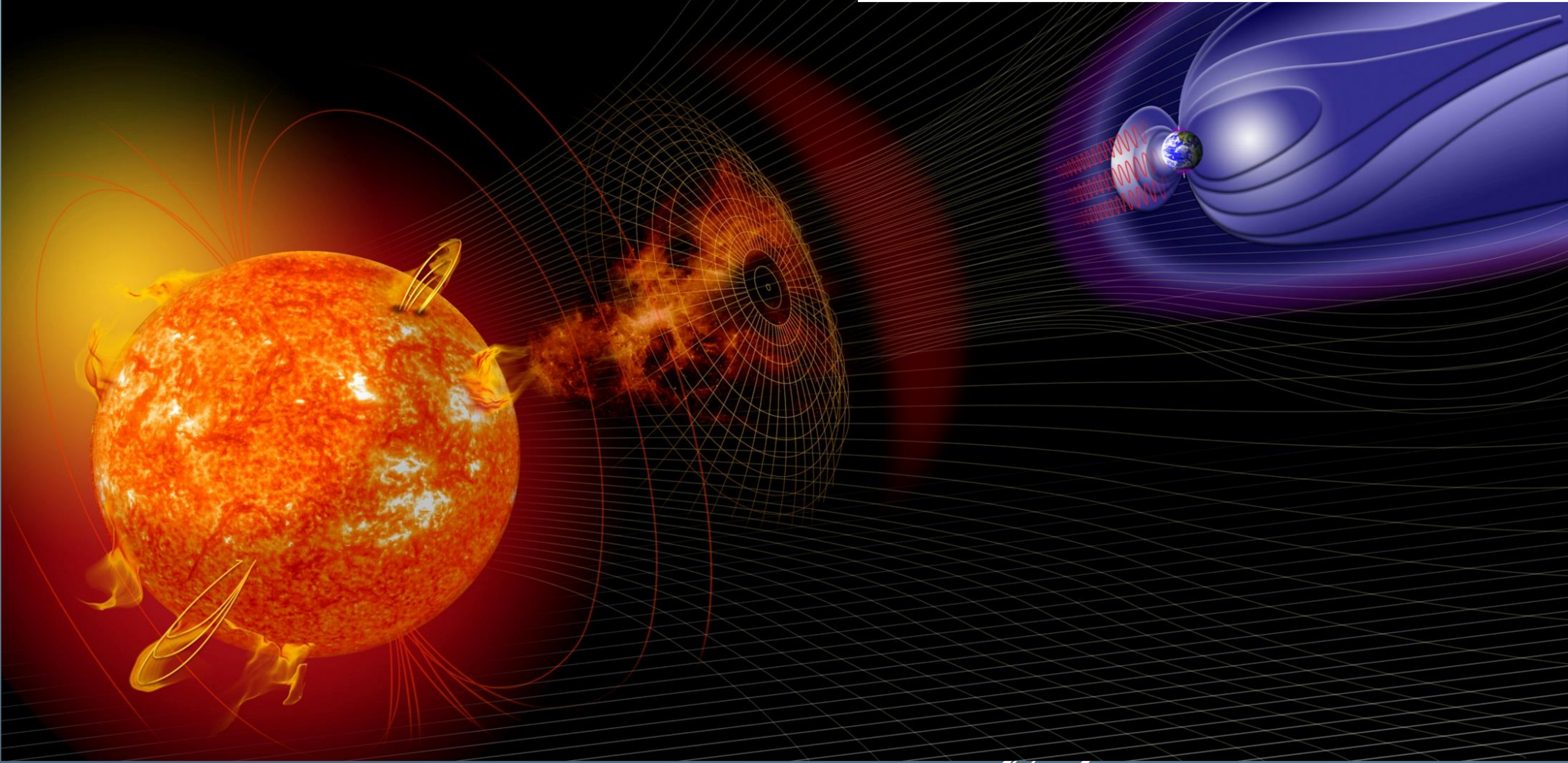

iSat Surface Charging and Thruster Plume Interactions Analysis

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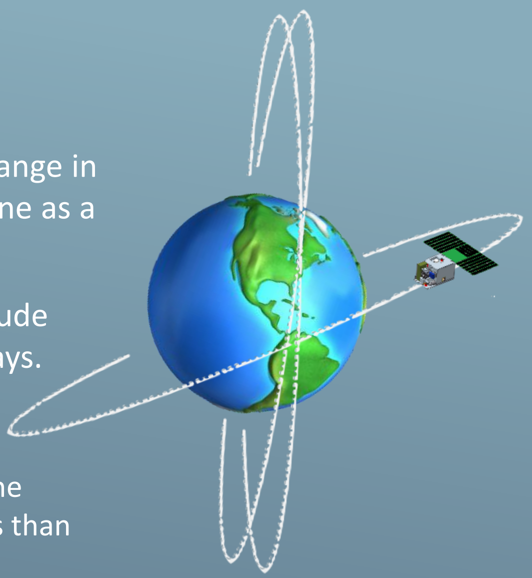
Emily Willis, NASA

Joseph Minow, NASA

Outline

- Program Overview
- Surface Charging Analysis
- Thruster Plume Spacecraft Interactions
- Plume analysis
- Summary

