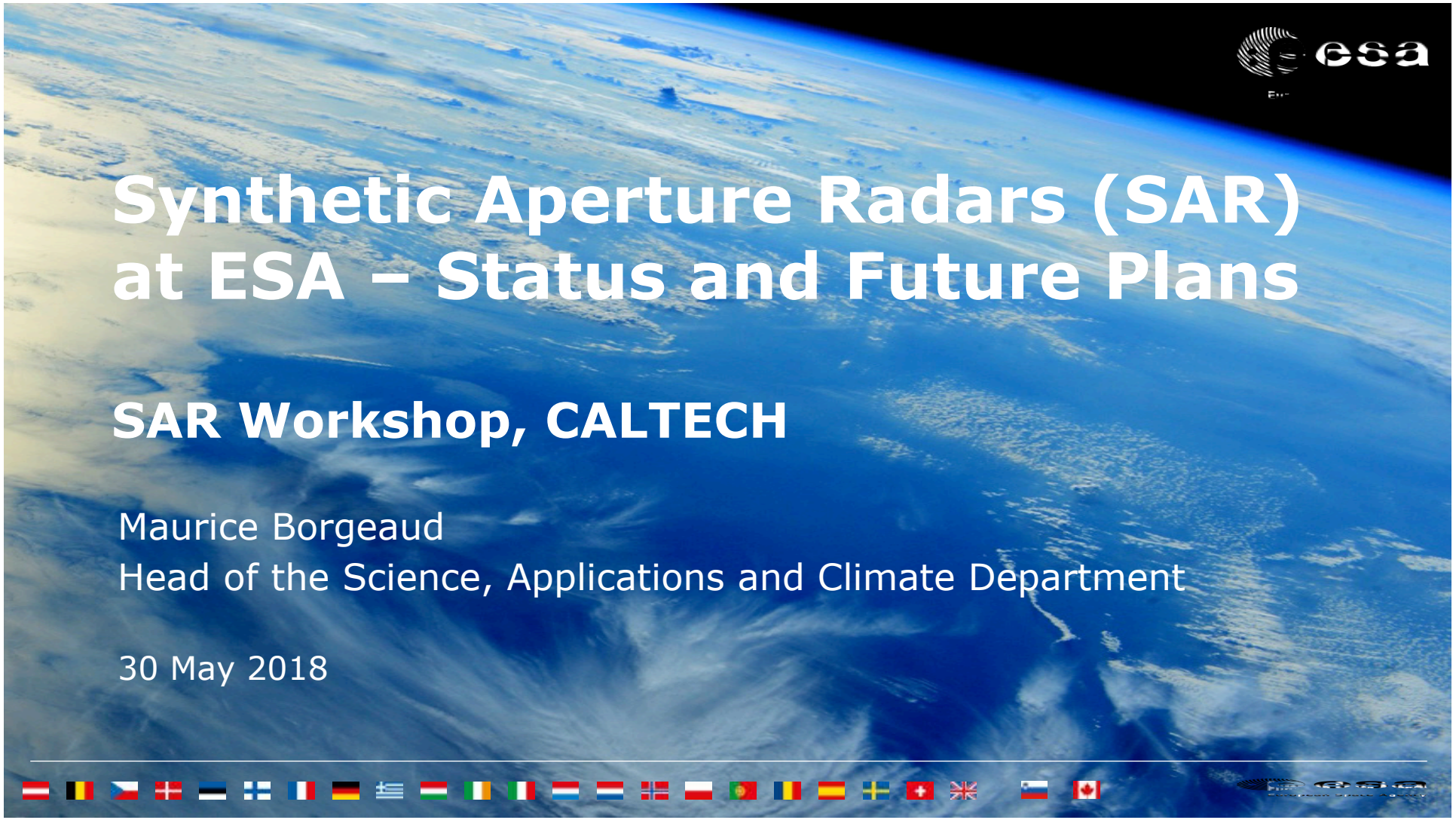


Synthetic Aperture Radars (SAR) at ESA – Status and Future Plans

SAR Workshop, CALTECH

Maurice Borgeaud
Head of the Science, Applications and Climate Department

30 May 2018

In memory to Wolfgang-Martin Boerner

- 1937-2018
- He should have been with us today!
- “The” father of radar polarimetry
- Full of empathy and endless enthusiasm (not only for radars…)
- May his dream become reality:

  A multi-frequency fully polarimetric wide-band spaceborne radar

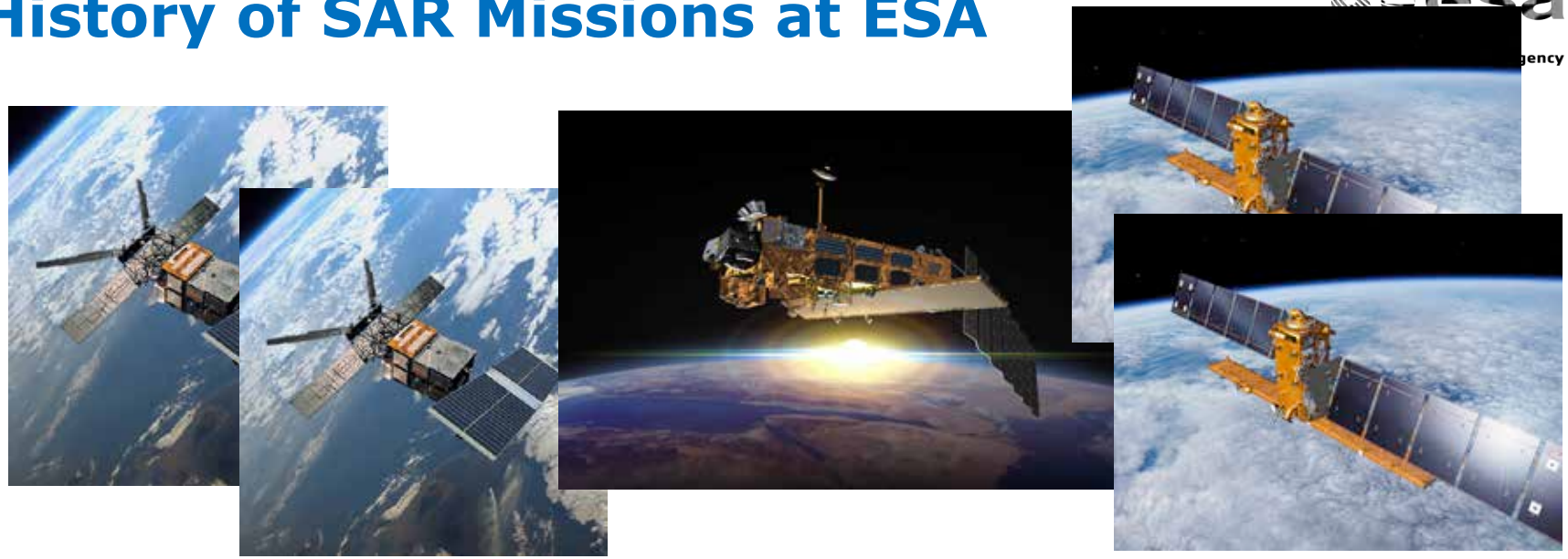
Outline

- History of SAR's at ESA
- Current SAR missions
- Approved SAR missions
- Future plans
- International collaboration
- On SAR data and Applications

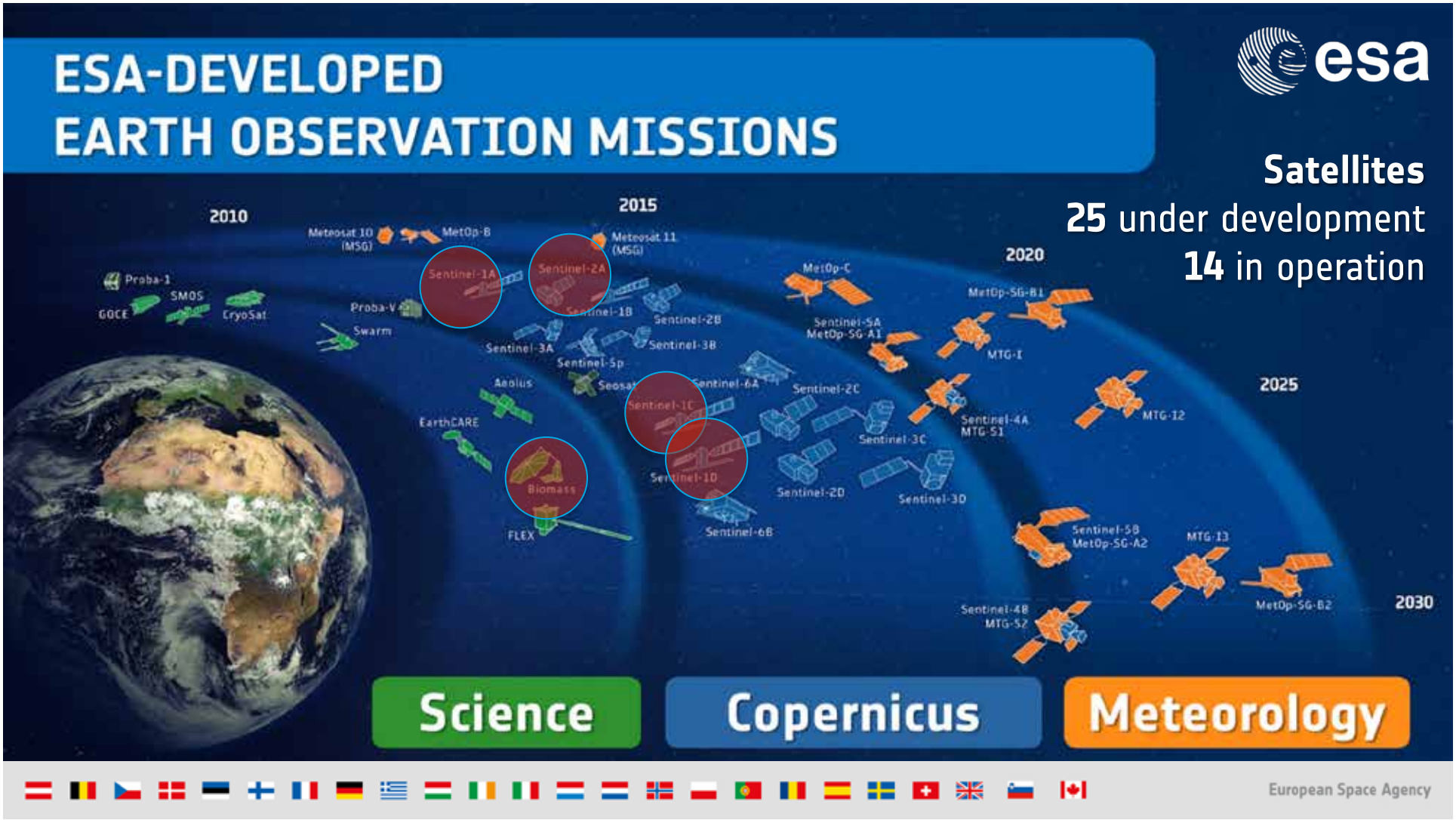
SEASAT, 1978 => 40 years ago

20 May 2017, Interferometric Wide Swath, VV/VH

History of SAR Missions at ESA



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
ERS-1																												
ERS-2																												
ENVISAT																												
Sentinel 1a																												
Sentinel 1b																												



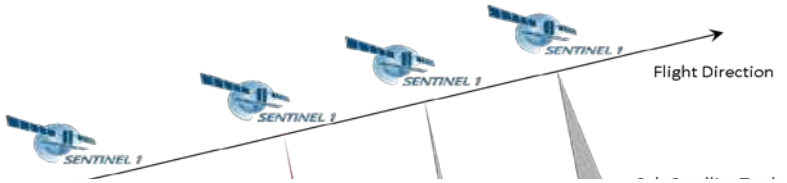
European Space Agency

Sentinel-1 System Baseline

European Space Agency

- Constellation of two satellites
- C-Band SAR Payload at 5.405 GHz
- Near-Polar, sun-synchronous (dawn-dusk) orbit at 698 km
- 6 days repeat cycle for the constellation
- Four Dual-P
- Data downli
  X-Band with
  (Svalbard, N
  Inuvik) and
- On-board A
  SAR acquisi

