Spacecraft Charging Studies in Japan

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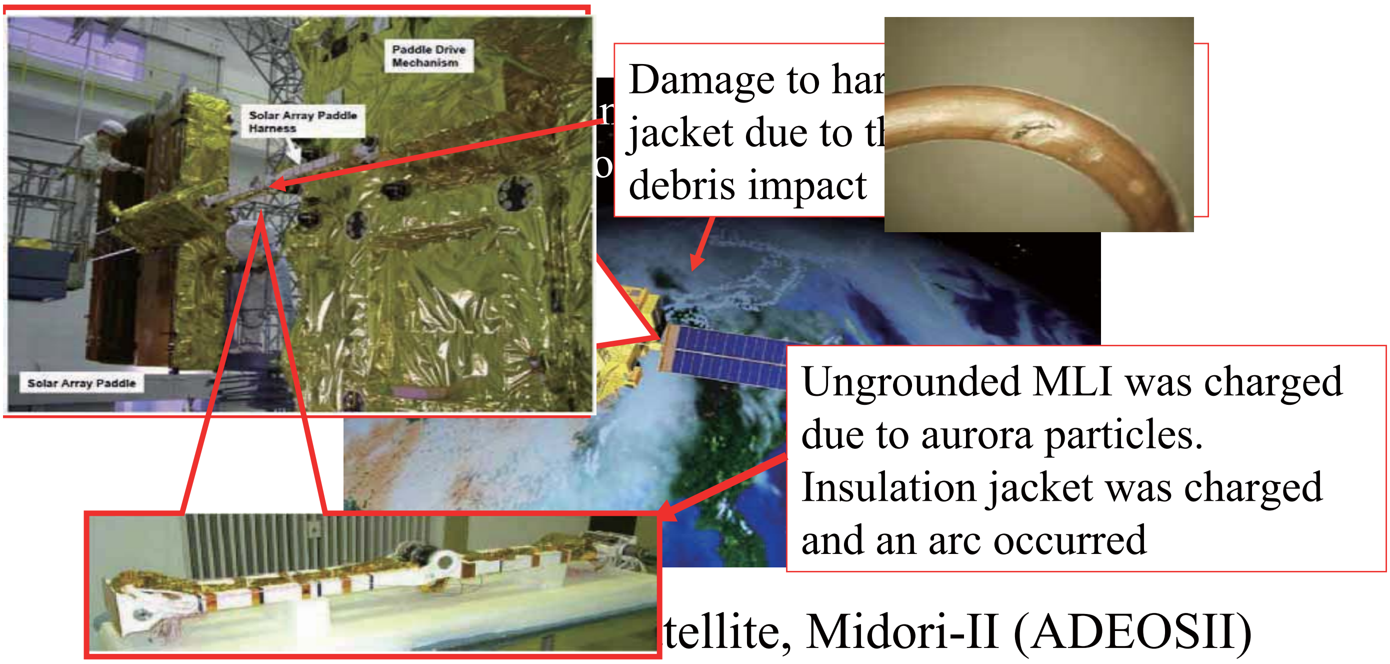
Space Environment Symposium

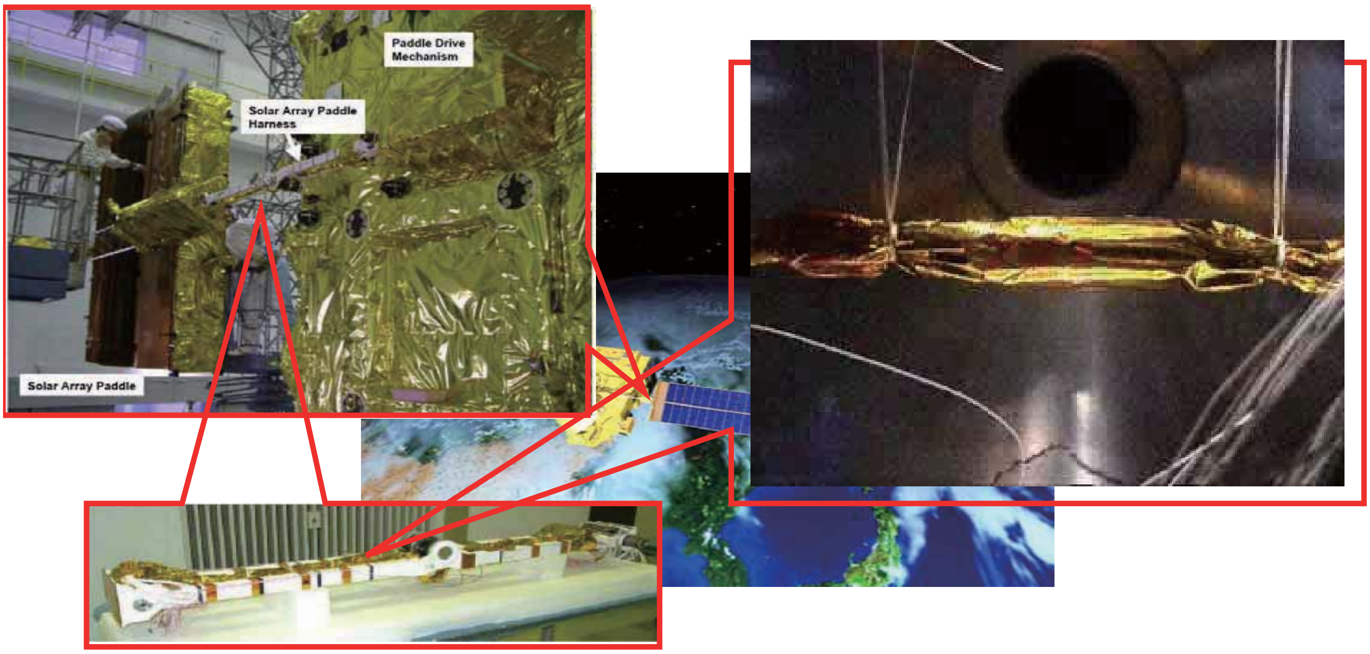
Failure of ADEOS-II



tellite, Midori-II (ADEOSII)

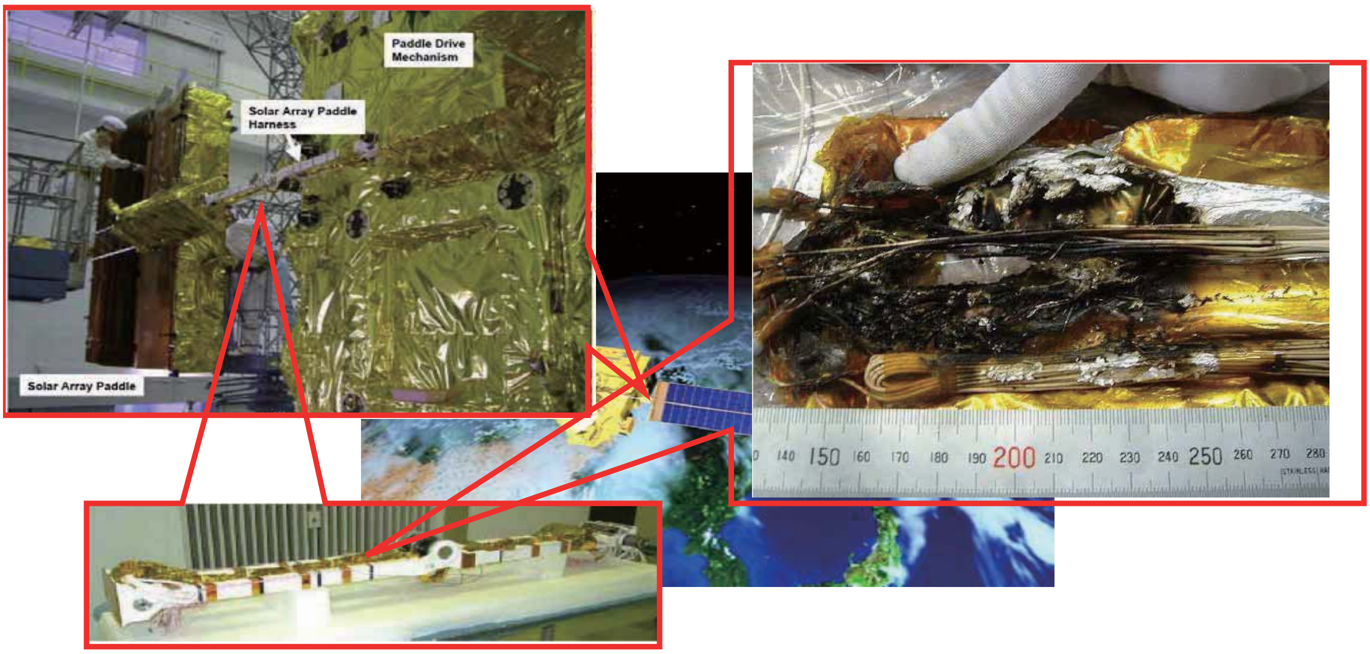
Dec.14, 2002: Launched to 800km PEO on December 14, 2002
Oct. 24, 2003: Complete loss due to power drop to 1kW from 6kW

Failure of ADEOS-II



Charging of power harness bundle by aurora
Arc propagated to 104 wire harnesses and destroyed all of them

Failure of ADEOS-II



Charging of power harness bundle by aurora
Arc propagated to 104 wire harnesses and destroyed all of them

Lessons learned from ADEOS-II failure

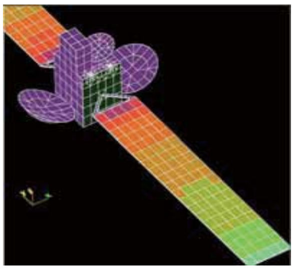
1. Severe charging possible in aurora zone
   - Reexamine PEO satellite designs
2. Charging hazard should be identified in design phases
   - Need of a charging analysis tool
   - Need of experts
3. No floating metal
   - Charging design guideline
4. Importance of pre-launch ground test
5. Importance of cable insulation
6. Importance of thermal analysis
7. Avoid single-point-of-failure
   - Two solar paddles for any spacecraft
8. Promotion of basic spacecraft environment interaction researches
   - Charging mitigation, insulation, cable, debris, material, etc.

