Spacecraft Plasma Environmental Interaction

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OUTLINE

- Space Research Lab, NRIAG
- What is the space system?
- Overview of Space Environment and its Effects?
- Space Plasma.
- Spacecraft Charging and Discharging Phnomena

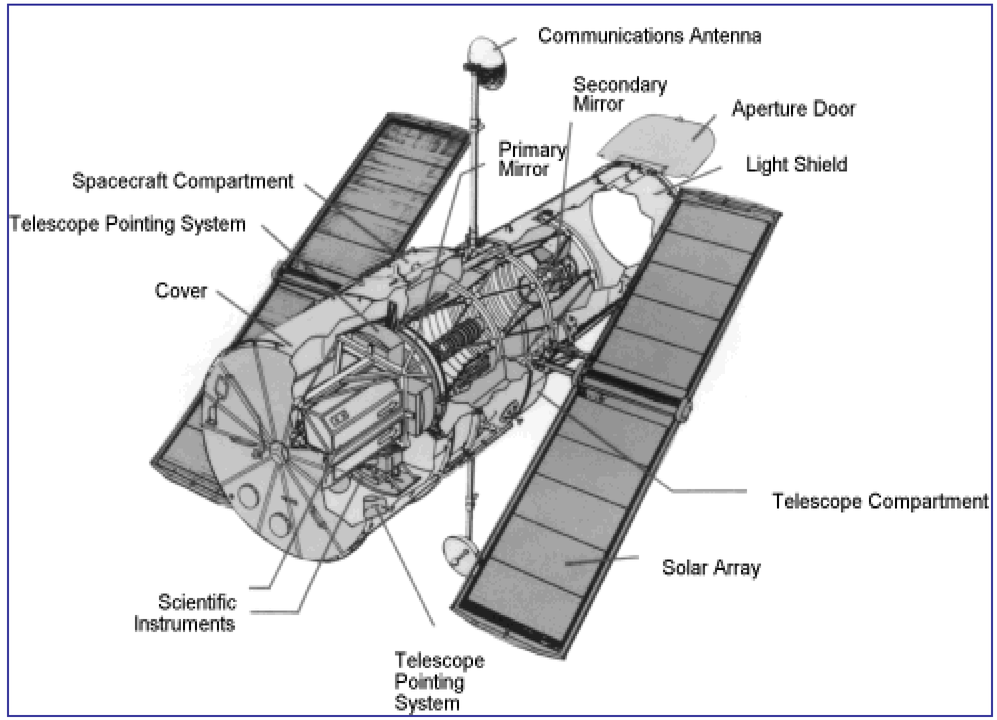
What is a Space System?

- **Ground**
  - Spaceflight Operations
  - Payload Operations (Can be separate)
  - Payload Data Processing (Hubble)
- **Space**
  - Spacecraft
  - Supporting Craft (TDRSS, Progress)
- **Launch**
  - Launch Vehicle Integration
  - Launch Operations

What Does a Spacecraft "Look" Like?

- **Spacecraft "appearance"** is almost always **<u>function</u> over <u>form</u>**
- **Physical constraints:**
  - Launch Vehicle
    - Payload Fairing
    - Loads
  - Power Required
  - Vehicle dynamics
    - Mission Trajectory
    - Pointing

HST



Spacecraft Description

- **Spacecraft have two main parts:**
  - Mission Payload
  - Spacecraft Bus
- **Mission Payload**
  - A subsystem of the spacecraft that performs the actual mission (communications, remote sensing etc.)
  - All hardware, software, tele-communications of payload data and/or telemetry and command
  - There can be secondary payloads
- **Spacecraft Bus**
- Hardware & software designed to support the Mission Payload
  - Provides
    - Power
    - Temperature control
    - Structural support
    - Guidance, Navigation
  - May provide for telemetry and command control for the payload as well as the vehicle bus

Mars Global Surveyor

Spacecraft Bus Subsystems

- **Electronic Power System (EPS)**
- **Position and Attitude Control:**
  - Attitude Control System (ACS)
  - Guidance, Navigation and Control (GNC)
  - Propulsion (OK, we'll call it "Prop")
- **Command and Data Handling (C&DH):**
  - Data Handling (Mission Data)
  - Telemetry, Tracking and Command System (TT&C)
- **Thermal Control System (TCS)**
- **Structural Subsystem**

Ground

- **Ground Activities:**
  - Spacecraft Flight Operations
  - Payload Operations
  - Payload Data Processing
  - Payload Data Dissemination

Can Be Merged

- **Facilitated By:**
  - Real-Time Processing
  - Payload Dissemination Infrastructure
  - Powerful Payload Processing Facilities
  - Mission Simulations

Launch

- **Selection:**
  - Enough “throw weight”
  - Enough “cube” (volume)
  - Acceptable ride
  - Good record…
- **Integration:**
  - Launch loads imparted to spacecraft
  - Mechanical/Electrical Integration
  - Understand launch “flow” and count

Space System Development

1. All systems development start with a "mission need" (**the Why**)
2. Then **<u>mission requirements</u>** are developed to meet this need (**the What**) often along with a **<u>concept of operations</u>**

   Note: Often we make the mistake of putting "the How" in the Mission Requirement
3. From 1 and 2 above develop **<u>derived requirements</u>** for (**the How**):
   - Space
     - Mission orbit
     - Payload Types (Communications, remote sensing, data relay)
     - Spacecraft Design
   - Ground
     - Facilities and locations
     - Computers/Software
     - Personnel/Training
   - Launch segments

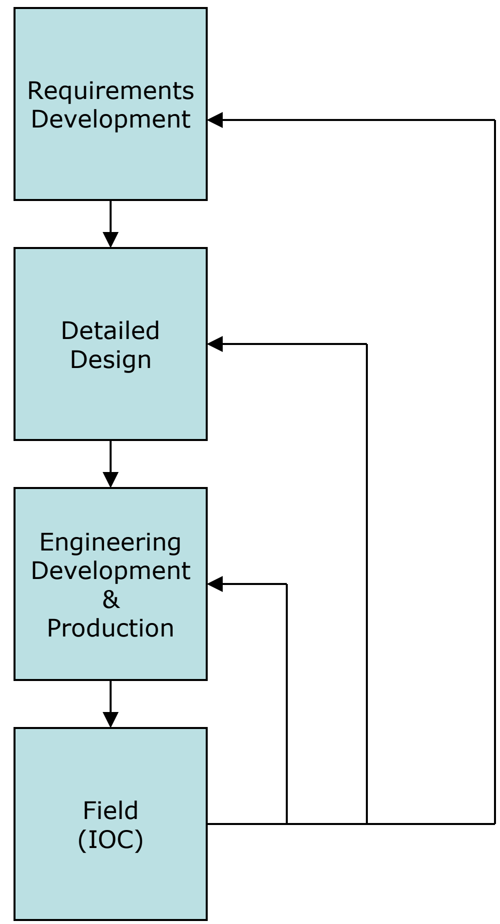
- Note: The requirements generation process is often <u>iterative</u> and involves <u>compromises</u>

Spacecraft Development Process

- **Some types:**
  - Waterfall (sequential)
  - Spiral (iterative)

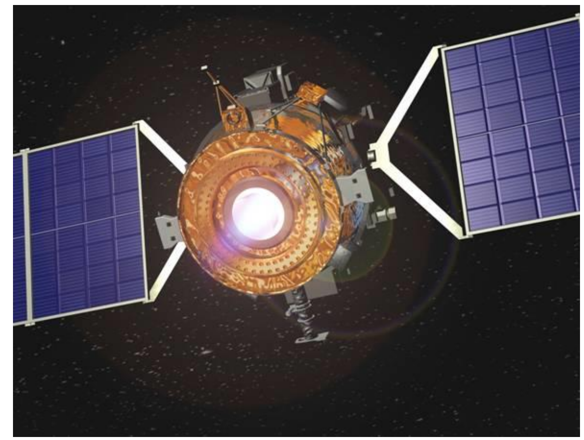
- **Basic Sequence:**
  1. Conceptual design
  2. Detailed design
  3. Develop detailed engineering models
  4. Start production
  5. Field system
  6. Maintain until decommissioned

- **DoD mandates** integrated, iterative product development process



Systems Engineering

- **A logical process for system development**
- ***Functional & physical decomposition*** *of system into logical parts*
- **Involves development of system requirements**:
  - System Analysis
  - Requirements Development
  - Interface Requirements
- **Requirements Validation**
  - Test & Demonstration
  - Simulation
  - Analysis
- ***Physical/functional*** configuration inspection
- **Integration & Test** Planning
- **"Cradle to Grave"** lifecycle planning
  - Treaty provisions and DoD regulations require disposal of satellites at the end of life.



Deep Space 1

Spacecraft Integration and Test

- Methodical process for test of spacecraft to validate requirements at all levels

- Sequence:
  1. Perform **component or unit** level tests
  2. Integrate components/units into **subsystems**
  3. Perform subsystem tests
  4. Integrate subsystems into **spacecraft**
  5. Perform **spacecraft level test**
  6. Integrate spacecraft into **system**
  7. Perform system test when practical

System Integration and Test

NOAA-N Prime, 6 Sep 03

- **Types**:
  - Functional testing
    - Do subsystems work together?
    - "Fit" check payload fairing, adapter
  - Environmental testing
    - Plasma, Atomic oxygen, Outgassing, Radiation,Thermal vacuum, shock and vibration testing
  - Combined functional and environmental testing
    - Usually spacecraft level thermal vacuum involved integrated functional testing
  - Final System demo: Do all segments work together, mainly ground and space
- **Payload or system characterization**
  - Performance can be altered by the space environment
  - Often performed in thermal vacuum chamber
- **Can Use a combination of "hardware in loop" and simulation:**
  - Ground Testing
  - Systems like propulsion and attitude control cannot be operated safely on the ground
  - May use "stimulators" for sensors like sun & earth sensor, or star tracker.

Got to the site below and play the movies if internet connection available:
http://www.boeing.com/defense-space/space/bss/hsc_pressreleases/photogallery/uhf_f11/uhf11_video/uhf11_movies.html

Summary:

- **Functions:**
  - Mechanical (form and fit)
  - Electrical/Electronic (power up to operational test)

- **Process**:
  - Starts at component level (e.g. transmitter, power supply…)
  - Continues at subsystem level (e.g. electronic power system, attitude control system…)
  - Ends with end-to-end test of entire system

- **Spacecraft Challenge:**
  - Effectively test spacecraft on the ground so it works in space!

Design Verification and Qualification Testing

- **Design Verification**
  - Validate design precepts and models
  - Examine system limitations
  - Build & Test, Build & Test…

- **Qualification:**
  - Determine system suitability for mission
  - Provides tool for customer to measure success of the enterprise
  - Allows time for fixes to meet requirements – may involve warranty period

DoD Test Process

- **Developmental Testing:**
  - Design Verification
  - Qualification
  - Acceptance Testing
- **Operational Testing:**
  - Operational Assessments (OA's)
  - Phased Operational Testing (OT)
  - Mandated by law to protect YOU!

From: COMOPTEVFOR's Web Page
http://www.cotf.navy.mil/

In 1971, however, OPTEVFOR was designated the Navy's sole independent agency for operational test and evaluation. This move was in response to Congressional and Secretary of Defense initiatives aimed at improving the defense material acquisition process.

Launch Flow

- **Pack and Ship (Spacecraft & Launcher)**
  - Dry run spacecraft moves, lifts etc.
  - Transportation loads can be driving cases for spacecraft structure
- **Establish launch operations**
  - Admin and work spaces for launch team
- **Test to insure no damage during shipping**
  - Perform limited subsystem and spacecraft tests
- **Establish communications with all players (launch base, groundstation)**
  - Perform rehearsals
  - Multiple data and voice networks must be established
  - Support spacecraft (TDRSS) must be in place

Review

- Discussed the Segments of a space system: Ground, Space and Launch
- Introduced major subsystems of typical spacecraft
- Introduced the concept of systems engineering
- Discussed Integration and Test of Spacecraft

Orbits

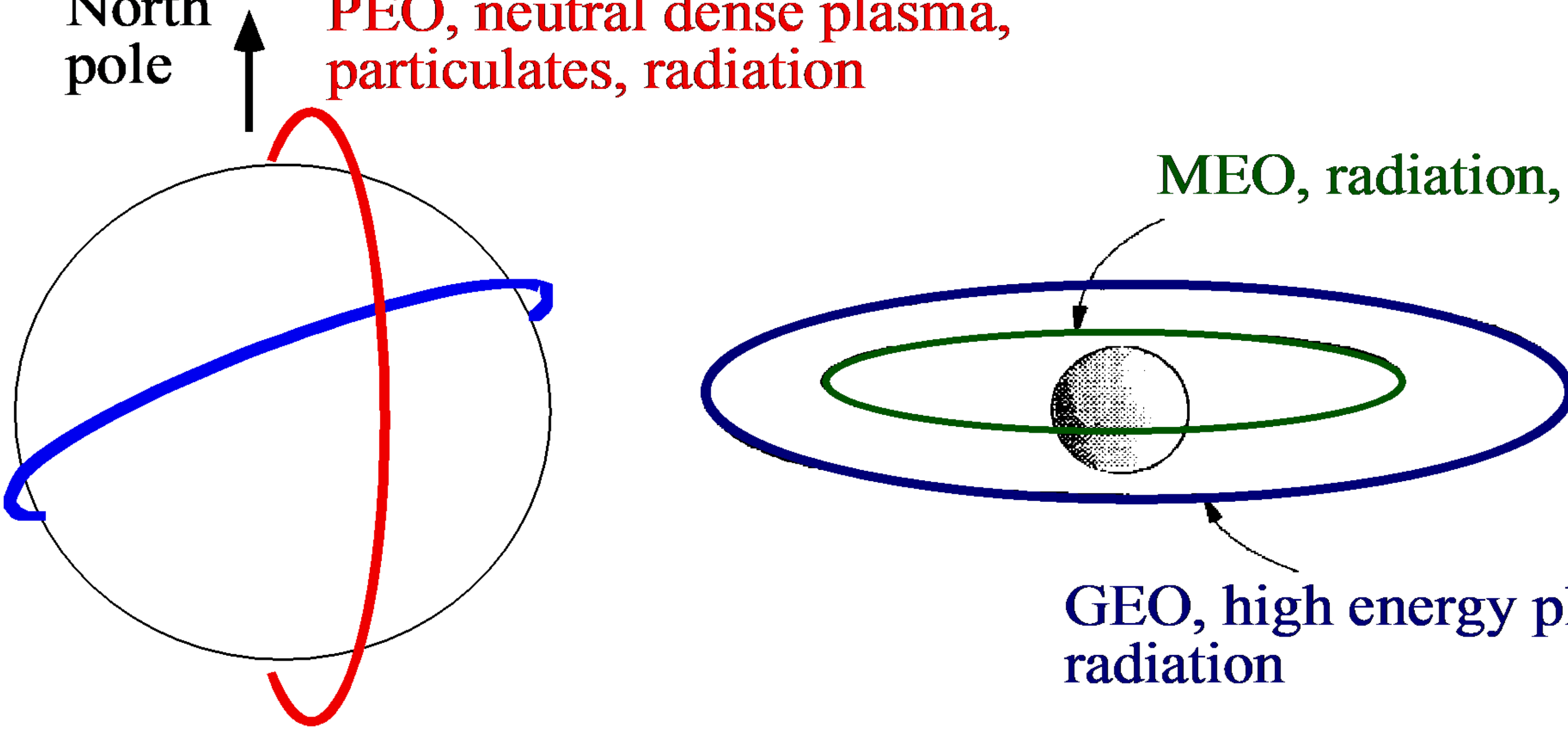
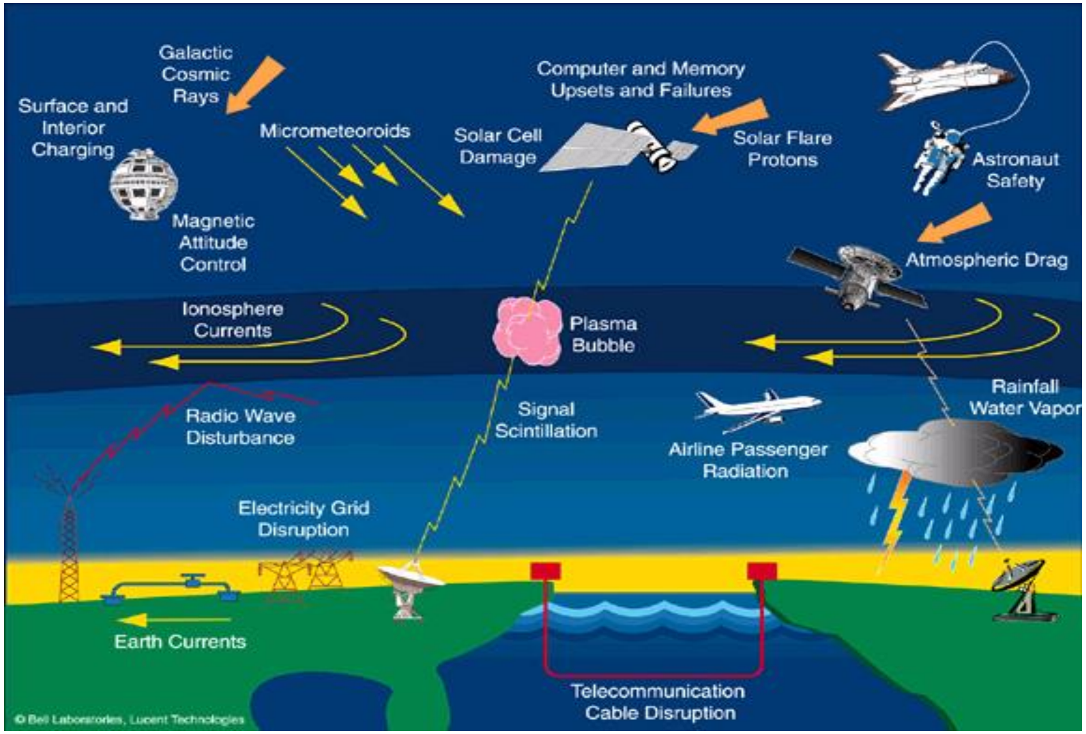
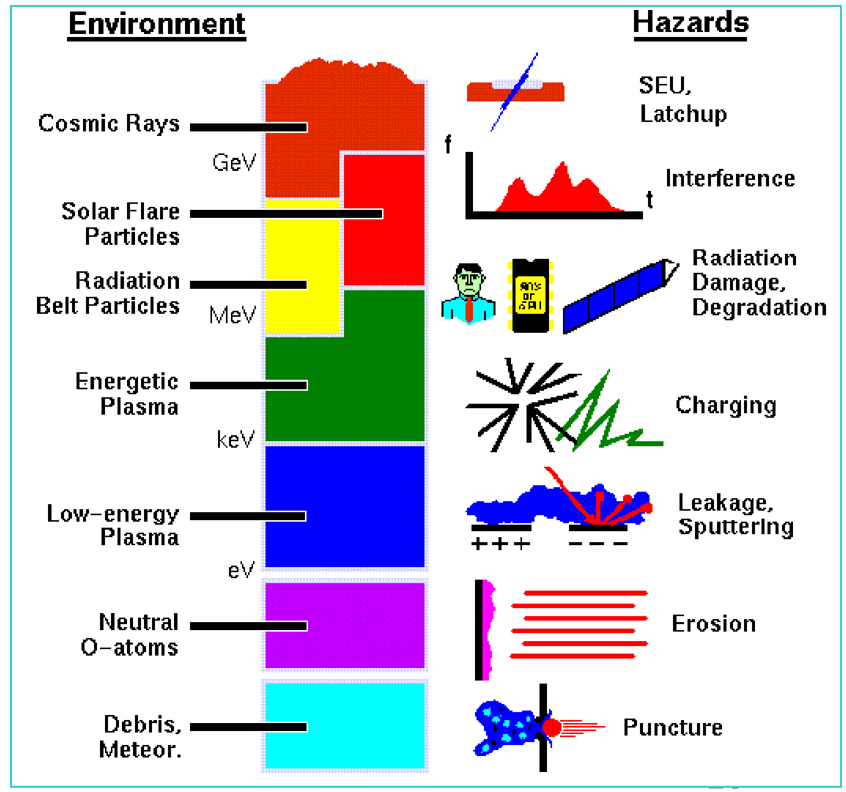