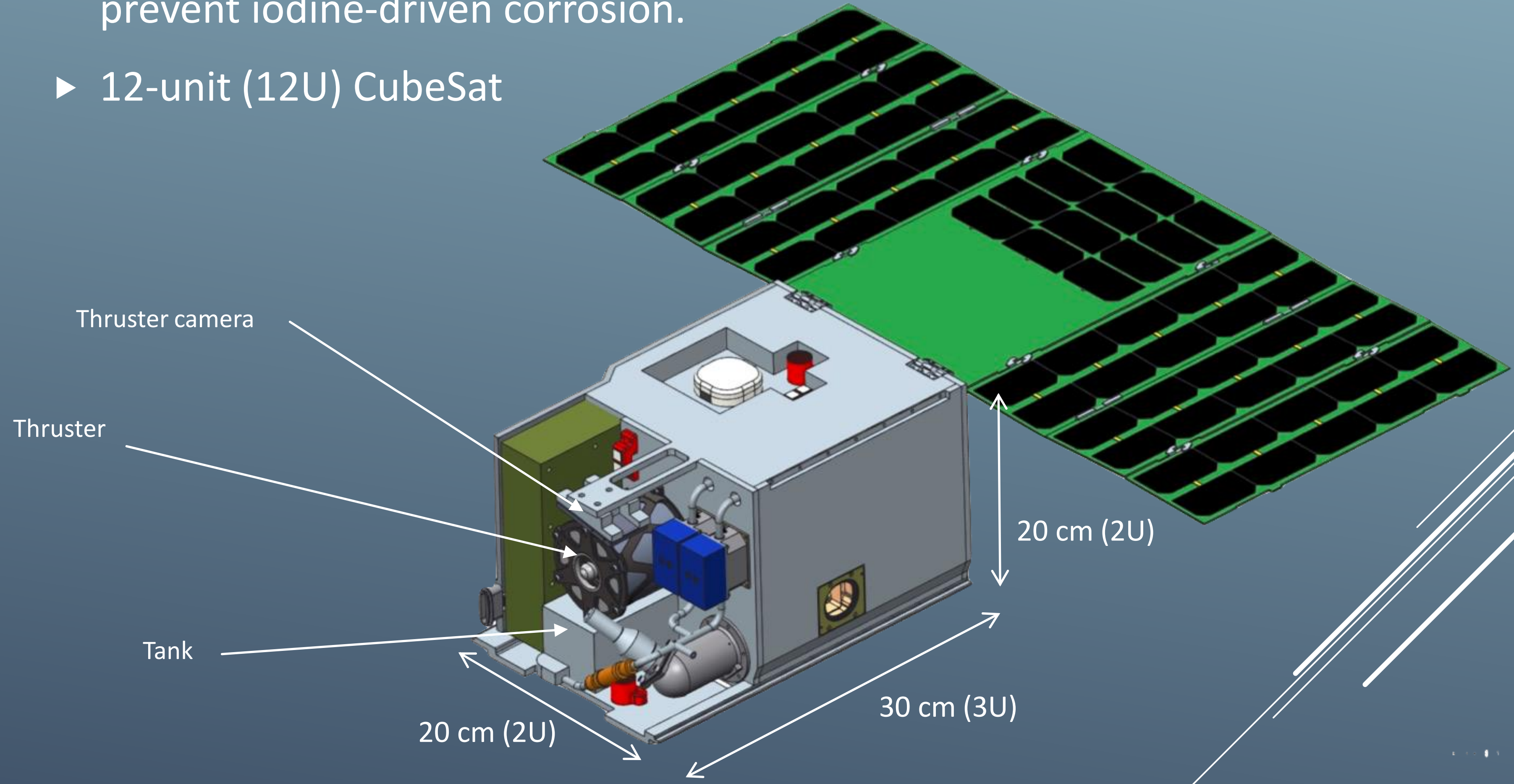
iSAT program overview



- The Iodine Satellite (iSat) spacecraft will be the first CubeSat to demonstrate high change in velocity from a primary propulsion system by using Hall thruster technology and iodine as a propellant.
- The mission will demonstrate CubeSat maneuverability, including plane change, altitude change and change perigee altitude to ensure atmospheric reentry in less than 90 days.
- Hall thruster technology is a type of electric propulsion.
  - Electric propulsion uses electricity, e.g., from solar panels, to ionize and accelerate the propellant. Electric propulsion can accelerate propellant to 10 times higher velocities than traditional chemical propulsion systems, which significantly increases fuel efficiency.
  - It allows for high Isp and continuous thrust
- iSat's iodine propulsion system consists of a 200 watt (W) Hall thruster, a cathode, a tank to store solid iodine, a power processing unit (PPU) and the feed system to supply the iodine.
- The cathode technology is planned to enable heaterless cathode conditioning, significantly increasing total system efficiency.
- The use of iodine as a propellant will allow it to be stored as an unpressurized solid on the ground and before flight operations. During operations, the tank is heated to vaporize the propellant. Iodine vapor is routed through custom flow control valves to control mass flow to the thruster and cathode assembly. The thruster then ionizes the vapor and accelerates it via magnetic and electrostatic fields, resulting in high specific impulse, characteristic of a highly efficient propulsion system.
- The mission is planned for launch in fall 2017.

iSat Model

- Spacecraft frame will be constructed from aluminum with a finish to prevent iodine-driven corrosion.
- 12-unit (12U) CubeSat



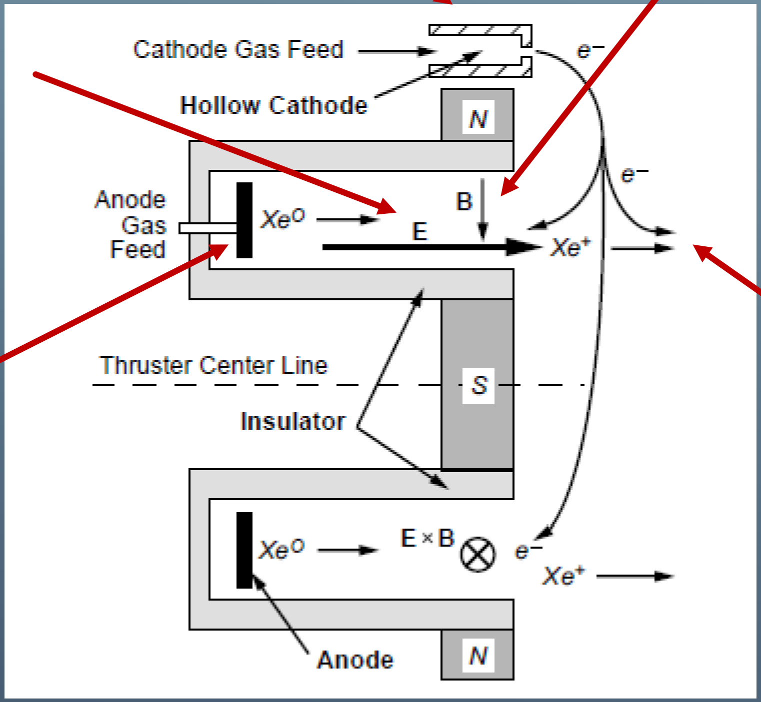
L. Neergaard Parker, 14th SCTC, 2016

Operations of a Typical HET

Hollow cathode source provides the electrons for the discharge and neutralizes the ion beam.

Axial E field created by anode and hollow-cathode plasma produced outside of the thruster channel

Radial B field prevents electrons from streaming directly to the anode, instead spiraling along the B field lines in the E x B azimuthal direction (Hall Current) and diffuse to the anode ionizing the propellant.