- Rad. Stability better than 0.6dB (3σ)
- Rad. Accuracy better than 1.0dB (3σ)
- NESZ better than -22dB



Mode	Incidence Angle	Resolution	Swath Width	Polarization (H = Horizontal V = Vertical)
Stripmap	20 - 45	5 x 5 m	80 km	HH+HV, VH+VV, HH, VV
Interferometric Wide swath	29 - 46	5 x 20 m	250 km	HH+HV, VH+VV, HH, VV
Extra Wide swath	19 - 47	20 x 40 m	400 km	HH+HV, VH+VV, HH, VV
Wave	22 - 35 35 - 38	5 x 5 m	20 x 20 km	HH, VV

Swath Mode (IW)

Sentinel Status

esa

S-1

Radar

A	3 Apr. 2014
B	25 Apr. 2016
C	2022/23
D	> 2022/23

S-2

High Res. Optical

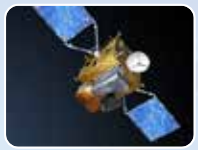
A	23 Jun. 2015
B	6 Mar. 2017
C	2022/23
D	> 2022/23

S-3

Medium Res. Optical & Altimetry

A	16 Feb. 2016
B	25 Apr. 2018
C	2023
D	> 2023

S-4



Atmospheric Chemistry (GEO)

A	2021
B	2027

S-5P

Atmospheric Chemistry (LEO)

A	13 Oct. 2017

S-5

Atmospheric Chemistry (LEO)

A	2021
B	2027
C	> 2027

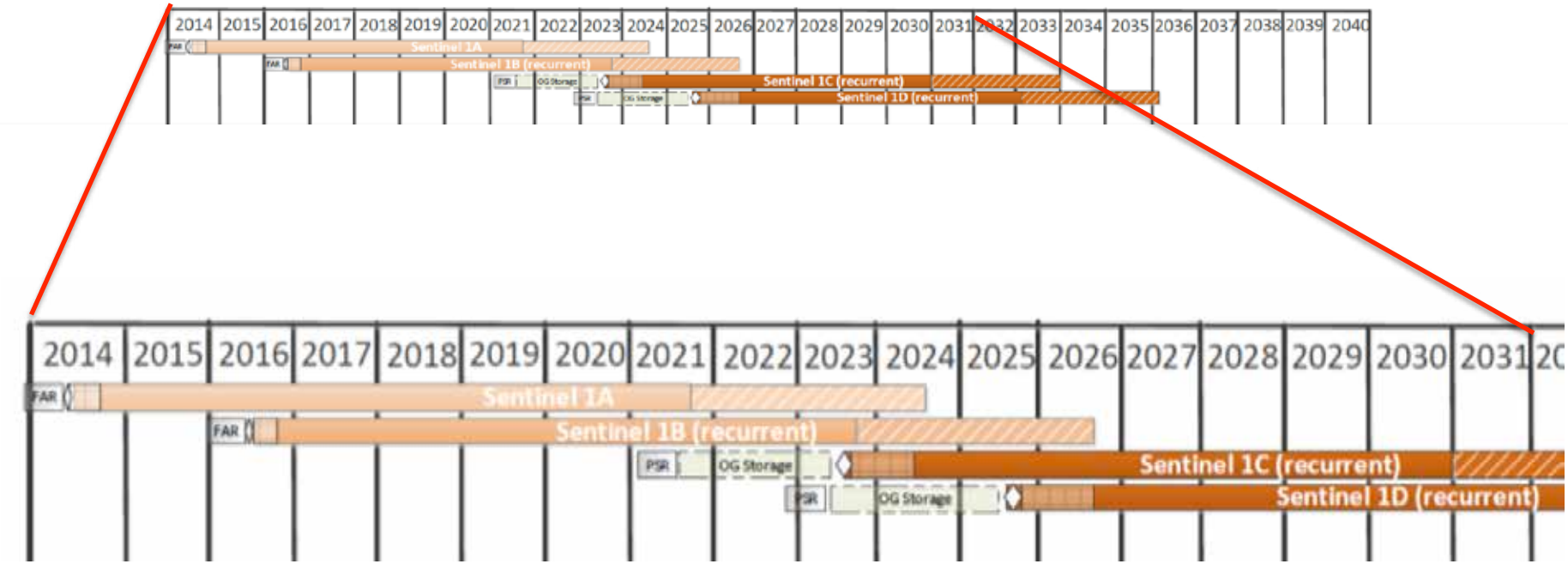
S-6

Altimetry

A	2020
B	2025

Copernicus Constellation Deployment

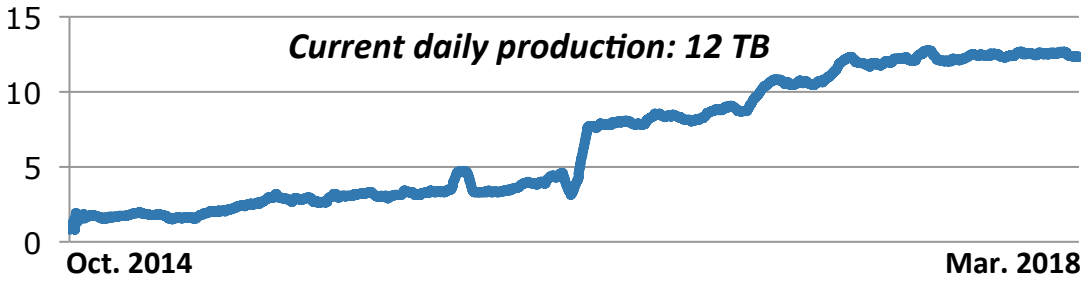
European Space Agency



Sentinel-1A/-1B Mission Status

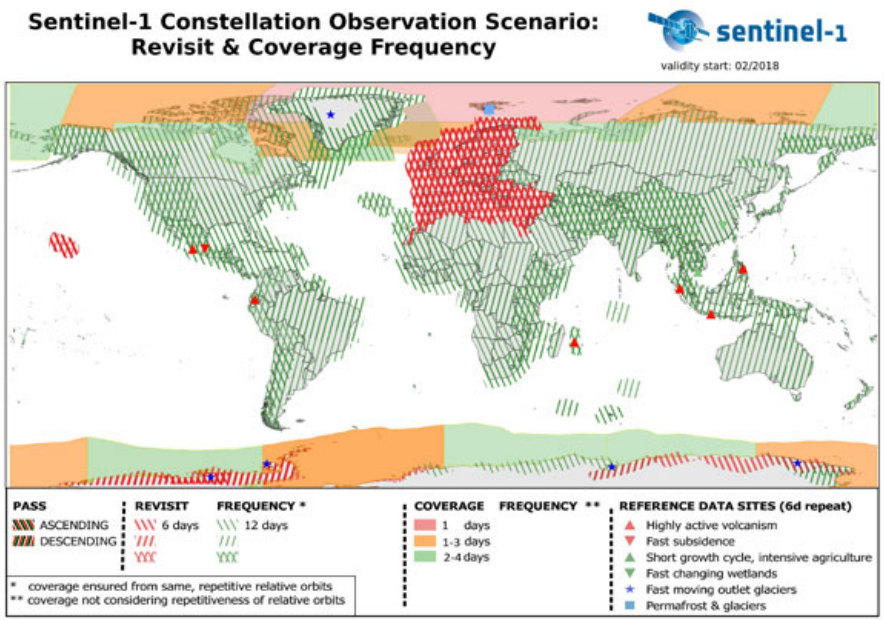
European Space Agency

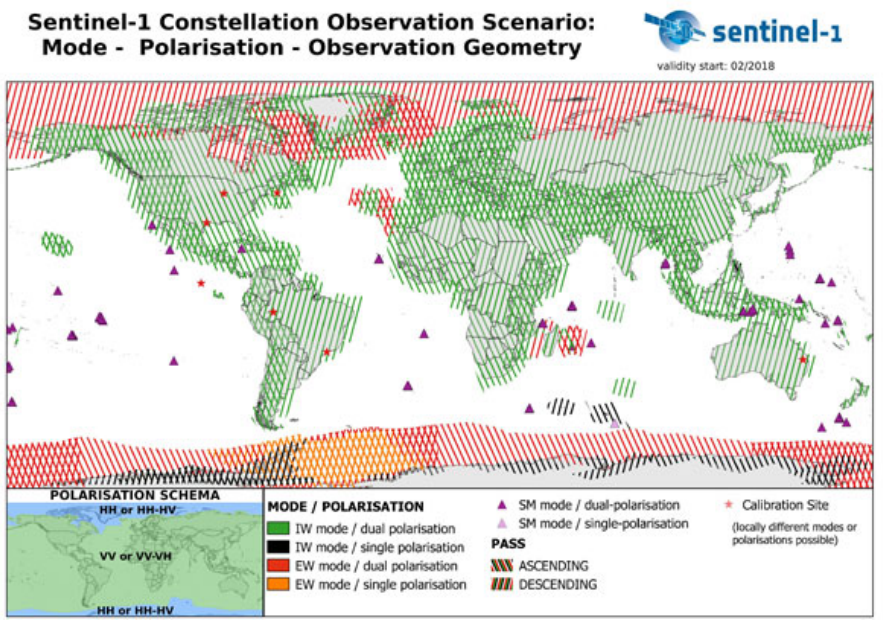
- Sentinel-1A and Sentinel-1B mission operations → **nominal**
- Data policy: **free, open … and full**
- Operations concept:
  - ✓ **stable** acquisition plan,
  - ✓ **systematic** production of Level 0, Level 1 and Level 2 products,
  - ✓ **wide** availability of products for download



Oil spill detected by Sentinel-1B on 4th April 2018, Huelva, Spain

Sentinel-1 mission acquisition plan

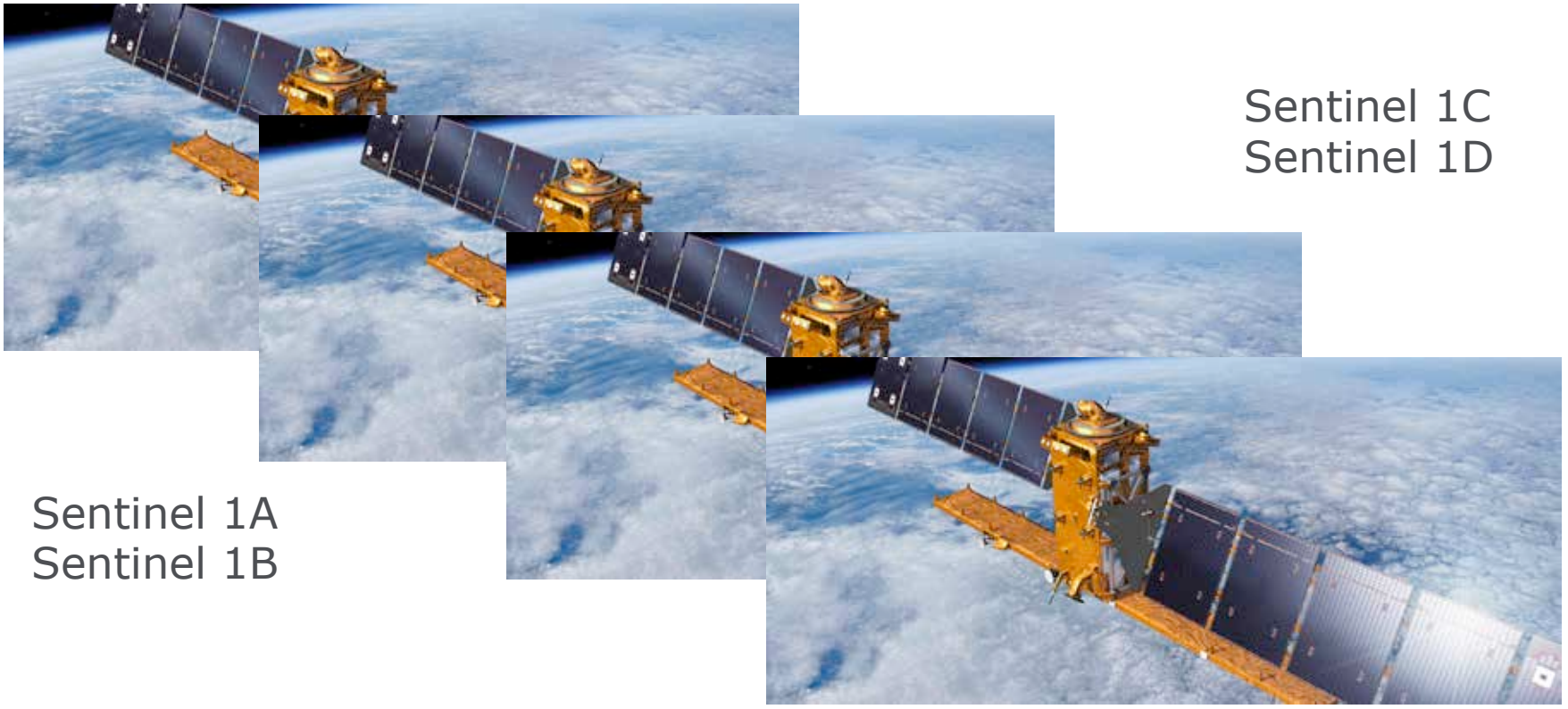




Sentinel-1 (Sentinel-1A + Sentinel-1B) data acquisition plan stable:

- a revision of the Sentinel High Level Operations Plan (HLOP) was released in March 2018
- it takes into account the current needs of the European Commission, in particular those of the Copernicus services, as well as the needs of the ESA Member States.

