Exploration and Utilization of Asteroids as Interplanetary Communication Relays

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Abstract—**There are more than 17,000 asteroids found near Earth and nearly 2 million asteroids estimated in the main belt between Mars and Jupiter. Asteroid come in diverse forms, some may hold valuable resources such as water, carbon and rare metals that may one day supply a spacefaring civilization. However, asteroids maybe also valuable as relay stations for a permanent high-speed, high–bandwidth interplanetary communication network. Asteroids are typically pock-marked with craters and grooves. Pristine craters resemble a parabolic communication antenna, but without the reflective coating or a receiver/transmitter at the focus. In this work, we evaluate two scenarios, the preliminary feasibility of setting up such a radio antenna on the Martian moon Phobos and Deimos (thought to be captured asteroids) that would act as a communication relay between the Martian system and Earth. Phobos is closer to Mars and is tidally locked. This would require two craters converted to antennas, one perpetually pointing at Mars, another pointing at Earth and a local interconnection between the two. Alternately, the relay on Deimos would need just a single crater relay station. We will then compare this communication relay to the current state-of-the-art, namely the Mars Reconnaissance Orbiter (MRO). The proposed communication antennas would be achieved by landing a swarm of CubeSats onto a crater to form the parabolic reflector. Each CubeSat has a mass of 4 kg and a volume of 3U or 3400 cc with one side forming the surface of the reflector. These CubeSats would hop, roll and fly into the crater and distribute themselves to cover maximum surface area. Each CubeSat has deployable reflectors to fill the gap between adjacent neighbors. A parabolic reflector would be able to reflect radio waves with a gap of one-tenth of the wavelength. A large 12U CubeSat would be positioned at the crater center and extend a deployable tower with a feed antenna to the focus. To achieve the current data rate of MRO, which is 4 Mbps, the power needs of a pair of 20 m^2 aperture antennas on Phobos and the interlink will be evaluated. For Deimos, a single 20 m^2 antenna will be considered. In both cases, the intent is to have an antenna gain of 50 dBi per crater. The analysis will also be extended to a 200 m^2 aperture antenna that can provide a data rate of 40 Mbps and antenna gain of 60 dBi per crater. Our approach to the mission design exploits machine learning to perform formulation, design, planning and operations. The results from these preliminary mission design studies will be used to identify a pathway towards detailed design and field studies in a simulated environment.**

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1. INTRODUCTION

Future exploration of Mars and the outer solar system will require a major upgrade to deep-space communication assets to enable high-resolution science data, video and telemetry to be communicated back to Earth. Current techniques for installing these assets require development of ever larger spacecraft such as the MRO that act as communication relays. However, in the long run, this approach may not be sustainable as these orbiting spacecraft have limited life due to limitations of the attitude control system components such as reaction wheels and the finite fuel required to desaturate them. These limits can be overcome by building permanent communications assets on an off-world environment. Such a facility overcomes the limited life of a communications relay spacecraft in deep-space. A credible choice is to plant these communication assets on the Moon, small-bodies such as near-Earth asteroids and captured asteroids such as Martian Phobos and Deimos.

In this paper, we present a low-cost, distributed network (swarm) of CubeSat landers that would be dropped-off from a large carrier spacecraft to form one or more communication relays on the surface of an off-world environment (see Figure 1). For our initial scenarios, we consider use of captured asteroids such as the Martian moon Phobos and Deimos as targets. Each CubeSat lander would utilize a tensegrity landing system and land without bouncing onto a pre-selected crater [8-9]. Each lander would then deploy an inflatable reflector, forming a large segmented parabolic reflector structure. In addition, several landers will deploy forming a receiver array. The landers would be powered using onboard photo-voltaics and would be expected to operate for twenty years.

In this concept (Figure 1), each CubeSat lander would have a mass of 4 kg, a stowed volume of 10 cm × 10 cm × 34 cm and include a self-contained design that would operate in synchrony with the network of other landers. For this size and volume, tens to hundreds can dispersed onto a crater surface as shown.

