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

Phase-0 Study

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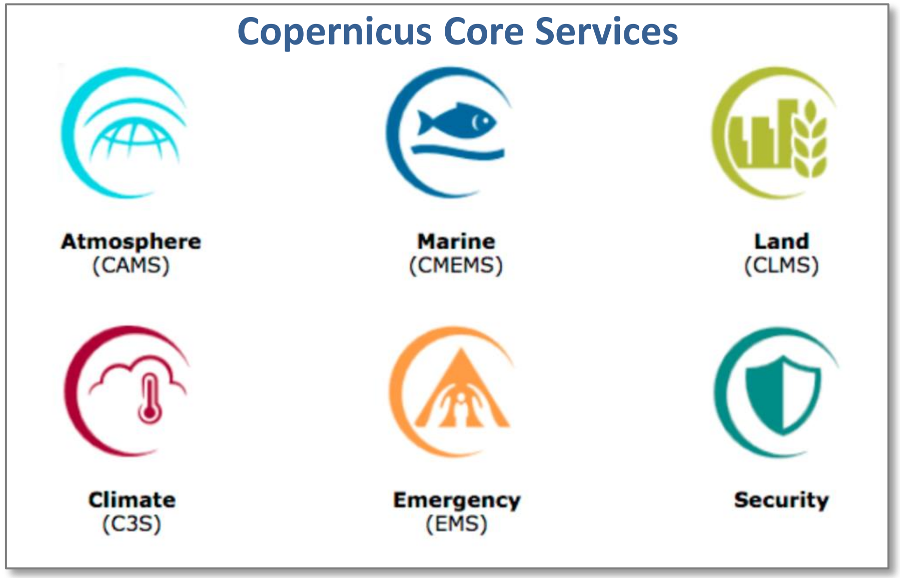
Motivations and Sentinel-1 Next Generation Main Objectives

- 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 m^2**
- **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

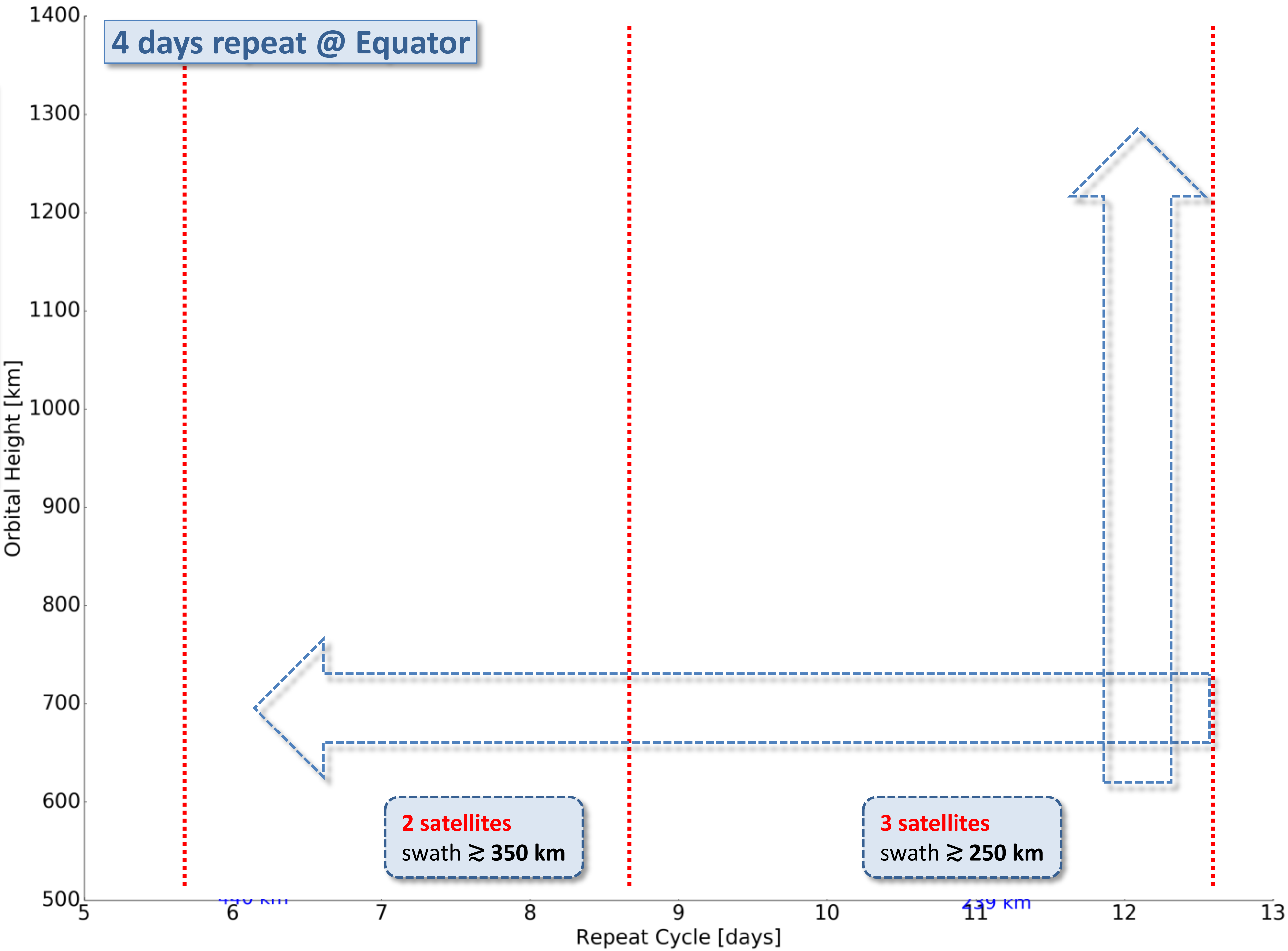
Orbit Selection

Key Factors:

- **Orbit**
  - **repeat cycle**
  - **altitude**
  - **n. of revolutions**

  (in **red** in the figure)
- Required **swath width**

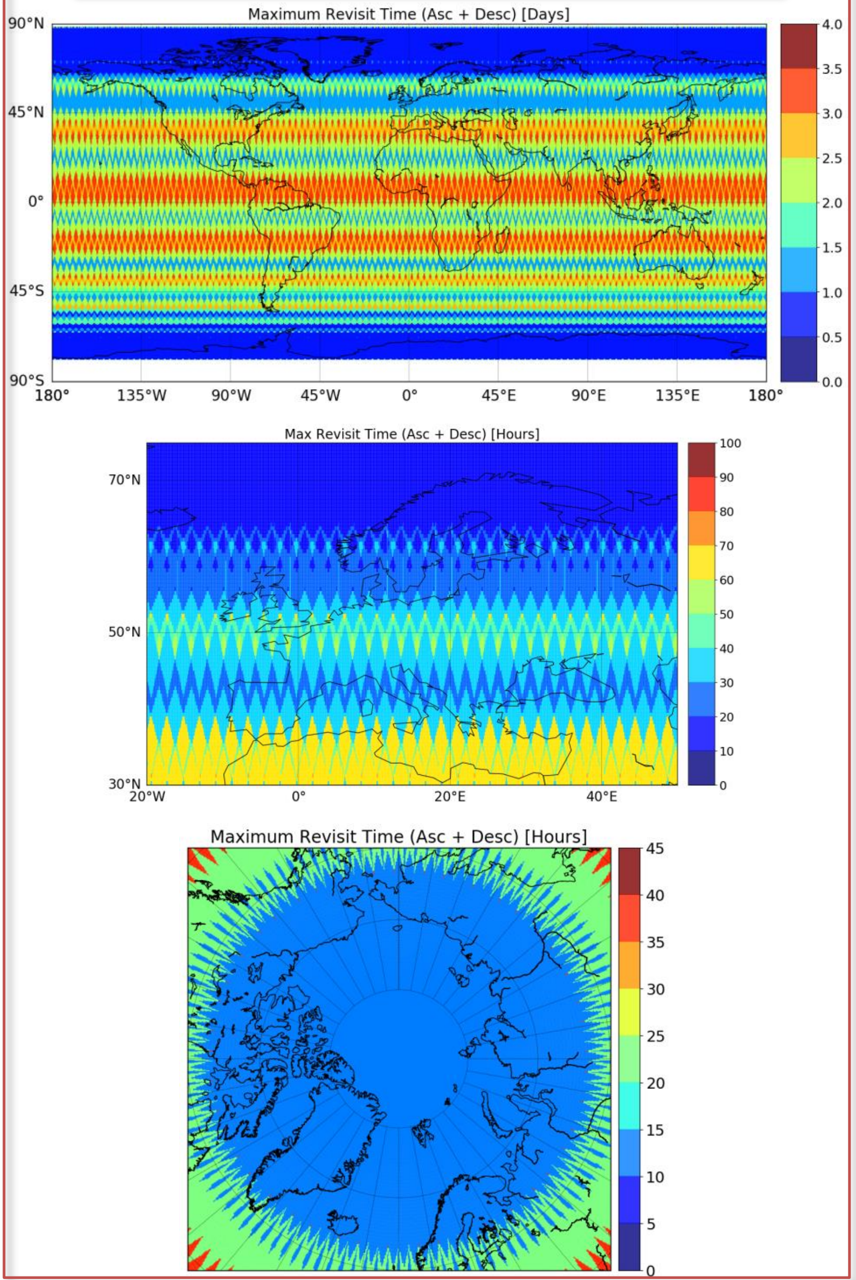
  (in **blue** in the figure)
- **Number of satellites**



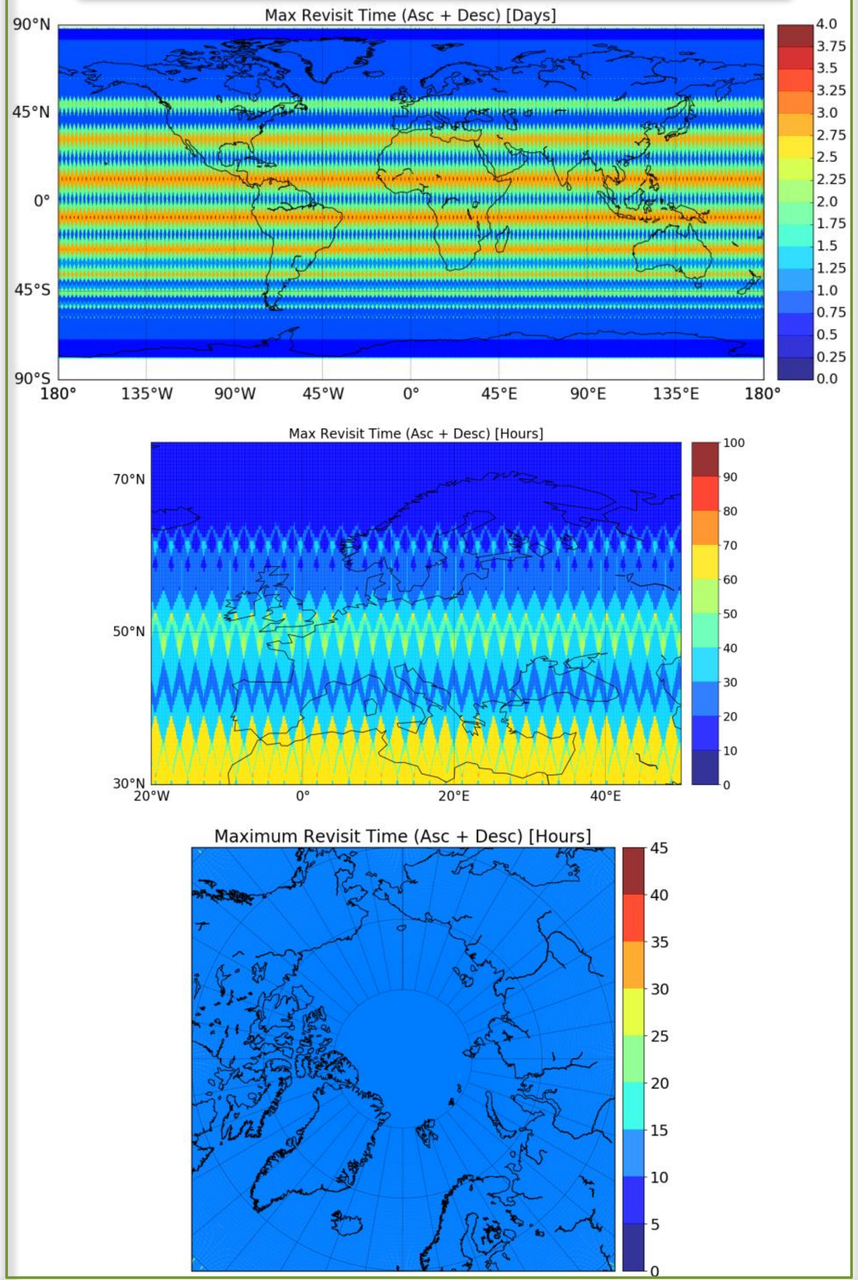
Exemplary Revisit Time Performance

Global/Europe (400 km) - North Pole (600 km)

