Status of Copernicus Sentinel-1, Sentinel-1 Next Generation and ESA's Earth Explorer 10 Harmony

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Copernicus SAR Context

CURRENT GENERATION SENTINELS

Sentinel-1 A + B C-Band Radar	**Sentinel-1 C + D** C-Band Radar
Sentinel-2 A + B High Res Optical	**Sentinel-2 C + D** High Res Optical
Sentinel-3 A + B MR Optical + Altimeter	**Sentinel-3 C + D** MR Optical + Altimeter
Sentinel-4 A Atm. Chemistry (GEO)	**Sentinel-4 B** Atm. Chemistry (GEO)
Sentinel-5P Atm. Chemistry (LEO)	**Sentinel-5 A** Atm. Chemistry (LEO)
Sentinel-6 A Altimeter	**Sentinel-6 B** Altimeter

NEXT GENERATION SENTINELS

- **Sentinel-1 NG**
  C-Band Radar
- **Sentinel-2 NG**
  High Res Optical
- **Sentinel-3 NG**
  MR Optical + Altimeter

HIGH-PRIORITY CANDIDATES MISSIONS

- **ROSE-L**
  L-Band Radar for Arctic and Crysphere Monitoring, Land and Emergency Mapping, Ground Motion, Soil Moisture
- **CO2M**
  Carbon Dioxide Monitoring
- **CRISTAL**
  Polar Ice & Snow Topography Altim.
- **CHIME**
  Hyperspectral Imaging
- **LSTM**
  Land Surface Temperature
- **CIMR**
  Imaging Microwave Radiometer

PROGRAMME OF THE EUROPEAN UNION

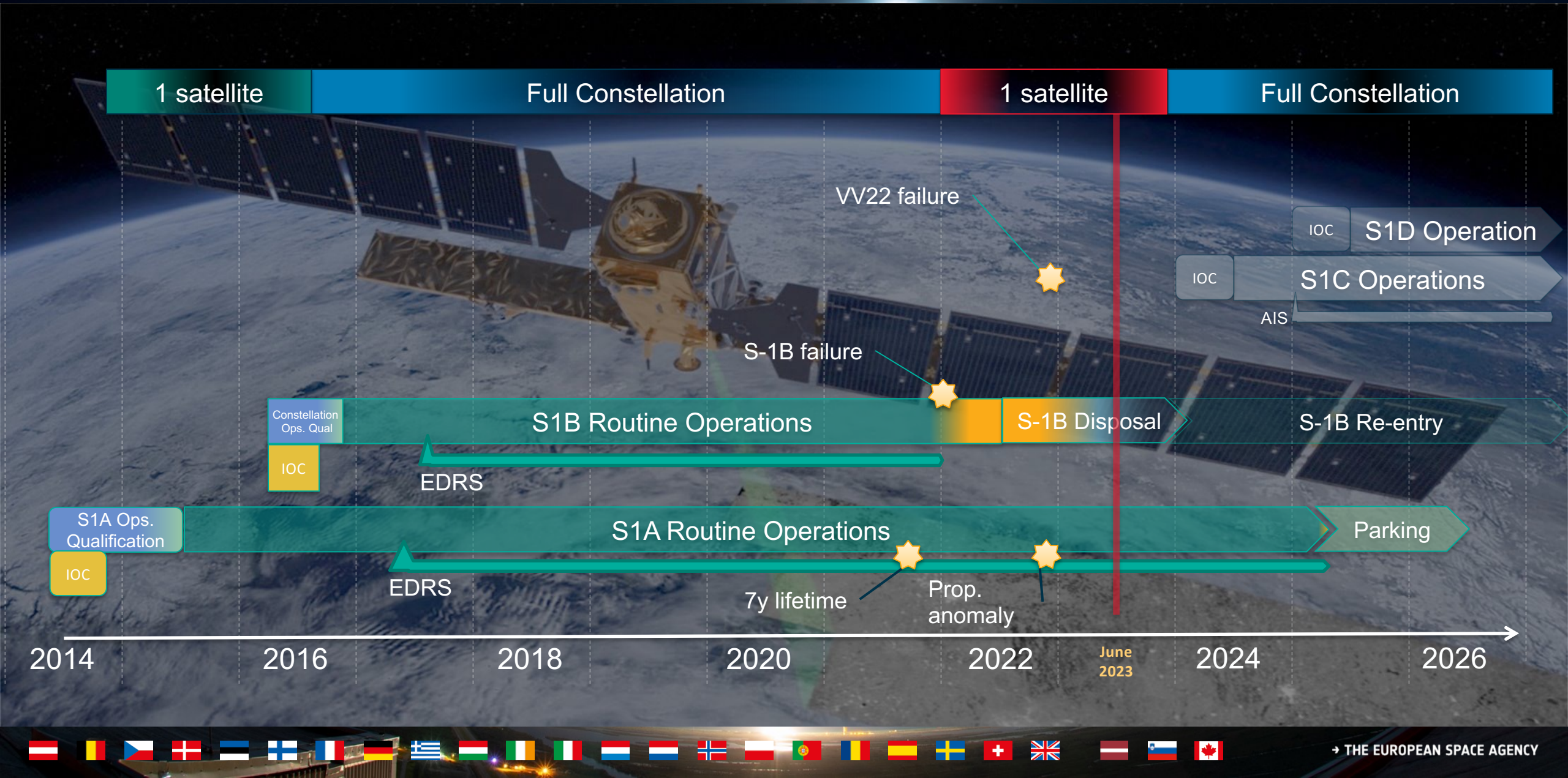
Copernicus Europe's eyes on Earth

esa

→ RADAR VISION FOR COPERNICUS

Sentinel-1 Overall Mission Status

Sentinel-1 First Generation timeline



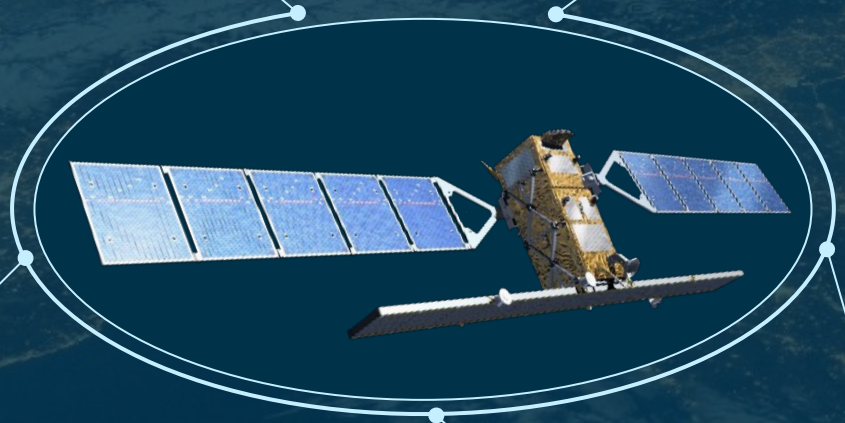
Sentinel-1 Mission in a Nutshell

MISSION PROFILE

- Constellation of two identical SAR C-band (5.405 GHz) satellites: (A & B → C units)
- Near-Polar, sun-synchronous (dawn-dusk) orbit at 698 km altitude
- 7.25 years lifetime (consumables for 12 years)
- 12-day repeat cycle (each satellite), 6 days for the constellation

OPERATIONS

- Systematic SAR data acquisition using a predefined observation scenario
- Instrument duty cycle of max. 25 min/orbit in High Bit Rate modes (30 min outside eclipse) and 75 min/orbit in Low Bit Rate mode (Wave)



PROGRAMMATICS

- Sentinel-1C launch Q4 2023
- Sentinel-1D currently in storage to be launched as needed

PAYLOAD

- C-Band SAR
  - Centre frequency: 5.405 GHz
  - Polarizations: HH, VV, HH/HV, VV/VH
  - Incidence angle: 20º - 45º
  - Radiometric accuracy: 1 dB (3σ)
  - Radiometric stability: 0.55 dB (3σ), 0.45 (3σ) for S-1 C/D
  - NESZ: -22 dB
  - DTAR: -22 dB
- **AIS Instrument marine surveillance (for S-1 C and D)**

IMAGING MODES

- Strip Map Mode: 80 km swath and 5x5 m (range x azimuth) resolution
- Interferometric Wide-Swath Mode: 250 km swath, 5x20 m resolution
- Extra-Wide-Swath Mode: 400 km swath and 20x40 m resolution
- Wave Mode: 5x5 m resolution, leap-frog sampled images of 20x20 km

SENTINEL-1 MISSION STATUS

PROGRAMME OF THE EUROPEAN UNION

SENTINEL-1A IS OPERATING WELL SINCE LAUNCH

- S-1A Launched in April 2014 for a designed lifetime of 7.25 years → extended lifetime
- Following S-1B permanent failure, the Sentinel-1 mission relies entirely on S-1A
- CCMs (RSAT-2, PAZ, TS-X, ICEEYE) and RCM are mitigating the S-1B gap thanks to increased quotas for Copernicus services.

