HALL CURRENT THRUSTER PLUME MODELING:
A DIAGNOSTIC TOOL FOR SPACECRAFT SUBSYSTEM IMPACT

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ABSTRACT

Hall Current Thrusters (HCT) generate very different environments and spacecraft interactions than do conventional on-board propulsion schemes. Interactions include sputtering by primary beam ions that may erode spacecraft surfaces, dense plasmas that can affect spacecraft communications, and optical emissions that may confuse star trackers, among others. We have developed an integrated model of HCT environments and their interactions.

We develop a set of calculation techniques for two-dimensional modeling of the plasma plume from an HCT and calculate plume densities and particle velocities over a non-uniform two-dimensional grid. We integrate this grid of values into the Environment Work Bench (EWB) three-dimensional spacecraft and environments impact engineering tool. This tool is then used to assess the impact of the thruster plume on other spacecraft systems.

The plume densities and velocities are calculated over a non-uniform grid of points and written into a database. This plume database becomes the foundation of the "engineering" model integrated into EWB, where it is implemented with a three-dimensional spacecraft model by rotating about the beam axis. Given a plume model, EWB contains the machinery to calculate plume impingement on spacecraft surfaces, object shielding and wakes, contamination, erosion and sputtering, and other 3-D geometrical effects. We describe the integration of the plume map into EWB, the plume impingement surface effects models, and perform some sample calculations of plume effects on spacecraft subsystems.

INTRODUCTION

Hall Current Thrusters (HCT) generate very different environments and spacecraft interactions than do conventional on-board propulsion schemes. Interactions include sputtering by primary beam ions that may erode spacecraft surfaces, dense plasmas that can affect spacecraft communications, and optical emissions that may confuse star trackers, among others. We have developed an integrated model of HCT environments and their interactions.

The major computational effort in this work is the calculation of the interactions between the HCT plume and spacecraft surfaces. The interactions modeled include plasma densities, sputtering of spacecraft surfaces, and contamination of other surfaces by sputtered material. Heating of surfaces due to kinetic and ionization energy transfer was also modeled. The performance of these calculations required incorporation of the plume map and interaction models in the Environment WorkBench (EWB), a space environment interactions tool originally designed to model the ISS plasma interactions. In EWB the plume map is integrated with spacecraft geometry allowing for calculation of plume impingement effects on spacecraft surfaces. Several new capabilities were added to EWB, including gridding of spacecraft surfaces, 3-D visualization of surface effects, integration of the HCT plume map, and calculation of fluxes, sputtering and surface effects. We discuss these capabilities in detail below.

ENVIRONMENT WORK BENCH

Environment Work Bench (EWB) is an engineering tool for simulation of space environments interactions with spacecraft, developed under contract to NASA/GRC for modeling plasma interactions of the International Space Station. EWB has been developed over a period of 10 years involving dozens of person-years of effort. Environments models in EWB are standard models used by NASA, i.e., IRI90 for plasma,

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MSIS86 for neutrals, etc. The EWB Manual documents these models in detail[1]. The underlying architecture of EWB makes it relatively easy to integrate new models without affecting existing code.. EWB models have been extensively validated against existing codes and with data from several space flights. Figure 1 below illustrates the capabilities of EWB including spacecraft geometry definition (with solar array sun-pointing), surface materials, orbit generation, space environments, interactions effects, and general mission and point-on-orbit trade studies.

