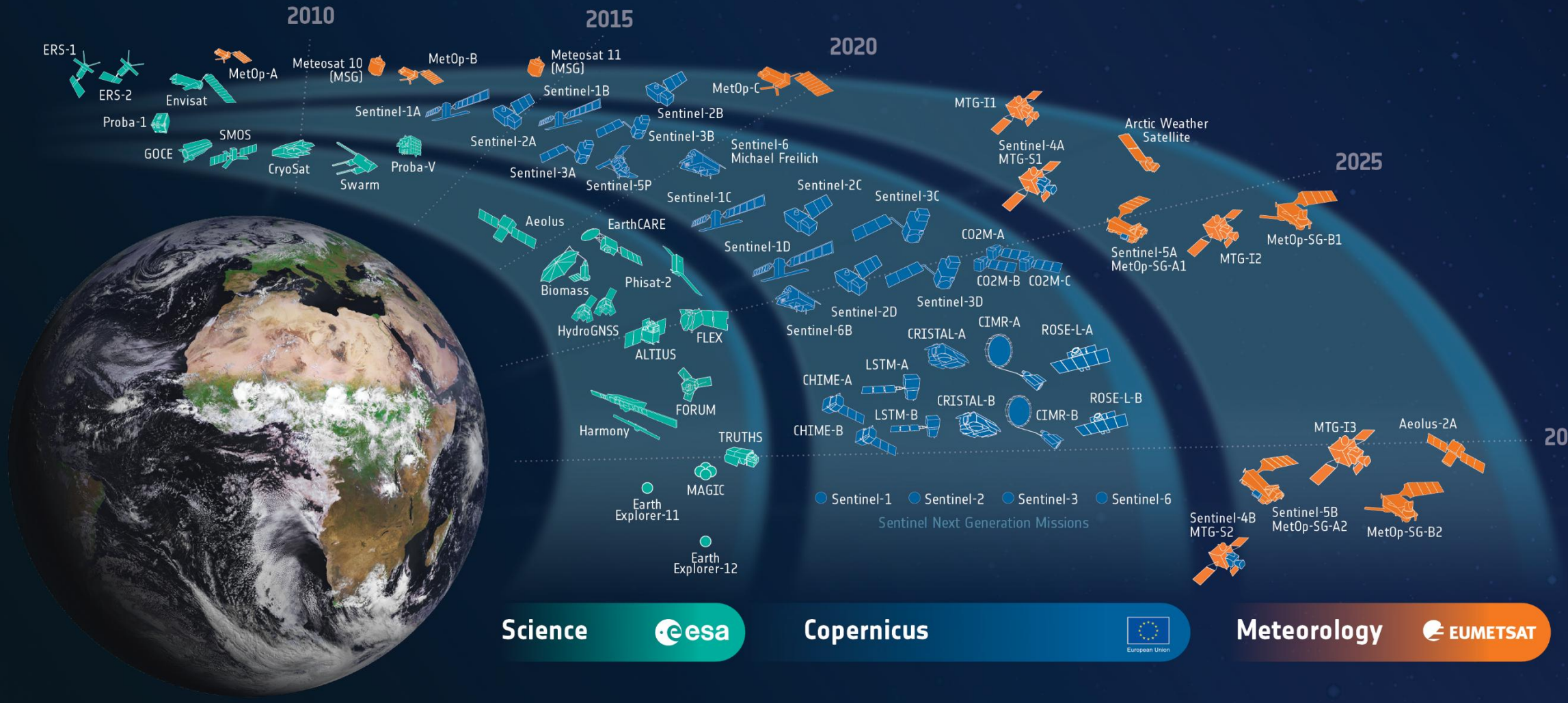
Optical pre-processing and hyperspectral analysis

Marco Celesti

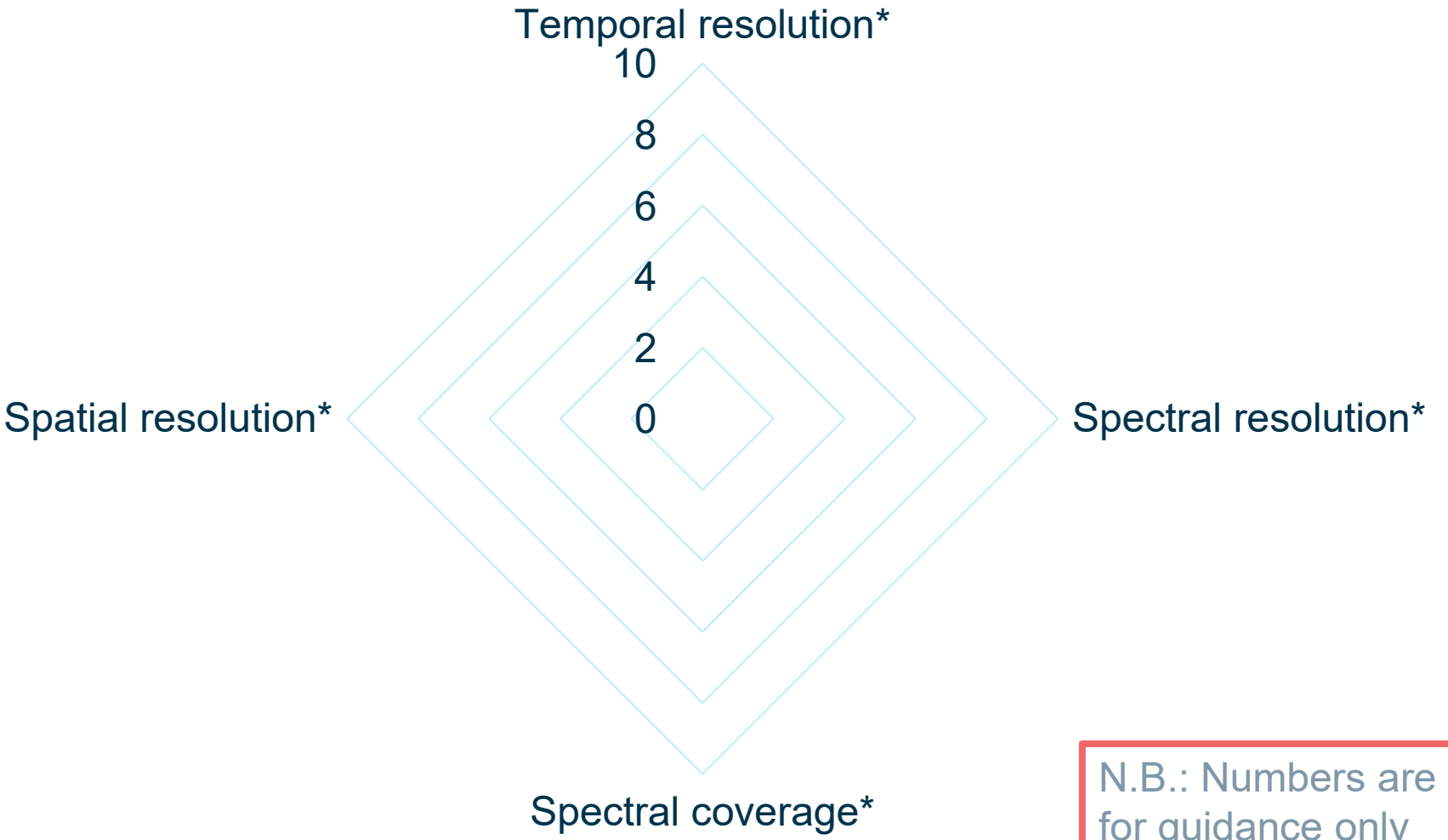
with contributions from Roberto Colombo (UNIMIB), Sara Liburdi (Uni. Sapienza) and Alexander Roessel (ESA)

