SURFACE CHARGING SIMULATIONS OF AN ORION-LIKE SPACECRAFT IN A GEOSYNCHRONOUS SPACE PLASMA

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ABSTRACT

Surface charging in a space plasma environment is a critical safety issue for many space vehicles. This is particularly true for vehicles that spend time in geosynchronous altitudes. We present results on surface charging for an Orion-like spacecraft in a geosynchronous plasma environment, with an emphasis on examining numerical sensitivities to different meshing algorithms. Our surface charging simulation is performed using the Nascap-2k spacecraft charging software suite. In our approach, we have created and implemented EMA3D software tools that enable the user to generate Nascap-2k objects for simulation from an external CAD platform. These tools include the capability to quickly generate simulation models with different meshing algorithms and resolutions. We demonstrate our geometry development techniques and present results on differential voltages between adjacent surfaces, normal surface E-fields and voltage to plasma.

1. INTRODUCTION

A strategically designed space vehicle can often reduce or eliminate risks associated with surface charging. When space vehicles spend time in a space plasma, voltages may build up between the vehicle and the plasma [1] or between dielectrics and conductors on the vehicle. A general rule is that a potential of 400 Volts between a dielectric and adjacent conductor (or ground) presents a threshold value in a geosynchronous plasma for risk of dielectric discharge [2].

In this paper, we investigate the surface charging for an Orion-like spacecraft in a geosynchronous space plasma. Our goal is to present an analysis which illuminates various technical approaches and sheds light on certain physical phenomena which are important in evaluating the surface charging risk for a space program. We will pay particularly close attention to the effect different meshing algorithms may have on the numerical stability of results. Our model and analysis techniques are explained in subsequent sections.

2. ANALYSIS TOOLS

In this section we discuss the tools we have implemented to perform our surface charging analysis.

2.1. Geometry and Mesh Development with EMA3D/CADfix

Geometry development is a significant part of any simulation program, and surface charging is no exception. In the present analysis, we have developed our geometry using EMA3D [3] and its CAD platform, CADfix. EMA3D has developed a Nascap platform that allows the user to develop detailed geometry within the CADfix environment, assign materials to the model, mesh the model, and then export it directly into a Nascap ready object for simulation.

We will take advantage of these capabilities in our sensitivity analysis. We will analyze how different meshing algorithms and meshing resolutions impact the numerical results of our simulations. The EMA3D/CADfix platform allows the user to quickly generate meshes of different mesh type and resolution. We will discuss the particular meshes we implement further below, where we show our CADfix model and corresponding Nascap simulation objects in section 3.

2.2. Nascap-2k Spacecraft Charging Software

Once our geometry is developed, our surface charging analysis is performed using Nascap-2k [4]. Nascap-2k is a spacecraft charging and plasma interactions code based on a numerical solution to Maxwell's divergence equation using finite element computational methods. It has long been considered a powerful and versatile tool to investigate the physics of space charging and provides the user with many environment options including plasma characterizations and sunlight illumination scenarios. We will take advantage of this versatility in our surface charging analysis.

2.3. EMA3D/Nascap Processing

The Nascap-2k framework provides the user with a graphical representation of voltages with respect to plasma on all of the surface elements, as well as normal electric fields and several other physical quantities. It also provides the time dependence of quantities such as the maximum and minimum induced voltages on the spacecraft during charging.

We will take advantage of these easily accessible results from Nascap-2k in our analysis below. However, to take full advantage of the Nascap-2k results database we have developed dedicated EMA3D Nascap processing tools. These tools directly access the Nascap NDB file and calculate information on surface-to-surface differential voltages and other quantities, all broken down by material. This is information not accessible directly from Nascap without custom processing tools.

When we speak of surface-to-surface differential voltages, we are reporting on the worst case voltage difference between neighboring elements of different materials. If a material - say Kapton - has a differential voltage reported as 320 Volts, this means that the highest voltage difference between Kapton and any other adjacent surface material on the vehicle is 320 Volts.

3. ORION-LIKE MODEL

As alluded to previously, our simulation model is motivated by NASA's Orion spacecraft, which we have called an *Orion-like model*. This high profile mission is a natural study case for spacecraft charging with many publicly available resources giving partial descriptions or images of the design [5, 6].

