汎用宇宙機帯電解析ソフトウェア
MUSCATについて

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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 Oct. 2003
ADEOS-II* lost most of its electric power

Location of failure examined (high-voltage wire harness)

*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

2004年11月開発開始、2007年3月初版公表

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<td>Univ.,</td>
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How MUSCAT Works? (procedures)

Client local PC

- Converter
  - Input file system (folder, data set)
  - Transfer
  - 3D satellite model
  - material properties
  - space environment parameters

Integrated GUI Tool “Vineyard”

Data Visualization

Numerical server

- Work folder
- Numerical output
- Simulation monitoring
- Script files
- Parametric runs
- MUSCAT main solver
- Optional Analysis
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)

File menu
Project base

File system

Log file
Tab panel

default parameter at each orbit
environment parameters
numerical control parameters

material parameters
3D modeler
Example of Satellite Modeling

WINDS (GEO satellite)
Wideband Inter Networking engineering test and Demonstration Satellite

Surface Properties

shape
surface index
size
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)

2D Sliced Surface

Visualization of Numerical Data (3)

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

Development of Solver
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
\( \times 10^3 \sim 10^5 \)

body potential \( \tau_0 \) <<<< growth of differential voltage \( \tau_1 \)

Obtain steady saturation voltage as fast as possible

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

Example of S/C Charging Analysis

WINDS (GEO satellite)
Wideband Inter Networking engineering test and Demonstration Satellite
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 $n_{bi}$, $n_{ne}$, $n_{ceX}$, $\Phi$, and $T_e$ 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

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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 \( n_{\text{CEX}} \) profile by PIC method
  - Solve following non-linear Poisson equation

\[
-e_c \nabla^2 \phi = e \left( n_{\text{bi}}(x) + n_{\text{CEX}}(x) - n_\text{e} \exp \left( \frac{e \phi}{k T_e} \right) \right)
\]

\( n_\text{e} \): 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
- Compare plasma density during thruster operation
  - 1D angular distribution at 30, 60, 90 cm from the exit

Table (left) :
Specifications of the T5 Ion Engine

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Propellant Gas</td>
<td>Xe (M=130)</td>
</tr>
<tr>
<td>Thruster Diameter, cm</td>
<td>10</td>
</tr>
<tr>
<td>Mass Flow Rate, mg/s</td>
<td>0.808</td>
</tr>
<tr>
<td>Thrust, mN</td>
<td>27</td>
</tr>
<tr>
<td>Ionization Efficiency</td>
<td>0.77</td>
</tr>
<tr>
<td>Beam Ion Current, A</td>
<td>0.458</td>
</tr>
<tr>
<td>Average Exhaust Velocity, m/s</td>
<td>30940</td>
</tr>
<tr>
<td>Specific Impulse, s</td>
<td>3157</td>
</tr>
<tr>
<td>Beam Divergence Angle, deg</td>
<td>12</td>
</tr>
<tr>
<td>Neutral Permeability</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* Typical values are used

Numerical Result (1)

<table>
<thead>
<tr>
<th>Numerical domain</th>
<th>64 x 32 x 32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object size</td>
<td>10 x 10 x 10</td>
</tr>
<tr>
<td>dx</td>
<td>5 cm</td>
</tr>
<tr>
<td>time</td>
<td>1.05 x 10^{-3} s</td>
</tr>
</tbody>
</table>

Neutral gas density
- propellant : 8.34 x 10^{16} [m^{-3}]
- background : 3.34 x 10^{16} [m^{-3}]

(1 x 10^{-6} Torr)

![Image of numerical result and satellite model, CEX ion, and beam ion]
Numerical Result (2)

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

<table>
<thead>
<tr>
<th>Condition</th>
<th>Orbit</th>
<th>Model</th>
<th>Validating Function</th>
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<tr>
<td>BG plasma</td>
<td>LEO</td>
<td>Cubic electrode</td>
<td>Sheath Current collection</td>
</tr>
<tr>
<td>BG plasma w/ flow</td>
<td>LEO</td>
<td>Plate</td>
<td>Sheath (wake) Current collection</td>
</tr>
<tr>
<td>Electron beam</td>
<td>GEO</td>
<td>3D-satellite model</td>
<td>Current collection SEE</td>
</tr>
<tr>
<td>BG plasma w/ Electron beam</td>
<td>PEO</td>
<td>Plate</td>
<td>Sheath Current collection SEE</td>
</tr>
</tbody>
</table>

*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 $10^{11}$~$10^{12}\text{m}^{-3}$, temperature 2~3 eV
Electron beam : ~30 keV, ~300 $\mu$A

electron beam gun
vacuum chamber
surface potential probe
IR lamp for heating
$\phi 1000\text{mm}$
$\phi 200\text{mm}$
turbo pump
(exhaust velocity 1000 l/s)
traverse system
for measurement

Schematic of Probe Circuit
Emissive probe (EP): for electric potential
Langmuir probe (LP): for IV characteristic curve

chamber wall
KX-100L 6A
DMM Keithley model 2000

EP
cubic electrode

A: Bipolar Power Supply BWS-40
B: DC Power Supply PMC250-0.25A

-40~40V
-50~50V
Cubic Electrode of Langmuir Probe

Adjust the shape to **rectangular grid** system of MUSCAT

Aluminum cube
size=(60mm)$^3$–$(10\lambda_D)^3$
(T=2 eV, n=3x10$^{12}$ m$^{-3}$)

Simulation Geometry

MUSCAT employs Rectangular grid system

Plasmas
$v=v_{th}$

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

$\Delta x : 6\text{mm}(1.0\lambda_D)$
(T=2 eV, n=3x10$^{12}$ m$^{-3}$)

$\phi=0$ at the boundary
Spatial Distribution of Electric Potential

Experiment MUSCAT

Good agreement in values and distributions

LP bias voltage: -20V

-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0
Potential, V

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 computation 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