Spacecraft Charging Activities in Japan since ADEOS-II

- Development of MUSCAT
- Material characterization campaign
- ESD tests
- ISO standardization of solar panel ESD tests
- Charging design guideline
- On-orbit measurement
- Development of charging mitigation methods

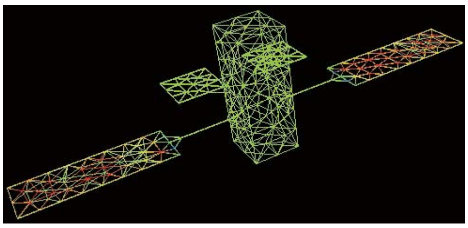
Development of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT)

Next Generation S/C Charging Analysis Tools



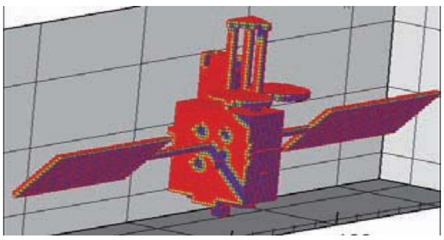
U.S.A : NASCAP-2K
(NASA Charging Analyzer Program 2000)

→ Subject of export restrictions



Europe : SPIS
(Spacecraft Plasma Interaction Software)

→ Open source
Need simulation experience



Japan : MUSCAT (KIT & JAXA)
(Multi-Utility Spacecraft Charging Analysis Tool)

→ Completed Ver.1 (March, 2007)

Development of MUSCAT

- MUSCAT (Multi-Utility Spacecraft Charging Analysis Tool)
  - Developed at KIT with JAXA from December 2004 to March 2007
    - Employed 4 full-time post-docs
  - Spacecraft charging of LEO, PEO, GEO satellites
  - First version release in spring 2007

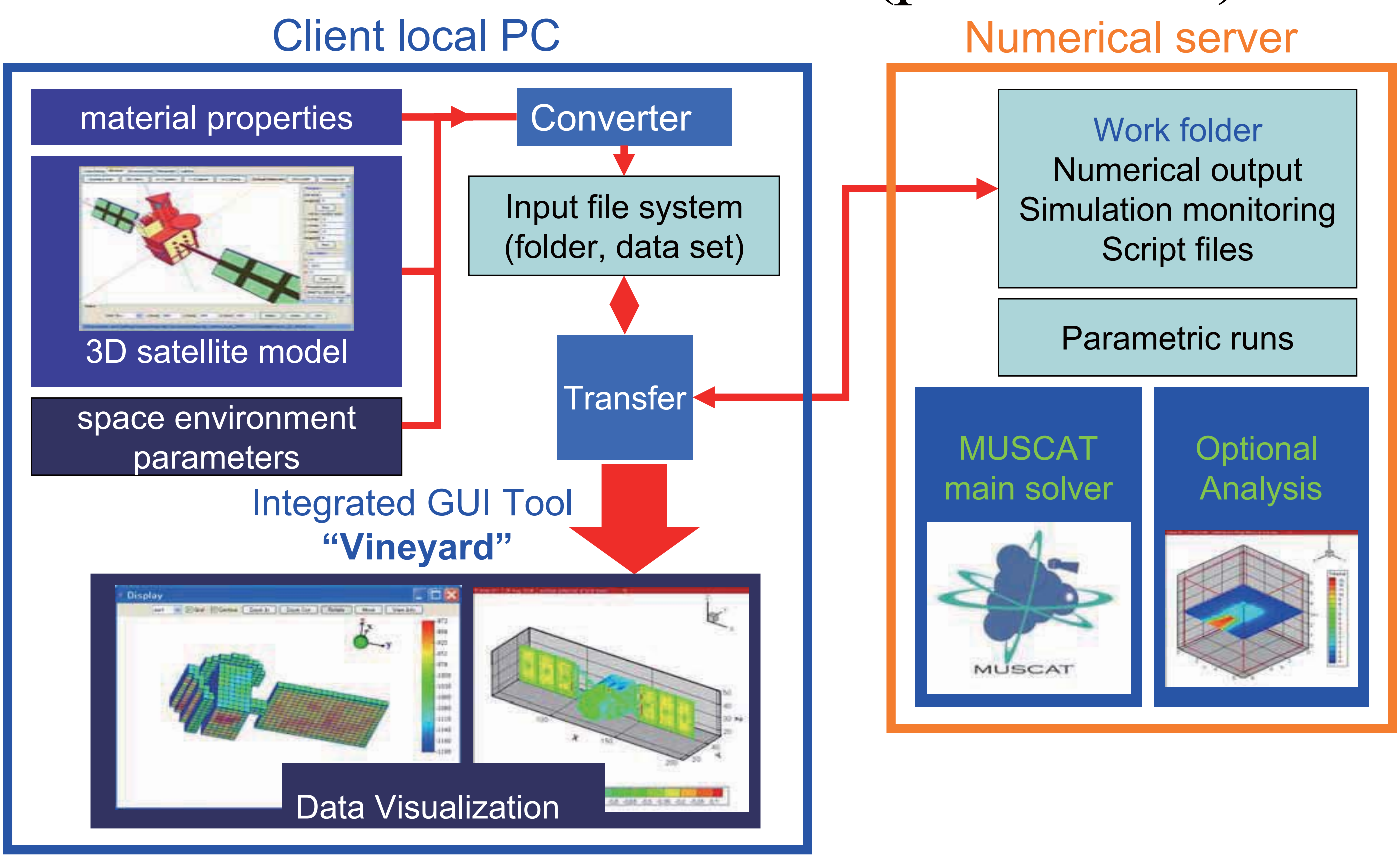
Development strategy

1. Multi-Utility Use → LEO, PEO, GEO
2. User-friendly → Graphical User Interface (GUI)
   → Client-Server model
3. High-speed → Parallelization and tuning
4. Accuracy → Code Validation
5. Parametric runs → Robust computation function
6. Traceability → Support by a commercial company

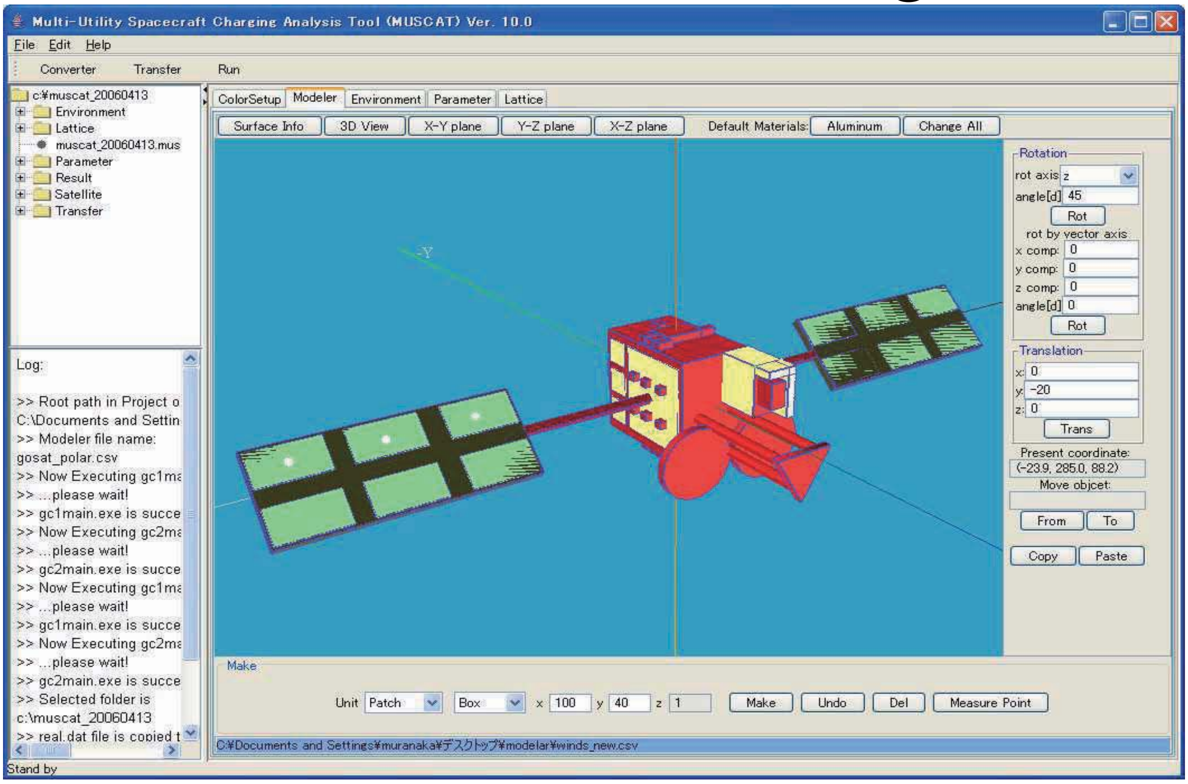
Development framework

General overview	JAXA
Code development	KIT
Validation experiment	KIT
	ISAS/JAXA
Space environmental parameters	JAXA
	NICT
Validation by large scale simulation	GES (Kyoto Univ., NIPR)