Operational System & Long-Term Continuity

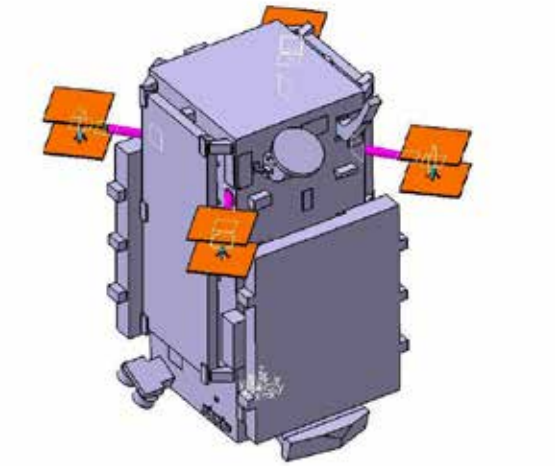


Sentinel 1C
Sentinel 1D

Sentinel 1A
Sentinel 1B

Sentinel-1C/D

- Built on Sentinel-1A/B design
- Evolution:
  - AIS Instrument for augmentation of SAR marine services (provide ship identification data contemporaneous to SAR images)
  - Design compatible with Space Debris Casualty Ratio less than 10^{-4} (release of the SAR Antenna during re-entry)
- Improvements:
  - SAR Instrument stability (redesign of the most important contributor) from 0.60dB-3σ to 0.45dB-3σ
    - Internal calibration (from 5 to 3 cal pulses)
    - Continuous noise measurement
  - AOCS (star-tracker calibration)
  - Propulsion (more efficient thrust)



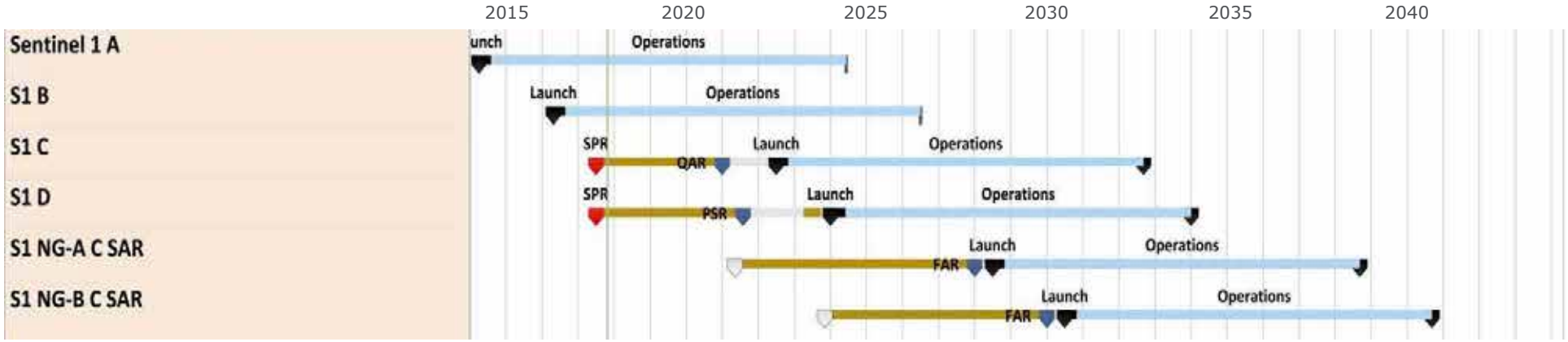
Sentinel-1 Schedule

- Sentinel-1A/B KO: May 2007
- Sentinel-1A launched 3 Apr 2014
- Sentinel-1A commissioned 23 Sep 2014
- Sentinel-1B launched 25 Apr 2016
- Sentinel-1B commissioned 14 Sep 2016

- Sentinel-1C/D KO: Dec 2015
- Sentinel-1C/D SPR: 13 Sep 2017
- Sentinel-1C FAR expected Dec 2020
- Sentinel-1D PSR expected Jul 2021

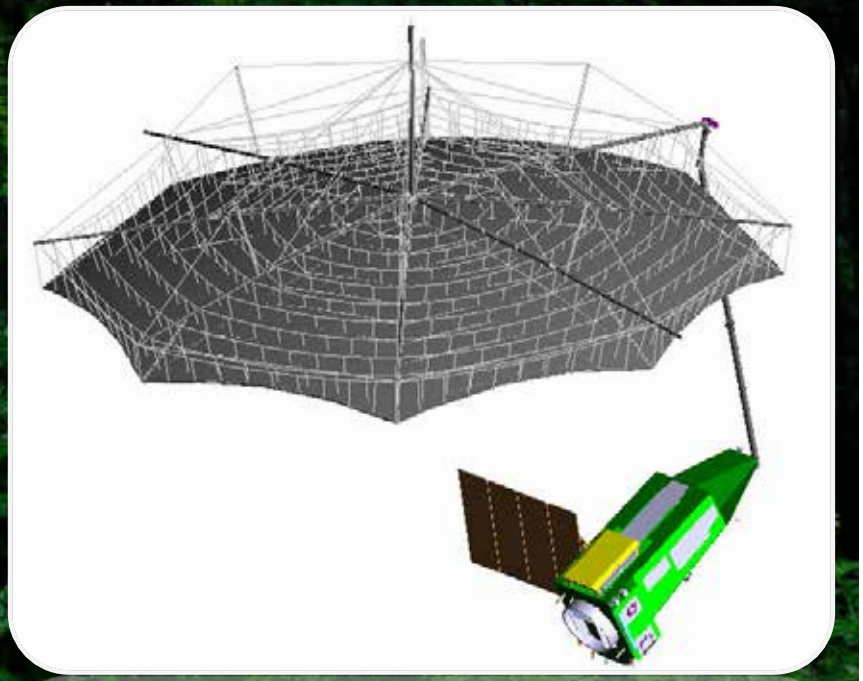
S1C and S1D will go in storage after FAR and PSR respectively

Sentinel-1 Long Term Scenario (ESA/PB-EO/2018/12)



BIOMASS

Mission	Measure of forest biomass and height (200 m. pixel resolution)
Payload	P-Band radar
Orbit	SSO, alt: 666 km; LTAN: 6h00
Satellite	1250 Kg
Consortium	Prime: ADS-UK, Instrument: ADS-DE
Launch date	2022
Lifetime	5.5 years



Biomass will map forest biomass, height and change with unprecedented accuracy

European Space Agency

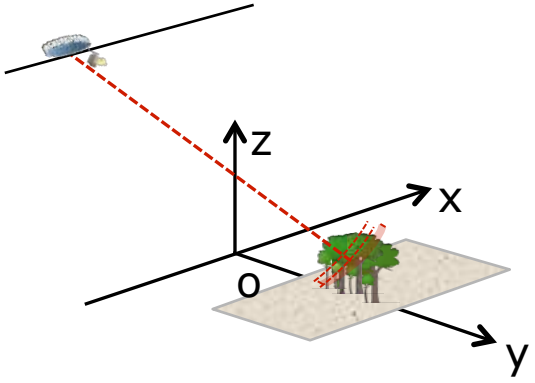
Forest biomass and forest height: global, 200 m scale, every 6 months for 4 years, 20% accuracy in biomass, 20-30%

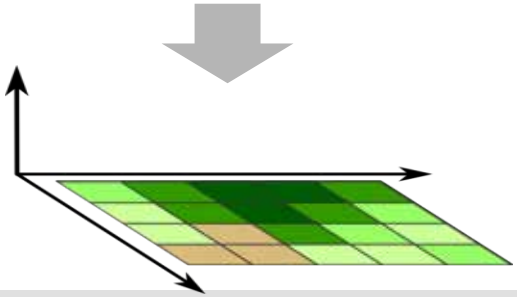
Disturbances: global, at 50 m scale

Biomass will deliver 3 independent types of information related to biomass

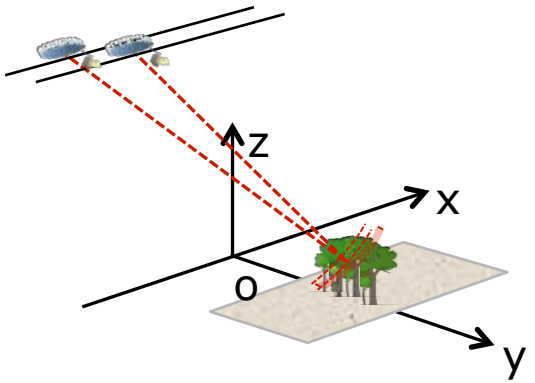
European Space Agency

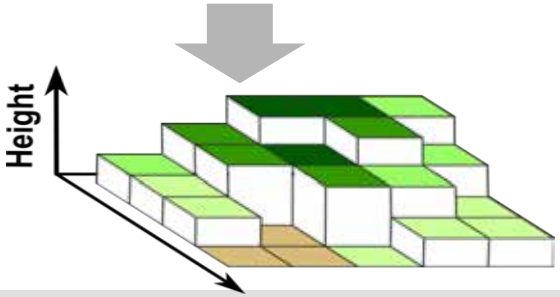
PolSAR
(SAR Polarimetry)



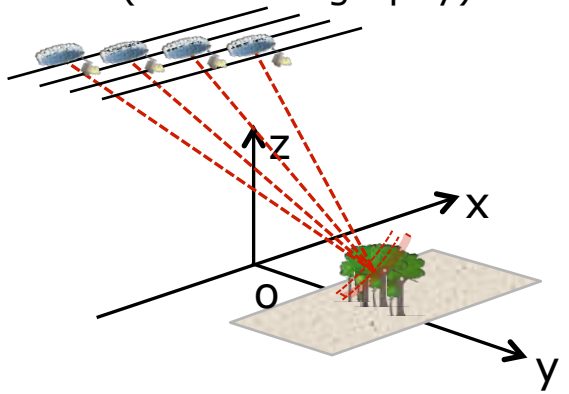


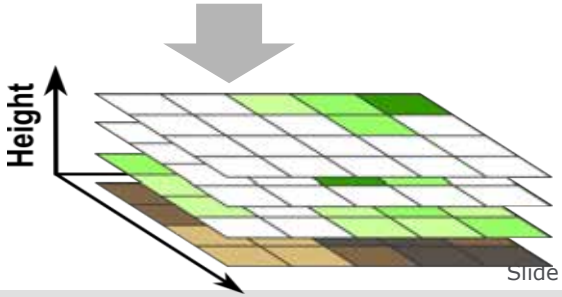
PolInSAR
(Polarimetric SAR Interferometry)





TomoSAR
(SAR Tomography)





Biomass Fact Sheet

European Space Agency

Biomass Mission

The mission provides global maps of forest biomass and height (at 200 m resolution) and forest disturbance (at 50 m resolution) every 6 months to:

- reduce the major uncertainties in carbon fluxes linked to land use change, forest degradation and regrowth;
- provide support for international agreements (UNFCCC and REDD+);
- infer landscape carbon dynamics and supporting predictions;
- initialize and test the land component of Earth system models;
- provide key information on forest resources, ecosystem services, biodiversity and conservation.