29/09/2025

ESA-developed Earth Observation Missions



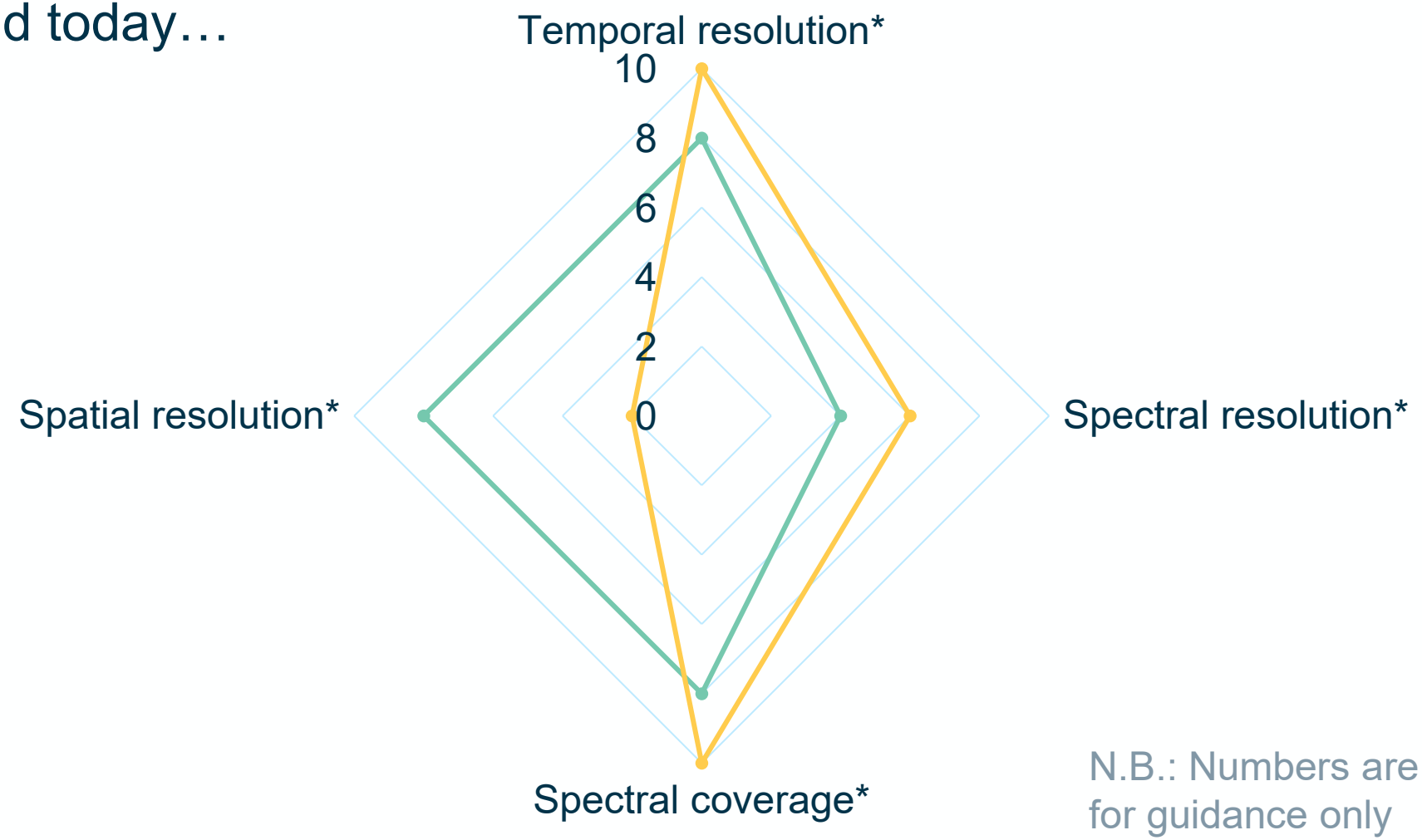
Which one is the Swiss Army Knife?



