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


IAC-22,B2,4,x71894

# Communications architecture for martian surface exploration with a swarm of wind-driven rovers

**Felix Abel[a]*, Cristian Ferent[a], Prem Sundaramoorthy[b], Raj Thilak Rajan[c]**
[a] *Team Tumbleweed, Delft, The Netherlands*
[b] *Eindhoven University of Technology, Eindhoven, The Netherlands*
[c] *Faculty of EEMCS, Delft University of Technolgy, Delft, The Netherlands*
* Corresponding Author, felix@teamtumbleweed.eu

**Abstract**

This decade has seen growing interest in Mars exploration. Advances in distributed systems, miniaturization and commoditization of space electronics and innovations in communications permit us to rethink the current paradigm of relying on a few heavy, slow and expensive high-tech rovers for Mars surface exploration. In this work, we address the demanding communication needs for a mission that deploys a swarm of uncontrolled wind-driven exploration rovers onto the martian surface.

The concept for these lightweight, autonomous, ellipsoid ”Tumbleweed” rovers — named after the desert plant — is not new, and was studied and validated by NASA researchers decades ago. Recently, a new plan to turn the Tumbleweed mission into reality has been proposed to the ESA open space innovation platform (OSIP). The idea is to launch approximately 90 Tumbleweeds in one transfer vehicle and release them on the martian surface to survey the northern hemisphere of Mars over a mission duration of three months. Reliable communication is one of the key challenges for this mission. The rovers' instruments, e.g. cameras, generate large volumes of data, and many rovers need to be served simultaneously. Furthermore, the tumbling motion on the martian surface constitutes unprecedented challenges in terms of antenna pointing for planetary exploration rovers.

We present a trade-off analysis between direct to Earth communication and relayed communication using satellites orbiting Mars culminating in a baseline communication architecture for the Tumbleweed mission. For this purpose we model the kinematics of the Tumbleweed rovers and relay satellites w.r.t the Earth. A numerical simulation of all potential communication links over the full mission duration is conducted. The analysis shows that direct communication to Earth is infeasible due to the rolling motion of the rover. Hence, the relayed communication scenario is proposed, as it does not require a directional antenna on the Tumbleweed rovers. Therefore, we propose a constellation of three relay satellites in a circular, Earth-facing orbital plane around Mars, which communicate with the Tumbleweed rovers using the UHF frequency band. Commercial ground stations on Earth in Ka-band are used for the relay-ground link. The proposed communications architecture is estimated to achieve a raw data throughput of $\geqslant$84Mbit per Tumbleweed rover per Sol.

**Keywords: Tumbleweed mission, Mars exploration, rover, swarm, deep space communication, communication relay**

## 1 Introduction

In the past decades, the miniaturization in electronics and decreasing launch cost facilitated a rising number of distributed space systems with increasing number of nodes in such systems. For example, constellations like Starlink, OneWeb or Project Kuiper offer broadband internet from space [1] and companies like Planet Labs or Spire Global offer Earth observation [2, 3] using satellites that are placed in low Earth orbit. Recently, miniaturized and distributed space systems began to be increasingly used for exploration missions beyond Earth orbit, e.g. the Lunar mission Capstone [4], Milani and Juventas CubeSats on the Hera mission [5], and the Mars helicopter Ingenuity [6]. For such systems the challenges of organizing communication of a distributed system and bridging the long distance to Earth have to be addressed.

This paper addresses the communication architecture of a proposed Mars surface exploration mission using lightweight wind-driven and uncontrolled rovers i.e., the “Tumbleweed” mission. The original concept for the Tumbleweed rover dates back a couple of decades, and is inspired by, and named after the Tumbleweed desert plant [7].

Recently, a mission has been proposed to release around 90 such Tumbleweed rovers on Mars to survey its surface [8, 9]. The downlink of data collected by such a large number of uncontrolled rovers is one of the mission's core challenges. Firstly, we present the mission and its communication challenge in more detail and conduct a brief literature study into the communication solutions of legacy Mars missions. Next, the modeling approach and simulation setup for geometry of the Tumbleweed mission are presented. Then, the results are presented and discussed showing that the proposed mission requires relay satellites in martian orbit both for coverage and data volume reasons.

## 2 Tumbleweed mission communications challenge

The term Tumbleweed is used to describe spherical or ellipsoid wind-driven planetary exploration rovers, which would "tumble" across Mars. The concept has been examined by several studies for its feasibility during past decades. The work by Antol et al. [7] gives an overview of the use case of wind-driven rovers for Mars exploration.

Recently, a plan to turn the Tumbleweed mission into reality has been proposed to the ESA open space innovation platform (OSIP) [8]. The aim of this proposal is to send 90 Tumbleweeds in one launch vehicle and release them over the martian north pole to then survey the northern hemisphere of Mars over a mission duration of 90 days. According to the proposed plan, the Tumbleweed mission can *open up new avenues in research, augment the current set of exploration technologies and broaden the access to Mars* [8]. The term Tumbleweed will be used to refer to a single, wind-driven Mars rover. Rothenbuchner et al. detail the mission, rover design and science use case in a separate paper in this conference. With instruments such as radio beacons, laser retro-reflectors, atmospheric sensors and cameras, the Tumbleweed mission will cater to the science objectives set forth by the Mars Exploration Program Analysis Group (MEPAG) [9]. In another paper presented in this conference, Rothenbuchner et al. propose the **I**n-situ **MA**rs **G**eodetic **I**nstrument **NE**twork (IMAGINE) for the Tumbleweed mission, to explore the Tharsis region of Mars [10].

The operations of 90 rovers in another planet poses many unique challenges, one of which is the communication. The number of rovers combined with the fact that they move in an unpredictable manner, make the transmission of data from rover to the Earth a major challenge. Legacy missions typically rely on a combination of direct and relayed links to downlink the obtained data from Mars to Earth. In this paper, legacy Mars missions are analyzed for their communication architecture. Next, we model various aspects of the Tumbleweed communication architecture. Finally, a simulation of the communication link of the Tumbleweed mission is conducted to compare the direct link case with a relayed communication architecture which leads to preliminary estimates of the achievable data rate and a design decision for mission communication architecture.

## 3 Legacy missions

In this section, we present a brief survey on communication technologies used in legacy Mars missions, with the main focus on finding solutions for Tumbleweed rovers with rather stringent requirements on mass, power consumption and data rate. In table 1, we list 5 key missions, and various features of their communication architecture.

It can be observed from table 1, that the preferred communication architecture of NASA and ESA, is the use of a relay orbiter to transmit the data from the rover back to Earth. The rover establishes an uplink communication channel with a relay orbiter using an ultra-high frequency (UHF) antenna with a frequency of approximately 400 MHz, while the orbiter relays the data back to the ground station, through the high gain antenna (HGA) in X-Band. NASA Perseverance mission has claimed 2 Mbit per second in good conditions [11], using the UHF uplink to the relay orbiter. MSL (Curiosity rover) can transmit a data volume via the UHF uplink of 800 Mbit/s per martian sol, with 2 passes of the Mars Reconnaissance Orbiter and Mars Odyssey (which will store and relay data to the Earth). Although these data rates are encouraging, the common communication equipment for the aforementioned missions and the satellite orbiters ExoMars and MAVEN, are equipped with Electra and Electra Lite radios, which are robust but too heavy and expensive and can thus not be considered for the Tumbleweed mission.

With the advent of CubeSats, NASA's Jet Propulsion Laboratory (JPL) prototyped a CubeSat-specific transponder called Iris initially intended to fly on the INSPIRE mission. This opened up the possibility of exploring a Mars CubeSat mission. The mission is named MarCO (Mars Cube One) [12]. MarCO is part of NASA Insight lander mission, which in the same manner as MSL will communicate via UHF link with the Mars Reconnaissance Orbiter and Mars Odyssey while the MarCO cubesats will simultaneously flyby Mars at an altitude of 3500km receiving UHF data, adding framing information and re-transmitting data back to Earth. The success from the MarCO CubeSat mission as a technology demonstrator, has shown encouraging results using UHF uplink and X-band downlink to Earth. The UHF antennas from the MarCO CubeSat are mechanically deployed, with spring loaded hinges, offering a potential option for the Tumbleweed rovers.