SENTINEL-1B IS BEING DISPOSED

- S-1B Launched in April 2016. Nominal operation until permanent failure in December 2021
  - Power unit supplying current to the SAR
  - Instrument and other platform functions working nominally
- S-1B disposal on-going June to December 2023. Atmosphere re-entry within 12y (worst case)
- The entire S-1B data is available on the Copernicus Data Access platform

SENTINEL-1 CONTINUITY

PROGRAMME OF THE EUROPEAN UNION

LONG-TERM CONTINUITY

- Continuity through the 20's decade and beyond is ensured by the almost identical S-1C and S-1D units
  - Addition of AIS instrument
  - General improvement of SAR performance (radiometric stability)
- Sentinel-1 first generation will provide continuity with the **Sentinel-1 Next Generation** in 30's decade

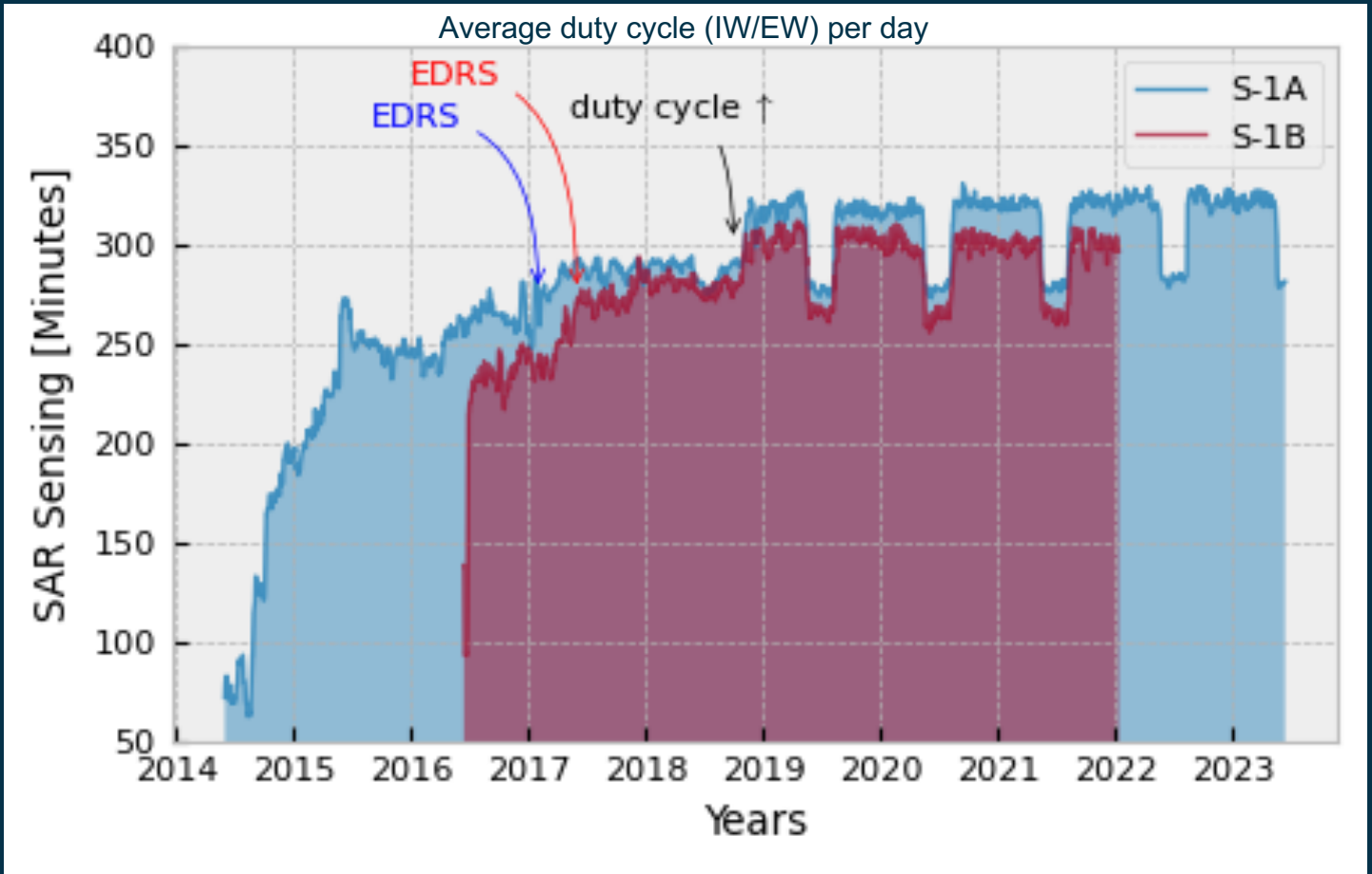
Sentinel-1C launch

PROGRAMME OF THE EUROPEAN UNION

- **SCHEDULE**
  - Sentinel-1C launch was supposed to take place in May 2023, followed by an IOC of about 4 months
  - Following VV22 failure, Sentinel-1C launch has been postponed:
    - Arianespace is expected to provide in July 2023 more information on the launch manifest and a Sentinel-1C launch slot (1 month launch window)
    - Sentinel-1C has been proposed to be the passenger for the return-to-flight of Vega-C aimed at in December 2023
    - Arianespace is also expected in July to provide a 6-month launch window for Sentinel-1D launch.
  - During IOC, S-1C will fly in a 1-day tandem configuration for 4 cycles and then will be placed in the nominal 6 days configuration for the remainder of the IOC.

SENTINEL-1 Duty Cycle

SAR DUTY CYCLE | Sentinel-1 can acquire up to 30min (per unit) of HBR (IW& EW) within an orbit rolling window (outside eclipse season)

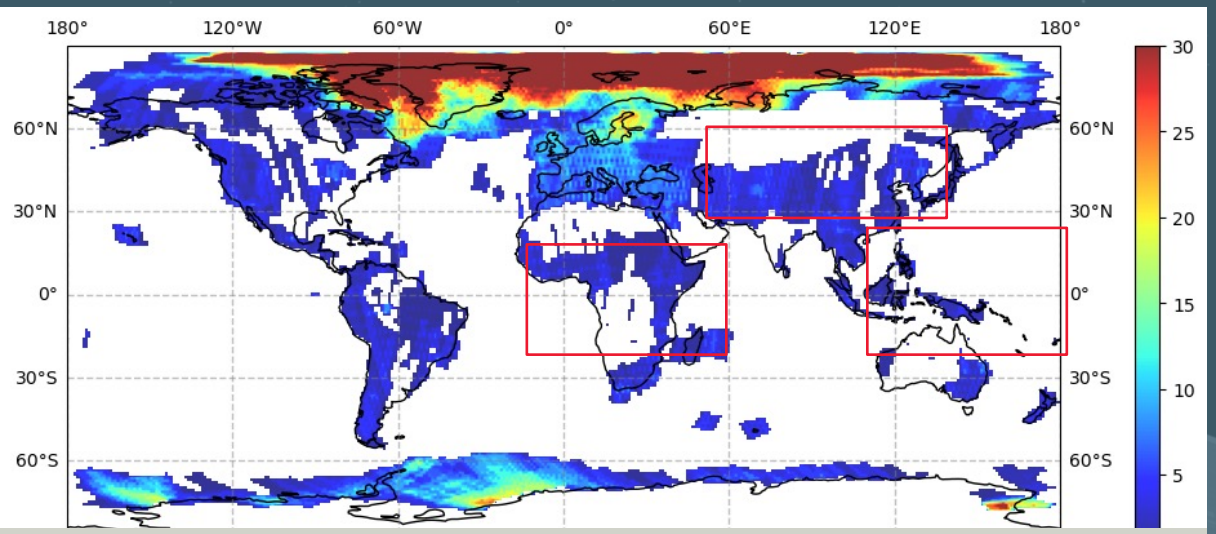


SAR duty cycle has increased with resulting from the optimisation of the operations:

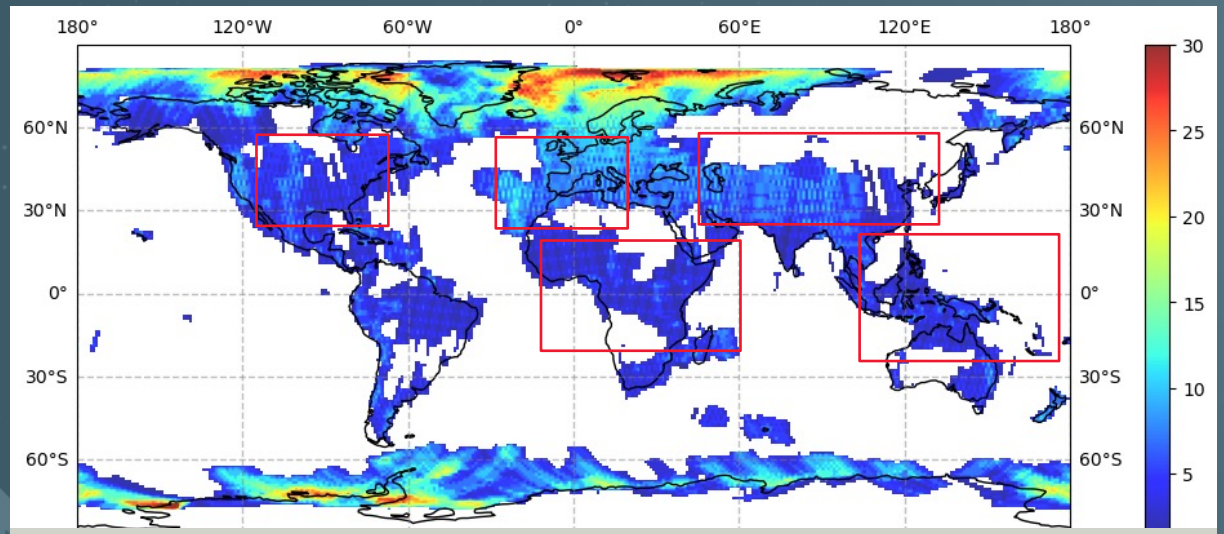
- **2014-2015 |** Initial ramp-up
- **2017 |** inclusion of EDRS in routine ops
- **2018 |** Relaxation of 25 min constraint outside eclipse
- **2021 |** slight increase of S-1A duty cycle to cope with S-1B loss

>> NO CAPACITY LEFT IN S-1A

S-1A Observation Scenario



Jan. 2016 **Pre** Sentinel1-B

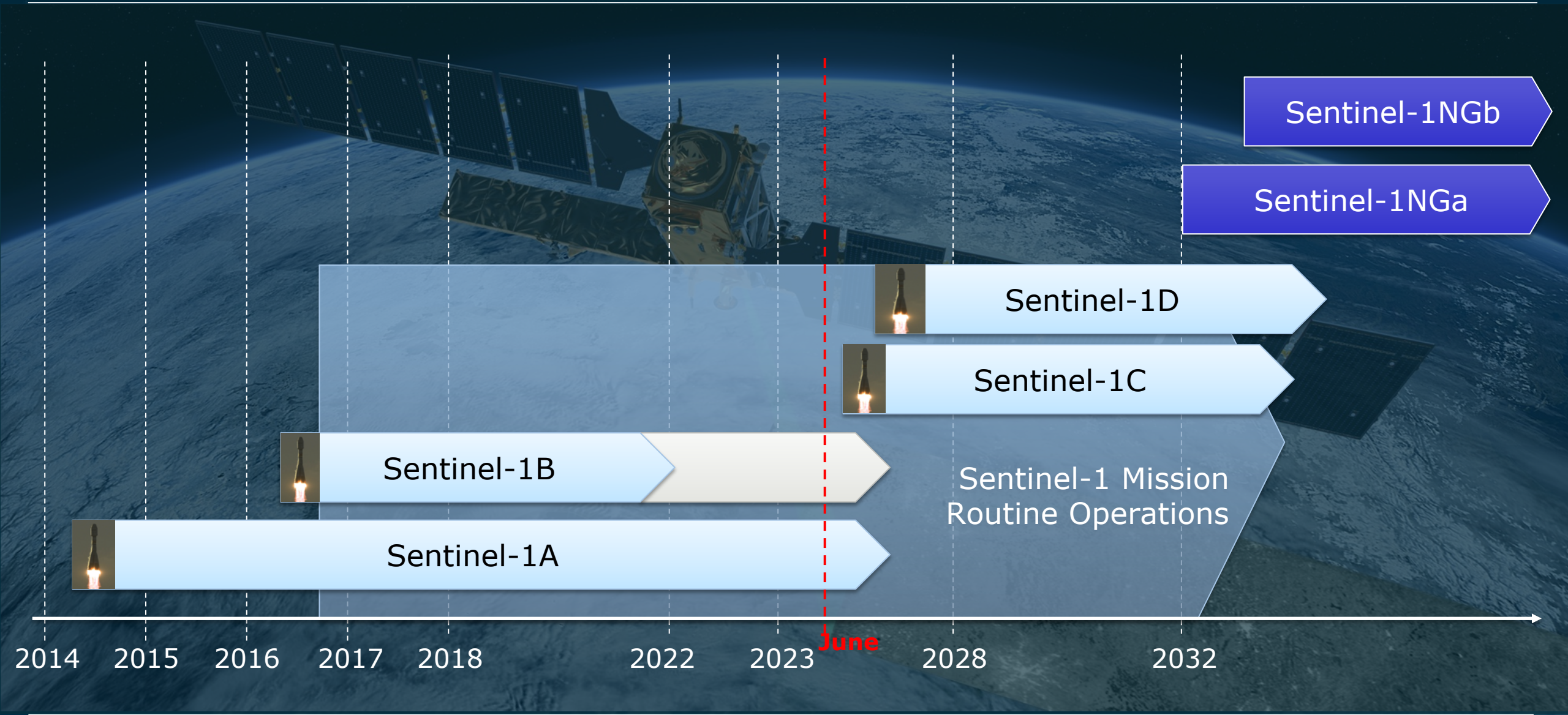


Jan. 2023 **Post** Sentinel1-B

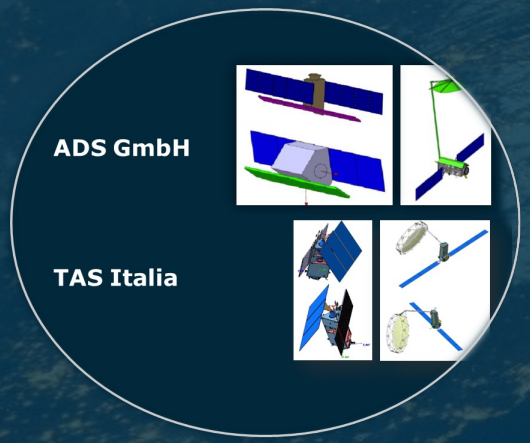
- **S-1 OBSERVATION SCENARIO MITIGATIONS after S-1B permanent unavailability**
  - Mission capacity to perform global coverage has been compromised
  - Current S-1A observation provides (compared to 2016) has been tuned to preserve time series worldwide with the side effect of reduced capacity over Northern areas
    - Northern areas are covered by RCM thanks to CSA/ESA contingency agreement

Sentinel-1 Next Generation Mission Enhanced C-Band Data Continuity

Sentinel-1 C-Band SAR Evolution Context



Sentinel-1 NG Highlights



OBJECTIVES

- *Ensure continuity* and expansion of services and applications relying on Sentinel-1
- *Enhance* existing services and applications
- *Enable* new application developments building on improved performance and observation gaps (e.g. resolution, revisit and others)

MISSION AND SYSTEM REQUIREMENTS

- Performance shall be equal or better than Sentinel-1 FG
- Revisit: 3 days Global, 0.5 days Arctic and sea ice
- Resolution ≤ 25 m^2
- NESZ ≤ -26 dB
- Full continuity in Dual-Pol with Quad-Pol capability
- Use of a dedicated Mission Mode to cover the North Pole region
- **Same orbit of S1FG / ROSE-L in constellation of two satellites**