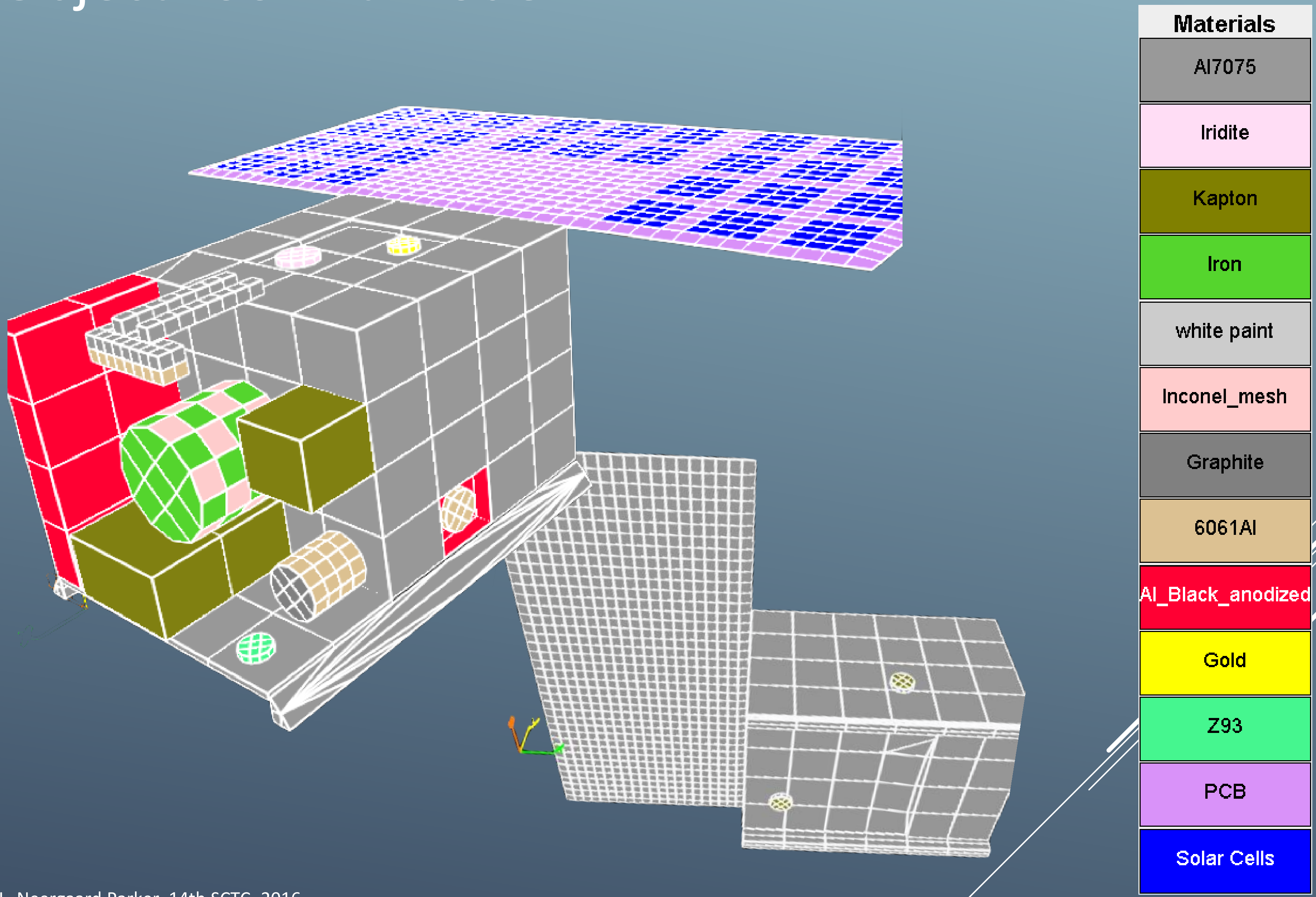
Electrically biased metallic anode at the base where propellant gas is injected into the thruster.

The ionized gas is accelerated by the E field to form the thrust beam.

Nascap-2k Surface Charging Analysis

- Nascap-2k auroral surface charging analysis performed for iSAT
  - Auroral charging in polar orbits is the worst case charging environment for the candidate iSAT orbits
- Environments
  - Ambient plasma density and temperature: $N_e = 6 \times 10^5\ m^{-3}$, $T_e = 0.2$ eV
  - Energetic particles modeled as a Fontheim distribution with accelerated auroral electron beam at ~10 keV (drives charging)
  - Particle species included in analysis: electrons, 90% H^+, 10% O^+
- Model
  - iSAT structure modeled in Object Tool Kit for incorporating into Nascap-2k analysis
  - iSAT dimensions, surface materials, and grounding configurations provided by iSAT program
  - High fidelity model for Nascap-2k, lower fidelity model also developed for EPIC

Object Tool Kit Model



Material Properties

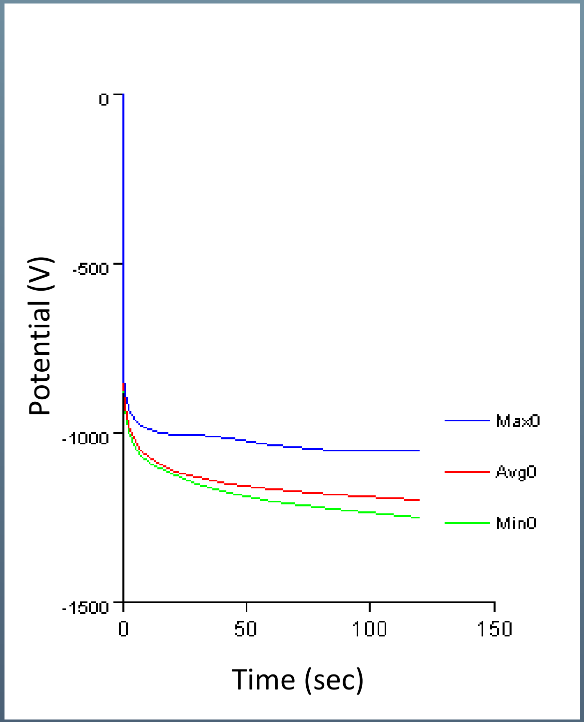
Material	Dielectric Constant	Thickness	Bbulk Conductivity 1/Ω•m	Photoemission Current Density	Surface Resistivity
Solar Cells	3.8	1.25E-04	1.00E-13	2.00E-05	1.00E+19
PCB (kapton)	3.5	1.27E-04	1.00E-15	2.00E-05	1.00E+16
Kapton	3.5	1.27E-04	1.00E-15	2.00E-05	1.00E+16
White paint (Al)	1	1.00E-03	-1	4.00E-05	-1
Al_black_anodized – aluminum	1	1.00E-03	-1	4.00E-05	-1
7075 T6 Aluminum – Al default	1	1.00E-03	-1	4.00E-05	-1
Gold	1	1.00E-03	-1	2.90E-05	-1
Irridite (Al)	1	1.00E-03	-1	4.00E-05	-1
Iron (some gold)	3.5	1.27E-04	-1	2.90E-05	-1
Inconel mesh (nickel and cromium??)	3.5	1.27E-04	-1	2.90E-05	-1
Graphite	1	1.00E-03	-1	7.20E-06	-1
6061 Al	3.5	1.27E-04	-1	4.00E-05	-1
Z93 (Gold)	3.5	1.27E-04	-1	2.90E-05	-1

