Multi-functional miniaturized slot antenna system for small satellites

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OUTLINE

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1. SYSTEM REQUIREMENTS
SYSTEM REQUIREMENTS

- ESA-ESTEC Contract Number: 1-5822 to EPFL-LEMA (Prime-Contractor), EPFL Space Center and JAST.
- To develop a multi-functional antenna system suitable to be accommodated into a micro/nano-satellites.
- The antenna system shall provide 3 different coverage modes:
  - **Omnidirectional full-sphere coverage**
  - **One directive beam**
  - **4 tracking-lobes at a time**

<table>
<thead>
<tr>
<th>Antenna Coverage Mode</th>
<th>Frequency</th>
<th>Return loss</th>
<th>Polarization</th>
<th>Gain G (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full sphere</td>
<td></td>
<td></td>
<td></td>
<td>&gt; -3 Gain ripple 6 dB</td>
</tr>
<tr>
<td>Directional (60°cone)</td>
<td>S-band (2025 - 2300 MHz)</td>
<td>≤ -15dB</td>
<td>Circular polarisation</td>
<td>&gt; 5 Gain ripple 3 dB</td>
</tr>
<tr>
<td>RF-tracking (4 tracking lobes</td>
<td></td>
<td></td>
<td></td>
<td>Minimum gain TBD Gain ripple 1dB</td>
</tr>
<tr>
<td>within a 60°cone)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. DESIGN CONSIDERATIONS
DESIGN CONSIDERATIONS

- Size of a micro/nano-satellite?
  - **Between cubic box of 0.25m (9.8”) side and a 0.6m×0.6m×0.1m (23.6”x23.6”x3.9”) box.**

- **UHF/VHF** → a small satellite is ‘a point’ from the antenna point of view; transparent for radiation. No need to take into account the satellite shape or size.

- **S-band** → size of the satellite ≈ wavelength
  - **Spacecraft geometry impacts the radiation pattern much more than usually.**

- **High integration degree** → Trade-off between cohabitation of the antenna system and the spacecraft and its instruments.

- Best solution: **combine a small number of simple radiators**, carefully distributed and integrated onto the spacecraft surface.
3. EM MODEL: DESCRIPTION AND CONFIGURATIONS
EM MODEL: DESCRIPTION AND CONFIGURATIONS (I)

- Omnidirectional full-sphere mode → most challenging antenna mode.
- Use a reduced number of elements (a priori) “randomly” distributed over the satellite surface.
- Simulation and further optimization process with current commercial software accounting for the spacecraft structure → unaffordable computation time.
- Need of a fast computation tool able to predict 3D array factors for any generic satellite structure.

**In-house MATLAB® software: SatAF (SATellite Array Factor)**
EM MODEL: DESCRIPTION AND CONFIGURATIONS (II)

- Analytical models:  
  - Infinitesimal source 
  - Dipole 
  - Slot 
  - Patch 
  - Current loop

- External software simulations

SatAF

Radiation components

Direct radiation
Platform interactions
Mutual coupling

Outputs
- Electric field
- Directivity
- Gain
- Axial Ratio

Components
- Total
- Theta, phi
- R- / LHCP
- “Best” R-/LHCP

Patterns
- 3D polar
- 2D diagram
- Rectangular plot
- Polar plot

Function & Scale
- Magnitude / dB
- Linear / logarithmic

Predominant contribution to the radiated power
EM MODEL: DESCRIPTION AND CONFIGURATIONS (III)
4. ANTENNA ELEMENT DESIGN
ANTENNA ELEMENT DESIGN (I)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Slots</th>
<th>Patches</th>
<th>Printed Dipoles</th>
<th>PIFA</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size – surface</td>
<td></td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>Size – height</td>
<td>🌟</td>
<td></td>
<td>🌟</td>
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<tr>
<td>Integration level (SP, instruments, edges..)</td>
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<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>Performances (Gain, BW..)</td>
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<td>🌟</td>
<td>🌟</td>
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<td>🌟</td>
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<tr>
<td>Polarization purity</td>
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<td>🌟</td>
<td>🌟</td>
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<tr>
<td>BFN design</td>
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<td>🌟</td>
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<tr>
<td>Mech. Implementation</td>
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<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
<tr>
<td>Robustness against metallic surfaces</td>
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<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
<td>🌟</td>
</tr>
</tbody>
</table>

- Integration easiness
- Robustness against metallic environment
- Flat mounting, avoids vertical mounting non-compatible with sat separation method of very small satellites and CubeSats
- Efforts focused on solving the problem of height → back reflector at λ/4 (35mm=1.38”)
ANTENNA ELEMENT DESIGN (II)

Innovative low-profile high-efficient broadband cavity-backed slot exciter

- Slot aperture composed of compacted double dog-bone slots customized configuration
- Slots bent to: 1) decrease the occupied length and 2) facilitate the combination to form arrays
- Size of the “via-based cavity”: $a \times b = 60 \times 42$ mm (2.36” x 1.65”)
  $h_1 + h_2 = 12.8$ mm (0.5”)
  (35% of$\lambda/4 = 35$ mm (1.38”)
• Element carefully optimized to provide a large impedance bandwidth

• Covers frequency band allocated for space applications (2025 - 2300 MHz) with a return loss figure < -15dB → 13% relative bandwidth at 2.16 GHz

• The proposed element presents a typical slot radiation pattern, linearly polarized, with a simulated gain around 5.3 dB and efficiency >85%
5. MULTI-FUNCTIONAL ANTENNA SYSTEM DESIGN
MULTI-FUNCTIONAL ANTENNA SYSTEM DESIGN (I)

- For a generic cubic satellite → **75% of omnidirectional coverage** within the specifications (mixing RHCP and LHCP)
• For a generic octagonal satellite → **92% of omnidirectional coverage** within the specifications (mixing RHCP and LHCP)
MULTI-FUNCTIONAL ANTENNA SYSTEM DESIGN (III)

- Each face of the satellite → directive beam ~10dBi of $D_{\text{max}}$

- 4 slot radiators arranged in a squared configuration per face. Optimized configuration to minimize the low-elevation radiation.

- Circular polarization → sequential rotation. Beam Forming Network (BFN) phase shift of $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$. 
• Proof-of-Concept demonstrator: Mock-up of a generic small cube satellite

• Dimensions of the PoC chosen to be within the range of existing small satellites: cubic shape of 250x250x250mm ~ 1.8λx1.8λx1.8λ @ 2.16GHz.
MULTI-FUNCTIONAL ANTENNA SYSTEM DESIGN (V)

- Main planes of the PoC satellite have been measured
- Good agreement w.r.t. simulated SatAF expected results
• The high directivity of this sub-array of 4 exciters/face (D≈10dBi) → a **directive beam** on each face
MULTI-FUNCTIONAL ANTENNA SYSTEM DESIGN (VII)

- Versatility of the sub-array of 4 exciters/face configuration + new BFN + switches → generate the **four tracking beams**.
6. CONCLUSIONS
CONCLUSIONS

- Developed a fast computation tool able to predict 3D array factors for any generic satellite structure: SatAF
- Designed an innovative low-profile high-efficient broadband cavity-backed slot exciter
- A multi-functional miniaturized antenna system which can be integrated within the walls of a generic small satellite has been presented
- Achieve speeds between 256kbps and 512kbps, depending on details of mission design (payload, ground station, ...).
- The antenna patterns achieved are implemented in EPFL- Space Center’s Concurrent Design Facility Telecommunication Subsystem to model data link budgets for the future missions such as a small exoplanets observatory.
THANKS!

QUESTIONS?

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