# A Comparison of ARTEMIS Data with the Lunar Plasma Design Environment for NASA Crewed Missions

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## I. Introduction

NASA's Gateway will provide the capability for sustaining a human presence in cis-lunar space. Operations of the Gateway will include spacecraft dockings, extra vehicular activities (EVA), and high-power solar arrays. NASA's experience with the International Space Station highlighted the importance of evaluating spacecraft charging effects for such operations. For crewed spacecraft, which tend to employ the use of dielectric surfaces in this dynamic plasma environment, reliance on spacecraft charging simulation packages, such as the NASA/Air Force Spacecraft Charging Analyzer Program (Nascap-2k) [Mandell et al., 2006] and Spacecraft Plasma Interaction System (SPIS) [Roussel et al., 2008], is required to understand the risks to hardware and humans. The variability in the lunar plasma environment as the Moon revolves around the Earth, lunar wake effects, and a strong dependency on photoemission and secondary electron emission creates challenges for spacecraft charging analysis. The Design Specification for Natural Environments (DSNE) [NASA, MSFC] is the primary resource for space environments affecting NASA's crewed missions, and the DSNE provides plasma environments in a standard form for input into simulation packages. NASA developed the existing lunar plasma environment using data from Geotail [Nishida, 1994] along with published lunar plasma wake models [Halekas et al., 2005] based on Lunar Prospector. Since 2011, NASA's twin Acceleration Reconnection Turbulence & Electrodynamics of Moon's Interaction with the Sun (ARTEMIS) satellites [Angelopoulos, 2010] have been collecting high resolution plasma and fields observations within the lunar plasma environment providing a much larger dataset of the plasma properties in cislunar space. This research compares the existing lunar plasma environment definition with ARTEMIS data and makes recommendations on the refinement of the environment definition for future lunar missions.

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## II. The Gateway

The Gateway will provide the capability for sustaining a human presence in cis-lunar space and supporting human surface operations. The preliminary concept is for a 2500 km x 75000 km near rectilinear halo orbit (NRHO), but lower altitudes, down to 100 km, are also being considered. The image shown in Fig. 1 is a visualization of a possible Gateway configuration. It will include a Power and Propulsion Element (PPE) with large solar arrays, a habitation area, and docking capabilities for Orion and other vehicles. Operations of the Gateway will be similar to those performed for the ISS, including vehicle dockings and EVAs. These types of activities can be sensitive to spacecraft charging effects and were closely studied for the ISS program. The lunar plasma environment is very different from low Earth orbit, therefore the effects of spacecraft charging must be reconsidered for this region of space.

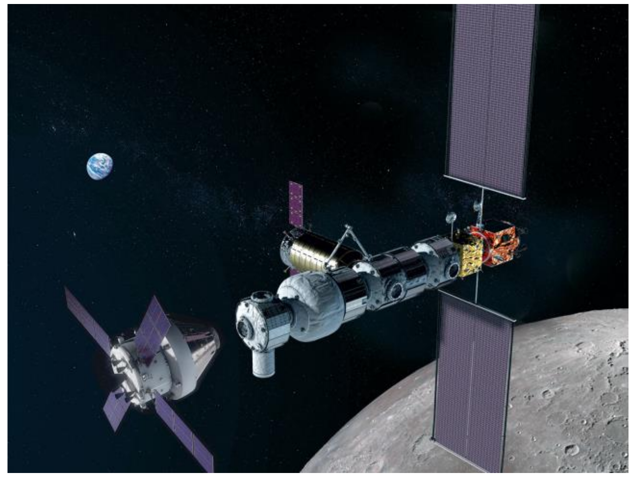

Figure 1. Visualization [image: NASA] of a possible Gateway configuration.

Surface charging is the result of balancing currents from the environment and spacecraft. It is dependent on the energy and density of the local plasma environment, photoemission, and emission of secondary electrons. Photoemission and the emission of secondary electrons are material and design dependent. Due to the low ambient density in the lunar environment and the tendency of electron energies being near the energy of maximum secondary electron generation, this becomes a complex spacecraft charging problem to solve. For crewed spacecraft, which tend to employ the use of dielectric surfaces, reliance on spacecraft charging simulation packages, such as Nascap-2k and SPIS, is required to understand the risks to hardware and humans caused by spacecraft charging.