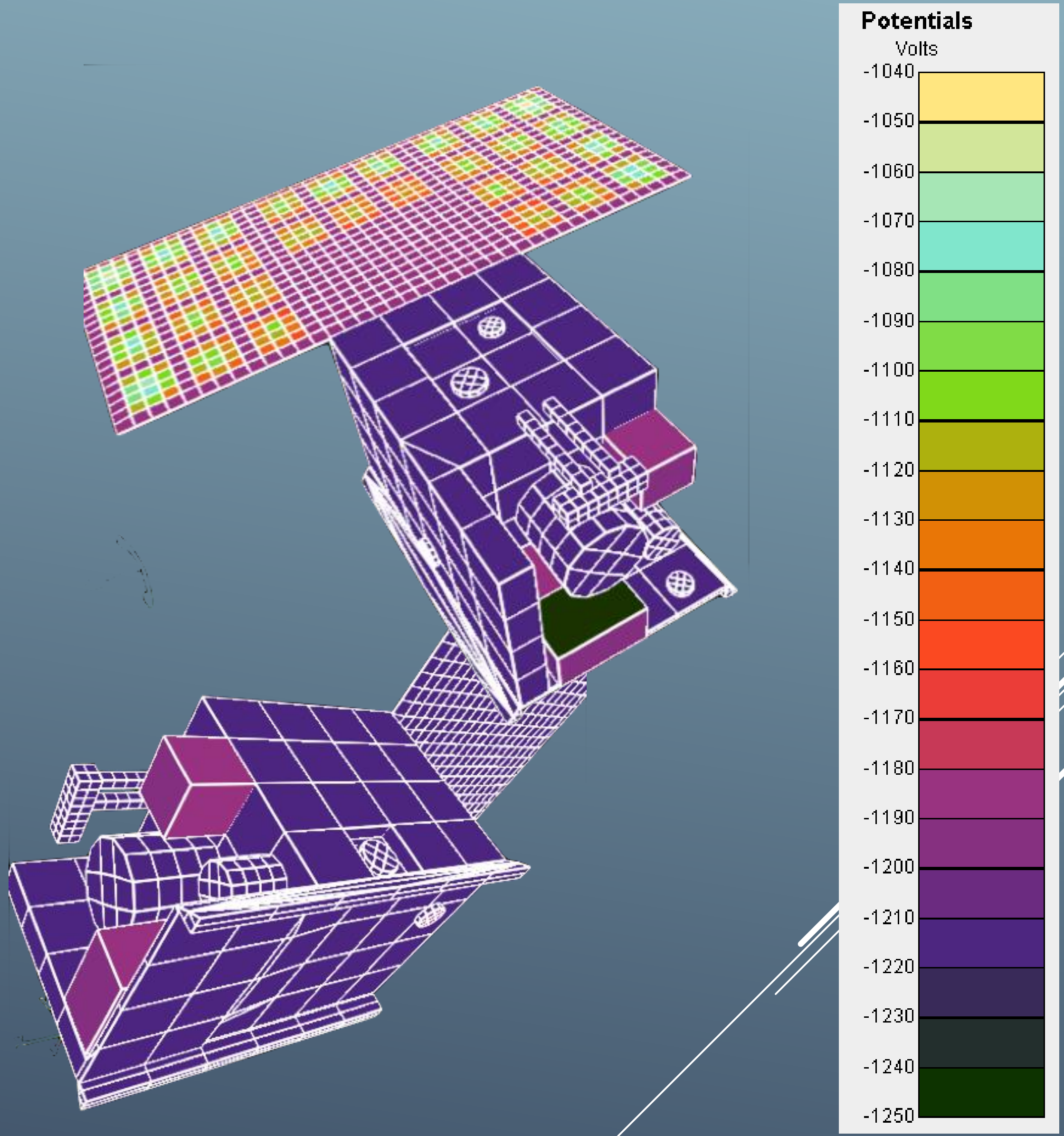
Auroral Charging Environment

- Velocity = 7000 km/s
- Environment in the iSat Natural Space Environment Specifications is a typical polar orbit plasma environment. Used a more extreme environment:
  - Due to model requirements to avoid numerical noise and
  - To give worst case results
- Particle species using electrons (100%), hydrogen ions (91%), and oxygen ions (9%).
- Sunlight in the y-direction when applicable.
- Xenon added for Plume model analysis.

	Ambient	Power Law	Maxwellian	Gaussian
n (m^{-3})	6.0e5			
e^- current (A/m^2)	7.2e-9	5.0e-8	5.0e-7	2.0e-6
Energy1 (keV)	0.2	0.050	25	25
Energy2 (keV)		1.6e3		
Width (keV)				5

Surface Charging (eclipse)