Through the study of legacy Mars missions, we found that the Electra and Electra lite radios using UHF frequencies of around 400 MHz have emerged as the quasi-standard for rover – relay communications, while X-band is prevalent for direct to Earth links.

| **Mission** | **MAVEN** | **MSL** | **Perseverance** | **ExoMars** | **MarCO Cubesat** |
|---|---|---|---|---|---|
| Type of spacecraft | Orbiter | Rover | Rover | Rover | Cubesat Orbiter relay |
| Year of Lauch | 2013 | 2011 | 2020 | tbd | 2018 |
| Orbit height [km] | Elliptical Mars orbit 4500 x 150 | NA | NA | Elliptical Mars orbit, 450 (Low orbit) | Elliptical Mars orbit |
| Element launch mass [kg] | 2454 | 3839 | 1025 | 2720 | 14 |
| Link I | Downlink | Downlink | Downlink | Downlink | Downlink |
| Antenna | Parabolic high gain, diameter 2.1m | No data | Patch array, diameter 30 cm | 2.2m Parabolic High-Gain (X-band) | omnidirectional LGA, Folded HGA |
| Frequency | X-band 7 – 8 GHz | X-band 7 - 8 GHz | X-band 7- 8 GHz | X-band 7- 8 GHz | X-band 7.14–7.23 GHz (receive). 8.4–8.5 GHz (transmit) |
| Transmit power | 100 W | 15 W | No data | 5 W | 10 W |
| Ground station | DSN | DSN | DSN | ESTRACK, DSN, RNS | DSN |
| Link II | Rover – Orbiter | Rover - Orbiter | Rover - Orbiter | Rover - Orbiter | Rover - Orbiter |
| Antenna | Quadrifilar helix | No data | No data | Quadrifilar helix | deployed antenna |
| Frequency | UHF, 390 – 450 MHz | UHF, 400 MHz | UHF, 400 MHz | UHF, 390 – 450 MHz | UHF, 401 MHz |
| Transmit power | Rover dependent | 9 W | No data | 65 W | 10 W |
| Ground station | Mars rover | Mars rover | Mars rover | Mars rover | Mars rover |

Table 1: Legacy Mars missions [11, 12, 13, 14, 15]

## 4 Tumbleweed communication modeling

The model to simulate communication links of the Tumbleweed Mars mission consists of three parts: the swarm of rovers, the relay satellites and the ground stations. The swarm consists of $N$ identical nodes, each of which can communicate to the $M$ relay satellites and the ground station. Assuming that the ground station network is able to achieve full coverage, the ground station is modeled to be a single station that is on the optimal point of Earth's surface with respect to the spacecraft. Large institutional networks like NASA's Deep Space Network (DSN) and ESA's tracking stations (ESTRACK) or commercial network stations can fulfill this coverage requirement. Based on results from the previous sections UHF-band is assumed for the rover – relay link to ensure compatibility with existing orbiter infrastructure and Ka-band is assumed for the direct to Earth link as it can offer higher data rates than X-band and has been demonstrated for Mars communications [16]. The main equations on orbits, geometry and communications used in this work to model the communication architecture are briefly introduced in the following subsections.

### 4.1 Orbits and geometry

The equations on orbits and geometry introduced next are required to model the movement of planets around the Sun and the Tumbleweed rovers on Mars. As per Kepler's 3rd law, the orbital period is defined as

$$T = 2\pi\sqrt{\frac{a^3}{G(m_1+m_2)}}, \tag{1}$$

with the semi-major axis $a$, the masses of the two bodies $\{m_1, m_2\}$ and the gravitational constant $G = 6.674 \times 10^{-11} \frac{m^3}{kgs^2}$. When $m_1 \gg m_2$ — which is the case for artificial satellites orbiting celestial bodies — the mass of the satellite can be neglected.

Equations (2) give the rotation matrices for anti-clockwise rotations around $x$, $y$ and $z$ axes in a Cartesian coordinate system, where $\mathbf{R_k v}$ denotes the rotation of vector $v$ around axis $k$ by an angle of $\alpha$.

$$\mathbf{R_x}(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{2a}$$

$$\mathbf{R_y}(\alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \tag{2b}$$

$$\mathbf{R_z}(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2c}$$

### 4.2 Communication link

The following equations are used to compute the data rate as figure of merit for each communication link. Equation (3) describes the free space attenuation $a_0$ [17, p. 28] as

$$a_0 = \left(\frac{4\pi df}{c}\right)^2, \tag{3}$$

where $d$ is the distance between transmitter and receiver, $f$ is the carrier frequency and $c$ the propagation speed.

Equation (4) describes signal-to-noise ratio (SNR)

$$\frac{S}{N} = \frac{P_t G_t G_r}{kBT_{sys} a_0 a_r M}, \tag{4}$$

where $P_t$ is the transmit power, $G_t$ is the transmit antenna gain, $G_r$ is the receive antenna gain, $k$ is the Boltzmann constant, $B$ is the bandwidth, $T_{sys}$ is the receiver system noise temperature, $a_0$ is the free space attenuation, $a_r$ is addition attenuation (e.g. atmospheric, rain) and $M$ is the optional design margin.

Equation (5) describes gain of an aperture antenna [18, p. 1069] as

$$G = \varepsilon \frac{4\pi A f^2}{c^2}, \tag{5}$$

where $\varepsilon < 1$ is the antenna efficiency and $A$ is the antenna area.

Equation (6) describes energy per bit to noise power spectral density ratio $\frac{E_b}{N_0}$ [17, p. 160]

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{r_b}, \tag{6}$$

where $r_b[bit/s]$ is the bit rate.

Equation (7) gives the relation between bit error rate $BER$ and the energy per bit to noise power spectral density ratio $\frac{E_b}{N_0}$ [17, p. 160] as

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right), \tag{7}$$

when using a binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK) Modulation scheme. The complementary error function is denoted as $erfc(\cdot)$.

Computing the SNR as per equations (3-5) and then solving equations (6-7) for the bit rate allows to use said raw bit rate as figure of merit.

### 4.3 Tumbleweed communication architecture

To calculate the communications budget of a link, the bit rate is computed as a function of antenna gains, frequency and other parameters. For the Tumbleweed mission, three different links are to be considered and their bit rate determined:

1. from swarm element to ground station $r_{b,s-g}$
2. from swarm element to relay satellite $r_{b,s-r}$
3. from relay satellite to ground station $r_{b,r-g}$

The communications link will be implemented in a two stage approach. In the first stage as shown in figure 1, geometric and communication electronics parameters are used to compute the effective bit rates of each individual link.

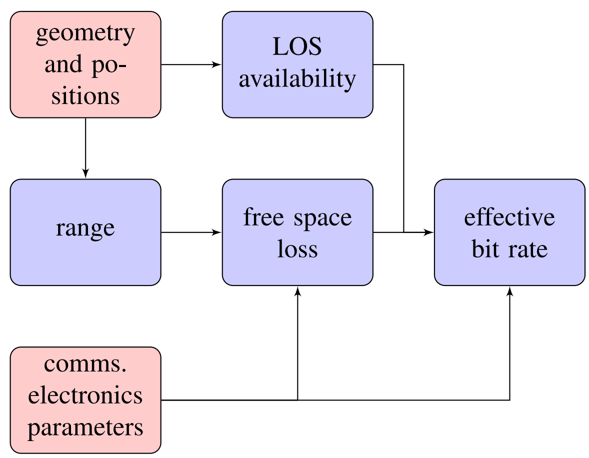


Figure 1: Link model

Simulation of link 1 yields the effective bit rate for direct communication. The minimum bit rate out of links 2 and 3 returns the the effective bit rate using relayed communication. The best possible bit rate for the mission is that of the more favourable scenario as per equations (8).

$$r_{b,direct} = N r_{b,s-g} \tag{8a}$$

$$r_{b,relayed} = \min\{N r_{b,s-r}\ ,\ M r_{bf,r-g}\} \tag{8b}$$

$$r_{b,mission} = \max\{r_{b,direct}\ ,\ r_{b,relayed}\} \tag{8c}$$

These results, together with information on the configuration of the swarm and relay can then be used to compute the total throughput for the mission and identify bottlenecks (see figure 2), and ultimately make a decision on the communication architecture for martian surface exploration with a swarm of wind-driven rovers.