Mission Duration

- Commissioning phase: 6 months
- Tomographic phase (TOM): 14 months
- Interferometric phase (INT): 4 years
- Lifetime: 5.5 years
- Launch: mid 2022

Mission Orbit and Satellite Attitude

- Orbit Type: LEO, drifting sun-synchronous
- Altitude: 666 km
- Repeat Cycle: 3 days
- LTAN: 06:00 AM/18:00 PM
- Inclination: 97.97°
- Interferometric baseline: 1.5 km (TOM) / 3 km (INT)
- Attitude Control: 3-axis stabilized with yaw steering

Payload

Full polarimetric single beam Synthetic Aperture Radar, operating in interferometric stripmap mode:

- Frequency: 435 MHz (P-band)
- Bandwidth: 6 MHz
- Large deployable reflector: 12 m projected diameter
- Swaths: Satellite rolls for beam repointing to cover 3 swaths of about 60 km / 50 km / 50 km for a combined 160 km swath width
- Payload data rate: 115 Mbit/s
- Cross polarization ratio: < -25 dB
- Resolution with 6 looks: 60 m x 50 m
- Noise equivalent σ0: < - 27 dB
- Total ambiguity ratio: < - 18 dB

Satellite

Mass

- Mass: <1250 kg

Power

- Deployable solar array at fixed cant angle based on GaAs triple junction cells with an area of 4.1 m2
- Average power: <750 W
- Li-ion battery nominal capacity: 156 Ah

Communication Links

- X-Band downlink 500 Mbps
- S-Band 64 kbps uplink
  571 kbps downlink

Launch Vehicle

Vega is the baseline launch service provider.
Antares as backup.

Flight Operations

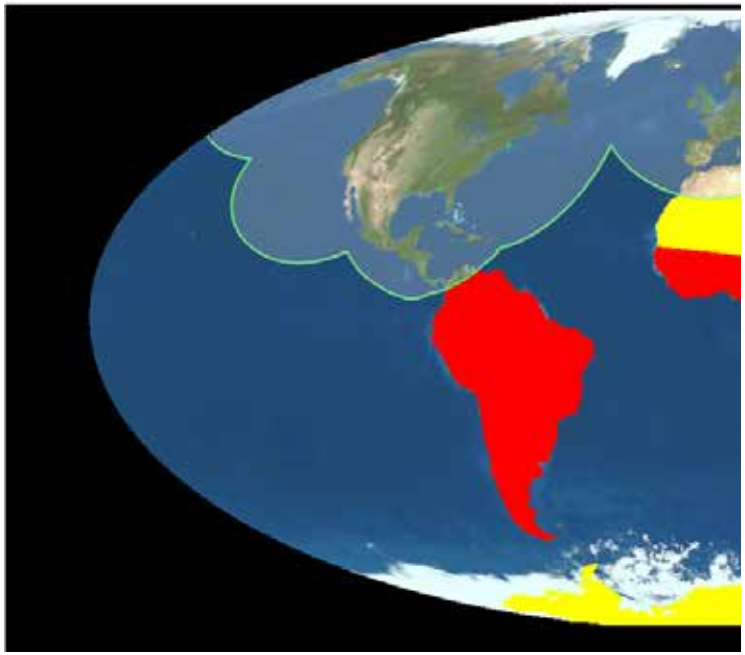
Spacecraft Operations with ESOC
Ground Station: Kiruna.

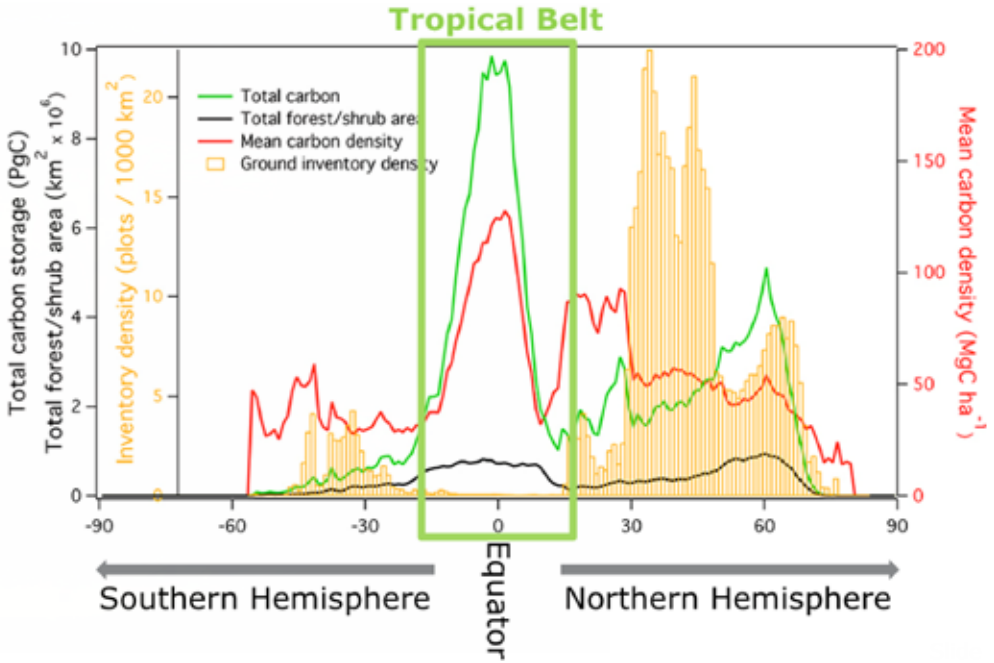
Payload Data Processing

User Services and Payload Data Processing Centre under responsibility of ESRIN.

Biomass and SOTR's

US DoD operates Space Object Tracking Radars (SOTR) at P-band and SAR cannot be put into operations within view of SOTR's

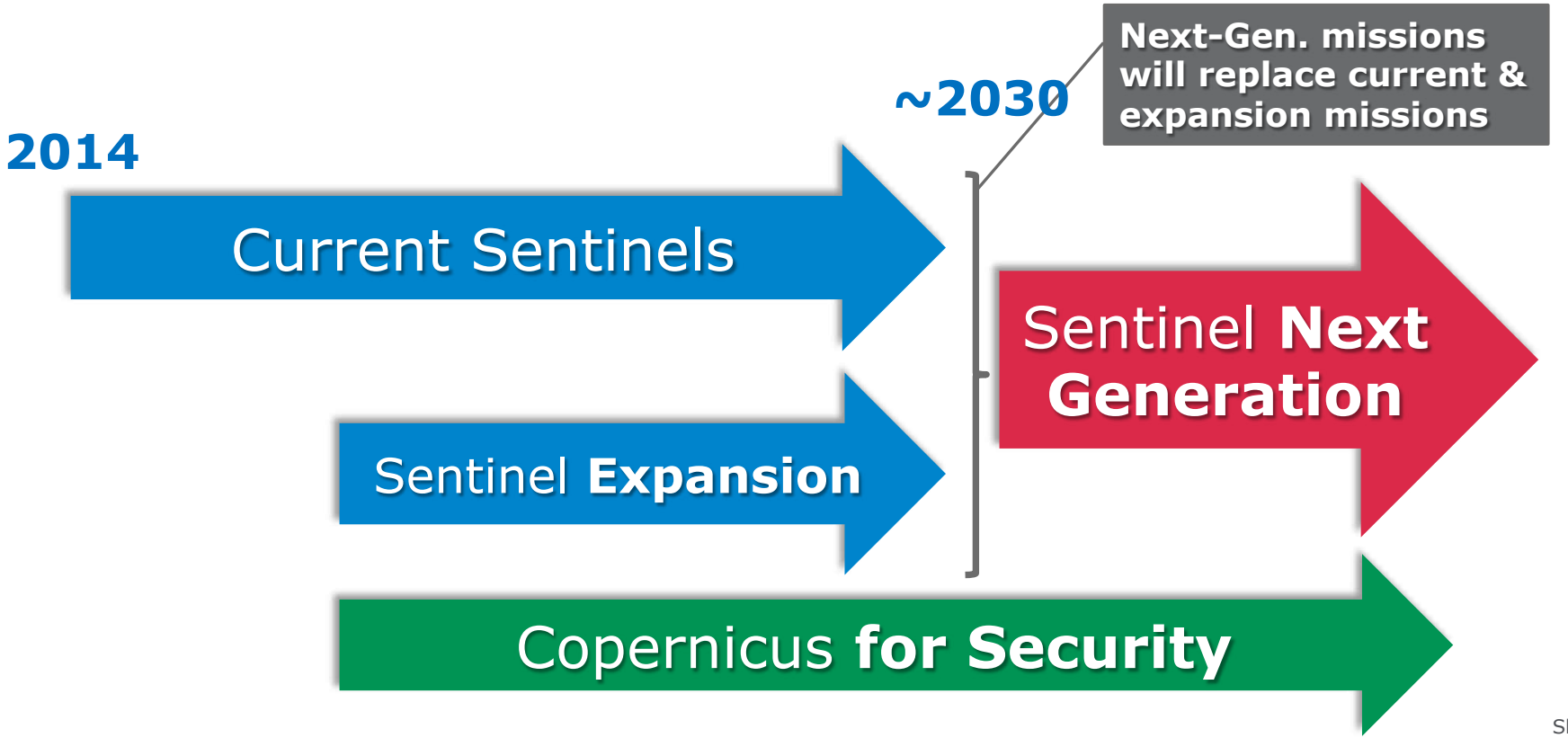





esa
The Future is Now

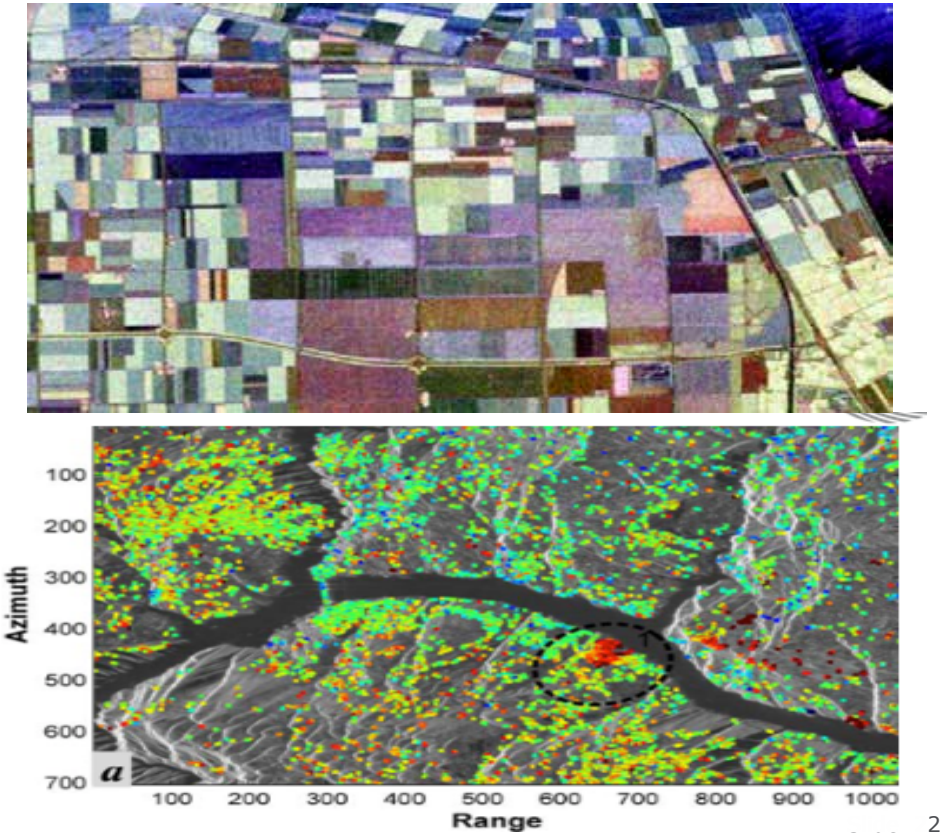
Copernicus Space Component Evolution

European Space Agency



Copernicus Expansion Candidate Mission L-band SAR (EROS-L)