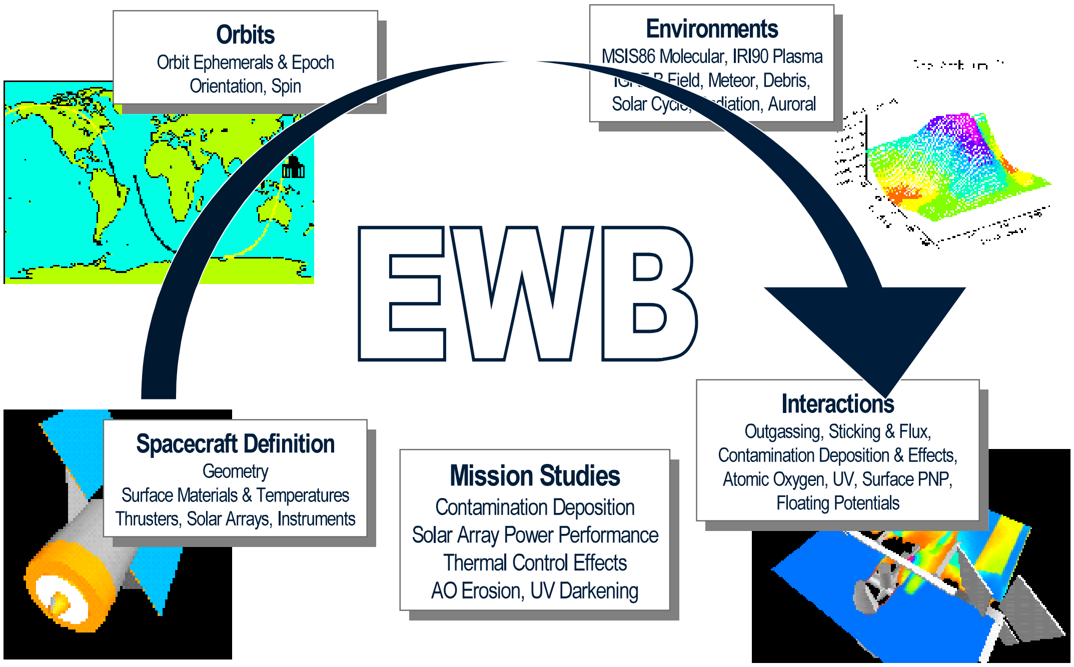

Figure 1. The EWB engineering tool models spacecraft/environments interactions and has been extensively validated.

HCT PLUME MAP

The HCT plume map is generated on a 30 meter grid starting at $r=2x10^{-3}$ m, with 95 radial values and 42 angular ones (0 to 3.06 radians) as shown in Figure 2. The plume map consists of multiple components. For example, the main beam ions of different energies, and low-energy charge-exchange plume. This map is in the form of a text file to be used for integration into EWB (see below). The map contains ion densities and velocities (with V_r and V_z velocity components) for each beam component.

The densities are calculated to produce the correct ion currents assuming all xenon particles are singly ionized. It should be noted that densities could actually be several times higher at a given point in time due to thruster oscillations. This is important to consider for calculating RF interactions.

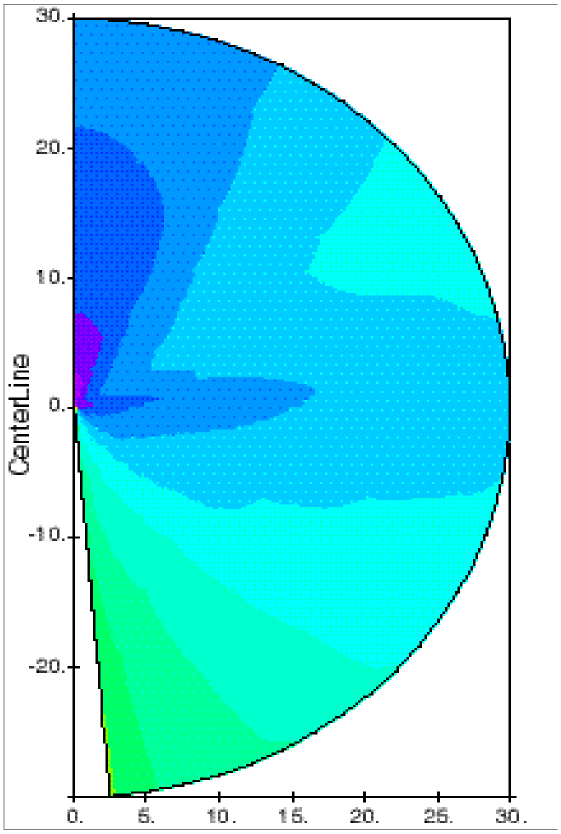

Figure 2. The HCT plume map is generated on a 30 meter grid from θ=0 to 3.06 radians.

PLUME MAP INTEGRATION INTO EWB

The results of the HCT plume calculations described above are saved in a text file containing plume densities and velocities on an R,θ grid as described above. It includes, as separate components, the primary beam, and the charge-exchange plume. EWB reads the densities and velocities of each of the components, saving them in separate arrays, and summing appropriately as necessary. To calculate the density or flux at any point in space, EWB interpolates into this map. Presently, the map stops at 30 m and densities and velocities are assumed to be zero beyond that point. Figure 3 shows an example of plume densities in space around a typical communications spacecraft as calculated by EWB.

