汎用宇宙機帯電解析ソフトウェア MUSCATについて

○村中崇信[1], 八田真児[2], 金正浩[2], 細田聡史[1],
趙孟佑[3],上田裕子[1], 古賀清一[1], 五家建夫[1]

[1]宇宙航空研究開発機構
[2]MUSCATスペースエンジニアリング（株）
[3]九州工業大学

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Outline

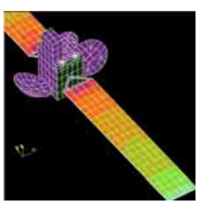
- Background
- Overview of MUSCAT functions
- Details of each function
  - Graphical User Interface
  - Main solver
  - Tuning and high-speed computation
  - Optional analysis (Plasma plume analysis)
  - Validation experiments
- Conclusion

Background

Spacecraft Charging-Arcing problem lead to the spacecraft failure

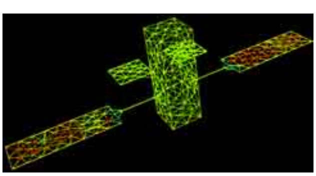
*ADEOS-II : Polar Orbit Satellite: paddle size 3 x 24 (m) (JAPAN)

Next Generation S/C Charging Analysis Tools



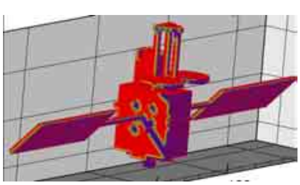
U.S.A : NASCAP-2K
(NASA Charging Analyzer Program 2000)

→ 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)

Fundamental Specification of MUSCAT (complete version)

1. Available for LEO, GEO and PEO satellites analysis (Multy-Utility)
2. Satellite engineers w/o experience of numerical simulation can use (User-Friendly)
3. Reasonable computation time for users (about half a day)
4. Parametric run is available (robust calculation in 10 minutes)
5. Accuracy of the solver is examined

Development Tasks for the Specification

1. Multi-Utility Use → Expansion of the solver function
2. User-friendly → Graphical User Interface (GUI)
   → Client-Server model
3. Run in half a day → High-speed computation
4. Parametric run → Robust computation function
5. Accuracy → Code Validation

Framework of the development

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2004年11月開発開始，2007年3月初版公表

General overview		JAXA
Code development	Solver Speeding up GUI	KIT
Validation experiment		KIT
		ISAS/JAXA
Offering space environmental parameters		JAXA
		NICT
Validation by large scale calculation		GES (Kyoto Univ., NIPR)

How MUSCAT Works? (procedures)

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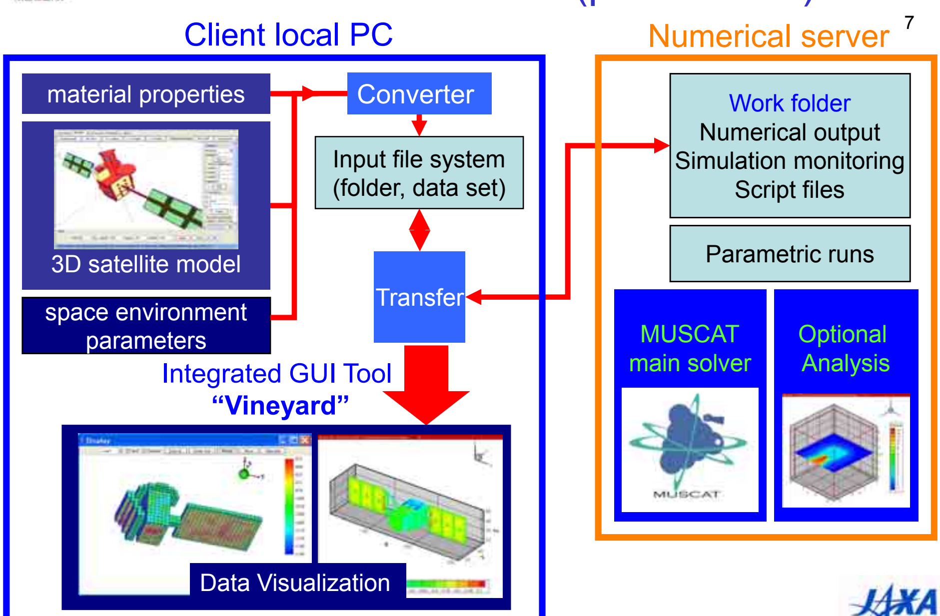
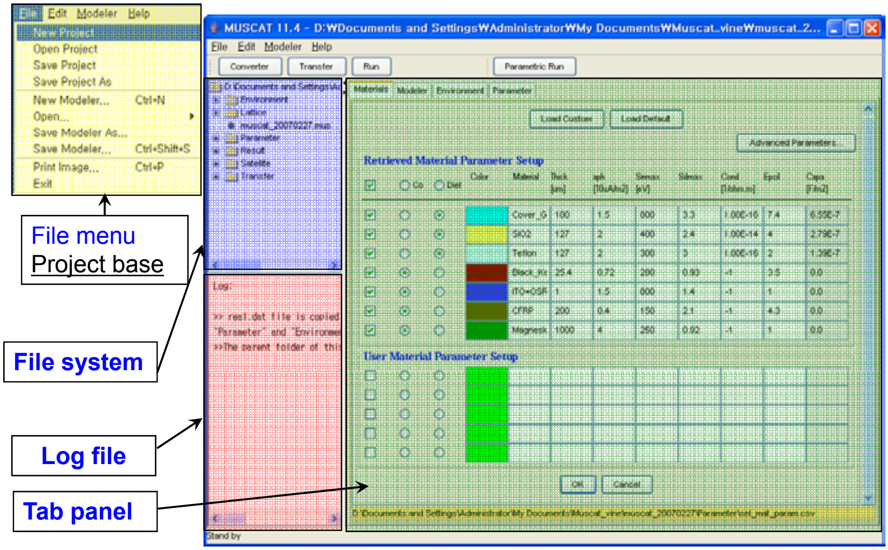