- One of 6 Expansion Missions included in Phase-A/-B1 studies (=> Sept 2019)
- Responds to EC policies and Copernicus service needs
- **Fill measurement gaps from space leveraging unique information provided at L-band SAR for**
  - **Land monitoring**
  - **Emergency management**
  - **Cryosphere**
- Vegetation biomass information
- Ground motion information in vegetated areas
- Land cover mapping
- Greatly enhanced information on sea and land ice parameters



C-Band Sentinel-1 Next Generation

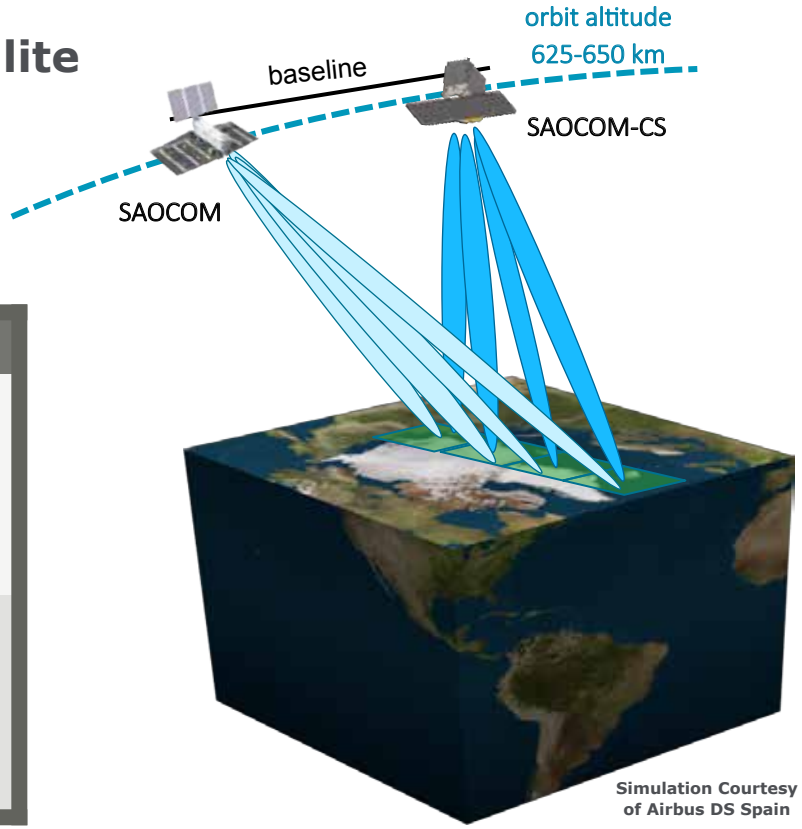
- The phase 0 studies for the next generation of C-band SAR is currently being initiated.
- The requirements on imaging capability are significantly increased
- The information collected per orbit is improved by a factor of 13 with respect to resolution, swath width and orbit duty cycle compared to the current S1 satellites.
- This becomes possible through High Resolution Wide Swath (HWRS) SAR with scan on receive and multiple azimuth phase centers
- Deployment of S-1 NG constellation may start in 2028

	Sentinel-1	S-1 Next Generation
Resolution	5m x 20m	5m x 5m
Swath Width	250 km	400 km
NESZ	-22dB	-22dB
Polarization	Dual	Quad @250 km swath
Orbit Duty Cycle	25.5 %	53 %

SAOCOM-CS. L-band companion satellite

L-band single satellite

bi-static follower



Look Angles	
Dual-Pol DP1	20.7°
Dual-Pol DP2	24.5°
Dual-Pol DP3	28.3°
Dual-Pol DP4	32.3°
Quad-Pol QP1	16.9°
Quad-Pol QP2	18.6°
Quad-Pol QP3	20.2°
Quad-Pol QP4	22.0°

Baselines	
Tomographic	AT 5-7 km XT +/- 12 km
Bistatic-along	AT 250 km
Bistatic-perp.	AT 250 km XT 260 km
Specular	AT 0 km XT 520 km

Stripmap mode only

Mission Phases

- Three science mission phases: **tomographic**, **bi-static**, **specular**

Tomographic phase

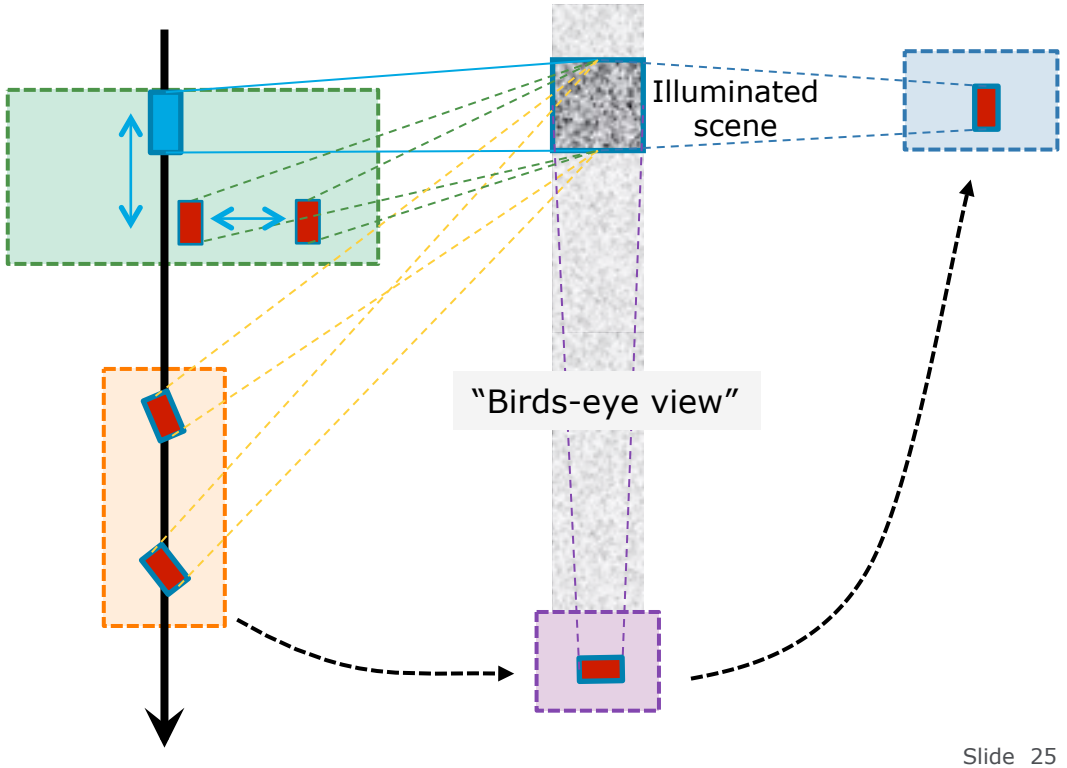
✓5 km < AT baseline < 7 km
✓-12 km < XT baseline <12km
✓Science mission driver
✓Duration ~2.5 years

Bi-static 1, Bi-static 2

- ✓ AT baseline < 250 km
- ✓ Small XT baseline (phase 1)
- ✓ Large XT baseline (phase 2)
- ✓ Duration ~2 years

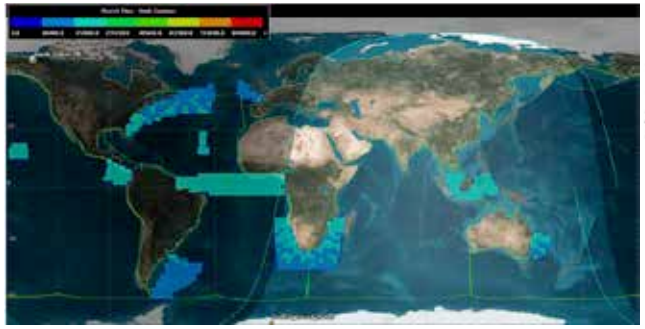
Specular phase

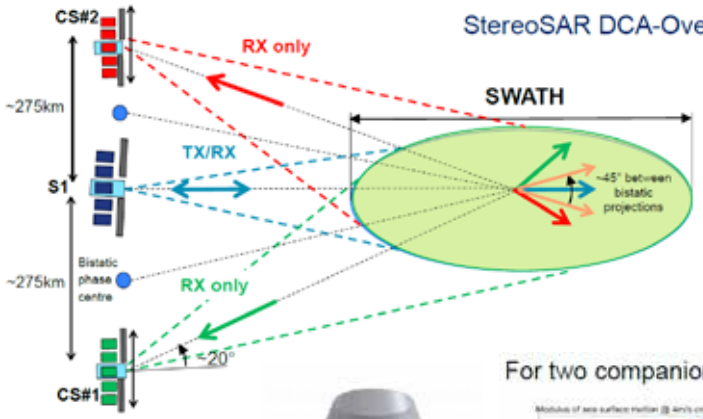
- ✓ Experimental
- ✓ Duration limited by S/C resources

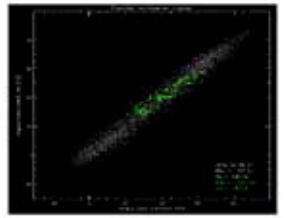


StereoSAR

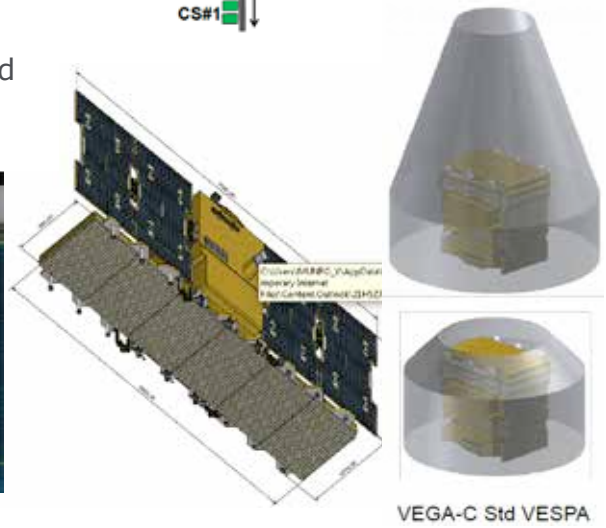
- Concept of passive, bistatic follower to S-1
- Two followers, 3 ocean views
- Backscatter + Doppler → wind, waves and currents
- 3-5 km resolution
- Revisit and coverage science requirements fully met with combination of synergistic and non-synergistic observation scenario's
- Small mission, fits in VEGA-C
- State of the art accuracy for DCA method with S-1 data: 2-3 Hz, or 14-21 cm/s





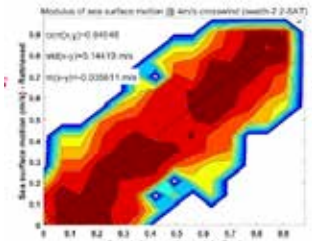


Scatterplot of DC model versus measured DC from the period of 26-31.10.16 S1b in

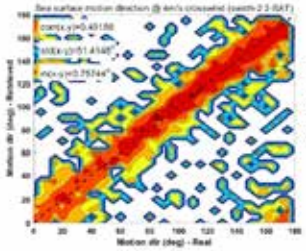


VEGA-C Std VESPA

For two companion satellites



$corr(x,y) = 0.94548$
$std(x-y) = 0.14419 m/s$
$m(x-y) = -0.035611 m/s$



$corr(x,y) = 0.49188$
$std(x-y) = 51.4148°$
$m(x-y) = 0.75744°$

ICEYE commercial µSAR Satellites

- The ICEYE-X1 µ-SAR satellite was successfully launched on 12 Jan. 2018
- This first demonstrator currently delivers about 10 images per day
- The ICEYE-X1 has a mass of only 65kg with a X-band antenna of 3.2m x 0.2m
- It is planned to deploy a full constellation of SAR satellites
- The following ICEYE satellites shall have improved capabilities
- ICEYE is Finnish start-up company financed by venture capital as well as some EU and Finnish public funding
- ESA is supporting ICEYE with characterizing one of the following satellites in the ESTEC test facilities

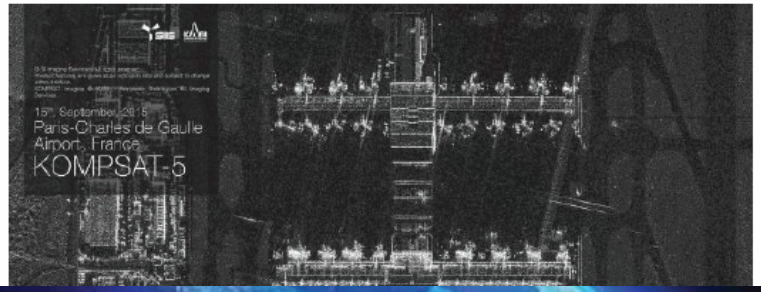
ICEYE-X1 EXAMPLE IMAGERY:SINGAPORE STRAIT

TECHNICAL SPECIFICATIONS	
Area of Interest	Kara Strait
Resolution	10m x 10m
Processing format	GeoTIFF
Original Scene	66 x 82 km
Look Angle	22°
Polarisation	Single, VV
Date	2018/01/28

µSAR and NewSpace

European Space Agency

Not convinced of the pr
of commercial radar sat
Meet the radar mafia.