Fig. 3.1 of SEI

Overview of Space Environment Effects



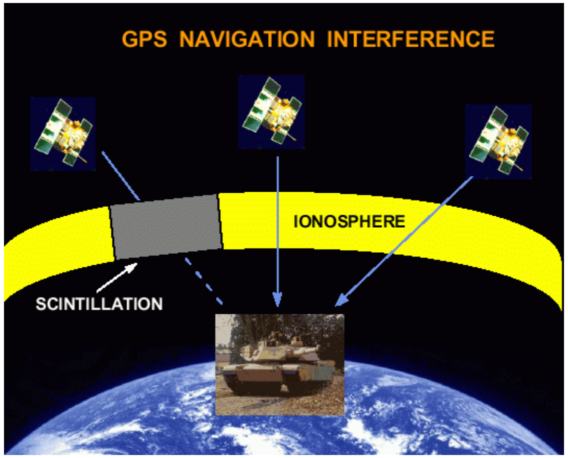
Lanzerotti, 2001



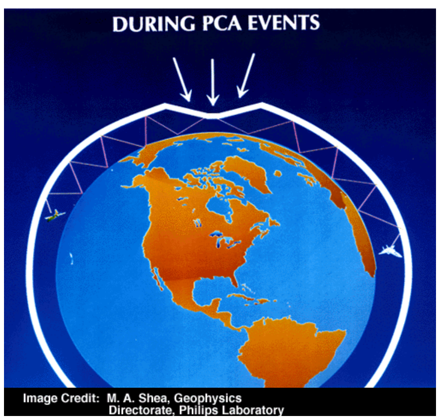
ESTEC, Space Environments and Effects Analysis Section

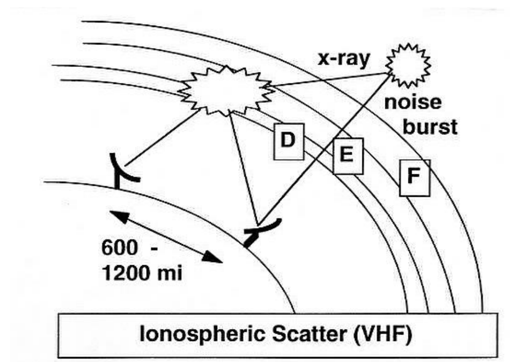
Overview of space Environment effects

- **Effects on communication, navigation and positioning**

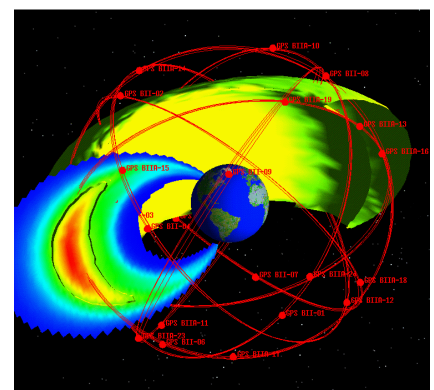


- Signal "scintillation"
  - Loss of signal lock on satellites
  - Both single and dual frequency systems may be affected
- The Total Electron Content (TEC) along the path of a GPS signal can introduce a positioning error (up to 100 m)





A 7-10 km height change of the lower ionosphere can give position errors of 1-12 km



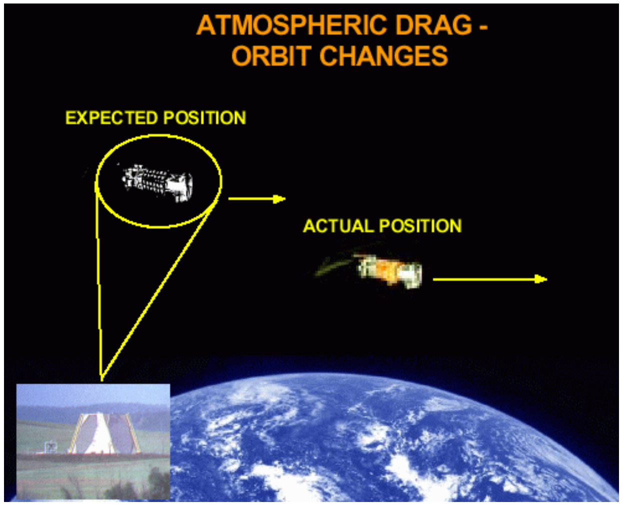
Overview of space Environment effects

- **Atmospheric drag of satellites**

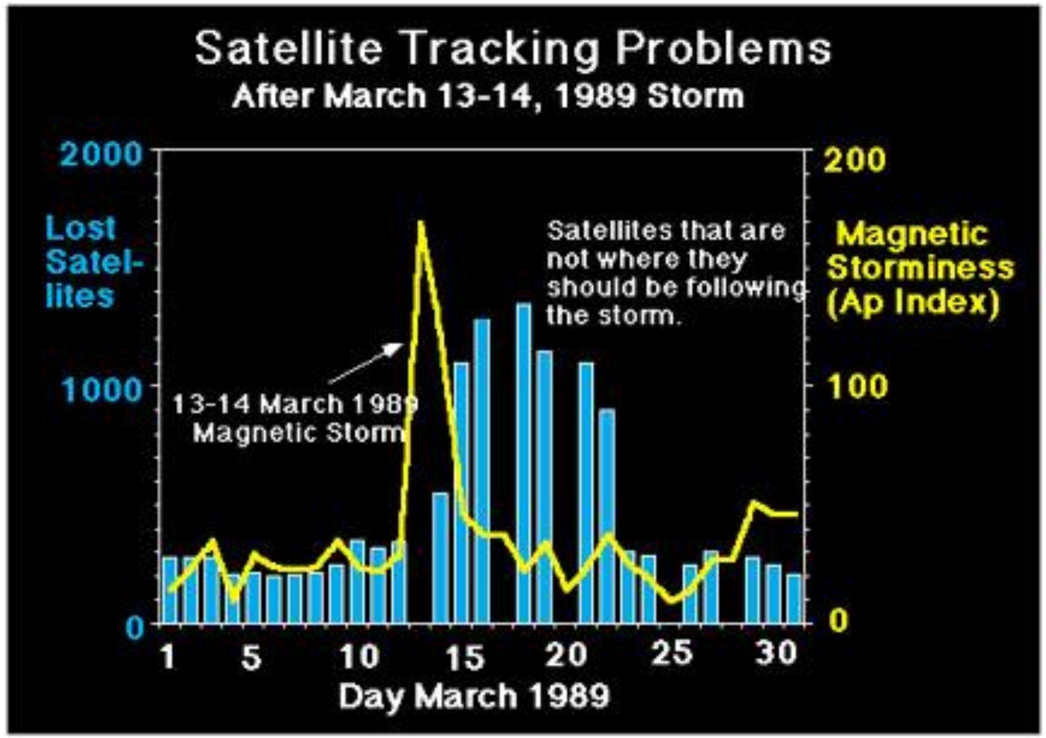
In addition to loose altitude satellites can also start tumbling since the satellites in most cases are non-symmetrical

- Hubble Space Telescope drops 10-15 km per year
- Skylab re-entered several years earlier than planned

    - **Tumbling** - Low Earth Orbit (LEO) magnetic linkage between satellite and momentum transfer wheel affected by field-aligned currents during substorms & other dynamic events.

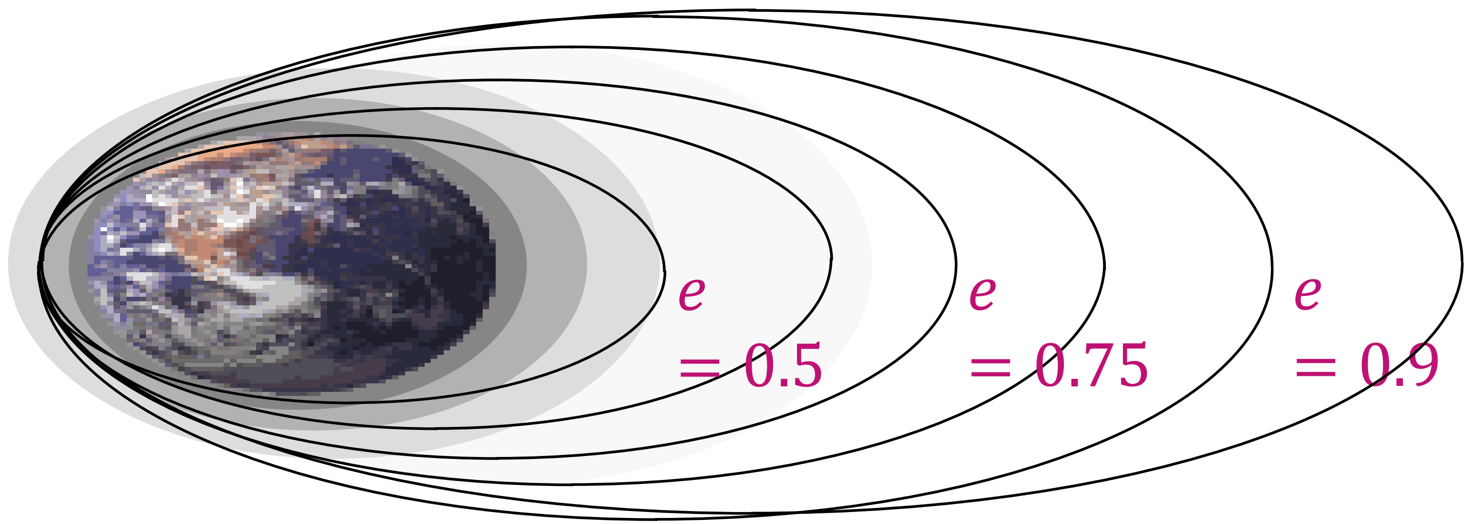


Increased satellite drag and loss of orbit tracking magnifies the risk of collisions with orbiting debris



Natural decay by Atmospheric Drag

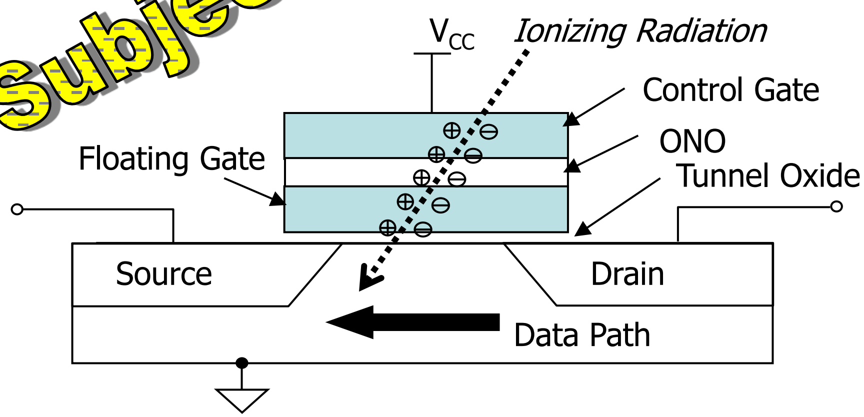
- **The basic effect of atmospheric drag, is changing the semi-major axis and eccentricity of the orbit secularly.**
- **for elliptical orbit only, depends upon two orbital elements, the semi-major axis (a) and the eccentricity (e), because it indicates the size and shape of orbit.**

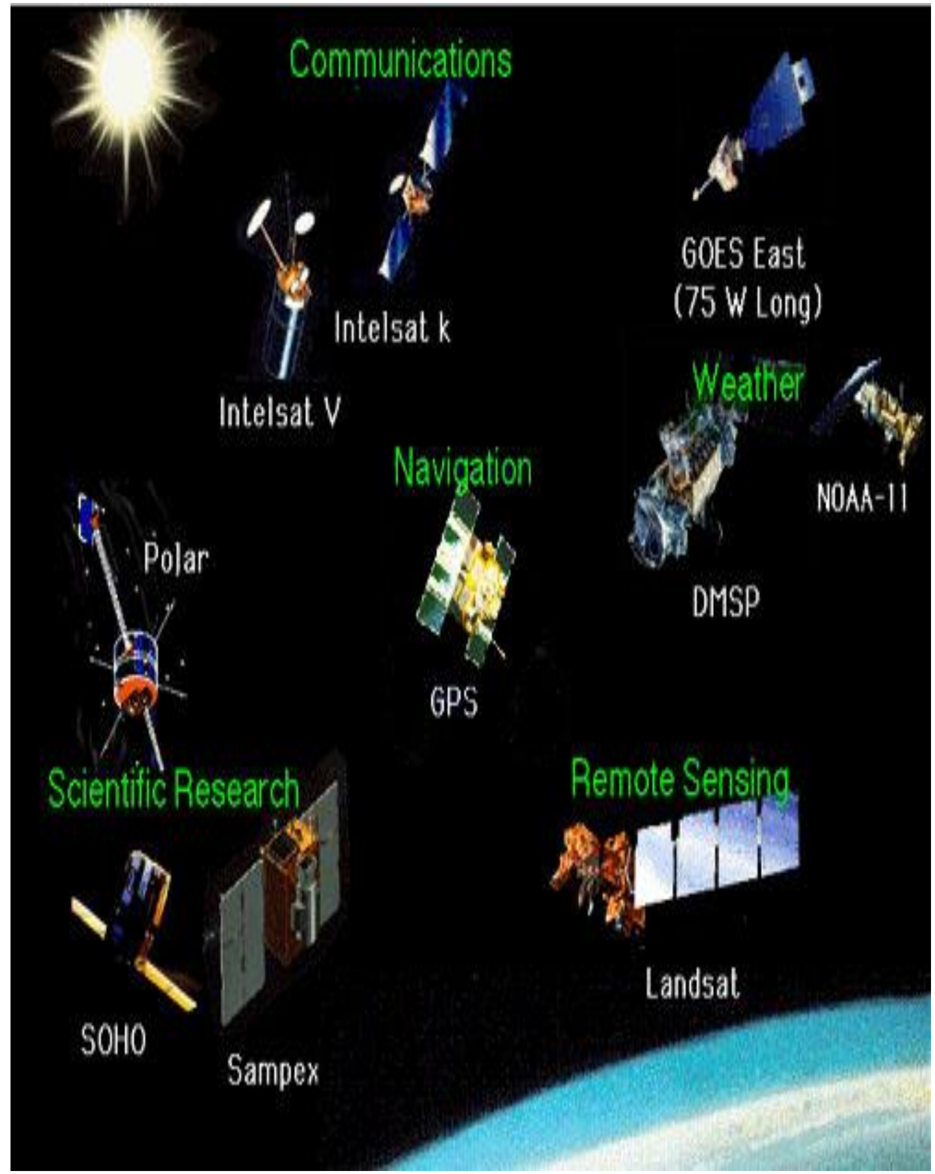


Overview of space weather effects

- **Effects on technologies in space**
  - Surface charging
  - Internal charging
  - Total ionising dose
  - Displacement damage
  - Single event effects
  - Interference and background in instruments