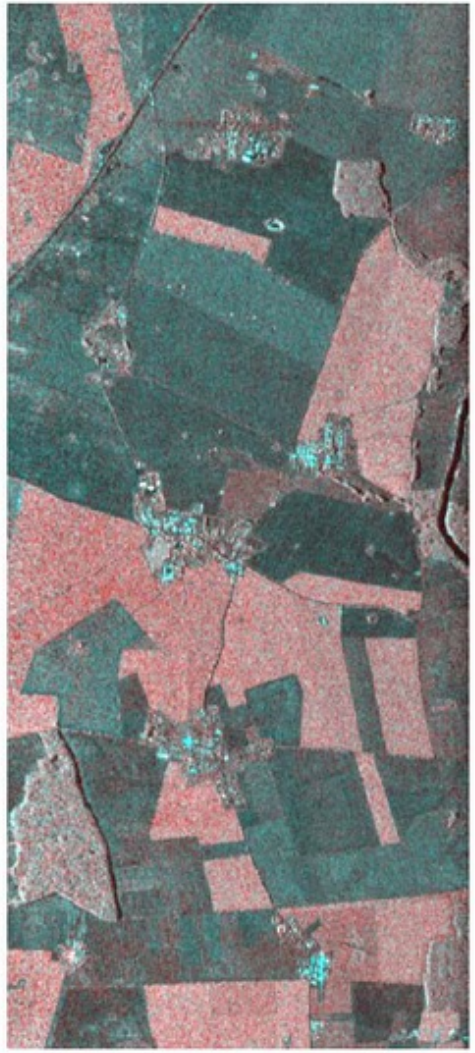
Sentinel-1 NG Requirements (Phase-AB1)

Performance Requirements	Sentinel-1 NG	Sentinel-1
Latitude coverage	**-80 to +90 deg**	North-pole gap
Revisit	Goal: **3 days** Global Goal: **0.5 days** Arctic and Sea Ice	Up to 12 days
Latency	**10 min** European Waters **120 min** Global	10 min RT, 1 h NRT emergency, > 3 h Global
Repeat pass InSAR	**6 / 12 days** (S1 & ROSE-L orbit)	6 / 12 days
Incidence angle access	**Better than 20 – 45 deg**	20 – 45 deg
Swath width	**Larger than 400 km**	250 IW – 400 EW
Resolution	**25 m2**	~100m2 IW - ~800m2 EW
NESZ	**-26 dB**	-22 dB
Polarization capability	**SP, DP and QP**	SP and DP
Duty cycle	**43% average (~43 min/orbit)**	25min/orbit

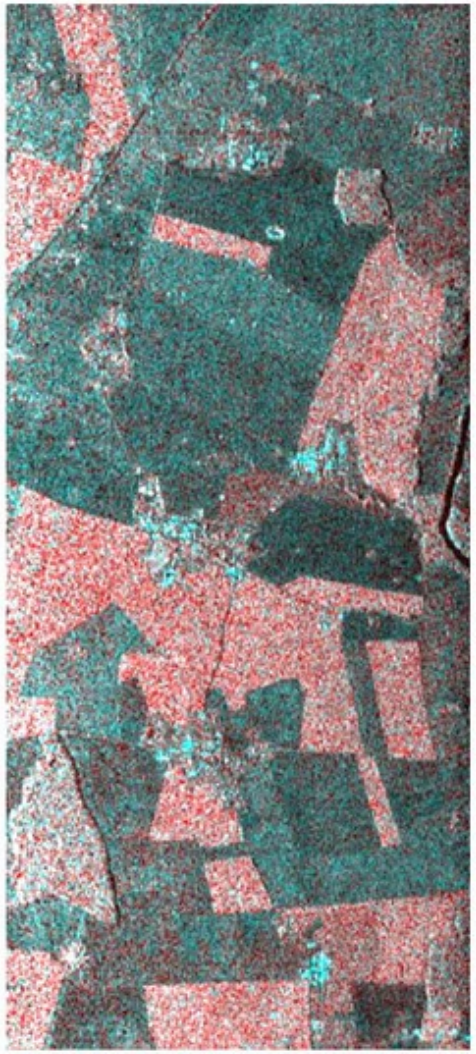
Other Mission Requirements
Enhanced operations through the **potential integration of additional satellites**
Automatic Identification System (AIS) payload to augment maritime services
Over open oceans the mission shall support the generation of **wave mode products**

Next Generation Imaging

E-SAR standard (8 looks)



S1 SM [~S1-NG] (4 looks)



S1 IWS (4 looks)

Lower NESZ (-26 dB)

will further enhance mapping and characterisation of weak scatterers (benefits in soil moisture, oil spills, sea ice mapping, etc…)

E-SAR data for ESA AgriSAR campaign with Sentinel-1 simulation in stripmap and IWS mode. Color coding is RGB: HV-HH-HH. Stripmap resolution is the same as S1-NG, although with higher NESZ (DLR)

S1NG Candidate Concepts

Two parallel Phase A/B1 have taken place from April 2021 until April 2023

One consortium led by ADS GmbH and the other by TAS-I

- Highlights from these activities:
  - Constellation of 2 satellites (same as in S1FG)
  - Flying the same orbit than S1FG (and ROSE-L)
  - SAR instrument based on planar phased array antenna exploiting state-of-the-art SAR technology based on SCORE and MAPS
  - Full coverage of North Pole will be warranted with a dedicated Polar Mode
- Constraints:
  - VEGA family launcher (VEGA-E)
  - Technology readiness
- The instrument is based on SCORE (DBF in elevation) and MAPS (DBF on-ground in azimuth)
- Similar to S1FG, a minimum number of modes is to be implemented
- S1NG will support the potential Harmony mission extension beyond S-1C/D
- AIS instrument providing continuity with the S-1C & S-1D payloads

Sentinel-1 NG Programmatics

- Phase 0 (Mission Identification) carried out in 2019-2020
- Phase A/B1 in two years 2021-2023
  - PRR carried out in February/March 2022 for both consortia
  - ISRR concluded in March/April 2023 for both consortia
- ITT for Development Phase (Phase B2/C/D) expected in November 2023
- Expected KO B2/C/D first half 2024
- Expected launch > 2032

MISSION REQUIREMENTS

- Ad-hoc Expert Group (AHEG) October'20-January'21 – drafted the preliminary MR for the Phase A/B1 ITT
- Mission Advisory Group (MAG) supported the Mission Trade-offs during Phase A/B1 and the evolution of the mission requirements

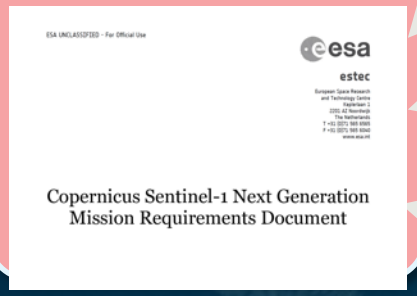
Sentinel-1 NG and Copernicus Services

User Needs

- EC
- Polar Expert Group
- REDD+
- UNFCCC
- ….