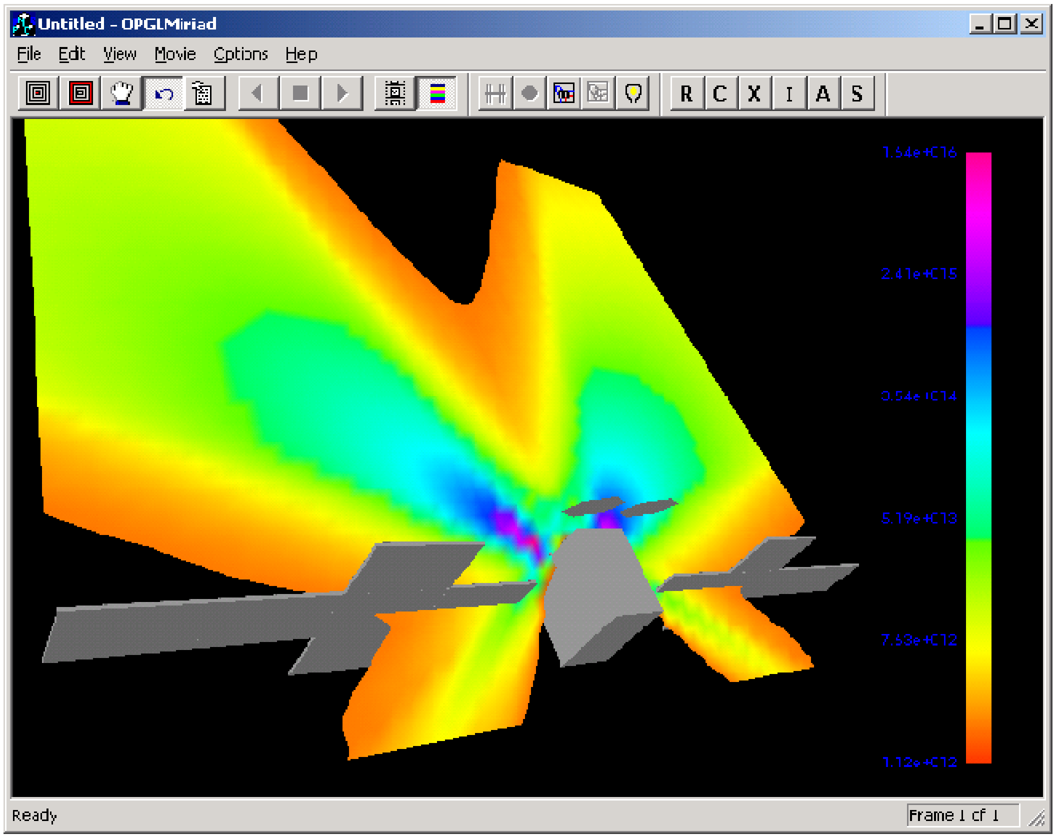

Figure 3. EWB ion densities calculated by interpolation into plume map and integrated with spacecraft geometry.

CAPABILITIES ADDED TO EWB

Surface Gridding

The EWB engineering tool is optimally designed for fairly rough spacecraft geometry definition, that is, surfaces with dimensions on the order of meters. Spacecraft definition is achieved by creating multiple “objects” or components out of simple 3-D geometric shapes, i.e., boxes, cylinders and cones. The creation of a typical spacecraft out of component objects with centimeter-size dimensions would be awkward for the user and make calculation time unwieldy. However, to obtain meaningful results, it is necessary to calculate thruster ion fluxes to surfaces at a higher resolution than that of the EWB geometry components. Therefore, under this effort, we added a capability to EWB to allow for gridding up component surfaces at a finer resolution. This resolution is defined by the user (eg., .2 m grid spacing on surfaces).

The gridding is achieved as follows: If the surface is indeed larger than the resolution desired, a rectangular grid is built in the surface's bounding box. Grid cells with all four points inside the surface are accepted, and grid cells with all four points outside are rejected. For the remaining surfaces, exterior nodes are moved to the boundary of the original polygon, forming new triangular and quadrilateral zones.

Special cases occur when one or both of the bounding box dimensions are smaller than the desired resolution. Also, some checks are made to correct failure modes that may occur for non-convex or otherwise pathological polygons.

Figure 4 shows an example of an EWB spacecraft model that has been gridded up at a .2-meter resolution.