N.B.: Numbers are arbitrary and for guidance only

Sentinel-2
Sentinel-2 NG
Sentinel-3
Sentinel-3 NGO
CHIME
FLEX
LSTM

Where we stand today…



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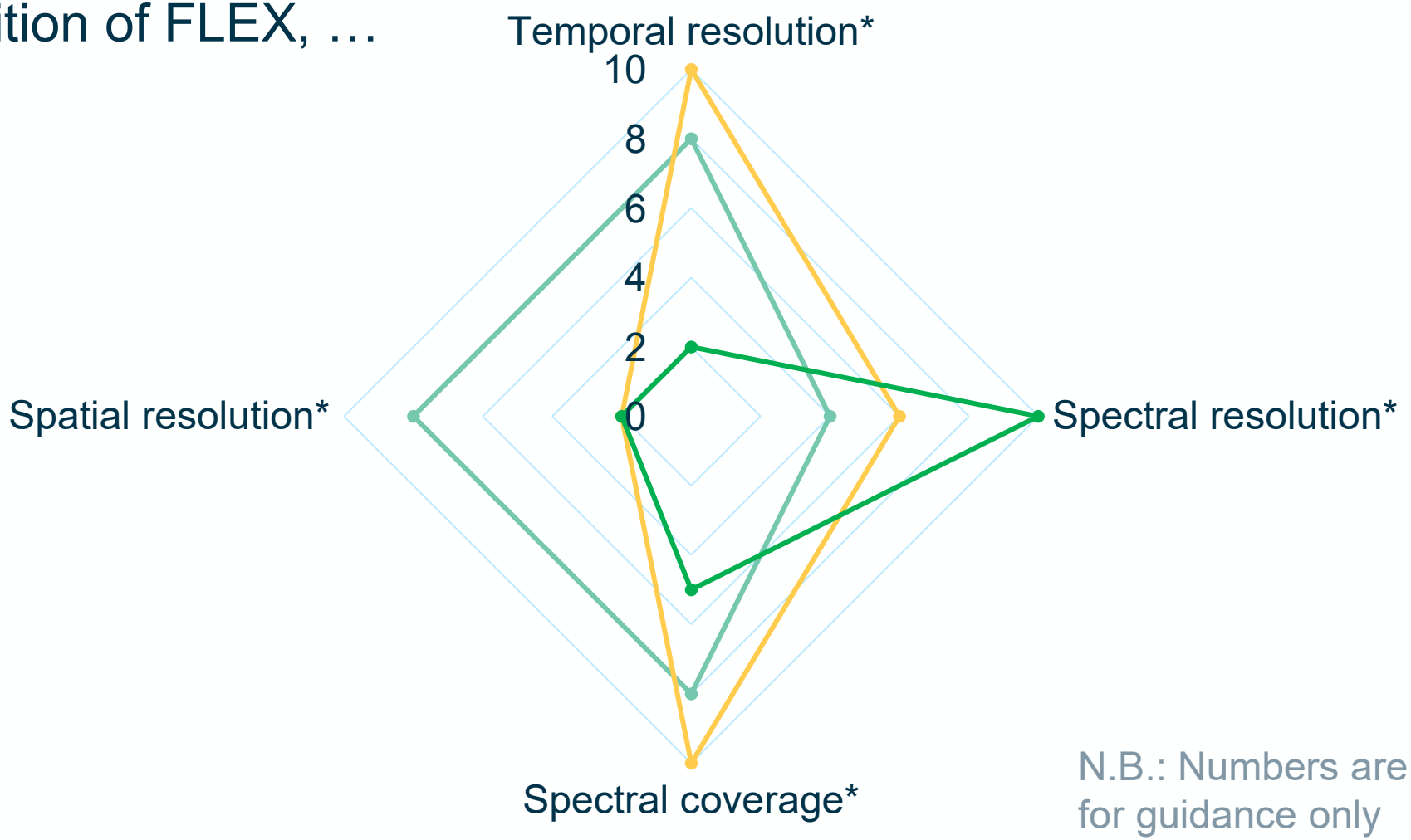
… with the addition of FLEX, …



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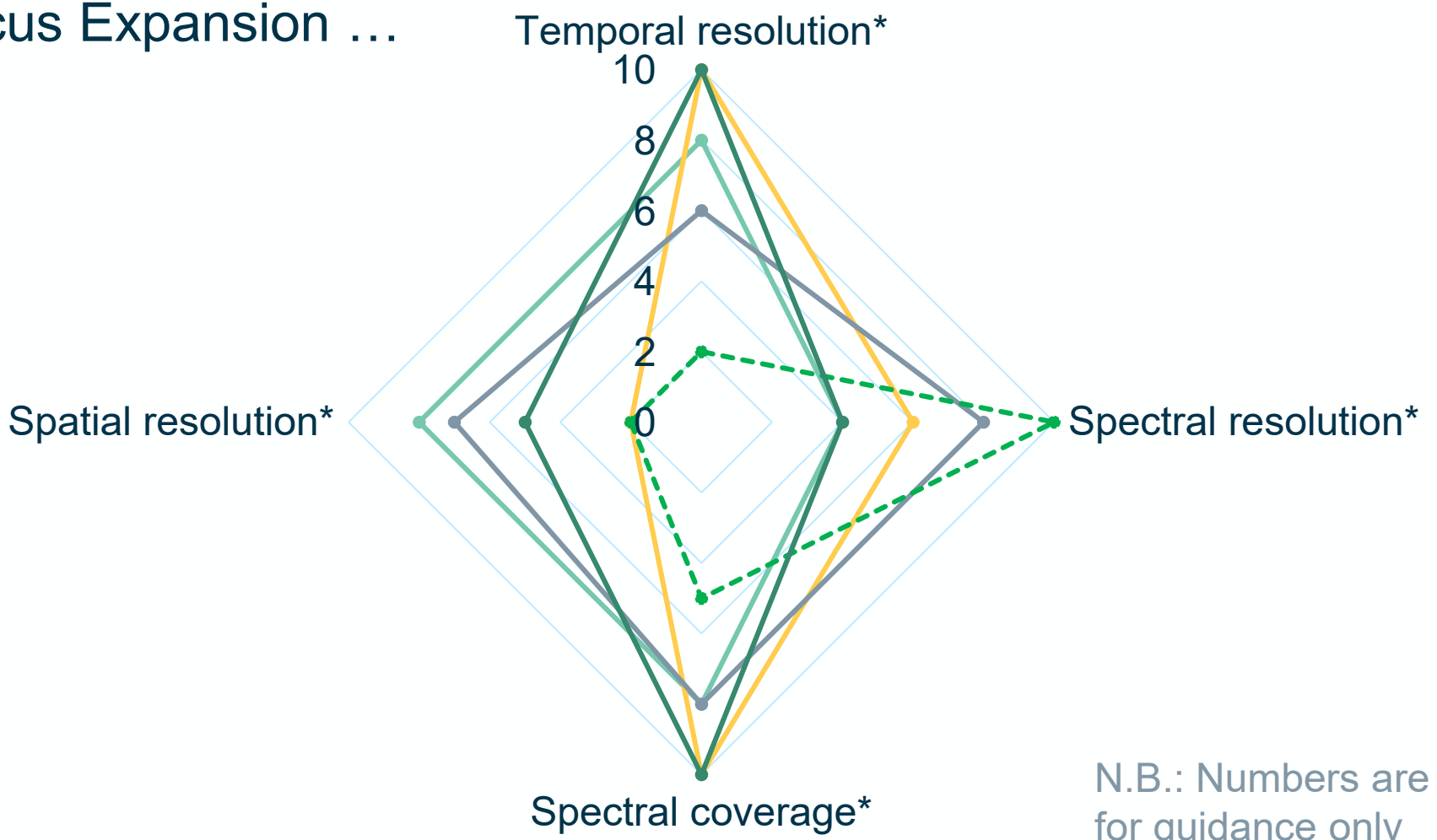
… the Copernicus Expansion …