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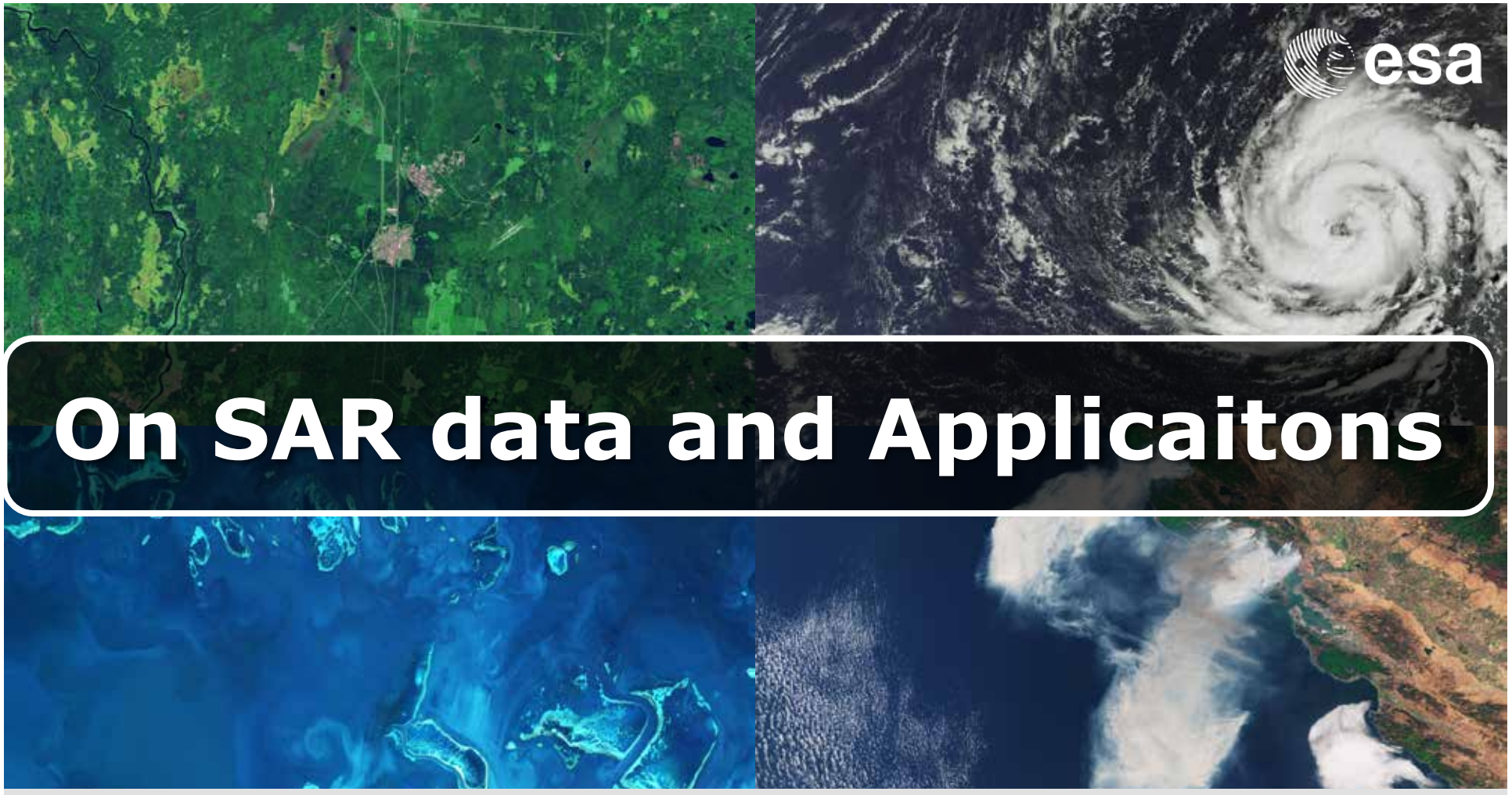
Synthetic aperture radar is genuinely in demand

Geospatial industry exploiting radar, RF data for maritime security and disaster re

In January, ICEYE proved it could operate a synthetic aperture radar on a microsatellite. Now the company is preparing to launch a constellation

The 70-kilogram ICEYE-X1 satellite launched Jan. 12 on a PSLV rocket carrying India's Cartosat-2 and 30 smaller satellites.



On SAR data and Applicaitons

European Space Agency

Copernicus Sentinel Data Policy

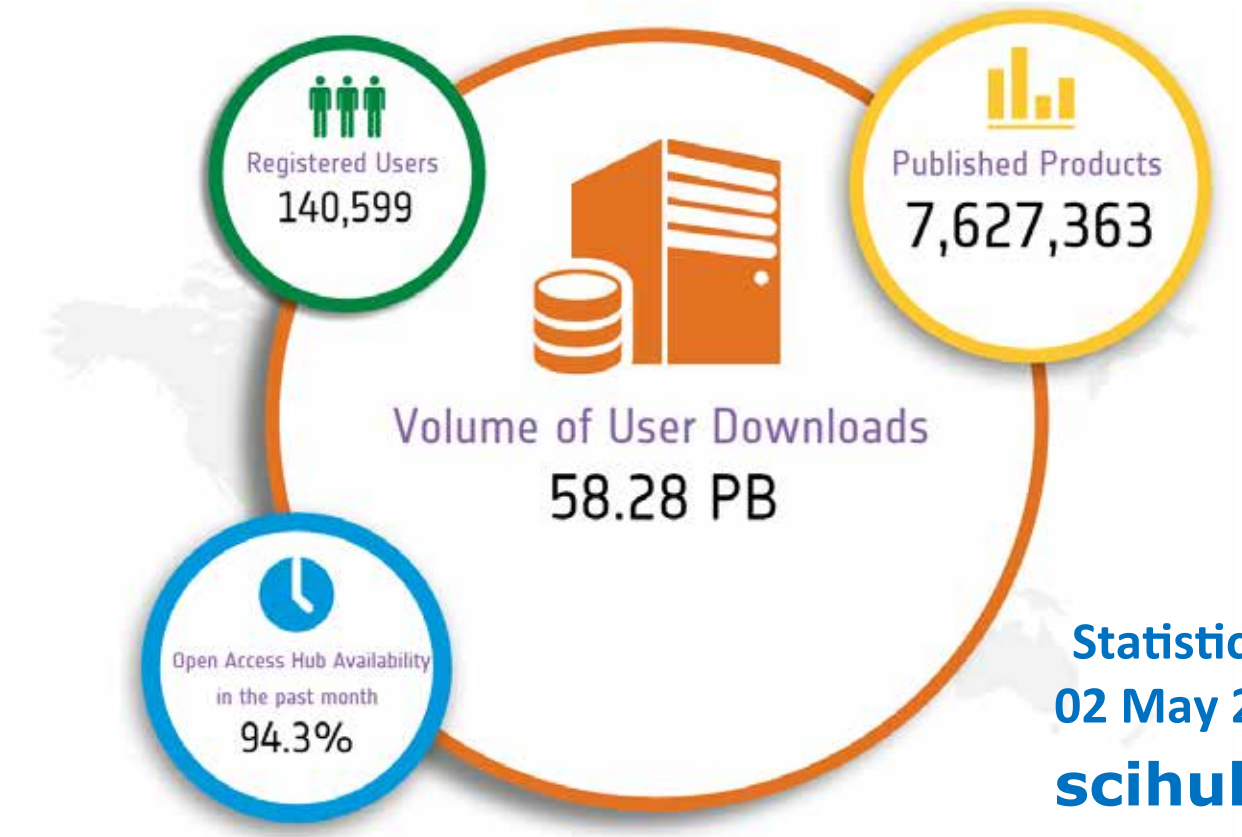
Sentinel data are available:

- ✓ **Free, Full and Open***
- ✓ **Over very long term**
- ✓ **Systematically, Operationally**