Our basic design for the model takes advantage of these descriptions and uses other common design choices for spacecraft (including Apollo) described here: [7, 8, 9, 10]. Specifically:

- The crew module has four fused silica windows and three antennas, as well as strips of non-conductive exposed thermal protection system (TPS) near the top hatch.
- The crew module has a conductive aluminized kapton tape in the regions other than the windows and antennas. The antenna regions are non-conductive TPS.
- Our non-conductive TPS is reaction cured glass (RCG) (glass-like).
- The region between the crew module and the service module is coated with a condutive white paint with one antenna. The antenna region is felt-reusable surface insulation (FRSI), a non-condutive teflon-like material.

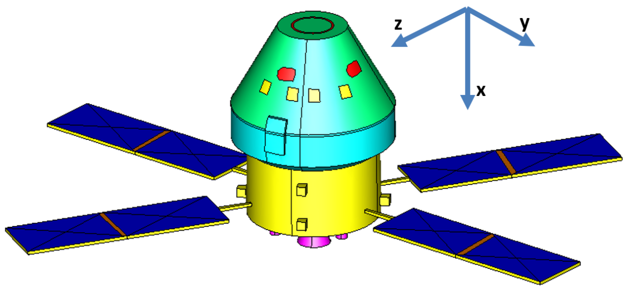


Figure 1: The Orion-like spacecraft used in this analysis and described in section 3. The depiction is the CAD based model used for development of the geometry. Colors represent different material regions. See the text for more information.

- The service module is coated with conductive white paint.
- The nozzles are conductive.
- The solary arrays are non-conductive and have exposed regions of non-conductive RTV-silicone (RTV).

The design described provides a reasonable mix of a mostly conductive spacecraft with several non-conductive regions representative of the common dielectrics seen on space vehicles. Our model is shown in Figure 1.

3.1. Materials Characterization

The physics of surface charging involves many aspects of the underlying materials' properties. For example, the Nascap simulation requires 18 inputs for each material. Most of these inputs describe in one way or another how conductive a material is or how they absorb incident charge flux from the space plasma environment. We have characterized our materials using the references listed above and in some cases the Nascap database.

3.2. Meshes Employed

The model shown in Figure 1 serves as the basis from which a mesh can be created. The mesh in turn can be used as the basis for a Nascap-2K simulation object and the subsequent surface charging simulations.

The tools described in Section 2 allow us to conveniently generate various mesh representations of the geometry of Figure 1, which are then exported into a Nascap-2K object ready for simulation. The material assignments automatically carry over, so we can generate multiple meshes for use in Nascap-2K without having to assign materials element-by- element.

We will consider three different mesh algorithms and several different mesh resolutions. The three mesh algorithms are:

- DELM - Delauney free tri mesh with internal nodes. Tends to produce a uniform mesh and tries to respects the overall shape of the geometry. May not respect the curvature of individual surfaces.
- DELT - Delauney free tri mesh without internal nodes. A variation of DELM. May not respect the overall shape of the geometry as well as DELM does.
- DELC - Delauney curvature sensitive mesh. Respects the curvature and size of individual surfaces. Tends to produce a non-uniform mesh and may not accurately reflect spatial gradients in some cases.

The three mesh representations of our model are shown in Figure 2, where we are showing the Nascap-2K objects actually used in the simulations. The DELM model (Figure 2(a)) is our baseline mesh. The other meshes will be utilized in the sensitivity comparison.

4. RESULTS

We will first examine results from the baseline model described in section 3 and represented by the DELM mesh of Figure 2(a). Then we will examine the sensitivity to the mesh variations.

4.1. Simulation Environment

As indicated above, we perform our surface charging analysis in a geosynchronous space plasma and consider different illumination scenarios. We will here consider a 'worst case' geosynchronous environment as characterized in reference [2]. That environment is a plasma of electrons and ions with the following values: electron density = 1.12 cm^{-3}, electron temperature = 1.2×10^4 eV, ion density = 0.236 cm^{-3}, ion temperature = 2.95×10^4 eV.