## III. Lunar Plasma Environment

The Moon is described as "a fundamental physics laboratory" in a recent review of the lunar environment [Halekas et al., 2011] due the dynamic and complex plasma processes there. In its orbit around the Earth, the Moon passes through the solar wind, bow shock, magnetosheath, and the magnetotail. Each region of space has different plasma characteristics and important electric and magnetic field interactions to consider. In the solar wind there are interplanetary magnetic field (IMF) inductive effects, a wake, and downstream diamagnetic current systems. In the magnetosheath, the ambient plasma density is low such that the lunar exosphere becomes important, and in the magnetotail there are interactions with the plasma sheet. Our challenge is to describe the environment in a way that can be used as input into the spacecraft charging packages and useful for spacecraft design.

The purpose of the DSNE is to document space environment specifications for the design of NASA crewed missions. Plasma environments are defined according to their specific characteristics in different regions of space and are provided in a form that can be used as inputs into spacecraft charging tools such as Nascap-2k and SPIS. The goal is to document a reasonable worst-case for each relevant region in the simplest form possible. This goal can be difficult to achieve for very complex plasma environments such as the plasma in the vicinity of the Moon.

Figure 2 shows the lunar environment definition currently in the DSNE. The lunar environment points to the interplanetary environment for plasma density, temperature, and ion velocity. It has values for the magnetotail and solar wind, and a wake correction which accounts for decreases in density and increases in temperature in the lunar wake regions. These parameters can easily be inserted into a software package such as Nascap-2k.

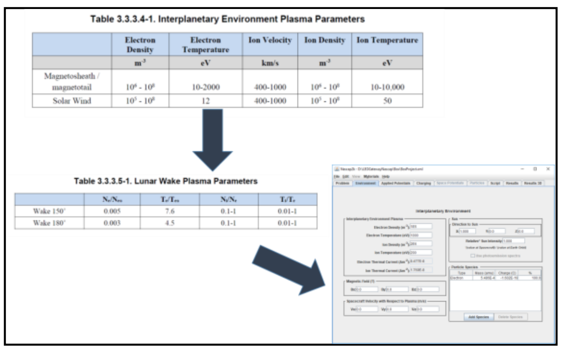

Table 3.3.3.4-1. Interplanetary Environment Plasma Parameters

| | Electron Density | Electron Temperature | Ion Velocity | Ion Density | Ion Temperature |
|---|---|---|---|---|---|
| | $m^{-3}$ | eV | km/s | $m^{-3}$ | eV |
| Magnetosheath / magnetotail | $10^6$ - $10^8$ | 10-2000 | 400-1000 | $10^6$ - $10^8$ | 10-10,000 |
| Solar Wind | $10^5$ - $10^8$ | 12 | 400-1000 | $10^5$ - $10^8$ | 50 |

Table 3.3.3.5-1. Lunar Wake Plasma Parameters

| | $N_e/N_{eo}$ | $T_e/T_{eo}$ | $N_i/N_e$ | $T_i/T_e$ |
|---|---|---|---|---|
| Wake 150° | 0.005 | 7.6 | 0.1-1 | 0.01-1 |
| Wake 180° | 0.003 | 4.5 | 0.1-1 | 0.01-1 |

Figure 2. DSNE lunar environment and Nascap-2k input window.

Generally, the software packages model the environments using a Maxwellian, a double Maxwellian, or a kappa distribution, but user defined distributions are also allowed.

The existing DSNE environment was developed prior to the beginning of the ARTEMIS mission [Angelopoulos, 2010]. Since July of 2011, the two ARTEMIS satellites have been in equatorial, 100 km x 19,000 km orbits. The orbital period is 26 hours and the satellites sample a large range of altitudes on both the sunlit and dark hemispheres of the moon. Each satellite has twin instrument suites consisting of an electric field instrument, fluxgate magnetometers, search coil magnetometers, axial and spin plane electric field sensors, solid state telescopes, and electrostatic analyzers (ESA). The large dataset, which is available on the CDAWeb, provides a unique opportunity to refine our lunar environment for each of the regions of space that the gateway will encounter.

