comes with challenges of its own. Regardless of all the mentioned benefits the use of an electrically steered antenna array offers, the integration of a phased antenna array, including complex electronics essential for switching and steering the antennas, still exerts a great toll in terms of cost, volume, mass and power. When compared with the two far simpler design options, both utilizing the use of a single antenna design, it is necessary to carefully analyze the trade-offs between each. Additionally, the antenna's placement on the rover's external structure heightens its susceptibility to physical interactions and the environmental effects stemming from the Martian terrain.

The array is modelled as a circular array, where the gain pattern can be found in [7, ch 6.12]. It is assumed, that the array is steered such that the main lobe points towards the targeted relay satellite. In that case, the phase shifts are chosen such that the array factor is $d = N$, where $N$ is the number of elements. The input power needs to be spread over the $N$ elements leading to a directivity of the array of $d = 1$, assuming that the individual elements are modeled as isotropic radiators, as it is unknown what type of antenna would lend itself best for integration into the structure.

### 3.4 Antenna hardware

Below in Table 1 a list of possible single, fixed antennas is compiled, along with some of their most relevant properties.

Table 1. Antenna hardware list, along with some relevant antenna properties. [8] [9]

| **Product** | **UHF Antenna III** | **CubeSat Antenna System for 1U/3U** | **NanoCom ANT430** |
|---|---|---|---|
| **Type** | Whip/Burnwire | Tape | Turnstile |
| **Center frequency** | 435 to 438 MHz | 400 to 500 MHz | 400 or 435 MHz |
| **Gain (dBi)** | >0 | 0 | 1.5 to -1 |
| **Module size (mm)** | 100x100x10 (estimated) | 98x98x7 (stowed) | 98x98x - |
| **Mass (g)** | 85 | 89 | 30 |
| **Polarization** | Right-hand circular | Linear or circular | Circular |
| **Company** | EnduroSat | ISIS | GOMspace |
| **Flight heritage** | Yes, (N/A) | Since July 2010 on several missions | GOMX-3 |

## 4 Simulation

This section discusses the simulation of the communications of the Tumbleweed mission. The goal of this simulation is to, amongst other things, compute the realized EIRP from each one of the antenna architecture options discussed in section 3. This section presents the method by which this task was done, dividing the procedure into two subsections. The first is subsection 4.1, which describes the set-up of the different coordinate systems required for the rest of the simulation. Subsection 4.2 documents the gain simulation process.

To compute the EIRP, the realized gain pattern of the respective antenna needs to be determined. A three-step approach is followed to do so:

1) Simulate distance and pointing vector in Rover centered coordinate system as function of time.
2) Make antenna model for each antenna type that gives EIRP (angle).
3) Compute average realized antenna gain based on EIRP.

### 4.1 Defining the rover coordinate system

To simulate the movement of rovers and relay satellites on Mars, we use the simulation framework presented in last year's paper [4] as

$$\mathbf{p}_{TW1}(t) = \mathbf{R_y}\left(\frac{\pi}{2}\frac{t}{T_{TW}}\right) r_{MA}\hat{z} \tag{5a}$$

$$\mathbf{p}_{TW2}(t,n) = \mathbf{R_z}\left(2\pi\frac{n}{N}\right)\mathbf{p}_{TW1}(t) \tag{5b}$$

$$\mathbf{p}_{TW3}(t,n) = \mathbf{R_z}\left(2\pi\frac{t}{T_{MSD}}\right)\mathbf{p}_{TW2}(t) \tag{5c}$$

$$\mathbf{p}_{TW4}(t,n) = \mathbf{R_y}\left(\theta_M\right)\mathbf{p}_{TW3}(t) \tag{5d}$$

This incorporates the following assumptions for the rovers' positioning. They are initially positioned on the martian north pole and equally rotated around the martian z-axis. They then roll south with a constant velocity to reach Mars' equator in exactly 90 days.