Sentinel-1 NG

Mission Requirements Document


ESA UNCLASSIFIED - For Official Use

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estec

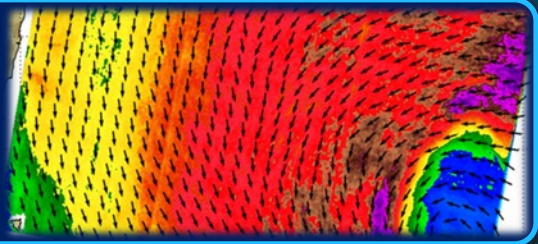
Copernicus Sentinel-1 Next Generation
Mission Requirements Document

C3S

- Sea ice type, concentration and motion
- Ice sheets & glaciers velocity, Grounding line
- Ground movement
- Ice sheets margins and glacier surface height
- Ice sheet melt/freeze extent

CMEMS

- Sea ice type, concentration and motion
- Iceberg location, size and drift
- Ocean surface currents
- Ocean surface wind vectors
- Swell properties



CLMS

- Land use and land use change, including agriculture and forestry
- Ice sheets & glaciers velocity
- Wet snow extent
- Ground movement
- Soil moisture

EU-GMS

European Ground Motion Service

EMS

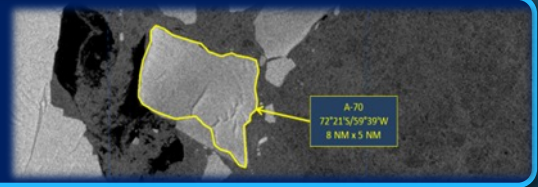
- Flooded area
- Ground movement
- Soil moisture
- Abrupt surface elevation changes

Security

EMSA

FRONTEX

- Iceberg location, size and drift
- Vessel location, size and velocity
- Oil spill location and morphology



Moving to RTC

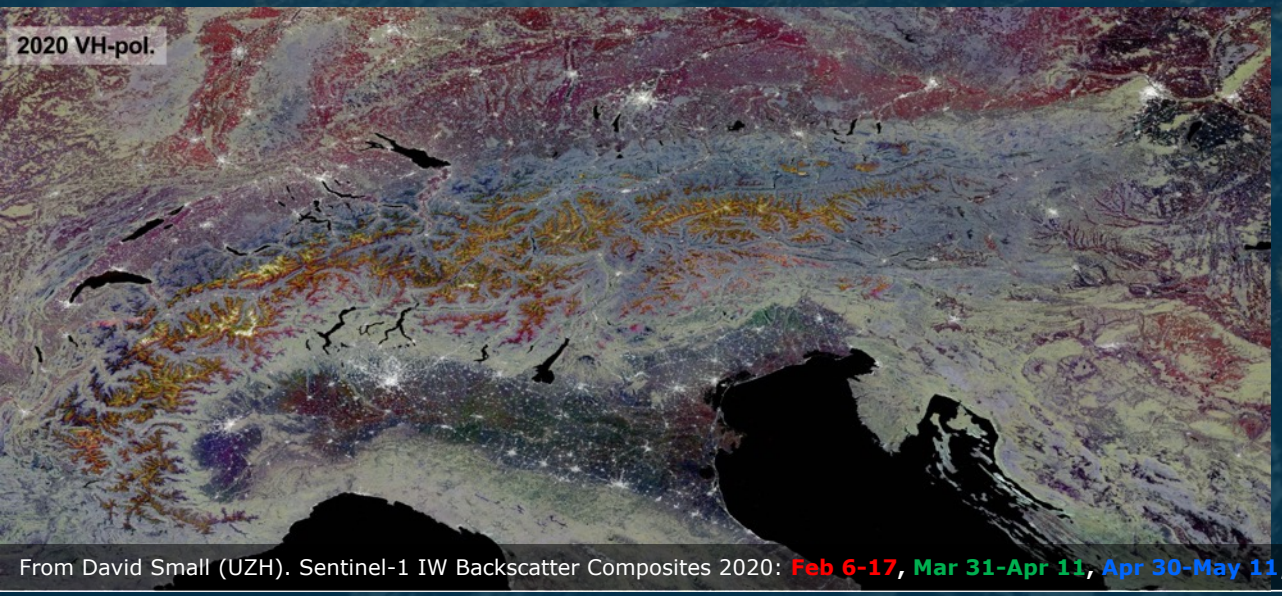
In order to broaden user community on the use of dense time-series

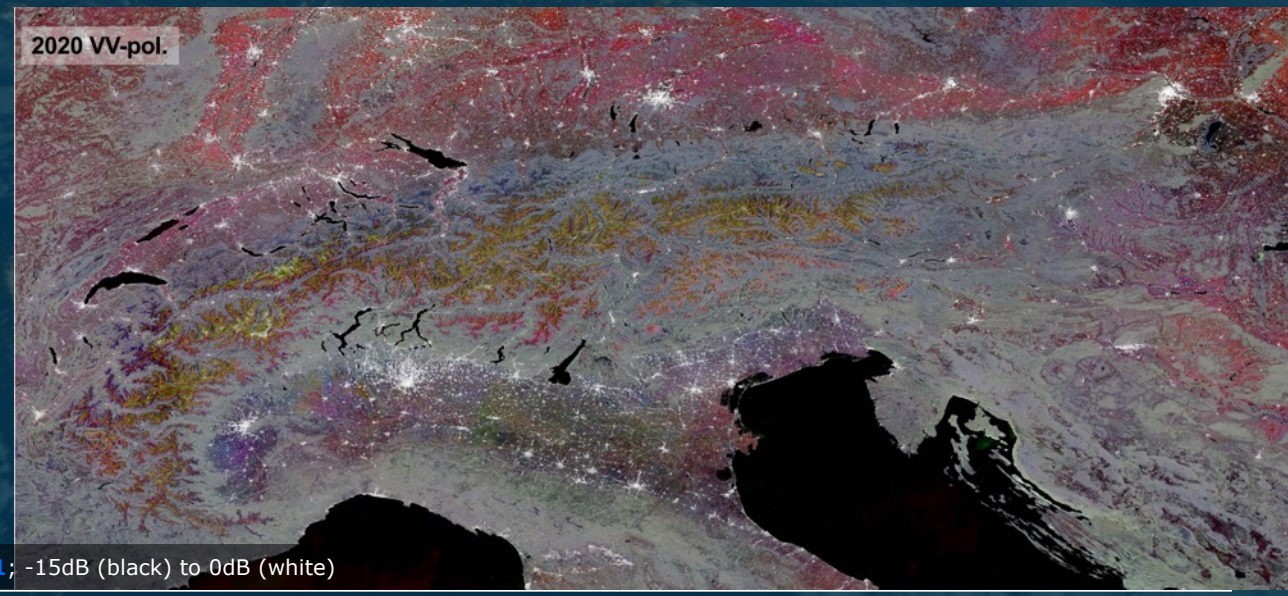
- Provide data products that do not require expert knowledge
- Move from radar geometry (slant & ground range) to map coordinates

GRD product likely to be replaced in the Sentinel Expansion / Next Gen mission processors by ARD data, including for instance the RTC product (Radiometric Terrain Correction).

RTC: Product family specification of Normalized Radar Backscatter (NRB) is formulated by the CEOS-ARD initiative (https://ceos.org/ard/)

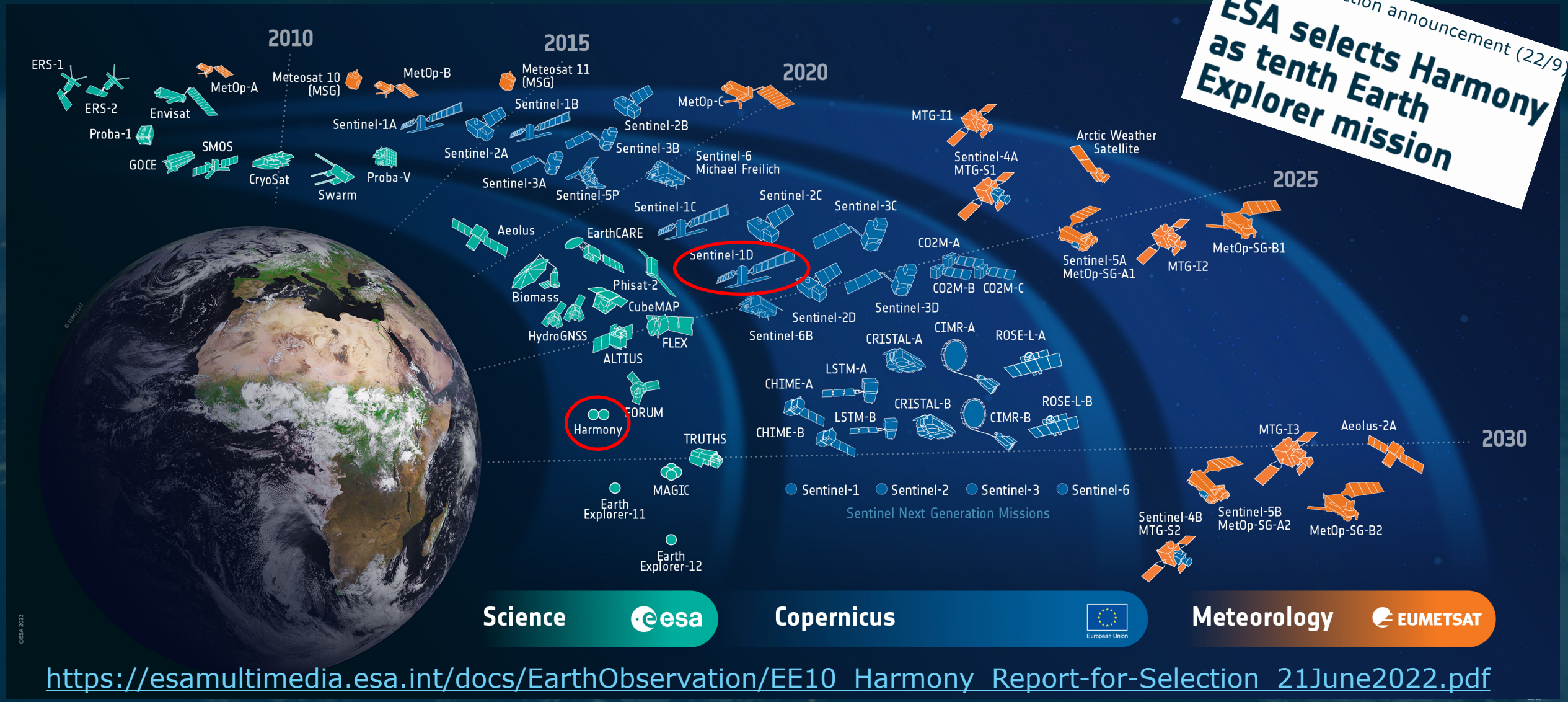
- Backscatter normalized using local scattering area, not incident angle
- Facilitates multi-sensor data integration