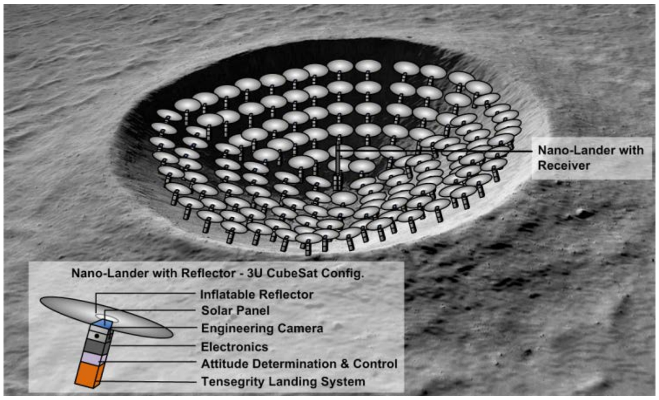

Figure 1. A swarm of nano-landers form a large communication antenna inside a crater.

A major advantage with this communication relay architecture is that each module consists of a relatively low-cost, dispensable CubeSat. The reflectors can be actuated by repurposing the tensegrity landing system to tilt the CubeSat base. More CubeSats can be added to increase the size and capability of the relay, while damaged ones can be readily replaced. Furthermore, the relay maybe dynamically divided to focus on multiple targets at once. Importantly, compared to a conventional spacecraft-based relay, the system can stay operational for 20 years or more and is not limited by fuel for reaction wheel desaturation.

The primary technical challenge for this concept lies with the overall integration of the tensegrity landing system, with an inflatable reflector system in a 3U CubeSat. There remains an important challenge in coordination and control of the network of CubeSat landers to form the communication relay. A secondary challenge is thermal control and energy storage to ensure all critical electronic components remain within a temperature of -40 ºC to +60 ºC and this has been shown in the laboratory [20-21]. Control of tens to hundreds of robots to solve complex tasks have already been demonstrated in a laboratory setting and this has important applications to the presented concept [10-13].

2. RELATED WORK

Exploration of asteroids and the Martian moons, Phobos and Deimos in the past few decades have shown that the major landforms on its surface are craters and grooves. Phobos has ~1300 craters > 200 m, ~70 craters > 1 km and ~30 craters > 2 km in diameter [1]. These asteroids have been observed by ground based telescopes and space observatories for decades, but recent missions like Hayabusa I, Hayabusa II, and OSIRIS-Rex show the pathway to explore these asteroids through touch and go missions.

The task of landing on these off-world environments while keeping the payload safe is a challenging one. Work has been done on designing tensegrity based probes for entry, descent and landing phases for a mission to Titan. Tensegrity structures have some major advantages, as they can offer the lowest mass design and thus increased allocation for science payload compared to conventional planetary landers [2]. Controlled descent and pinpoint landing is also suggested by using Guidance Navigation and Control (GNC) devices [3]. Overall, tensegrity systems are relatively new to aerospace, but are simple architectures that can be designed to have high redundancy and robustness [8-9].

The proposed CubeSat lander design is comparable to JPL’s Technology Demonstrator (TDO) concepts proposed for several Discovery missions [19] but include a tensegrity landing system and inflatable reflector antenna. Both technologies are fundamentally simple and are expected to be highly reliable. Inflatables have been proven in space and have been shown to be an effective landing system [17, 18]. They are currently being developed as communication antennas for small satellites [13-16]. The challenges as described earlier come from integration of these component technologies to derive the proposed swarm system.

3. MISSION ANALYSIS

An extensive mission analysis is first presented to construct the proposed communication relay at Phobos or Deimos. Any trajectory to Mars involves three phases: earth escape, transfer orbit and Mars capture orbit.

Phase I and II

The first phase consists of a geocentric hyperbola as the spacecraft escapes from earth’s sphere of influence (SOI). The second phase is an elliptical trajectory around the sun while the spacecraft travels to Mars as shown in Figure 2.