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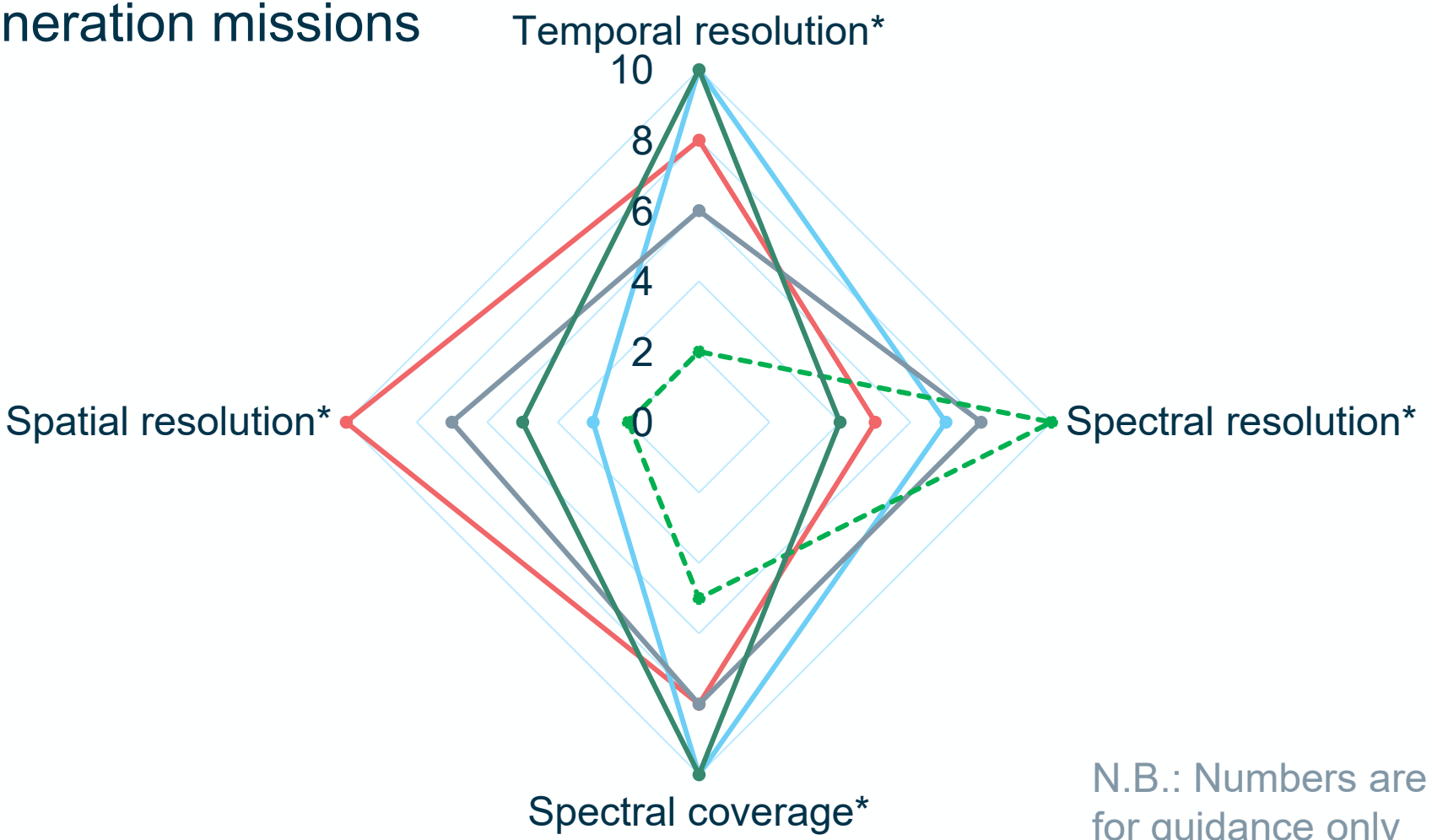
… and Next Generation missions



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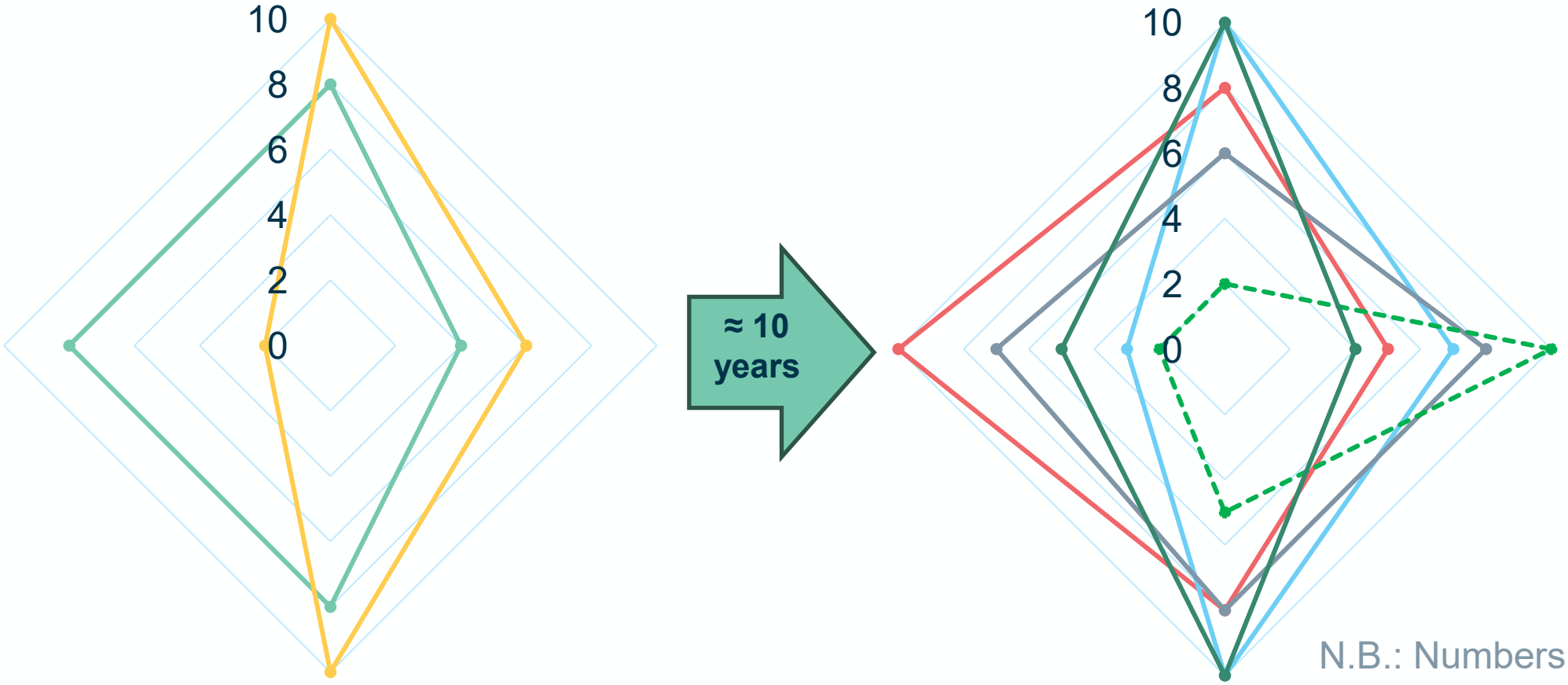