Additionally, we define the rover reference frame in the Martian reference frame of one rover that is travelling down the xz plane of Mars as

$$\hat{\mathbf{x}}_{TW1}(t) = \mathbf{R_y}\left(\frac{\pi}{2}\frac{t}{T_{TW}}\right)\hat{\mathbf{x}} \tag{6a}$$

$$\hat{\mathbf{y}}_{TW1}(t) = \hat{\mathbf{y}} \tag{6b}$$

$$\hat{\mathbf{z}}_{TW1}(t) = \mathbf{R_y}\left(\frac{\pi}{2}\frac{t}{T_{TW}}\right)\hat{\mathbf{z}} \tag{6c}$$

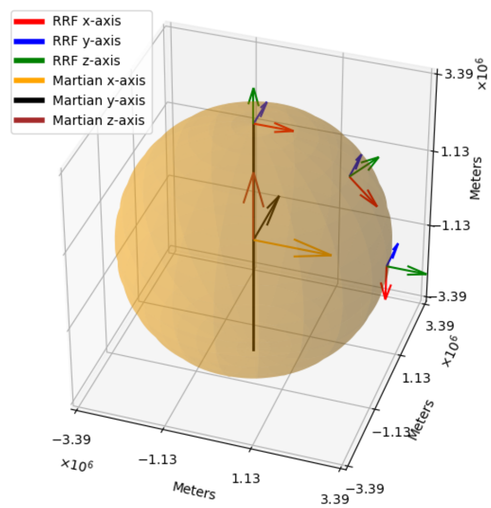


Fig. 1. Reference frames at three timesteps of a single rover travelling down on the xz-plane

In matrix notation, let the rover reference frame be defined as

$$\mathbf{X}_{TW1}(t) = \begin{bmatrix}\hat{\mathbf{x}}_{TW1}(t) & \hat{\mathbf{y}}_{TW1}(t) & \hat{\mathbf{z}}_{TW1}(t)\end{bmatrix} \tag{7}$$

Next, we can extend the equation to multiple rovers, including the rotation and axial tilt of Mars as

$$\mathbf{X}_{TW2}(t,n) = \mathbf{R_z}\left(2\pi\frac{n}{N}\right)\mathbf{X}_{TW1}(t) \tag{8a}$$

$$\mathbf{X}_{TW3}(t,n) = \mathbf{R_z}\left(2\pi\frac{t}{T_{MSD}}\right)\mathbf{X}_{TW2}(t) \tag{8b}$$

$$\mathbf{X}_{TW4}(t,n) = \mathbf{R_y}\left(\theta_M\right)\mathbf{X}_{TW3}(t) \tag{8c}$$

Now, we can use $\mathbf{X}_{TW4}(t,n)$ itself as a rotation matrix to transform the LOS poynting vector $\mathbf{v}_M$

from the Martian reference frame into the rover reference frame as

$$\mathbf{v}_R(t,n,r) = \mathbf{X}_{TW4}^T(t,n)\mathbf{v}_M(t,n,r), \quad (9)$$

where superscript $(\cdot)^T$ denotes the matrix transpose operator.

### 4.2 Modeling the antenna gain

Each antenna type is modelled using a dedicated function for calculating the gain of the antenna in a specific direction, where the elevation and azimuth angles are given as parameters. The gains for the first and second antenna options are calculated based on equations 1 and 2 respectively. For the third option (circular array), a linear gain of 1 is always assumed when there is a line-of-sight.

Figures 2, 3 and 4 illustrate a single rover's position, reference frames and the radiation patterns of each of the three antenna designs over 50 000 timesteps. For clarity, only every 600th timestep has been rendered.

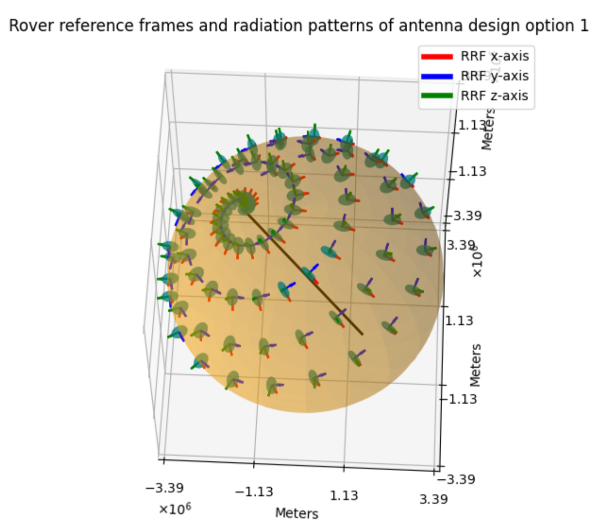


Fig. 2. Rover reference frames and the first antenna option (halfwave dipole) radiation patterns for every 600th rover over 50k timestamps

