Final Presentation

Assessment of Interactions between Spacecraft and Electric Propulsion Systems

Astrium Satellites - Toulouse

Matias Wartelski Christophe Theroude

2013-03-20

All the space you need
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Context (1/2)

- **Interest increase for electric propulsion**
  - Mission enabler in scientific missions like BepiColombo or Lisa Pathfinder
  - Gain of competitiveness of telecommunications platforms

- **Electric thrusters generate an ion and electron cloud called plume (whose form and nature depends on the thruster) around the spacecraft**

- **This plume interacts with the SC in different ways:**
  - Erosion of sensitive SC parts by impinging ions
  - Contamination of sensitive SC parts by eroded parts
  - Spacecraft absolute and differential charging is modified
  - Plume-induced dynamic effects: forces and torques
  - Disturbance of RF signal
  - Electromagnetic interference induced by both the plume and thruster
  - Optical disturbance due to plume luminiscence
Context (2/2)

- Some of these interactions (mainly erosion, RF disturbance and EMI) highly constraint and consequently drive EP implementation on SC in terms of position, orientation and operation.

- These interactions are thus assessed to help design and select EP architectures.

- Assessment is based on simulations built with suites of models tuned/correlated to experimental data when available.
AISEPS goals

- Gain more understanding on SC-EP interactions
- Gather available experimental plume data
- Consolidate plume modelling methods developed in the past 10 years
- Develop an advanced tool for modelling EP plume-SC interactions
  - Implement plume models in SPIS—a tool dedicated to SC charging and interactions with plasma-
  - This is a step forward!
AISEPS team organisation

- **Astrium Satellites SAS** is prime contractor in charge of:
  - Study management
  - Development of a system tool based on SPIS
  - Plume models validation and system analyses

- **FOTEC (formerly Austrian Institute of Technology):**
  - EP Plume database elaboration
  - Specification of plume models

- **Astrium ST GmbH (with University of Gießen):**
  - RIT4 test at the Corona chamber of ESA EPL

- **ONERA (since CCN3):**
  - Specific developments of SPIS science
  - Support to the merging of AISEPS development with core SPIS numerical branch including SPIS-science
### AISEPS planning

#### January 2010

| Task 1.1 | WP 1.1 EPT Plume data handbook |
| Task 1.2 | WP 1.2 EPT Plume database |
| Task 1.3 | WP 1.3 EPT plume models definition |
| Task 2.1 | WP 2.1 Plume models validation |
| Task 2.2 | WP 2.2 System tool definition |
| Task 3.1 | WP 3.1.1 Validation with experimental plume data |
| Task 3.2 | WP 3.1.2 Grounded versus floating |
| Task 3.3 | WP 3.1.3 Validation with a test on background pressure - test |
| Task 4.1 | WP 4.1 Test definition for database improvement |
| Task 4.2 | WP 4.2 EPDP configuration for Bepi & SGEO |

#### March 2013

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<th>Meeting</th>
<th>Date</th>
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<td>Jan 2010</td>
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<td>Tri 2, 2010</td>
<td>Feb 2010</td>
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<td>Tri 3, 2010</td>
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<td>Tri 2, 2013</td>
<td>Feb 2013</td>
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**All the space you need**

**Date - 8**
AISEPS approach

Plume level

Plume models specification → Plume models implementation

→ Plume models validation & optimization

Plume database

System level simulations

RIT4 test: different neutraliser configurations

Implementation of NTR modelling method

Validation of the system tool

SMART1, BepiColombo, Small GEO simulations

Num code modifications and merging to official SPIS release

• Astrium ST GmbH
• Univ. of Giessen
• ESA ESTEC EPL

• OnERA DESP
• Astrium Satellites SAS

Astrium Satellites SAS

FOTEC
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Plume database improvement

- **Minimum required information per thruster:**
  - Current density at least at 1 distance between 0.5 and 1.5m at all angles between 0 and at least 90° wrt to plume axis.
  - Ion energy distribution between 0.5 and 1.5m at least in 2 positions: one in the main beam and one at a high angle.