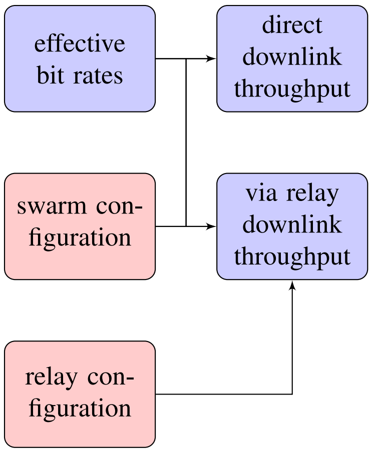


Figure 2: Mission model

Besides equations (1 - 7), astronomic data and constants shown in table 2 are needed to compute orbit parameters and distances.

Table 2: Astronomic constants [19]

| description | variable | value |
|---|---|---|
| Sun-Earth mean distance | $d_{SE}$ | $149,600,000$km |
| Sun-Mars mean distance | $d_{SM}$ | $227,940,000$km |
| Earth radius | $r_E$ | $6,371$km |
| Mars radius | $r_{MA}$ | $3,389$km |
| Earth mass | $m_E$ | $5.9722 \cdot 10^{24}$kg |
| Mars mass | $m_{MA}$ | $6.4171 \cdot 10^{23}$kg |
| Earth's orbit period | $T_{EO}$ | 356.256d |
| Mars' orbit period | $T_{MO}$ | 687d |
| Mars sidereal day | $T_{MSD}$ | 24.623d |
| Mars axial tilt | $\theta_M$ | $25.3°$ |

## 5 Simulation setup

To simulate the Tumbleweed mission a Sun-referenced coordinate system will be used. The orbits of Earth and Mars are assumed to be circular and coplanar. The orbits are modeled in the xy-plane of the 3-dimensional Cartesian coordinate system, with the Earth's center on the x-axis at the starting time of the simulation. Said time is defined by the arrival of the Tumbleweeds on the surface of Mars. Mars' angular position is offset with respect to the Earth by angle $\Phi_M$. Assuming a Hohmann transfer one can find from [20], that on arrival of the spacecraft at Mars after completing the Hohmann transfer, Mars will lag behind Earth by $79°$. Neglecting the time needed for entry, descent and landing, $\Phi_M = -79°$.

The position vectors $\mathbf{p}_E$ and $\mathbf{p}_M$ of Earth's and Mars' centers can then be expressed as

$$\mathbf{p}_E(t) = \mathbf{R_z}\left(2\pi \frac{t}{T_{EO}}\right) d_{ES}\hat{x} \quad (9a)$$

$$\mathbf{p}_M(t) = \mathbf{R_z}\left(2\pi \frac{t}{T_{MO}} + \Phi_M\right) d_{MS}\hat{x} \quad (9b)$$

where $\mathbf{R_k}(\cdot)$, as defined in (2), denotes a rotation around axis k and hence models the two planets orbiting the Sun. The x-axis unit vector is expressed as $\hat{x}$, or, more generally $\hat{k}$ is a unit column vector. Distances $d$ and orbit periods $T$ are known (see table 2). Figure 3 shows the orbits of Earth in blue and Mars in red using dotted lines. The radii are indicated by dashed lines, the starting positions by an x each and the orbit segment covered during a mission time of $T_{TW} = 90$ days [8] by solid lines as described in equations (9a–9b).

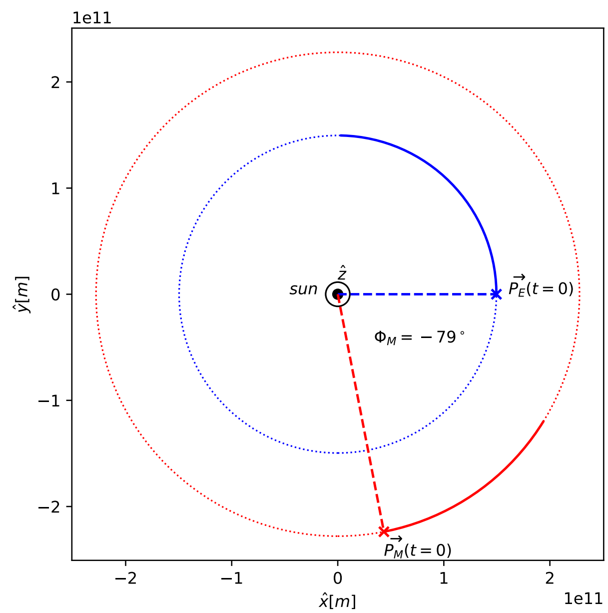


Figure 3: Earth's and Mars' orbit (dotted lines) for a 90 day mission (solid lines) as described in (9a–9b)

To model the movement of the Tumbleweeds on Mars, some initial assumptions are made. All Tumbleweeds are released on the martian north pole and then — equally distributed in longitude — roll south on the spherical martian surface with constant velocity to reach its equator at the end of the mission time of 90 days.
The modeling of the Tumbleweeds and the relay satellites will initially be done in a Mars-referenced, Cartesian coordinate system. Let the rotational axis of Mars initially

coincide with the z-axis. A single Tumbleweed can then be modeled by a vector oriented along z-axis of length $r_{MA}$ that, over the duration of the mission, rotates $90°$ around the y-axis. The resulting equation (10a) can easily be extended to $N$ Tumbleweeds by rotating them around the z-axis, as described in (10b) and illustrated in figure 4.

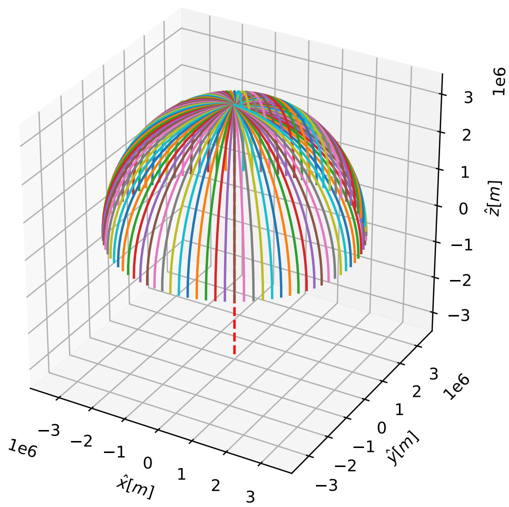


Figure 4: 90 Tumbleweeds starting out from the martian north pole, moving towards the martian equator as described by $\mathbf{p}_{TW2}(t,n)$; dashed red line shows Mars' axis of rotation (here colinear with z-axis)

$$\mathbf{p}_{TW1}(t) = \mathbf{R_y}\left(\frac{\pi}{2}\frac{t}{T_{TW}}\right) r_{MA}\hat{z} \tag{10a}$$

$$\mathbf{p}_{TW2}(t,n) = \mathbf{R_z}\left(2\pi\frac{n}{N}\right)\mathbf{p}_{TW1}(t) \tag{10b}$$

$$\mathbf{p}_{TW3}(t,n) = \mathbf{R_z}\left(2\pi\frac{t}{T_{MSD}}\right)\mathbf{p}_{TW2}(t) \tag{10c}$$

$$\mathbf{p}_{TW4}(t,n) = \mathbf{R_y}\left(\theta_M\right)\mathbf{p}_{TW3}(t) \tag{10d}$$

To further account for Mars' rotation around itself, another rotation around z-axis depending on the ratio of elapsed mission time to the duration of the martian day $T_{MSD}$ is applied in (10c). So far, the axial tilt $\theta_M$ of Mars' rotation axis has been neglected. To account for this, a rotation around y-axis by $\theta_M$ will be applied to the previous equation. This results in equation (10d), which fully describes the position of the $n$-th Tumbleweed at time $t$ with reference to Mars. The axial tilt becomes apparent in the visualization in figure 5.