Development of GUI

Integrated GUI Tool “Vineyard”

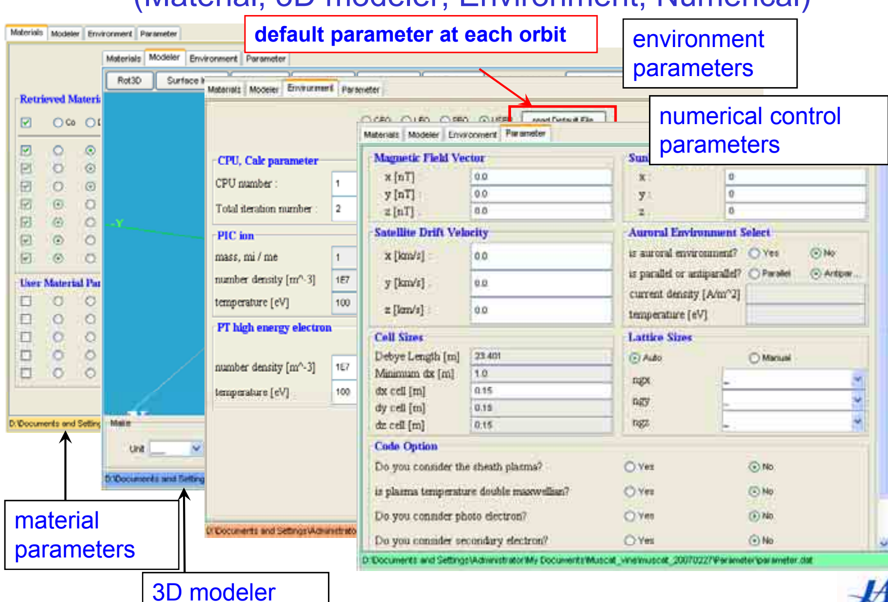
- Developed in JAXA & JAVA3D
- Parameter Input
  - 3D satellite modeling
  - Material property on each surface
  - Space environment
  - Numerical control
- Select solver function
  - Physical functions
  - Standard or robust
  - Optional analysis (plasma plume)
- Generate rectangular grid points
  - General 3D→Rectangular for the solver
- Monitoring a simulation (Communication)
- Visualization of numerical data
  - 2D, 3D plot & property time evolution at measurement point

Starting up “Vineyard”



Parameter Input Tab Panels

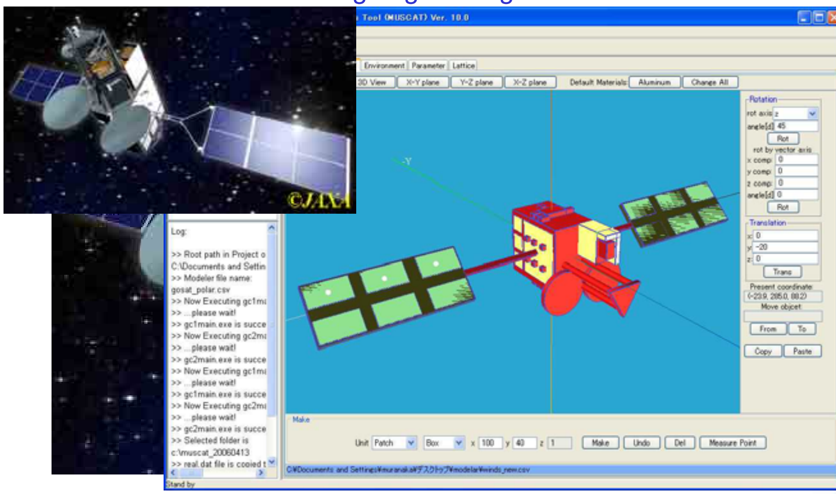
(Material, 3D modeler, Environment, Numerical)