From David Small (UZH). Sentinel-1 IW Backscatter Composites 2020: Feb 6-17, Mar 31-Apr 11, Apr 30-May 11; -15dB (black) to 0dB (white)

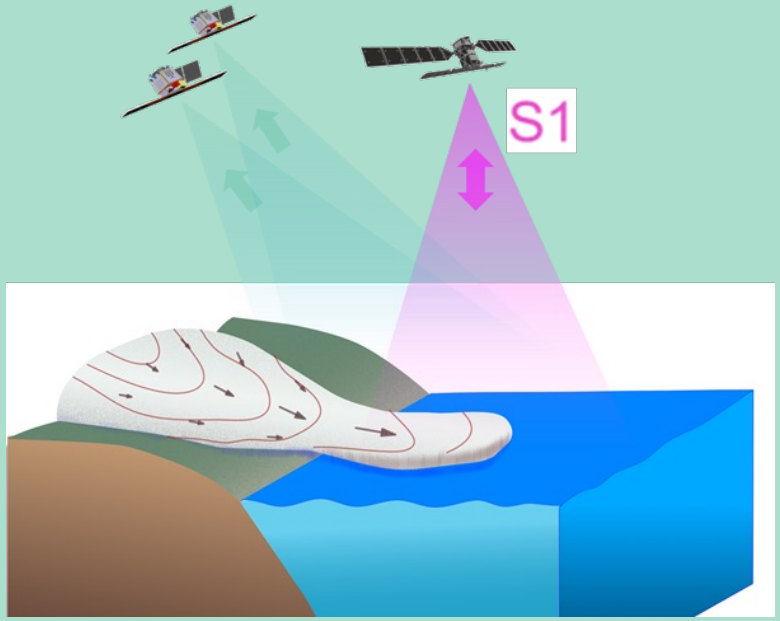
Harmony within ESA's EO missions landscape



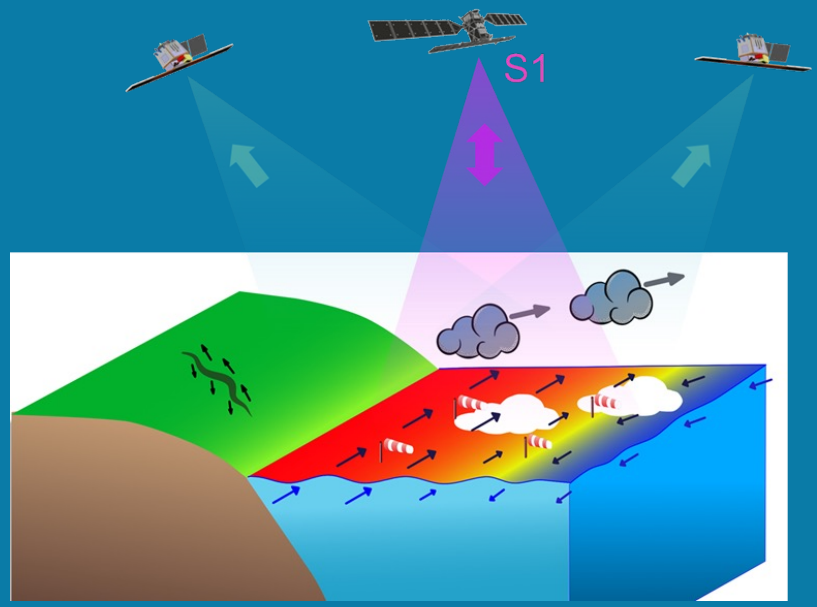
https://esamultimedia.esa.int/docs/EarthObservation/EE10_Harmony_Report-for-Selection_21June2022.pdf

Harmony in a nutshell

Harmony is ESA's Earth Explorer 10 mission, comprised of two companion satellites in a loose convoy with Sentinel-1D (along-track separation ~350 km)
Its payload suite consists of a passive SAR and a multi-view TIR instrument



Cross-track Interferometric phase covering land applications like glaciers, permafrost, volcanoes.



Stereo phase covering 3-D surface deformation ocean applications: surface motion, surface winds, sea surface temperature, cloud motion.

Year 1 | Year 2 | Year 3 | Year 4 | Year 5

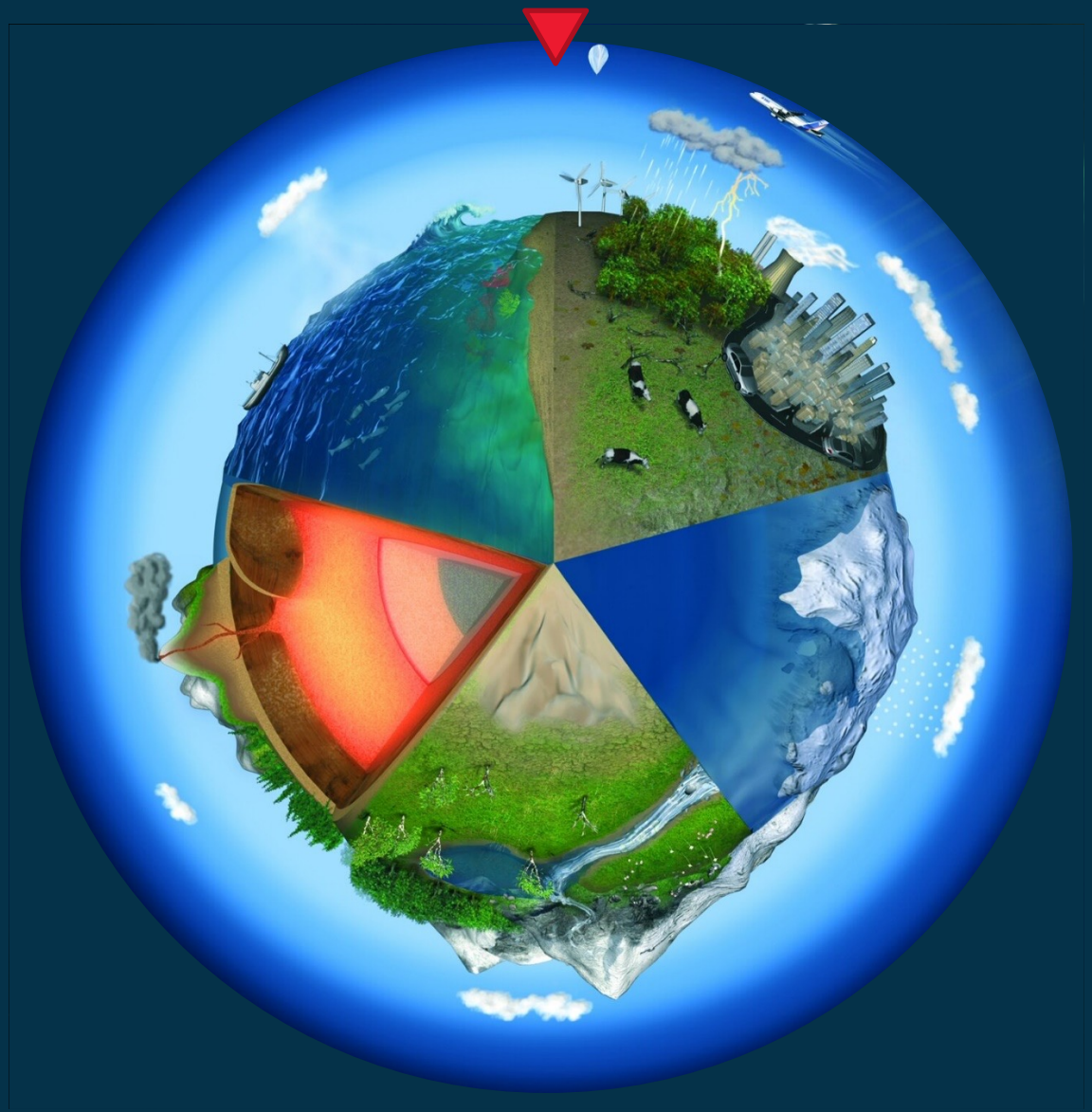
Harmony – a multi-domain “Earth System” mission