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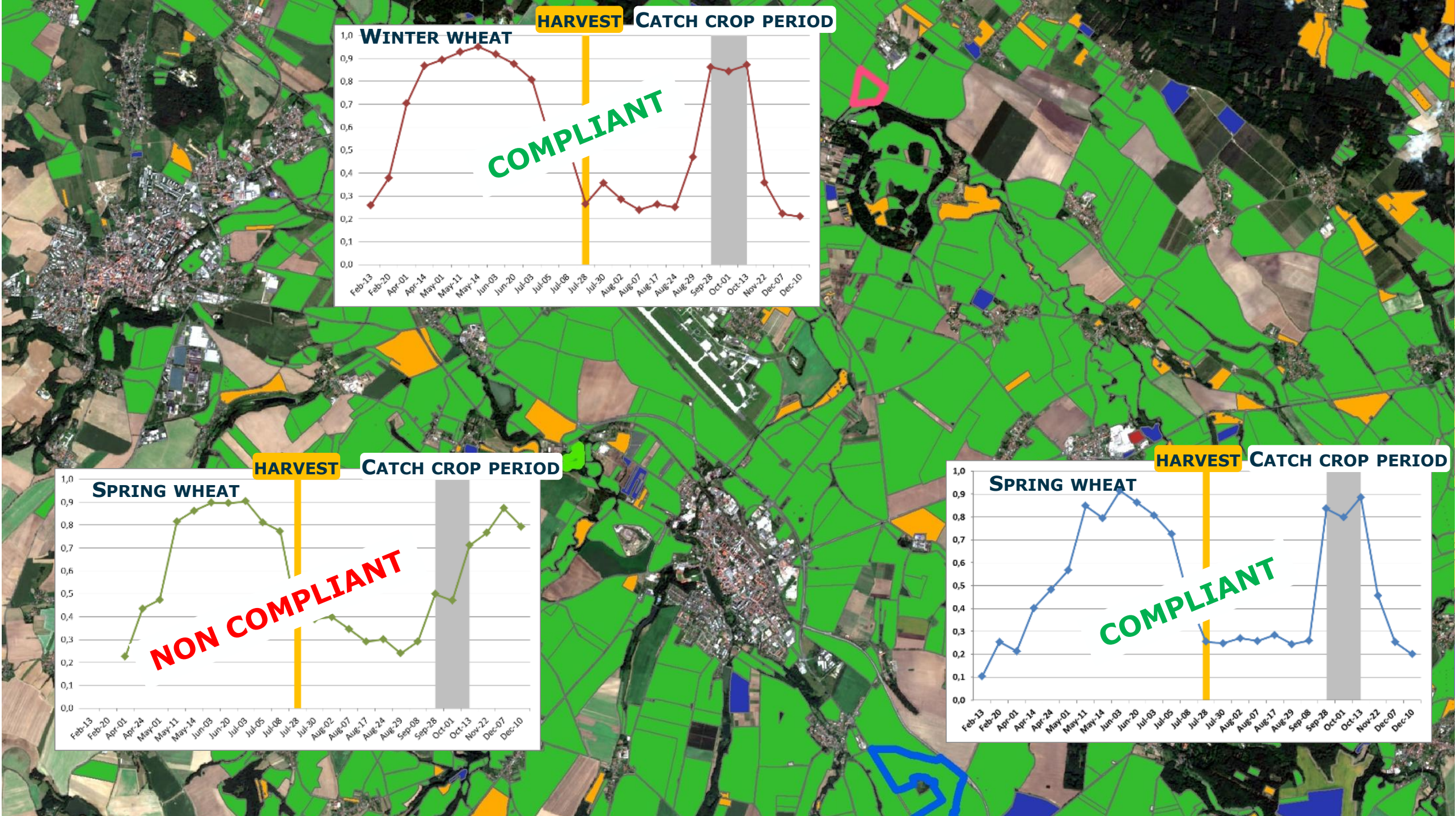
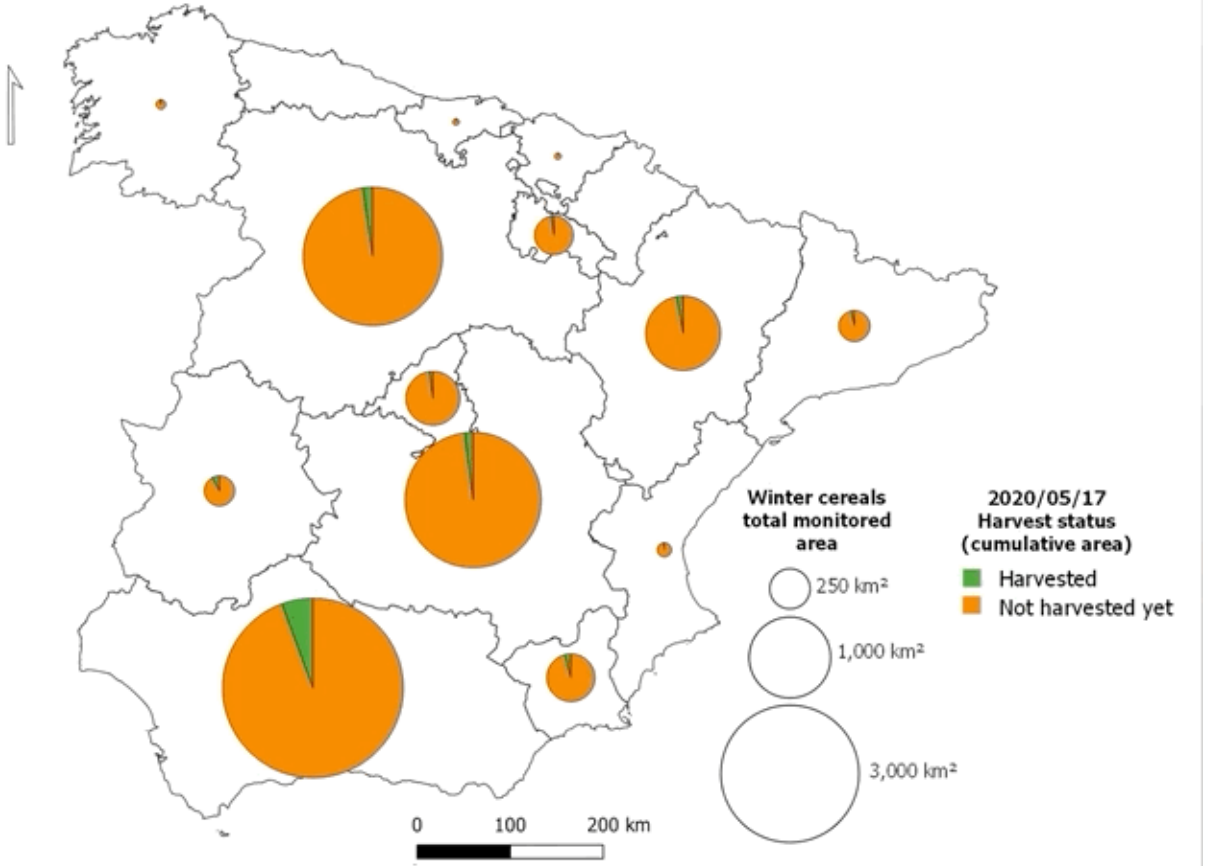
How do we get from data to science and applications?