We have defined four regions to characterize as shown in Fig 3. They are the solar wind, magnetosheath, magnetotail lobes, and the plasma sheet. For each of these regions we are analyzing the high altitude, low altitude, and surface environment for both the sunlit and dark hemispheres of the Moon. We will define an average and worst-case environment for each region. This detailed definition will allow the Gateway program to make design decisions and define operational constraints which avoid certain activities, such as docking or an EVA, in high-risk environments.

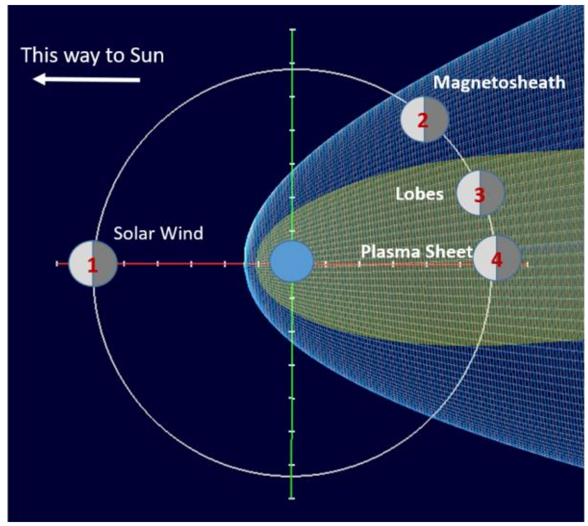


Figure 3. Regions of space defined for the lunar plasma environment.

## IV. ARTEMIS DATA

The two ARTEMIS satellites have been collecting data in lunar orbit since 2011. An example of the ARTEMIS electron density and temperature data is shown in Fig. 4. The ESA electron data is plotted as a function of time for March, 2015. The light gray shading indicates when the satellite is inside the magnetosheath (region 2), and the darker gray indicates when the satellite is inside the magnetotail (regions 3 and 4). The dashed line shows the maximum value that is currently defined in the DSNE, and the dotted line shows the minimum. As the satellite enters the magnetopause and magnetotail, the data shows an increase in electron temperature and a decrease in density from the solar wind plasma. The maximum DSNE values bound the data well. The minimum DSNE value bounds the magnetotail temperature well, but the density is consistently lower than the DSNE minimum. The periodic spikes in the solar wind data are from measurements when the satellite is in the lunar wake.

Fig. 5. shows a close-up of the lunar wake data. The gray shading indicates when the satellite is in the lunar wake, and the dashed and dotted lines again show the maximum and minimum DSNE values, respectively. In this instance, the electron temperature data does slightly violate the minimum and maximum DSNE definitions. The electron density is

slightly above the DSNE maximum at the beginning of the wake transit, but is well bounded by the DSNE minimum.

Fig. 6 shows some examples of small excursions above the maximum DSNE electron temperature values. In these cases the temperature values are above 2000 eV for a short period of time. Again, the density is below the minimum DSNE values. Due to the challenges of making low density measurements, these density and temperature results need to be further discussed with the mission instrument team.

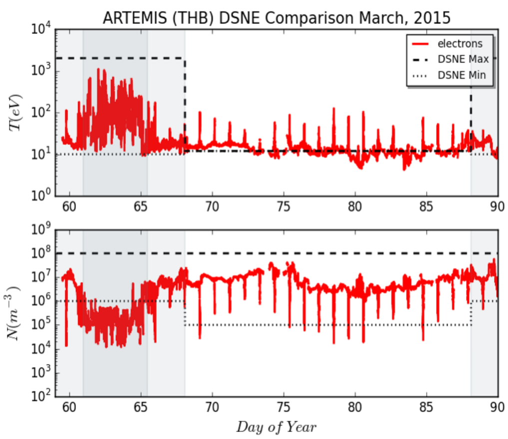


Figure 4. ARTEMIS electron density and temperature data for one complete lunar orbit. Dark grey magnetotail, light grey magnetosphere. See Figure 5 for DSNE solar wind wake requirements.