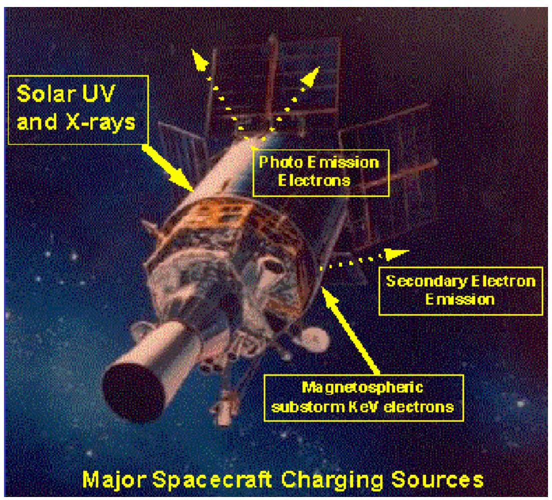
Subjects of the lecture

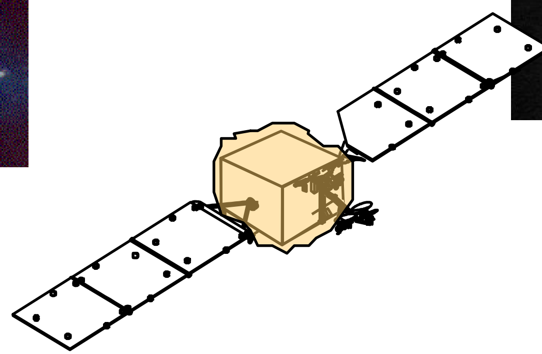




Plasma effects

- Surface charging
- Plasma effects on instruments

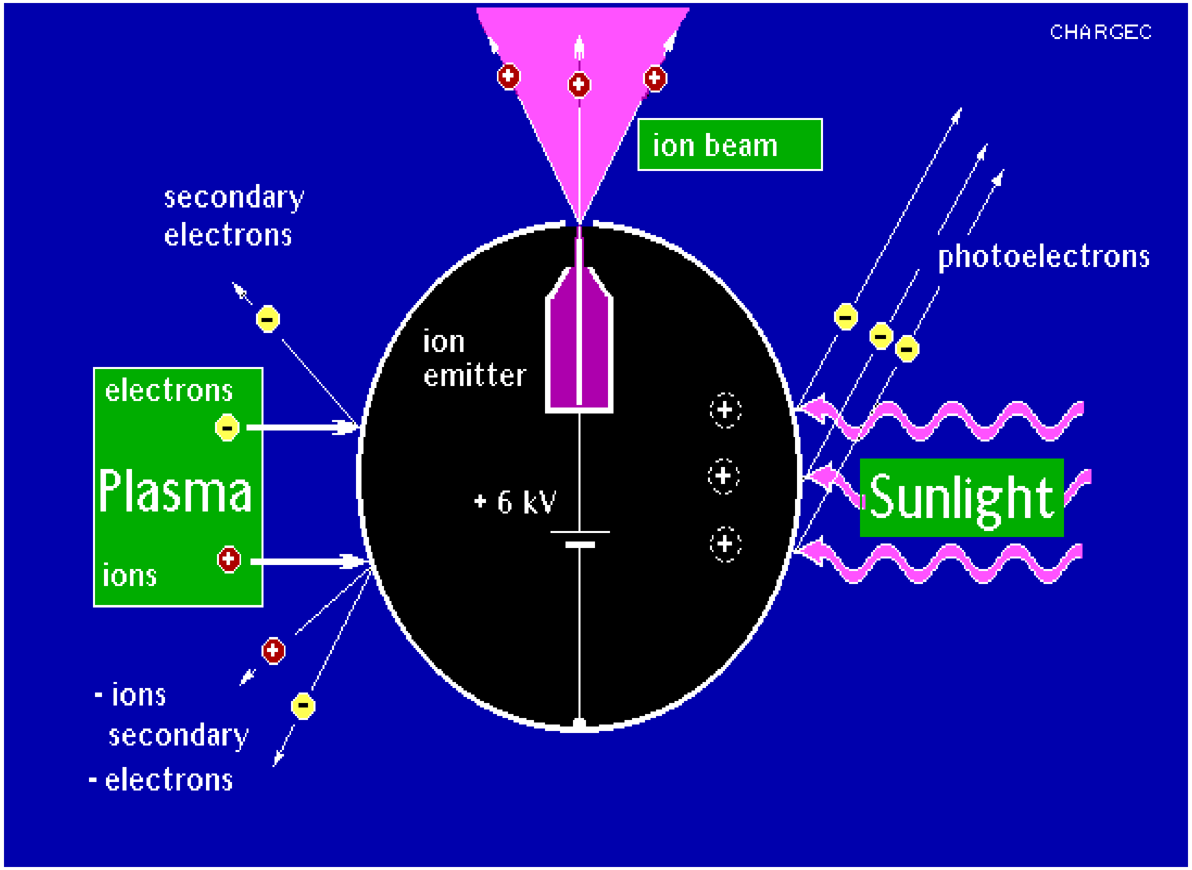




Surface charging

- Absolute charging: build up of high potentials on spacecraft relative to the ambient plasma
  - fast process (microseconds)
  - not in itself necessarily a serious concern
  - enhances surface contamination degrading thermal properties
  - compromises scientific missions seeking to measure properties of space environment
- Differential charging: build up of potential differences between various parts of a spacecraft
  - relatively slow process (minutes) because of capacitance
  - non-uniform material properties
  - shaded or sunlit
  - anisotropic plasma fluxes
- Effects by discharge arcing

Charging Mechanisms



•While there are several mechanisms which contribute to spacecraft charging, the three most important ones are:

(a) Charge flow from the ambient plasma

(b) Photoelectron emission from the spacecraft

(c) Secondary emission due to plasma bombardment

These currents produce a current flow to the satellite, and generally result in a non-zero charge on the satellite body (and surfaces), and hence non-zero potentials. These potentials can be quite large. The general scenario is presented in figure, where the different current sources are identified.

Surface charging

- Object placed in a plasma will charge negatively due to the greater mobility of electrons compared to ions
- Current equilibrium condition: at potential V

$$\underbrace{I_e+I_i}_{\text{plasma}}+I_{pe}+I_{sec}+I_{back}+I_{art}=0$$

photoelecrons

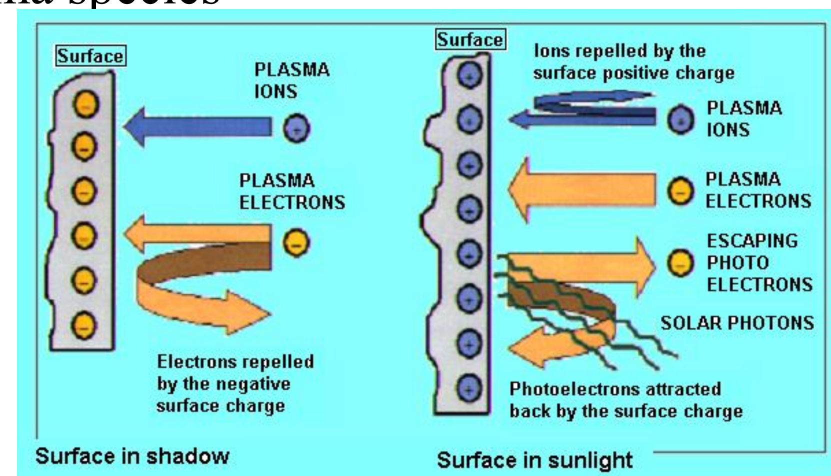
secondary electrons

backscattered electrons

artificial source

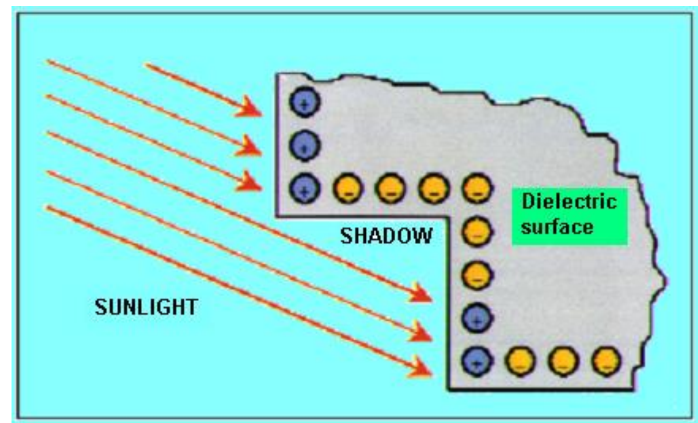
- Negative surface charge prevents eV-electrons to reach the surface
- Equilibrium reached when the sheath region sufficient to balance currents due to positive and negative plasma species
- Spacecraft will assume a floating potential different from the plasma
- Assuming a single Maxwellian distribution for the plasma gives

  $V \approx -T_e$ in eclipse (and $T_e > 1$ keV)



Surface charging

- In sunlight photocurrent from a surface much higher than plasma currents: equilibrium controlled by emission and reattraction of photoelectrons by UV flux
- In conditions with no sunlight and low cold plasma density (outside of the plasmasphere) surfaces can charge to very high potentials
- Upon exiting eclipse various surface materials discharge at different rates → possibility of large differential potentials



- Wake effect in LEO: spacecraft velocity > ion velocity, but < electron velocity → ions impact only ram surfaces, electrons all surfaces → differential charging
  - worsens the otherwise favourable environment of high-density low-energy plasma

Surface charging

- Modeling discharge characteristics
  - Spacecraft in space considered as a capacitor relative to the space plasma potential
  - Dielectroc surfaces divide the spacecraft into many capacitors
  - The components of the system of capacitors are charged at different rates dependent on incident fluxes, time constants, spacecraft configuration effects etc.
  - Sophisticated computer programs needed taking into account 3-dimensional effects
    - NASA Charging Analyzer Program (NASCAP)
- Mitigation in design
  - Basic geometry and grounding of surfaces
  - Conductive surfaces
  - Knowledge and selection of
    - dielectric thickness
    - dielectric constant (→ surface capacitance)
    - dielectric resistivity (generally not a constant in space environment)
    - surface resistivity
    - secondary emission yields
    - photoelectron yield

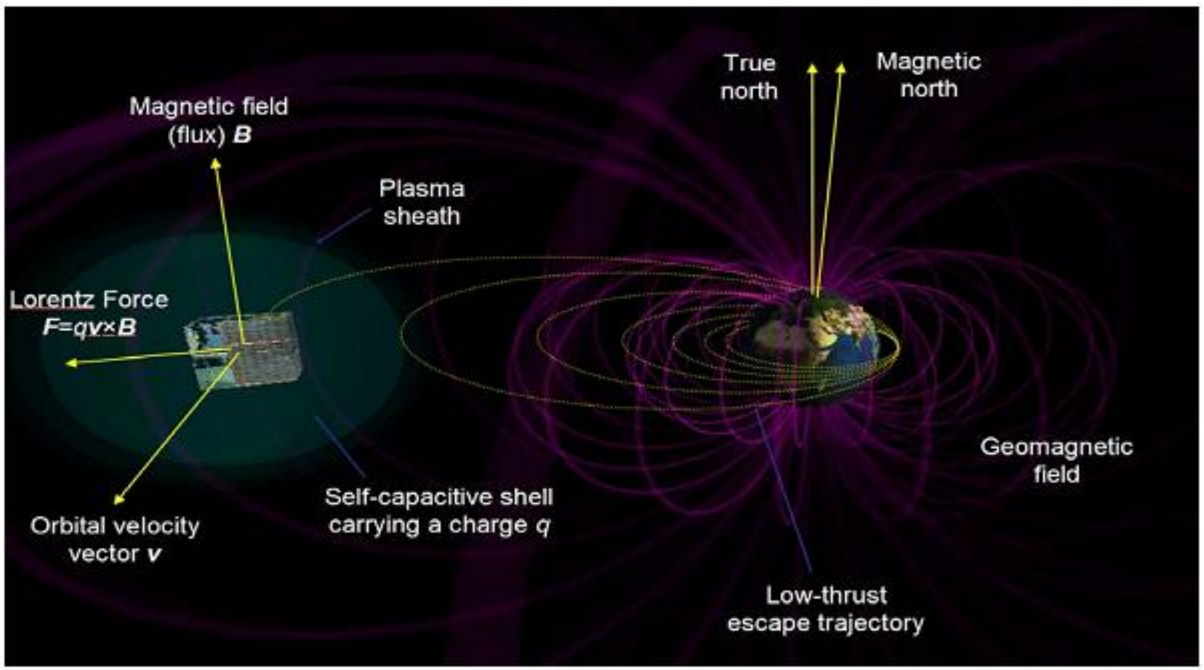
Surface charging

- Surface charging effects
  - Charging leads to arc-discharge process releasing large amounts of charge
    - currents flowing in structures
    - broad-band electromagnetic field coupling into electronics
  - Undesired effects due to discharge arcing currents and EMI generation
    - dielectric breakdown (punch-through)
    - between surfaces (flash-over)
      - noise in data and wiring
      - telemetry glitches
      - logic upsets
      - spurious commands
      - materials damage (sputtering, change of conductivity, darkening)
      - attraction of chemically active materials
  - Examples
    - Marecs-A, 1981, GEO, 617 anomalies in status monitoring circuits
    - Anik E1 and E2, 1991, GEO, a large number of mode switches
  - Koons et al., Aerospace Report No TR-99(1670)-1:

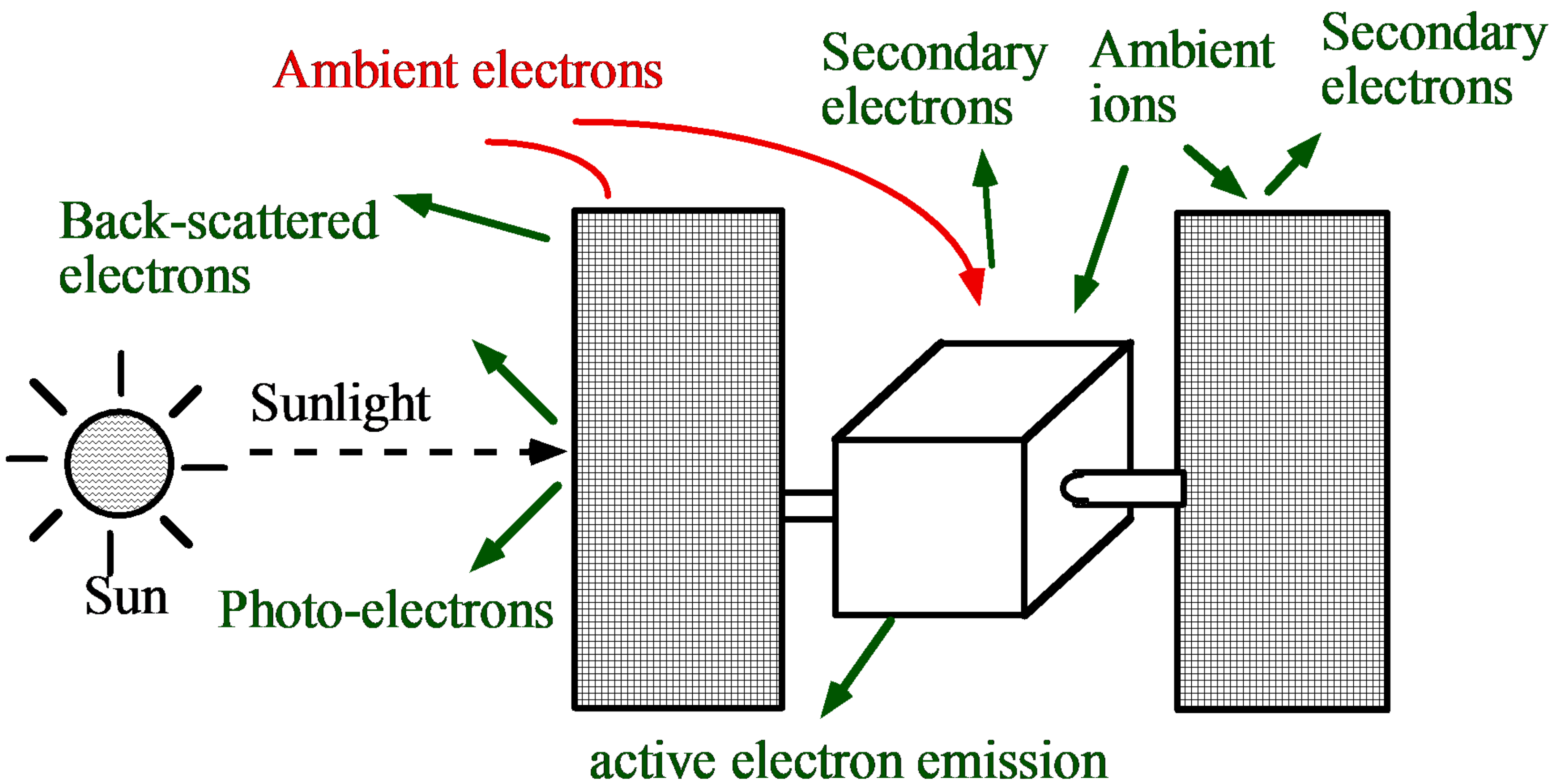
    The most serious spacecraft anomalies have been caused by surface charging, including 4 out of 11 missions lost or terminated due to space weather effects

Effect of Orbit Height on Debye Length

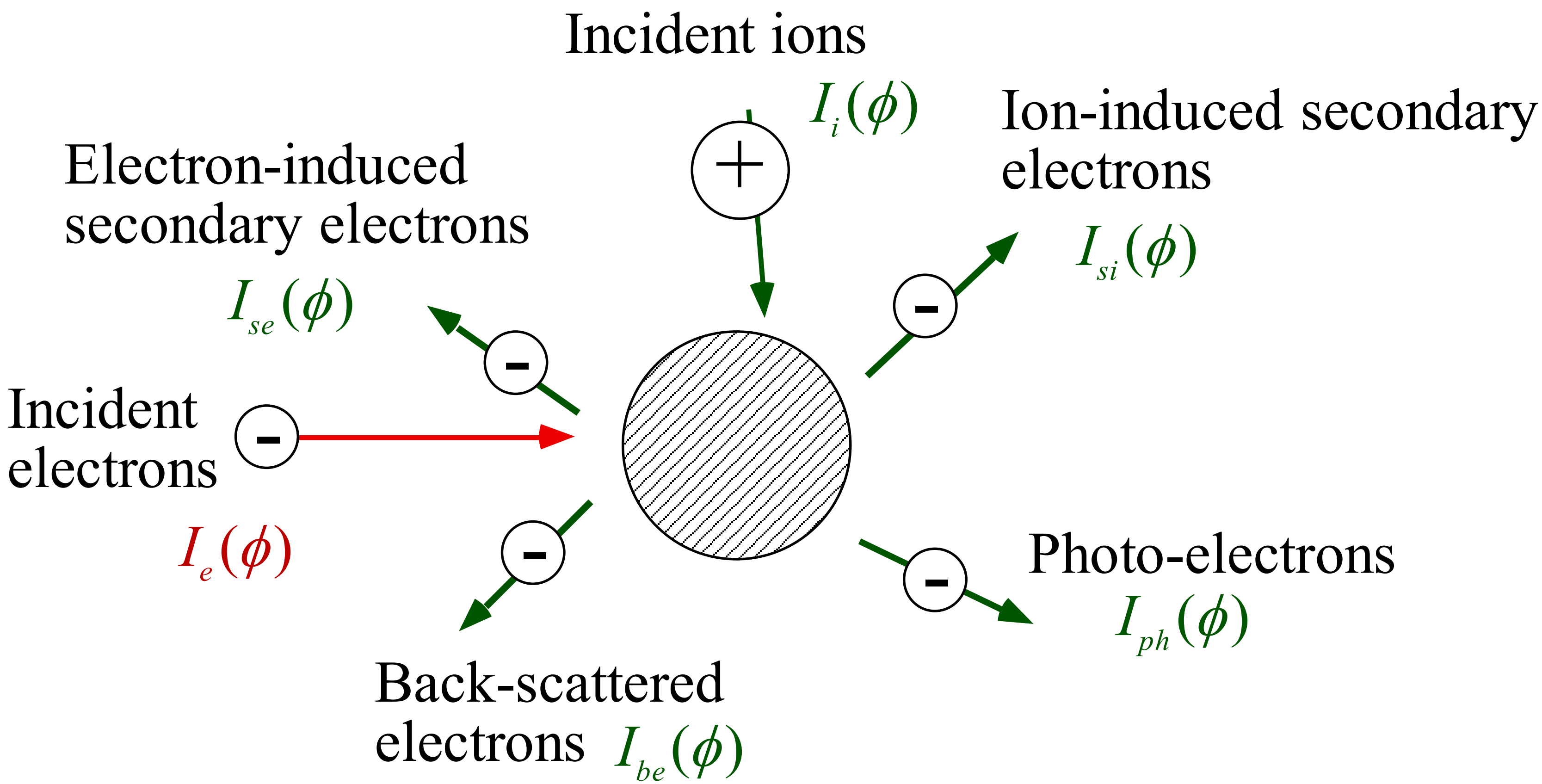
	LEO	GEO
Debye Length	O(1 cm)	O(10 m)
Ratio of circular speed to speed of magnetic field	High	Near 1
Coulomb Force	Near zero	High
Lorentz Force	High	Near zero



Current sources to a spacecraft



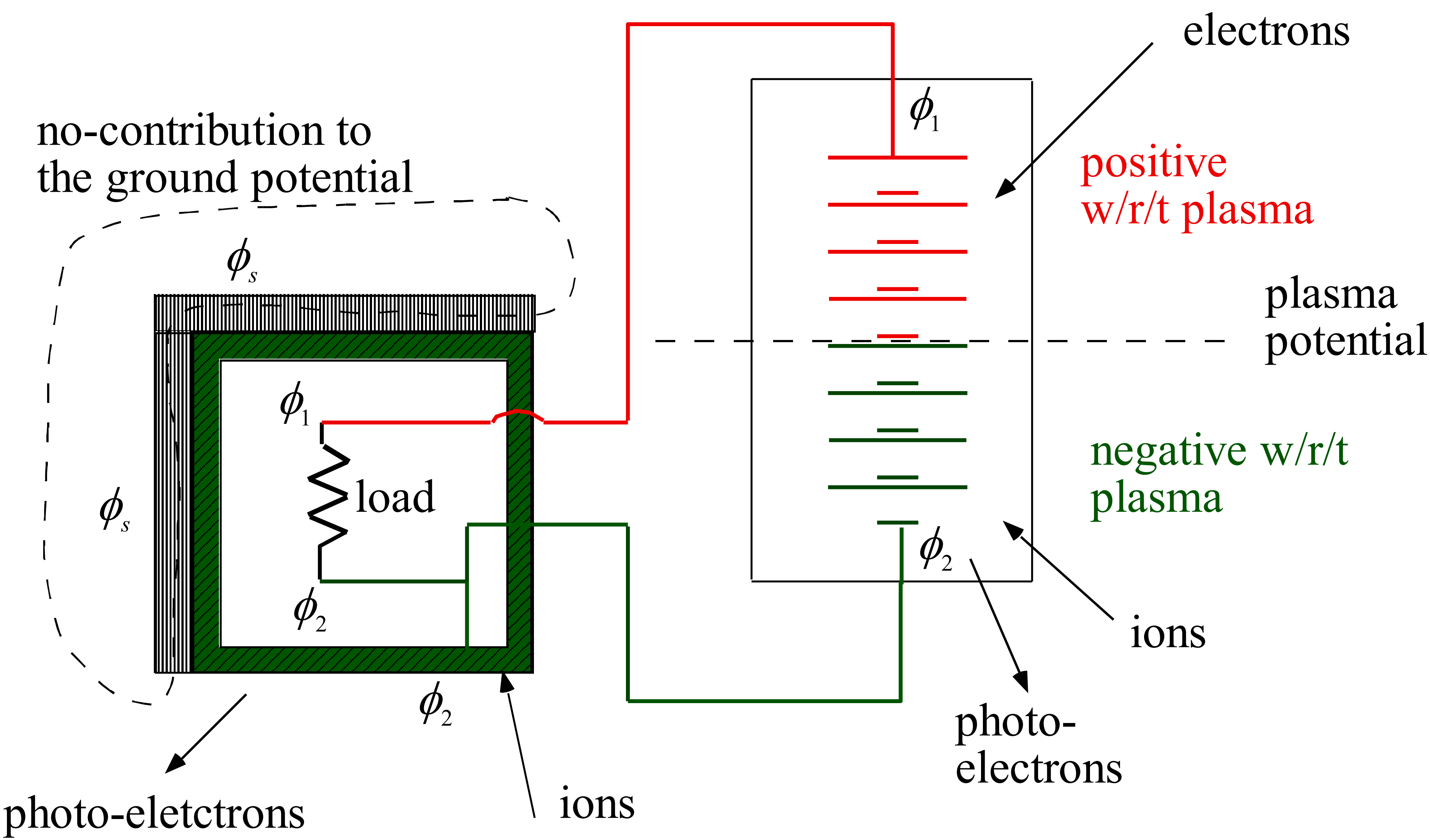
If a spacecraft is modeled as a conducting sphere



Spacecraft potential ϕ is determined to satisfy

$$\boxed{I_{net} = I_i(\phi) - I_e(\phi) + I_{se}(\phi) + I_{si}(\phi) + I_{ph}(\phi) + I_{be}(\phi) = 0}$$

How is the structure 'ground' potential ϕ_2 is determined?



Plasma effects on instruments

- Discharges in high-voltage circuits
- High potentials in plasma instruments
  - Distorts energy distribution of incident ions
    - instrument bias with respect to plasma ground
  - Perturbation of particle trajectories
    - angular resolution
    - sensitivity
  - High ground potentials
- Sputtering of surfaces due to considerable ion kinetic energy
  - X-ray mirrors
  - Contamination source
    - re-attraction of ionised outgassing and sputtering products
  - Change of thermo-optical properties of thermal control surfaces
- Dust generation and shedding
  - Startracker anomalies
  - Infrared sensor interference

Discharge in LEO

In LEO, the charging is mainly due to ionospheric electrons and ions.

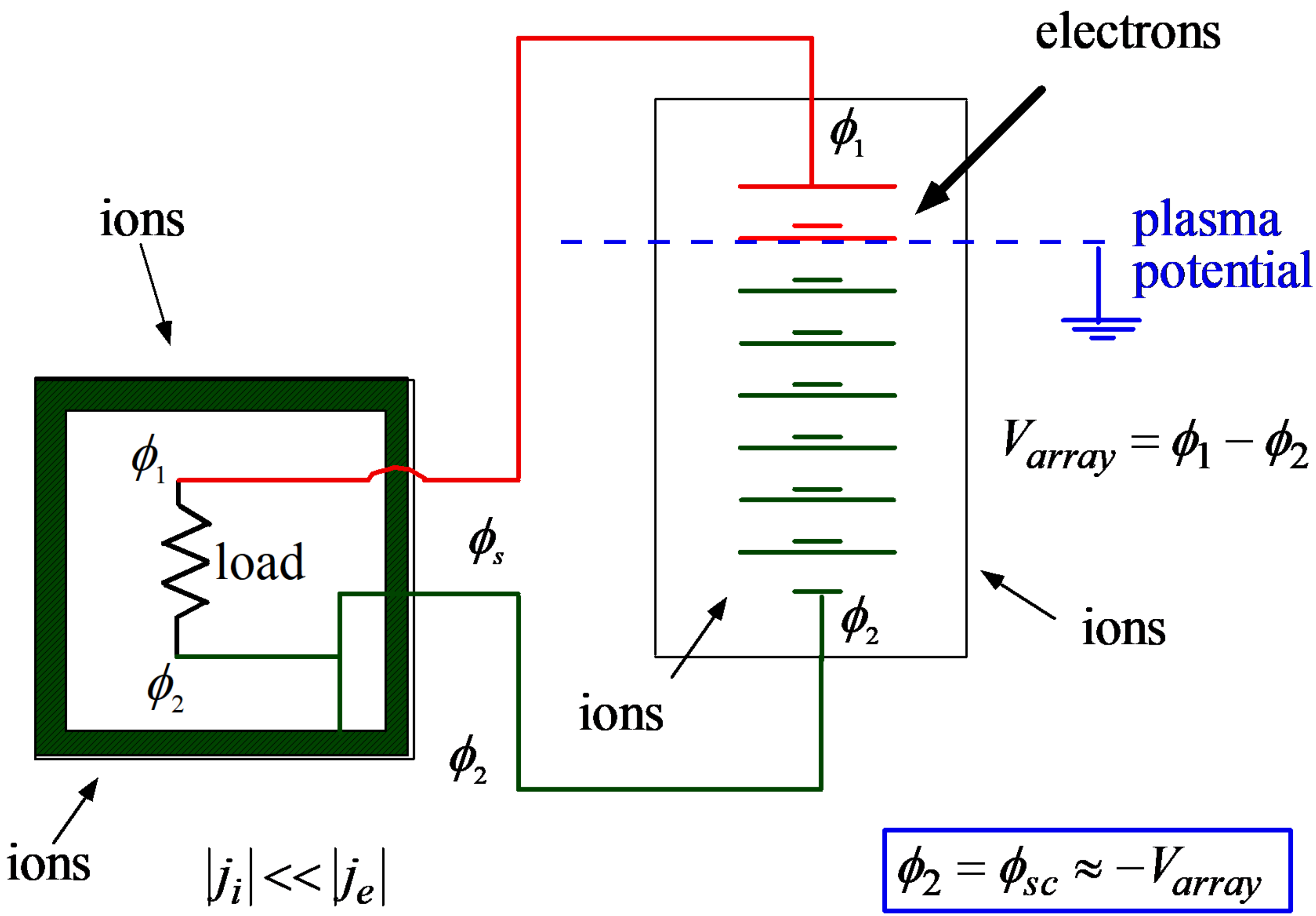
Low temperature (~0.1eV)

No serious differential charging

UNLESS

Spacecraft is operated at a high voltage (>100V)

