System and Mission Trade-offs for Sentinel-1 Next Generation

Phase-0 Study

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German Aerospace Center (DLR)
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Motivations and Sentinel-1 Next Generation Main Objectives

- The **Copernicus program** has been established to respond to the European needs of accurate and timely information services.
- **Sentinel-1 C-band Synthetic Aperture Radar (SAR)** observations constitute an essential component of Copernicus with *wide-swath systematic global observations* to build-up a *long-term archive of globally consistent data*.
- The *next generation of the Sentinel-1 mission (S1-NG)* is conceived to *broaden* the spectrum of potential *applications and services* of the current S1 mission by means of a **C-band SAR** with *advanced capabilities*.
- S1-NG will employ a C-band SAR instrument operating with *full polarimetric capabilities*.
- The C-band SAR mission *target applications* are maritime surveillance, ocean surface current velocity measurement, sea ice mapping, sea ice drift, iceberg detection, glacier motion, oil spill detection, surface deformation mapping, land cover mapping, ...
- ESA has funded two **S1NG Phase-0 studies**.
- **DLR and TAS-I** are conducting one of the two Phase-0 Studies funded by ESA with the objective of proposing mission concepts and system architectures for the **next generation of Sentinel-1 (S1-NG) satellites**.
Sentinel-1 Next Generation (S1NG): Key Mission and System Requirements

High Level Mission Requirements

- Systematic global coverage with **mission repeat interval ≤ 4 days**
- **Daily** full coverage ±45° latitude (optionally +30° lat); twice daily coverage above +60° lat
- Ocean surface current velocity measurement with an **accuracy of 1m/s** (prob. ≥ 68.3%)
- **Pointing knowledge ≤ 0.5 mdeg** (prob. 99.7%)
- **Ship detection** with size of 15 m for Sea State of 5 (prob. 95%) and **ship speed detection** accuracy 2-5 m/s (radial) and 5-10 m/s (along track), both with a (prob. 99.7%)

System Requirements

- **Swath width > 400 km** for Single/Dual Pol observations
- Single-look ground resolution of 25 m²
- **Swath width > 280 km** for Quad Pol observations
- **Swath width > 600 km** for Dual Pol observations with a NESZ<-25 dB and **resolution TBD** for Sea Ice observations
- System **NESZ ≤ -22 dB** for the single, dual and quad pol modes
- **European launcher**, i.e. [VEGA-C (G) / and (T)] VEGA-E
Proposed Mission Concepts and Associated Performance
Key Factors:
- Orbit
  - repeat cycle
  - altitude
  - n. of revolutions
    (in red in the figure)
- Required **swath width**
  (in blue in the figure)
- **Number of satellites**

**Orbit Selection**

- 2 satellites
  - swath \(\geq 350\) km

- 3 satellites
  - swath \(\geq 250\) km

4 days repeat @ Equator
Exemplary Revisit Time Performance

2 S/C on 8-days orbit @ 679 km height

3 S/C on 12-days orbit @ 693 km height

3 S/C on 12-days orbit @ 1224 km height

Global/Europe (400 km) - North Pole (600 km)
Key Mission Trade-Offs And Performance

**N. of satellites is a key performance driver!**

- **Higher number** of satellites provide **better performance**
- Higher number of satellite **reduces the orbital altitude impact on the performance** (i.e., for the 12 days orbits from 700 km to 850 km and 1200 km the required swath width increases only of a few tens of km, achieving similar performance).

3 S/C on 12 days orbits vs 2 S/C on 8 days orbits

- **Global:**
  - 400 km enable **< 4 days revisit time**
  - 280 km swath leaves **gaps at the equator with 2 S/C (over 8 days orbits)**
- **Europe** (30° and 45° latitude): it is **not possible** to meet the daily revisit requirement
- **North Pole** (above 60° lat) with 600 km swath width
  - 3 sats: twice daily
  - 2 sats: twice daily almost met

- **Lower orbits and shorter orbit repeat cycles** demand for **wider swaths** and consequently **increased instrument complexity**
- Higher orbits offer **reduced incident angle range** → better observation consistency and **more uniform performance**
- Easier to enable 600 km swath width and coverage of the North Pole
- Longer downlink time

Orbits with larger repeat (12 days orbits) require 1 satellite more (of 8/7 days orbits)

For wider swath widths a lower N. of S/C is required

N. Of Satellites

Orbit altitude, repeat cycle

Instrument complexity, Access range, Swath width

[Diagram showing relationships between satellites, orbit altitude, repeat cycle, instrument complexity, access range, and swath width]
Proposed Instruments Concepts and Associated Performance
Proposed Instrument Concepts