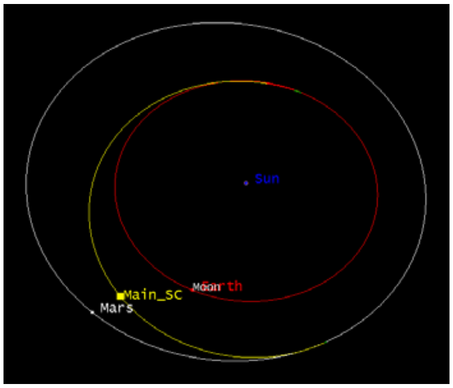

Figure 2. Earth to Mars transfer: Heliocentric View

Phase III

The third phase starts at the edge of Mars' SOI, which is a hyperbolic approach capture trajectory with the gravitational force of Mars as the attracting force as shown in Figure 3.

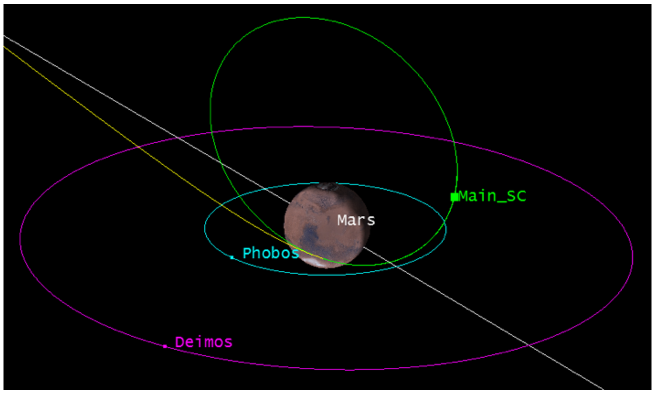

Figure 3. Mars Capture Orbit

Proximity Operations on Phobos and Deimos

Mars' gravitational field has significant influence on Phobos and Deimos and this presents some important challenges. The effective pseudo-potential of Phobos is shown in Figure 4 with the location of L1 and L2 Lagrange points at an altitude of approximately 3-4 km. They are saddle points for the pseudo-potential and hence a Mars orbiter would be motionless but unstable in the Phobos-Mars direction. This makes Phobos and Deimos incapable of supporting any practical Keplerian orbit and hence making proximity operations on it far more complicated than landing on the Moon, asteroid or comet. However, orbits of a special kind called quasi-satellite orbits exists and can be sufficiently stable to allow many months of operations in the vicinity of both Phobos and Deimos [4].

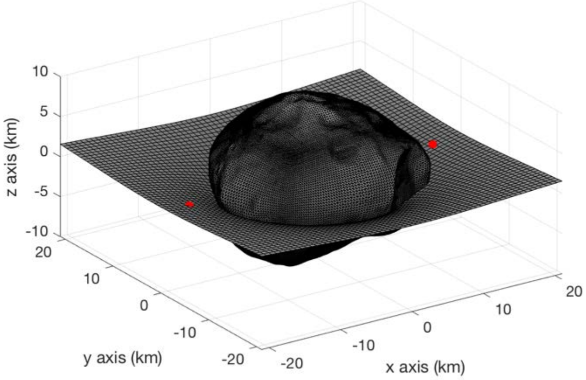

Figure 4. Pseudo-potential of Phobos. The red dots are L1 and L2 Lagrange points. Mars is along negative x-axis.

4. LANDING ON PHOBOS AND DEIMOS

We proposed to eject a swarm of CubeSat landers onto Phobos or Deimos. The tensegrity landing system would absorb any impact landing shock and protect the rest of the lander. Each CubeSat lander has a mass of 4 kg and a volume of 3U or 3400 cm^3. Figure 5 shows the external view of the CubeSat Lander. The lower 1U of the lander consists of the tensegrity landing system. The top 1U of the lander consists of the deployable reflective surface.