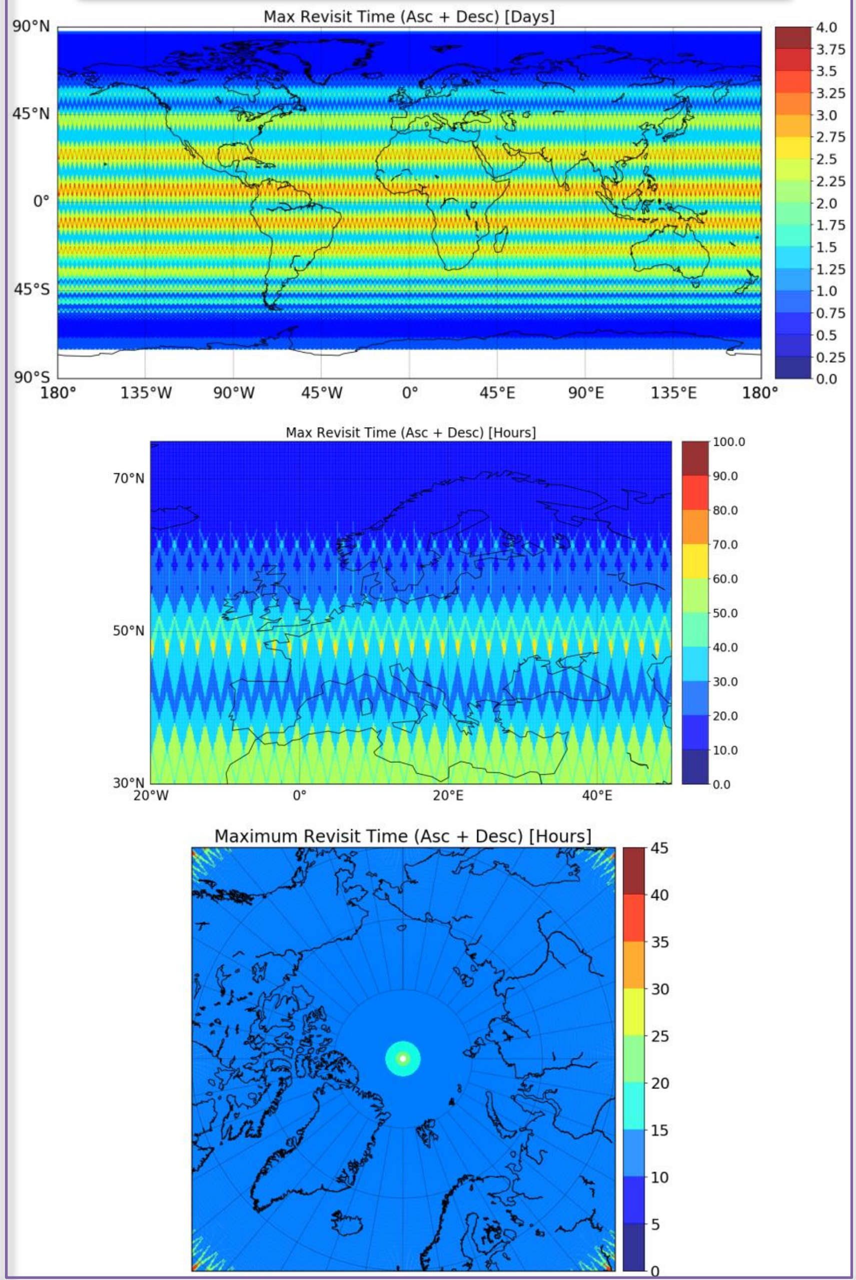
2 S/C on 8-days orbit @ 679 km height



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



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



Key Mission Trade-Offs And Performance

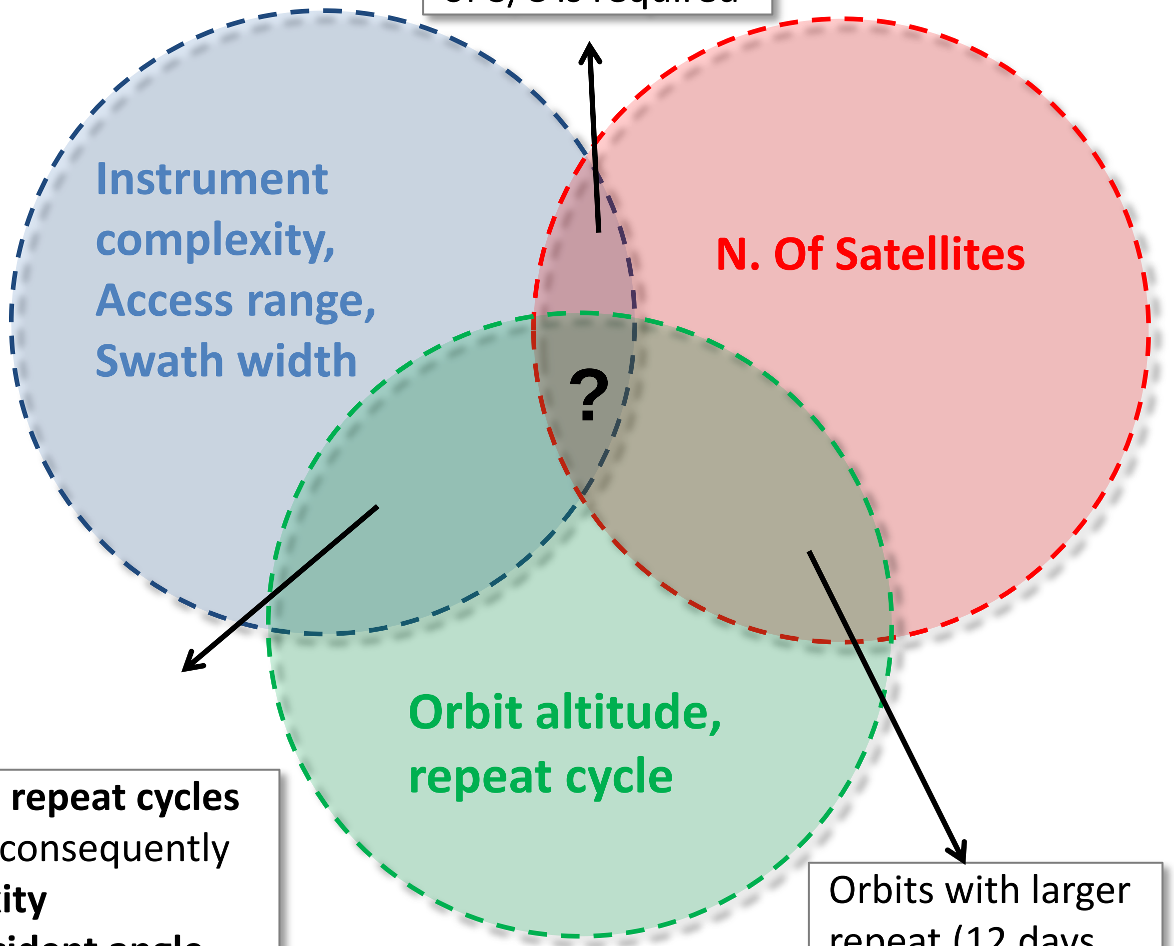
N. of satellites is a key performance driver!

- **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

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



- **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)

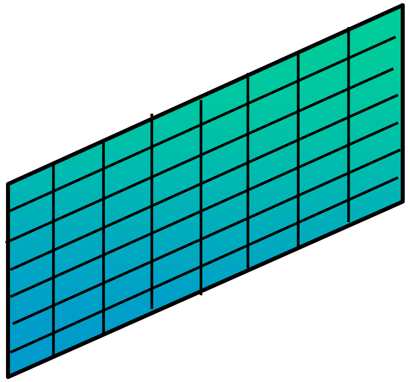
Proposed Instruments Concepts and Associated Performance

Proposed Instrument Concepts

Planar Antenna

Multi-channel ScanSAR

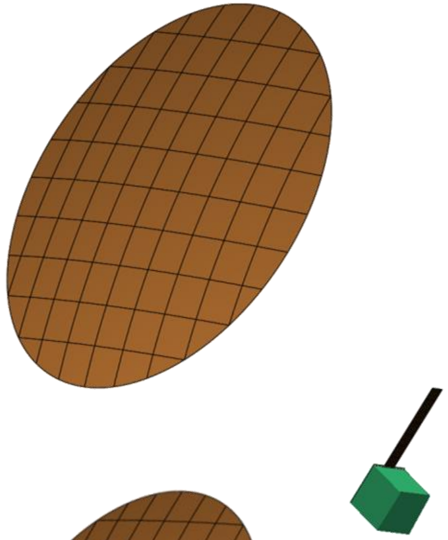
- Heavier and more complex solution
  - Ariane 6.2 (ideally dual-launch)