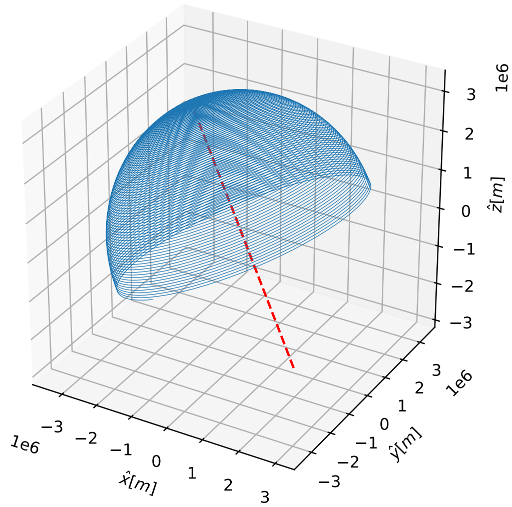


Figure 5: Movement of a single Tumbleweed relative to martian centered coordinate system taking into account Mars' rotation around its own axis and its axial tilt as described by $\mathbf{p}_{TW4}(t, n = 0)$

The Sun-referenced position of the Tumbleweeds can now be obtained by superimposing the position of Mars relative to the Sun (9b) with the Mars-referenced position of the Tumbleweeds(10d). Resulting equation (11) is valid for $t = [0, T_{TW}]$ and $n = [0, ..., N-1]$.

$$\mathbf{p}_{TW}(t,n) = \mathbf{p}_{TW4}(t,n) + \mathbf{p}_M(t) \tag{11}$$

The following assumptions about the relays position are made: For model simplicity, the $M$ relays are equidistantly distributed in one circular orbit. The orbital plane is chosen such that it is always normal to the vector from Mars to Earth. Owing to Mars' and Earth's relative movement, the orbital plane of the relay satellites will slightly turn over time. This has the advantageous effect that the relay satellites have constant line-of-sight connection with Earth. The modeling of the relay satellites will again initially be done in a Mars-referenced, Cartesian coordinate system. A single relay satellite can then be modeled by a vector oriented along y-axis of length $h_R + r_{MA}$ that — over the duration of an orbital period of $T_R$ — describes a full circle around the x-axis. The resulting equation (12a) does not yet account for the desired orientation towards Earth. This equation can easily be extended to $M$ relay satellites by rotating them around the x-axis and thereby equally distributing them on the orbit, as described in (12b) and illustrated for 3 satellites in figure 6. To ensure constant LOS to Earth, the orbit plane needs to be turned around z-axis by $\Phi_R$, which is time dependent. Its tangent is the ratio of the x and y component of the vector from Mars to Earth (12c). Knowing $\Phi_R(t)$, one can give equation (12d) which fully describes the position of the $m$-th relay satellite at time $t$ with reference to Mars. Equation (12d) is visualized for 1 relay satellite in figure 6 showing only every 50th orbit for visual clarity.

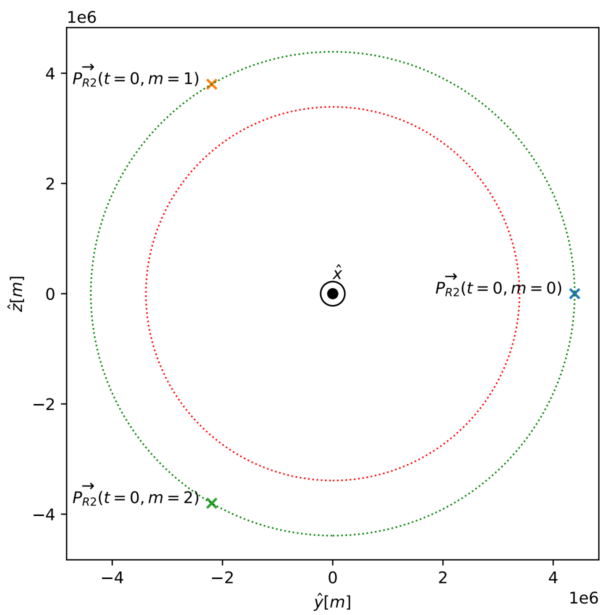


Figure 6: M=3 relay satellites in yz-plane at starting positions on their circular orbit (green dotted line) around Mars (red dotted line) as described by $\mathbf{p}_{R2}(t = 0, m)$, neglecting the rotation of the orbit around z-axis

$$\mathbf{p}_{R1}(t) = \mathbf{R_x}\left(2\pi\frac{t}{T_R}\right)(h_R + r_{MA})\hat{y} \tag{12a}$$

$$\mathbf{p}_{R2}(t,m) = \mathbf{R_x}\left(2\pi\frac{m}{M}\right)\mathbf{p}_{R1}(t) \tag{12b}$$

$$\Phi_R(t) = \tan^{-1}\left(\frac{\hat{y}^T\left(\mathbf{p}_E(t) - \mathbf{p}_M(t)\right)}{\hat{x}^T\left(\mathbf{p}_E(t) - \mathbf{p}_M(t)\right)}\right) \tag{12c}$$

$$\mathbf{p}_{R3}(t,m) = \mathbf{R_z}\left(\Phi_R(t)\right)\mathbf{p}_{R2}(t) \tag{12d}$$

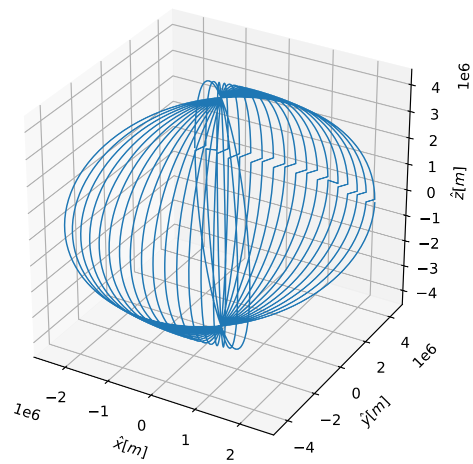


Figure 7: Movements of a single relay satellite as described by $\mathbf{p}_{R3}(t = 0, m)$, including the rotation of the orbit around z-axis relative to martian centered coordinate system. For visual clarity only every 50th orbit is depicted, which leads to the discontinuities in the plot

The Sun-referenced position of the relay satellites (13) can now be obtained by superimposing the position of Mars relative to the Sun (9b) with the Mars-referenced position of the relay satellites (12d). The equation holds for $t = [0, T_{TW}]$ and $m = [0, ..., M-1]$.

$$\mathbf{p}_R(t,m) = \mathbf{p}_{R3}(t,m) + \mathbf{p}_M(t) \tag{13}$$

The antenna properties of the Tumbleweed rovers are not known. However, it is known that the Tumbleweeds will roll over the surface of Mars. Even if the Tumbleweeds are constructed such, that they have a stable axis of rotation, the best assumption to be made at this stage is that the antenna on the Tumbleweed needs to be non-directional, hence a gain of $0\text{dBi}$. As isotropic radiators do not exist, an non-directional antenna could for instance consist of multiple directional antennas. The implementation of such an antenna on the Tumbleweed is beyond the scope of this case study. The power consumption of the whole transmit receive module of the Tumbleweed can consume $25.8\text{W}$. Assuming $50\%$ of this is actually transmitted, the transmit power is $12.9\text{W}$. The system noise temperatures are set to $135\text{K}$ for all receivers. Typically, a bit error rate of $10^{-6}$ is satisfactory for space applications. That corresponds to $\frac{E_b}{N_0} = 10.53dB$ which will thus be used.

