

Article

# Satellite Requirements for Observation of Close Proximity Celestial Bodies †

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**Abstract:** Celestial bodies of our solar system remain as a major unexplored and unexploited reserve of natural resources available to humans. Furthermore, those constitute a valuable source of information about the origins and evolution of the solar system and an alternative to establish human settlements in the future. Observation and understanding of the land conditions of those celestial bodies is vital to learn more about those celestial bodies, to generate accurate maps of them, to look for natural resources of interest, and to evaluate the feasibility and help in the preparation of future land missions. A satellite constellation constitutes an important infrastructure element to observe those celestial bodies and to transmit the retrieved information back to Earth. Nonetheless, the operation of sensing satellites in other planets needs understanding of the requirements to perform such observations. In this paper we discuss those sensing requirements from the point of view of orbits and payload requirements for one of our closest neighbors of the solar system (Moon, Mars). To analyze the orbit of the sensing satellite, we discuss the required altitude to facilitate ground observation, the orbit's conditions (such as radiation levels and orbital perturbations, among others), suitable orbit configurations, required number of satellites, and ways to estimate the required time to perform full observation of the celestial body. To evaluate suitable payloads, we discuss available information in the literature (such as known atmospheric and land conditions) to determine the best observation frequencies and determine the best kind of payload (such as sensors, a camera, or a lower frequency observation payload) to study that celestial body. Finally, we discuss some important considerations such as the requirements of satellite communication link to transmit the retrieved information back to Earth.

**Keywords:** nanosatellites; orbits; payload; sensing satellite



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## 1. Introduction

The celestial bodies of the solar system remain as an unexploited reservoir of many materials and substances of interest for our societies. Nonetheless, large distances and extreme conditions to humans have prevented the obtainment, processing, and utilization of those resources. Among the closest celestial bodies to our planet are Mercury, Venus, Mars, and the Moon. Those, in addition to their shorter relative distance to us, compared to other objects of our solar system, are rocky planets similar to Earth and resource extraction [1,2] from them seems much more feasible than e.g., from gaseous planets.

Table 1 shows the minimum distance from Earth, radius and mass of the major celestial bodies of our solar system. In this table, it is clearly observable our closest neighbors are the Moon, and then Venus and Mars at distances around 100 and 140 times, respectively, larger than for the Moon. In addition to the distance, other characteristics make the Moon

one of our best options for exploration compared with Venus and Mars among them are the surface conditions (such as temperature and pressure) and the required exit velocity of the celestial body.

**Table 1.** Characteristics of main celestial bodies of our the solar system.

Celestial Body	Minimum Distance from Earth (10 <sup>6</sup> km)	Mean Radius (km)	Mass (10 <sup>24</sup> kg)
Mercury	77.6	2440	0.3301
Venus	38.2	6052	4.8673
Earth	–	6371	5.9722
Moon	0.38	1737	0.0735
Mars	54.6	3389	0.6417
Jupiter	588.5	69,911	1,898.1
Saturn	1205.5	58,232	568.32
Uranus	2580.6	25,362	86.811
Neptune	24,622	4319	102.409

The temperature and pressure of a celestial object is mainly determined by its atmosphere. In the absence of this, pressure will be close to null and the temperature of the planet will vary according to its exposition to the Solar rays. For our closest neighbors, Venus has remarkable extreme conditions, including a high an almost uniform temperature of around 450K and a pressure close to 90atm; those conditions are mainly caused by its dense carbon-dioxide atmosphere.

On the other hand, the Moon has no considerable atmosphere and thus, pressure is close to 0 atm and temperature varies (from 95K to 390K). The temperature of the Moon and its variations were extensively analyzed by the Lunar Reconnaissance Orbiter (LRO) and their results including diverse maps are available at [3]

The escape velocity,  $v_e$ , of a celestial body is the minimum speed for leaving the gravitational effect of the celestial object, and it is defined as

$$v_e = \sqrt{\frac{Gm}{R}} \tag{1}$$

where  $m$  is the mass of the and  $R$  is the radius of the celestial body. From this equation, it is clear that  $v_e$  increases as the ratio  $m/R$  augments, and we can infer that it would take much more fuel and oxidizer to leave a celestial body such as Venus ( $v_e = 10.36$  km/s) compared to Mercury ( $v_e = 4.25$  km/s), Mars ( $v_e = 5.03$  km/s), or the Moon ( $v_e = 2.38$  km/s). From the materials extraction perspective, it is important to consider the scape velocity since it will determine the amount of required trust for the rockets to leave the celestial body.