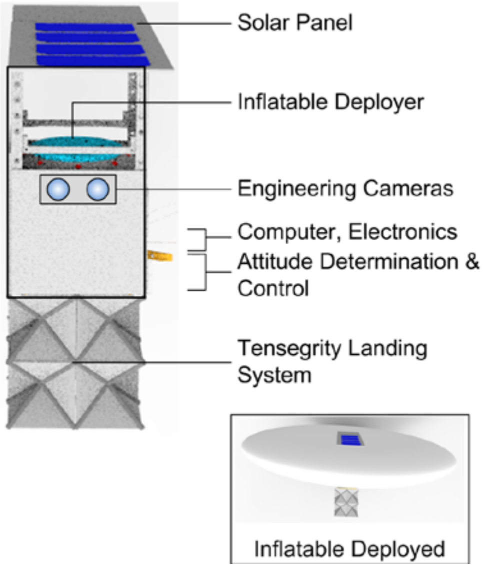

Figure 5. Side-View of a 3U CubeSat Nano-Lander with an Inflatable Reflector Payload

The middle 1U consists of the ADCS system and avionics which consists of an on-board computer, IMU, radio transceivers, power board and batteries. The attitude control consists of two modes: pointing mode, which is the nominal mode during descent and landing operations and the free fall mode engaged during free fall. The pointing mode controls the attitude of the lander to land vertically on its tensegrity landing system. Attitude guidance is based on the triad algorithm to compute the reference attitude from the set of reference vectors [3].

Upon ejection from the main spacecraft, each lander impacts the surface of Phobos or Deimos at about 15 m/s. The tensegrity landing system is configured for a fully deployed shock absorbing state. The landing system absorbs and distributes the impact stresses while protecting the main payload, much like an airbag. Tensegrity structures are made of axially loaded compression elements encompassed within a network of tensional elements, with each element experiencing either pure linear compression or pure linear tension. These structures are ideal for operation in dynamic environments where contact forces cannot always be predicted like the regolith filled surfaces of Phobos and Deimos [2].

Landing simulation with the tensegrity structure

Two types of tensegrity structures are used for landing simulations in this paper. Figure 6(a) shows a 3-Bar tensegrity prism and Figure 6(b) shows a 4-Bar tensegrity prism. The bars do not connect directly with other bars. They are connected indirectly by cables, resulting in a 'continuous tension network.' In addition to the tensegrity landing structure shown in Figure 6, we attach the remainder of the lander consisting of the 2U payload.

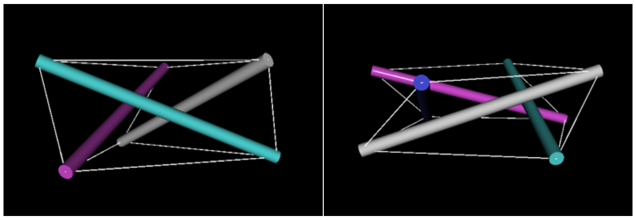

Figure 1. (Left) 3-Bar Tensegrity prism and (right) 4-Bar Tensegrity prism.

To simulate the payload landing with this tensegrity structure, we utilized two methods. First, we used a 4th order Runge-Kutta integrator for a Euler-Lagrange approach which is an analytical model for tensegrity systems using Skelton's dynamic equations [5] and then also used the NASA Tensegrity Robotics Toolkit (NTRT) which is based on the Bullet physics engine [6]. Figure 7 shows a graphical illustration of the impact simulation for the 3-Bar tensegrity prism with the payload on top of it. Similarly, Figure 8 shows the graphical illustration of the impact simulation for the 4-Bar tensegrity prism with the payload on top of it. It can be seen that before impact all the strings are equally stretched and after impact, the payload moves, deforming the tensegrity structure.

For our tensegrity landing system, a comparative analysis of the 3-Bar structure and 4-Bar structure is done attempting to land on the surface of Phobos. We add an initial velocity to both the structures such that it impacts the surface with a speed of 10 m/s. Figure 9 shows the horizontal components (x, y) and the vertical component (z) of the position of the center of mass of the payload for both the 3-Bar and 4-Bar mechanisms. Figure 10 shows the length of the horizontal cables, vertical cables and payload cables within the 3-Bar mechanism during the impact simulation.