Spacecraft potential in LEO



$$\boxed{\phi_2 = \phi_{sc} \approx -V_{array}}$$

Discharge on high voltage solar array in LEO

Discharge is observed at the negative end of the solar array

The discharge occurs at a voltage as low as -200 volts or even smaller

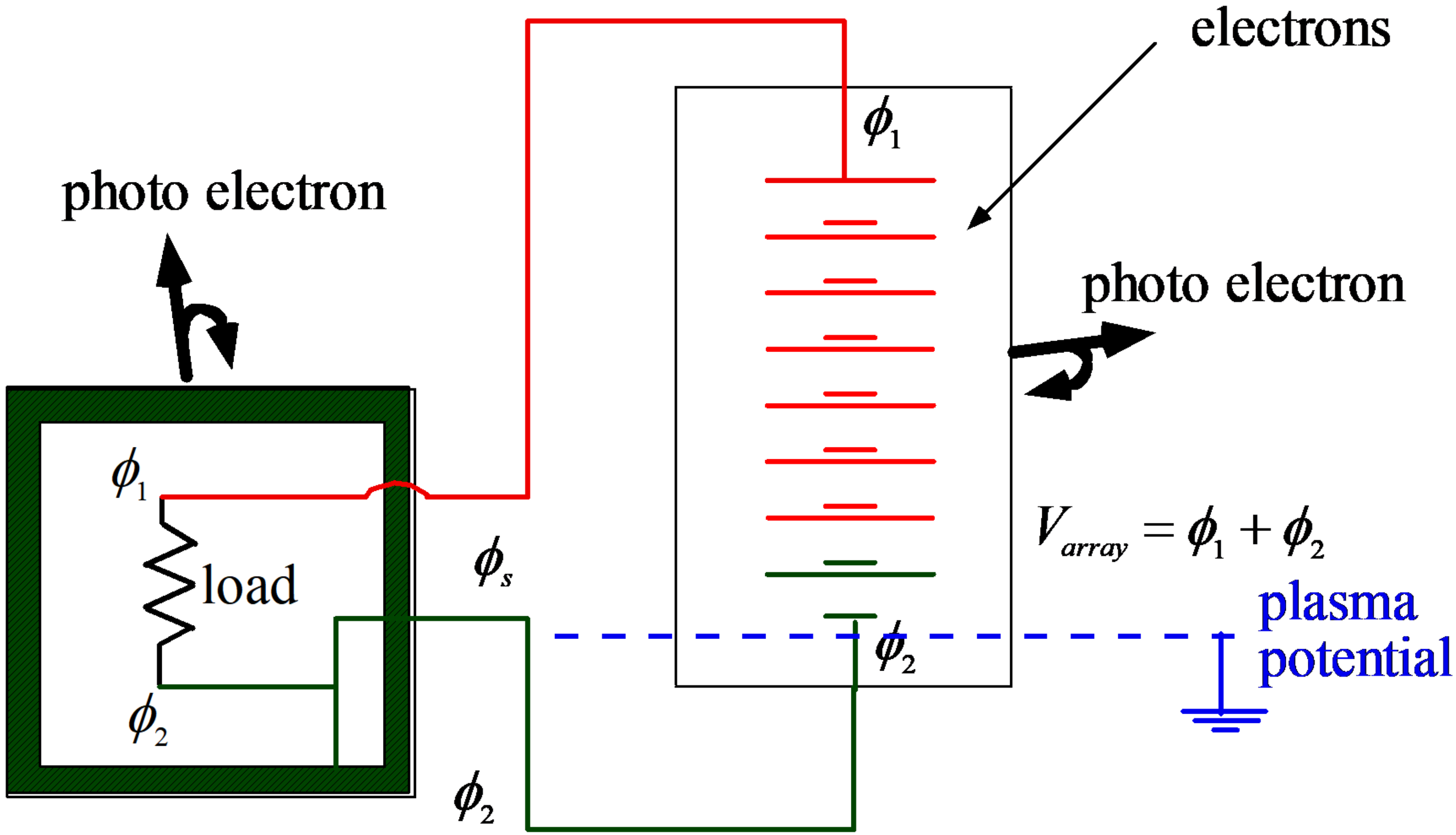
The limit on spacecraft voltage

Repeated discharge with a certain rate

The discharge rate depends on

Plasma density
Voltage
Temperature

Spacecraft potential in GEO



$|j_i| << |j_e| \leq |j_{ph}|$

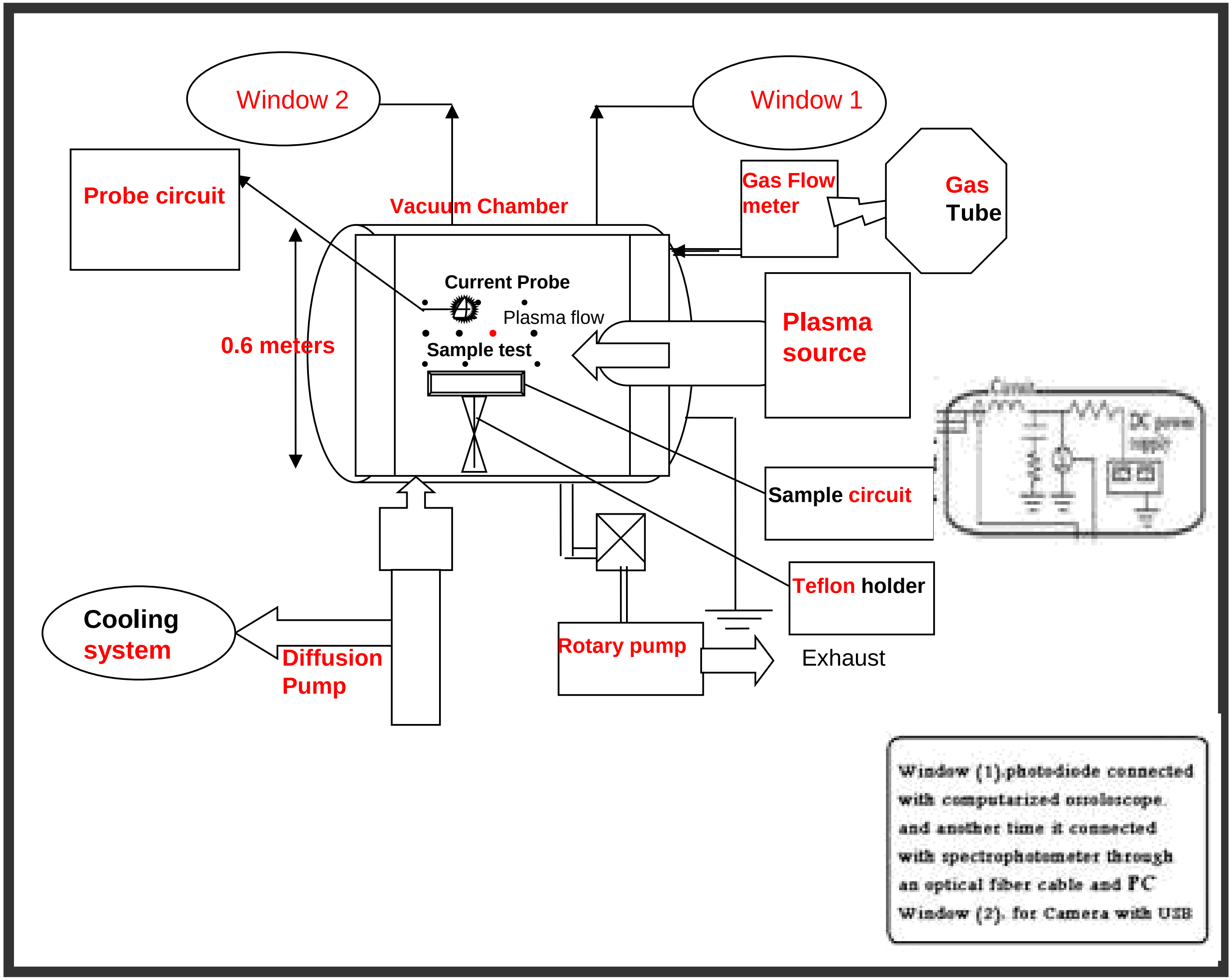
As long as it is well illuminated, $\boxed{\phi_2 = \phi_{sc} \approx \kappa T_{pe} \approx 2eV}$

Temperature of photoelectrons

The Space Laboratory Units at NRIAG

It is build to generate plasma with specific properties in high vacuum plasma chamber.
The space-plasma setup contains single and double probes, photo diode, and computerized oscilloscope, very sensitive and low-noise CCD camera with optical microscope, spectrophotometer, and sample of solar arrays and cells with different configurations.

The experimental and simulated tests of this system show the plasma effects on different components of spacecraft s' surface. This mechanism studies the charging process, which leads the different surface potentials



Schematic diagram of experimental setup

Space Plasma

- **The plasma is a collection of charged particles, and it response to magnetic field variation.**
- **In LEO, the plasma is cold and dense, but further away, its density drops significantly but the mean energy of the plasma increases**
- **The space plasma environment can affect spacecraft in any orbit.**

Test Conditions	*N-plasma*
Neutral density	**10^{14} m-3**
Debye length	**0.44 mm**
Plasma sheath	**$3x10^{-3}$cm**
Plasma density	**10^{11} m^{-3}**
Electron temperature	**~1.5 eV**
Ion temperature	**0.03eV**
Degree of ionization	**10-5**
Array Temperature	**60 C0**
External Capacitance	**~ µF**

Properties of N- plasma

Test Conditions	*Ar-plasma*
Neutral density	**10^{16} m-3**
Debye length	**0.5mm**
Plasma sheath	**$6x10^{-3}$cm**
Plasma density	**10^{12} m^{-3}**
Electron temperature	**1 eV**
Ion temperature	**0.027 eV**
Degree of ionization	**10^{-4}**
Array Temperature	**60 C^0**
External Capacitance	**~ µF**

Properties of Ar- plasma

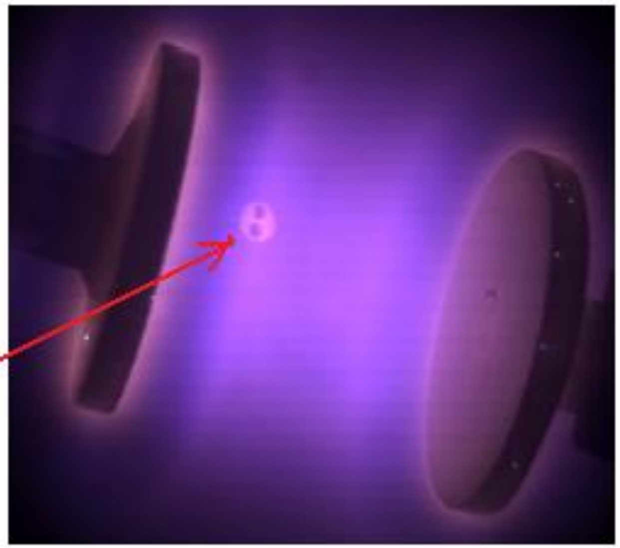


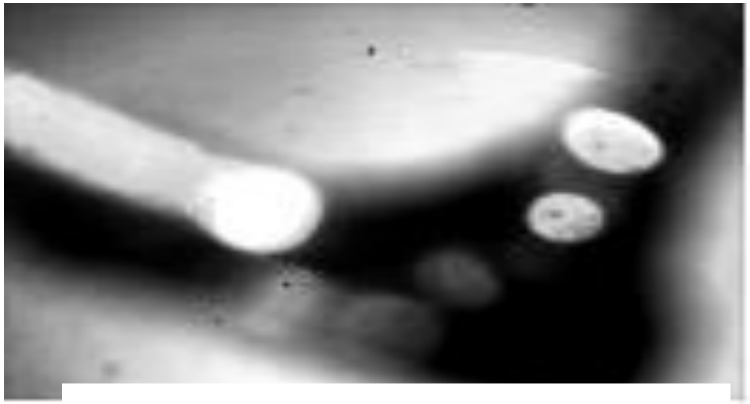
Image of area (5mmx5mm)

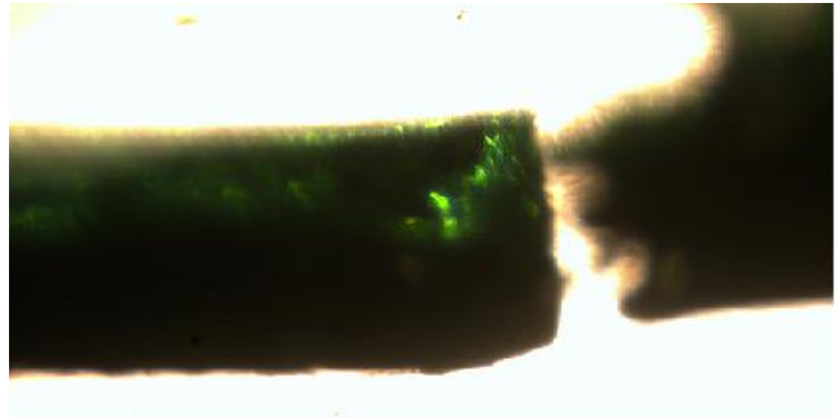
Ar-plasma

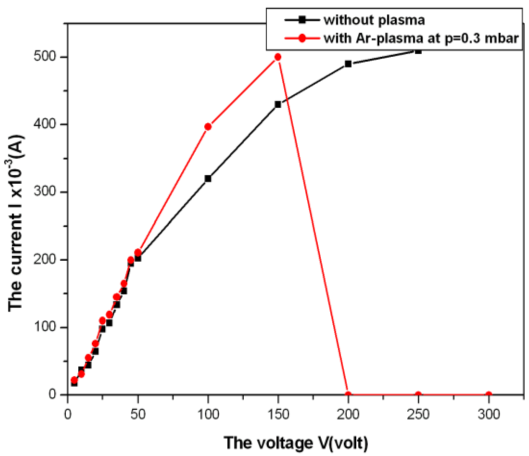
(I) Material Samples

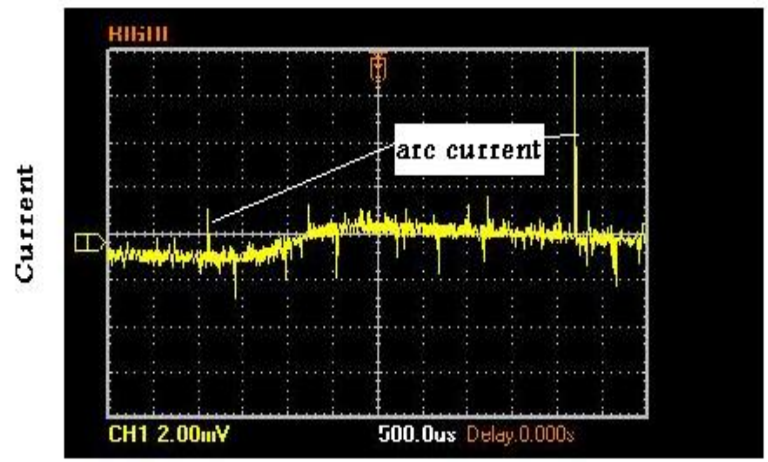
Effects of the plasma on the connector materials

Results





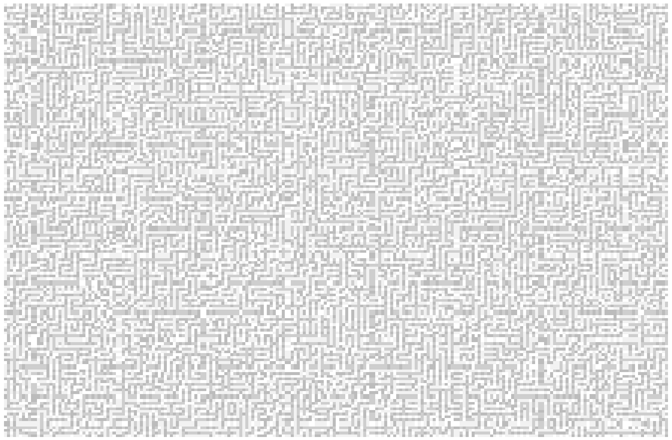


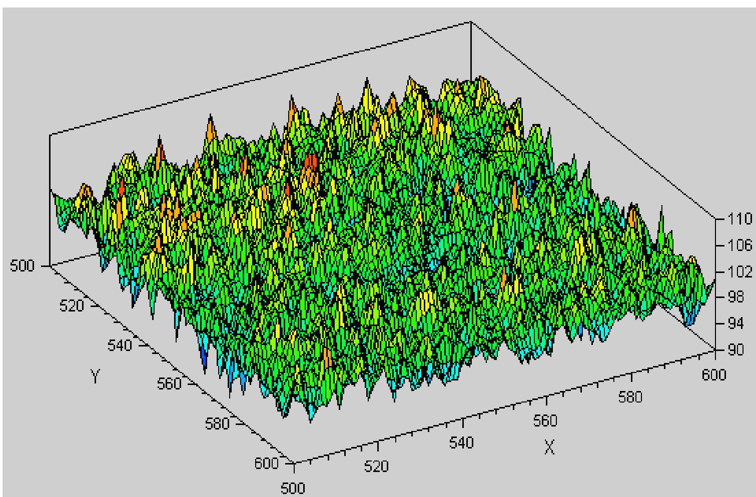


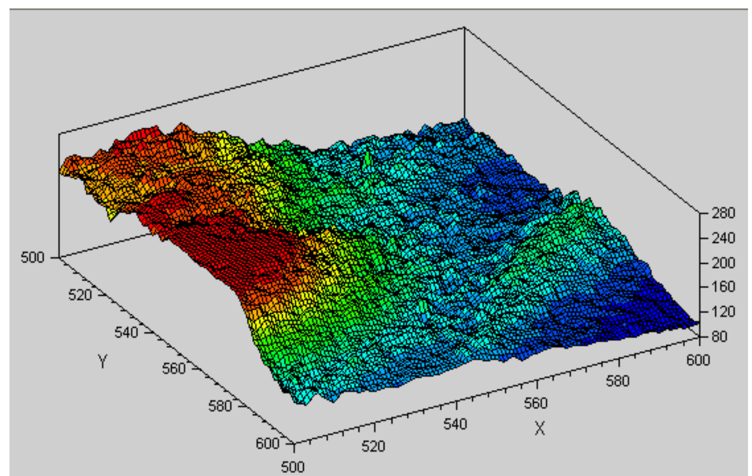
The resultant images and data show the threshold value or the break potential at which the current is cut off in the connector during the plasma flowing. Without plasma it is noticed that the current is in continently increases.