**Planar Antenna**
*Multi-channel ScanSAR*
- **Heavier and more complex solution**
  - Ariane 6.2 (ideally dual-launch)
  - $12.5 \times 2.5 \text{ m antenna}$
  - **compliant performance** for all the imaging modes
- **Mass-compliant with VEGA-E**
  - $12.2 \times 1.3 \text{ m antenna}$
  - relaxed SAR performance

**Reflector-Based Antenna**
*Staggered SAR*
- **Altitude: 1208 km and 845 km**
- **Diameter: 9 meter**
- **Feed offset: 3 meters**
- **Direct access to the North Pole**

**Hybrid**
*(same platform, planar Tx – reflector Rx)*
*Staggered SAR*
- **Altitude: 1208 km and 845 km**
- **Diameter: 9 meter**
- **Transmit antenna: 8 m x 1 m**
Baseline Architectures Inherent Features

**Planar Antenna**
- **Pros:**
  - Flexible *beam steering*
  - Map an arbitrary *wide swath*
  - ATI
  - Less challenging *pointing* knowledge and accuracy
- **Cons:**
  - Mass
  - Instrument complexity
  - Power demand
  - Better suited for lower orbits (i.e., S1 orbit)

**Reflector-based Antenna**
- **Pros:**
  - Large *aperture:*
    - High *gain*, higher *sensitivity*
    - Low *power demand*
  - Low *weight*
  - Simplified *instrument architecture*
- **Cons:**
  - ATI
  - Pointing knowledge and accuracy
  - Electronic beam steering and access range
  - Better suited for higher orbits (i.e., 800 – 1500 km)

**Hybrid: Tx Planar- Rx Reflector**
- **Pros:**
  - Large *aperture:*
    - High *gain*, higher sensitivity from reflector
  - Low *power demand*
  - Simplified *instrument architecture*
  - No TR module:
    - Reduced losses
    - Reduced *noise* figure
  - ATI by splitting Tx antenna
  - Pointing knowledge and accuracy less problematic
  - High peak power by *tube amplifier*
- **Cons:**
  - Higher fairing capacity (*extra Tx antenna*)
  - Limited *Tx beam shaping*
  - Better suited for higher orbits (i.e., 800 – 1500 km)
Proposed Instrument Concepts: Planar Antenna solutions

**Planar Antenna**

*Multi-channel ScanSAR*

- Heavier and more complex solution
  - Ariane 6.2 (ideally dual-launch)
  - 12.5 x 2.5 m antenna
  - compliant performance for all the imaging modes
- Mass-compliant with VEGA-E:
  - 12.2 x 1.3 m antenna
  - relaxed SAR performance

**Vega-E compliant Design:**

- ~ **300 km swath** (enough for 12 days repeat cycle orbits to get global coverage) both in single-pol and quad-pol
- **same 2 burst geometry** both for single-/dual- and quad-pol
- In quad-pol, the **same** overall PRF is used (shared between the 2 Tx polarizations), but the **azimuth resolution is worsened** to allow adequate performance (dedicated azimuth beams)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single</th>
<th>Quad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit height</td>
<td>693 km</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>Single</td>
<td>Quad</td>
</tr>
<tr>
<td>Swath width</td>
<td>303 km</td>
<td>303 km</td>
</tr>
<tr>
<td>Number of bursts</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Antenna Size (az, el)</td>
<td>12.2 m x 1.3 m</td>
<td></td>
</tr>
<tr>
<td>Number of Channels (azimuth, elevation)</td>
<td>(5, 30)</td>
<td></td>
</tr>
<tr>
<td>Pulse duty cycle</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Average transmitted power</td>
<td>1350 W</td>
<td></td>
</tr>
</tbody>
</table>
Mass-Compliant Planar System: Imaging Performance

<table>
<thead>
<tr>
<th></th>
<th>Single-pol</th>
<th>Quad-pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath width</td>
<td>303 km</td>
<td>303 km</td>
</tr>
<tr>
<td>Resolution ($\delta_x \times \delta_{gr}$) [m²]</td>
<td>&lt; 20</td>
<td>&lt; 60</td>
</tr>
<tr>
<td>AASR [dB]</td>
<td>&lt; -31</td>
<td>&lt; -24.5</td>
</tr>
<tr>
<td>RASR [dB]</td>
<td>&lt; -30</td>
<td>&lt; -24.5</td>
</tr>
<tr>
<td>NESZ [dB]</td>
<td>&lt; -23</td>
<td>&lt; -23</td>
</tr>
<tr>
<td>SAR performance satisfied</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