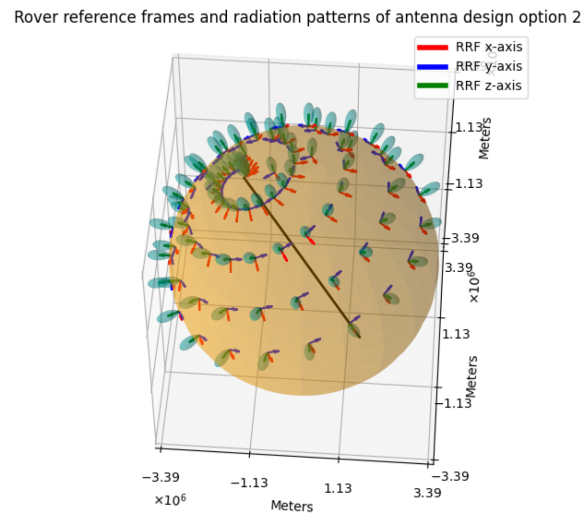


Fig. 3. Rover reference frames and the second antenna options (microstrip patch) radiation patterns for every 600th rover over 50k timestamps

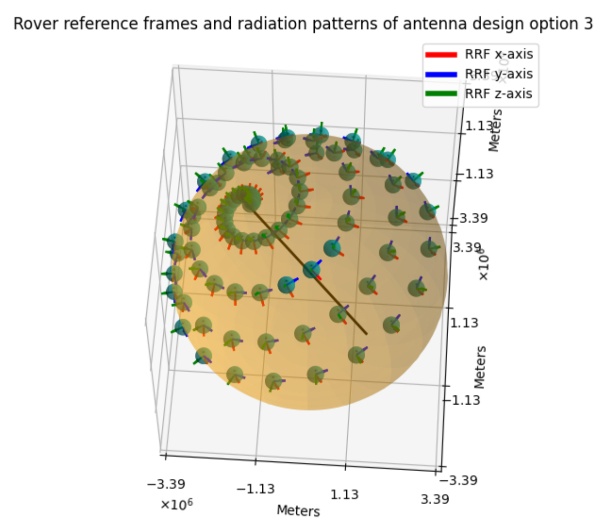


Fig. 4. Rover reference frames and the third antenna option (circular array) radiation patterns for every 600th rover over 50k timestamps

With the antenna gain functions and the rovers' local reference frames available, we calculate the line-of-sight vectors and convert them into polar coordinates within each rover's reference frame for every timestep. Furthermore, the gains are then attained by inputting these coordinates into the gain functions.

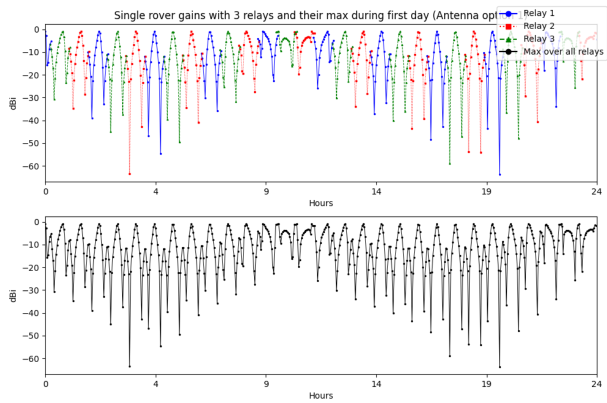


Fig. 5. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the first antenna option during the first mission day

For a clearer analysis and in order to comprehensively assess the performance of a single rover, the gain simulations were executed using one rover and three relays. Figures 5, 6 and 7 display the gains for the three antenna design options over the mission's initial 24 hours. The top of each figure presents the rover's gains for each relay, while the bottom illustrates the maximum gain across all relays.