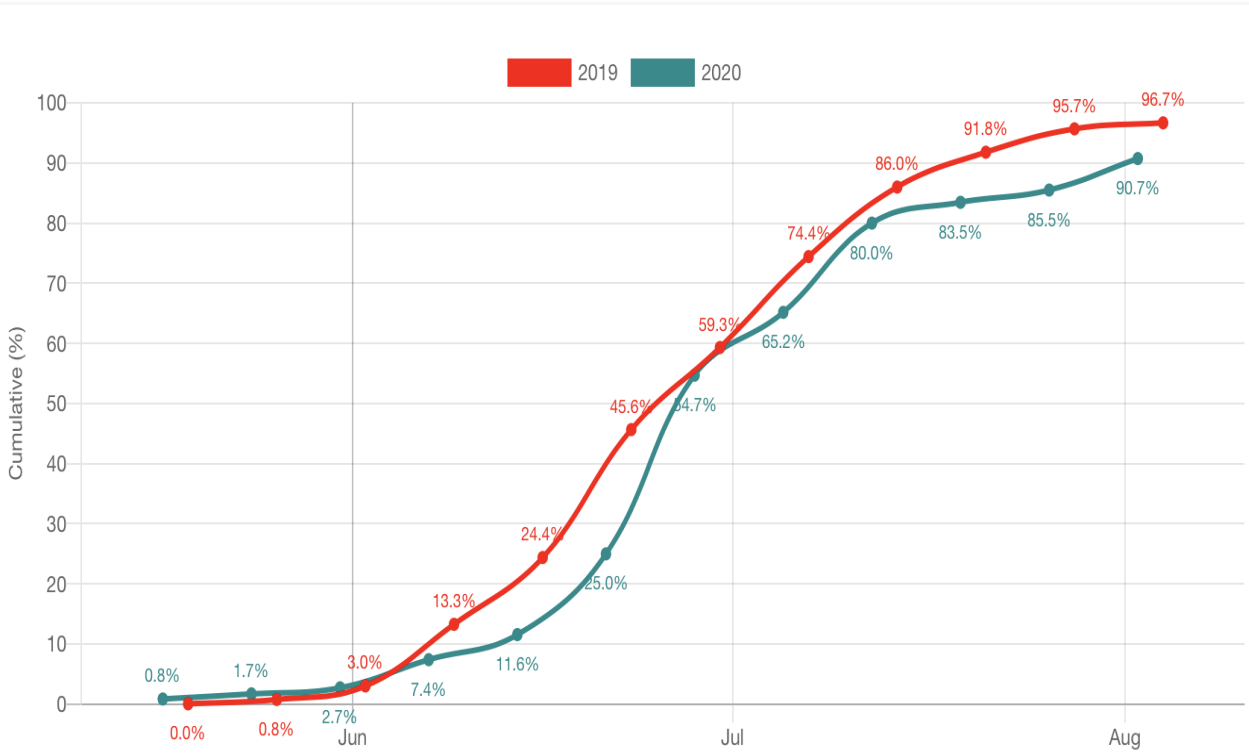

HARVEST
CATCH CROP PERIOD
WINTER WHEAT
COMPLIANT
HARVEST
CATCH CROP PERIOD
SPRING WHEAT
NON COMPLIANT
HARVEST
CATCH CROP PERIOD
SPRING WHEAT
COMPLIANT