*** ESA Sentinel Data Policy** (Sep 2013) and **EU Delegated Act** on Copernicus Data and Information Policy (Dec 2013)

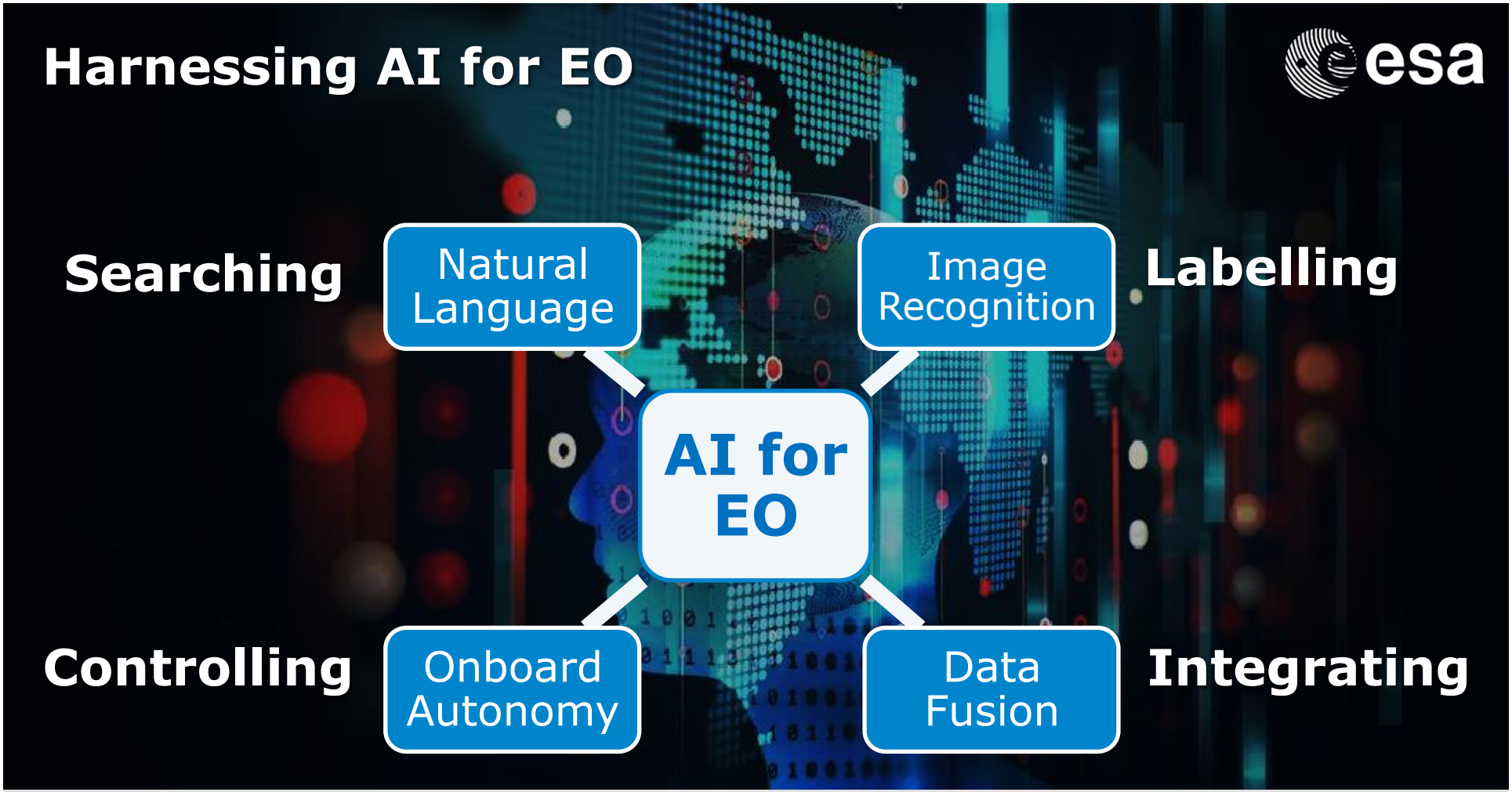
Sentinel Open Access Data Hub

European Space Agency



Statistics on
02 May 2018

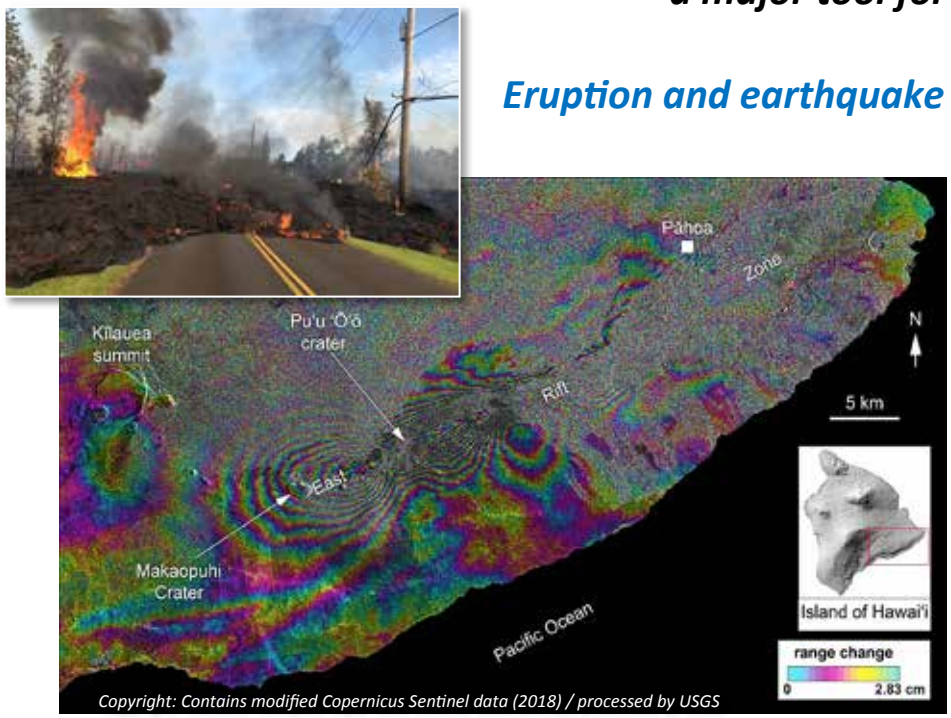
scihub.copernicus.eu


Harnessing AI for EO
esa
Searching
Natural Language
Image Recognition
Labelling
AI for EO
Controlling
Onboard Autonomy
Data Fusion
Integrating
European Space Agency

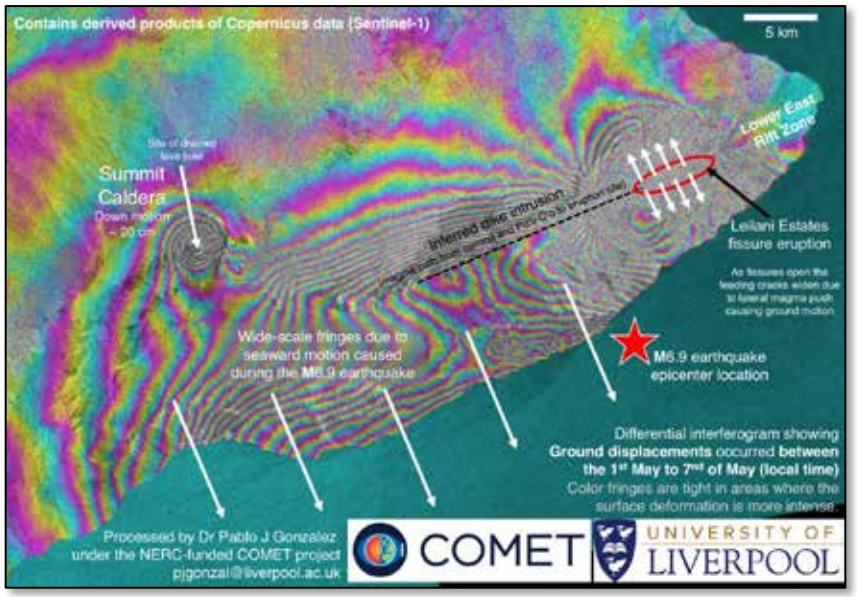
Sentinel-1 mission status

a major tool for geophysicists

Eruption and earthquake near Kilauea volcano, Hawaii (3 May 2018)



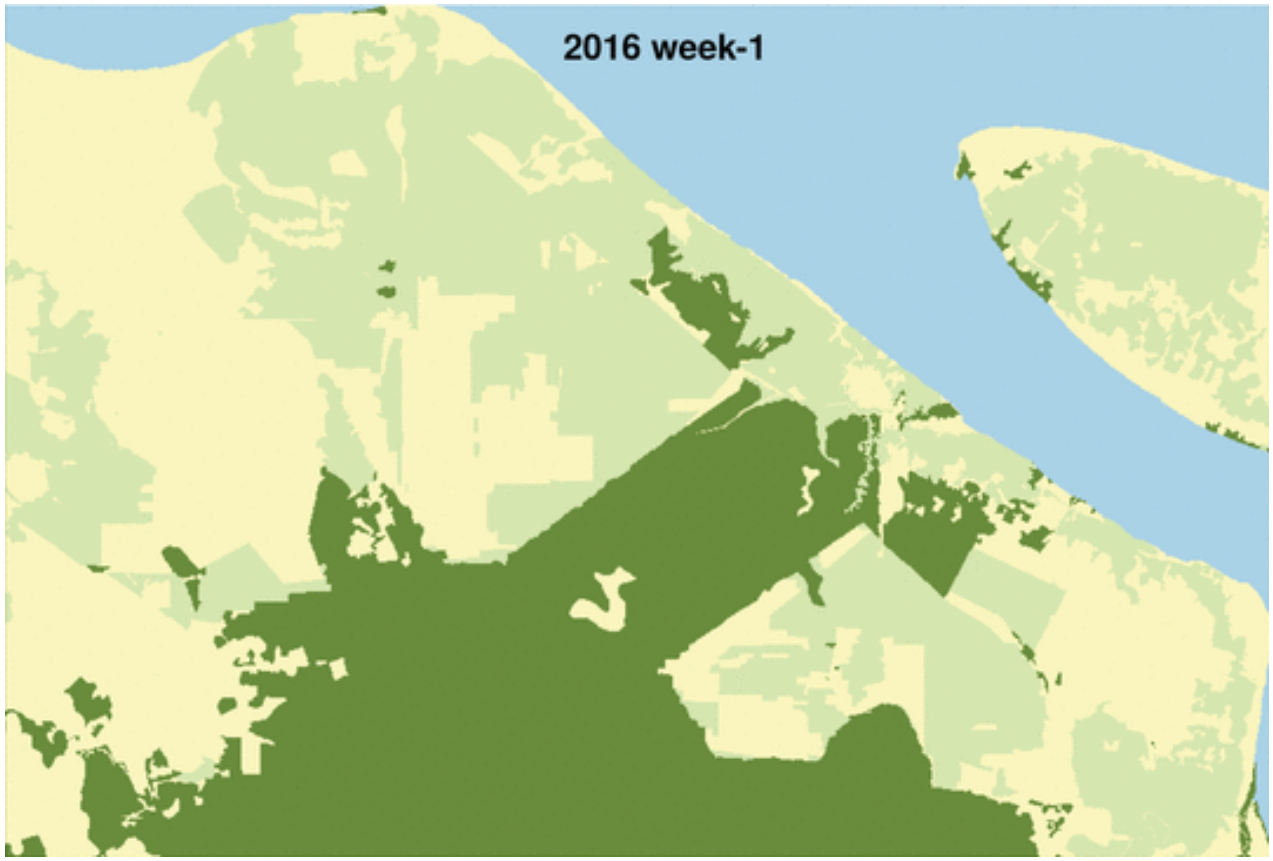
*Sentinel-1 interferogram (19 April – **1 May 2018**)*



*Sentinel-1 interferogram (**1 May – 7 May 2018**)*

Deformation due to magmatic intrusion → magma withdrawn from middle East Rift Zone and intruded beneath lower East Rift Zone.

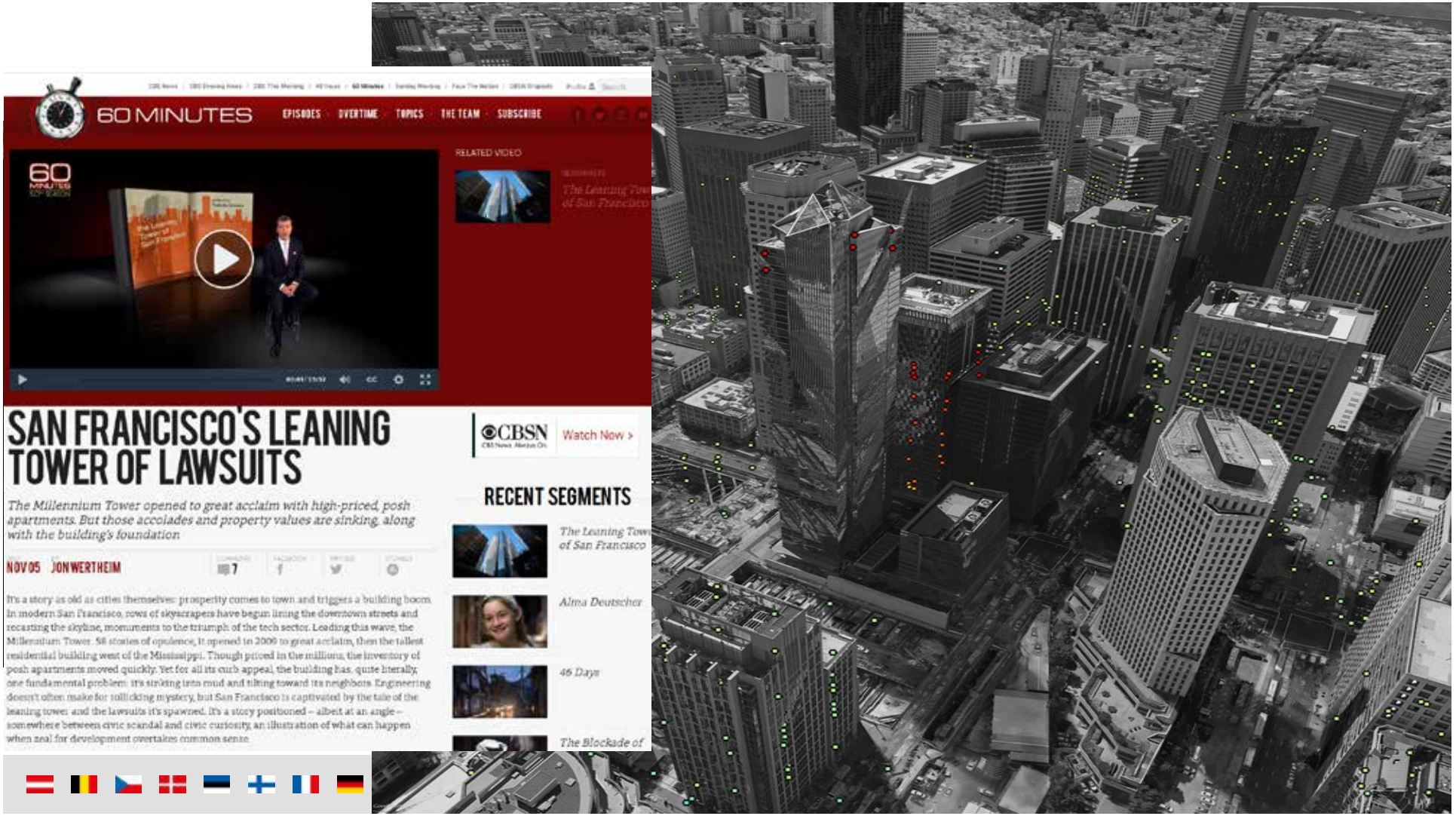
Sentinel-1 Radar Alerts on Forest Disturbances