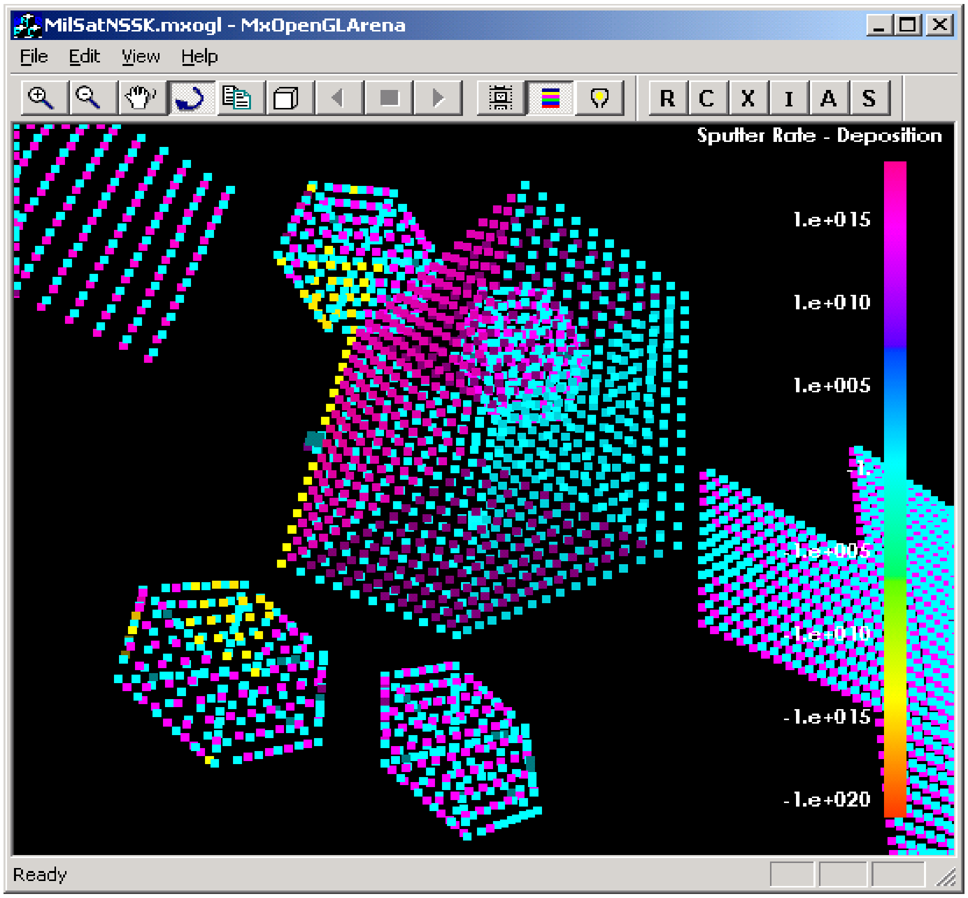

Figure 4. The spacecraft is defined using a combination of simple 3-D geometric objects. The object surfaces are then gridded up to a user-defined resolution for surface effects calculations.

3D Surface Effects Display

Existing capabilities in EWB allowed for viewing of surface effects by displaying the numerical value at component surface centroids only. When surfaces of several meters dimensions are gridded up to centimeter-size resolution, the numerical display of surface effects becomes awkward to interpret and unwieldy to display. Therefore, under this effort, we added a capability to display surfaces colored by effects values calculated at the grid points in a 3-D visualization tool (OpenGL). A variety of options in the display tool were developed, including showing the grid points only, a wire frame view, linear and log contouring, and Gouraud shading or discreet contour levels. Figure 5 illustrates some of these capabilities. All of the effects modeled here can be displayed using this visualizer.

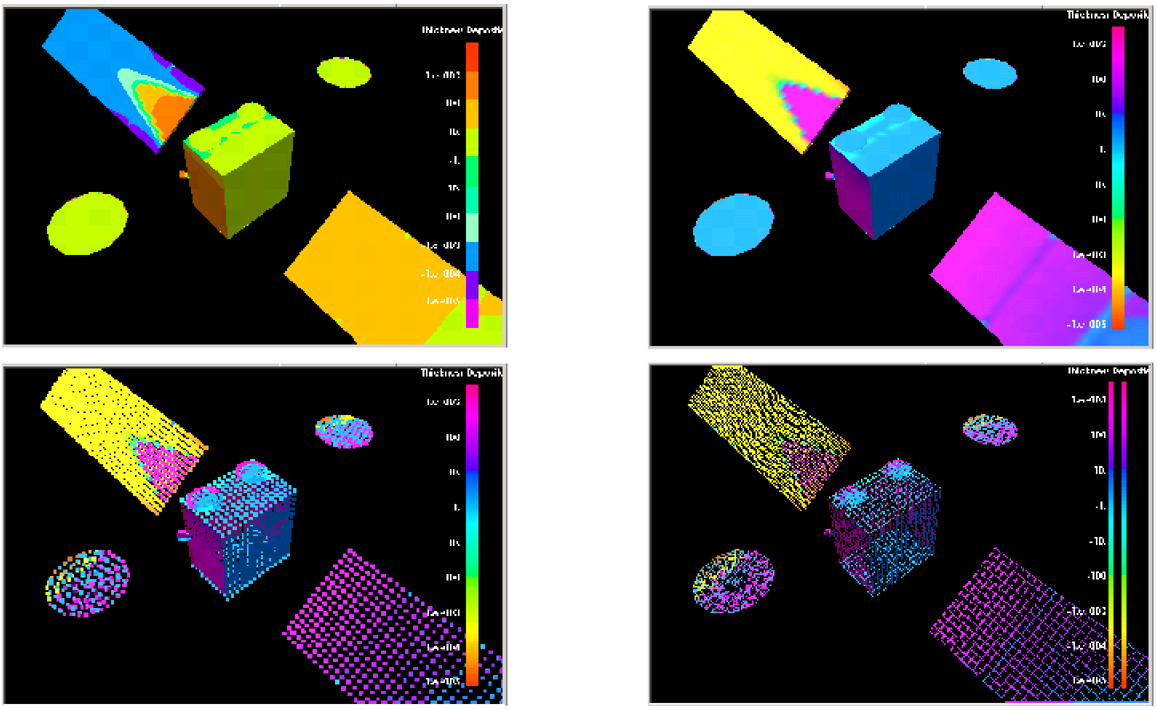

Figure 5. Three-dimensional surface effects display capabilities include grid points, wire-frame, gradual shading, and discreet contour levels.