- **For more advanced plume modelling:**
  - Plasma potential and electron temperature evolution in the axial and radial directions from thruster exit to at least 1m.

- **More information concerning the neutraliser configuration during tests**

- Plume data in dual-firing firing like BepiColombo
## Plume database improvement

<table>
<thead>
<tr>
<th>Thruster</th>
<th>On-ground</th>
<th>On-orbit</th>
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<tbody>
<tr>
<td>SPT-100</td>
<td>Sufficient data available.</td>
<td>Express-A 2 &amp; 3</td>
</tr>
<tr>
<td>PPS-1350-G</td>
<td>Sufficient data available.</td>
<td>SMART-1</td>
</tr>
<tr>
<td>PPS-5000</td>
<td>No plume data available. Necessary to fully characterise the plume at the high and low power operation points.</td>
<td>No</td>
</tr>
<tr>
<td>RIT-10</td>
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</tr>
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<td>RIT-22</td>
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</tr>
<tr>
<td>RIT-4</td>
<td>Sufficient data available.</td>
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<td>HEMP3050</td>
<td>CEX ion energy distribution missing.</td>
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</tr>
<tr>
<td>T5</td>
<td>CEX ion energy distribution missing.</td>
<td>No</td>
</tr>
<tr>
<td>T6</td>
<td>Current density and ion energy distribution at high angles missing. In the frame of the BepiColombo project, these data are available but not public since February 2012. They should be included in the database.</td>
<td>No</td>
</tr>
<tr>
<td>Cs-FEEP</td>
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<tr>
<td>In-FEEP</td>
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</tbody>
</table>
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- « Spacecraft Plasma Interaction System »: 3D open-source free-ware tool developed under ESA contracts by ONERA/Artemun (constantly being improved/completed)
Plume models: modelling philosophy

- At each simulation, the plume is modelled from the thruster exit plane to SC surfaces
Plume models: modelling philosophy

- The plume itself is simulated with an approach widely used in industry with different codes (SmartPIC, PICPlus, Astrium internal code, American codes…)
  - Results from a trade-off between accuracy needs and time + computer resources constraints

- The approach described hereafter can be used on a wide range of problems

- However, other approaches/tools may appear more pertinent or efficient in some configurations
Plume modelling: ions injection and modelling

- All ions ($\text{Xe}^+, \text{Xe}^{++} \ldots$) are modelled with the Particle-in-cell (PIC) method.

- Fast ions are injected at thruster exit plane:
  - 11 injection models: SPT100, PPS1350, PPS5000, RIT4, RIT10, RIT22, T5, T6, HEMP3050, In-FEEP, Cs-FEEP.
Plume modelling: potential and electrons

- Different options for plasma potential and electrons modelling

<table>
<thead>
<tr>
<th>Options</th>
<th>Plasma potential</th>
<th>e⁻ temperature</th>
<th>e⁻ density</th>
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<tr>
<td>1</td>
<td>Barometric law</td>
<td>Constant</td>
<td>( n_e = n_i )</td>
</tr>
<tr>
<td></td>
<td>(Boltzmann)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Barometric law 2</td>
<td>Variable</td>
<td>( n_e = n_i )</td>
</tr>
<tr>
<td></td>
<td>(Boltzmann-type)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Poisson solver</td>
<td>Constant</td>
<td>Barometric law (Boltzmann)</td>
</tr>
<tr>
<td>4</td>
<td>Poisson solver</td>
<td>Variable</td>
<td>Barometric law 2 (Boltzmann-type)</td>
</tr>
</tbody>
</table>
Plume modelling: CEX collisions

- Charge-exchange collisions highly influence the plume profile and interactions with SC
  - Physical equation: $Xe^+_\text{fast} + Xe_{\text{slow}} \rightarrow Xe_{\text{fast}} + Xe^+_\text{slow}$
  - $Xe^+_\text{fast}$: ions accelerated by thruster → modelled with PIC
  - $Xe_{\text{slow}}$: neutral particles from thruster (modelled with PIC or analytical distrib) and/or vacuum chamber pressure (modelled as a constant density)
  - $Xe^+_\text{slow}$: so called CEX ions → modelled with PIC
  - $Xe_{\text{fast}}$: not modelled (only Monte-Carlo Collision model in SPIS)
Not included in implemented models

- Thruster discharge channel not modelled: simplified ion injection distributions at thruster exit.