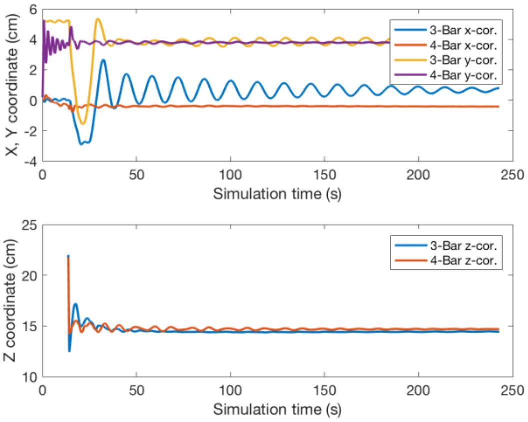

Figure 9. Position coordinates of the center of mass of the payload

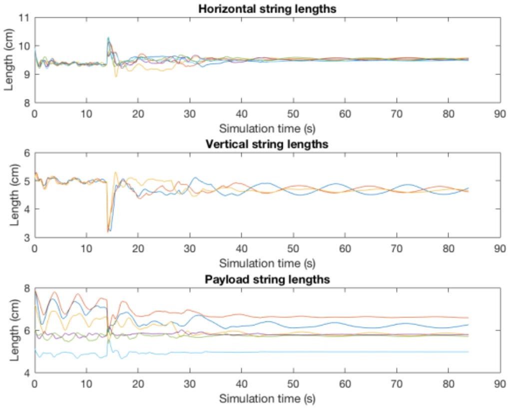

Figure 10. Cable lengths of the 3-Bar tensegrity structure

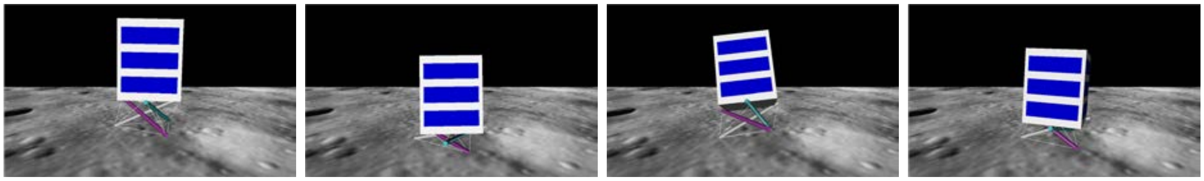

Figure 7. Graphical illustration of the impact simulation for the 3-Bar Tensegrity Prism with the payload on the top

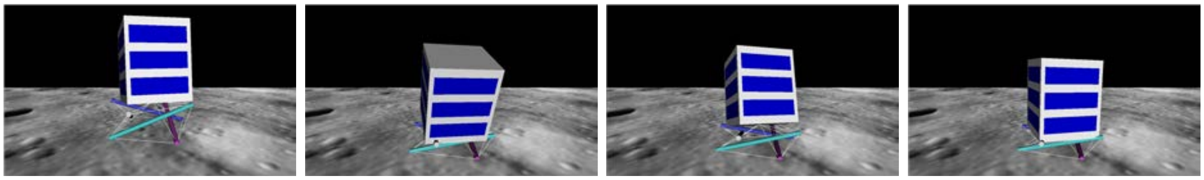

Figure 8. Graphical illustration of the impact simulation for the 4-Bar Tensegrity Prism with the payload on the top

Figure 11 shows the length of the horizontal cables, vertical cables and payload cables the 4-Bar mechanism during the impact simulation. It is evident that the 4-Bar mechanism is structurally more stable compared to the 3-Bar mechanism. The 4-Bar mechanism absorbs the impact force and damps the vibration at a much faster rate with less amplitude of vibration.