MODELS ADDED TO EWB

Fluxes to Surfaces

The thruster ion flux at any point, “i” on a surface “j” due to plume component “k”is calculated as follows:

$$F_{ik} = \rho_{ik} \left| \vec{v}_{ik} \right| \cos(\theta_{ik})$$

$$\cos(\theta_{ik}) = \frac{\vec{n}_j \bullet \vec{v}_{ik}}{\left| n_j v_{ik} \right|}$$

where ρ_{ik} is the density at point “i” due to component “k”, v_{ik} is the ion velocity at point “i” of component “k”, and $\cos(\theta)$ is the cosine of the angle between the surface normal and the particle velocity vector. These component fluxes are maintained separately until their resulting effect on surface sputtering is summed at each surface grid point. Fluxes to points on surfaces include blocking of other spacecraft surfaces such that if a straight line between the point in question and the thruster orifice intercepts any other surface, the flux to that point is zero.

Sputtering of S/C Surfaces

The sputtering of a spacecraft surface “j” at a point “i” due to thruster plume impingement is calculated as follows:

$$R^{S}_{ij} = \Sigma_k Y_{ijk} F_{ik}$$

Where “k” is summed over the plume components, and Y_{ijk} is the sputter yield at point “i” for surface “j” and plume component “k”. The sputter yield of a surface depends on the surface material, the energy of the ions impacting that surface and the angle between the flux vector and the surface normal. The sputter yield model used is as follows:

$$Y_{ijk}(E_{ik}, \theta_{ijk}) = (a+bE_{ik})(1.00-0.72\,\theta_{ijk} +11.72\,\theta_{ijk}^{2} -3.13\,\theta_{ijk}^{3} -2.57\,\theta_{ijk}^{4})$$

The yield is given in atoms/ion. The coefficients for energy dependence are material specific, and the angular dependence is from Roussel et. al.[2] Figure 6 shows the sputter yield as a function of angle of impingement for 280 eV ions.

Figure 7 illustrates the sputtering rate calculated for a typical communications satellite and displayed in the new OpenGL surface effects viewer.

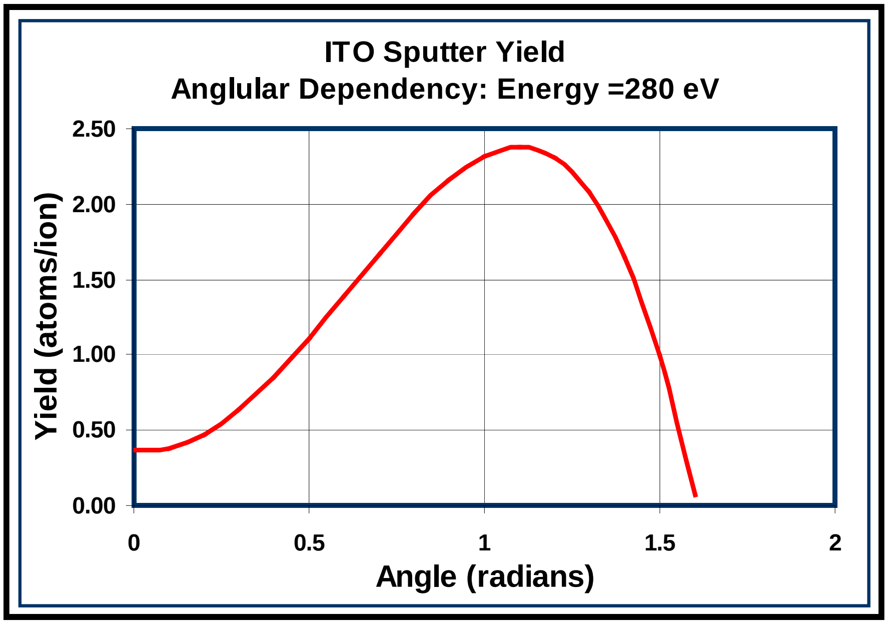

Figure 6. Sputter yield as a function of angle between surface normal and ion flux vector for 280eV ions.