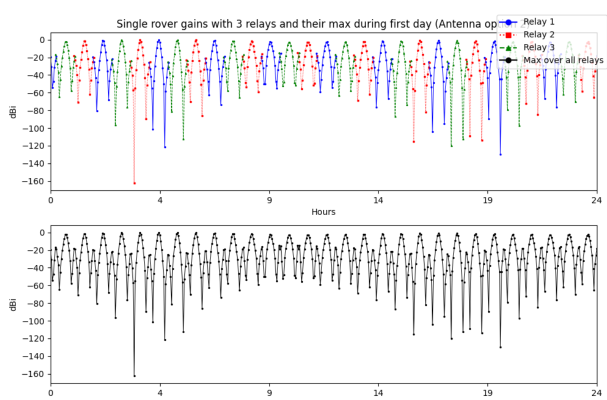


Fig. 6. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the second antenna option during the first mission day

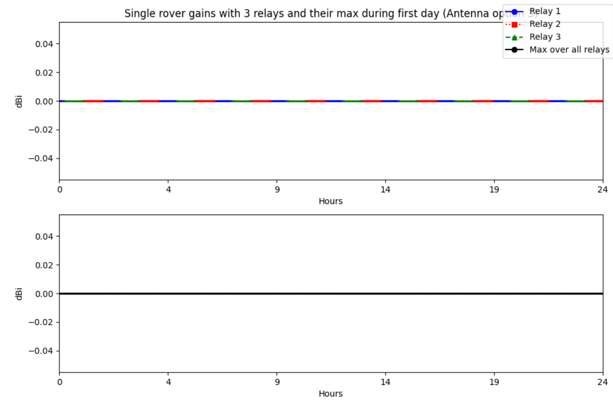


Fig. 7. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the third antenna option during the first mission day

As shown in these figures, at the start of the mission a constant line-of-sight is achieved with the orientation of the 3 orbiting relays. However, this is shown to not be the case near the end of the mission on day 80, as illustrated in figures 8, 9 and 10.

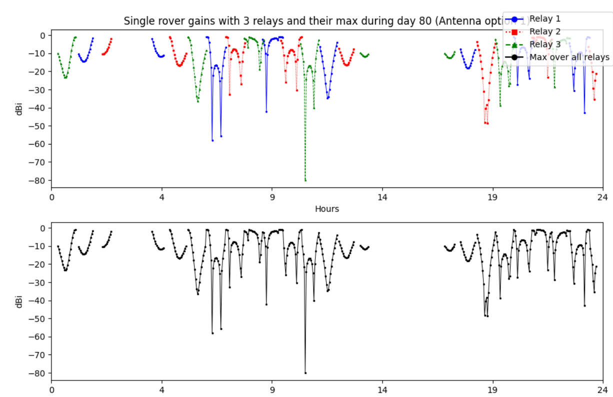


Fig. 8. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the first antenna option during the 80th mission day

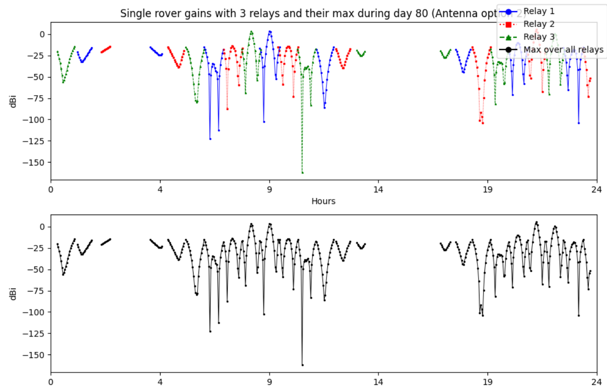


Fig. 9. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the second antenna option during the 80th mission day

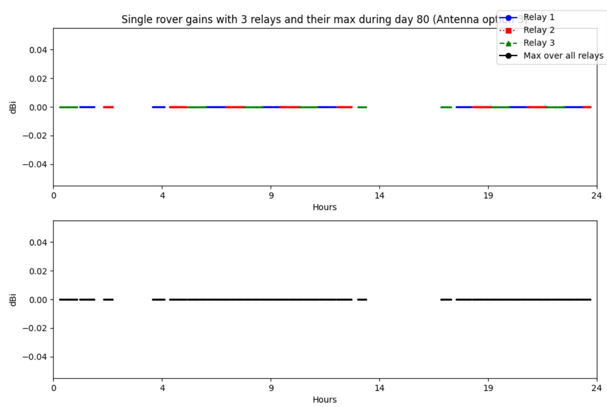


Fig. 10. The gains for a single rover with 3 relays (top), and the maximum gains over all relays (bottom) for the third antenna option during the 80th mission day

Upon further examination of the figures, it is evident that the third antenna option, the circular array, significantly outperforms the first and second antenna options in terms of gain reliability. Its capability to direct the main beam towards the relays during any line-of-sight occurrences ensures that the gain consistently reaches peak values during LOS periods.