Upper oceans and ocean-atmosphere interactions

Land ice and sea ice

Tectonic strain and volcanic processes

Bringing Harmony to a dynamic world

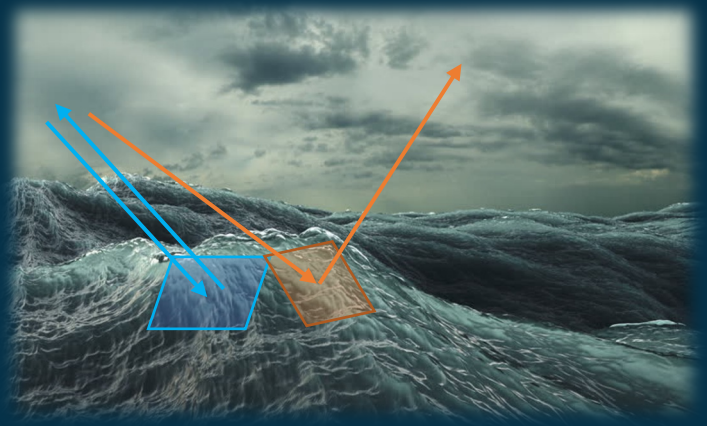


Harmony will resolve (sub) kilometer scale motion vectors and topography changes associated to dynamic Earth System processes:

- heat, gas and momentum exchanges at the air-sea interface;
- the inner structure of ocean-atmosphere extremes;
- gradual and dynamic volume changes of global mountain and polar glaciers;
- instantaneous sea-ice motions to characterise sea-ice dynamics;
- 3-D deformation vectors associated to tectonic strain;
- topographic change at active volcanoes worldwide.

Harmony Polarimetry

Azimuth sensitivity



Polarisation behaviour

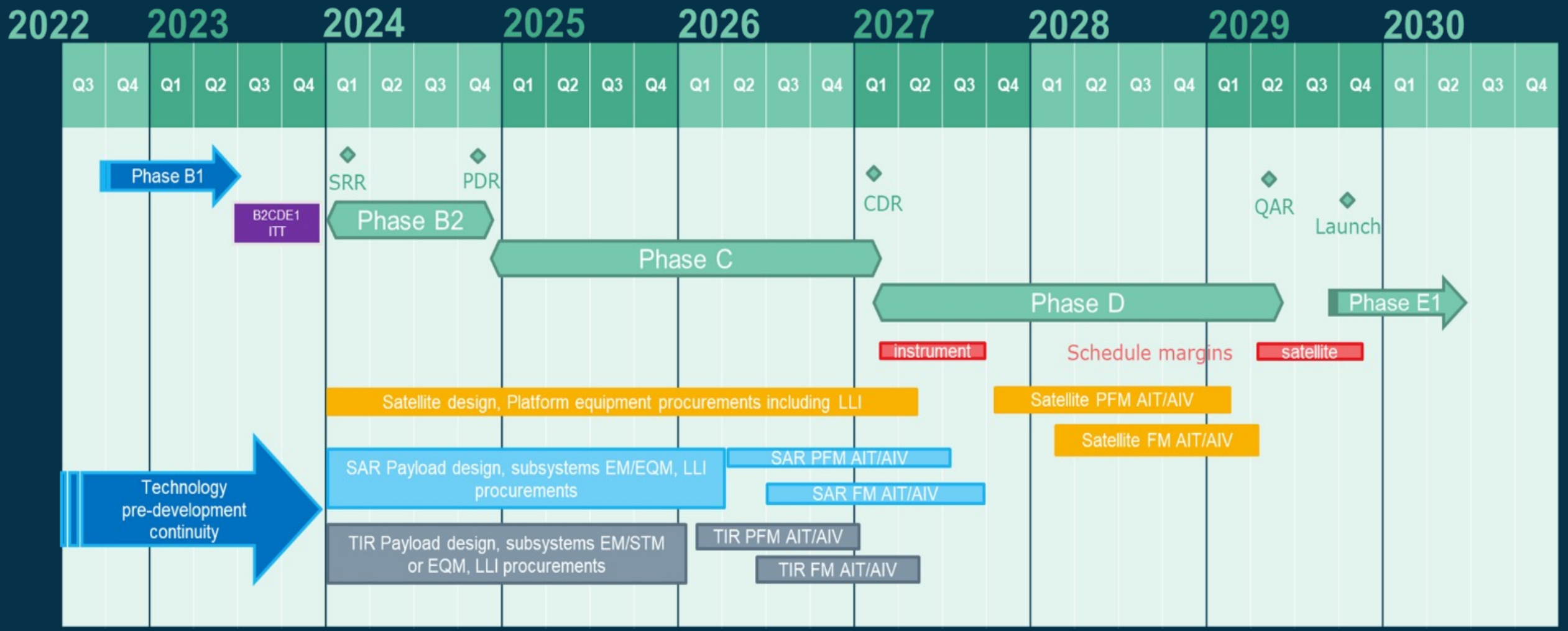
- Reciprocity is lost

$$S_{HV} \neq S_{VH}$$

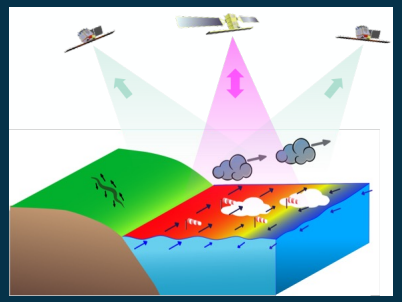
- Canonical scattering mechanisms (planes, diplanes, dipoles, etc..) maintain DoP (degree of polarisation) but a polarisation rotation is introduced
- More complex targets:
  - Depolarisation
  - Loss/Appearence of Bragg
- Rotation of the polarisation basis

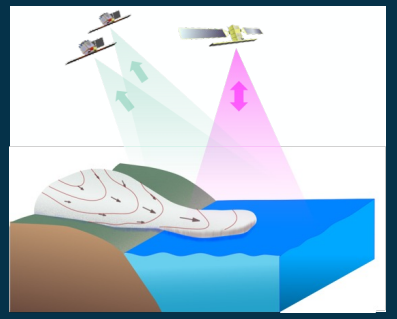
See TGRS paper L. Iannini et al. (2022): *Rough-Surface Polarimetry in Companion SAR Missions*