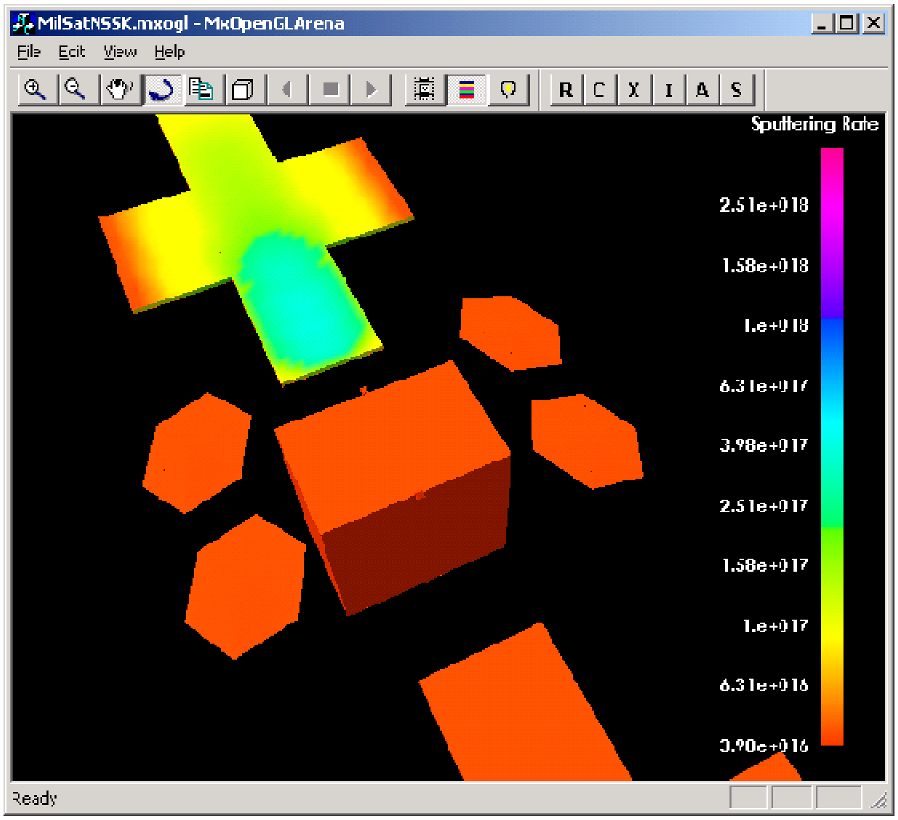

Figure 7. Surface sputtering rate on typical communication satellite.

Surface Erosion and Deposition

In addition to surface sputtering and resultant erosion, we calculate redeposition of surface sputtered particles onto other spacecraft surfaces. It should be noted that for the purposes of this calculation we do not differentiate between materials such that only a net erosion or deposition of materials is calculated. As a result, erosion of one material and redeposition of an equal amount of another is indistinguishable from no effect at all. A net erosion/deposition rate is calculated as follows. For each surface, the sputtering rates at all points on that surface are averaged to produce a source term located at the centroid of that surface. This is done for the purpose of calculation size and time. This source term is then used to calculate a deposition rate at each of the grid points as follows:

$$R^D_i=\Sigma_j R^S_j \cos(\theta)*\Omega_{ij}/2\pi$$

Where Ω_{ij} is the solid angle subtended by surface “j” at point “i”, and θ is the angle between the depositing surface normal and a ray from the sputtering surface centroid to the point “i”.

The net rate is then calculated at each surface grid point “i”:

$$R_i=R^D_i-R^S_i$$

If $R_i > 0$ it is a deposition rate, if $R_i < 0$, it is an erosion rate. This rate is then integrated over the mission duration to get a total number of particles per square meter deposited. The integration over mission duration is done by calculating the rate at random points in time over the mission, averaging, and multiplying by the mission duration. This allows us to take time-dependent changes in spacecraft geometry into consideration (such as solar array sun-pointing). Once we have the total particle deposition/erosion, we calculate the thickness or depth as follows:

$$T(\text{Å})=N(\#\ m^{-2})*MW(gm\ mole^{-1})*10^{8}(\text{Å}\ cm^{-1})*10^{-4}(m^{2}\ cm^{-2})/\rho(gm\ m^{-3})*6.02x10^{23}(\#\ mole^{-1})$$