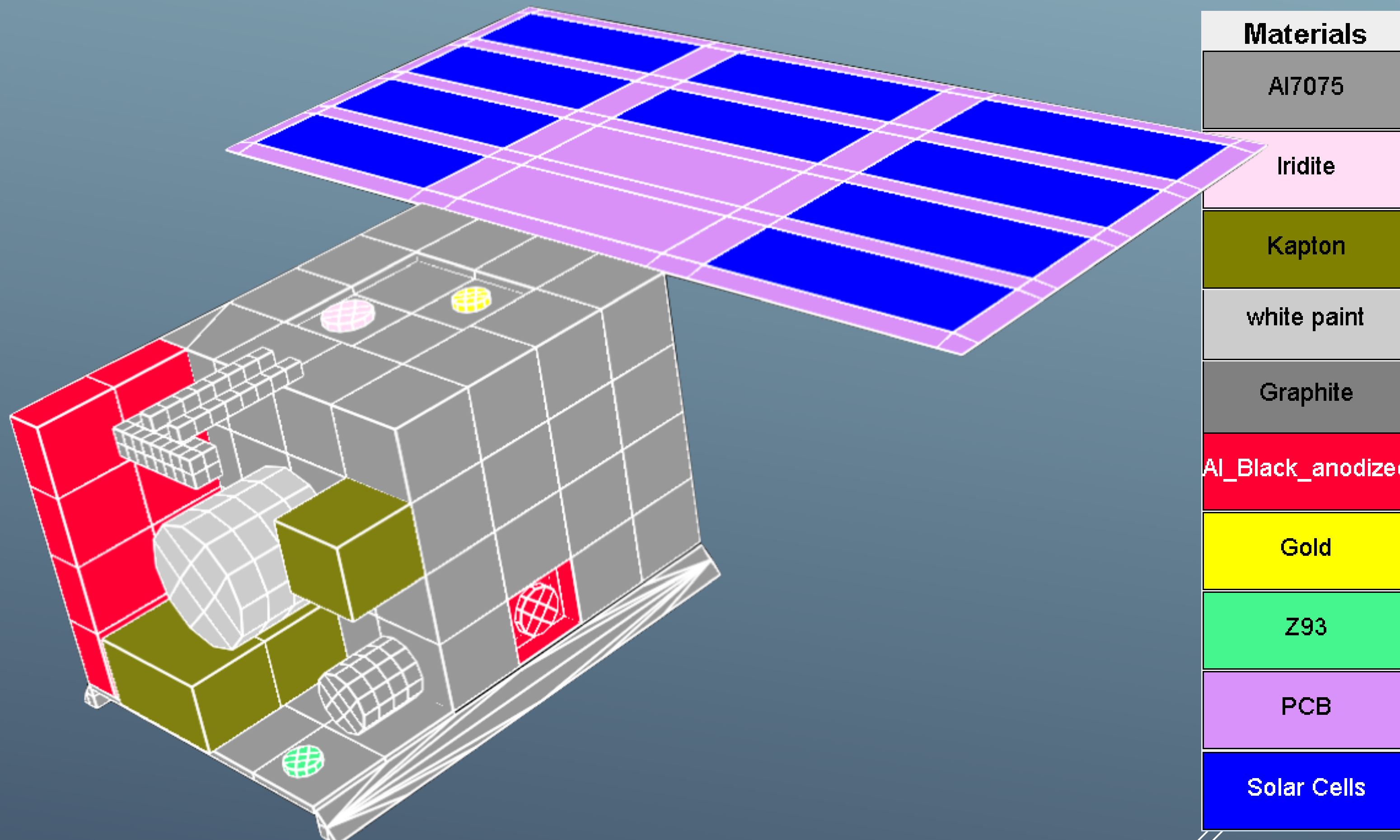
L. Neergaard Parker, 14th SCTC, 2016

Summary of Charging Results

Potentials (volts)	Surface charging in sunlight (volts)	Surface charging in darkness (volts)	With plume in sunlight (volts)	With plume in darkness (volts)	Kapton on back of solar arrays, sunlit case (volts)	Kapton on back of solar arrays, in eclipse (volts)
Min/max	-3000 to -300	-1050 to -1250	-300 to -2950	-1040 to -1240	-550 to -2235	-1040 to -1225
Solar arrays (top)	-365 to -300	-1050 to -1150	-300 to -365	-1040 to -1150	-555 to -605	-1040 to -1140
Solar arrays (bottom)	-400	-1200	-400	-1200	-835	-1180
Thruster	-400	-1200	-400	-1200	-600	-1200
Structure	-400	-1200	-400	-1200	-600	-1200
Tank	-3000 to -800	-1200 to -1250	-740 to -2950	-1200 to -1240	-815 to -2235	-1190 to -1220
Cathode mount	-900 to -570		-570 to -930	~ -1185	-685 to -935	~ -1180

EPIC ANALYSIS

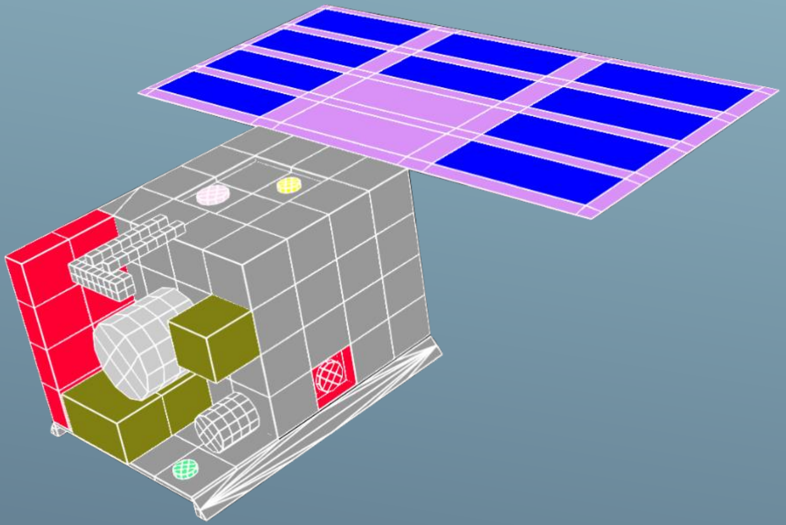
Simplified iSAT Model for EPIC



Model Limitations

- EPIC:
  - Number of model elements limits spacecraft fidelity.
  - Inability to change the size of the thruster in the spacecraft model, limiting visibility of spacecraft surfaces for smaller satellites. It should not affect results.
  - Thruster “cone” model can only be one material.
  - Some simulation inputs have built-in parameters for Xenon.
    - Scattering
    - Boundary condition simulation (not used for this)
  - PlumeTool does not export neutral flux, this must be user defined.
  - Only 3 flux fractions allowed and only for monatomic gas.
  - Does not allow for variable plume temperature. Typical variations are from 12eV to 2eV.
  - Surface heating limited to incident heat flux due to ion impact.
- iSAT:
  - Unknown material parameters for Solar Cells and PCB.
  - Unknown plume electron temperature and propellant utilization.

Plume Spacecraft Interaction Effects



- Spacecraft Model:
  - Simplified model due to limitations of EPIC
    - Aluminum
    - Solar Cells
    - PCB
- Erosion/Deposition of Sputtered Materials
  - EPIC only calculated deposition of materials sputtered from the spacecraft, it does not calculate deposition of Iodine.
  - Net amount of material sputtered or deposited at the surface over the duration of the mission. The rate of change is determine by the difference between the deposition and erosion rates
  - Sputtering Yield (atoms/ion) depends on the ion incident angle, the energy of the ion, the masses of the ion and target atoms, and the surface binding energy of atoms in the target.
  - Calculated using the "Yamamura-Tawara" model. A linear model is also available.

Inputs for Plume Model

Status	Description	Value	Source
	Inner radius of the accelerating channel (cm)	0.75	measure
	Outer radius of the accelerating channel (cm)	2.05	measure
	Largest radial dimension of the engine housing	4.6	measure
	Neutralizer distance from the axis of symmetry (cm)	4.64	CAD
	Neutralizer height (cm). 10.6 cm from plate.	3.7	CAD
	Atomic mass of propellant particle (I2 is 253.8) amu	126.9	Szabo et al
	Propellant flow rate injected through the anode (mg/sec)	0.82	Polzin
	Speed of propellant neutrals at the thruster exit(m/s). Assume Thermal Speed at 350C. Sqrt(2KT/π*m).	114	Polzin
	Neutralizer mass flow rate (mg/sec) (typically 1/12 of Fa)	0.07	Polzin
	Thrust(mN)	12.1	Polzin
	Propellant utilization: ratio of ion flow rate to anode flow rate	0.9	default
	Single, double, and triple ion flux fractions	.935 (I2+ and I+), .049, .016	Szabo et al
	Plume electron temperature	2eV	Szabo email
	Neutralizer effective temperature	703.15	D. Calvert
	Reference electron density (m-3)	1.00E+15	default
	Artificial Damping Coefficient	1	default
	Max Radial Velocity (2-1 axial to radial at thruster exit) (m/s)	8198	Polzin
	Charge exchange cross section areas ($Å^2$)	59.2, 25, 10	First Number - Hause, Prince, and Bermish Paper, Others are Xenon default.