- Magnetic field: not modeled. Its influence is partially included by fitting exp data at 0.5 ot 1m.

- Collisions: only CEX are modeled. Fast neutrals created by CEX not modelled.

- Environment plasma not modelled so connection of plume with it not simulated.
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Plume models validation: plume axis

Excellent fit of measured currents in the plume axis for all thrusters!
Plume models validation: high angles

Ratio ~ 1.5

RIT22 current density at 1 m

Ratio ~ 3.5

HEMP3050 current density normalized to 1 A at 1 m

CEX region: same order of magnitude but slight underestimation wrt on-ground data!

T6 current density at 0.9 m

PPS1350 current density at 0.7 m

SPT100 vs King data

SPT100 current density at 0.5 m compared with King data

SPT100 vs Manzella data

SPT100 current density at 0.6 m compared with Manzella data
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All the space you need
Specific RIT4 firing test

RIT4

Filament neutraliser

RPA

Faraday Cups

Thruster

RPA 2
300 V

h_{r}=10

e=3

h_{FP}=11

d_{1}=91

d_{2}=13

d_{3}=75

RPA 3kV

h_{w}=10

RPA 1
300 V

Arm stepper motor

h_{r}=10

Faraday Cups

RPA

All the space you need
Test matrix

- Thrust and beam current levels:
  - 100µN (2.1mA)
  - 250µN (4.4mA)
  - 500µN (7.6mA)

- Chamber pressures:
  - 1.2e-6 mbar
  - 3e-6 mbar
  - 6e-6 mbar

- Neutraliser electrical coupling wrt chamber
  - Grounded
  - Floating
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Goals of system simulations

- **RIT4 vacuum chamber test**
  - Reproduce the measured current density profiles
  - Show that SPIS can be used for system simulations taking into account the neutraliser behaviour and chamber pressure

- **SMART1, Bepi Colombo, SmallGEO, Astrium SC**
  - Show the ability of SPIS to simulate a plume and its interactions with a whole SC
  - Show how SPIS can be used to predict SC charging during EP firing taking into account neutraliser configuration
  - Tune system models with SMART1 in-flight data, in particular measurements of CRP (Cathode Reference Potential)
RIT4 current density: SPIS vs test data.

Thrust: 500µN

- Test 6e-5 mbar
- Test 3e-5 mbar
- Test 1e-5 mbar
- SPIS 6e-5 mbar
- SPIS 3e-5 mbar
- SPIS 1e-5 mbar

All the space you need
RIT4: simulation of the neutraliser-chamber electric coupling

- The phenomenological behaviour (I-V curve) of the neutraliser could be implemented and reproduced in SPIS.

**Graph:**
- X-axis: Chamber-neutraliser coupling potential in Volt
- Y-axis: NTR Current, mA
- Data points for different pressure levels:
  - 500µN - 7.6mA
  - 250µN - 4.4mA
  - 100µN - 2.1mA
- Grounded, all thrust levels

*Exp data, linear fits*
Lessons learnt from RIT4 test and simulations

- In-flight SC charging and neutraliser behaviour (which are coupled) can be modelled in SPIS

- The neutraliser I-V behaviour depends on:
  - Neutraliser technology
  - Position of the neutraliser wrt to thruster
  - Thruster configuration (thrust level, plume, background P…)

- The I-V curve of a specific neutraliser configuration can be measured on ground

- The I-V curve is extrapolated to vacuum and implemented in SPIS
Approach for modelling of SC charging and EP neutraliser behaviour
SMART-1 (PPS1350 thruster): flight experience and lessons learnt