  - **12.5 x 2.5 m antenna**
  - **compliant performance** for all the imaging modes
- Mass-compliant with VEGA-E
  - **12.2 x 1.3 m antenna**
  - **relaxed SAR performance**



Reflector-Based Antenna

Staggered SAR

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



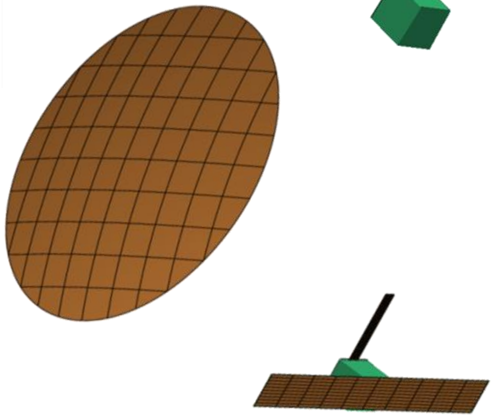
Hybrid

(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

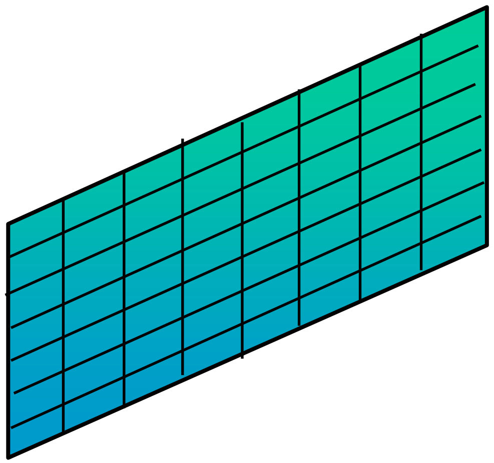
- **Pros:**
  - Large a**perture:**
    - high **gain**, higher sensitivity from reflector
    - **Low power demand**
  - Simplified **instrument architecture**
  - **No TR module:**
    - **Reduced losses**
    - **Reduced noise** figure
  - **ATI** by splitting Tx antenna
  - **Pointing** knowledge 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:

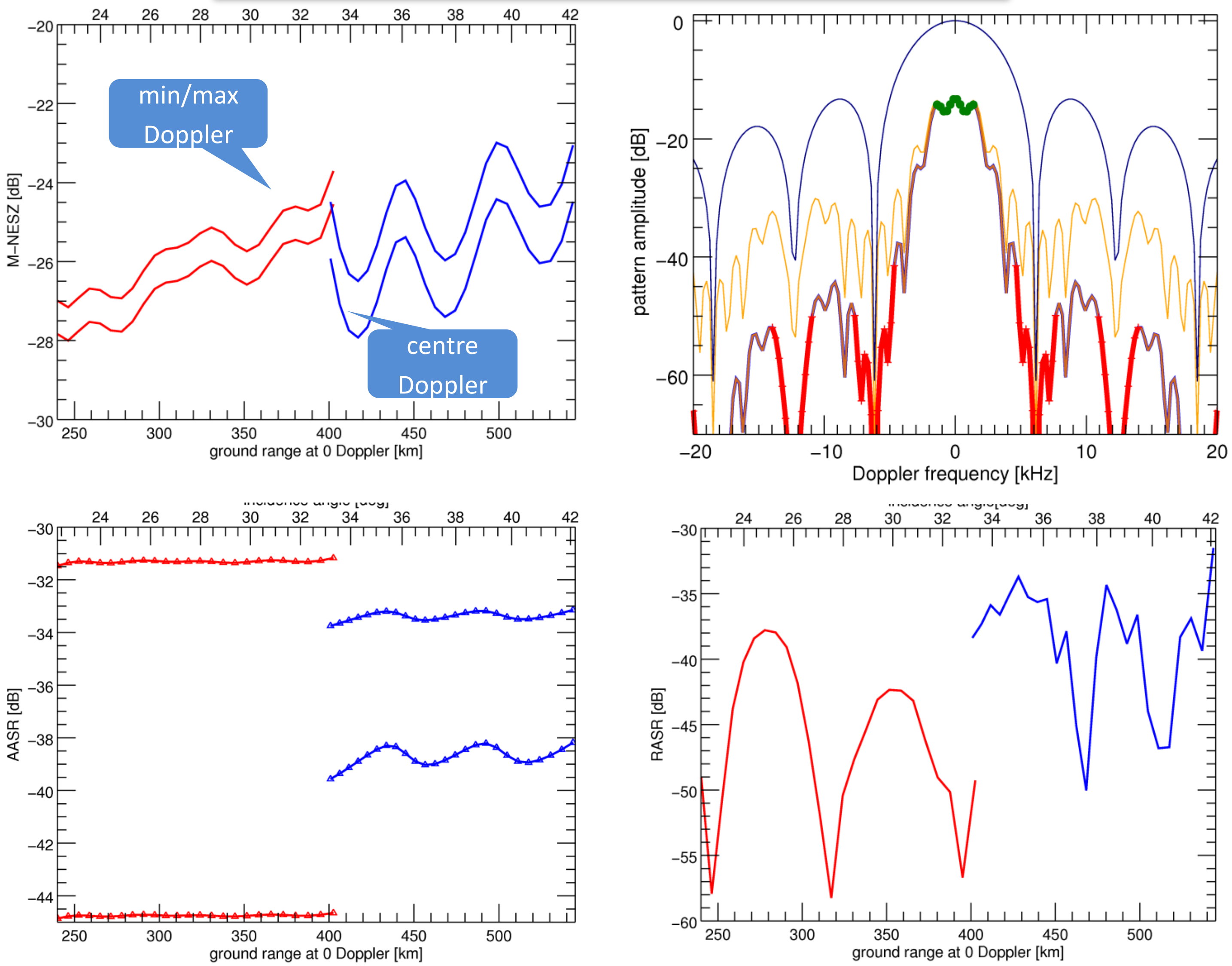
- **~ 300 km swath** (enough for 12 days repeat cycle orbits to get global coverage) both in **single-pol and quad-pole**
- **same 2 burst geometry** both for single-/dual- and quad-pol
- in **quad-pol**, the **same** overall **PRF** is used (shared between the 2 Tx polarizations), but the **azimuth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

Orbit height	693 km	
Polarization	**Single**	**Quad**
Swath width	303 km	303 km
Number of bursts	2	2
Antenna Size (az, el)	12.2 m x 1.3 m	
Number of Channels (azimuth, elevation)	(5, 30)	
Pulse duty cycle	10%	
Average transmitted power	1350 W	

Mass-Compliant Planar System: Imaging Performance

	Single-pol	Quad-pol
Swath width	303 km	303 km
Resolution ($\delta_x \times \delta_{gr}$) [m^2]	< 20	< 60
AASR [dB]	< -31	< -24.5
RASR [dB]	< -30	< -24.5
NESZ [dB]	< -23	< -23
SAR performance satisfied	+	+
Margin for optimization	• Medium: Antenna parameters, phase spoilling 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	