Table 3: Tumbleweed parameters

| description | variable | value |
|---|---|---|
| Mars angular offset | $\Phi_M$ | 79deg |
| orbit height relay | $h_R$ | 1,000km |
| orbit period relay | $T_R$ | 2.453h |
| Tumbleweed mission duration [8] | $T_{TW}$ | 90d |
| number of swarm elements | $N$ | 90 |
| number of relay elements | $M$ | 3 |
| swarm element ant. gain | | 0dBi |
| relay receive ant. diameter | | 0.5m |
| relay transmit ant. diameter | | 3m |
| ground station ant. diameter | | 7.3m |
| swarm element tx power | | 12.9W |
| relay element tx power | | 100W |
| antenna efficiency | | 0.55 |
| energy per bit to noise power spectral density ratio | $\frac{E_b}{N_0}$ | 10.53dB |
| system noise temperature | $T_{sys}$ | 135K |

## 6 Results and discussion

The purpose of the next two subsections is to show the data rate and availability of direct and relayed communication over the duration of the mission and compare these results. The results for the Tumbleweed mission have been computed for frequencies in UHF and Ka-band. Results of the downlink scenario for swarm element – relay, swarm element – ground station and relay – ground station were computed.

### 6.1 Direct to Earth

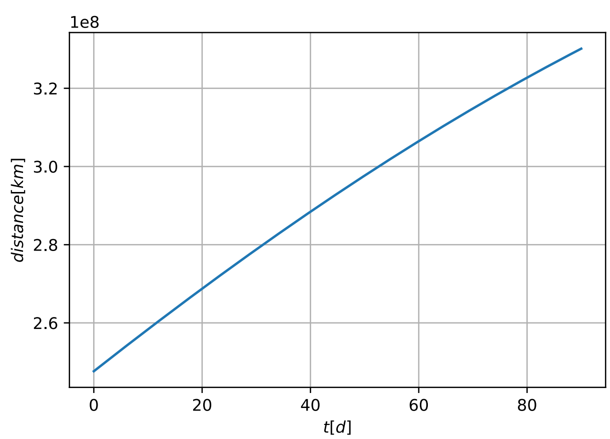


Figure 8: Mars - ground station distance

For the interplanetary links from the swarm elements and the relay to the ground station, figures 8 and 9 show the distance over time and the free space loss for UHF-band and Ka-band.

The distance increases from around $240 \times 10^6$km to around $330 \times 10^6$km over the mission duration. One should note, that delaying the landing on Mars after arrival would further increase the worst case Mars-Earth distance to up to $d_{SE}+d_{SM} = 378\times10^6$km, which would slightly, but not significantly increase the free space loss.

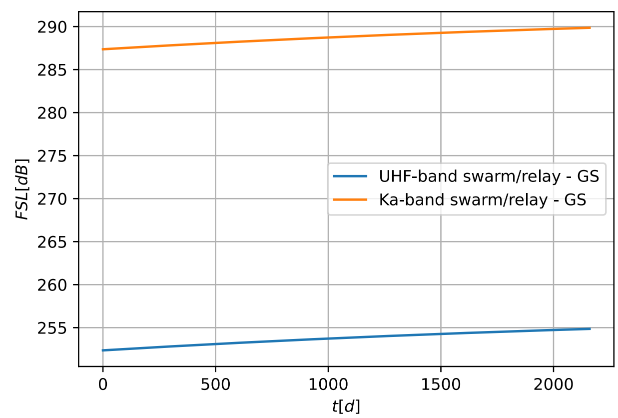


Figure 9: FSL Mars - ground station for 2 frequency bands

The orbits of the relay satellites have been chosen such, that the relay satellites have constant line of sight with Earth, meaning that — assuming ground station coverage — communication is always possible. For the link from a Tumbleweed to the ground station, communication can be impossible when the rover is on the far side of Mars and has no line of sight with Earth. As part of the simulation this LOS availability has been computed for each element over the mission time. The results are visualized in figure 10 which shows that for the first few days of the mission, none of the elements have LOS to Earth. Their position at or near the pole, combined with the axial tilt of Mars leaves all swarm elements literally in the dark. Rolling towards the equator with progressing mission time, more Tumbleweeds become visible to the ground station converging to around $\frac{N}{2} = 45$ towards the end of the mission. Lack of communications in the critical mission phase right after landing on Mars is highly undesirable. Whether, and to which extent this effect will occur depends on the exact constellation of Mars and Earth when landing on Mars and hence on the exact launch window, the transfer orbit and the time between arrival in martian orbit and landing on its surface. At this stage of the Tumbleweed project, a communication architecture that cannot ensure continuous line of sight communications during critical mission phases should be avoided. Consequently, a communication architecture that relies solely on direct communications from the swarm elements to the ground station is rejected.

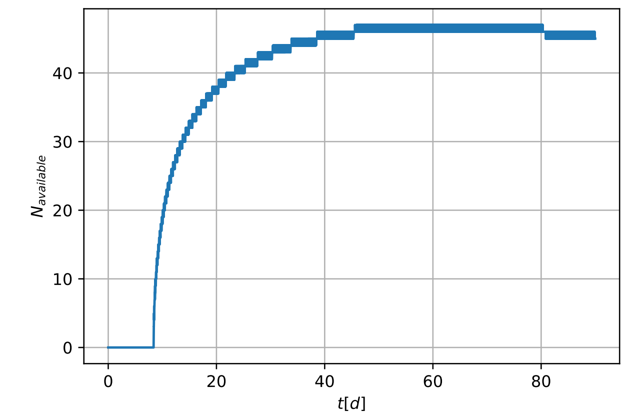


Figure 10: Number of available swarm elements over time of the swarm - GS link

Next, the bit rates can be analyzed. The effective bit rate for each swarm element is computed by combining the possible bit rate with the availability of the link and then averaging over the time of one martian day.

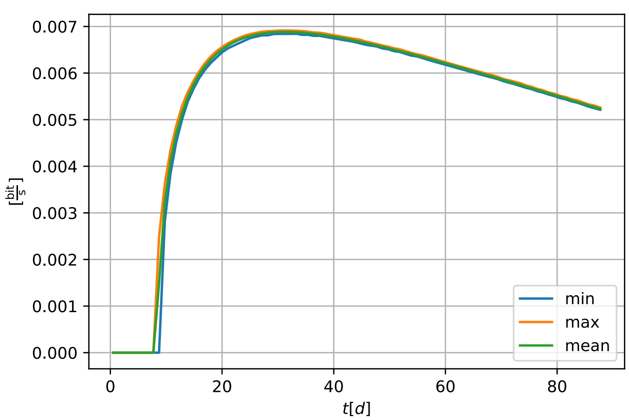


Figure 11: Swarm – ground station bit rates $r_{b,eff}$ for the worst swarm element (blue), best swarm element (orange) and averaged over all elements (green) averaged over 1 martian day against mission time

Figure 11 shows the bit rates of the best and worst element and averaged over all elements. The results for both frequency bands are the same, as the antenna gain of the ground station antenna and the free space loss are both proportional to $f^2$. Hence, the frequency dependence cancels out. For the ground station link of this case study the bit rates exhibit a positive correlation with frequency as for these links both the antennas have a constant antenna area and therefore $G \propto f^2$. The mean bit rate is affected both by the increasing availability of the link and by the increasing distance between Mars and Earth. The bit rate is so low, that it is not usable for transmitting data, which further reinforces the earlier finding, that direct communication from each Tumbleweed to ground is not sufficient.