- $V_{\text{cathode/environment}} = V_{\text{cathode/chamber}} = -18.5\text{V}$
  - Justifies ground-to-space extrapolation of NTR behaviour
  - Thus, CRP is an indirect measurement of the SC potential

- CRP daily variation was correlated to SA rotation
  - SA rotation changes interconnector exposure to plume
  - IC (with a potential bias up to $+55\text{V}$ wrt to ground) drain large $e^-$ currents and drive SC ground potential
  - CRP ranged from -5 to 14V (=TM saturation value) and the average CRP excursion for a 180° SA rotation was ~6V
  - The CRP range indicates SC potential between -13 and 32V
SMART1 SPIS model

- Geometry and coatings based on inputs sent by E. Gengembre (ESA)
SMART1 SPIS model

- PPS1350 plume: validated during AISEPS
- Cathode configuration: floating
- Satellite potentials: floating
- Solar array model: improvement from model 1 up to model 6 (see next slide)
## SMART1 solar array models

<table>
<thead>
<tr>
<th>Model -&gt;</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>Solar panels</td>
<td>Only first panel on +Y side</td>
<td>All panels: 3 per +/−Y side</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SA angles in degrees</td>
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<td>0, 45, 90, 180</td>
<td>0, 45, 180</td>
<td>0, 180</td>
<td>0</td>
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<tr>
<td>IC geom model</td>
<td>Small surface exposed to plasma</td>
<td>Uniform distribution over whole panel, not exposed to plasma (screened by coverglass)</td>
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<tr>
<td>IC potential</td>
<td>$V_{ground} + 50V$</td>
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<td>Linearly variation from $V_{ground}$ to $V_{ground} + 55V$</td>
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<tr>
<td>SA mesh</td>
<td>Coarse: −200mm</td>
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<td></td>
<td>Refined: 50mm</td>
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<tr>
<td>IC collection ratio</td>
<td>N/A</td>
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</tr>
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</table>
SMART1 model 1

- IC with $V_{IC} > V_{ground} + 45V$ are included in the model as a surface of equivalent area directly exposed to undisturbed plume plasma (OML law for electron current)

- Fast $Xe^+$
  - $n_i = 10^{14}$ m$^3$

- CEX $Xe^+$
  - $n_i = 10^{14}$ m$^3$
SMART-1 old IC model: SPIS-obtained potentials

- CRP = -0.5 V
- CRP = +15 V

Measured CRP during whole mission: -5 to +14 V but average excursion of 180° SA rotation ~6V
New interconnectors modelling approach

- IC potential is assumed to be screened by the coverglass potential
  - The undisturbed plasma « sees » only the coverglass so that the total ion and electron current reaching the solar array is calculated as a function (e.g., OML law) of coverglass potential

- No need to include the IC on the geom model

- The user specifies the analytical potential distribution of the IC:
New interconnectors modelling approach

- Ion and $e^-$ current reaching the SA surface: distributed between coverglass and IC according to a function of:

$$V_{\text{reduced}} = \frac{V_{\text{interconntor}} - V_{\text{coverglass}}}{E_{\text{particle}}}$$
SMART1 Model 2: new IC mod approach

- Same as model 1 but new IC mod approach:
  - Only 1 solar panel with IC uniformly distributed
  - Solar array position: 0°, 45°, 90°, 180°
  - Only high potential interconnectors: \( V_{IC} = V_{ground} + 50V \)
  - Interconnectors collection ratio -> model A:

![Graph showing IC collection ratio vs. reduced potential](image-url)
SMART 1 model 2: results

- Panel model more stable and smoother results

Surface potentials (V)
**SMART1 model 2: results**

- The effect on SC potential of a 180° rotation of the SA is successfully reproduced
- 180°: unchanged SC ground potential (-17.7V)
- 0°: potential (-28V) more positive than model 1 (-35V)
SMART1 model 3: from 1 to 6 panels