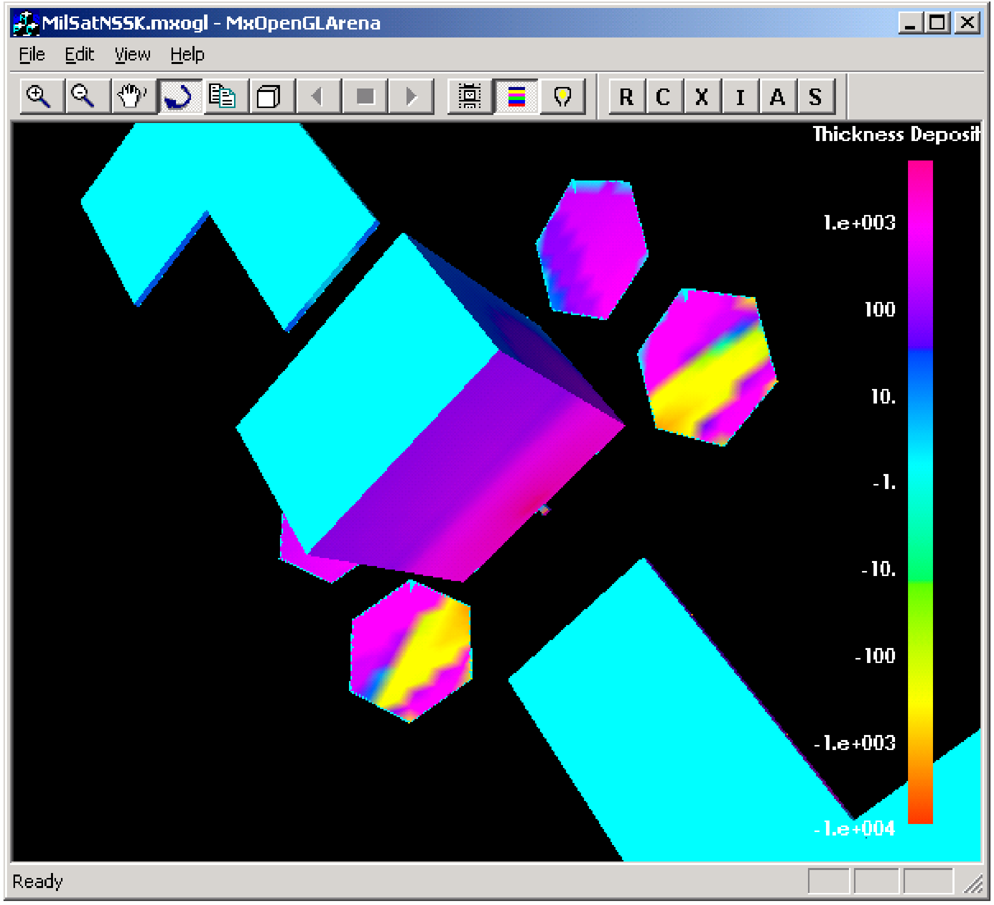

Figure 8. Sputtered erosion depth and redeposition thickness on typical communications satellite.

where N is the number of particles per square meter, MW is the molecule weight and ρ is the surface material density. The molecular weight and density are parameters in a material database and are changeable by the user. Thickness and depth are calculated and viewed in Angstroms. Fluxes, sputter rates and deposition rates are displayed in MKS units. Figure 8 shows deposition and erosion on antenna for a communications satellite, while Figure 9 illustrates the erosion due to sputtering on solar array surfaces.

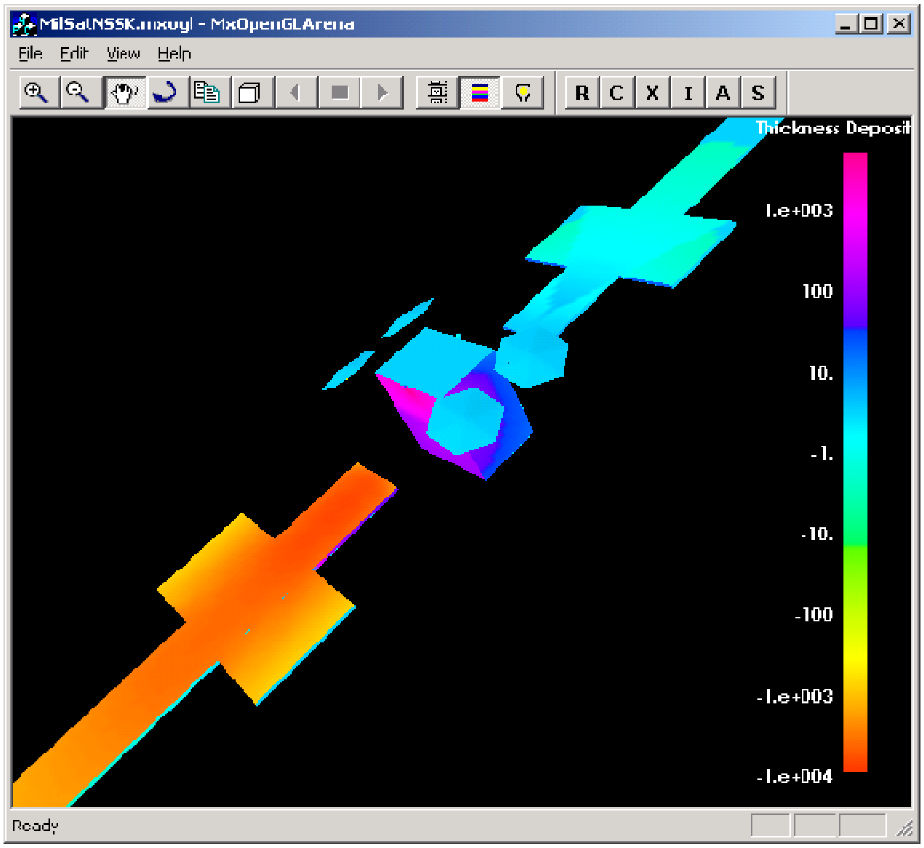

Figure 9. Erosion on solar array wing due to thruster plume on typical communications satellite.

Surface Heating

Heating of spacecraft surfaces due to thruster plume impact is calculated as follows:

$$H_i = \sum_k K_\perp F_{ik} \left(\frac{1}{2} m (v_{ik\perp})_i^2 \right) + K_\parallel F_{ik} \left(\frac{1}{2} m (v_{ik\parallel})_i^2 \right) + F_{ik} (e\phi_{ionize})$$

where F_{ik} is the flux at point “i” of plume component “k”, m is the thruster ion (xenon) mass, the v_{ik}*’s* are the perpendicular and parallel velocity components of the flux, K’s are perpendicular and parallel accommodation coefficients, e is the electron charge and ϕ_{ionize} is the ionization energy of xenon (12.13 eV). For the purpose of this calculation, we assume all particles are singly ionized. Figure 10 illustrates this surface heating model.