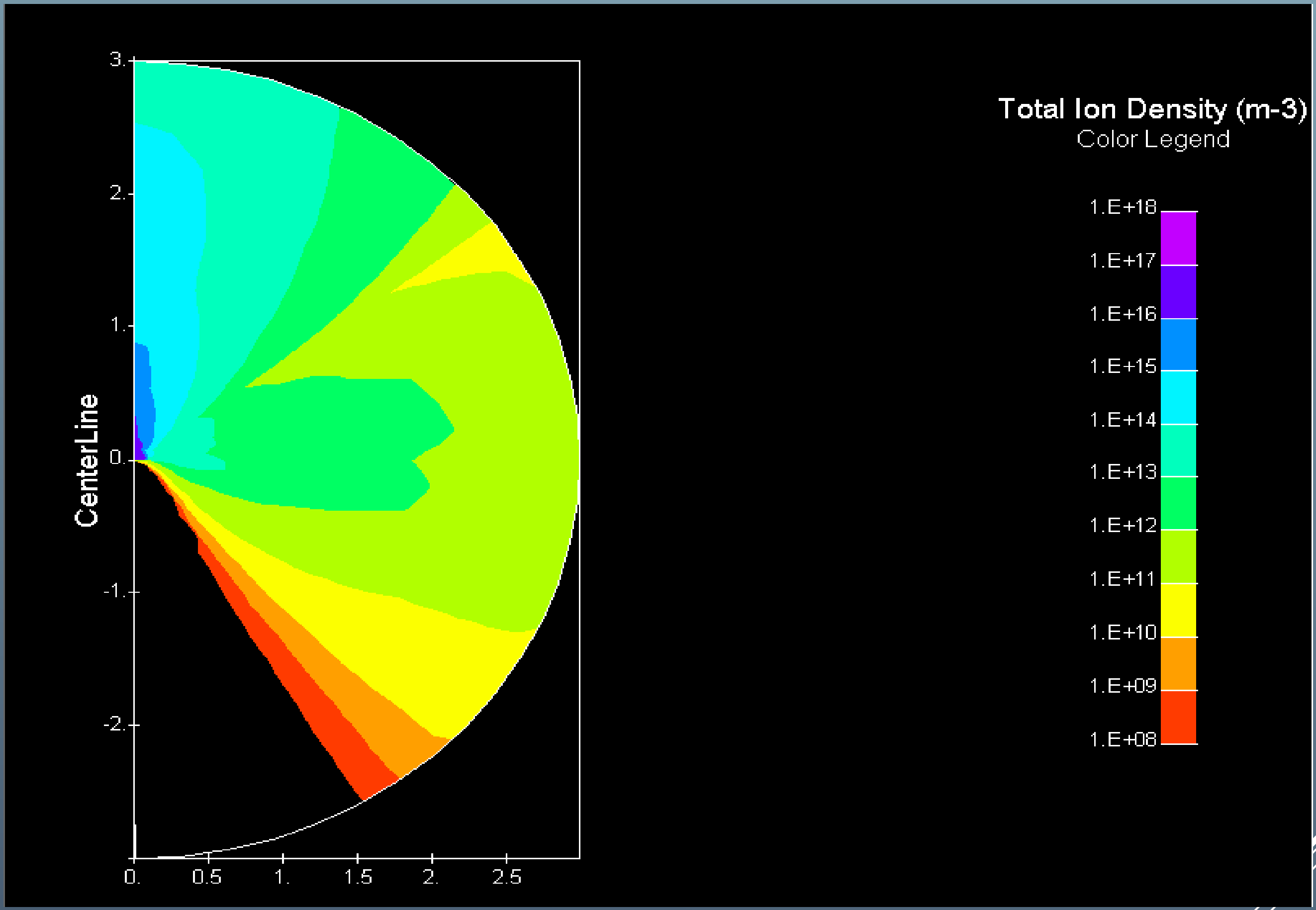
Value obtained by measurement or from iSAT project personnel.

Not exact, but the best we can do with this model.