The gain figures for the first and second antenna options exhibit relatively similar behaviour. The gains oscillate between low values and peaks or near-peaks. Yet, regardless of the higher maximum gain of the second antenna design option, the exceedingly narrow beam results in it having much fewer peak gains with the relays, compared to the first antenna with a donut-shaped radiation pattern.

Finally, to get a more thorough understanding of the overall achievable gains for the three antenna designs over the mission, their daily average gains are measured. Figures 11, 12 and 13 present the daily average gains over the mission's estimated 90 day period. The top section of each figure depicts the daily averages for each relay, while the bottom section displays the maximum gain across all relays.

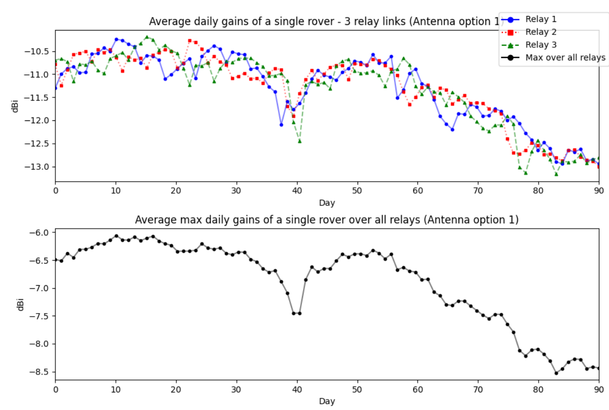


Fig. 11. The daily average gains for a rover and 3 relays (top) and their max over all relays (bottom) for antenna design option 1

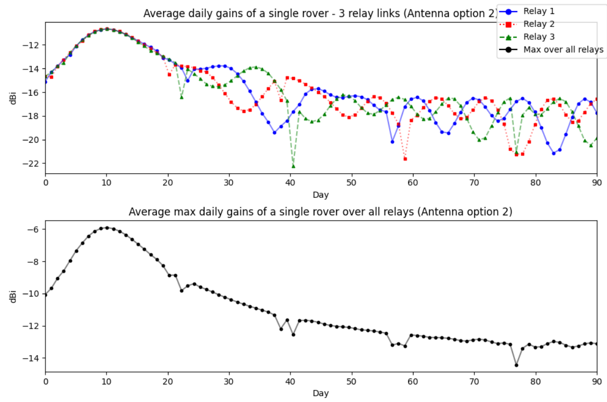


Fig. 12. The daily average gains for a rover and 3 relays (top) and their max over all relays (bottom) for antenna design option 2

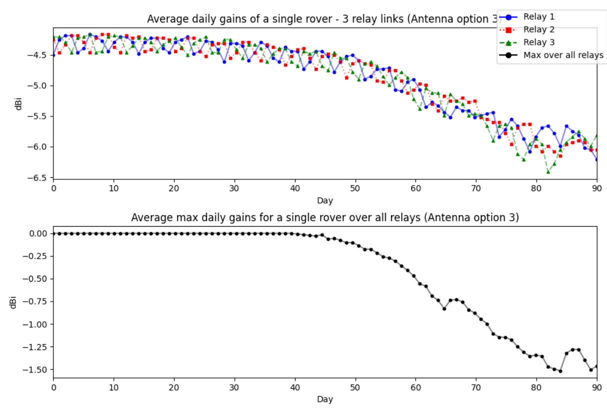


Fig. 13. The daily average gains for a rover and 3 relays (top) and their max over all relays (bottom) for antenna design option 3

Figure 14 presents the maximums of each antenna design over all the relays. As illustrated in figures 7 and 10 the third antenna option displays minimal fluctuation in its daily average gains, marking it as the most effective across the mission duration. The first antenna option also manages to keep a fairly high gain average for each day, However, due to its reliance on a single antenna element and a wide radiation pattern, it does not rival the gains of the third design. Predictably, the second antenna option trails in terms of average gains, since consistently positioning the relays directly on top of the rover's local zenith pointing axis is not feasible.

Below, the final resulting average linear gains over the whole mission are presented for each antenna option. Note that these are the average gains only for periods with a LOS.