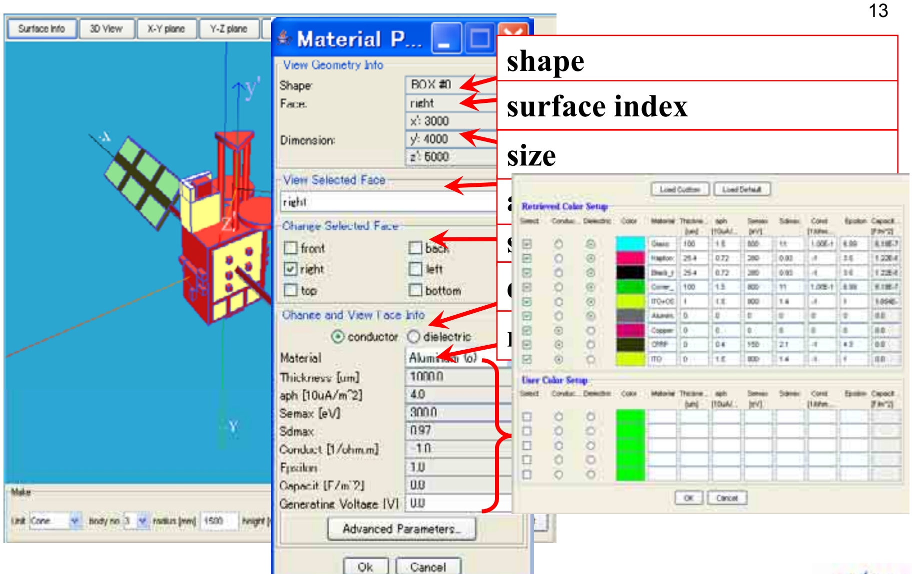
Example of Satellite Modeling

WINDS (GEO satellite)

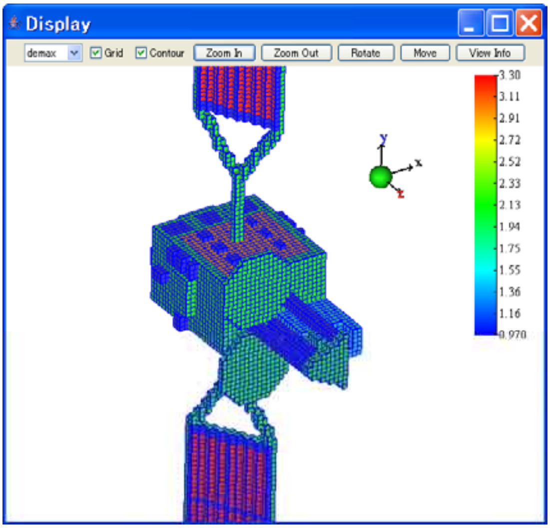
Wideband Inter Networking engineering test and Demonstration Satellite



Surface Properties



Geometry Conversion to Rectangular Elements

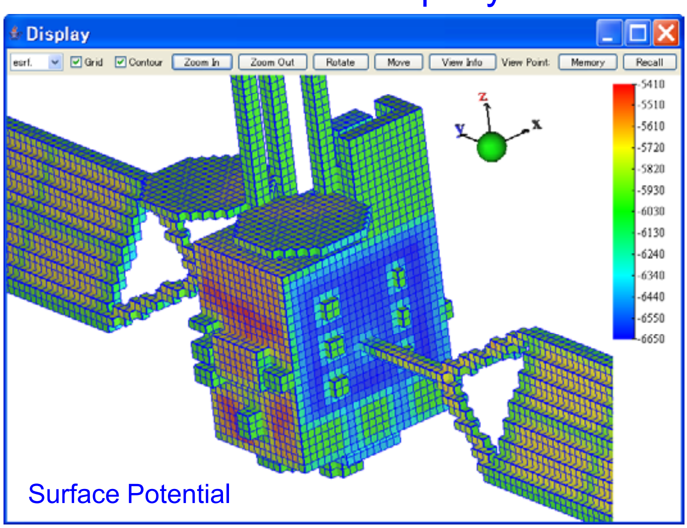


General 3D geometry

Rectangular grid
(for the MUSCAT solver)

Visualization of Numerical Data (1)

3D Surface Property



Surface Potential

Visualization of Numerical Data (2)

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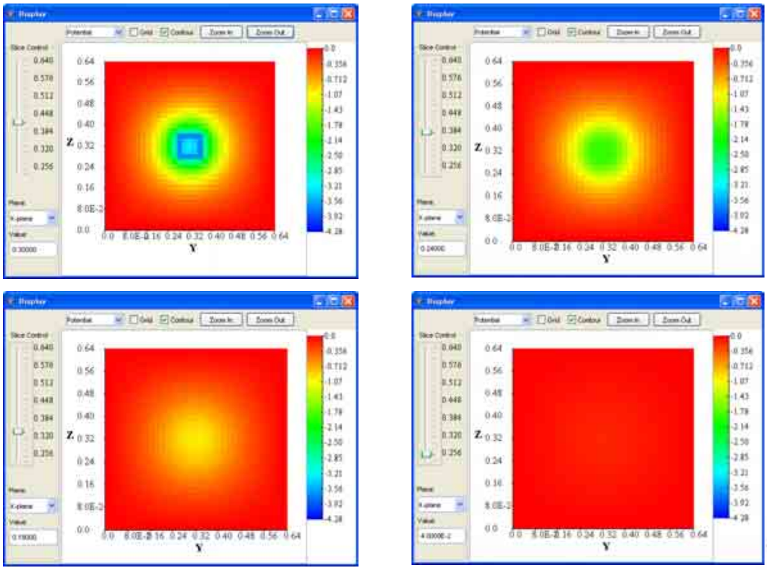
2D Sliced Surface



Visualization of Numerical Data (3)