An estimate, more accurate results could be obtained with more accurate inputs

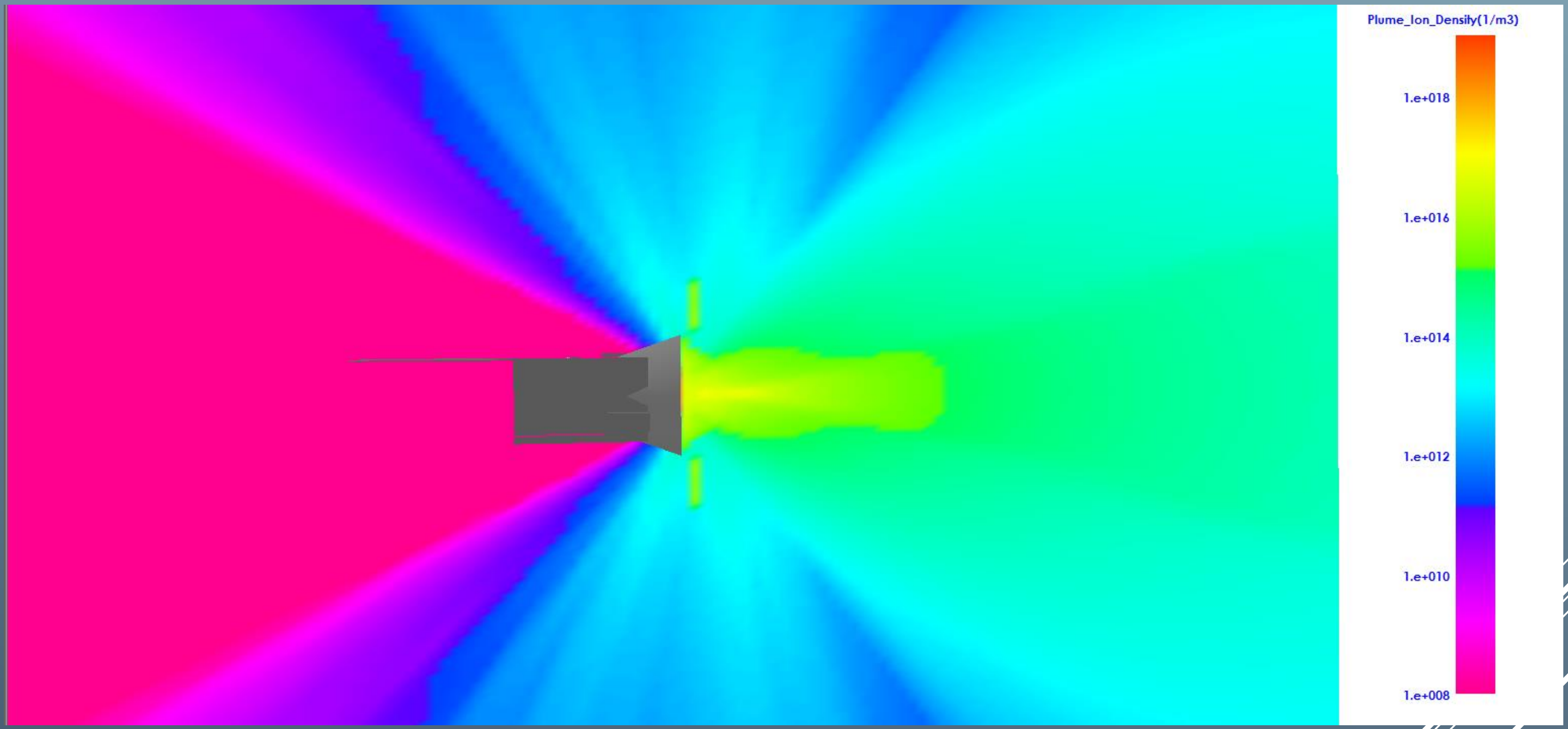
Total Ion Density

Includes Scattering and Charge Exchange



3 x 3 meter area

iSAT model with Thruster Plume



Thruster PlumeTool Model

- Initial Neutral Gas Flow:
  - Thruster geometry, thruster operating parameters, and performance
- Main Ion Beam Expansion:
  - Temperature of neutralizer electrons, reference electron density, ion flux fractions, max radial velocity
- Charge Exchange (CEX) Ions:
  - Interaction of main beam with neutrals generates low energy ions around the spacecraft
  - Rate of charge exchange ion production calculated from neutral density, beam ion density, CEX cross section area, beam velocity
  - PIC algorithm calculates potential from beam and charge exchange ions and iterates until the density and potential are self-consistent.
- Scattered Ions:
  - Interaction of main beam with neutrals generates high energy ions at large angles (greater than 45 degrees)
  - Differential cross section calculated based on interaction potentials between Xe+ and Xe.
- Results
  - Ion Beam consisting of main beam ions +CEX ions + scattered ions exported to a map for use in EPIC
    - Calculated for a specified area around the thruster, at radial distances larger than this, the plasma flux varies inversely with the square of the distance from the thruster.
  - Neutral Beam: PlumeTool <u>does not</u> calculate and export a neutral plume map. If a neutral plume is desired it must be generated separately by the user for use in EPIC.

Inputs for Erosion/Deposition

	Density (g/cm^3)	Molecular Mass (amu)	Atomic Number	YT Model Inputs			
				Us (surface binding energy)	Q	W	s
Aluminum	2.7	27	13	3.39	1	2.17	2.5
Solar Cells (EPIC Default)	2.6	50	10	4	1	1.4	2.5
PCB	1.85	50	10	4	1	1.4	2.5
Thruster	2.1	38.4	7.6	4	1	1.4	2.5
Al7075 (Aluminum)	2.7	27	13	3.39	1	2.17	2.5
Iridite (Aluminum)	2.7	27	13	3.39	1	2.17	2.5
Kapton	1.42	45	14	4	1	1.4	2.5
White Paint (Aluminum)	2.7	27	13	3.39	1	2.17	2.5
Al Black Anodized (Aluminum)	2.7	27	13	3.39	1	2.17	2.5
Gold	19.3	197	79	3.81	1.08	1.64	2.8
Z-93 (EPIC Default)	2	45	14	4	1	1.4	2.5

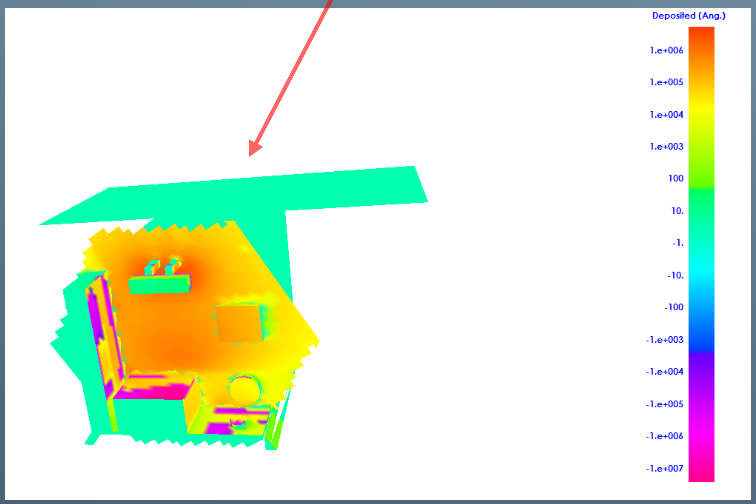
- The primary source of deposited materials comes from sputtering of thruster materials and other materials very near the thruster. One thruster material can be modeled, current values are estimates based on a BN SiO_2 material as a placeholder. Deposition of neutral thruster propellant is not modeled.
- PCB material parameters, other than density, are unknown. They are currently set to the same value as solar cells.
- Material Properties for Iridite, White Paint, and Black Anodized Aluminum are set to the values of Aluminum as a placeholder.
- YT inputs for Solar Cells/PCB/Thruster are set to a default as recommended by Yamamura, Y., and Tawara, H. , “Energy Dependence of Ion-Induced Sputtering Yields from Monatomic Solids at Normal Incidence,” Atomic Data and Nuclear Data Tables Vol. 62, 1996, pp. 149-253.