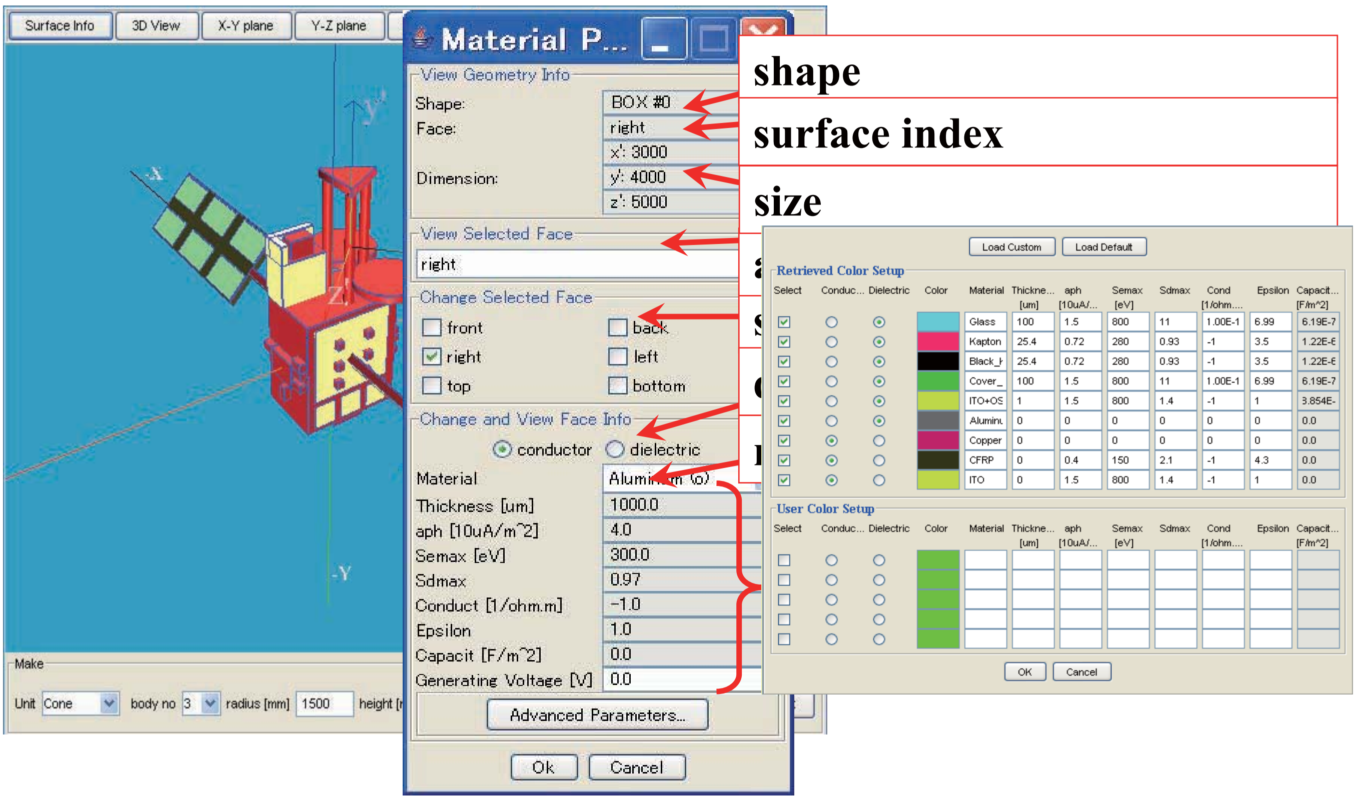
How MUSCAT Work? (procedures)



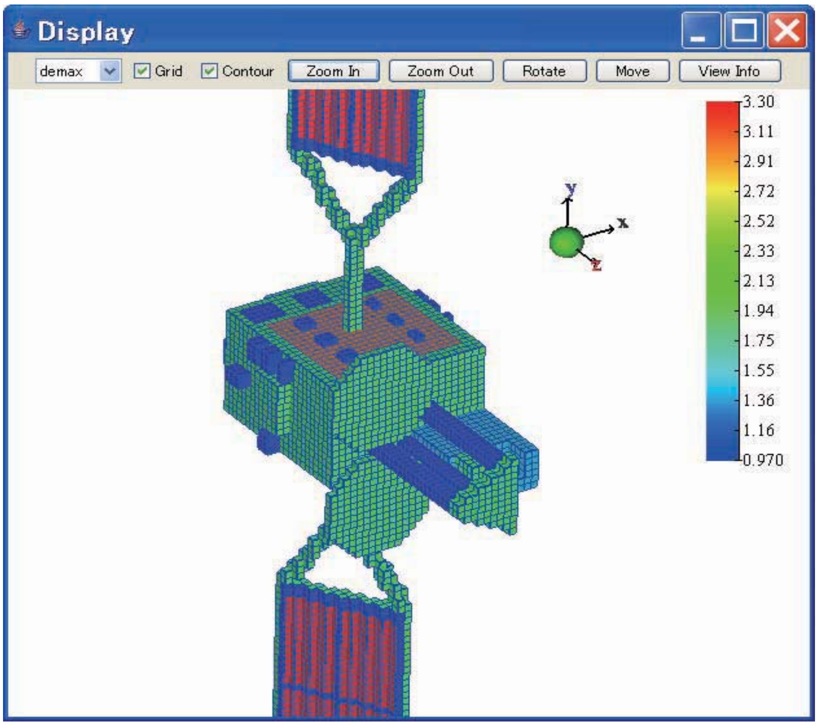
3D Satellite Modeling



Surface Properties



Geometry Conversion to Rectangular Elements

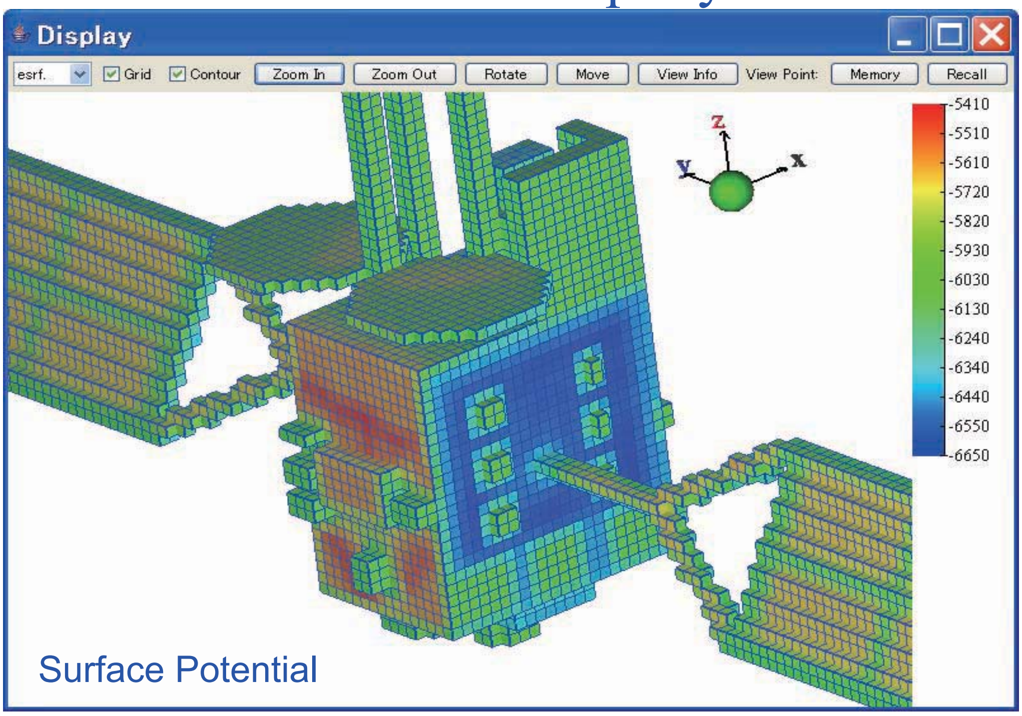


General 3D geometry

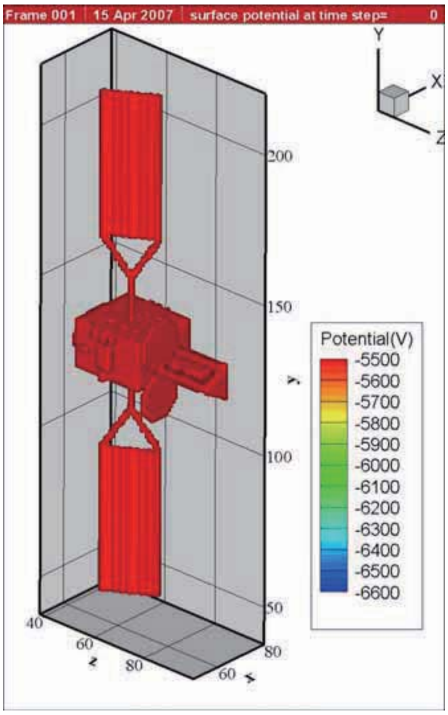
Rectangular grid
(for the MUSCAT solver)

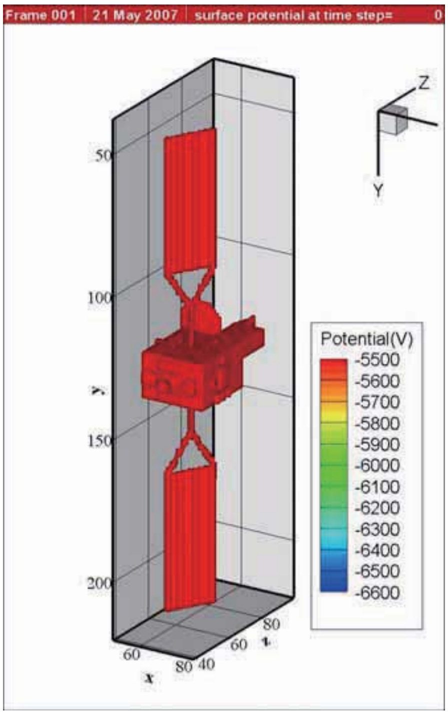
Visualization of Numerical Data (1)

3D Surface Property



Simulation results





3D spacecraft charging simulation

Accuracy depends on

1. Material charging property data
   - Secondary electron, photo-electron, conductivity, etc
2. Environment data
   - Plasma density, temperature
3. Satellite geometry

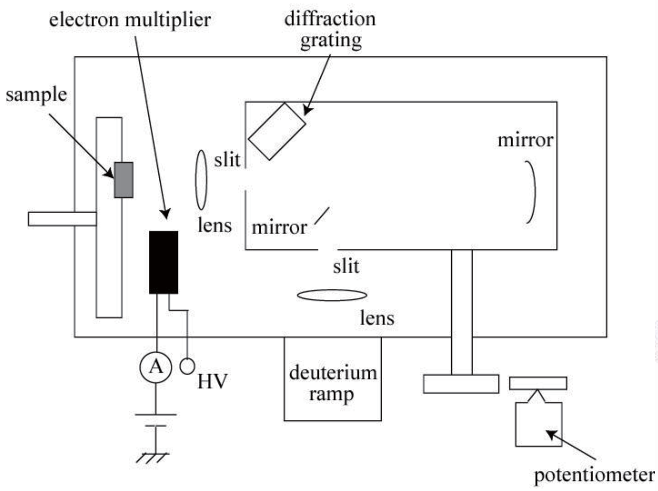
Material properties measurement

- Secondary electron emission ("Delta Max" and "E-Max")
- Photoelectron emission
- Bulk resistivity
- Surface resistivity
- JAXA campaign (2005~)
  – For BOL and EOL material
- KIT campaign(2008~)
  – For EOL material