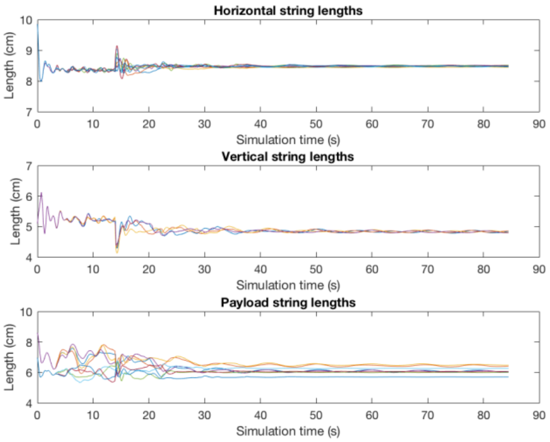

Figure 11. Cable lengths of the 4-Bar tensegrity structure

5. FEASIBILITY

After landing on Phobos or Deimos, each CubeSat Lander will hop into the crater and distribute themselves to cover the maximum area and finally deploy the reflectors [7]. A large 12U CubeSat would be positioned at the crater center and extend a deployable tower with a feed antenna to the focus. The gain of the antenna is directly proportional to the aperture area and efficiency of the antenna and inversely proportional to the square of the wavelength of the radio waves as shown in Equation 1.

$$G = \frac{4\pi A\, e_A}{\lambda^2} = \left(\frac{\pi d}{\lambda}\right)^2 e_A \tag{1}$$

where, G is the gain of the reflector antenna, λ is the wavelength of the radio wave, A is the aperture area, d is the diameter of the parabolic reflector and e_A is the aperture efficiency. Figure 12 shows the theoretical variation of antenna gain with aperture area.

X-band has considerably lower wavelength range of 2.5-3.75 cm and is considered for our analysis with the NASA Deep Space Network (DSN) acting as the ground station. The dependence of data rates on transmitted power for various aperture area is shown in Figure 13. The link margin is shown next to each point. A 20 m^2 parabolic antenna of 50dB gain and 100W transmitted power is sufficient to achieve a data rate of 4 Mbps from Phobos to Earth which is same as the Mars Reconnaissance Orbiter. For the same transmitted power, the data rate can be increased to 40 Mbps with a 200 m^2 antenna and 80 Mbps with a 400 m^2 antenna.

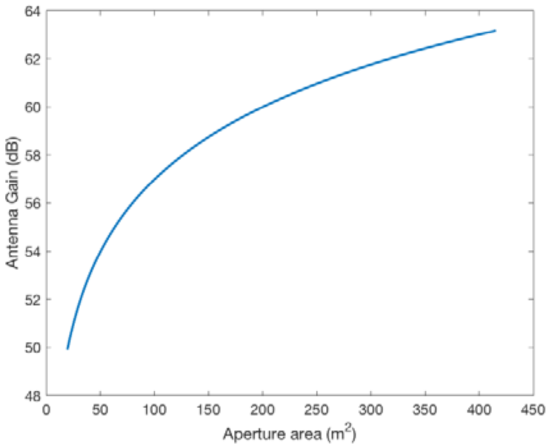

Figure 12. Gain of a parabolic antenna at 8450 MHz

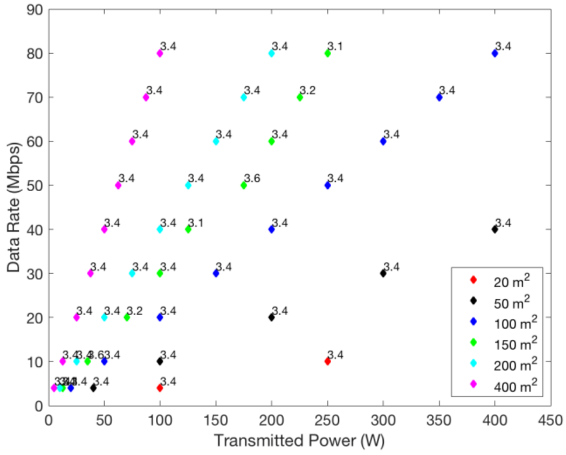

Figure 13. Theoretical data rates achievable at 8450 MHz, the values next to each point shows the link margin.