Single-Pol Performance

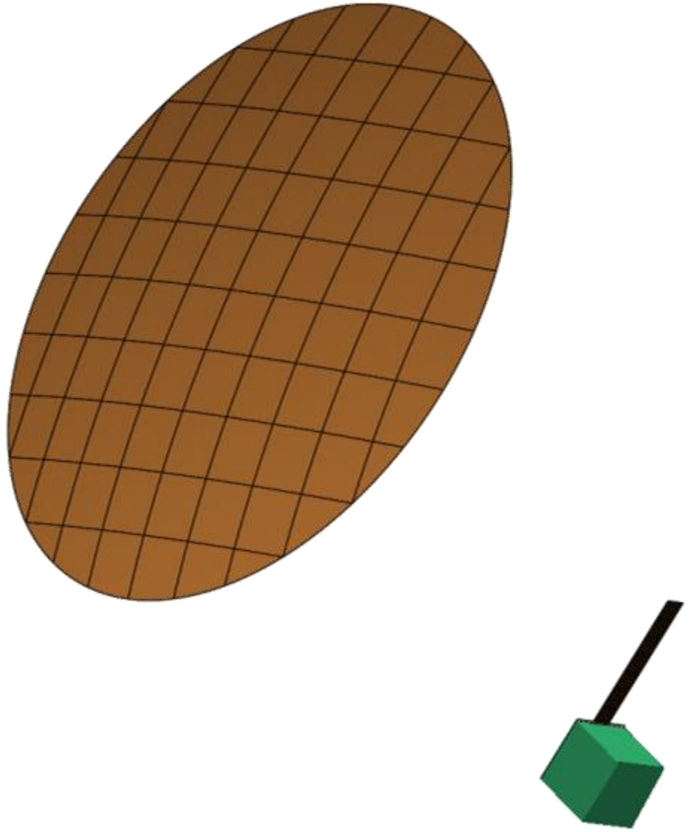


Proposed Instrument Concepts: Reflector-Based Antenna Solutions

Reflector-Based Antenna

Staggered SAR

- **Altitude: 1**
- Diameter:
- Feed offse
- **Direct acc**

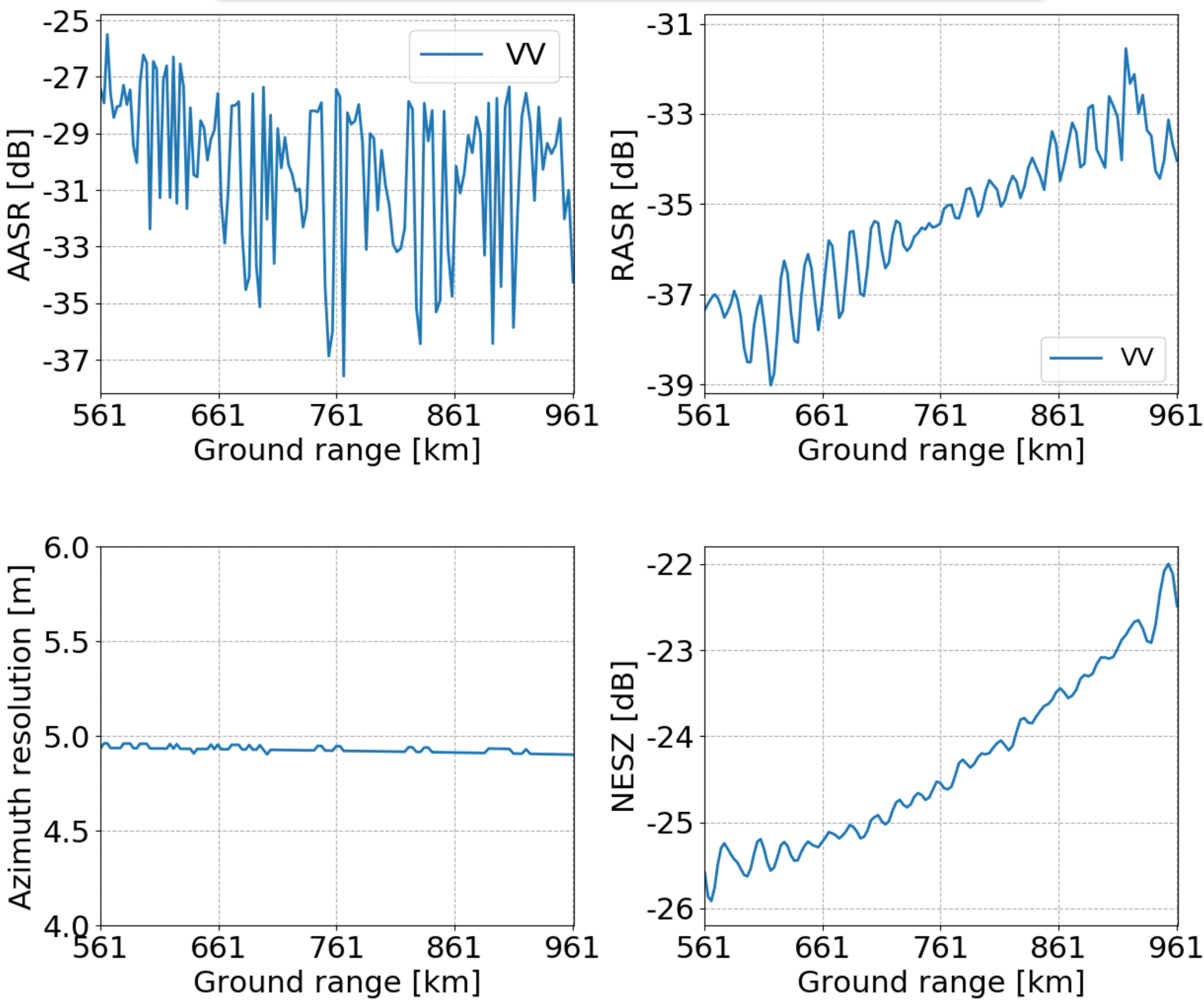


Parameter	1200 km
Diameter D	9 m
Focal length F	9 m
F/D ratio	1.0
Frequency	5.405 GHz
Offset in azimuth	0.0 m
Offset in elevation	3.0 m
Feed tilt angle θ_f	18.92°
Number of elevation feed elements	91 (for 600 km)
Number of azimuth feed doublets	5
Element spacing (elevation/azimuth)	0.6λ / 0.6λ
Feed length (elevation)	≈ 3.0 m
Feed height (azimuth)	0.33 m
Bus size	1 m3
Boresight (look) angle	32.35°
Elevation angle span	[-8.85, 9.25] °
Azimuth beamforming	LCMV: combining 5 azimuth doublets into 1 channel
Elevation beamforming	Combine 10 elevation elements on receive to form a SCORE beam

9m reflector antenna @ 1208 km – Imaging Performance

	Single-pol (400 km) staggered SAR	Single-pol (600 km) staggered SAR	Quad-pol (280 km) staggered SAR	Quad-pol (382 km) staggered SAR
Resolution ($\delta_x \times \delta_{gr}$)	5 m x 5 m	5 m x 27.3 m	5 m x 5 m	5 m x 5 m
AASR [dB]	< -25	< -23	< -23	< -23
RASR [dB]	< -31	< -23	< -21	< -17
NESZ [dB]	< -22	< -25	< -20.5	< -19.5
SAR performance satisfied	+++	++	++	+
Margin for optimization		yes, e.g., side-lobe suppresion	intermediate, e.g., side-lobe suppresion, additional azimuth doublets, …	yes, e.g., side-lobe suppresion, additional azimuth doublets, …
Peak power demand	87 W per TRM			
Launcher compatibility	Vega E			