Harmony development schedule key dates



Uniqueness in Harmony





Simultaneous,
O(1 km) scale

SST

Cloud-top Motion

Directional roughness

Directional Doppler

C-band = all weather

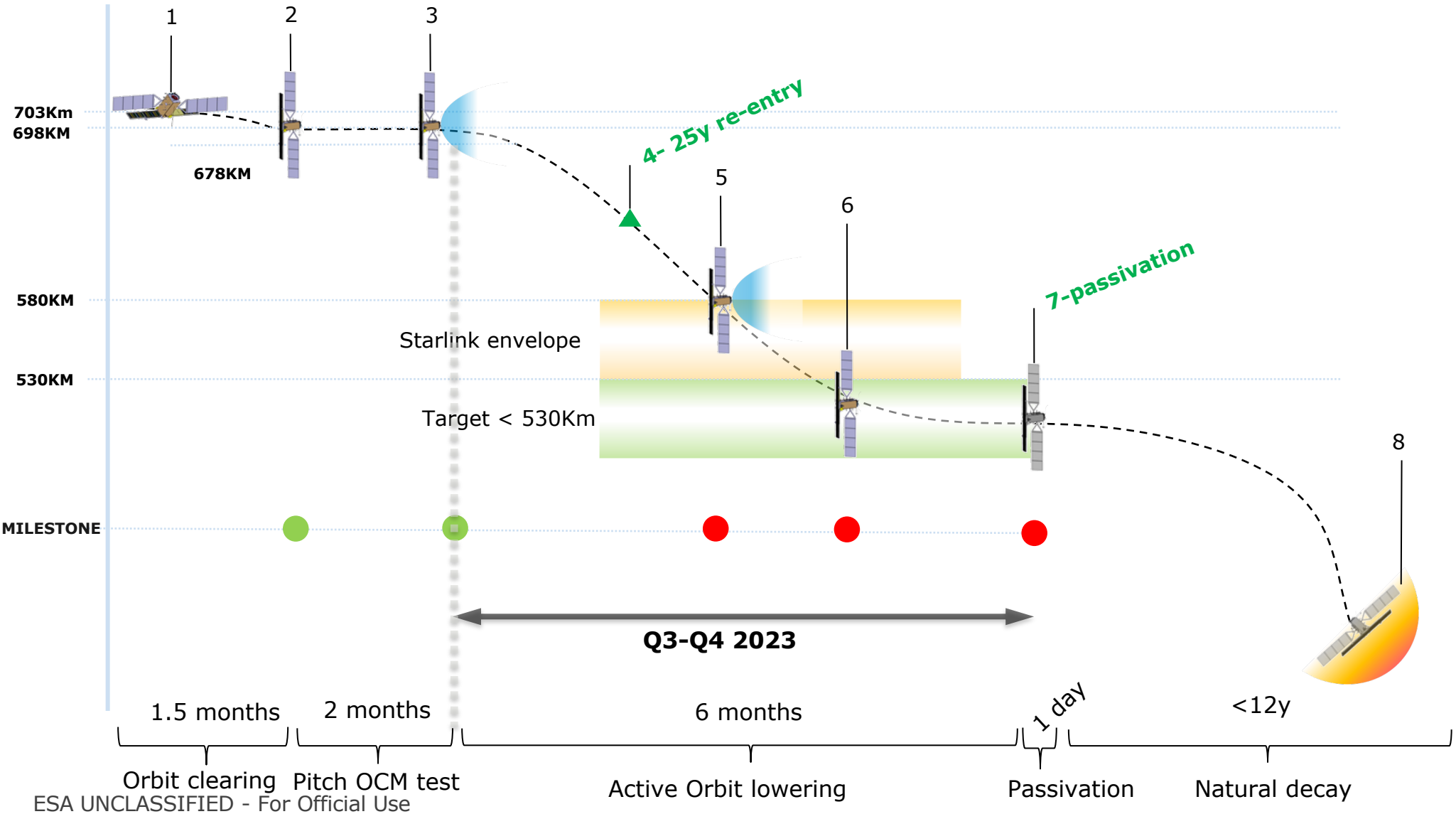
3-D repeat pass InSAR

Dense DSM time-series

Simultaneous,
O(50m) scale

- Data driven ocean-atmosphere couplings and statistical. characterisation of vertical fluxes in ESM 2.0.
- Understanding of air-sea interactions within extremes.
- Sea-ice dynamics.
- Global strain maps.
- Understand cycles of topographic change at volcanoes.
- Global and temporally consistent map of ice volume change (loss).
- Improved understanding of glacier dynamics.

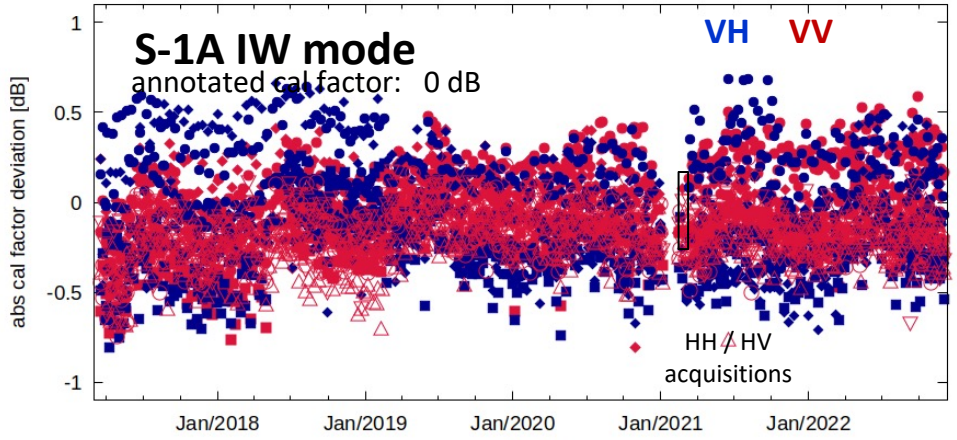
Sentinel-1B Disposal approach



1. Orbit Clearing Start
2. Pitch In-plane OCM campaign Start
3. Active lowering start: 126 OCMs
4. 25y re-entry
5. Starklink envelope Reached
6. Fuel depletion burns
7. Passivation
8. Re-entry in atmosphere

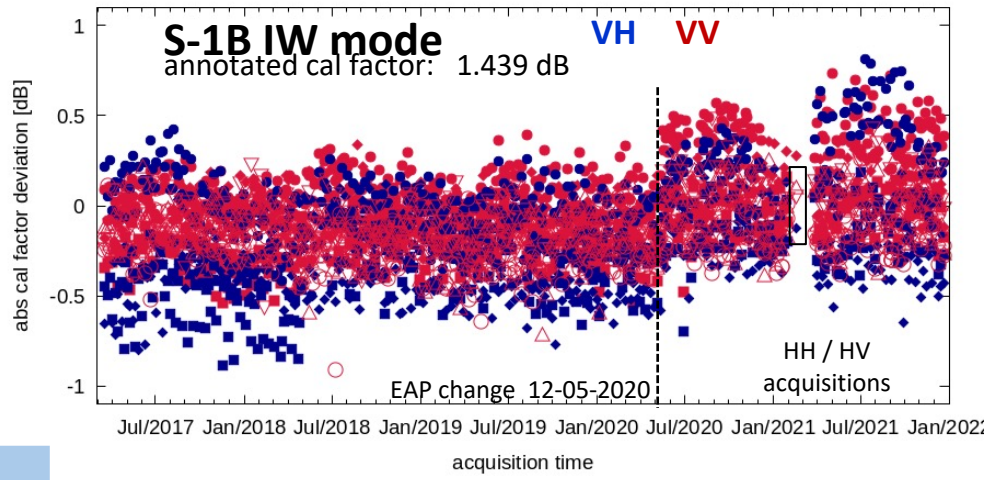
Data quality: Radiometric stability

Observation period: 03/2017 – 12/2022



	S-1A		S-1B	
	μ [dB]	σ [dB]	μ [dB]	σ [dB]
IW1 VV	-0.13	0.23	-0.02	0.22
IW1 VH	-0.20	0.24	-0.20	0.29
IW1 VV&VH	**-0.16**	**0.24**	**-0.09**	**0.26**
IW2 VV	-0.11	0.17	-0.12	0.17
IW2 VH	-0.00	0.30	-0.25	0.25
IW2 VV&VH	**-0.08**	**0.21**	**-0.15**	**0.20**
IW3 VV	-0.05	0.23	-0.02	0.20
IW3 VH	0.08	0.30	-0.04	0.26
IW3 VV&VH	**0.00**	**0.27**	**-0.03**	**0.23**
IW 1-3 VV	-0.10	0.21	-0.06	0.21
IW 1-3 VH	-0.09	0.30	-0.17	0.28
IW 1-3 VV&VH	**-0.104**	**0.242**	**-0.096**	**0.240**

Observation period: 03/2017 – 12/2021



Derived radiometric accuracy

	S-1A	S-1B
absolute radiometric accuracy (1σ)*	0.325 dB	0.323 dB

* including

Long term stability of the instrument	0.05 dB (1σ)
Dynamic range error	0.067 dB (1σ)
Reference target accuracy	0.20 dB (1σ)

Radiometric accuracy continues to be within mission requirements and stable over time