Access Time Interval Analysis

Both the moons of Mars, Phobos and Deimos are tidally locked, always presenting the same face towards Mars but always has a direct line of sight to Earth. Creating an antenna on a single crater will not be able to point towards Earth all the time, but strategically placing multiple antennas on different craters will increase the access time interval with Earth. With the three facilities of NASA DSN - Goldstone, Canberra and Madrid acting as a network of ground station at Earth, various scenarios have been simulated for a time span of 5 years from 1 Oct 2018 19:00:00.000 UTGC to 1 Oct 2023 19:00.000 UTGC.

Three simulated scenarios have been presented in this paper for analysis of the time interval during which access is achieved between the NASA DSN and parabolic antennas on Phobos and Deimos

Scenario I: One Antenna on Phobos

A single parabolic antenna is placed on Phobos inside the Drunlo crater and the access time interval is analyzed. Drunlo is a 4.2 km diameter crater located at coordinates

36.5^0N, 92^0W. The parabolic antenna of gain 40 dBi is placed at its center and analyzed. The scenario simulated over 5 years shows that this antenna on Drunlo crater has an access with at least one of the NASA DSN facilities for a total duration of 21,578 hours in 5 years which is 49.23% of the total analysis time. Figure 14 shows the access time interval of this antenna with the NASA DSN for an interval of 4 days. The green bars show the interval during which access is gained with the x-axis denoting Epoch time in hours.

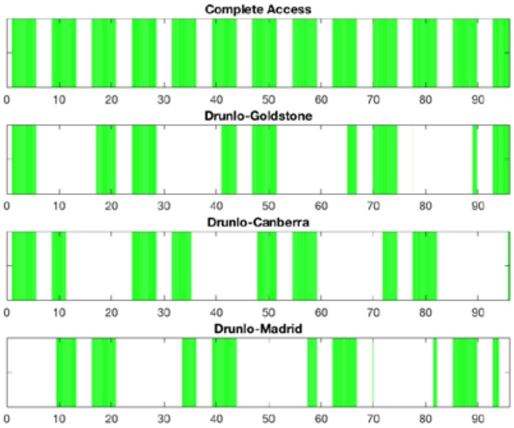

Figure 14. Access time interval of an antenna on Drunlo crater with NASA DSN.

Scenario II: Two Antennas on Phobos

The second scenario involves two parabolic antennas placed on Phobos, one inside the Drunlo crater and the other inside the Öpik crater. Öpik is a 2-km diameter crater located at coordinates 7^0S, 63^0E. Both the parabolic antennas are placed at the respective centers with gain 40 dBi and simulated for 5 years. This network of two antennas have access with at least one of the NASA DSN facilities for a total duration of 40,376 hours in 5 years which is 92.10% of the total analysis time. Figure 15 shows the access time interval of both the antennas with the NASA DSN for an interval of 4 days.

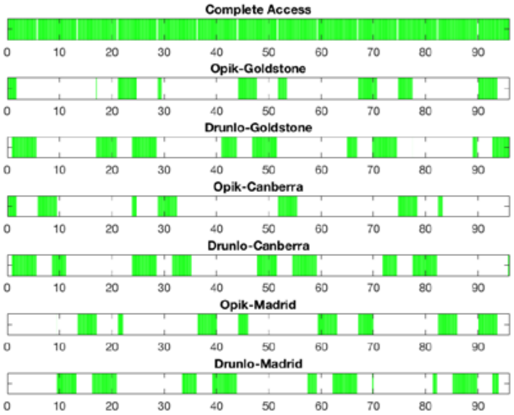

Figure 2. Access time interval of a network of antenna on Öpik and Drunlo crater with NASA DSN.