Single-Pol Performance

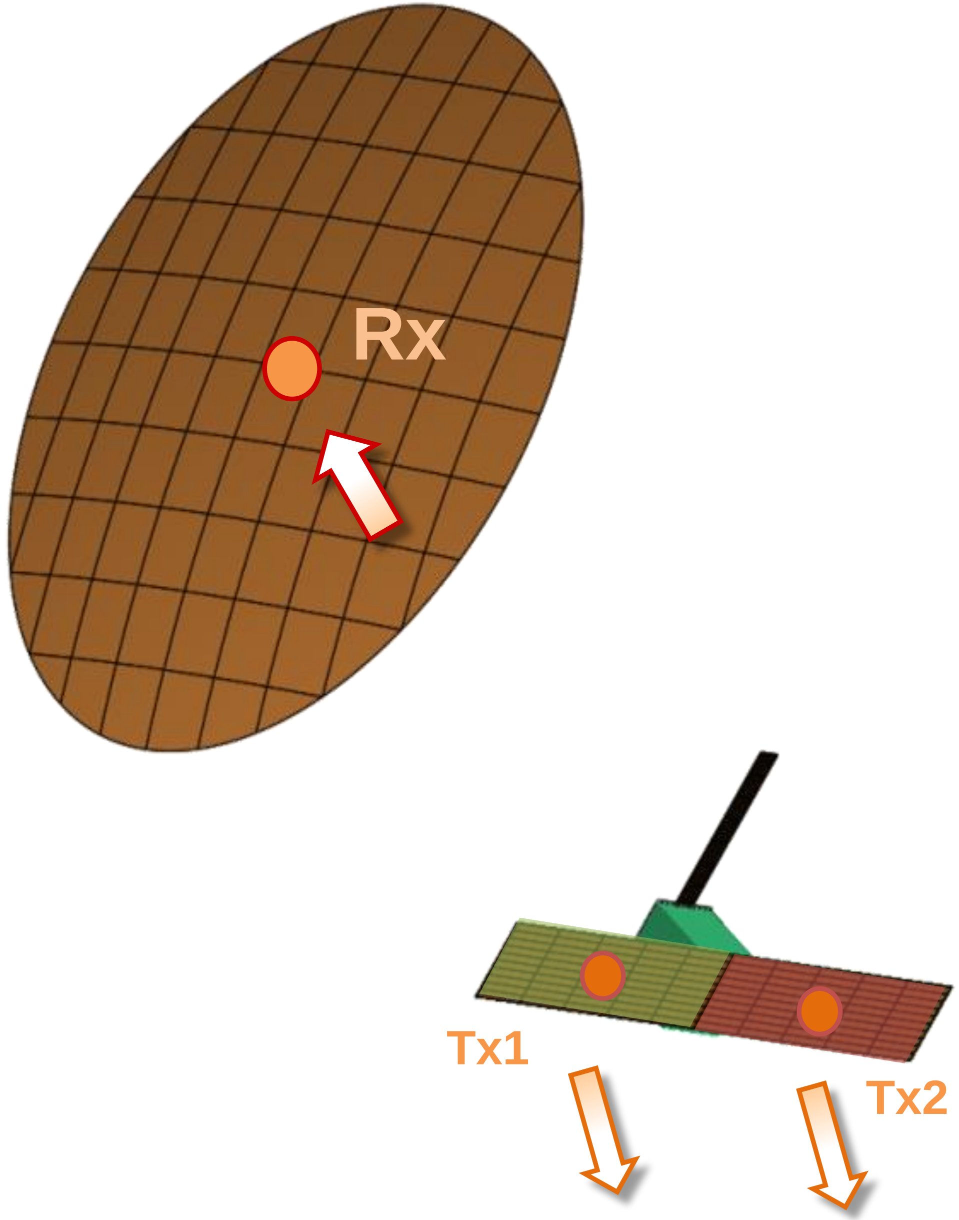


Proposed Instrument Concepts: Hybrid Solution

Hybrid (same platform, planar Tx – reflector Rx)

Staggered SAR

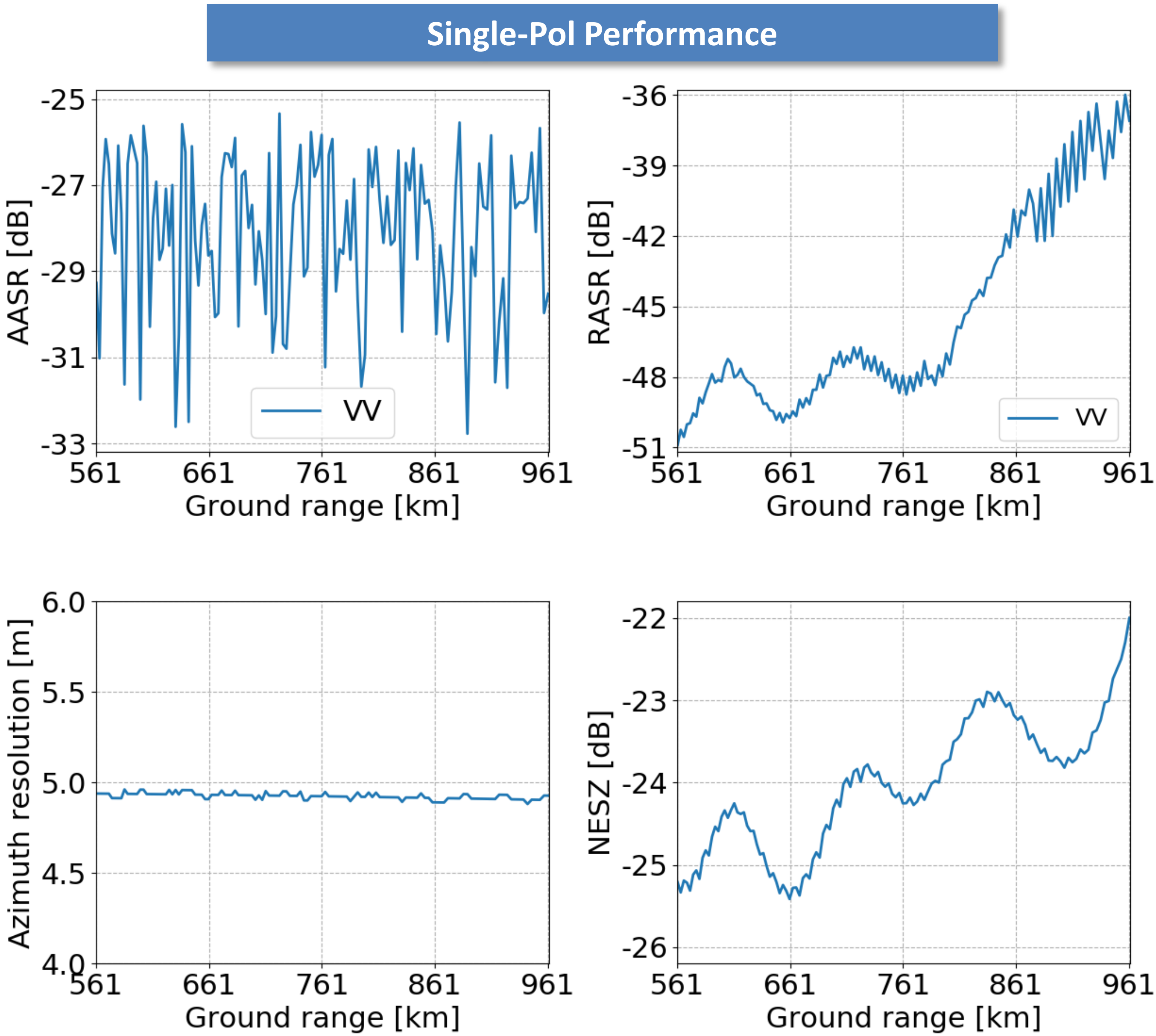
- **Altitude: 1208 km and 845 km**
- Transmit antenna: 8 m x 1 m