### 6.2 Swarm – relay – Earth

In case of the relay – ground station link, all relay elements have constant line of sight and the same distance to the ground station thanks to the orbit design. The slight decrease in bit rate plotted in figure 12 is purely due to increasing Mars – Earth distance. As the bit rate of this link has a positive correlation with frequency, the higher results for Ka-band are superior.

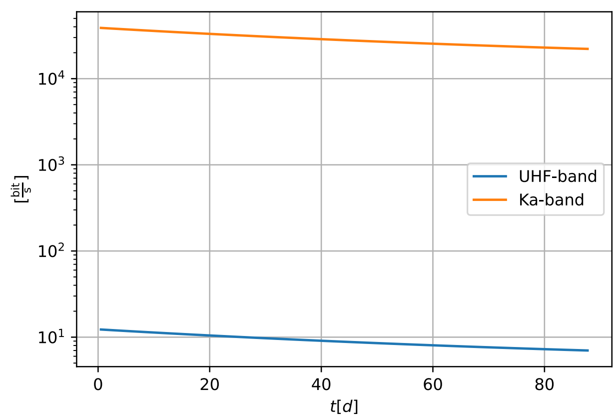


Figure 12: Relay – ground station effective bit rates for UHF-band (blue) and Ka-band (orange) $r_{b,eff}$ averaged over 1 martian day against mission time

For the analysis of the swarm - relay link, the scenario is quite dynamic as the swarm elements and the relay are both rotating around multiple different axes at different frequencies at the same time relative to martian center. The changes in distances are pronounced in this scenario. Figure 13 shows the distance between elements 0, 22 and 45 of the swarm and one of the relay satellites. As all relay satellites follow the same orbit, the results are — apart from a time-shift — the same for all satellites. The distances are shown in two windows with the duration of one martian sidereal day, one at the end and one towards the beginning of the mission. One can see that the distances are lower bound by $h_R = 1{,}000\text{km}$ and upper bound by $h_R + 2r_{MA} = 7{,}778\text{km}$. At the start of the mission, all the swarm elements exhibit similar behavior as they are all at or near the pole. For the same reason, the distance does not vary depending on the daytime, but only depending on the orbit of the relay satellites. The frequency of the oscillations in the top part of figure 13 corresponds to the orbital period of the relay satellites. In the bottom part, a few days before mission end, the swarm - relay distance still experiences the aforementioned oscillation, however, this time enveloped by a lower frequency oscillation corresponding to about half of the duration of a martian sidereal day. This makes sense, as, due to martian rotation around its own axis, the path of the rovers crosses the orbital plane of the relay satellites roughly twice per martian day. Furthermore, the distance curves of the three swarm elements are shifted by quarter a martian day.

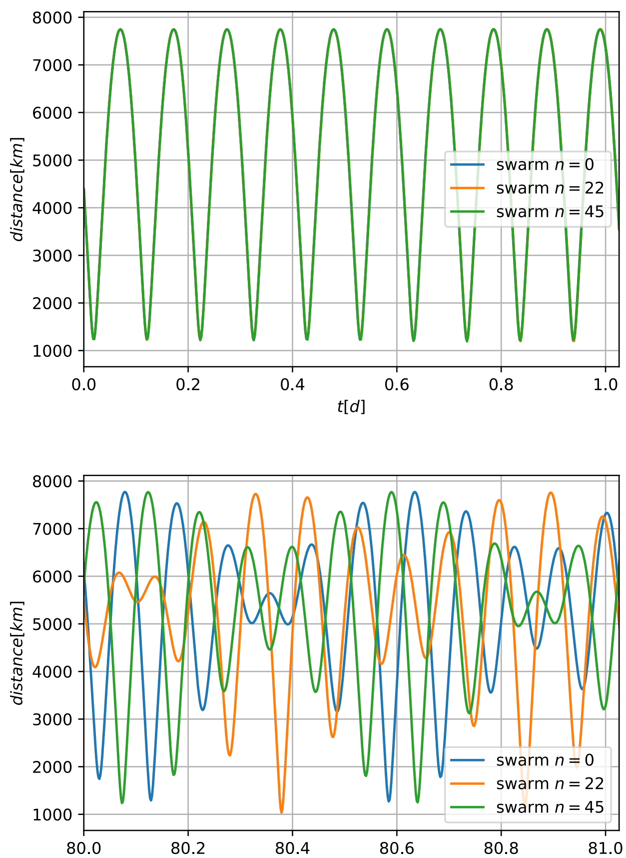


Figure 13: Tumbleweed distance swarm $n = [0, 22, 45]$ – relay $m = 0$ link at beginning (top) and towards the end (bottom) of the mission for the duration of a martian sidereal day

The link between the swarm elements and the relay satellites is not always available, as Mars can block the line of sight between transmitter and receiver. To illustrate this effect, figure 14 shows the free space loss for the links between 1 swarm element and all 3 relay satellites in two frequency bands. The FSL is plotted as a solid line for times at which the link is available and as a dotted line for times when LOS is blocked. The time windows remain the same as in the previous figure. Showing the links to all 3 relay satellites allows to identify whether the swarm element in question experiences gaps in coverage by the relays.

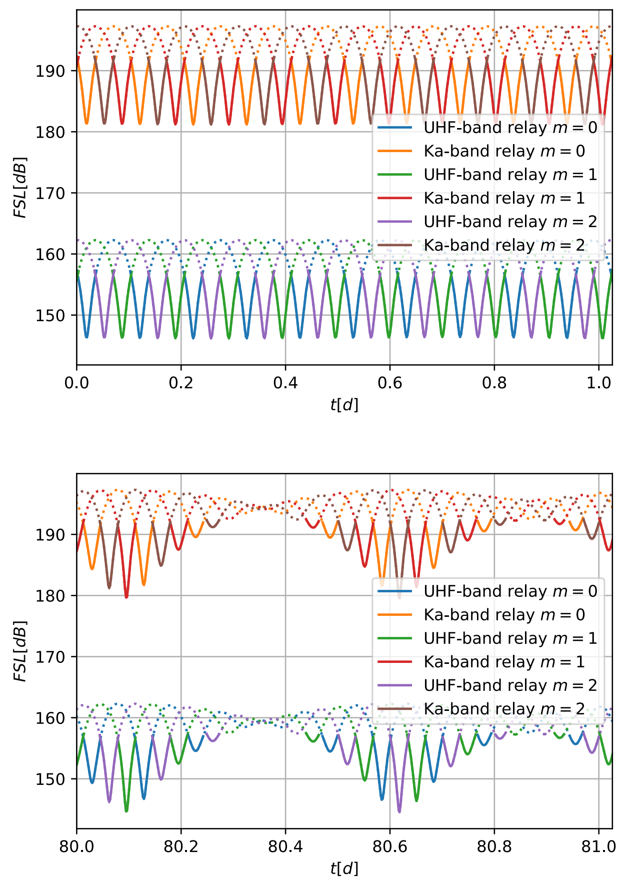


Figure 14: Tumbleweed free space loss swarm $n = 0$ – relay $m = [0, 1, 2]$ link at beginning (top) and towards the end (bottom) of the mission for the duration of a martian sidereal day

The top of the figure — again representing the beginning of the mission — shows that the availabilities of the 3 individual relay satellites overlap, such that in this critical mission phase all swarm elements would have constant contact to at least one relay at a time. Towards the end of the mission, as can be seen in the bottom part of figure 14, the availability is interrupted, sometimes for several hours at a time. However, coverage is achieved most of the time. Taking into account that this figure only shows one element for one martian day, more systematic analysis has to be conducted in order to determine average and worst case availability times. The figure further illustrates that the FSL, at times when the link is available, does not exceed $193\text{dB}$ for Ka-band and $168\text{dB}$ for UHF-band.