## 2. Methodology for Orbit and Communication Resources Selection

### 2.1. Constellation Design

There are several methodologies for satellite constellation design, among those are designed by Walker [4] and Rider [5] for circular inclined orbits. Those well known design strategies result in the Walker and Rider constellations, respectively, which have been used for constellation design on Earth, such as Starlink and One Web.

A Walker constellation is described by the notation  $T/P/F$ , where  $T$  is the total number of satellites in the constellation,  $P$  is the quantity of orbital planes,  $F$  is the relative phasing parameter, which indicates the right ascension of the ascending node (RAAN) separation between orbital planes. For this methodology, the number of satellites is the same for each plane,  $S = T/P$ , the RAAN distance between orbital planes is the same for each orbit, and satellites are evenly spaced in each orbital plane through their true anomaly.

### 2.2. Determination of Suitable Orbits for Observation

There are several considerations for the selection of orbits for observation and data collection in the Moon and Mars. First of all, it is important to consider the area of interest to observe in the celestial body, this constraint will help to determine a optimal orbit inclination and altitude. Orbit’s height can also be determined based on the payload, e.g., for a camera, a close distance to the surface would be suitable to observe detailed soil and terrain characteristics, but would take more time to complete a large observation campaign than at higher altitudes. In addition, if satellites are being used for sensors data collection on the surface [6], higher altitudes would degrade the signal more than shorter distances. Figure 1 shows with gray color the region covered by a satellite in a circular orbit with inclination,  $i$ .

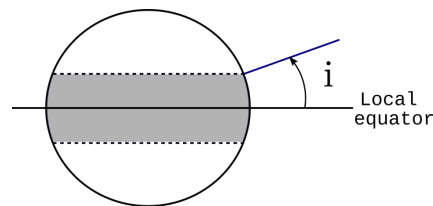


Figure 1. Orbit inclination and coverage.

Inclined orbits offer great advantages for focusing into an areas close to the local equator of the moon and Mars for both the Moon. Furthermore, the Moon poles contain some of the coldest places of the solar system [3] where hardware implementation would be difficult as well as in-site activities with rovers or sensors.

#### 2.2.1. Required Number of Satellites

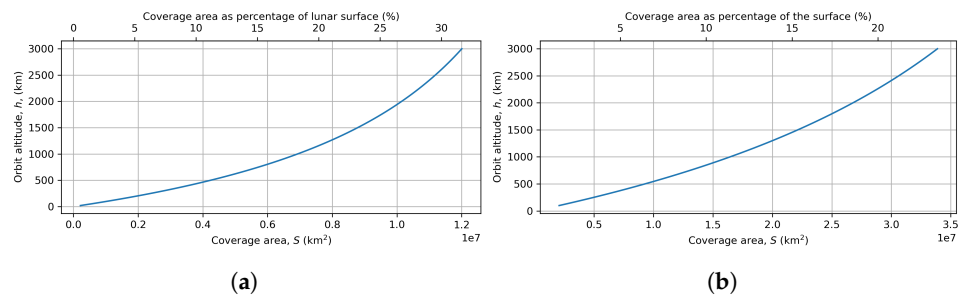
The required number of satellites for continuous communication depends on their footprint, which is the area in which the satellite is able to provide link availability, and this region is inside the coverage area. The coverage area is important because footprint can usually be steered inside this area to cover an specific spot. Coverage  $S$  is defined as the maximum area from which a satellite can be visible [7], and it can be calculated as

$$S = 2\pi R^2(1 - \cos(\alpha_{max})) \tag{2}$$

where the central angle  $\alpha_{max}$  is given by

$$\alpha = \cos^{-1}\left(\frac{R}{R + h}\right) \tag{3}$$

Figure 2 shows the coverage that can be obtained by a satellite orbiting the moon as a function of its altitude. The coverage is shown in  $\text{km}^2$  and as percentage of the lunar surface. Low orbiting altitudes, e.g., from a tens of kilometers, are possible in the moon due to the almost inexistent atmosphere, which in case of being denser, would cause drag forces and faster orbital decaying in the satellites. In addition, orbital perturbations are mainly caused by the solar pressure radiation and the gravitational influence of Earth, as well as the nonsphericity of the Moon [8]