We consider seven sunlight illumination scenarios or environments. The environments are characterized by a vector indicating the direction *to the sun*, with coordinate system shown in Figure 1(a). The different environments are intended to span the different permutations of sunlight (including eclipse, or total shade) possibly incident on the vehicle:

- Environment 1 = shaded (all eclipse)
- Environment 2 = +x
- Environment 3 = +y
- Environment 4 = +z
- Environment 5 = -x
- Environment 6 = -y
- Environment 7 = -z

Material	Diff V	Env	V-Cnd	Env	EF-Norm	Env	V-Plas	Env
AlK Tape	2.22E+01	5	0.00E+00	1	2.24E+03	1	4.91E+03	1
FRSI	1.71E+04	3	1.71E+04	3	1.94E+05	3	1.73E+04	1
Windows	2.04E+01	6	2.04E+01	6	1.35E+03	1	4.92E+03	1
Paint 1	1.71E+04	3	0.00E+00	3	1.62E+05	3	4.91E+03	1
Paint 2	1.56E+03	1	0.00E+00	1	1.74E+04	1	4.91E+03	1
Nozzles	0.00E+00	1	0.00E+00	1	3.68E+03	1	4.91E+03	1
RTV	1.15E+03	1	1.29E+03	1	1.62E+03	3	3.86E+03	1
Solar Panels	1.56E+03	1	1.56E+03	1	7.72E+02	4	4.56E+03	1
TPS (RCG)	2.22E+01	5	2.22E+01	5	1.43E+03	1	4.91E+03	1

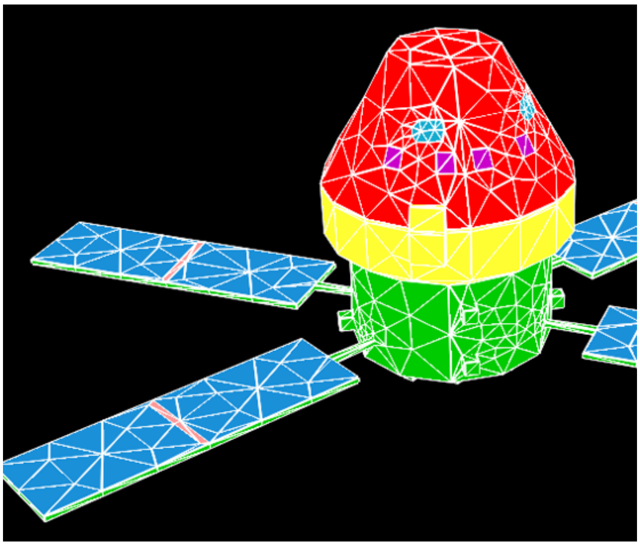
Table 1: The table shows the EMA3D processing output for the worst-case results across all illumination scenarios for each material (absolute values in each case). The *Env* heading to the right of each quantity indicates which illumination scenario produced the worst charging result for that material and quantity. See the text for more details.

The reader should refer to these environments or scenarios when interpreting the results presented in the following. Note that the -x direction indicates sunlight incident from forward to aft on this vehicle, while y/z are incident from the sides.

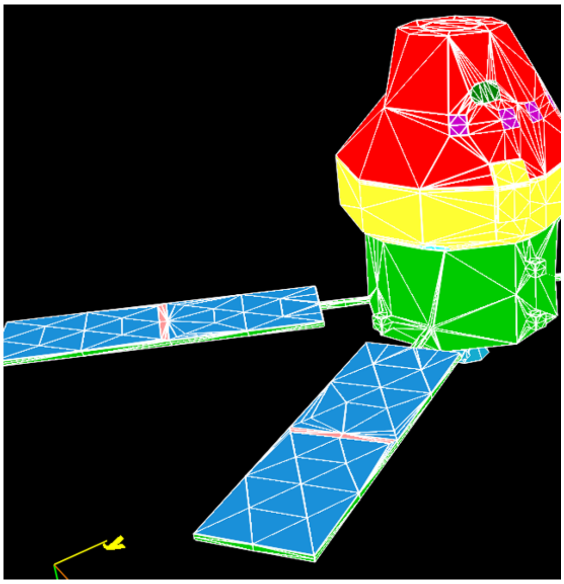
4.2. Physical Quantities Reported On

In the results shown below, we will refer to four primary physical quantities. In each case, we report the absolute value for each quantity:

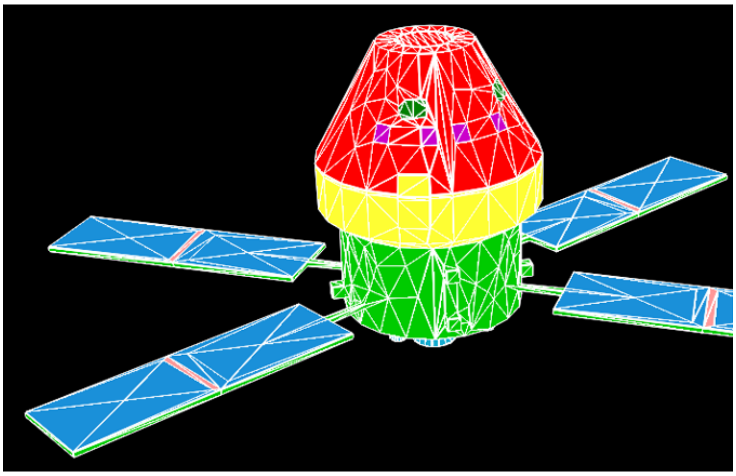
- **Diff-V**: This indicates the largest differential voltage with respect to adjacent surfaces for a particular material. If a material - say Kapton - has a differential voltage reported as 320 Volts, this means that the highest voltage difference between Kapton and any other adjacent surface material on the vehicle is 320 Volts. 400 Volts is a threshold for where dielectric breakdown may occur.
- **V-Cnd**: This indicates the largest voltage between surfaces of a given material and vehicle ground. Conductive materials typically have values close to zero for this quantity. 400 Volts is a threshold for where dielectric breakdown may occur.
- **EF-Norm**: The largest electric field component pointing outward, toward the plasma, for a given material.



(a) DELM mesh (baseline model) - 1388 elements



(b) DELT mesh - 1514 elements



(c) DELC mesh - 1294 elements

Figure 2: The three different mesh representations of our model. The algorithms are described in section 3.2. We have included the number of elements in each mesh. We will also consider variations in the resolution of the meshes. In those cases, we will indicate how the number of elements changes.

- **V-Plas**: This indicates the largest voltage between surfaces of a given material and the plamsa. 2,000 Volts is a threshold for where discharges to the plasma may occur.
- **Env**: This indicates which illumination environment (or scenario) produced the maximum observed value for a given quantity. It will always appear to the right of the quantity in any tables.

4.3. Baseline Model Results

Before presenting any plots or detailed numerical results, we attempt to explain what we have observed to give the reader insight.

- Large differential charging results in the region of FRSI ($\sim$17,000 volts), and to a lesser extent the solar panels ($\sim$1,500 volts). The rest of the vehicle experiences minor differential charging ($\sim$100 volts).
- Sunlight illumination can serve to greatly reduce or almost eliminate the differential charging threat. This is true when sunlight is incident on the FRSI.
- Sunlight illumination can also serve to make the differential charging worse. This is true when the sunlight is not incident on the FRSI.
- The differential charging and voltage to conductor indicate a dielectric breakdown is highly likely. The voltage to plasma indicates discharges to plasma are also highly likely.

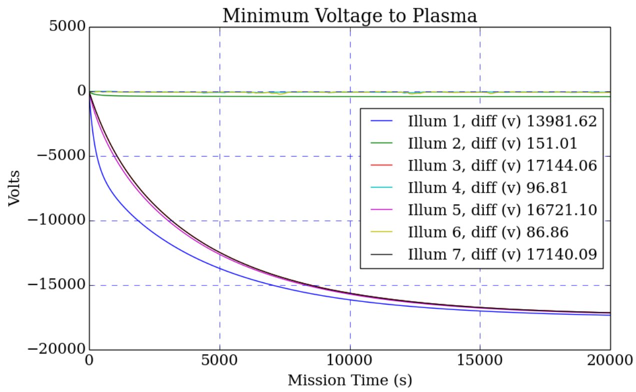


Figure 3: The plot shows the minimum voltage induced on the vehicle as a function of time for each illumination scenario. The value next to *diff* refers to the difference between the minimum and maximum voltage seen on the vehicle at the end time - not differential voltage in terms of neighboring surfaces. See text for details.