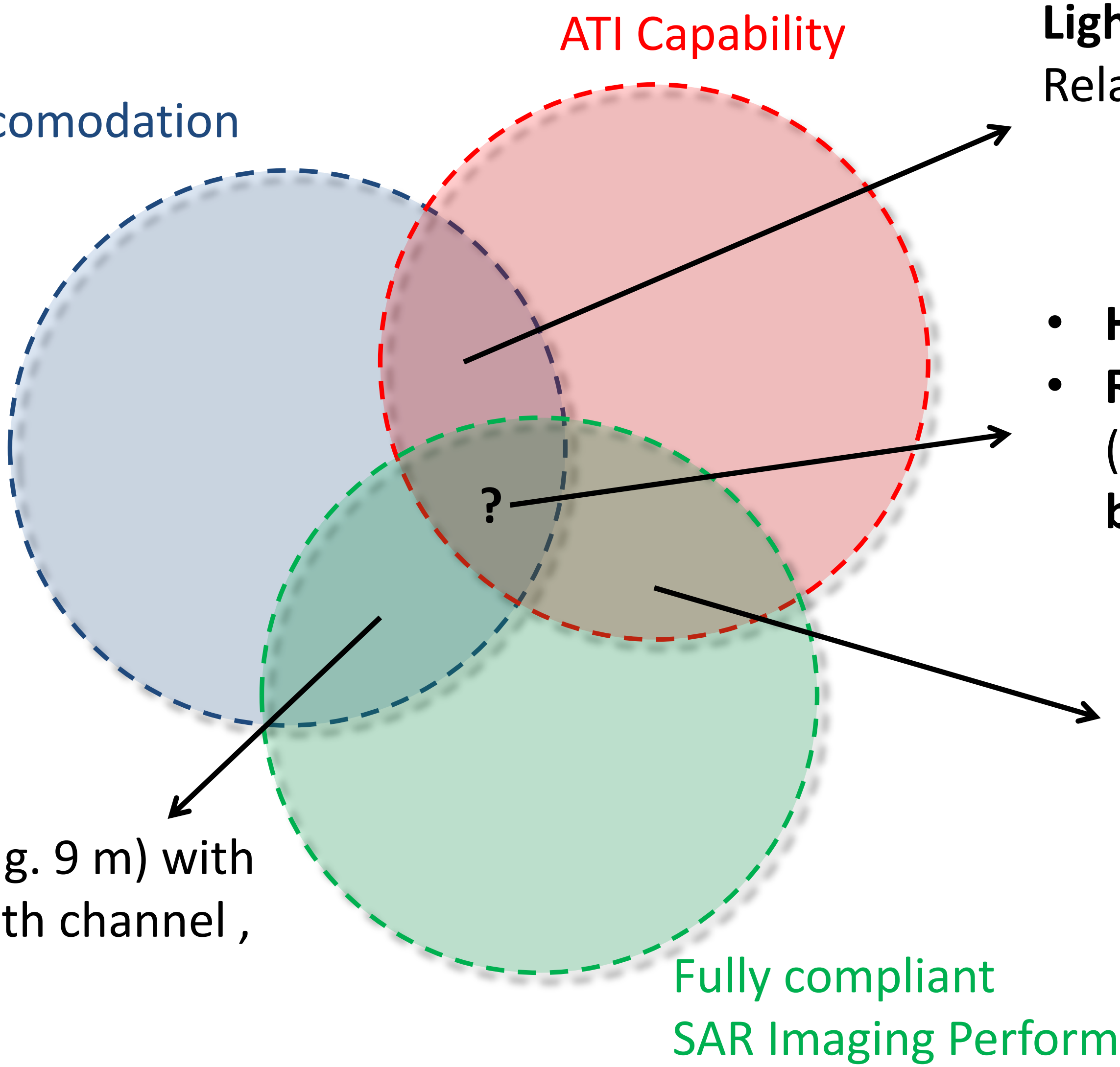
- Rx-only reflector antenna and Tx-only planar antenna
- **No need for T/R modules or circulators** thanks to Tx / Rx separation
  - **Reduced system noise figure**
  - **Higher peak power** can be achieved, e.g., by using a travelling wave **tube amplifier**.
- **Tx antenna size** rather small for a 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.

Hybrid (Tx: 1 m x 8m antenna, Rx: 9m reflector) @ 1208 km – Imaging Performance

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



Trade-offs for Instrument Design Optimization



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 phisical **baselines 2-3 m**)

Heavy planar fully compliant system **12.5 m x 2.5 m**

Reflector (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 **$25m^2$ 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**
  - **….**

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