Deposition of Sputtered Materials

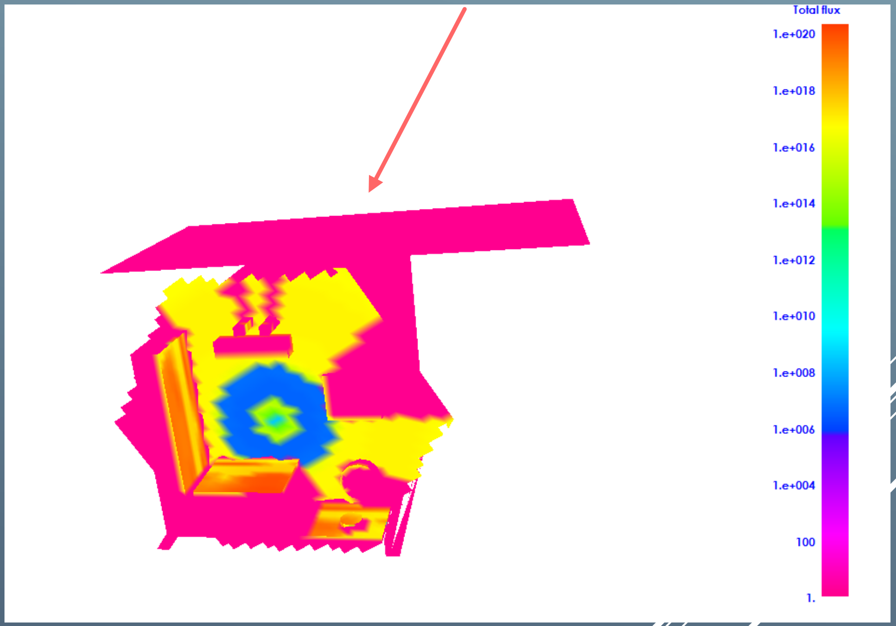
Deposition of Sputtered Materials

Ion Flux to Spacecraft Surfaces

Zero Deposition/Erosion

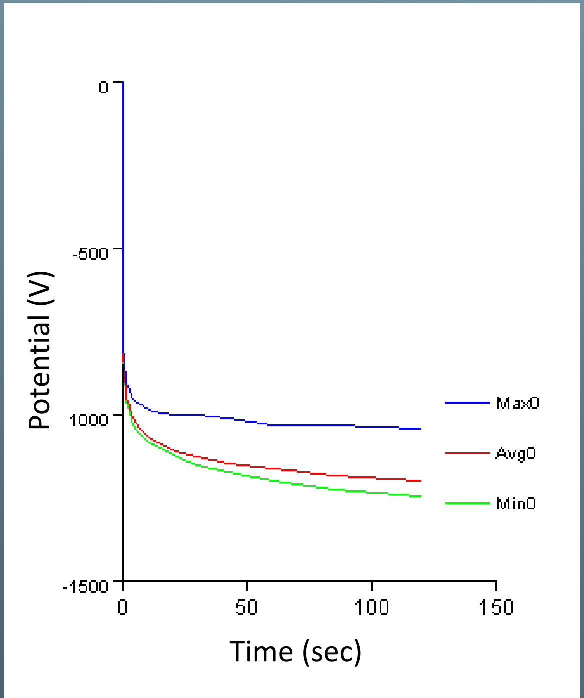


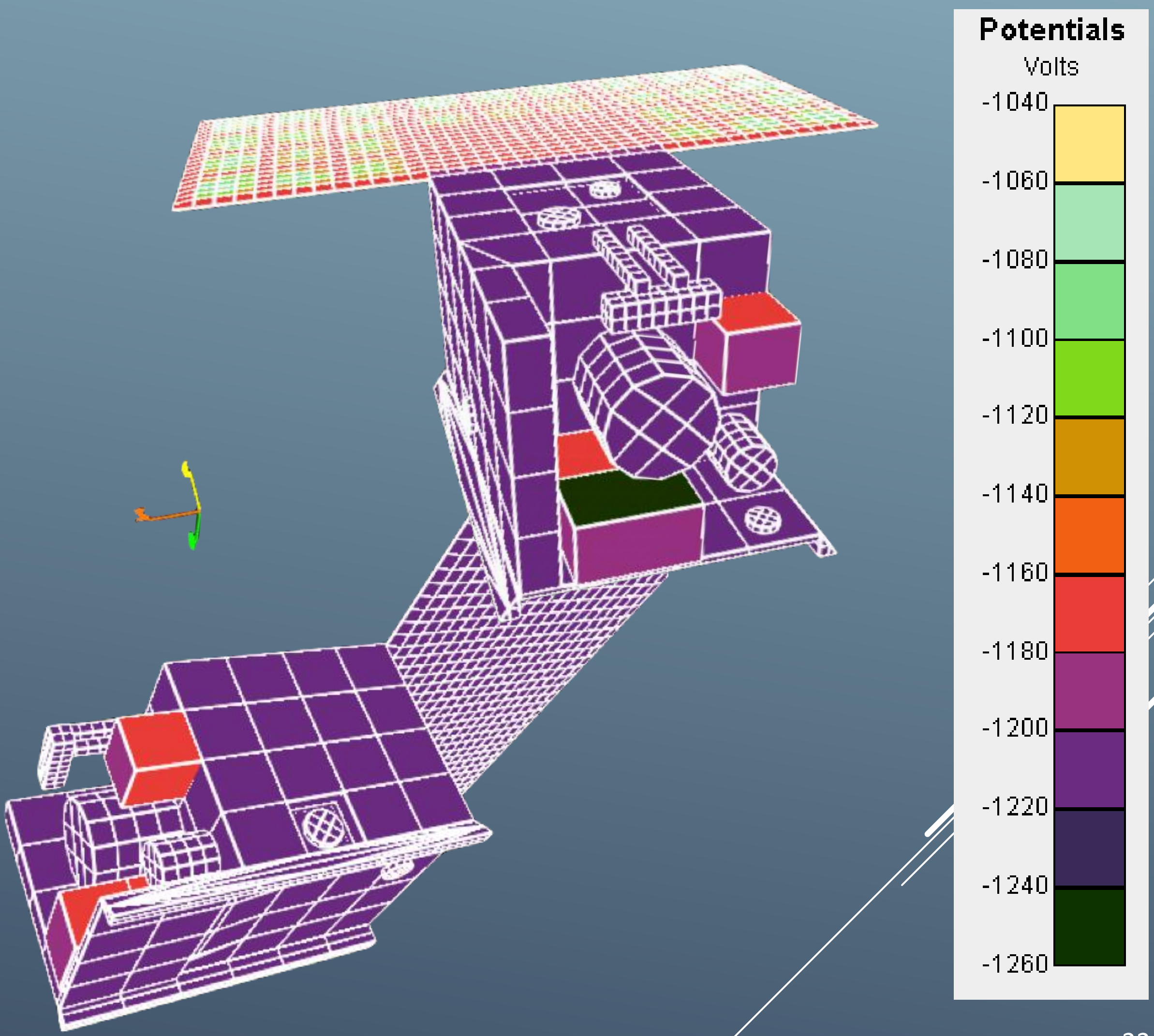
Zero Flux



Total for 3.5 days of thruster operation

Surface charging with plume (eclipse)





Summary of Results

- Surface charging analysis using Polar environment showed relatively high charging levels with ~200 V differential charging in eclipse conditions.
- Thruster Plume Tool Results
  - Ion Beam consisting of main beam ions +CEX ions + scattered ions exported to a map for use in EPIC
    - Calculated for a specified area around the thruster, at radial distances larger than this, the plasma flux varies inversely with the square of the distance from the thruster.
  - Neutral Beam: PlumeTool <u>does not</u> calculate and export a neutral plume map. If a neutral plume is desired it must be generated separately by the user for use in EPIC.
- Surface charging with Plume results – no increased levels of charging over the auroral environment
- When orbit is confirmed, Program may ask to redo the charging analysis with the appropriate environment.

iSat is scheduled to launch in 2017.