Effects on the Al-layer sample

Results





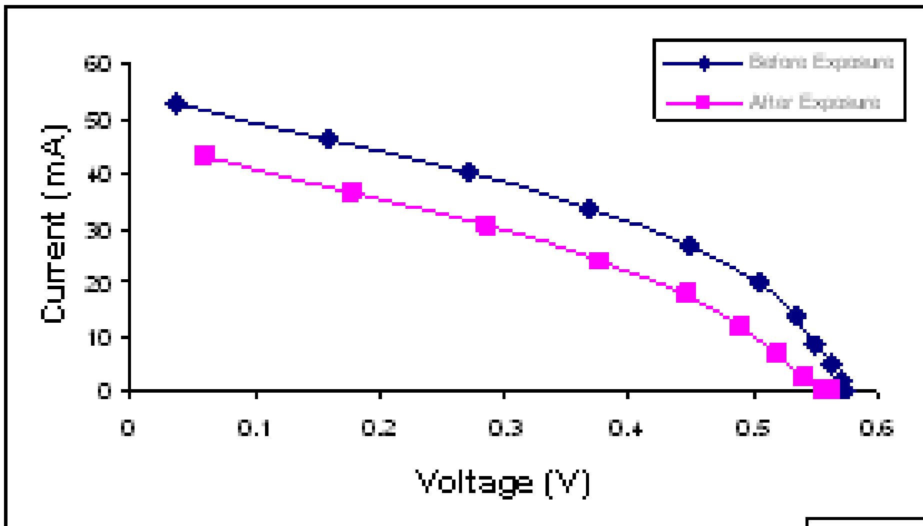


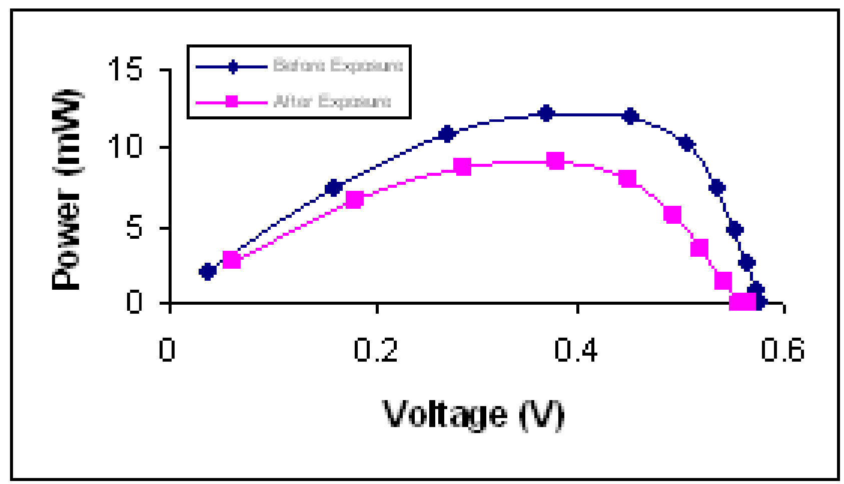
(II) Solar Array Sample

Plasma Effects on A mono Crystalline Si Solar Array Sample

Results

Work gas	Argon
Gas pressure	0.45 m bar
Discharge voltage	500 V
Exposure time in plasma	9 Hrs
Cell temperature	20 ºC
Cell area	$1cm^2$
Radiation intensity	1000 W/m2





➢ ***Ground-based experiments at NRIAG***

Experimental setup

****Glow discharge with Ar-gas flowing for Ar-plasma generation***

****High vacuum pump of pressure up to*** $6.5x10^{-5}$ **mbar (base pressure)**

****Fixed gas flow to steady pressure of*** 6.7×10^{-3} **mbar (working pressure)**

**** Applied voltage for plasma generation 50 V***

-LEO-plasma properties

- **Plasma density** ***14 x*** **10^6 /cm^3**
- **Plasma temperature 1.7 eV**

-Bias voltages

-80 V ; -100 V ; -200 V

Capacitance C = 20 μF

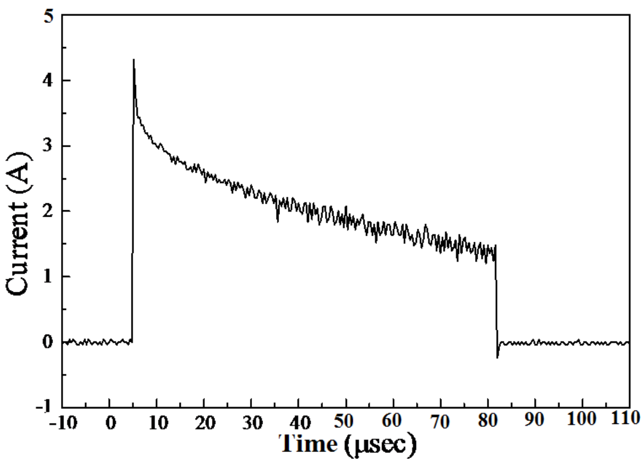
"The capacitance provides the charge to the arc current, which simulates the other parts of surfaces in real spacecraft. The capacitor is put in the circuit to simulate the capacitance of spacecraft.

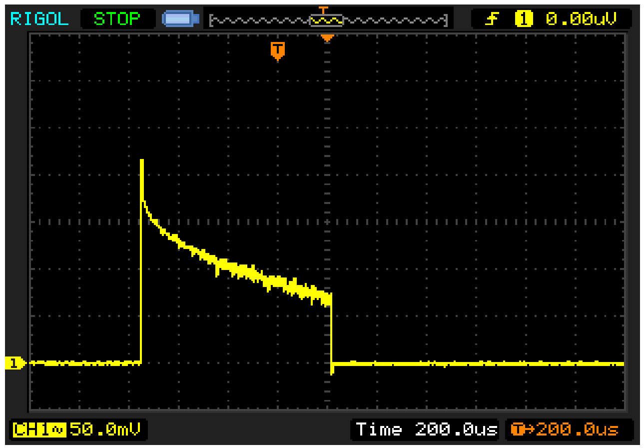
Resistance R=70 ohm

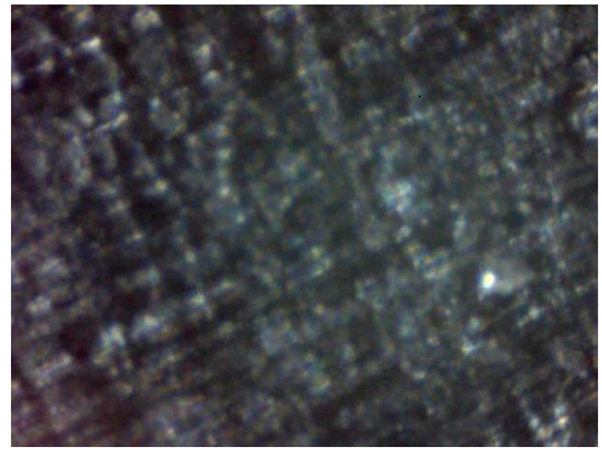
Discharging and arc processes

Alloy Sample 35 µm

Bias voltages -200 V







Potential waveform and current trace for trigger arcs of the Sample

Spot arcs of the sample after plasma exposure

Results

Anodic thickness (µm)	Bias -80 V		Bias -100 V		Bias -200 V	
	Width of the current trace Up to (µsec)	Arcs after exposure time (min , sec)	Width of the current trace Up to (µsec)	Arcs after exposure time (min, sec)	Width of the current trace Up to (µsec)	Arcs after exposure time (min, sec)
13	25	2	"failed"	"failed"	"failed"	"failed"
15	20	2,2	38	1,1	80	0,30
25	30	2,5	60	1,2	66	1,11
35	20	6,44	35	5,15	80	2

Conditions of discharging and arc processes for the anodic surfaces of the sample after plasma effect

From: Advances in Space Research >

To: Yehia Abdel-Aziz > Hide

AS

Your Submission - AISR-D-20-01074R1 - Accept

Today at 4:20 AM

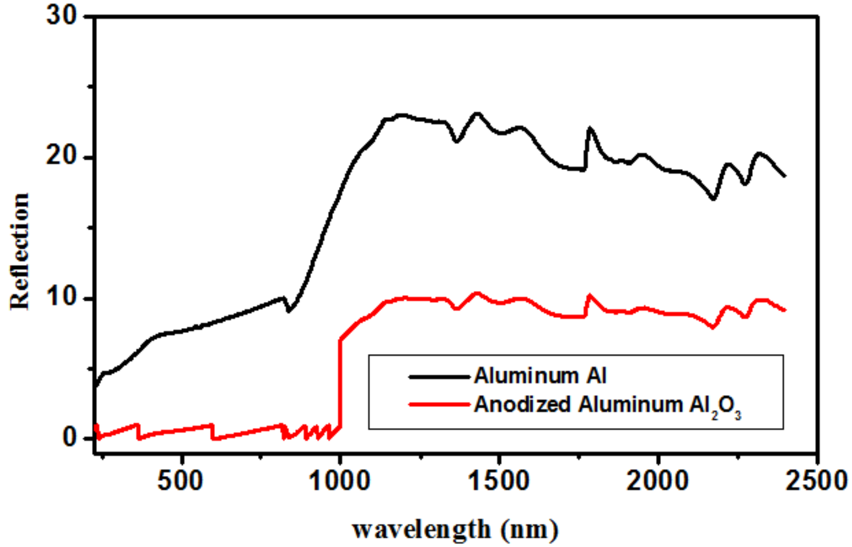
Manuscript Number: AISR-D-20-01074R1
Section: ST -Space Technology, Policy & Education
Article Title: Effects of Space Plasma on an Oxide Coating of Spacecraft's Surface Materials
Advances in Space Research

Dear Professor Abdel-Aziz,

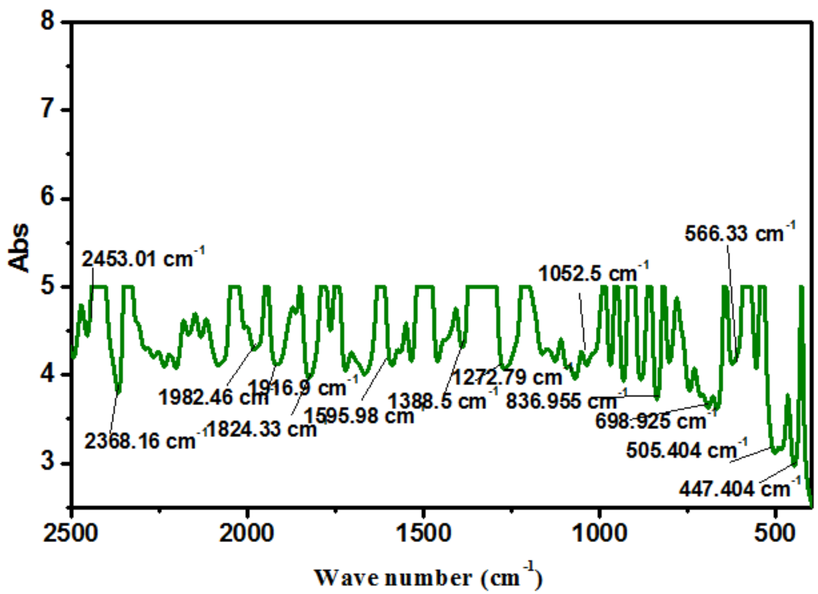
I am pleased to tell you that your manuscript has now been accepted for publication in Advances in Space Research and will shortly be sent to the publisher for processing.

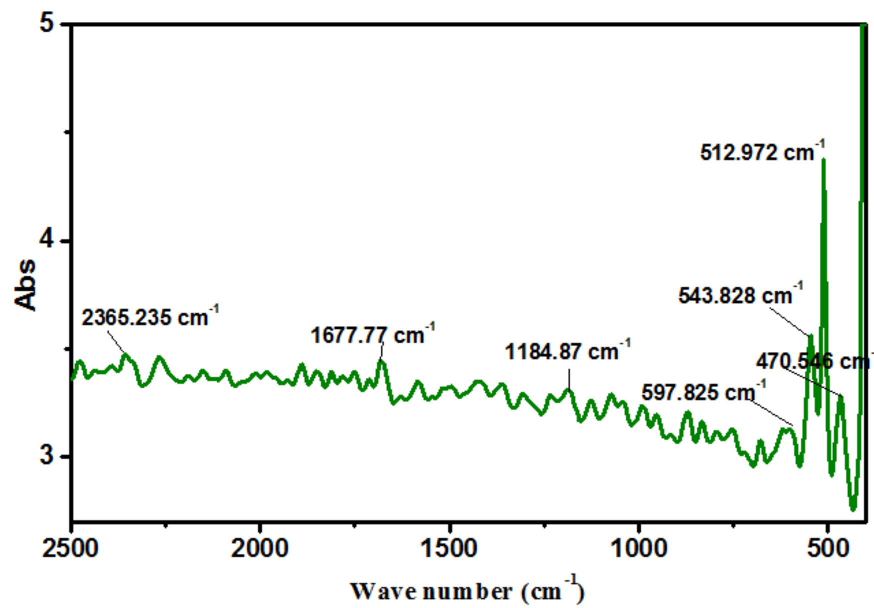
Please note that ASR articles are published online almost directly after Acceptance, in the format as accepted by the editor. Should you wish to exclude your article from this early publication, please send a message immediately to asr-editorialoffice@elsevier.com

The anodizing process is an electrochemical technique that converts the metal surface into an oxide. At the National Space Plasma Interactions Unit (N-SPI-U) of the NRIAG Institute, thin-film anodic oxide coating is produced on a sample of an aluminum plate and prepared using an electrochemical cell with an aqueous solution of sulfuric acid (15 wt % H_2SO_4, 22°C, 12 V) at a current density (2 A/dm^2). In this method, two plates of stainless steel (cathode) and aluminum to be anodized (anode) are immersed in the solution. The time period for the anodic process is chosen to be 60 minutes followed by hot water used to seal the sample for about 15 minutes

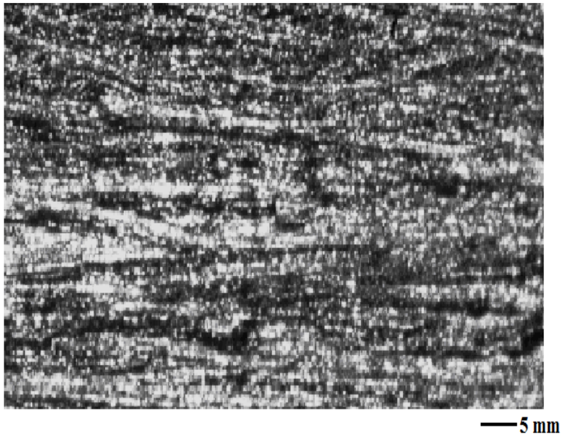


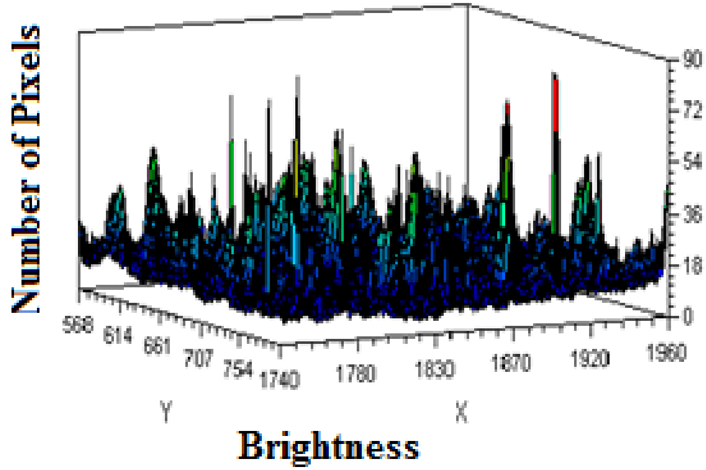
UV/Vis/NIR reflection spectra of Al (RED) and Al_2O_3 film after the anodic process (BLACK).





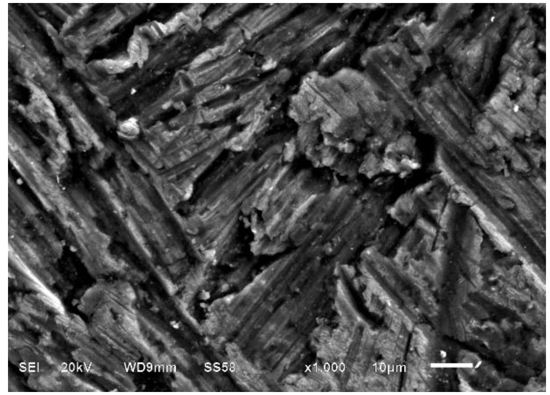
FTIR absorption spectra of the Aluminum (Al) surface sample anodic oxide surface Al_2O_3.