For a more systematic analysis, the LOS availability of the swarm – relay link has been computed for each element over the mission time. The swarm – relay link is considered available at time $t$ for swarm element $n$ if it has LOS with at least one relay satellite. The results are visualized in figure 15. The percentage of available elements over mission time is shown. To account for fluctuation of availability over the period of a martian day, the results were split into time bins of length $T_{MSD}$. Then the time-average for each bin was computed. The bin-averages are plotted against time for the swarm element with minimal availability in blue, for the swarm element with maximal availability in orange and averaged over all elements in green. The swarm elements reach an average availability of almost $92\%$ with equal behavior of the individual elements. The near-equal results for all elements are expected due to the martian rotation around itself. As expected from the previous plot, in the beginning of the mission all swarm elements have permanent connection with at least one relay. This state persists until day 40 of the mission when the mean availability starts to drop. It hits its floor at around 71.5% percent at the end of the mission. Combined with figure 14, which shows loss of line of sight at least twice per martian day for slightly different durations which indicates that the maximum dark time (consecutive time period over which the link is not available) should be at around 15–20% of a martian day which corresponds to around 3.5 to 5 hours.

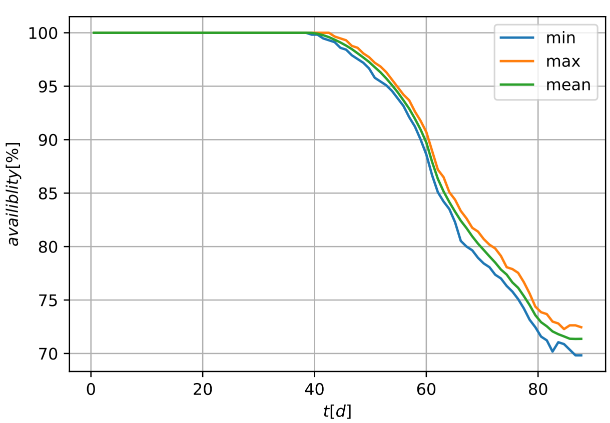


Figure 15: Availability (at least 1 relay in LOS) averaged over 1 martian day vs time for the worst swarm element (blue), best swarm element (orange) and averaged over all elements (green)

An average availability of $> 90\%$ and a minimal availability averaged over a martian day of $> 69\%$ combined with full availability during the critical first days after landing are a very good result for the swarm – relay link of the Tumbleweed mission. They also manage to satisfy the main availability requirement of the Tumbleweed mission for uplink communications which demands a delay of no more than 24h between transmitting a command from ground control to its execution.

Next, the bit rate can be analyzed. The effective bit rate for each swarm element to the relay is computed by combining the possible bit rate with the availability of the link and then averaging over the time of one martian day. Figure 16 shows the bit rates of the best and worst element and averaged over all elements. As for the swarm – GS link, the results for both frequency bands are the same. Three effects influence the bit rate of the swarm – relay link. First, the availability shown in figure 15 contributes to a decrease after day 40 of the mission. Secondly, the decreasing latitude of the swarm elements of the rover constantly increases the rovers' average distance to the orbital plan of the relay satellites. Third, the slight turn of the orbital plane such that it is always facing Earth changes the relative position of the martian rotation axis and the relays' orbital plane. The bit rate peaks, when the rotation axis of Mars coincides with the orbital plane. On average, an effective bit rate of just below $1\frac{\text{Mbit}}{\text{s}}$ can be achieved for the individual swarm – relay link.

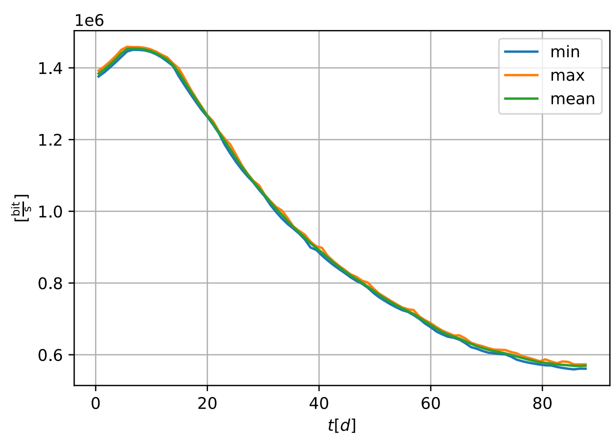


Figure 16: Tumbleweed effective bit rate $r_{b,eff}$ averaged over 1 martian day vs time for the worst swarm element (blue), best swarm element (orange) and averaged over all elements (green)

Using all the known transmitter and receiver parameters, one can compare what bit rates the different transmitter-receiver pairs achieve for different distances. The results are shown in a double logarithmic plot in figure 17.

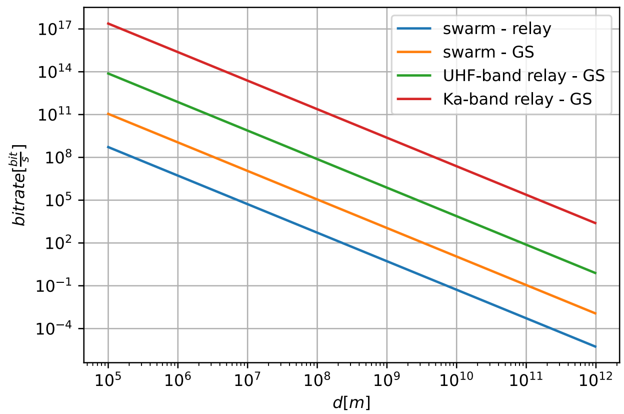


Figure 17: Tumbleweed bit rate for different transmitter – receiver pairs and frequencies over distance

### 6.3 Comparison

Table 4 shows the results for all individual links of the Tumbleweed mission.

Table 4: Tumbleweed results

| **transmitter** | **swarm** | | | |
|---|---|---|---|---|
| **receiver** | **relay** | | **GS** | |
| band | UHF | Ka | UHF | Ka |
| $P_t$[W] | 12.9 | | | |
| $f$[MHz] | 400 | 22500 | 400 | 22500 |
| $d_{min}$[km] | 1000 | | $2.476 \times 10^8$ | |
| $d_{mean}$[km] | 2992 | | $2.917 \times 10^8$ | |
| $d_{max}$[km] | 5544 | | $3.301 \times 10^8$ | |
| availability[%] | 91.7 | | 43.12 | |
| $t_{shade,max}$[h] | 4.06 | | 228.14 | |
| $r_{b,min}[\frac{\text{bit}}{\text{s}}]$ | $2.732 \times 10^5$ | | $1.030 \times 10^{-2}$ | |
| $r_{b,max}[\frac{\text{bit}}{\text{s}}]$ | $5.264 \times 10^6$ | | $1.704 \times 10^{-2}$ | |
| $r_{b,eff}[\frac{\text{bit}}{\text{s}}]$ | $9.219 \times 10^5$ | | $5.517 \times 10^{-3}$ | |

| **transmitter** | **relay** | |
|---|---|---|
| **receiver** | **GS** | |
| band | UHF | Ka |
| $P_t$[W] | 100 | |
| $f$[MHz] | 400 | 22500 |
| $d_{min}$[km] | $2.476 \times 10^8$ | |
| $d_{mean}$[km] | $2.917 \times 10^8$ | |
| $d_{max}$[km] | $3.301 \times 10^8$ | |
| $r_{b,eff}[\frac{\text{bit}}{\text{s}}]$ | 9.066 | $2.868 \times 10^4$ |

All results are shown for UHF and Ka-band. For swarm – relay and swarm – ground station links, the availability averaged over time and all elements was computed. Furthermore, the maximum shading time, meaning the longest time that one swarm element has no connection to any receiver of the respective link class was computed. For the minimal, mean and maximal distances, only those distances at which LOS communication is possible are included. The same is true for minimal bit rates, whereas the effective bit rates take into account periods where LOS is interrupted as 0 $\frac{\text{bit}}{\text{s}}$. If, like in the swarm – relay case, one swarm element has LOS with multiple relay satellites at a time, it is assumed that the swarm element will only communicate with the one closest relay satellite at any given time. The distances and bit rates are calculated based on this assumption.