**Margin for optimization**
- Medium: Antenna parameters, phase spoiling coefficients
- SAR performance margin in single-/dual-pol
- 600 km (@ worsened resolution, SAR performance under analysis)

**Average Tx power for -22 dB NESZ**
~1350 W

**Launcher compatibility**
Vega E
**Proposed Instrument Concepts: Reflector-Based Antenna Solutions**

- **Altitude**: 1208 km and 845 km
- **Diameter**: 9 m
- **Feed offset**: 3 m
- **Direct access to the North Pole**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1200 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter D</td>
<td>9 m</td>
</tr>
<tr>
<td>Focal length F</td>
<td>9 m</td>
</tr>
<tr>
<td>F/D ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.405 GHz</td>
</tr>
<tr>
<td>Offset in azimuth</td>
<td>0.0 m</td>
</tr>
<tr>
<td>Offset in elevation</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Feed tilt angle $\theta_f$</td>
<td>18.92°</td>
</tr>
<tr>
<td>Number of elevation feed elements</td>
<td>91 (for 600 km)</td>
</tr>
<tr>
<td>Number of azimuth feed doublets</td>
<td>5</td>
</tr>
<tr>
<td>Element spacing (elevation/azimuth)</td>
<td>$0.6\lambda / 0.6\lambda$</td>
</tr>
<tr>
<td>Feed length (elevation)</td>
<td>$\approx 3.0 \text{ m}$</td>
</tr>
<tr>
<td>Feed height (azimuth)</td>
<td>0.33 m</td>
</tr>
<tr>
<td>Bus size</td>
<td>1 m$^3$</td>
</tr>
<tr>
<td>Boresight (look) angle</td>
<td>32.35°</td>
</tr>
<tr>
<td>Elevation angle span</td>
<td>[-8.85, 9.25]°</td>
</tr>
<tr>
<td>Azimuth beamforming</td>
<td>LCMV: combining 5 azimuth doublets into 1 channel</td>
</tr>
<tr>
<td>Elevation beamforming</td>
<td>Combine 10 elevation elements on receive to form a SCORE beam</td>
</tr>
</tbody>
</table>
### 9m reflector antenna @ 1208 km – Imaging Performance

<table>
<thead>
<tr>
<th></th>
<th>Single-pol (400 km) staggered SAR</th>
<th>Single-pol (600 km) staggered SAR</th>
<th>Quad-pol (280 km) staggered SAR</th>
<th>Quad-pol (382 km) staggered SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution ((\delta_x \times \delta_{gr}))</td>
<td>5 m x 5 m</td>
<td>5 m x 27.3 m</td>
<td>5 m x 5 m</td>
<td>5 m x 5 m</td>
</tr>
<tr>
<td>AASR [dB]</td>
<td>&lt; -25</td>
<td>&lt; -23</td>
<td>&lt; -23</td>
<td>&lt; -23</td>
</tr>
<tr>
<td>RASR [dB]</td>
<td>&lt; -31</td>
<td>&lt; -23</td>
<td>&lt; -21</td>
<td>&lt; -17</td>
</tr>
<tr>
<td>NESZ [dB]</td>
<td>&lt; -22</td>
<td>&lt; -25</td>
<td>&lt; -20.5</td>
<td>&lt; -19.5</td>
</tr>
<tr>
<td>SAR performance satisfied</td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Margin for optimization</td>
<td>yes, e.g., side-lobe suppression</td>
<td>intermediates, e.g., side-lobe suppression, additional azimuth doublets, ...</td>
<td>yes, e.g., side-lobe suppression, additional azimuth doublets, ...</td>
<td></td>
</tr>
<tr>
<td>Peak power demand</td>
<td>87 W per TRM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launcher compatibility</td>
<td>Vega E</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Proposed Instrument Concepts: Hybrid Solution

**Hybrid** (same platform, planar Tx – reflector Rx)

- **Staggered SAR**

- **Rx**-only reflector antenna and **Tx**-only planar antenna
- **No need for T/R modules or circulators** thanks to **Tx** / **Rx** separation
  - Reduced system noise figure
  - Higher peak power can be achieved, e.g., by using a travelling wave **tube amplifier**.
- **Tx antenna size** rather small for a illuminated footprint:
  - 8 m long antenna in azimuth
- Possibility **dedicated mode for calibration** to meet the pointing knowledge requirement
- **Planar antenna** becomes a dual-transmit antenna, **ATI** is enabled.