- Edge wake effect
- Effect of plume gradients
- Surface potentials (V)
- MLI
SMART1 model 3: SC ground potential

- $180^\circ$: -17.7V unchanged (equal increase in ion & e\textsuperscript{-} current)
- $0^\circ$: potential more negative due to unchanged ion current on ground but e\textsuperscript{-} current on IC $\sim x 6$
SMART1 model 4: more realistic IC potential variation over panels

- More detailed model of IC potentials:
  - 180°: unchanged SC ground potential (-17.7V)
  - 0°: -18.3V (model 4) instead of -32V (model 3)
    - 1/ The IC collect e- only in a fraction of the SA surface
    - 2/ SA mesh too coarse to capture IC pot variation -> important effect on coverglass potential -> total current
SMART1 model 5: refined SA mesh

Coarse mesh: does not capture IC pot variation

Refined mesh: captures IC pot variation

Surface potential (V)
SMART1 model 6: tuned IC collection ratio

- IC collection ratio model: model B instead of model A

- IC collection ratio model B: tuned to match SMART1 in-flight CRP excursion
SMART1 model 6: surface potentials (V)

Date - 49
SMART1 model 6: plasma fields

Plasma potential (V)

CEX Density (#/m³)

All the space you need

Date - 50
SMART1 model 6 at 0°: equilibrium potentials and ground current balance

As expected, the positive net current on grounded surfaces is balanced by the e\textsuperscript{-} current on IC.

The SC ground reaches an equilibrium potential of -23.5V (\( \rightarrow \text{CRP} = -5V \)).

Each dielectric surface reaches an equilibrium potential depending on local plasma properties.

Coverglass potentials are affected by the presence of IC.

All the space you need
SMART1 model 6: CRP excursion

- 0°: -23.5V

- Simulated CRP excursion for a 180° SA rotation = 6.8V ~ 6V (average in flight)
Bepi-Colombo simulations (old IC model1)

Geometrical configuration

T6 neutraliser floating wrt to SC ground

T6 neutraliser grounded

All the space you need
SmallGEO (old IC model1)

- View of the plasma potential around the satellite
SmallGEO: old IC model
Erosion analysis on an Astrium project
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Conclusions

- Public plume data for 11 thrusters have been collected in an electronic database
- Plume models for 11 thrusters have been implemented in SPIS and tuned/correlated with experimental data
- A RIT4 firing test at CORONA has allowed to
  - Collect plume data
  - Study the influence of background pressure and neutraliser configuration on both plume and neutraliser performance
Conclusions

- The following system simulations have been successfully performed with SPIS:
  - RIT4 firing test
    - The influence on plume of the chamber pressure was reproduced
    - The NTR phenomenological behaviour was successfully implemented in SPIS and can be used for simulations of in-space SC behaviour
  - SMART1 SC with its PPS1350 plume
    - The CRP excursion for a 180° rotation of the SA was reproduced with SPIS and could be tuned to obtain the average CRP excursion measured in flight: 6V
  - BepiColombo
    - Both grounded and floating cathode conf were studied
Conclusions

- SmallGEO was simulated with a simplified model
- For the first time, Astrium used SPIS for operational erosion analyses on projects
Ways forward

- Plume models computation can be improved
  - Elastic collisions (with MCC or DSMC)
  - Electron cooling (ITT idea submitted by Astrium/ONERA/UPM) -> accurate energy distrib of CEX ions
  - spisNum improvement: make vol interactors consistent with complex pusher for more accurate&shorter simulations
AISEPS papers

- Final results may be presented and published at 33rd IEPC (October 2013)
  - Focused on latest results, i.e. SMART1 potentials with new solar panel modelling

- M. Wartelski et al., *Simulation of Interactions Between Spacecraft and Electric Thrusters Using the SPIS tool*, SP2012-2364082, May 2012
  - Focused on analysis of RIT4 test data and neutraliser modelling + first SC simulations and SMART1 potentials obtained with old modelling method

  - Presents the outcomes of the RIT4 firing test

  - Focused on plume models