JAXA campaign framework

Material property	The range of primary energy	Place
Secondary electron emission (SEE)	Acceleration voltage : 600V-5kV	High Energy Accelerator Research Organization (KEK)
	Acceleration voltage : 200V-1kV	Musashi Institute of Technology
Photoelectron emission (PE)	Wavelength 110 to 400 nm	Musashi Institute of Technology
Bulk resistivity, Surface resistivity		Saitama University

JAXA campaign framework



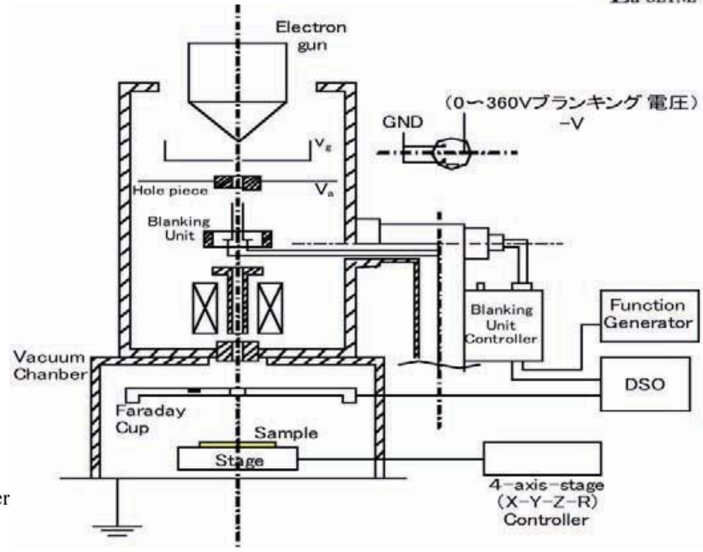


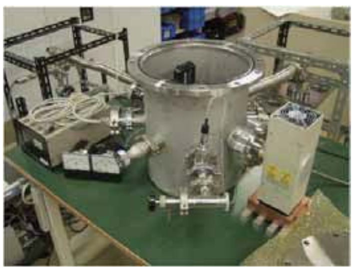
Photo-electron measurement @ Musashi Institute of Technology

Secondary-electron measurement @ KEK

From K. Nitta, JAXA

KIT campaign

- Material charging properties
  - Secondary electron coefficient
  - Photoelectron coefficient
  - Bulk Conductivity
  - Surface
- For degraded (UV, AO, thermal cycles) materials



UV

Thermal

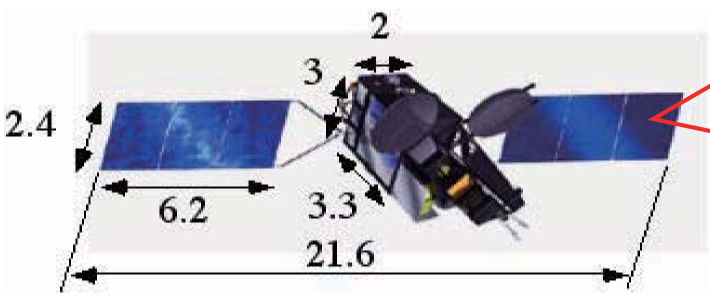
AO

Secondary and photo electrons

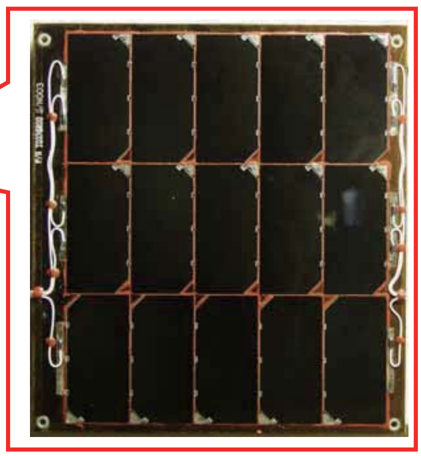
What do we do in satellite design in Japan?

- Before launch, we have to check
  - Does the satellite charge to the arc threshold?
    - Computer simulation
  - If yes
    - Ground test
      - Make sure that the satellite operates even with arcs

Electrostatic discharge test

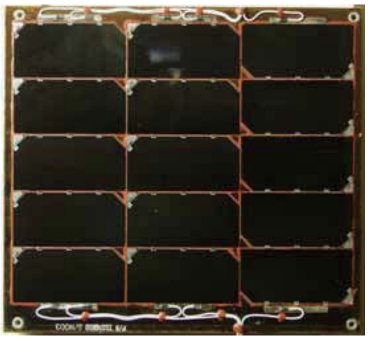


WINDS

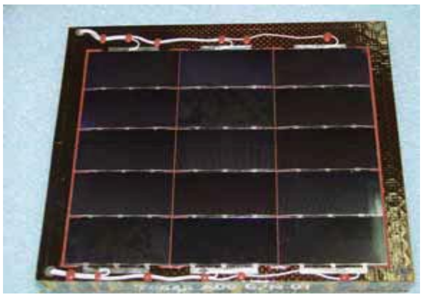


- Prepare flight-representative coupon made of same material and same production process
  - Real satellite uses thousands to several tens of thousands solar cells

Electrostatic discharge test



WINDS



ETS8/ALOS

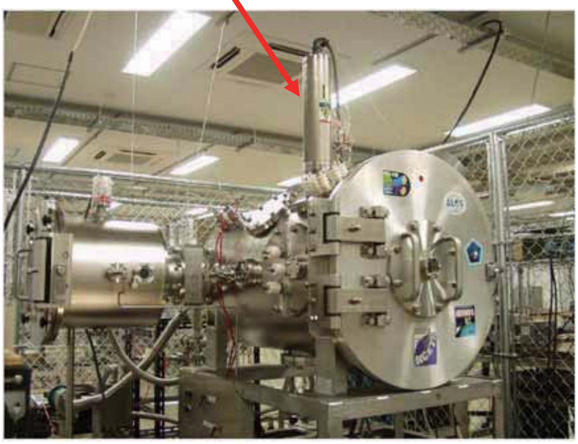
ALOS

- Prepare test coupons for each satellite

Electrostatic discharge test

Energetic electron beam

surface potential probe



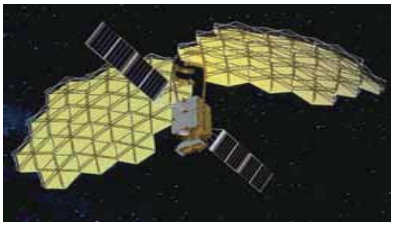
coupon

XY stage

- Reproduce the same environment as in orbit
  - Vacuum
  - Plasma

Records of Electrostatic Discharge Test at KIT


Hayabusa(2003)


Kiku-8 (2006)


Kizuna(2008)

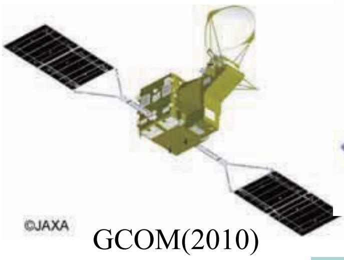

Himawari-7(2006)


Midori-2(2003)
Failure investigation

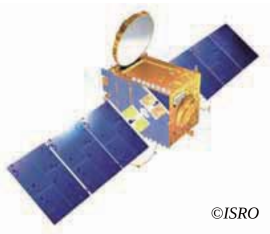

Daichi(2006)


Kirari(2005)


Ibuki(2008)



GCOM(2010)



India(ISRO)

USA(SS/L)

Chinese(CAST)

Testing of satellites from all over the world

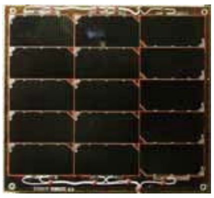
What do we investigate?

- Primary arc
  - Degradation due to repeated primary arcs
  - Estimate the power degradation at EOL
    - Number of ESD events from charging analysis
    - Primary arc inception threshold
    - Degradation probability per primary arc
- Secondary arc
  - Power circuit string failure
- Occasionally
  - Other components such as cable, connector and diode boards, etc.

Need of international standard

- Series of satellite anomalies due to ESD on solar array and power systems
- Different ground ESD test methods/conditions in each country
- Internationalization of commercial satellites demands standardization of ground test methods

Component maker



Satellite manufacturer

http://www.ssloral.com/html/satexp/optusc1.html

Launch provider

http://arianespace.com

Service provider

http://www.dishtvsatellite.net/

Insurance company

http://www.kanagawa-nissan.co.jp/ucar/flow.html

They can be all different countries. What if something goes wrong in space?