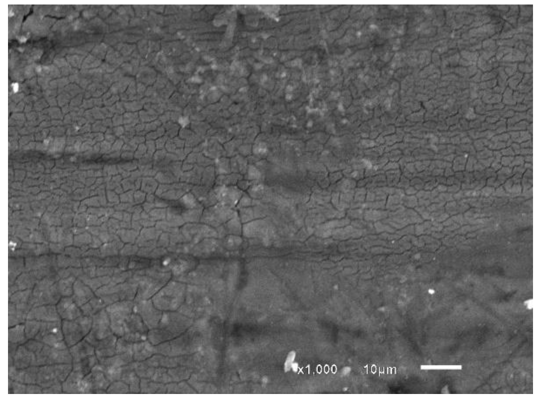


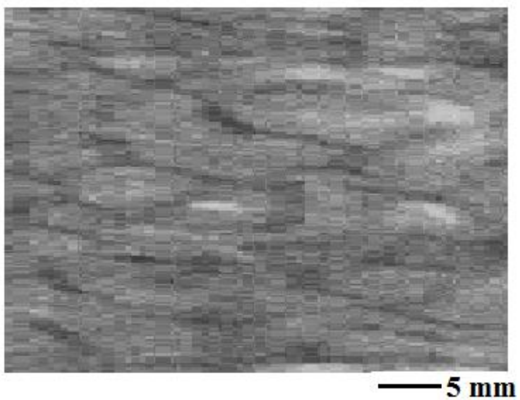


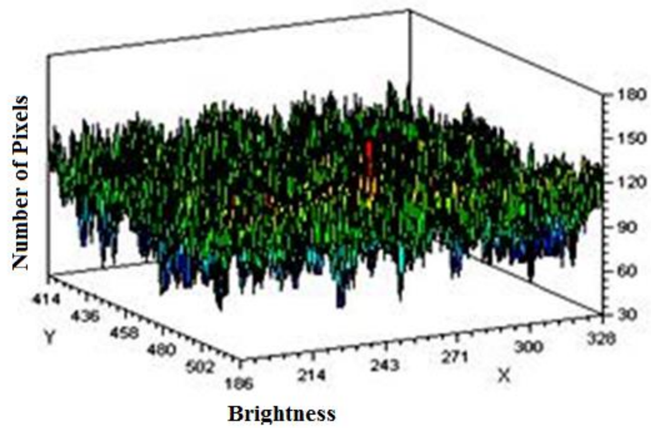
(a) (b)

(a) CCD- microscopic optical image of a selected area of the sample surface, before plasma exposure, and (b) the spatial distribution for the image (a), and with a relative mean value of pixels (intensity I = 155).



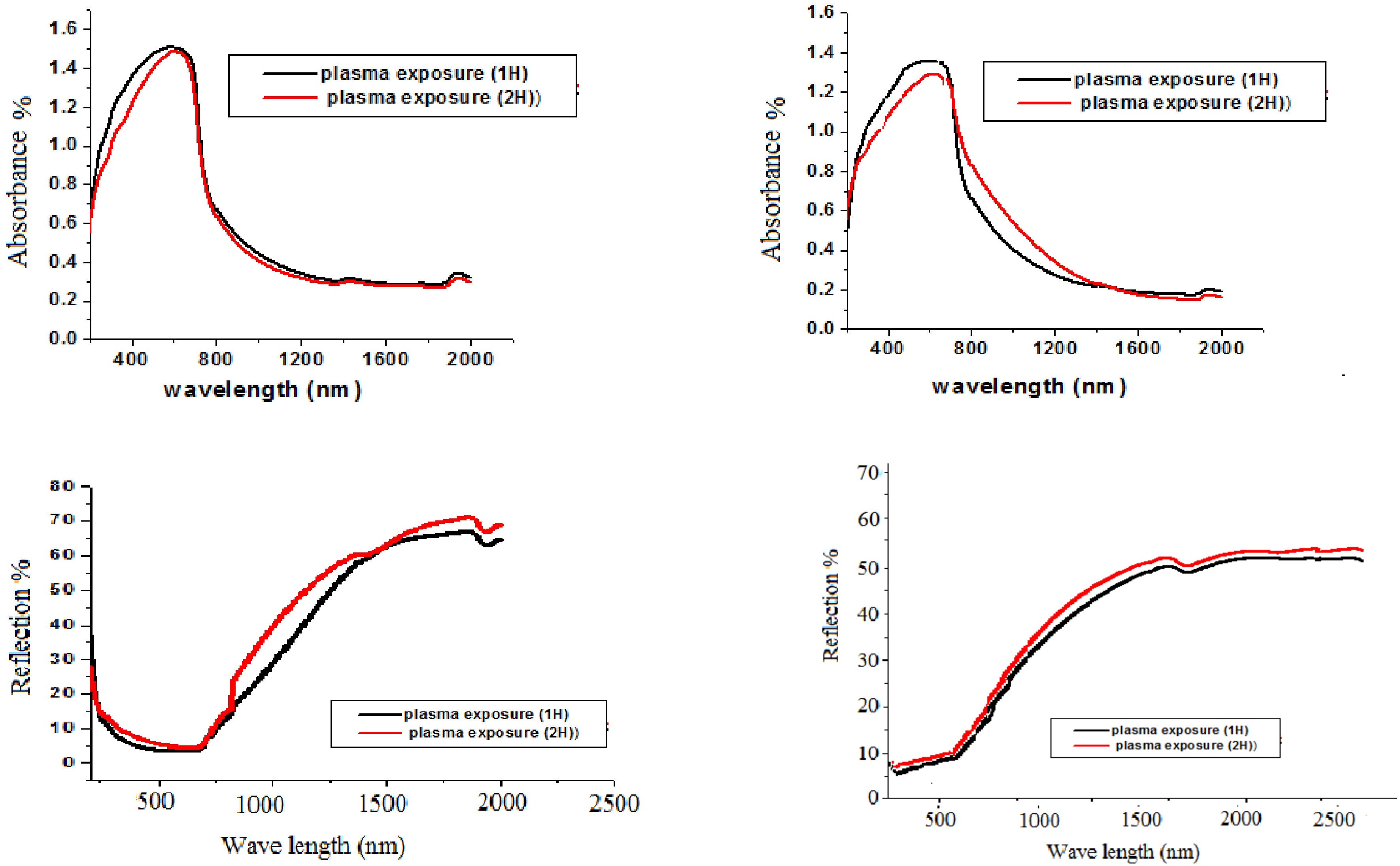






SEM images for the anodized surface Al_2O_3 (a) before plasma exposure and (b) after plasma exposure

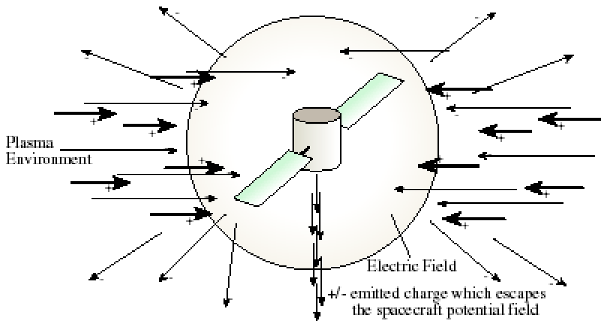
(a) CCD optical image for the same sample considered in figure 1(a), and taken after plasma exposure and (b) the spatial distribution for this image.

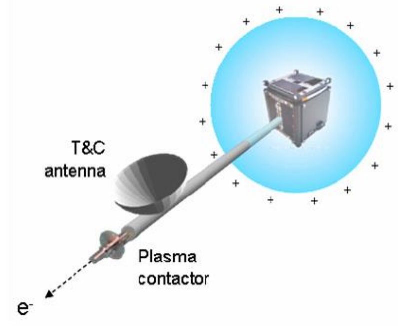


UV/Vis/NIR Absorption and reflection spectra of Al_2O_3 surface after plasma exposure for two different thickness 13 and 25µm.

Charging Strategy for Electrostatic Control of Spacecraft: New Approaches
Michael J. Golightly
NASA Johnson Space Center

Artificial Charging of Spacecraft





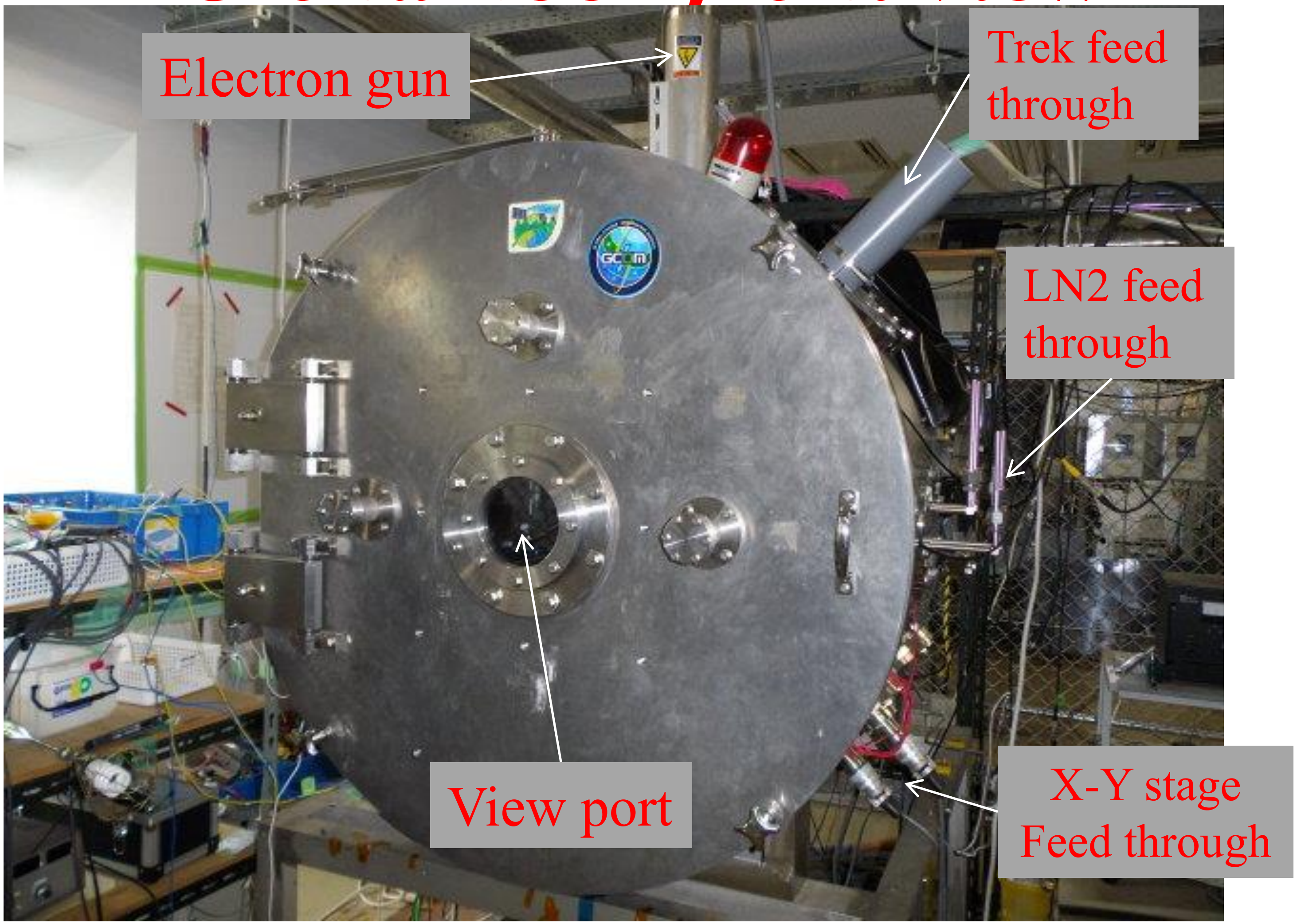
1-Lorentz spacecraft is an electrostatically charged space vehicle that could modulate its net charge on surface to induce Lorentz force via interaction with planetary magnetic field.

2- Natural spacecraft charging may reach to the order of10^ -8 C/kg (Garret and Whittlesey, 2000), which is insufficient to perturb the orbit in a significant way (Vokrouhlicky, 1989).

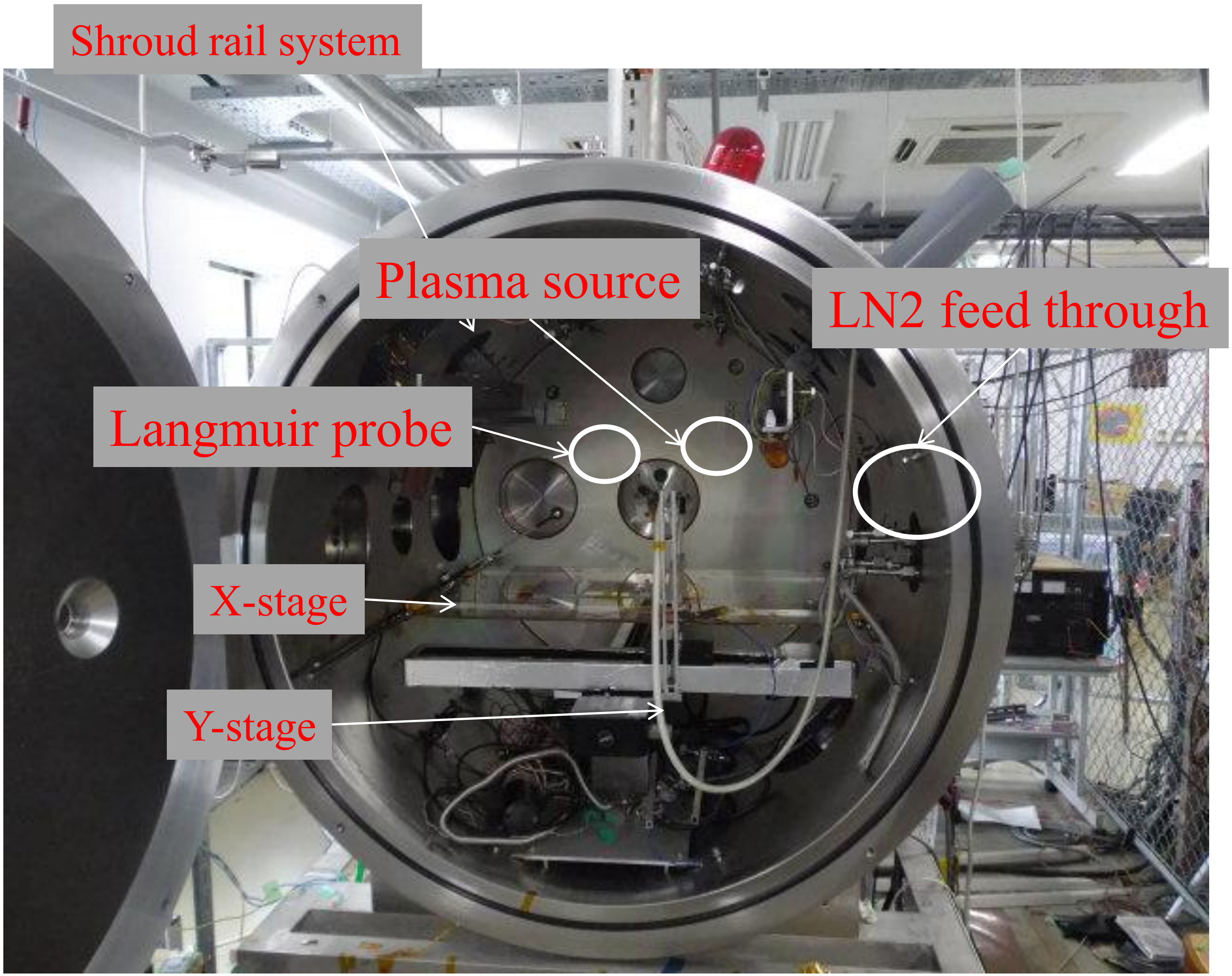
3- To enable more effective orbital maneuvering in LEO, specific charges (i.e., charge-to-mass ratio) on the order of 10^-5 C/kg or even higher will likely to be required (Pollock et al., 2010).