**Figure 2.** Satellite coverage area as function of a orbit altitude for the (a) Moon and (b) Mars.

### 2.3. Determination of Suitable Frequencies for Communication Link Evaluation

The link budget between devices on the moon can be evaluated according to the link budget equation as

$$P_R = P_{Tx} + G_{Tx} + G_{Rx} - L_{FS} - A_{Atm} \tag{4}$$

where  $P_R$  is the received power in dBW,  $G_{Tx}$  and  $G_{Rx}$  are the gain of the transmitter and receiver antenna in dBi, respectively, and  $L_{FS}$  in dB is the free space path loss, which is defined in function of the link distance,  $r$ , and the wavelength of the carrier frequency,  $\lambda$ , as

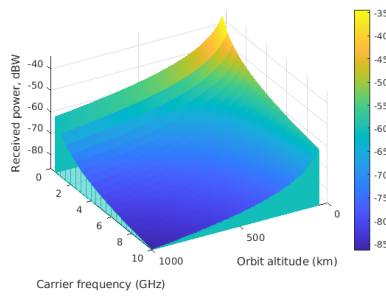
$$L_{FS} = 20 \log_{10} \left( \frac{2\pi r}{\lambda} \right) \tag{5}$$

Using the link budget equation we can determine the required sensibility of surface sensors for receiving commands from the satellites and the minimum transmitting power of those to be able to communicate to the satellites. A suitable carrier frequency can be determined based on the line of sight (LOS) availability of the ground devices, and the receiver sensibility.

In addition to the link budgets, channel models for the Moon and Mars need to consider the local environment and quickly adapt for changing conditions. As mention in [9,10], future space missions will require autonomous decision making, and possible, self channel determination (without expensive and time consuming measurement campaigns as in Earth) based on observed real time conditions and previous training, and power by artificial intelligence (AI). For the Moon, the absence of atmosphere have allowed solar rays to erode the surface and leave a rocky land which is known by their reflective behavior.

### 3. Discussion and Results

Nanosatellites constellations could be more easily deployed in the Moon or Mars compared with bigger satellites constellations. In addition, those will be cheaper to replace in the less protective atmospheres of the Moon and Mars. Based on analysis performed in [11,12], we can estimate the required number of nanosatellites to provide ubiquitous coverage (from a few of kbps until a few Mbps) in the Moon and Mars with the ratio of surface areas of the Moon and Mars to the Earth. This calculation results in a number of about 400 and 200 for Mars and the Moon, respectively. Nonetheless, current necessities on the Moon and Mars do not include ubiquitous communication coverage with several Mbps, an smaller constellations will work well for exploration. A Walker constellation design with configuration 8/2/90, as indicated in Section 2.1, is shown in Table 2. Similar nanosatellites constellation designs could be implemented both in the Moon and Mars at different altitudes and inclinations, resulting in a quicker and focused surface-area-sweep in the case of inclinations close to the local equator.



**Figure 3.** Link budget evaluation of the received power for different orbit altitudes in the Moon and Mars.

**Table 2.** Walker satellite constellation design for two orbital planes.

Satellite	Orbital Plane	RAAN (deg)	True Anomaly (deg)
1	1	0	0
2	1	0	90
3	1	0	180
4	1	0	270
5	2	180	90
6	2	180	180
7	2	180	270
8	2	180	0

The suitability of a communication payload and retrieval of data from sensors on the Moon [6] and Mars can be evaluated with a the link budget in the absence of a channel model as the ones that have been developed for Earth. Figure 3 shows a link budget evaluation for the received power at frequencies in the range of 500 MHz to 10 GHz, and altitudes from 50 km to 1000 km. The results show a much greater receiver power than in Earth, mainly caused by the negligible local atmospheres and suitability of orbits starting from a few tens of kilometers.

#### 4. Conclusions

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

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## Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
LRO	Lunar Reconnaissance Orbiter
LOS	Line of sight
RAAN	Right ascension of the ascending node

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