Weekly Sentinel-1 Radar alerts 2016-18, in the Province of Riau, Indonesia:

- Machine learning method based on Reiche et al. (2015, 2018; RSE)
- Open source tool
- Gap-free and consistent information in near real-time

Natural forest
Plantations
Old clearing
New clearing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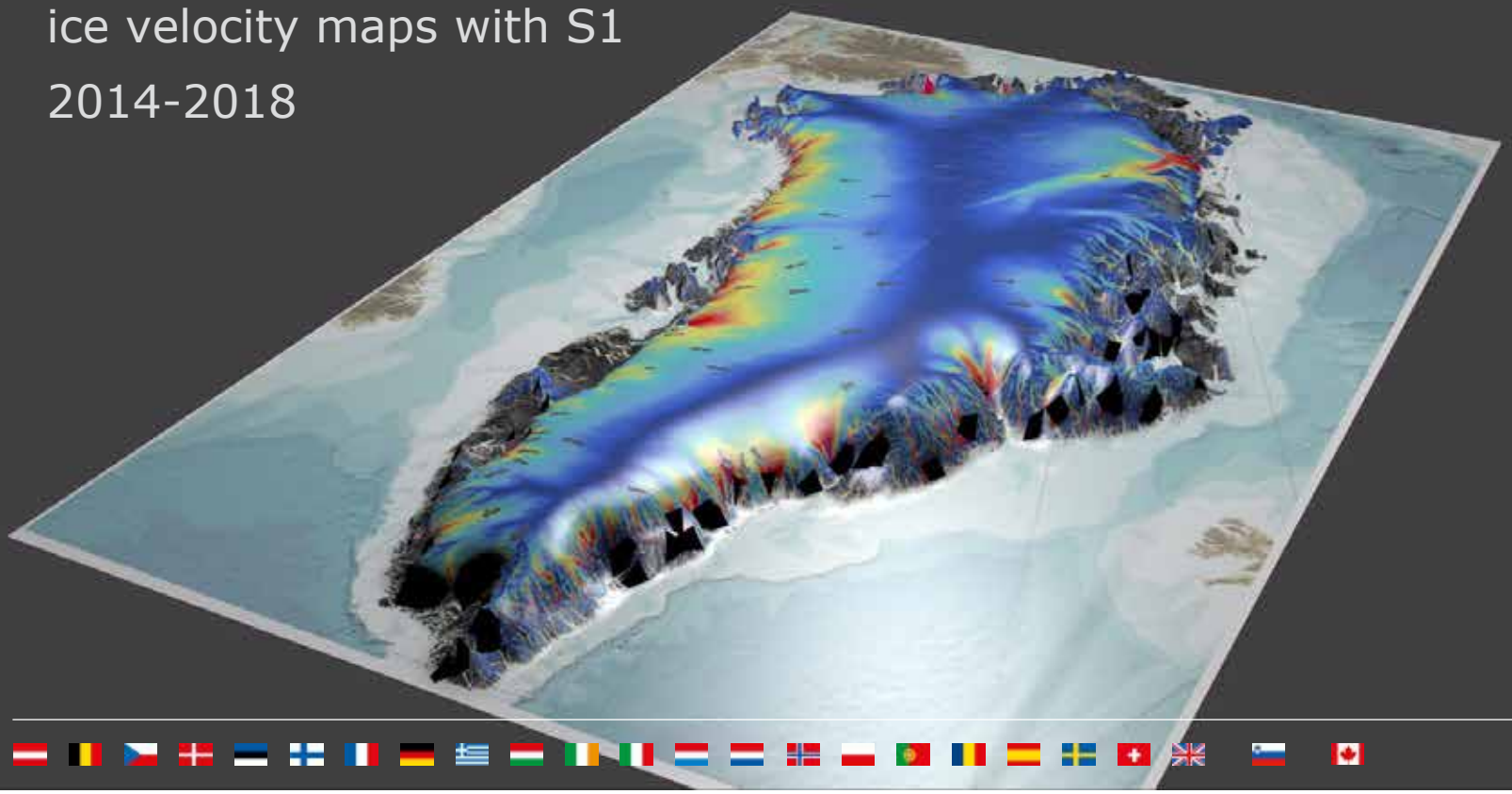
The Millennium Tower opened to great acclaim with high-priced, posh apartments. But those accolades and property values are sinking, along with the building's foundation
NOV 05
JON WERTHEIM
It's a story as old as cities themselves: prosperity comes to town and triggers a building boom. In modern San Francisco, rows of skyscrapers have begun lining the downtown streets and recasting the skyline, monuments to the triumph of the tech sector. Leading this wave, the Millennium Tower, 58 stories of opulence, it opened in 2009 to great acclaim, then the tallest residential building west of the Mississippi. Though priced in the millions, the inventory of posh apartments moved quickly. Yet for all its curb appeal, the building has, quite literally, one fundamental problem: it's sinking into mud and tilting toward its neighbors. Engineering doesn't often make for rollicking mystery, but San Francisco is captivated by the tale of the leaning tower and the lawsuits it's spawned. It's a story positioned – albeit at an angle – somewhere between civic scandal and civic curiosity, an illustration of what can happen when zeal for development overtakes common sense.
RECENT SEGMENTS
The Leaning Tower of San Francisco
Alma Deutscher
46 Days
The Blockade of

Ice Sheet Monitoring

Routine observations of
ice velocity maps with S1
2014-2018

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International Collaboration
European Space Agency

International Collaboration

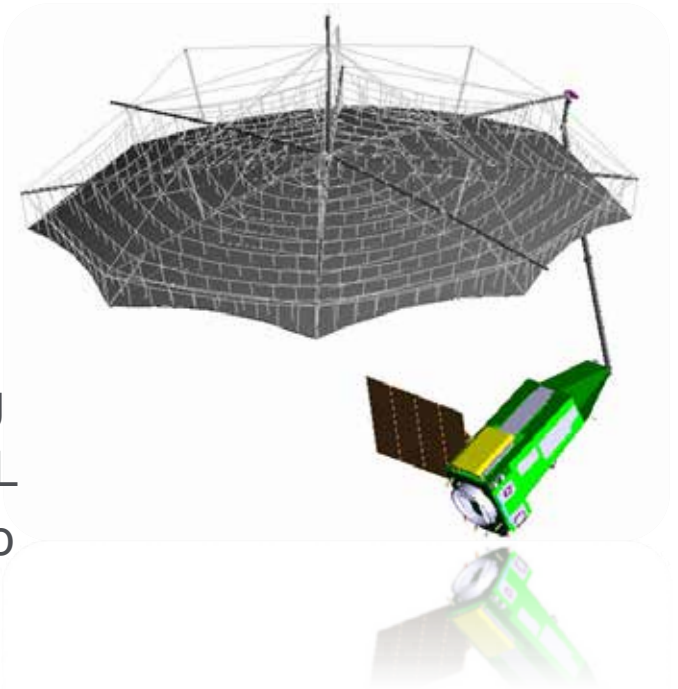
- By 2023, very likely to have 10-20 institutional spaceborne SAR missions flying (at least in –P, -L, -S, -C and X-band)
- Many NewSpace SAR's actors (commercial)
- Collaboration obvious for:
  - Cal/Val
  - Joint acquisitions and synergetic use of the data
  - New science and applications
  - Standards and coordination (e.g. ARD)
  - Bi- and multi-static experiments (e.g. ESA+CONAE on SAOCOM-CS)
  - Protection on EM spectrum

Coordination with RCM

- Sentinel-1 / Radarsat2 & RCM interference
  - Interference created from each-other backscatter observed between S1 and R2
  - Varying cyclically in time because of different orbit keeping strategy
  - A strategy for S1 / RCM can be defined to mitigate the interference problem
- ESA / CSA calibration working group to benefit from each-other's calibration tools and common calibration sites, and lessons learned
- Coordinated studies for protecting the C-band spectrum from extension of broadband wireless internet services (RLAN and HIPERLAN)
- System Compatibility
  - For improving the revisit frequency and InSAR-based Coherent Change applications, future C-band SAR missions can be made compatible in terms of requirements (partially or fully)
  - Eventually they could form a constellation (built-up over time) even using different spacecraft

ESA - JPL cooperation in Biomass

- JPL has gained extensive expertise with large deployable reflectors in the SMAP program.
- The ESA Biomass and the NASA NISAR missions both use similar large deployable reflectors (LDR), have very similar launch dates and overlap in their science objectives.
- ESA and JPL cooperate through NASA funding on the development of the Biomass where JPL provides engineering support and expertise to the Biomass Project Team.



Joint Biomass/NISAR/GEDI Mission Analysis Platform

=> *towards an ESA/NASA common data systems project*

European Space Agency

→ The joint **Mission Analysis Platform** (MAP) is a ***science focused virtual environment*** dedicated to the unique needs of sharing and processing data from relevant field, airborne and satellite measurements related to **3 ESA & NASA missions: BIOMASS, NISAR and GEDI**. The concept is jointly developed as part of ESA and NASA

Why should the same Mission Analysis Platform (MAP) deals with **BIOMASS, NISAR and GEDI** together?

- ✓ The three missions have ***similar scientific objectives*** (biosphere study, in particular forests);
- ✓ The three missions target the ***same (science) communities***;
- ✓ Both BIOMASS and NISAR missions are ***polarimetric SAR at low frequencies*** (P-band for BIOMASS and L-band for NISAR), with ***similar launch dates***;
- ✓ Both BIOMASS and NISAR missions are ***complementary***: P-band data (BIOMASS) is better adapted to monitor high biomasses while L-band data (NISAR) is going to be the only data available over Europe and the USA;
- ✓ The three missions will use the ***same type of in-situ measurements*** for algorithm training and Cal/Val.

CEOS Analysis Ready Data for Land (CARD4L)

CEOS Land Surface Imaging Virtual Constellation (LSI-VC) has defined 3 CARD4L product family specifications:

1. surface reflectance
2. land surface temperature
3. **radar backscatter**

in consultation with expert users during 2nd semester 2017:

- radar specification discussed at CEOS WG CalVal SAR subgroup meeting @ JPL in Nov 2017
- subsequent teleconfs to refine specs.

LSI-VC organising *SAR CARD4L "task team"* in Q2/Q3 2018 to:

- Propose additional product families for SAR, e.g. Polarimetry, Interferometry …
- Develop additional SAR Product Families from selected proposals

ITU C-Band Frequency Management

- The two bands adjacent to 5350-5470 MHz (Sentinel-1 and Radarsat family) already assigned to the mobile service and are being used for RLAN.
- In the case of Europe, the use of RLAN regulated => compatible with other services in the band:
  - 5150-5350 MHz: Only indoor use, mean EIRP limited to 200 mW.
  - 5470-5725 MHz: Indoor as well as outdoor use allowed, mean EIRP limited to 1W
- In the US, the use of Outdoor RLAN in the 5250-5350 MHz band also allowed:
  - "... may operate either indoors or outdoors at higher power (250 mW) but must deploy dynamic frequency selection (DFS) to protect incumbent radar operations and transmit power control (TPC) to protect the Earth exploration satellite service"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Thank you for your attention!
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