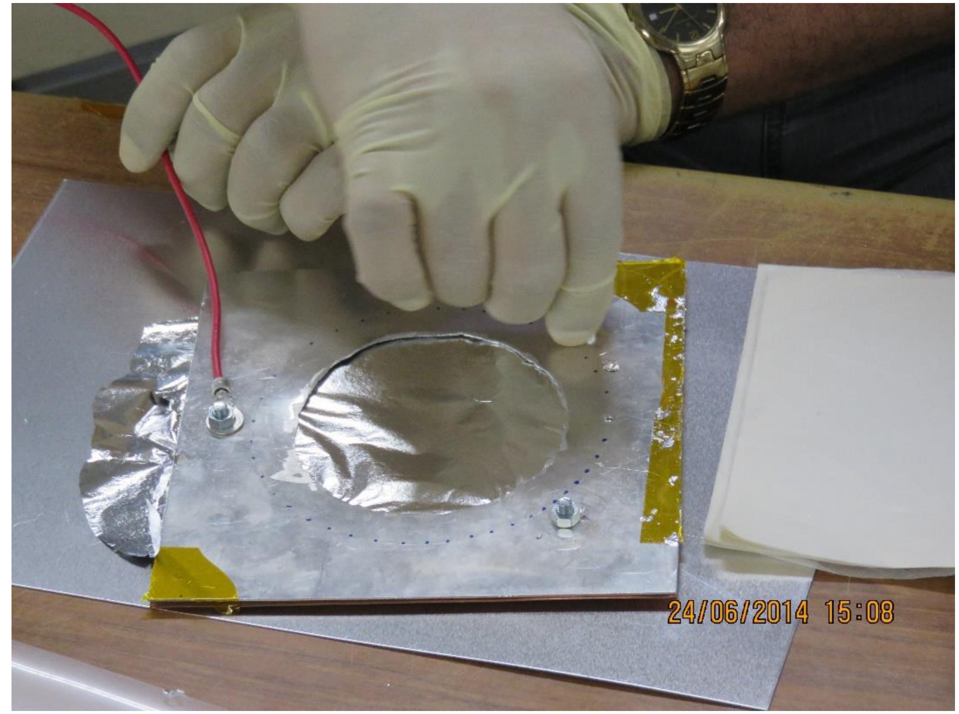
4- The experimental study of a Lorentz spacecraft is ongoing (Atchison

PEO chamber front view



PEO chamber inside view

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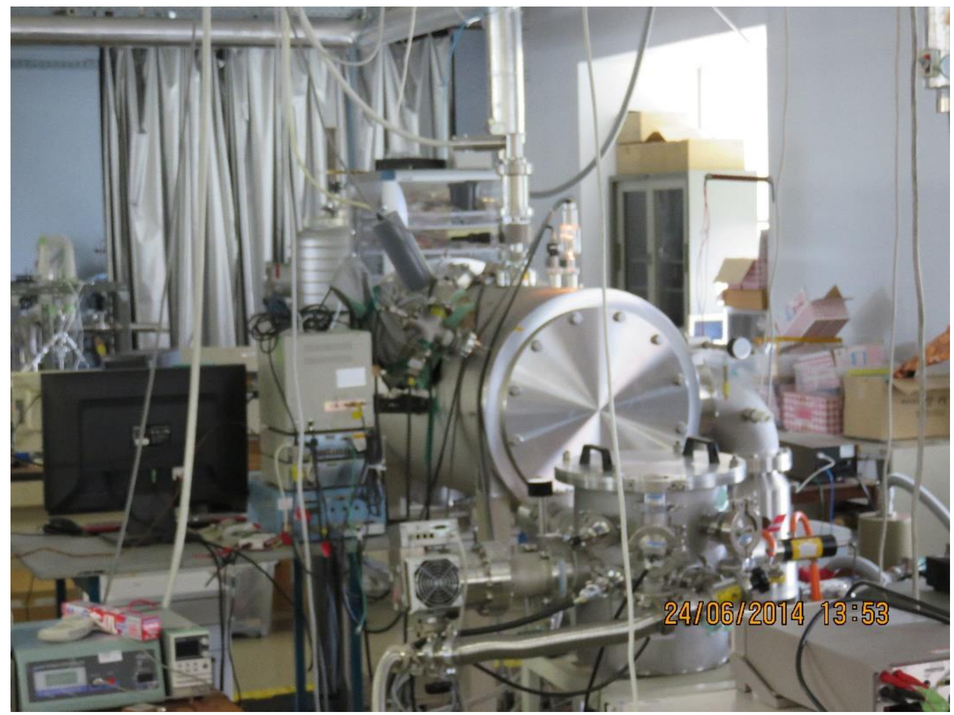
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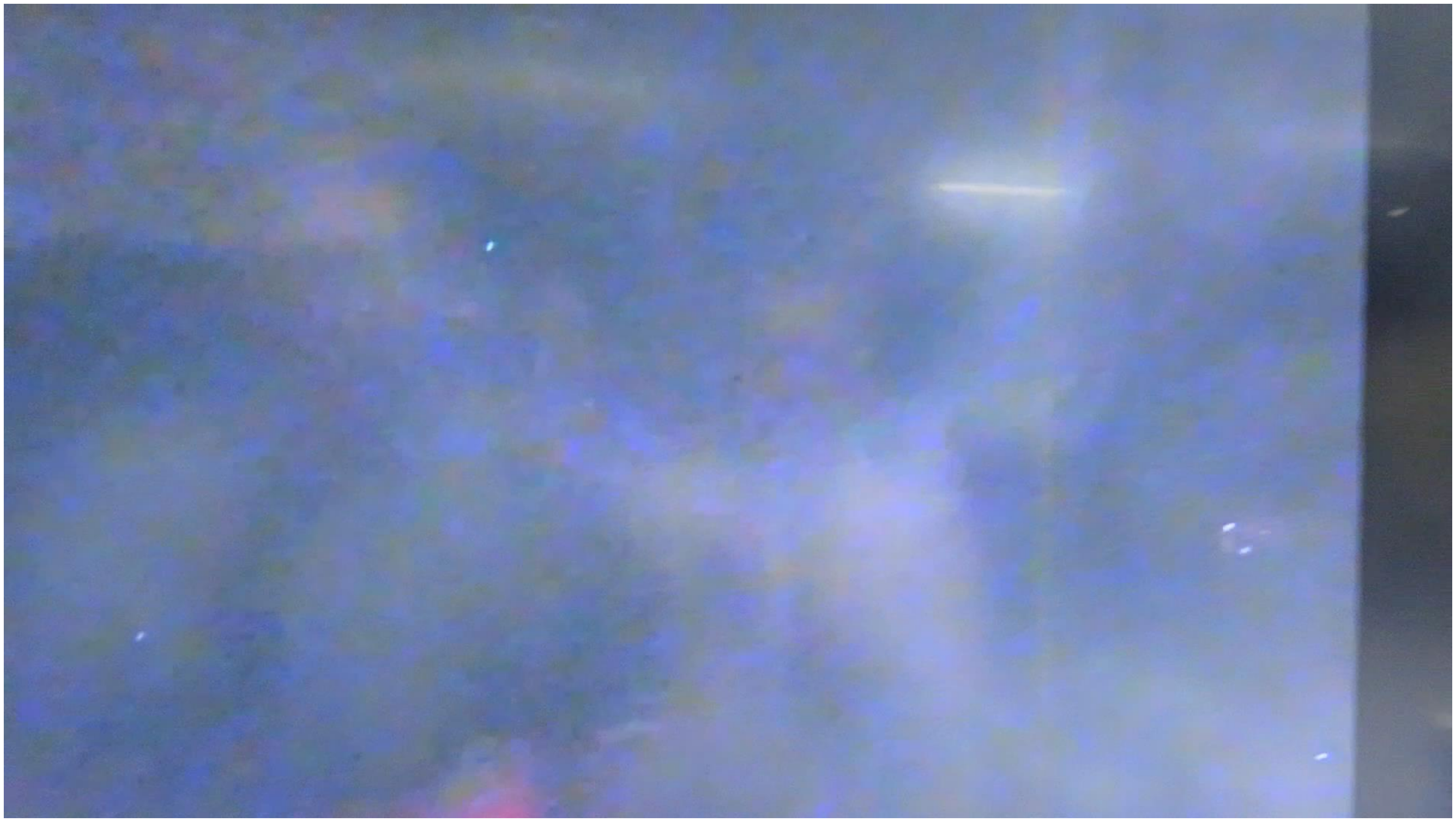
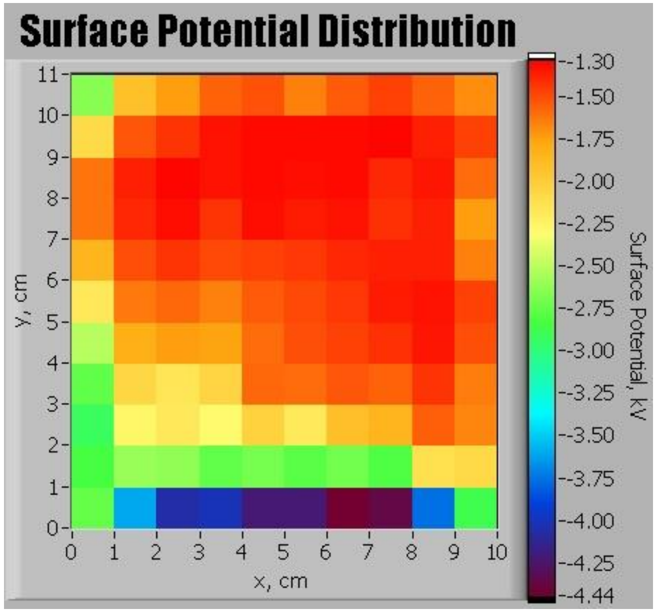
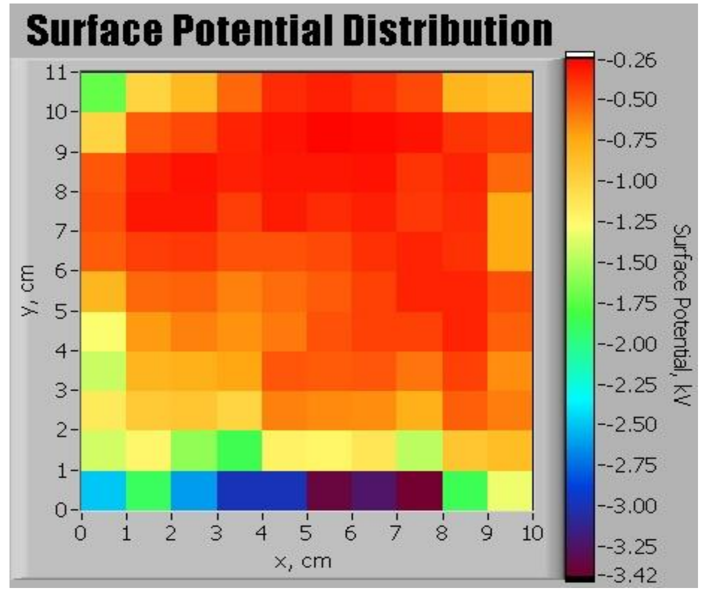
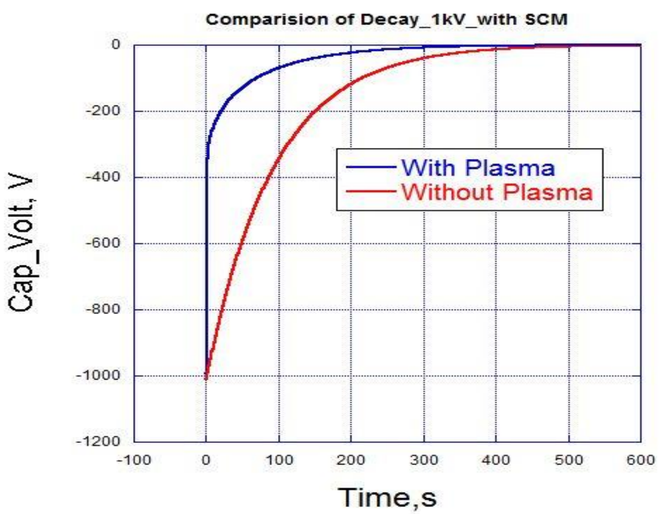
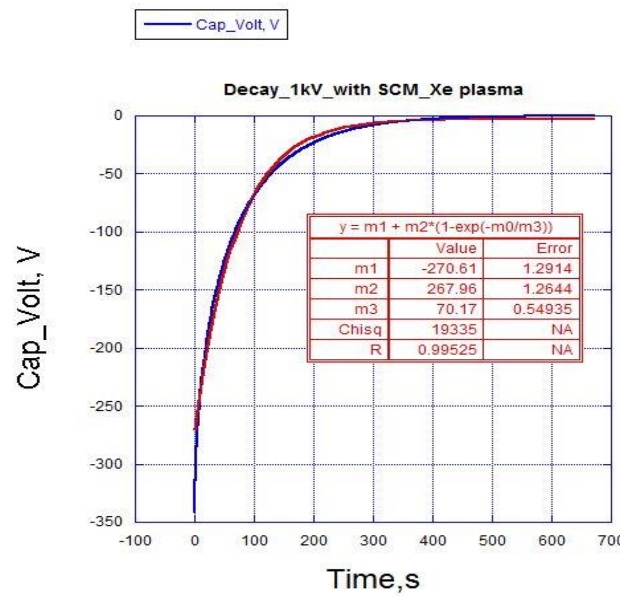


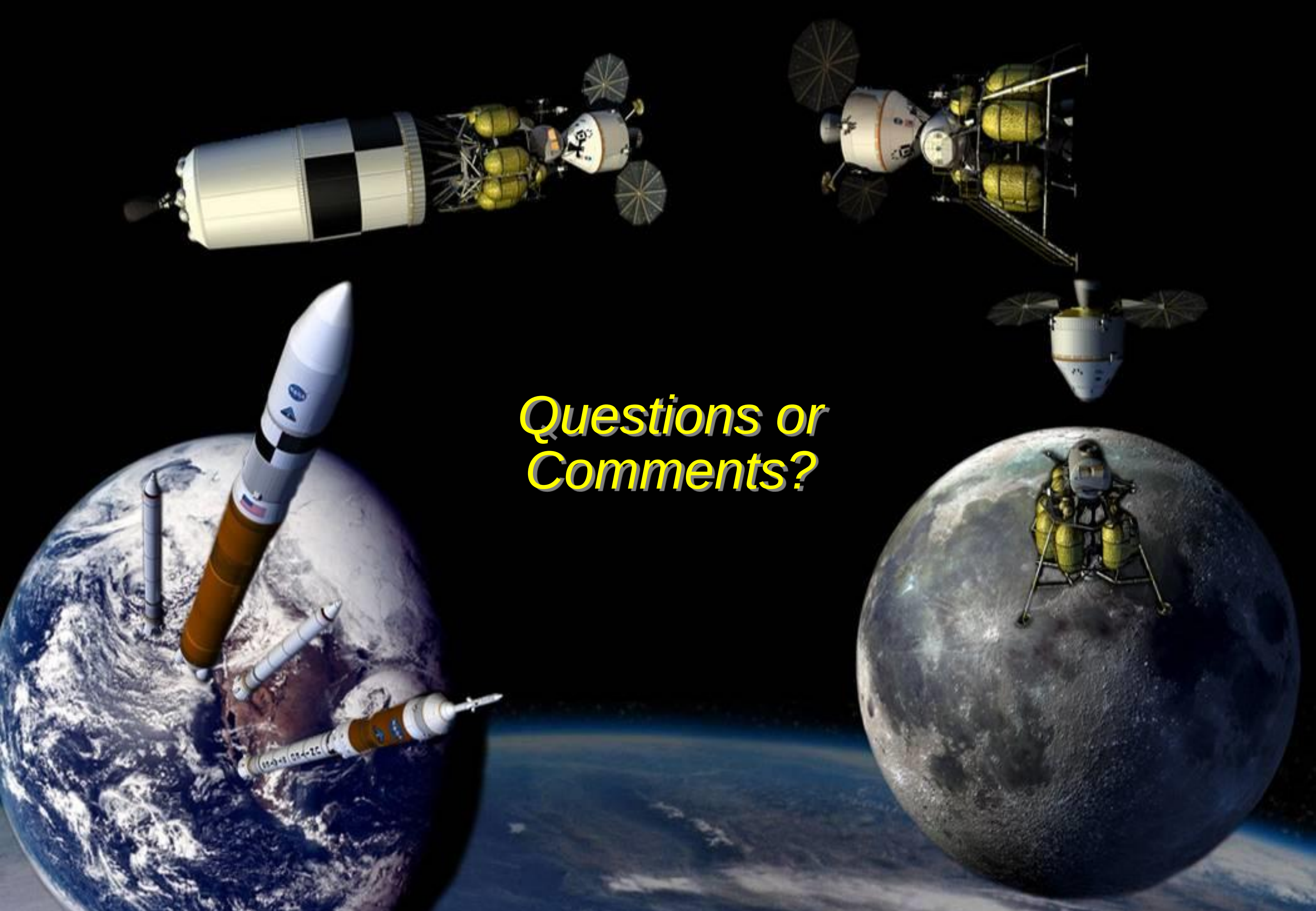
Charging and Discharging of a Spacecraft







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Comments?