- **Altitude**: 1208 km and 845 km
- **Transmit antenna**: 8 m x 1 m
### Hybrid (Tx: 1 m x 8m antenna, Rx: 9m reflector) @ 1208 km – Imaging Performance

<table>
<thead>
<tr>
<th></th>
<th>Single-pol (400 km) staggered SAR</th>
<th>Quad-pol (280 km) staggered SAR</th>
<th>Quad-pol (382 km) staggered SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resolution</strong> ($\delta_x \times \delta_{gr}$)</td>
<td>5 m x 5 m</td>
<td>5 m x 5 m</td>
<td>5 m x 5 m</td>
</tr>
<tr>
<td><strong>AASR [dB]</strong></td>
<td>&lt; -25</td>
<td>&lt; -25</td>
<td>&lt; -22</td>
</tr>
<tr>
<td><strong>RASR [dB]</strong></td>
<td>&lt; -36</td>
<td>&lt; -22</td>
<td>&lt; -21</td>
</tr>
<tr>
<td><strong>NESZ [dB]</strong></td>
<td>&lt; -22</td>
<td>&lt; -22</td>
<td>&lt; -22</td>
</tr>
<tr>
<td><strong>SAR performance satisfied</strong></td>
<td>+++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td><strong>Margin for optimization</strong></td>
<td>yes, e.g., side-lobe suppression</td>
<td>yes, e.g., side-lobe suppression, azimuth beamforming optimization</td>
<td></td>
</tr>
<tr>
<td><strong>Peak power demand</strong></td>
<td>5900 W</td>
<td>7960 W</td>
<td>9530 W</td>
</tr>
<tr>
<td><strong>Launcher compatibility</strong></td>
<td>Vega E</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Single-Pol Performance**

- **AASR [dB]**: 
  - VV: [Graph showing AASR vs. ground range]

- **RASR [dB]**: 
  - VV: [Graph showing RASR vs. ground range]

- **NESZ [dB]**: 
  - VV: [Graph showing NESZ vs. ground range]
Trade-offs for Instrument Design Optimization

Vega-E accommodation

ATI Capability

Lighter planar 12.2 m x 1.3 m
Relaxed Imaging Performance

- Hybrid (planar Tx, reflector Rx)
- Reflector with 2 azimuth channels
  (current design providing physical baselines 2-3 m)

Heavy planar fully compliant system
12.5 m x 2.5 m

Fully compliant
SAR Imaging Performance

Reflectors (e.g. 9 m) with single azimuth channel, no ATI
Conclusions and Way Forward for Future Phase A/B1

• **Sentinel-1** is serving several applications and services, being the first mission able to provide high resolution and wide swath systematic and globally consistent images.

• The **next generation of the Sentinel-1 mission (S1-NG)** will broaden the spectrum of potential applications and services and will show **advanced capabilities**, among which
  
  • single-pol acquisition with **25m² resolution at 400 km**
  
  • **fully polarimetric acquisitions** with **280 km**
  
  • Sea ice mode with **600 km at TBD**
  
  • very high imaging quality,
  
  • highly accurate pointing,
  
  • ATI capabilities...

• Improved mission objectives lead to multiple challenging requirements

• The **S1NG Phase 0 study** has aimed at developing **mission concepts** and designing **instrument architectures** fulfilling a number of them.
Conclusions and Way Forward for Future Phase A/B1

- **Key achievement and crucial trade-offs:**
  - **Mission level:** almost all the requirements in terms of revisit are satisfied (unique exception daily over Europe). Main trade-offs:
    - N. of satellites (3 vs 2 satellites)
    - Different orbits (higher vs lower orbits, shorter vs longer orbit repeat cycles)
  - **Instrument level:**
    - Proposed planar antenna and reflector-based antenna (plus architecture variations, i.e., reflector with 2 azimuth channels and hybrid design) that satisfy a high number of requirements. Main trade-offs and engineering challenges:
      - SAR imaging performance vs system mass/weight vs pointing knowledge and accuracy vs baseline for ATI
      - Additional optimization of the instrument design facing complexity and cost and TRL
  - **Next steps outlook:**
    - space segment design for the preferred instrument architecture(s) optimization:
      - Instrument design and operational modes (ad hoc operative mode for ocean observations to be further developed)
      - Associated spacecraft configurations
    - **observation scenario/timeline definition** for more realistic mission performance
      - associated data volume and tuning of the ground-segment resources
    - ....
System and mission trade-offs for Sentinel-1 Next Generation

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