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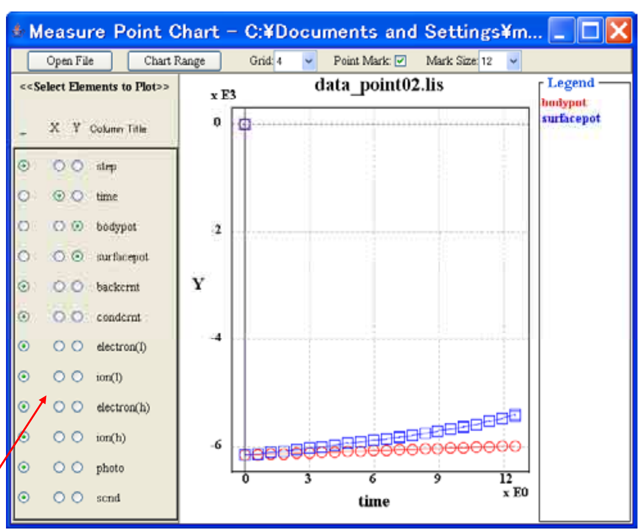
Time Evolution of Physical Properties on Measurement Point

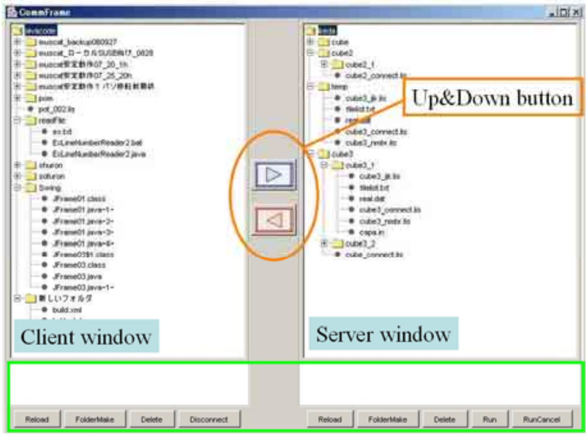


potential & currents

Communication Tool of “Vineyard”

Local PC and Numerical Server Communication (LAN)

- JAVA + shell script
- Users do not need Network Set-up



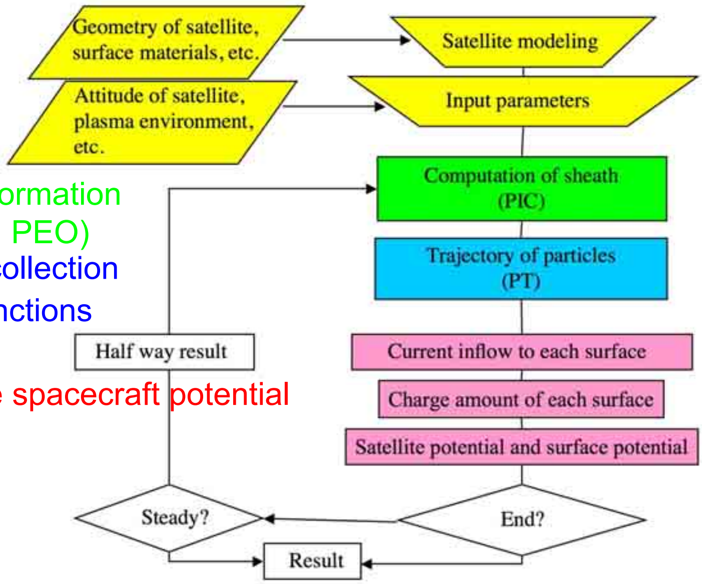
File Transfer Function

Operation button and input field

Development of Solver

Schematic of Algorithm

GUI



Sheath formation (LEO, PEO)

Current collection

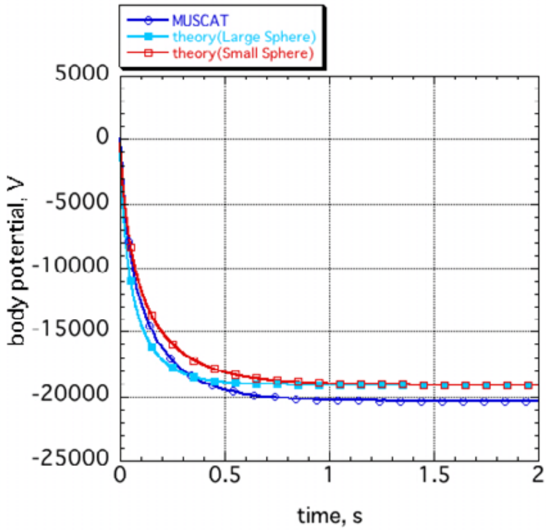
Sub-functions

Upgrade spacecraft potential

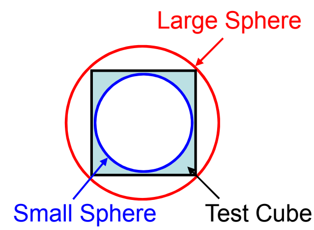
Developed physical functions

- Photoelectron emission (PEE)
  - Includes determination of sunlit surface
- Secondary electron emission (SEE)
- Auroral electron
- Conductive current
- Electrical physical functions
  - Power generation
  - More than one floating body
- Optional analysis
  - Plasma plume analysis (for Ion Engine)