Monitoring of Agricultural Practices

COVID19 Impact on Agricultural Production

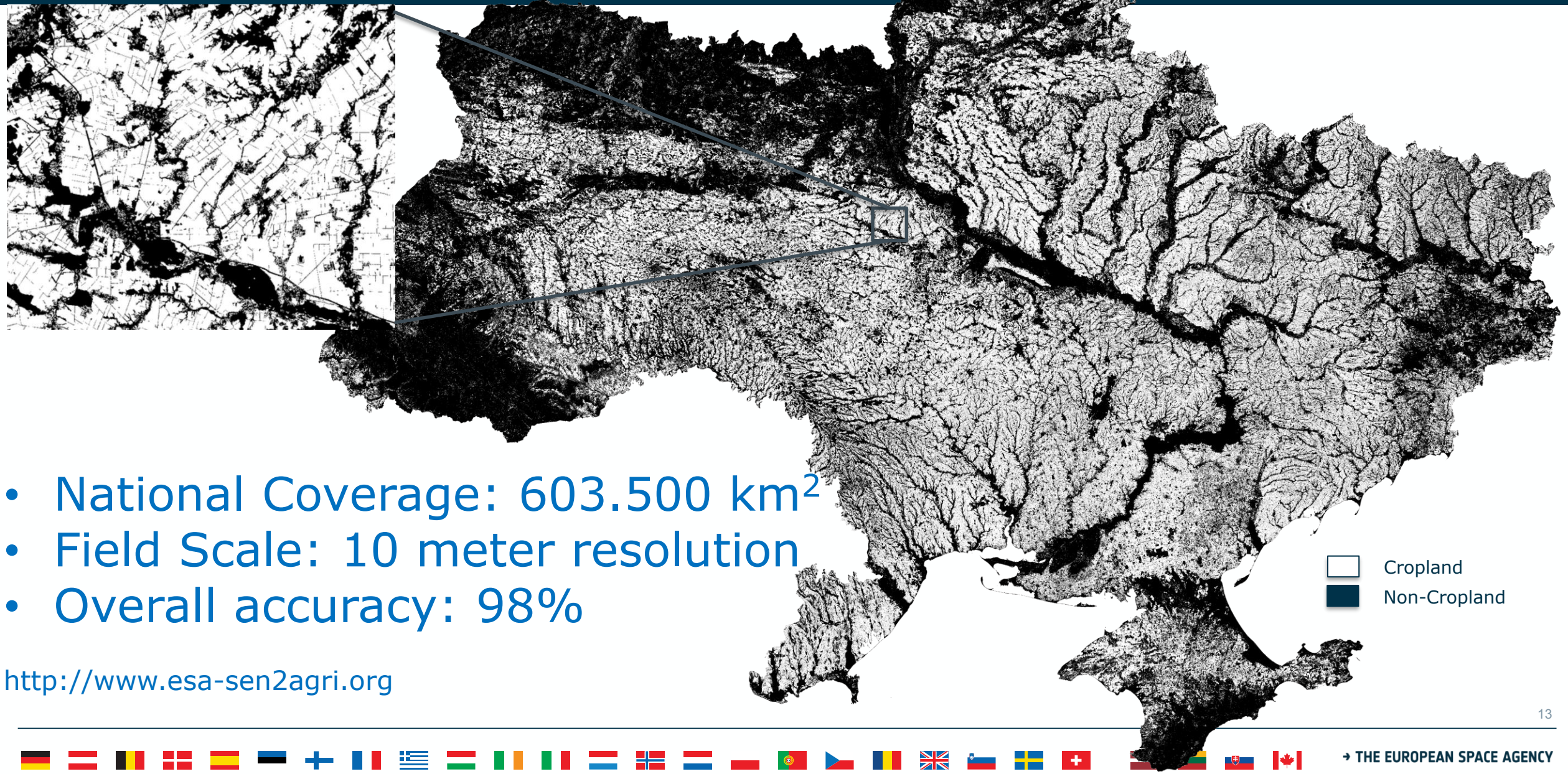
- Regional statistics of winter cereal harvesting, Spain 2020 – updated weekly
- Harvested area derived from Sentinel-1/2, Landsat





COVID19 EO Dashboard: https://race.esa.int/?poi=ES41-E10a7

Ukraine – National Crop Mask



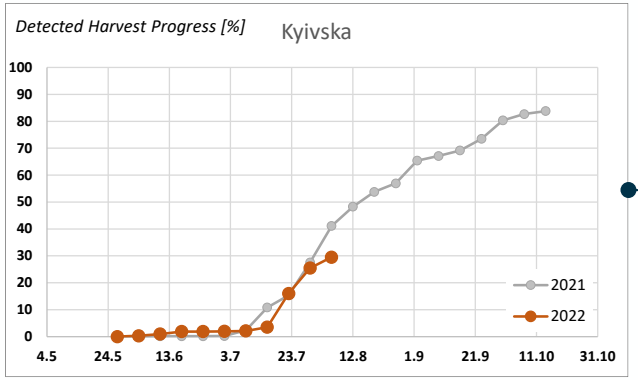
- National Coverage: 603.500 km^2
- Field Scale: 10 meter resolution
- Overall accuracy: 98%

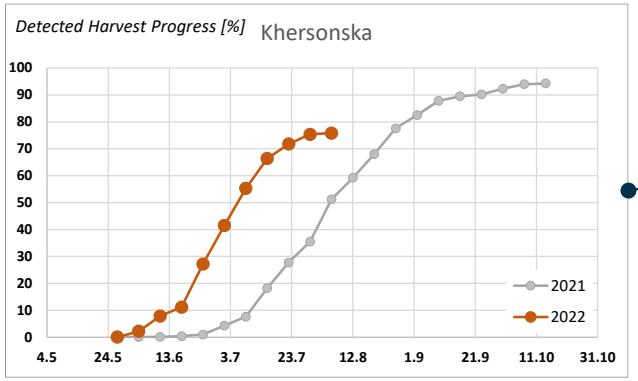
http://www.esa-sen2agri.org

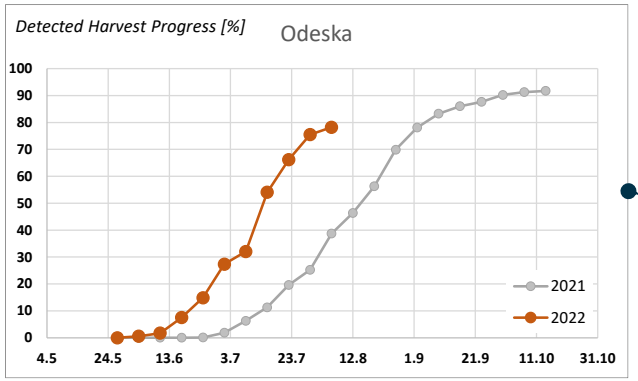
Year-to-year comparison of harvest progress