9th Spacecraft Charging Technology Conference

- 124 participants, April, 2005

Resolution passed at 9th SCTC

La SEINE

Experts on spacecraft ESD ground test who participated in the round table discussion on ESD test at 9th SCTC have agreed

- to fully cooperate and make best efforts as experts to draft an ISO standard on solar array ESD ground test by 10th SCTC and **establish the standard within 3 years**
- to try to resolve disputes over the test methods by 10th SCTC

9th SCTC
April, 6, 2005

NEDO-grant research

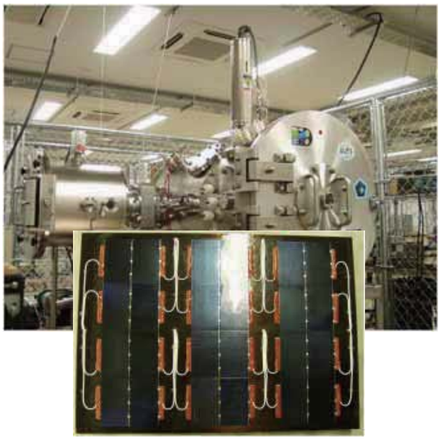
La SEINE

- **ISO Standardization of Electrostatic Discharge (ESD) Test of Satellite Solar Array**
  - Sponsored by NEDO (New Energy and Industrial Technology Development Organization) International Joint Research Project
  - Subsidiary of Ministry of Economy, Trade and Industry
  - 3year project from October 2005 ~ September 2008
  - Participation of KIT, JAXA, Sharp, Mitsubishi Electric, NEC-Toshiba Space, ONERA, CNES, Alcatel-Alenia Space, Astrium, NASA, OAI

International round-robin experiment

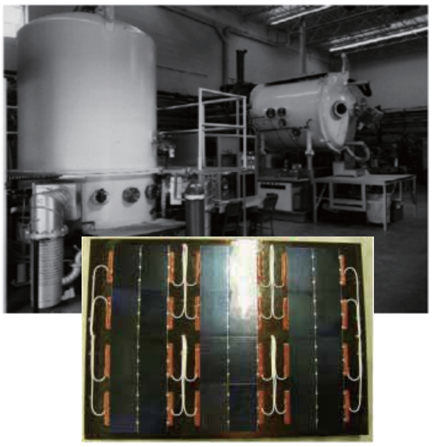
- Identical test coupons to 3 research institutions
- Resolve difference in physical understanding

KIT(Japan)



ONERA(France)

NASA/GRC(US)



ISO Standardization of Electrostatic Discharge (ESD) Test of Satellite Solar Array

1st workshop at Kitakyushu in November 2006

2nd workshop at Biarritz in June 2007

3rd workshop at Cleveland in September 2007

4th workshop at Tokyo in January 2008

–Currently registering as DIS (Draft International Standard) 11221

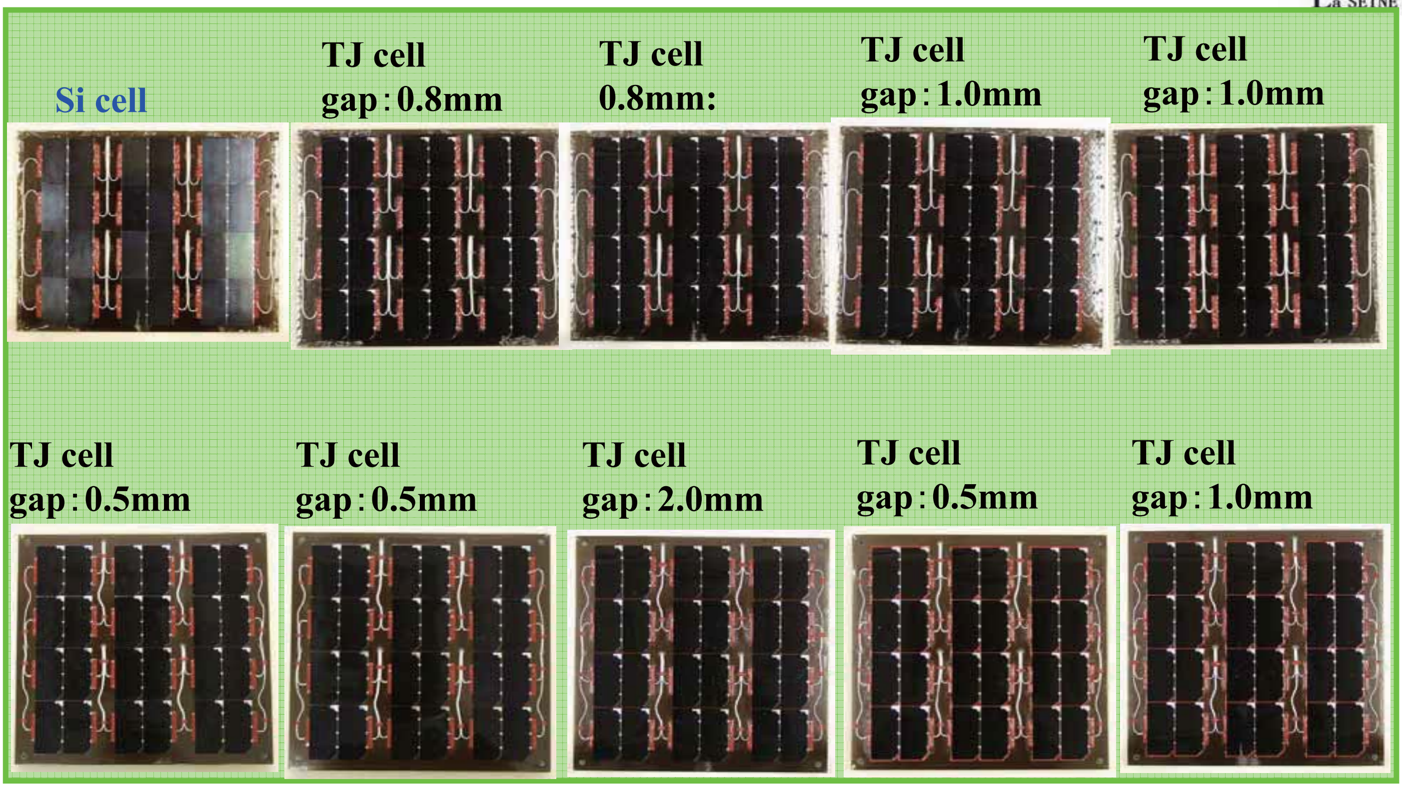
–Promoting ISO-based procedures in China and India

Expect to have ISO-11221 in 2009

Charging Design Guideline

- Japanese charging design guideline
  - Similar to NASA TP-2361, ECSS-E20-06
- Started in 2005
  - Participants from JAXA, industry and universities
- To be published as JERG-2-211 soon
- Take the data ourselves if it is unknown
  - Solar array secondary arc criteria
  - Material conductivity

Japanese spacecraft charging design guideline



Define TSA and PSA thresholds for various solar array designs
Sponsored work by JAXA

Design guideline

Triple-junction 1.0mm gap

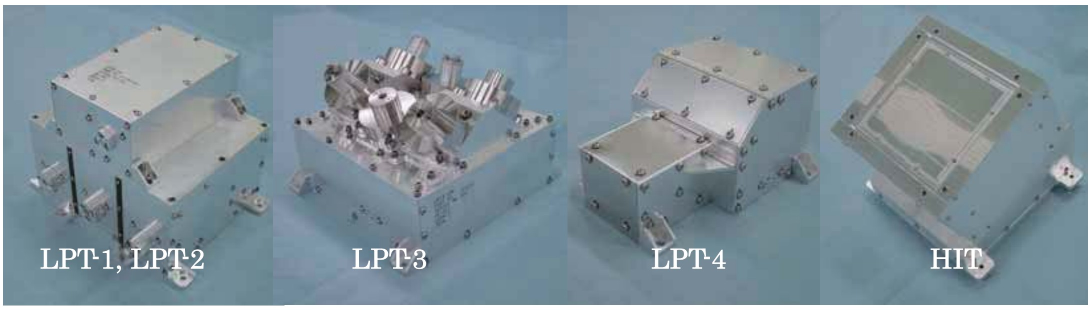
Gap voltage, V_{st}, V	String current, I_{st}, A			
	0.5	1.0	1.5	2.0
30	No secondary arc up to 4.0A			
50				
70				
90				
110				

PA **NSA** **TSA** **PSA**

Safety for Vst≦30V or Ist≦1.0A

On-orbit measurement

Ibuki, To be launched in January 2009



LPT: Light Particle Telescope
HIT: Heavy Ion Telescope

From H. Matsumoto

On-orbit measurement

Jason-2 satellite, launched on June 20, 2008

LPT-E

LPT-S

From T. Obara

Charging mitigation

1. All the surface is insulator
2. All the surface is (semi-) conductive
3. Discharge inception at safer place (lightning rod)
4. Emit charges from spacecraft (electron emitter)

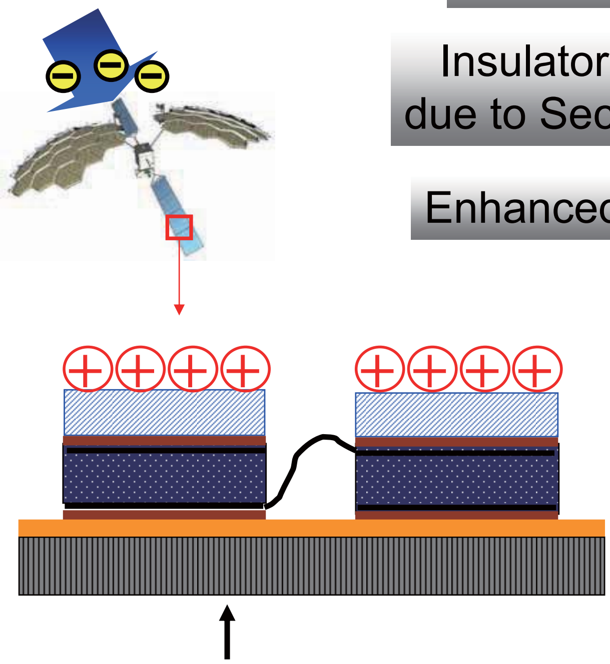
ESD Mechanism in GEO Satellite

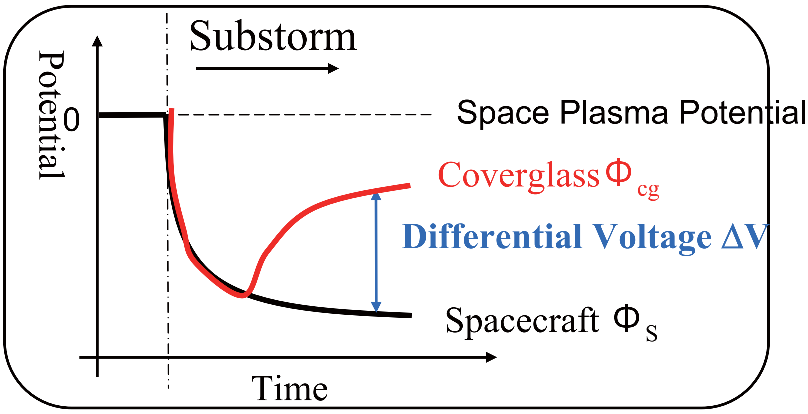
Encounter with Energetic Electrons during Substorm

Spacecraft Potential becomes Negative

Insulator Potential becomes more positive due to Secondary Electron and Photoelectron