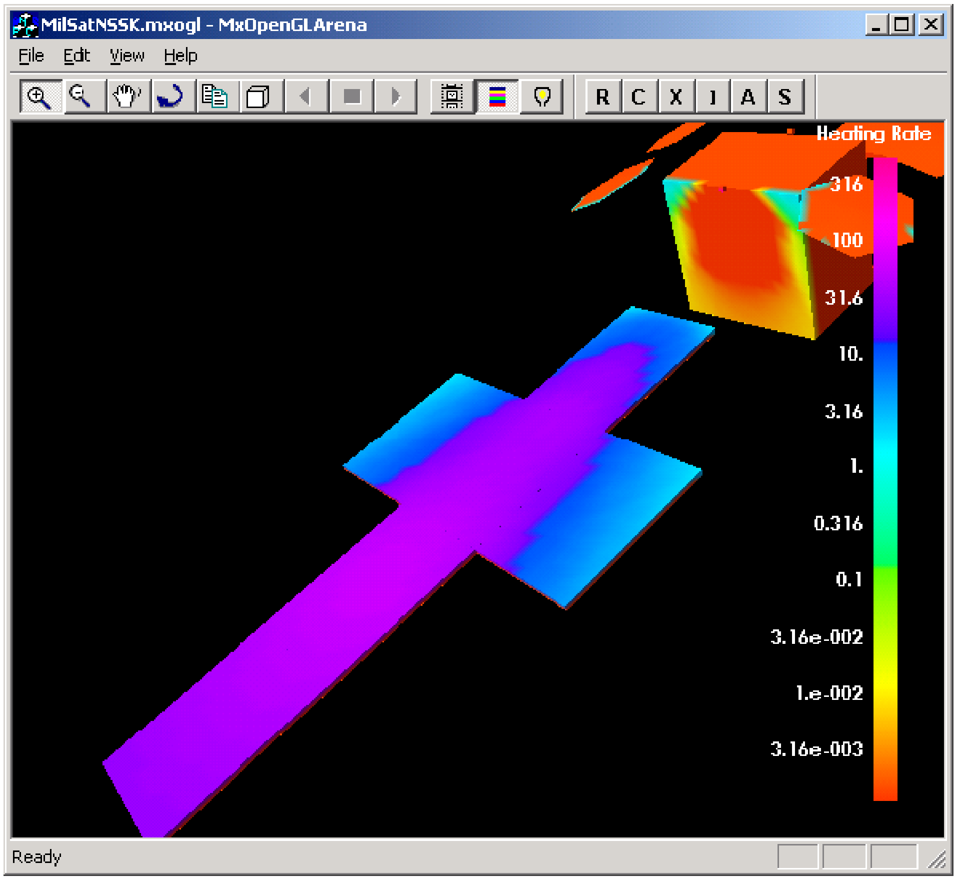

Figure 10. Surface heating due to thruster plume impingement and ionization.

Model Limitations

Model limitations for the integrated plume and surface effects in EWB include the following:

All surfaces are gridded to the same resolution.

As particles do not expand in straight lines from the thruster orifice, surface blocking by straight line to the thruster orifice may not always be appropriate.

There is no plume map outside of 30 meters from the thruster orifice. Additionally, the model should not be used to calculate phenomena very close to or inside the orifice (less than millimeters).

It is not presently possible to do two different timelines for two thrusters on one system. Additionally, integrated values are calculated assuming random distribution in time of firings, i.e., thrusters may be fired more often for one orientation of the solar arrays than for others. This is not modeled.

Individual material types for sputtered and deposited materials are not modeled. Additionally, all deposited materials are assumed to stick indefinitely. There are no “sticking” coefficients, or removal of deposited material by any means.

Sputtered material is assumed to come off uniformly distributed in space.

Presently there is one angular dependency model for sputtering yield for all materials. Energy dependence is linear with coefficients specifiable by the user for each material.

CONCLUSION

This effort has resulted in the production of a valuable tool for spacecraft designers and engineer. We have integrated a thruster plume map into EWB, developed some enhanced calculational and display capabilities, and developed and integrated effects models. The tool can be used with any plume map matching the input format, and allows for integration of a thruster plume map with spacecraft geometry. Spacecraft surface effects modeled include sputtering and redeposition of sputtered materials on spacecraft surfaces, with surface shielding and time-dependent geometry. Additionally, surface heating is calculated and integration of surface properties effects models will be a simple process (placeholders are already in existence). Additional work is being currently planned to address some of the model limitations and create additional capabilities.

REFERENCES

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[1] EWB User's Reference Manual, V. Davis, B. Gardner, T. Rankin, July 31, 1997.

[2] *Numerical Simulation of Induced Environment, Sputtering and Contamination of Satellite due to Electric Propulsion*, J.F. Roussel, J. Bernard, Y Garnier, ONERA-CERT/DERTS, Proc. Second European Spacecraft Propulsion Conference, 27-29 May, 1997.