These results are seen numerically in Table 1 and Figure 3. We will spend the next few paragraphs discussing these results since they contain a lot of information about the charging dynamics.

Table 1 shows the EMA3D processing output for the worst-case results across all illumination scenarios for each material (absolute values in each case). The *Env* heading to the right of each quantity indicates which illumination scenario produced the worst charging result for that material and quantity. In the case of 'Diff-V', the result shows the largest differential voltage with respect to adjacent surfaces for that material. Thus, 'FRSI' and 'Paint 1' each have the same 'Diff-V', since they are adjacent materials. However, it is the properties of 'FRSI' that are responsible for the large differential charging.

Figure 3 shows the minimum voltage induced on the vehicle as a function of time for each illumination scenario. The value next to *diff* refers to the difference between the minimum and maximum voltage seen on the vehicle at the end time - not differential voltage in terms of neighboring surfaces. The scenarios which show minimal charging (2, 4, 6) are those in which the sunlight hits the FRSI.

Notice that *diff* in Figure 3 is larger for scenario 3 than scenario 1 (the shaded scenario). This results because sunlight in scenario 3 acts to reduce the charging on most of the vehicle, but does not hit the FRSI. Thus, the FRSI still experiences strong negative charging but the rest of the vehicle experiences less negative charging due to the sunlight, resulting in large differential charging (see next subsection for more details). One final point from Figure 3 is that our numerical results appear to be stable and converge to well-defined values.

4.3.1. Physical Interpretation

In this subsection we attempt to provide more in-depth physical interpretation of the results shown above. As mentioned previously, the physics of surface charging involves many aspects of the underlying materials' properties. However, to first order the reader can gain solid intuition by thinking of each material in terms of its electron emission properties and its conductivity:

- Each material is subject to a current flux from the plasma environment, largely determined by the temperature and density of the plasma. This flux usually acts to charge surfaces negatively.
- Each material is also subject to a current flux from backscattered, secondary and photo electrons. This flux is sensitive to material properties which we refer to as *electron emission properties* and serves to charge surfaces positively (reduces the number of electrons).
- Each material has an intrinsic conductivity through which it tries to equilibrate with the vehicle ground.

In our model above, the results are dominated by a combination of the solar panels, the FRSI section and the conductive materials. In terms of *just* the electron emission properties:

- The conductive materials (paints and AlK tape) have electron emission properties such that they charge negatively in the plasma.
- The FRSI has electron emission properties such that it also tends to charge negatively, although a little less negatively than the conductive materials.
- Finally, the solar panels have electron emission properties such that they are almost neutral - if the vehicle only had the solar panel material, it would tend to charge slightly positively in the shaded environment.

When we also consider each material's intrinsic conductivity, the picture becomes more clear. Note that the FRSI conductivity is 1e-16 S/m, the solar panels' conductivity is 1e-13 S/m and the conductive materials are essentially perfect conductors. Here is what happens:

- The conductive materials begin to charge negatively in the plasma, and since they cover most of the vehicle and are very conductive, they alter the vehicle ground to be negatively charged with respect to the plasma.
- The solar panels want to remain neutral with respect to the plasma, but since the vehicle ground becomes negative (due to the conductive materials), the solar

panels become negatively charged and alter the vehicle ground to some intermediate value. This intermediate value is determined by the size of the conductive and solar regions and the conductivity of the solar panels.

- The FRSI wants to charge to some large negative value (similar to what the conductive materials would have charged to by themselves). Since the conductivity of the FRSI is so low, it is not as sensitive to the vehicle ground as the solar panels are and is able to charge negatively, resulting in the large differential voltages seen above.