Scenario III: One Antenna on Deimos

A single parabolic antenna is placed on Deimos inside a crater yet to be named located at 40^0S, 16^0E. The parabolic antenna of gain 40 dBi is placed at the center of the crater and analyzed. The scenario simulated over 5 years shows that this antenna on Drunlo crater has access with at least one of the NASA DSN facilities for a total duration of 22,221 hours in 5 years which is 50.70% of the total analysis time. Figure 16 shows the access time interval of this antenna with the NASA DSN for an interval of 4 days.

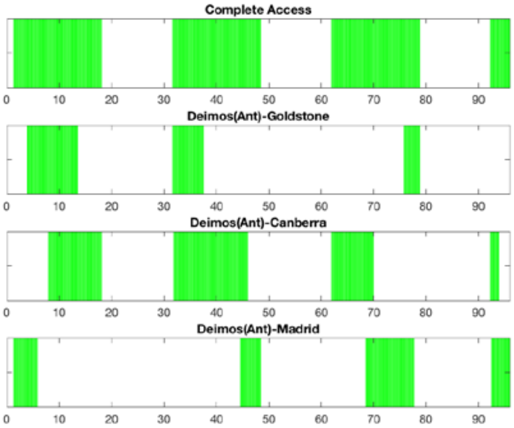

Figure 16. Access time interval of an antenna on a crater on Deimos with NASA DSN.

6. DISCUSSION

Our approach of landing a swarm of CubeSat landers on Phobos and Deimos to use their parabolic craters for high-speed, high-bandwidth interplanetary communication network presents important challenges but also new opportunities. We showed the initial feasibility of using multiple craters on Phobos to maintain connectivity with the NASA DSN facilities for more than 90% of the time. Similarly, using a single crater on Deimos offers access for more than 50% of the time. The proposed CubeSat lander with deployable reflectors offers a potential solution that utilizes Commercial Off-The-Self (COTS) technologies to provide access to the craters of the Martian moons. Despite significant research in the field of COTS components, many conventional options are not practical for an off-world environment, which needs further studies.

Our initial analysis shows the potential of a tensegrity structure for soft landing on the surface of Phobos with regolith. Our simulations show the advantages of using a 4-Bar tensegrity prism over a 3-Bar tensegrity prism. Further feasibility studies show that a 20 m^2 antenna with 100 W transmitted power can achieve a data rate of 4 Mbps comparable to the Mars Reconnaissance Orbiter with a link margin of 3.4 dB. For the same transmitted power, a 200 m^2 and a 400 m^2 antenna can achieve a data rate of 40 Mbps and 80 Mbps respectively.

Finally, we presented the feasible locations on Phobos and Deimos for setting up the antennas. A single antenna on the Drunlo crater on Phobos has an accessibility of 49.23% time, while a network of two antennas, one on the Drunlo crater and the other on the Öpik crater increases the accessibility time to 92.10% with the NASA DSN facilities. In the case of Deimos, a single crater on 40^0S, 16^0E offers an accessibility time of 50.70%. Overall, our approach shows a promising pathway towards further refining of our system design parameters and strategic identification of the locations on Phobos and Deimos towards detailed design of the mission concept.

7. CONCLUSIONS

This paper presents a new approach of landing on small-bodies such as asteroids to explore their parabolic craters and use them for building high-speed, high-bandwidth interplanetary communication networks. Most of the craters on asteroids and the Martian moons resemble a parabola, but without the reflective coating or a receiver/transmitter at the focus. With our approach, we can land a swarm of CubeSat landers with deployable reflectors onto the craters, distribute themselves over the crater surface, deploy their deployable reflectors and construct a deep space communication antenna over these craters. Building multiple antennas over specific locations can provide near-continuous access to the Earth's DSN network with substantially higher data rates compared to the Mars Reconnaissance Orbiter. Our analysis showed that we can achieve up to 80 Mbps of data rate from Phobos to Earth by setting up a 400 m^2 antenna. The results show a promising pathway towards detailed design and field studies in a simulated environment.

ACKNOWLEDGEMENTS

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BIOGRAPHY

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