Floating Potential at GEO Environment



Theory:
Analytical Solution of OML theory by 4th-order Runge-Kutta method



Speeding up (Tuning and Parallelization)

Development Platform

- Symmetric Multiple Processor (SMP) workstation
  – Server of 2nodes,
  – 4CPUs for each, 8CPUs in total
- CPU Itanium II 1.3GHz
- Memory 16GB (512MBx28+cash)
- HD 660GB
- OS
  – SuSE Linux Enterprise Server
- Compiler
  – Intel Fortran for Linux ver.8.1
  – Intel C^{++} for Linux ver.8.1

Speeding up of Computation

- Modification and present status
  – Hardware
    - Parallelization with Open-MP to PIC and PT parts
    - Modify particle arrangement to reduce memory access time

    →about 6 times faster
  – Algorithm
    - Time step control method (to reduce iteration time)
    - Modification of PT algorithm (to reduce the number of computation for particles)

    →obtain differential potential of LEO and GEO satellite in 2 days (with our 8 CPUs WS)

Time Step Control Method

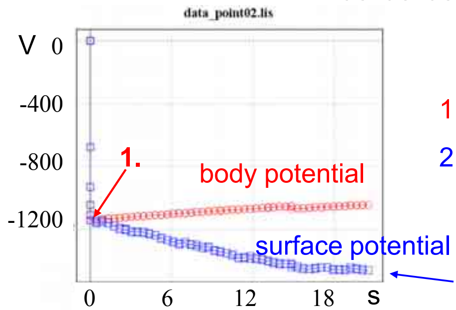
Time scale is quite different

x $10^3 \sim 10^5$

body potential τ_0 <<<< growth of differential voltage τ_1

we want to know for s/c charging!

Obtain steady saturation voltage as fast as possible



1. Saturation value of body potential
2. Saturation value of surface potential (differential potential)

n_0=1E^8, Te=600eV, Ti=400eV, PEE, time=20.5s

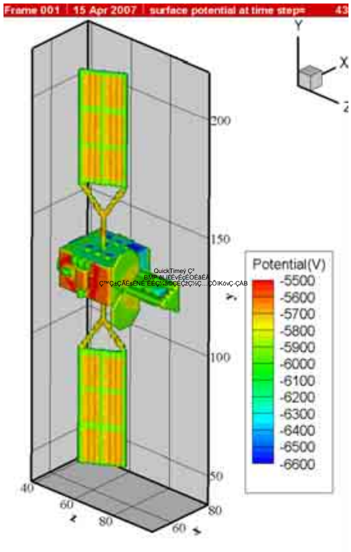
Example of S/C Charging Analysis

WINDS (GEO satellite)

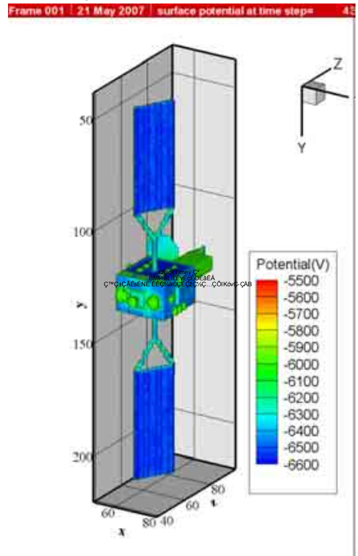
Wideband Inter Networking engineering test and Demonstration Satellite

実機の解析例

WINDS (GEO衛星)



日照面



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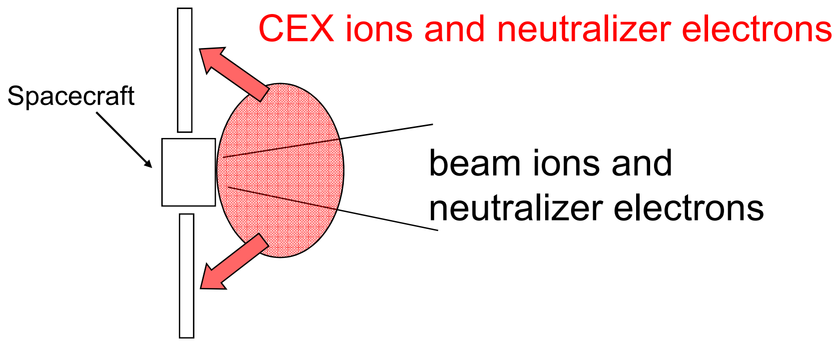
Application to Plasma Plume Analysis

Schematic of Active Plasma Emission



- CEX ions generated in beam plasma diffuse from positive electric potential in the beam plasma
- Ambipolar diffusion of CEX ions and neutralizer electrons
- Parameters of n_{bi},n_e,n_{cex},Φ,and Te are important

Why Need Plasma Plume Analysis?