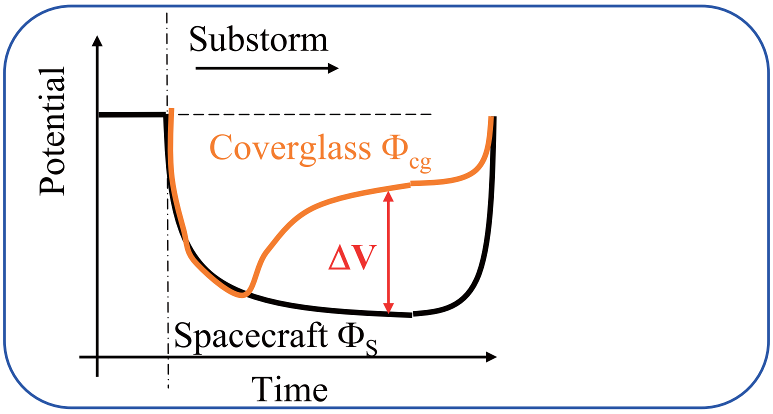
Enhanced Electrical Field on Triple Junction

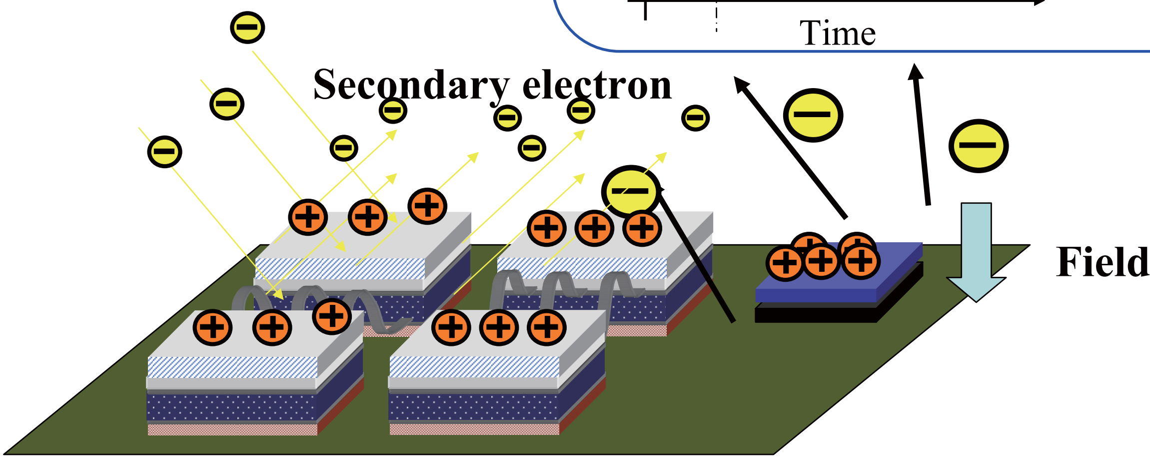




Danger: Inverted Potential Gradient (Threshold:400V)

ESD mitigation via electronemission



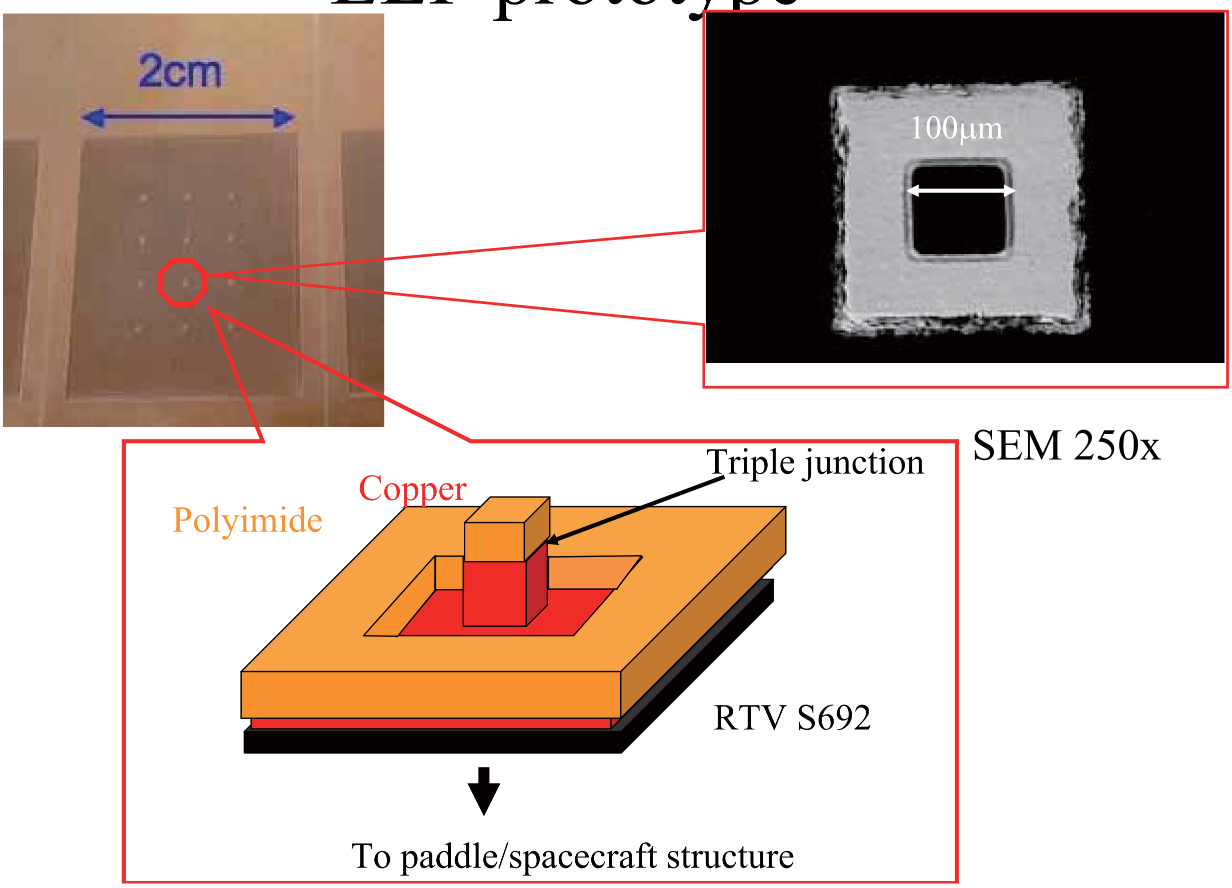


Unique Features of Device

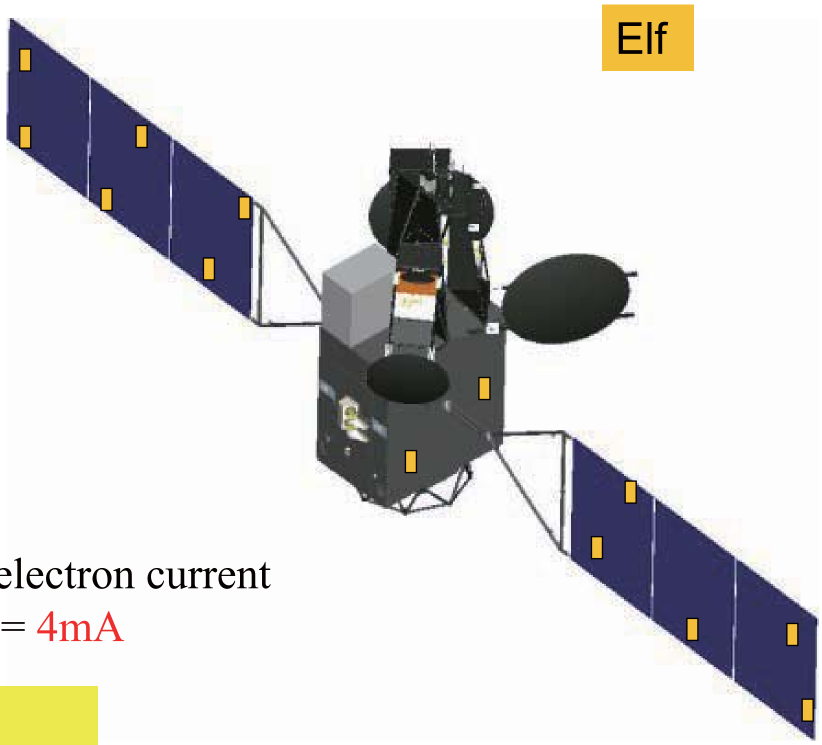
- Passive Device
  The device has the role of both the charging monitor and the electron emitter.
- No Electrical Power
- Light weight
- Space-Grade Materials are used
  All materials constituting the device are flight proven already.
- Attach Everywhere !
  No cable. The device is attached with flight-proven conductive adhesive.
- Robust
  Strong against air exposure and contamination.

