1 ATM-Sat specifications
2 Passive printed antenna design
3 RF electronics and system parameters*
4 Terminal architecture and construction*
5 Manufacturing guidelines

DLR, Institute of Communications and Navigation

2.1 Guiding principles and goals
2.2 Coplanar-waveguide-fed aperture-coupled patch and substrate selection
2.3 Array radiation characteristics
   Simulation of a large array including mutual coupling

* Source: Institut für Hochfrequenztechnik, Technische Universität Braunschweig
  Partner associated with DLR in the complementary project SANTANA (Smart ANTennA termiNAL)
# ATM-Sat specifications

Low Earth Orbit (LEO) satellite system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink-frequency</td>
<td>30 GHz</td>
</tr>
<tr>
<td>Downlink-frequency</td>
<td>20 GHz</td>
</tr>
<tr>
<td>Bandwidth (antenna)</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Polarisation (radiation)</td>
<td>Circular</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>35 dBi</td>
</tr>
<tr>
<td>Radiation pattern beamwidth (at -3 dB)</td>
<td>~ 5°</td>
</tr>
<tr>
<td>Side lobes level</td>
<td>&lt; -20 dB</td>
</tr>
<tr>
<td>Cross-polarisation</td>
<td>&lt; -20 dB</td>
</tr>
<tr>
<td>Maximum scan angle</td>
<td>60°</td>
</tr>
<tr>
<td>Antenna beams</td>
<td>1 transmit beam</td>
</tr>
<tr>
<td></td>
<td>2 receive beams</td>
</tr>
</tbody>
</table>
2 Passive printed antenna design

2.1 Guiding principles and goals

Thickness of the substrate supporting the radiating elements: selection criteria

- standard thicknesses of commercial substrates

- \textbf{min}: minimum relative thickness required to meet the targeted bandwidth

- \textbf{max}: maximum relative thickness recommended to avoid the occurrence of a scan blindness within the scan angle range

- Targeted bandwidths = 1 GHz

⇒ 5.0 % at 20 GHz
3.5 % at 30 GHz
2.1 Guiding principles and goals

Permittivity $\varepsilon_r$ of the substrate supporting the radiating elements

- $F=20$ GHz
- $F=30$ GHz

Minimum relative distance between patch edges to limit mutual coupling effects

Square patch dimension estimated by cavity model

Angular locations of the main beam and the first grating lobe

- $a$: element spacing in a conventional array
- $a$: subarray spacing if elements are sequentially rotated

$\lambda_0$: free space wavelength
2.2 Coplanar-waveguide-fed aperture-coupled patch and substrate selection

**Elementary radiator**

patch fed by a CPW line through an aperture (capacitive coupling)

At 30 GHz: patch edge $L_p = 1.6$ mm
CPW: strip $s = 0.5$ mm, gap $w = 0.1$ mm (impedance=50 Ω)
with the substrate parameters: permittivity = 6.15
thickness $h = 0.508$ mm

**Advantages**

- CPW* lines allow the use of a single substrate between the patch and its feed line
  - facilitate the fabrication
  - improve the feeding quality
- Aperture coupling is a non-contacting feeding
  - easy to implement and reliable
- Square patch preferred to maximise the circular polarisation purity

* coplanar waveguide
2.2 Coplanar-waveguide-fed aperture-coupled patch and substrate selection

Substrate thicknesses enabling to meet the targeted bandwidths with different permittivities*

- Operating bandwidths = 500 MHz
  - 2.5% at 20 GHz
  - 1.7% at 30 GHz

- Design goal
  Return loss lower than -10 dB over 1 GHz
  - 5.0% at 20 GHz
  - 3.5% at 30 GHz

- $\varepsilon_r = 6.15$
  minimum permittivity to be selected to reduce the subarray spacing to $0.6 \lambda_0$

* isolated radiator considered

$\lambda_0$: free space wavelength
Isolated, linearly-polarised patch operating at 30 GHz

Return loss

Bandwidth=1.4 GHz = 4.7 %
Resonant frequency=29.75 GHz
Radiation efficiency=95 %, gain=5.5 dB
Half-power beamwidth=105° for φ=0°
135° for φ=90°

Radiation patterns in the principal planes

radiation characteristics stable over the bandwidth
5 dB ≤ gain ≤ 5.8 dB, cross-polarisation ≤ -23 dB
2.3 Array radiation characteristics