Looking at the results, one can see quite satisfactory results for the swarm – relay links, averaging at $0.92\frac{\text{Mbit}}{\text{s}}$. Besides, the maximum time of unavailability of 4 hours is acceptable for a Mars mission without active control elements. As previously mentioned, swarm – relay and swarm – ground station links are frequency independent. For the swarm – ground station link, an average data rate of $0.017\frac{\text{bit}}{\text{s}}$ corresponds to a transmission time of 1 minute per bit which is not usable. Combined with the aforementioned lack of LOS at the beginning of the mission lasting for more than 9.5 days, a direct swarm ground station link is not sufficient, neither for housekeeping nor for payload data. The relay – ground station link has constant LOS with an effective bit rate of $9.099\frac{\text{bit}}{\text{s}}$ in UHF-band and $28.68\frac{\text{kbit}}{\text{s}}$ in Ka-band.

To calculate the average throughput on mission level, one has look at the swarm and relay configurations. Using equations 8, with $N = 90$ swarm elements and $M = 3$ relay satellites, one can see that the best mission bit rate can be achieved transmitting data via the relay satellites compared to direct communication which delivers worse results by several orders of magnitude. In this configuration, the relay – GS link is the limiting factor, as 3 relays have to support the data generated by 90 Tumbleweeds. Using the faster Ka-band link the mission can achieve average total data throughput of $7.63\text{Gbit}$ per martian day which amounts to $84.74\text{Mbit}$ per Tumbleweed per martian day.

## 7 Conclusions

The Tumbleweed mission aims to conduct large scale Mars exploration using 90 wind-driven Mars rovers. We conclude that relying on direct communication from the Tumbleweed rovers to the ground station is not feasible due to inadequately low data rates and risk of blocked line of sight to all rovers for several days after landing on Mars. As a solution, a communication architecture using 3 relay satellites in an Earth-facing circular Mars orbit has been proposed. It allows for a data throughput of $84.74\text{Mbit}$ per Tumbleweed per martian day. While this throughput enables to transmit significant amounts of scientific data, it would be a limiting factor when transmitting image data. The limiting factor is the relay – Earth link in Ka-band. Furthermore, we decide on the use of UHF frequencies for the rover – relay link to allow interoperability with existing relay infrastructure using Electra radios.

In future studies of the communication link, one could consider an optical communication link to increase throughput and decrease transceiver mass and size or study the option of using a directive antenna despite the rapid and uncontrolled movements of the rovers. A limitation of the current modeling is, that it does not account for atmospheric losses, pointing and polarization losses, multiple access and coding. Accounting for these factors combined with higher fidelity modeling of hardware and orbital geometries could lead to more accurate results in future studies. Furthermore, several aspects of the relay satellites should be more thoroughly investigated to find optimal orbits and number of relays, exploring possible use cases for ranging and triangulation, determine the feasibility of building such a relay constellation and comparing it to the option of using existing and projected institutional relays featuring the Electra payload for relay – rover communications.

For future research in the Tumbleweed project, following the conclusion that the data rate might remain a limiting factor for image data downlink, one could consider AI-based onboard feature recognition techniques, that allow to only transmit features instead of visual information or reduce redundant information at relay level. Besides, the results of this paper should be further validated and prepared for implementation. This involves realizing some of the proposed improvements to the communications and orbital model and, ultimately, the design of the rover communications module.

## References

[1] N. Pachler, I. del Portillo Barrios, E. Crawley, and B. Cameron, “An updated comparison of four low earth orbit satellite constellation systems to provide global broadband,” 06 2021, pp. 1–7.

[2] G. Denis, A. Claverie, X. Pasco, J.-P. Darnis, B. de Maupeou, M. Lafaye, and E. Morel, “Towards disruptions in earth observation? new earth observation systems and markets evolution: Possible scenarios and impacts,” *Acta Astronautica*, vol. 137, pp. 415–433, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576516313492

[3] C. J. Roesler, Y. J. Morton, Y. Wang, and R. S. Nerem, “Coherent gnss-reflections characterization over ocean and sea ice based on spire global cubesat data,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, pp. 1–18, 2022.

[4] B. Cheetham, *Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)*. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2021-4128

[5] F. Ferrari, V. Franzese, M. Pugliatti, C. Giordano, and F. Topputo, “Preliminary mission profile of hera’s milani cubesat,” *Advances in Space Research*, vol. 67, no. 6, pp. 2010–2029, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0273117720309078

[6] J. Balaram, M. Aung, and M. P. Golombek, “The ingenuity helicopter on the perseverance rover,” *Space Science Reviews*, vol. 217, no. 4, pp. 1–11, 2021.

[7] J. Antol, P. Calhoun, J. Flick, G. Hajos, R. Kolacinski, D. Minton, R. Owens, and J. Parker, “Low cost mars surface exploration: The mars tumbleweed,” *NASA Technical Memorandum*, 2003. [Online]. Available: https://ntrs.nasa.gov/citations/20030068113

[8] J. Rothenbuchner, L. Cohen, A. Pastinante, J. Łabor, F. Abel, and N. Weiroster, “Tumbleweed: Large scale martian surface exploration with wind-driven rovers.” *ESA Open Space Innovation Platform (OSIP) 2020, Idea: I-2020-05473*, 2020. [Online]. Available: https://ideas.esa.int/servlet/hype/IMT?userAction=Browse&templateName=\&documentId=03d9093021459def3a2da38239725788

[9] J. Rothenbuchner, L. Cohen, F. Abel, D. Buryaka, K. Cuervo, J. Kingsnorth, O. Mikulskytė, A. Phillips, M. Renoldner, and M. Sandrieser, “The Tumbleweed Mission: Enabling Novel Mars Data Sets through Low-Cost Rover Swarms, IAC-22,A3,IP,x72458,” in *73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.*

[10] J. Rothenbuchner, O. Mikulskyte, and B. Root, “Martian Interior Investigation Using Distributed Geodetic Sensor Network in the Tharsis Region of Mars, IAC-22,A3,IPB,35,x72466,” in *73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.*, 2022.

[11] NASA. Mars 2020 mission perseverance rover, communications. [Online]. Available: https://mars.nasa.gov/mars2020/spacecraft/rover/communications/

[12] A. Babuscia, “Telecommunication systems for small satellites operating at high frequencies: A review,”

*Information*, vol. 11, no. 5, 2020. [Online]. Available: https://www.mdpi.com/2078-2489/11/5/258

[13] NASA. (2013) The maven mission. [Online]. Available: https://www.nasa.gov/content/maven-launch/

[14] ——. Mars curiosity rover, communications. [Online]. Available: https://mars.nasa.gov/msl/spacecraft/rover/communication/#low-gain

[15] ESA. (2020) Exomars mission (2022). [Online]. Available: https://exploration.esa.int/web/mars/-/48088-mission-overview

[16] NASA. Mars reconnaissance orbiter, ka-band communications. [Online]. Available: https://mars.nasa.gov/mro/mission/communications/commkaband/

[17] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005. [Online]. Available: https://app.knovel.com/hotlink/toc/id:kpWC000002/wireless-communications/wireless-communications

[18] S. J. Orfanidis, *Electromagnetic Waves and Antennas*. Rutgers University, 2016. [Online]. Available: http://eceweb1.rutgers.edu/~orfanidi/ewa/

[19] Jet Propulsion Laboratory. (2021) Physical data & dynamical constants. [Online]. Available: https://ssd.jpl.nasa.gov/?phys_data

[20] NASA JPL. Let's go to mars! calculating launch windows. [Online]. Available: https://www.jpl.nasa.gov/edu/teach/activity/lets-go-to-mars-calculating-launch-windows/