- *Antenna option 1:* **0.2261**
- *Antenna option 2:* **0.1017**
- *Antenna option 3:* **1.0**

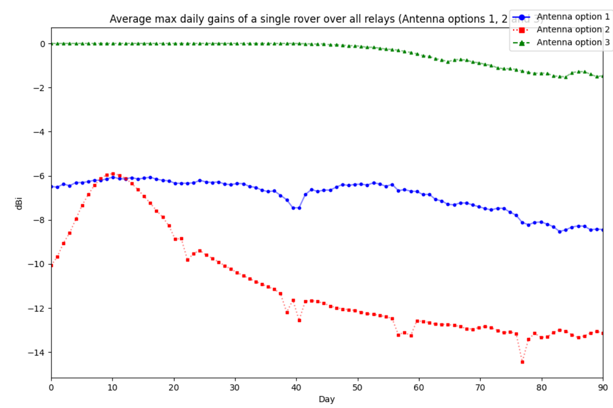


Fig. 14. Max gains of each antenna design over all three relays

## 5 Trade-Off

The following section discusses the trade-off between the three antenna architectures considered in this paper, along with a simulation of the antenna architectures. Below, the criteria considered in the trade-off are discussed, and the scores for each one of the architectures are thoroughly explained. The results of the trade-off are shown at the end of this chapter, in Table 2.

During the scoring process, each architecture was awarded a grade anywhere from 0 to 100, where 100 points signify that a certain architecture performs best in a certain criterion, while 0 represents an architecture that is completely undesired with respect for a certain criterion.

### 5.1 Realized EIRP

The first criterion considered is that of realized Effective Isotropic Radiative Power, which refers to the amount of power successfully transmitted from the transmitter to the receiver - or from the rover to the orbiting relays. This criterion is regarded as critical - hence why its weight accounts for one third of the total criteria weight - thus in order to properly compare the three different antenna architectures a simulation was drafted, which was discussed in section 4. Through the usage of this simulation, scores for each one of the antenna architecture options were generated. This involved the calculation of the average gain for the entire mission duration, each one of the antenna architectures, taking into account only the parts of the mission where the rovers have a line of sight to a relay.

The result of this simulation was that the antenna array architecture obtained the best average gain, with a value of 1.0. This was awarded a 100 in the trade-off, as it is the higher average gain value. The single fixed antenna obtained a value of about 0.23 - thus it was awarded a score of 23 on the trade-off - and the final architecture, the mechanically-steered antenna, achieved an average gain of approximately 0.10, obtaining 10 points in the trade-off.

### 5.2 Mass

Mass is considered as a criterion in this trade-off due to the nature of the Tumbleweed mission. Mass is critical as the large number of rovers to be deployed on Mars constrains the mass of each individual rover, thus its criterion weight is 20. This means that each rover - and each one of its components - should have its mass greatly limited. It is worthy to note that the mass budget for this system is approximately 250 grams.

The first option (single, fixed antenna) was assigned a score of 100 in this criterion. This score was reached after researching into architectures similar to the one being considered in this paper. For the single fixed antenna the three previously presented UHF antennas were chosen as analogues, although it must be noted that these analogues are for CubeSat spacecraft. Some of the relevant data for these antenna can be seen in Table 1. Averaging the masses of these antenna gave a mass of 68 grams. This turns out to be the lowest mass out of the three architectures, which results in this option obtaining the highest score.

The mechanically steered antenna was also assumed to be composed of the UHF antenna showcased in Table 1, and it was assumed that other hardware required to point the antenna is not included in the mass. Thus, this antenna architecture's average mass was 68 grams as well, therefore also obtaining 100 points for this criterion.

The antenna array architecture is considered next. For simplicity, it is assumed that the antenna array is made up of 10 UHF antennas, by which we can also use the antennas from the previous architectures, and simply multiply the average mass by 10. This results in a mass of 680 grams, which is 10 times higher than the lowest mass, thus resulting in a score of 10.

### 5.3 Volume

The next criterion to be discussed is volume. Volume is a significant parameter as the rovers are geometrically constrained by launcher requirements, although it is not as critical as mass, hence its low criterion weight. It is of interest to keep the volume taken up by the antenna to a minimum. The volume budget is 648 $cm^3$.