ELectron-emitting Film for Spacecraft CHARging Mitigation (ELF'S CHARM)

ELF prototype



Installation



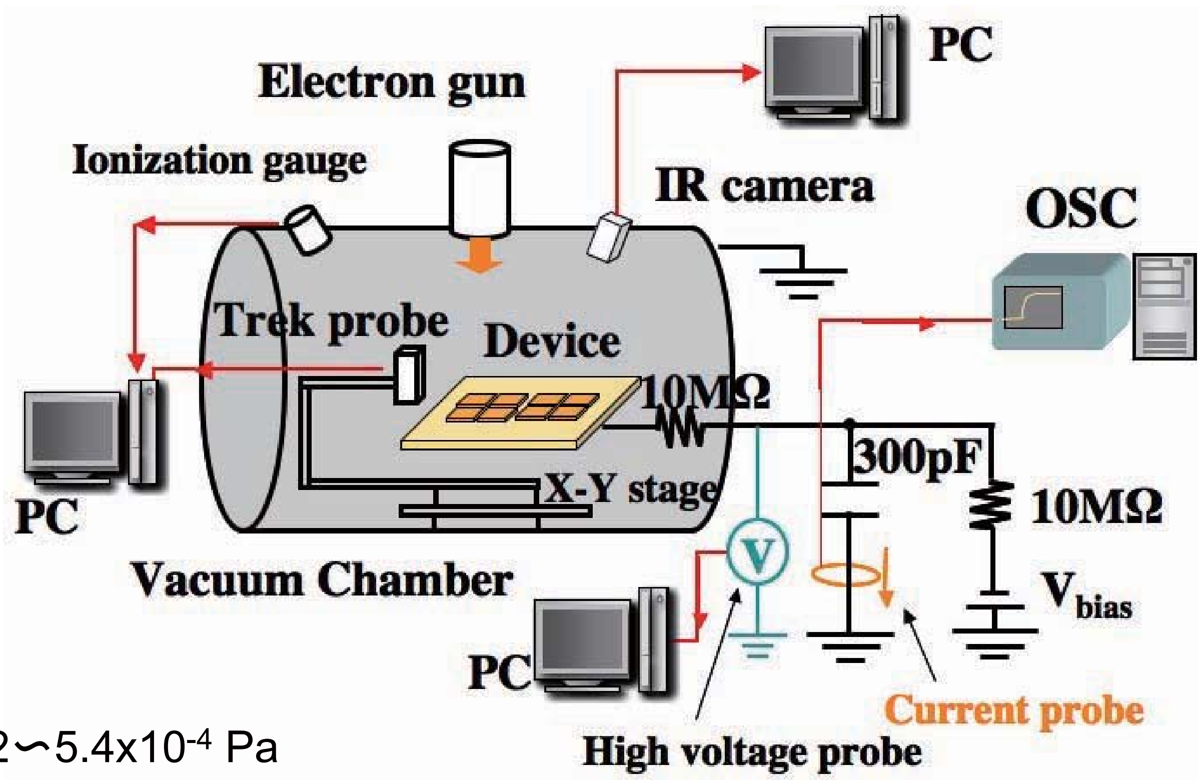
Each piece is
> 2cmx2cm
< 0.1g
≥ 50μA

Maximum incoming electron current
$= 400m^2 \times 10\mu A/m^2 = 4mA$

100 ELFs are enough

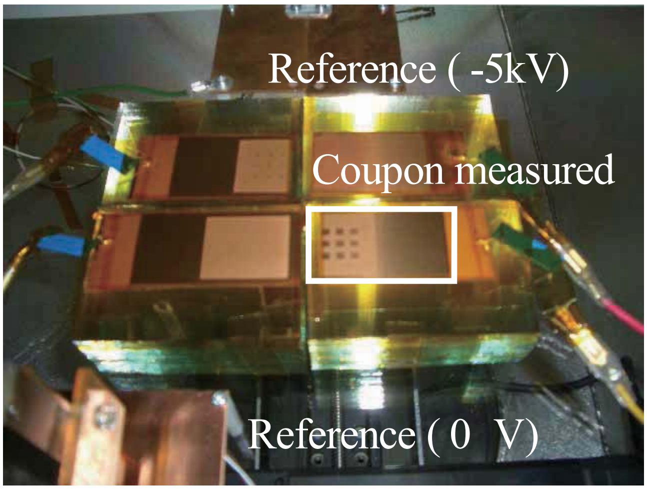
Total weight < 10gram

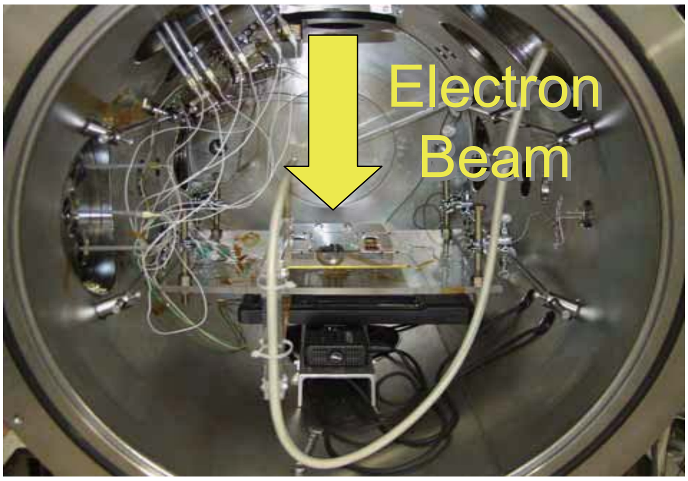
Laboratory experiment



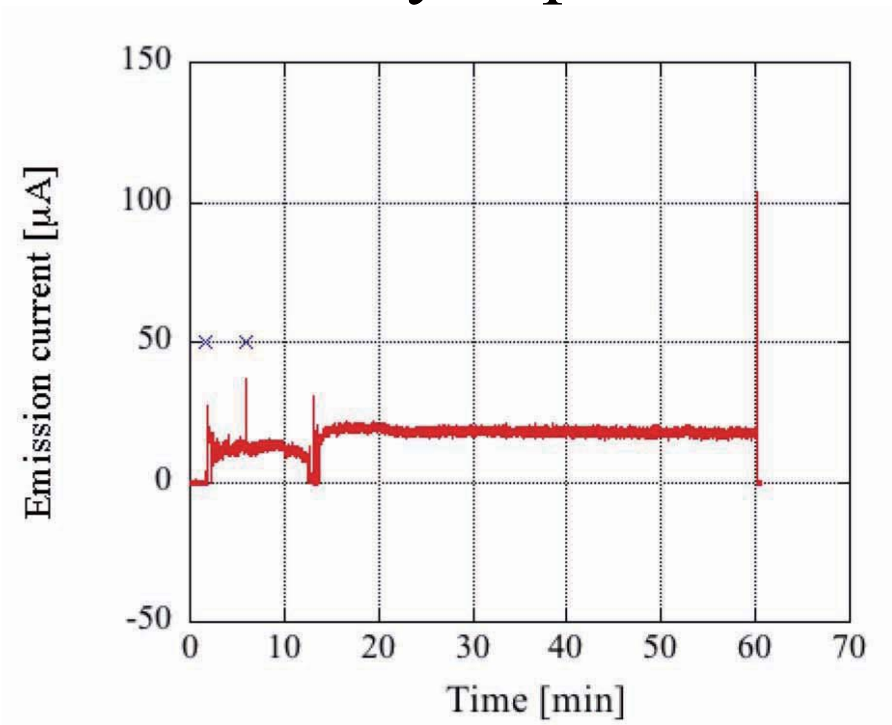
$2〜5.4 \times 10^{-4}$ Pa

Laboratory Experiment





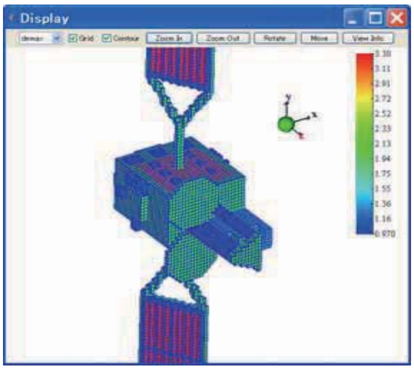
Laboratory experiment



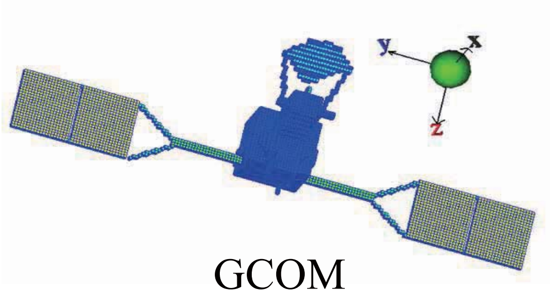
Stable emission of as long as 4 hours confirmed
Electron emission as high as 700μA confirmed

Future directions

- Improving satellite reliability via continuing efforts on
  - Spacecraft charging simulation via further update on MUSCAT
    - Incorporation of user feedback
    - Material property database
    - Environmental database
    - Integration with other environmental simulation tools such as radiation, debris impact, contamination, etc



WINDS



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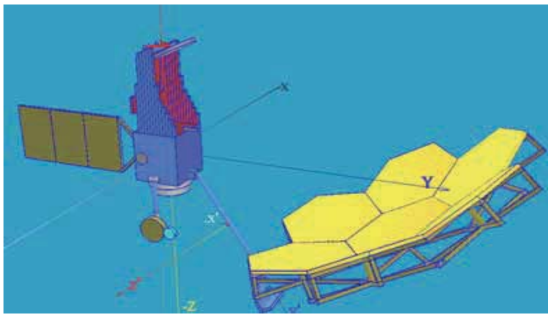
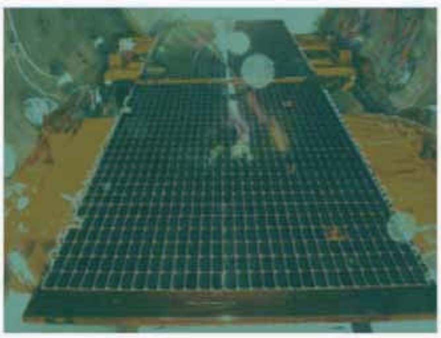


ASTRO-G

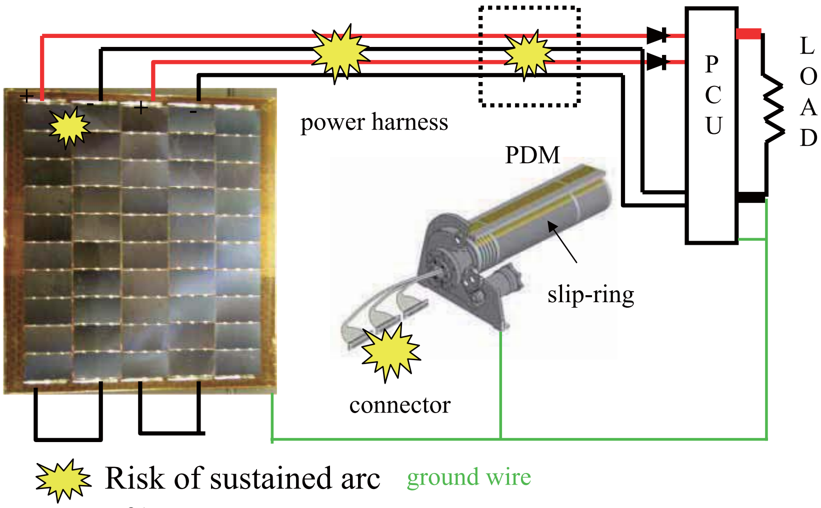
Future directions

- Improving satellite reliability via continuing efforts on
  - ESD ground test
    - Revising ISO standard and charging design guideline based on basic researches on
      - Flashover current
      - Effects of solar array impedance
      - Environmental exposure effects such as thermal cycle, radiation, etc
      - Statistical treatment of the test result
    - ESD tests on other components such as paddle drive motor, cable harness, connectors, diode board, etc
    - ESD tests on new technologies such as thin-film cells, monolithic diode, etc



Large solar panel test for flashover current measurement

From Mashidori et al.