Maximum broadside directivity $D_0$ of square arrays

- Realistic design goal: broadside antenna efficiency = 60%
  $\Rightarrow$ broadside realised gain ~ 30 dB

Good estimation for large arrays

$$D_0 = \left( \frac{4\pi}{\lambda_0^2} \right) A$$

- Targeted broadside directivity ~ 32 dB

Antenna surface

- $18 \times 18$ cm$^2$ at 20 GHz
- $12 \times 12$ cm$^2$ at 30 GHz
2.3 Array radiation characteristics

Arrays of sequentially rotated elements

- Sequential rotation of elementary radiators used to generate the circular polarisation
  - Geometrical rotation and electrical phase shift applied to each element in a subarray
  - Different element arrangements possible within a subarray (inward, outward or in-out excitations)
  - Subarrays can also be sequentially rotated to improve the axial ratio

- Subarrays should be spaced as close as possible to widen the scan angle range
  ⇒ coupling effects must be taken into account

Detail of a large array: module of 16 patches

Single element

Circulator polarised subarray (inward excitations)
Radiation characteristics of a 1600-element circularly polarised array at 30 GHz

Principal planes
\( \phi = 0°, 90° \)

Radiation patterns
- Scan angle
  \( (\phi_s = 0°, \theta_s = 0°) \)
- gain = 32 dB
- Efficiency = 92% (radiation)

Diagonal planes
\( \phi = 45°, 135° \)

Axial ratio = 0.15 dB
(over half-power beamwidth)

- Substrate parameters
  permittivity \( \varepsilon_r = 6.15 \)
  thickness \( h = 0.508 \text{ mm} \)
- 40×40-element array
  element spacing = 0.35 \( \lambda_0 \) within subarrays
  subarray spacing = 0.6 \( \lambda_0 \)
- Only patches are sequentially rotated
- LHCP: left-hand circular polarisation
  RHCP: right-hand circular polarisation
Radiation characteristics of a 1600-element circularly polarised array at 30 GHz

Radiation patterns – Beam scanned in a principal plane

Scan angle
($\phi_s=0^\circ, \theta_s=35^\circ$)

- Gain = 30.5 dB
- Efficiency = 85% (radiation)
- Axial ratio = 4.3 dB
Radiation characteristics of a 1600-element circularly polarised array at 30 GHz

Radiation patterns – Beam scanned in a diagonal plane

Scan angle
($\phi_s=45^\circ, \theta_s=35^\circ$)

Gain = 30.7 dB
Efficiency = 86 % (radiation)

Axial ratio = 2.7 dB
Radiation characteristics of a 1600-element circularly polarised array at 30 GHz

Circular polarisation quality

- Axial ratio ≤ 4.3 dB (< 3 dB for θ_s ≤ 25°)
- Cross-polarisation ≤ -12 dB
- Side lobes ≤ -13 dB
- Radiation efficiency ≥ 83%
- 30.5 dB ≤ Gain ≤ 32 dB (1600 elements)

Record

- For a scan angle θ_s varying up to (±) 35°
  
  - Axial ratio ≤ 4.3 dB (< 3 dB for θ_s ≤ 25°)
  - Cross-polarisation ≤ -12 dB
  - Side lobes ≤ -13 dB
  - Radiation efficiency ≥ 83%
  - 30.5 dB ≤ Gain ≤ 32 dB (1600 elements)

with element spacing=0.35 λ_0 (within subarrays)
subarray spacing=0.6 λ_0

Only patches are sequentially rotated

- Lower cross-polarisation expected when performing additionally a sequential rotation on the subarrays
  ⇒ reduced axial ratio, higher maximum scan angle
### 3 RF electronics and system parameters