A) Contamination of spacecraft by CEX ions
   - Ion flux to spacecraft surface

B) Power loss due to dense plasmas near solar array paddle
   - Electron density near spacecraft surface

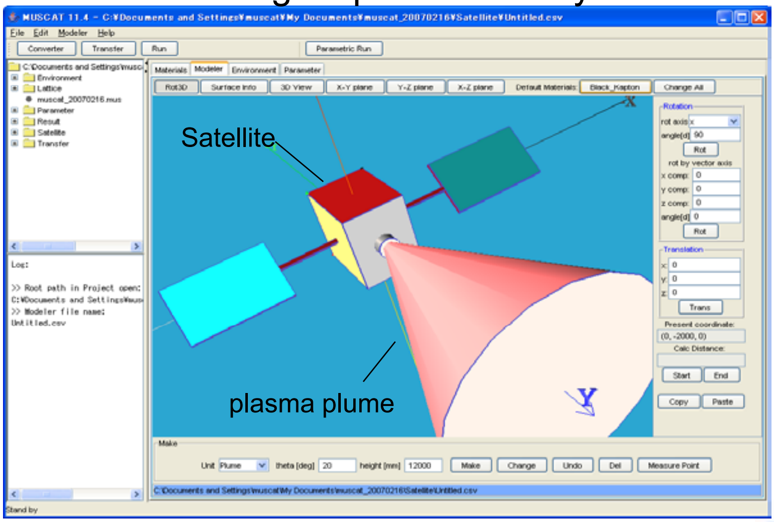
C) Relaxation of local spacecraft charging
   - Ion flux to the spacecraft surface

D) Fluctuation of spacecraft potential in the case of neutralization failure
   - Dynamic interaction between neutralizer and plume plasmas

– For the MUSCAT solver, A) and B) are considered

Example of Plasma Plume Modeling by the Optional Tool

- Determine Ion engine parameters by GUI



Basic Scheme of Plasma Plume Analysis

- Ion beam and Neutral particle profiles
  - Fixed, obtained analytically [Ref. Samanta Roy, 1996]
  - Modeling by “Vineyard” (GUI tool of MUSCAT)

- CEX ions and Electric Potential
  - Obtain time evolution of n_{cex} profile by PIC method
  - Solve following non-linear Poisson equation

$$-\varepsilon_o \nabla^2 \phi = e\left(n_{bi}(x) + n_{cex}(x) - n_o \exp\left(\frac{e\phi}{kT_e} \right) \right)$$

n_o: maximum density at plume exhaust point

Assume Boltzmann distribution for electrons
Adopt Newton-Raphson + SOR method

Validation of the Application for Plasma Plume Analysis

- Referenced experiment data
  - J.E. Pollard, “Plume Angular, Energy, and Mass Spectral Measurements with the T5 Ion Engine,” AIAA-95-2920
- Compare plasma density during thruster operation
  - 1D angular distribution at 30, 60, 90cm from the exit

Propellant Gas	Xe (M=130)
Thruster Diameter, cm	10
Mass Flow Rate, mg/s	0.808
Thrust, mN	27
Ionization Efficiency	0.77
Beam Ion Current, A	0.458
Avarage Exhaust Velocity, m/s	30940
Specific Impulse, s	3157
* Beam Divergence Angle, deg	12
* Neutral Permeability	0.24

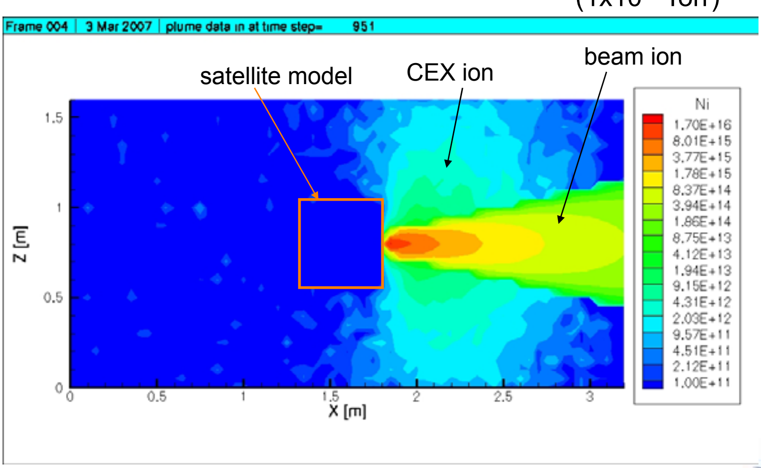
Table (left) :
Specifications of the T5 Ion Engine

* Typical values are used

Numerical Result (1)

Numerical domain 64 x 32 x 32
Object size 10 x 10 x 10
dx = 5cm, time = 1.05×10^{-3} s

Neutral gas density
propellant : 8.34×10^{16} [m^{-3}]
background : 3.34×10^{16} [m^{-3}]
(1×10^{-6} Torr)



Numerical Result (2)

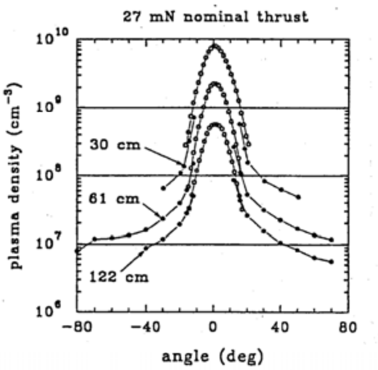
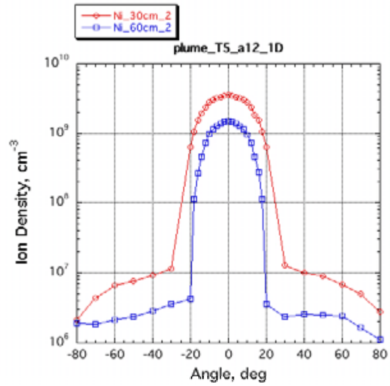


FIG. 6. Plasma density at 27 mN nominal thrust for the positions in Fig. 2. Open symbols (n_i) are determined from ion current, and filled symbols (n_e) are determined by least-squares fitting of electron current vs. voltage.