The approach taken to grade each one of the architectures is similar to the procedure from the previous subsection. For single fixed antenna, the data in Table 1 was used to calculate an average volume (although it was assumed that the NanoCom ANT430 has a height of 7 mm). This resulted in an average volume of 78.152 cm$^3$. Since this antenna architecture occupies the least amount of volume, it was awarded 100 as its score.

The mechanically steered antenna was treated similarly for volume as for mass - it was assumed that the volume taken up by the mechanically steered antenna is the same as for the single fixed antenna. This means that on this criterion, this architecture has a score of 100 as well.

For the antenna array architecture, it was assumed that 10 individual antennas are used, and that each antenna occupies the same volume as a single fixed antenna, so the total volume comes out to be 781.52 cm$^3$. This is 10 times worse than the best score, thus the score awarded to this architecture is a 10.

### 5.4 Rover accomodation

The rover accommodation criterion refers to the integration process of the antenna architectures into the rover's structure. The easier it is to integrate a certain architecture into the structure of the rover, the better, which is why comparatively this criterion has a large weight - 15. Architectures that require a large amount of modifications to the rover are undesirable, as they could result in potential delays to develop ways to integrate them into the structure of the rover.

The first architecture to be assessed is that of the fixed antenna. This architecture consists of a single antenna, where the main issue is that of keeping the antenna pointing upwards in a rover that is constantly changing its attitude. However, the fact that this architecture has no moving parts is an advantage, making it less complicated to integrate the architecture into the Tumbleweed rover. With that in mind, a score of 60 has been awarded to this architecture.

Next is the mechanically steered antenna, which consists of a single antenna that is pointed through a mechanism integrated into the rover structure. Implementation of a moving mechanism that can accurately point an antenna while the rover is moving across the Martian surface is a difficult task, especially when compared to the other architectures. Thus, this concept scores low in this specific criterion, with a final score of 30.

The third architecture considered is the antenna array, whose architecture is composed of a set of patch antennas that are integrated into the rover structure. Antenna arrays using patch antennas are widely used in structures not suitable for the implementation of more conventional antennas, making this specific architecture a suitable solution in this regard. Therefore the accommodation score awarded is that of 90 out of 100.

### 5.5 Complexity

Complexity is remarkably important, due to the fatal nature of failures in space, thus it is included as a criterion in this trade-off, with a weight of 7. In order to attempt to quantify this criterion, a simple approach was followed - that of evaluating the number of potentially-failing components in an architecture.

The fixed antenna architecture scores fairly high on the complexity scale, as the number of components required for this antenna is comparatively at a minimum. This means it is the least complex of all the architectures, and thus it is awarded a score of 80.

Next is the mechanically steered antenna architecture. This architecture contains more components than the single, fixed antenna, and many of these components have to move throughout the mission, depending on the rover's position. This makes this antenna architecture less complex by nature, lowering its score down to 40.

Although the antenna array architecture contains no moving parts - unlike the mechanically-steered antenna architecture - this architecture relies on multiple antenna patches, where the failure of an antenna patch may harm the performance of the architecture. Furthermore the cabling and supporting structure required for this architecture adds further complexity. For these reasons, this option is awarded the lowest score out of the three architectures, a 30.

### 5.6 Technology Readiness Level

Technology Readiness Level (TRL) refers to the scale used to judge the maturity of certain technologies, on a scale of 1 to 9. 1 indicates the lowest level on the TRL scale, representing basic research of the technology, while 9 refers to the highest score achievable, and is awarded when the technology is proven operational within its relevant environment. This scale was turned into a criterion as the maturity of the technologies at hand should be considered in the trade-off, and its criticality in the mission is reflected by its weight of 10. A technology that has already been proven to work within the Martian environment is preferred to one that has not.

Fixed antenna architectures have been widely used in past mission to Mars ([10]), and as such the TRL of this type of antenna is 9. However, mounting and integrating such an antenna on the Tumbleweed rover has not been done before, which slightly decreases the TRL score awarded. This leaves the final score at 90 out of 100.

Similarly to fixed antennas, mechanically steered antenna architectures have also been used in missions to Mars before, onboard rovers ([11]). Therefore it too scores a 9 on the TRL scale. However, positioning this type of antenna architecture poses a significant challenge to the mission's development, and as such its TRL score reflects this. Considering the added complexity of the moving mechanism, the final score of the TRL is significantly lower than that of the fixed antenna, with a final score of 70.