If we removed the solar panels from the baseline model, the FRSI would actually charge to a slightly higher potential (smaller absolute value) than the conductive materials and the overall differential voltage would be fairly small. It is the presence of the solar panels, combined with the conductivities of the various materials, that provides the interesting dynamic seen above.

As a final note, we point out that the sunlight illumination tends to complicate the situation, as can be recalled from Figure 3. When sunlight is on the vehicle, the conductive materials tend to charge much less negatively and stay mostly neutral with respect to the plasma. The same dynamic just described still occurs in that the solar panels and conductive materials find some compromise.

However, since both of those materials want to be close to neutral with respect to plasma, the compromise is not very dramatic. The FRSI still charges negatively with respect to plasma for the reasons described above, and hence the largest differential charging occurs in this scenario. The exception occurs when the sunlight is incident on the FRSI, in which case the FRSI tends to stay neutral and the whole vehicle only charges mildly with respect to the plasma.

4.4. Sensitivity Analysis

We finish our presentation by doing an analysis of the sensitivity of our results to our choice of mesh. We believe that such an analysis helps identify which meshes provide the most accurate results and how fine a mesh resolution is required to get accurate results. This will become clearer in what follows.

The meshes were shown in Figure 2 and described in Section 3.2. For our sensitivity test we will simply examine plots of the maximum voltage relative to plasma induced on the vehicle during simulation for each distinct mesh. Results are shown in Figure 4(a). In the Figure legend, the value next to *diff* refers to the difference between the minimum and maximum voltage seen on the vehicle at the end time - not differential voltage in terms of neighboring surfaces.

It is clear from the plot that all three meshes give noticeably different values for the maximum voltage on the vehicle. Furthermore, there is no obvious numerical instability in any of the curves which might give a hint as to which mesh is less reliable. One way to gain more insight in to what is happening is to increase the number of mesh elements for each mesh. Generally speaking, a finer mesh is more reliable than a coarser mesh. The goal would be to find that the different mesh algorithms begin to converge with a higher mesh resolution. This is what we have plotted in Figure 4(b). In this case, DELC has 3314 elements, DELT has 3098 elements and DELM has 2136 elements.

Here we find that the DELT and DELM meshes converge, but the DELC mesh continues to show discrepancy. Our inclination is to believe the meshes that agree over one that appears to be an outlier, however, to investigate further, we can consider a three dimensional plot of the induced voltages.

Figure 5 shows a three dimensional color plot of the induced voltage on the high resolution DELC mesh at the end of the simulation. We have focused in on the solar panels since that is where the maximum voltage is occurring.

The reader can see that the gradient on the solar panels is quite coarse with this mesh. In fact, the way this model has meshed has relegated the gradient on the solar panels to be limited to two regions. We have verified that the other meshes show much more detailed structure in this region and better represent the gradient on the solar panels.

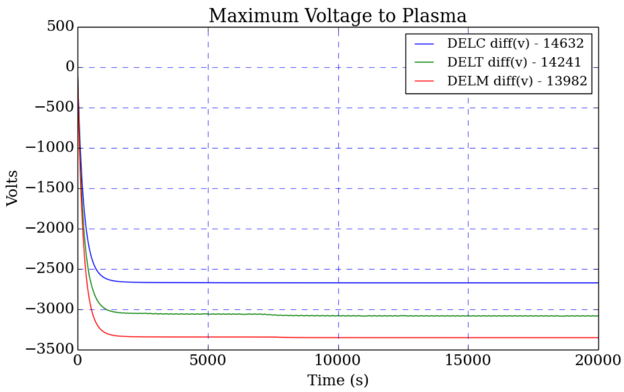
Our conclusion is that the DELM mesh, and to a lesser extent the DELT mesh, are the most reliable meshes for this model. Although we have not investigated it here, the best choice for the user may be to use the DELM mesh on the solar arrays and the DELC mesh on the rest of the model. This would provide a compromise of retaining curvature on the main body and resolution on the solar panels.

Lastly, in Figure 6 we show the maximum voltage as a function of time for four different resolutions of the DELM mesh. The resolutions range from RES1 to RES4: 2136, 1762, 1584 and 1208 elements. We see that 1762 elements is probably enough to extract the physics reliably, and that all of the resolutions are fairly close to each other. This type of analysis can help the user find a good balance between robust numerical results and computational efficiency.