Density profile at 30cm and 60cm from thruster exit
Almost in good agreement with the profiles
Envelope CEX plasma density is lower

Experiments for Code Validation

Validation Experiments

IV-characteristic curve, Space potential measurements

Condition	Orbit	Model	Validating Function
BG plasma	LEO PEO	Cubic electrode	Sheath Current collection
BG plasma w/ flow	LEO PEO	Plate	Sheath (wake) Current collection
Electron beam	GEO PEO	3D-satellite model	Current collection SEE
BG plasma w/ Electron beam	PEO	Plate	Sheath Current collection SEE

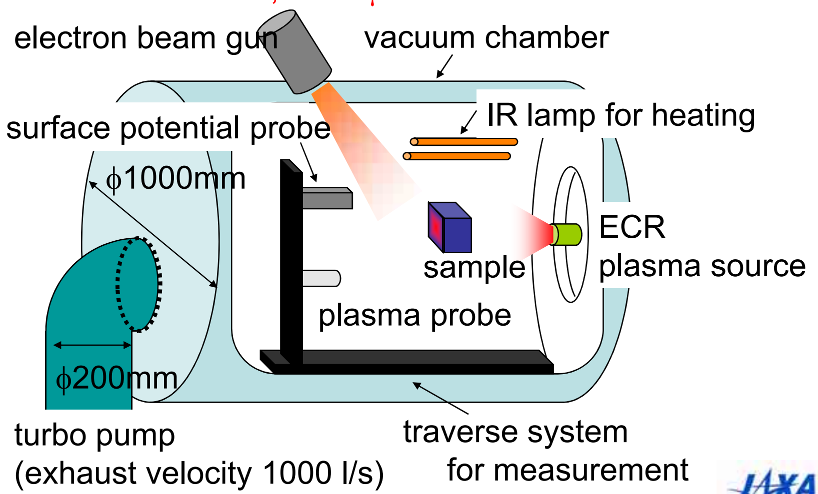
*BG plasma: Ambient plasma w/o flow

Validation Experiment Facility

Chamber to simulate Polar Earth Orbit Environment

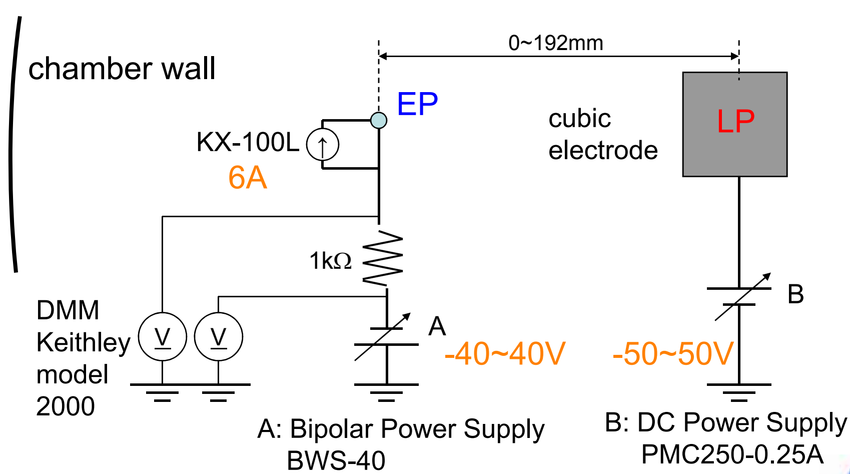
Schematic of the Chamber

Simulate LEO, GEO and PEO environment
Ambient plasma: density 10^{11}~10^{12}m^{-3}, temperature 2~3 eV
Electron beam : ~30 keV, ~300 μA



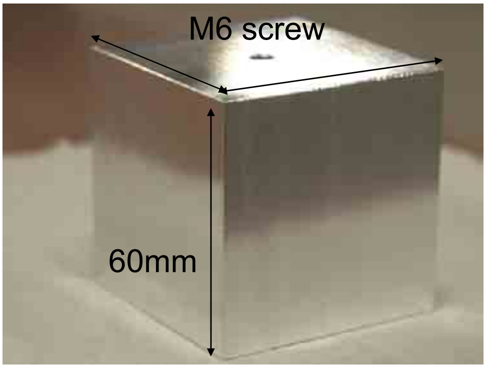
Schematic of Probe Circuit

Emissive probe (EP): for electric potential
Langmuir probe (LP): for IV characteristic curve