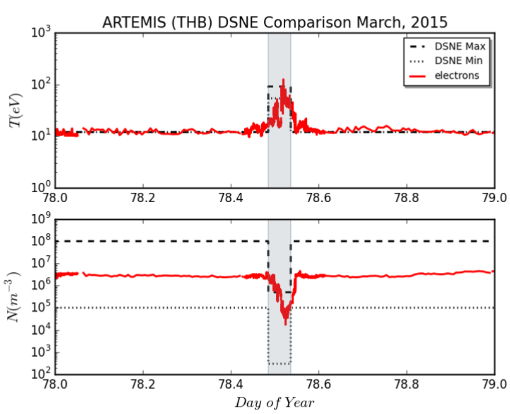


Figure 5. ARTEMIS electron density and temperature data for one wake pass.

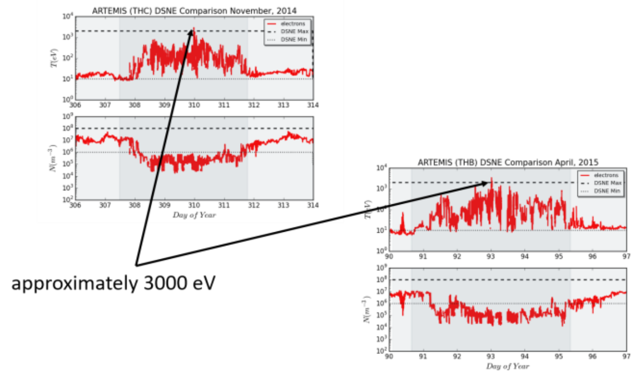


Figure 6. ARTEMIS electron density and temperature data showing small excursions above the DSNE maximum T and below DSNE minimum N within the Magnetosphere.

Fig 7. shows the results of a Nascap-2k charging analysis using a representative gateway vehicle and a sample of the ARTEMIS data as inputs. With an electron temperature of 3500 eV and a density of $4x10^4$ $m^{-3}$, the spacecraft can reach negative potentials; however, the result is highly dependent on the secondary electron emission material characteristics. A change as small as twenty percent in material secondary electron emission properties can result in differences on the order of thousands of volts in the potential. For spacecraft dockings and EVAs, even differential voltages of 100V can be a concern, so it is important to understand the sensitivity of the material properties to charging.

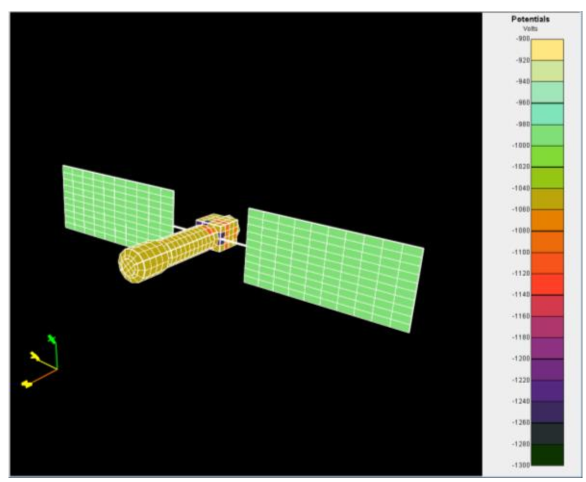


Figure 7. Representative Gateway vehicle Nascap-2k spacecraft charging analysis using ARTEMIS electron density and temperature data.

## V. Conclusions

Our preliminary look at three years of the Artemis data shows some minor disagreements with the environment design in the DSNE. The electron density tends to be lower in the magnetotail than the DSNE minimum. The electron energy tends to stay below the 2000 eV DSNE maximum, and there are excursions to higher temperatures in sunlight and darkness in the magnetotail. The solar wind wake temperatures and densities have small differences from the limits in the DSNE. Extreme events were not observed in the small subset of data we analyzed. A full data analysis is in work that will allow us to fully characterize the lunar plasma environment for the Gateway and Lander missions. We will use this data, along with other published data, to refine the lunar environment defined in the DSNE for average and extreme conditions.

## Acknowledgment

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Information on the Gateway can be found at www.nasa.gov/mission_pages/station/main/index.html. Information on the ARTEMIS mission can be found at http://artemis.ssl.berkeley.edu/.

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