Antenna arrays that are integrated into rover structures have also been tried on the surface of Mars, as seen in [12]. However this antenna architecture would require an integration solution never tried before, and its usage on the surface of Mars is much more limited compared to the first two architectures, which results in a notably low score of 20.

### 5.7 Robustness to Martian environment

Robustness to the Martian environment is a criterion that is relevant to this mission, as the rover's entire operational phase will take place on the Martian surface, where the rover and its components will be exposed to the harsh Martian environment. Thus, in the trade-off of these three antenna architectures the robustness of each one of the architectures should be considered. To reflect the importance of this criterion, it was assigned a weight of 10.

The first architecture, the fixed antenna, scored a 50 on this criterion. The robustness of this architecture mainly depends on the method used to integrate it into the rover. If a dipole is to be used, the robustness of the architecture mainly depends on the mechanism used to keep the antenna pointing upwards. It was therefore decided to give this a 50, when compared to the other two architectures.

The second architecture considered is that of a mechanically steered antenna. This architecture will be by far the most susceptible to the harsh environmental conditions found on Mars. Both the structure holding the antenna in its nominal position and any gimbal mechanism implemented to point the antenna towards the relays could be compromised at any point in the mission from the environment the rover will be traversing. Therefore the score awarded to this architecture was 20.

Finally, the antenna array is judged on this criterion. An antenna array integrated into the rover's structure is the least vulnerable architecture of the three options being considered, as it is most shielded. It would need to be attached to the rover's main structure, but only the antenna itself would be vulnerable to the elements - there are no other parts, moving or otherwise, that can fail due to a harsh environment. Therefore, this architecture is awarded the highest score when compared to the other architectures - an 80 on the 100 scale.

Below, the final trade-off is shown in Table 2. This includes the weights assigned to each one of the criteria - these are weights to represent the relative importance of each one of the criteria, as a percentage - which are multiplied by the scores from each individual criterion and then summed up, to give the final score for each architecture. The weights all sum up to 100.

Table 2. Trade-off of the generated criteria for the three different antenna architectures discussed in section 3.

| **Criteria** | **Criteria weight** | **Single fixed antenna** | **Mechanically steered antenna** | **Antenna array** |
|---|---|---|---|---|
| **Realized EIRP** | 33 | 23 | 10 | 100 |
| **Mass** | 20 | 100 | 100 | 10 |
| **Volume** | 5 | 100 | 100 | 10 |
| **Rover accomodation** | 15 | 60 | 30 | 90 |
| **Complexity** | 7 | 80 | 40 | 30 |
| **TRL** | 10 | 90 | 70 | 20 |
| **Robustness** | 10 | 50 | 20 | 80 |
| **Total** | | **6119** | **4460** | **6110** |

The results from the trade-off table show that the single, fixed antenna is the preferred antenna architecture for the Tumbleweed rover, with a score of 6119. Although this architecture did not perform as well as the antenna array in criteria such as the realized EIRP, rover accommodation or robustness, these drawbacks are outdone by other aspects of this architecture such as the mass, complexity or TRL. The disadvantages of this architecture are compensated by the fact that this architecture is fairly lightweight, simple and has been used a multitude of times on missions to Mars.

Although the antenna array got second place in this trade-off, it must be noted that it did so with 9 points less than the single, fixed antenna, with 6110 points. The small difference in scores indicates that either one of the two top choices could be a valid option, and thus a sensitivity analysis of the criteria's weights is recommended.

## 6 Conclusions

In summary, our paper has advanced the optimization of antenna architecture for the Tumbleweed Mission, which seeks to enhance our understanding of Mars through efficient data transmission. By rejecting one option (Option 2), we have refocused our efforts on exploring the potential of Options 1 and 3. This decision aligns with our objective of addressing the unique challenges posed by the Tumbleweed rover's design and the Martian environment. For future work, we intend look into modelling the characteristics of an array elements integrated into the rovers structure.

Our research contributes towards improving interplanetary exploration by enhancing communication within distributed space systems. We have successfully employed key design drivers, such as stability, mass, and environmental resilience, to conduct our qualitative and quantitative trade-off. Ultimately, this work contributes to the mission's goal of expanding our knowledge of Mars through reliable data transmission, positioning us closer to achieving groundbreaking discoveries on the Red Planet.

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