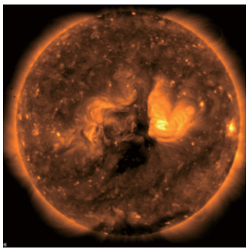
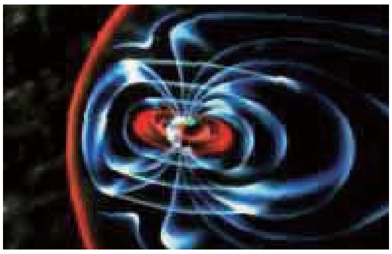
Future directions

- Improving satellite reliability via continuing efforts on
  - International collaboration through ESD test ISO standardization projects
    - Proposal of on-orbit ESD measurement
      - Measurement of flashover current
        - » How big and how long is the current waveform?
      - Measurement of solar cell I-V curve
        - » Hard evidence of solar cell degradation due to primary arc
      - Need to find a GEO (or PEO) satellite to carry instruments
      - International collaboration is the key to the success of the project
  - Development of charging mitigation device
    - On-orbit validation of the new charging mitigation methods such as
      - Electron emitting film
      - Semi-conductive coating

Future directions

- Promotion of fundamental studies
  - Interdisciplinary studies
    - Link to space weather

Solar activity → near-spacecraft environment → spacecraft charging

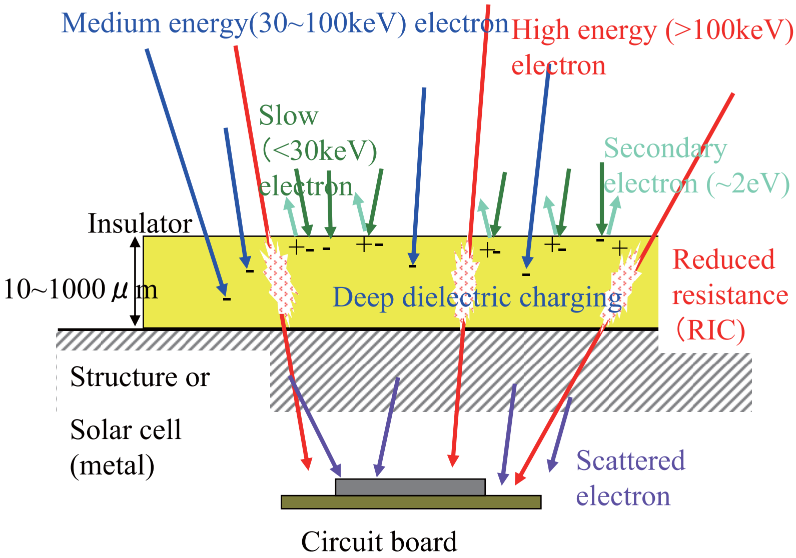

- Lunar and Planetary environment

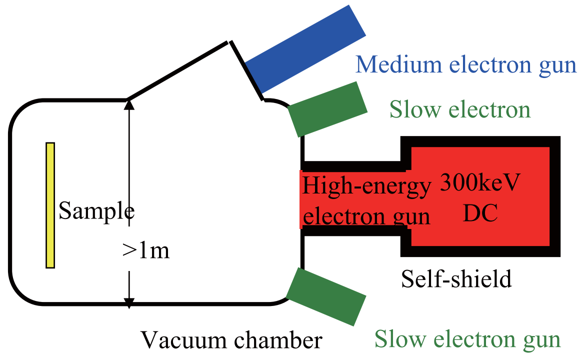
http://edu.jaxa.jp/materialDB/detail.php?material_id=71276

http://www.npr.org/templates/story/story.php?storyId=6907833

Future directions

- Promotion of fundamental studies
  - Experimental simulation
    - Multi-energy-spectrum charging test facility
    - Synergetic effects due to electrons of different energies

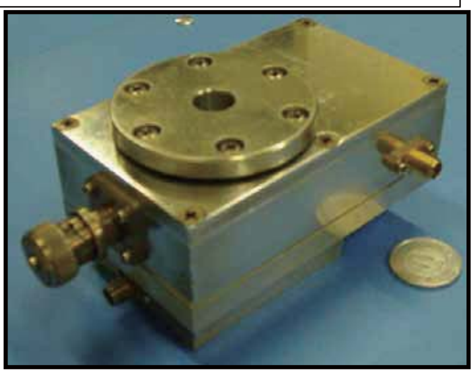




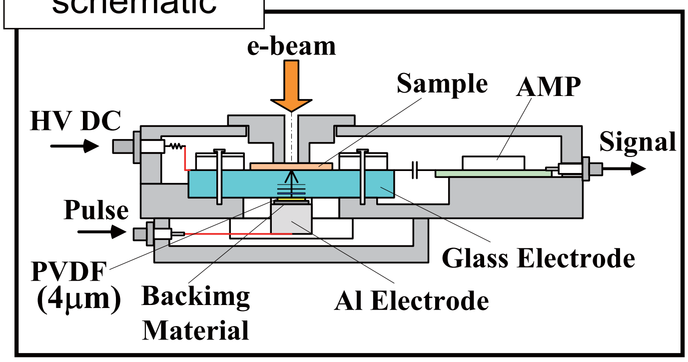
Future directions

- Promotion of fundamental studies
  - Experimental simulation
    - Multi-energy-spectrum charging test facility
    - Synergetic effects due to electrons of different energies

measurement apparatus of deep dielectric charging (PWP method)



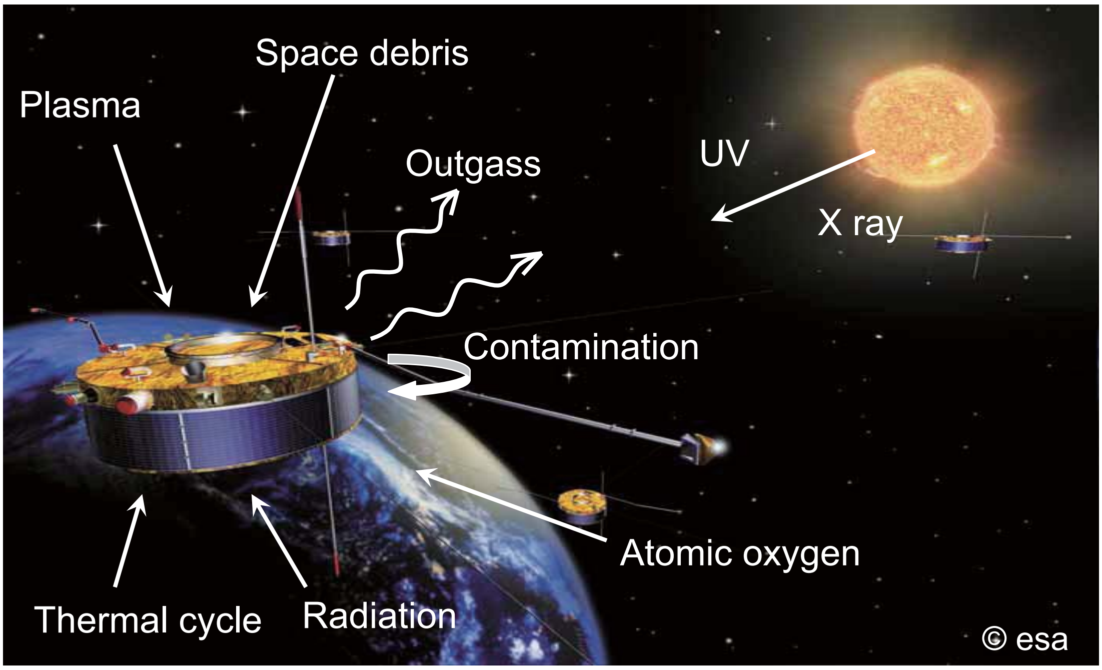
schematic



From Y. Tanaka, Musashi Inst. Tech.

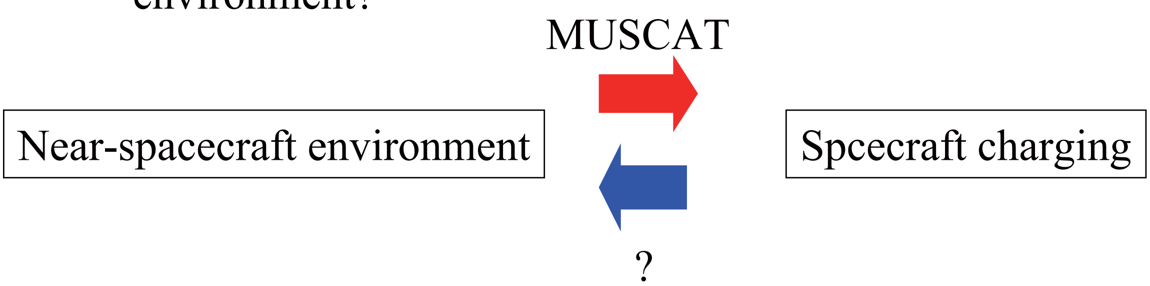
Future directions

- Promotion of fundamental studies
  - Why and how does the environmental exposure change the charging property?



Future directions

- Promotion of fundamental studies
  - How does the charged satellite alter the near-spacecraft environment?



  - Simulation of dust charging

Future directions

- Promotion of fundamental studies
  - On-orbit measurement via a dedicated small satellite
    - Knows every detail of satellite geometry and materials
    - Small enough (<50cm) to do
      - Full-scale laboratory simulation
      - Full-scale computer simulation
    - Carry sensors to measure
      - Ionospheric plasma density and temperature
      - Spacecraft chassis potential
      - High-energy particles
      - Radiation dose
      - Magnetic field
      - Surface potential
      - Internal charging
      - Discharge event

Thank you