Cubic Electrode of Langmuir Probe

Adjust the shape to rectangular grid system of MUSCAT



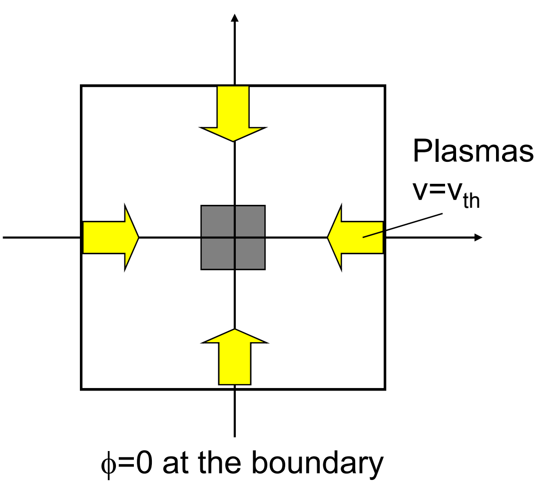
Aluminum cube

size=$(60\text{mm})^3 \sim (10\lambda_D)^3$

(T=2 eV, n=3×10^{12} m^{-3})

Simulation Geometry

MUSCAT employs Rectangular grid system

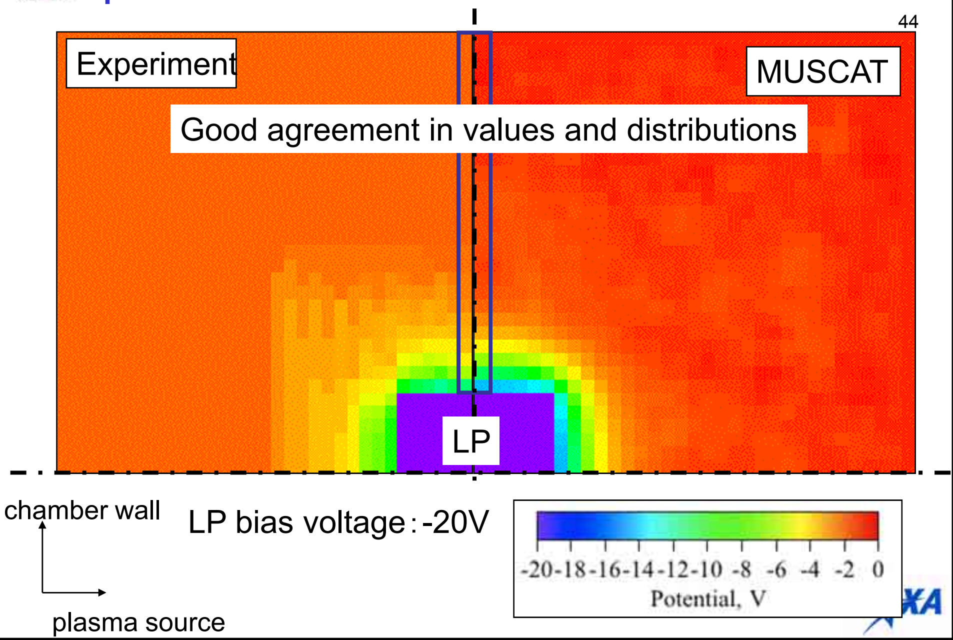


size(grids)
domain: 64x64x64
object : 10x10x10

Δx : 6mm($1.0\lambda_D$)

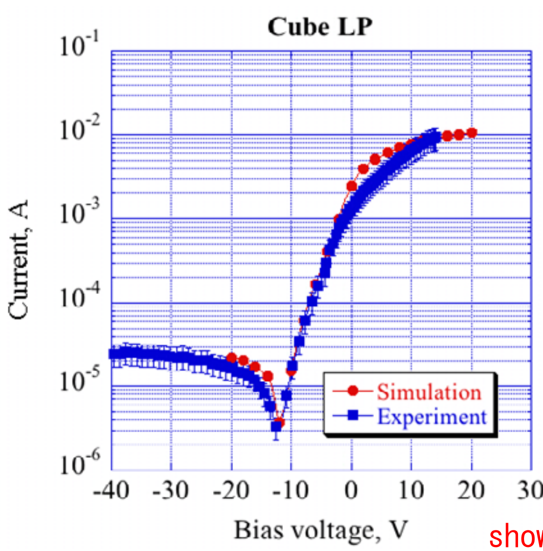
(T=2 eV, n=3×10^{12} m^{-3})

Spatial Distribution of Electric Potential



LP bias voltage：-20V

I-V Characteristic Curves



V is revised by subtracting Vs from Vp

V=Vp-Vs
Vp: probe potential
Vs: space potential(plasma)

Both are in good agreement

shows accuracy of the solver

Summary

- The final version of MUSCAT, "MUSCAT ver.1" had been released in March, 2007.
- Specification required has almost been included.
  - User-friendly Integrated GUI tool "Vineyard"
  - Multi-Utility solver functions available at LEO,GEO,PEO
  - High-speed computaion by parallelization and algorithm modification (large scale computation in 2days)
  - Accuracy was validated by experiments

Present Status and Future Task

- MUSCAT had already been used for a real PEO satellite charging analysis and contributed to determine the ground test condition.
- MUSCAT is a shareware available by the company, MUSE (MUSCAT Space Engineering, Co., Ltd)
- MUSCAT will be upgraded by the company after our development phase