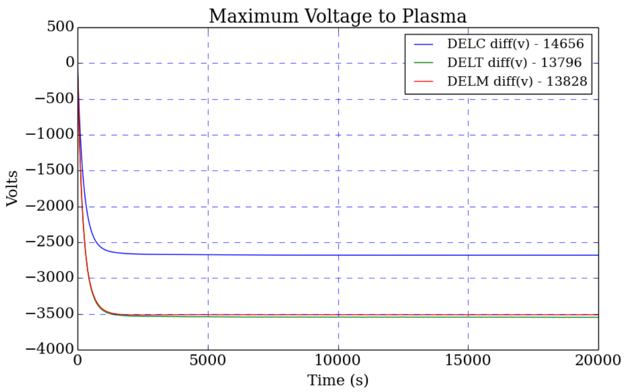
5. CONCLUSIONS

We have presented a surface charging analysis of an Orion-like spacecraft in a geosynchronous space environment. Some of the important points include:

- We have introduced EMA3D software tools to develop sophisticated geometry and meshes and to fa-



(a) Result of the meshes shown in Figure 2



(b) The same algorithms as in (a) but with finer resolution

Figure 4: The three different mesh representations of our model. The algorithms are described in section 3.2. We have included the number of elements in each mesh. We will also consider variations in the resolution of the meshes. In those cases, we will indicate how the number of elements changes.

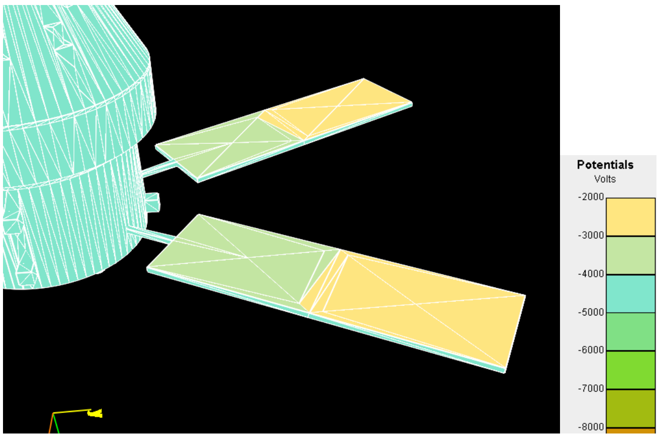


Figure 5: A three dimensional color plot of the induced voltage on the high resolution DELC mesh at the end of the simulation. We have focused in on the solar panel since that is where the maximum voltage is occuring.

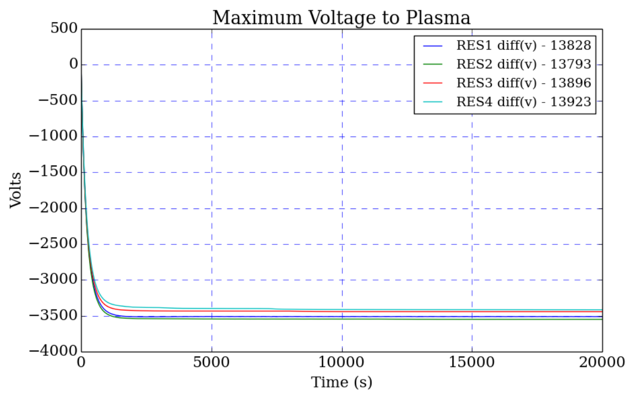


Figure 6: The maximum voltage as a function of time for four different resolutions of the DELM mesh. The resolutions range from RES1 to RES4: 2136, 1762, 1584 and 1208 elements.

cilitate detailed results processing within the Nascap platform.

- The surface charging results (see Table 1) show significant differential charging associated primarily with FRSI, but also the solar panels.
- We presented an extended physics discussion in section 4.3.1 and presented a mesh sensitivity analysis in section 4.4. The sensitivity analysis showed how one can use different mesh algorithms and resolutions to test the numerical reliability of their model.

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