Different options to perform the transmit, receive and calibration functions

<table>
<thead>
<tr>
<th>RF aspects</th>
<th>Options</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td>Homodyne architecture</td>
<td>relevant choice for monolithic integration</td>
</tr>
<tr>
<td></td>
<td>Heterodyne architecture*</td>
<td>conventional approach, good performance, space required, medium cost</td>
</tr>
<tr>
<td>Transmitter</td>
<td>Direct conversion</td>
<td>profitable only if integrated solutions exist</td>
</tr>
<tr>
<td></td>
<td>Dual conversion*</td>
<td>feasible right now, digital modulation possible and preferable</td>
</tr>
<tr>
<td>Components</td>
<td>LO built with discrete components</td>
<td>simplest option</td>
</tr>
<tr>
<td></td>
<td>1 Local Oscillator signal, distributed*</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>Internal calibration</td>
<td>optimum practical choice but expensive</td>
</tr>
<tr>
<td></td>
<td>External calibration</td>
<td>cost-effective but bulky</td>
</tr>
<tr>
<td></td>
<td>Calibration based on mutual coupling</td>
<td>may be interesting but experimental testing required</td>
</tr>
<tr>
<td></td>
<td>measurements</td>
<td></td>
</tr>
</tbody>
</table>

* options compatible with a short-term fabrication (requisite components presently on the market)
System parameters

**Receiver**

- **G/T [dB/K]**
  - **Num of Elements**
  - G/T vs Num of Elements

**Transmitter**

- **Terminal EIRP [dBW]**
  - **Num of Elements**
  - EIRP vs Num of Elements

**Assumptions**

- Antenna Noise Temp.: 290K
- Receiver Noise Figure: 4 dB
- Antenna efficiency: 60%
- Element spacing: 0.5 $\lambda_0$
- Element power: 10/15/20 dBm
4 Terminal architecture and construction

**Packaging architecture**

- **Module**
  - (actually including 16 patches)
- **Patch**
- **Baseplate**
- **Cooling**
- **Power supply**
- **LO / Clock distribution**
- **Beamforming / -steering**

**Terminal antenna construction (a)**

<table>
<thead>
<tr>
<th>Proposals</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modular construction</td>
<td>array subdivided into modules, module (2 \times 2) subarrays</td>
</tr>
<tr>
<td>Hybrid Tile- / Brick-architecture (for the module)</td>
<td>• RF parts of receiver/transmitter&lt;br&gt;• IF/BB circuitry&lt;br&gt;• AD/DA converters</td>
</tr>
<tr>
<td>Cross-module functions implemented at the module-base level</td>
<td>• DC-supply power&lt;br&gt;• Local-Oscillator signals&lt;br&gt;• Clock signals&lt;br&gt;• DSP functions&lt;br&gt;• Heat sink facilities</td>
</tr>
</tbody>
</table>
## Terminal antenna construction (b)

<table>
<thead>
<tr>
<th>Proposals</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Multichip-module laminate</strong></td>
<td>(+) robust and reliable construction</td>
</tr>
<tr>
<td></td>
<td>(+) most cost-effective technology</td>
</tr>
<tr>
<td>Fabrication steps</td>
<td></td>
</tr>
<tr>
<td><img src="photoresist-develop-etch-strip-laminate-drill-plate" alt="Fabrication steps" /></td>
<td></td>
</tr>
<tr>
<td><strong>Wire bonding</strong></td>
<td>(+) ready for implementation</td>
</tr>
<tr>
<td>(present standard technology)</td>
<td>(-) space-consuming</td>
</tr>
<tr>
<td></td>
<td>(-) fully automated fabrication not possible</td>
</tr>
<tr>
<td><strong>Flip-chip</strong></td>
<td>(+) fast, high-volume automated production</td>
</tr>
<tr>
<td>(next-generation technology)</td>
<td>(+) most mechanically rugged method</td>
</tr>
<tr>
<td></td>
<td>(+) compactness</td>
</tr>
<tr>
<td></td>
<td>(-) all needed chips not currently available</td>
</tr>
<tr>
<td></td>
<td>(+) advantages, (-) drawbacks</td>
</tr>
</tbody>
</table>
5 Manufacturing guidelines

Technological recommendations for fabricating full-scale terminals

• Receive and transmit functions performed by 2 separate antennas
  – Heterodyne receiver
  – Dual conversion transmitter

• Modular, hybrid architecture

• Multichip-module-laminate technology

• Flip-chip interconnections

• Digital beamforming

Further comments

• Iterative and progressive 3-step implementation suggested
  – module (16 elements)
  – intermediate building block (256 elements)
  – full-size terminal

• Factors limiting the antenna dimension
  – efficiency of the heat-sink process
  – performance and cost of components available when realising the complete active antenna

• An up-market-oriented product is targeted