Winter Wheat

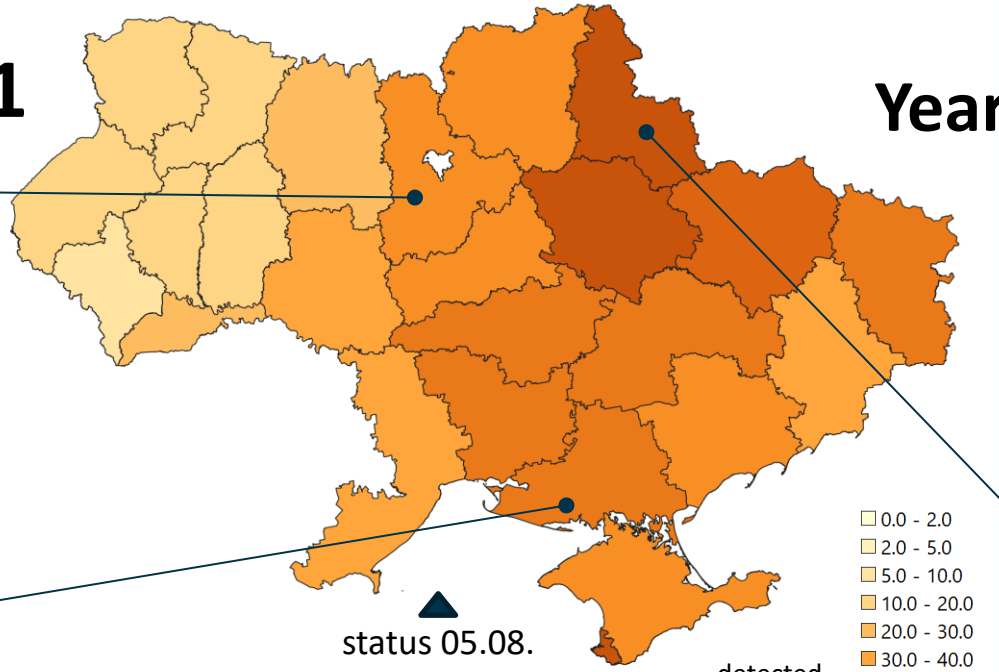
Ukraine





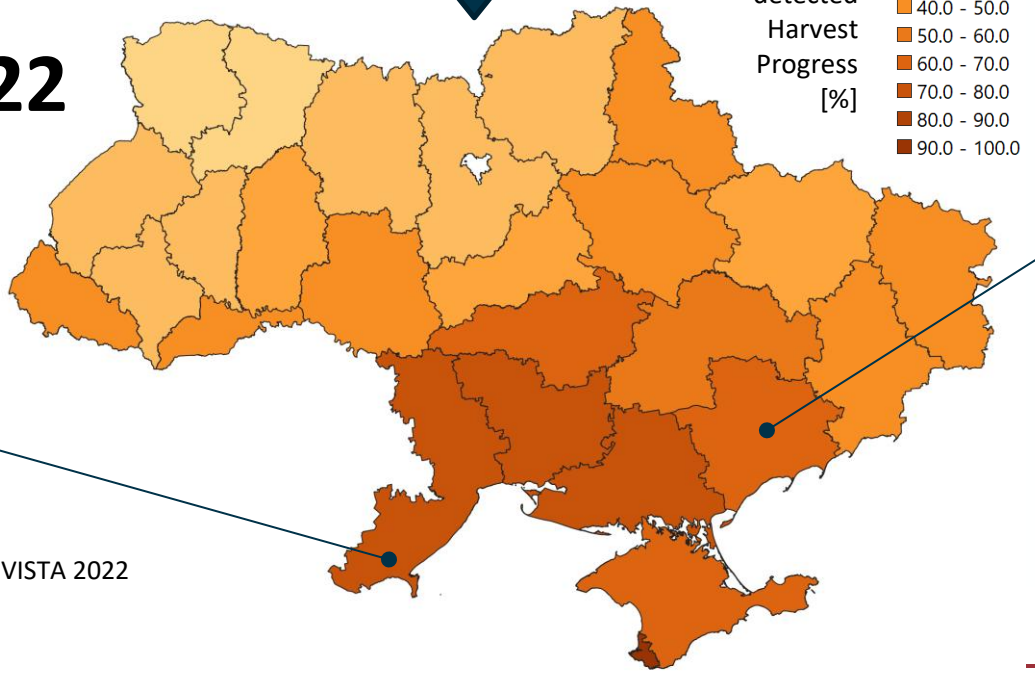


2021



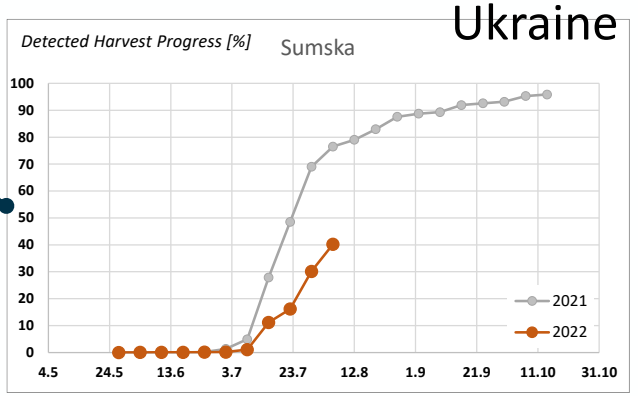
status 05.08.

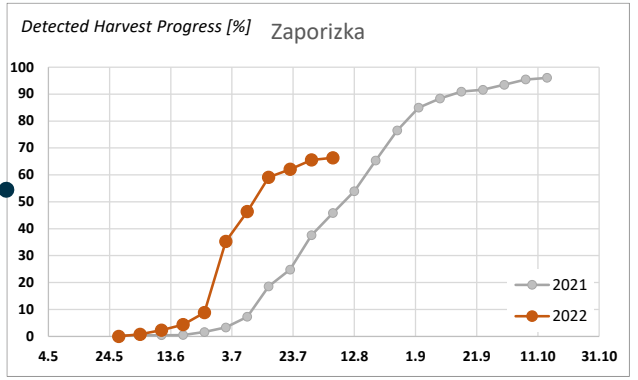
2022



detected Harvest Progress [%]

- 0.0 - 2.0
- 2.0 - 5.0
- 5.0 - 10.0
- 10.0 - 20.0
- 20.0 - 30.0
- 30.0 - 40.0
- 40.0 - 50.0
- 50.0 - 60.0
- 60.0 - 70.0
- 70.0 - 80.0
- 80.0 - 90.0
- 90.0 - 100.0

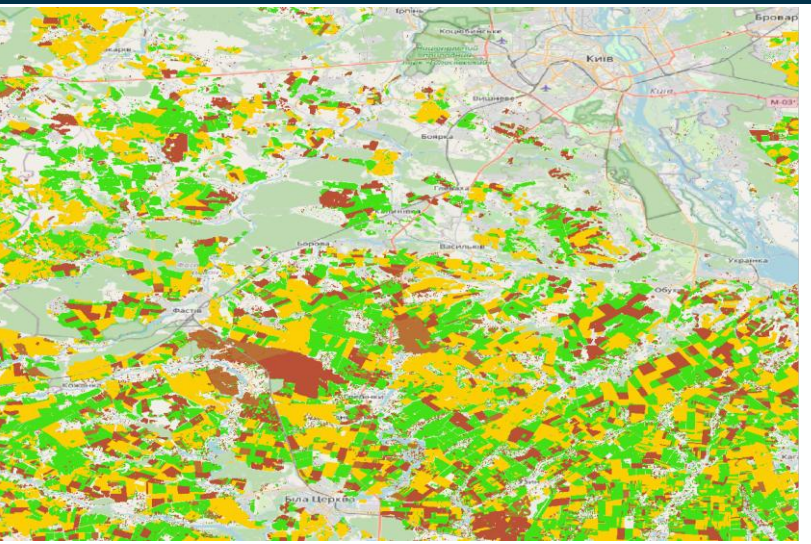




Results based on VISTAs Ypsilon and Sentinel-1 Coherence analysis

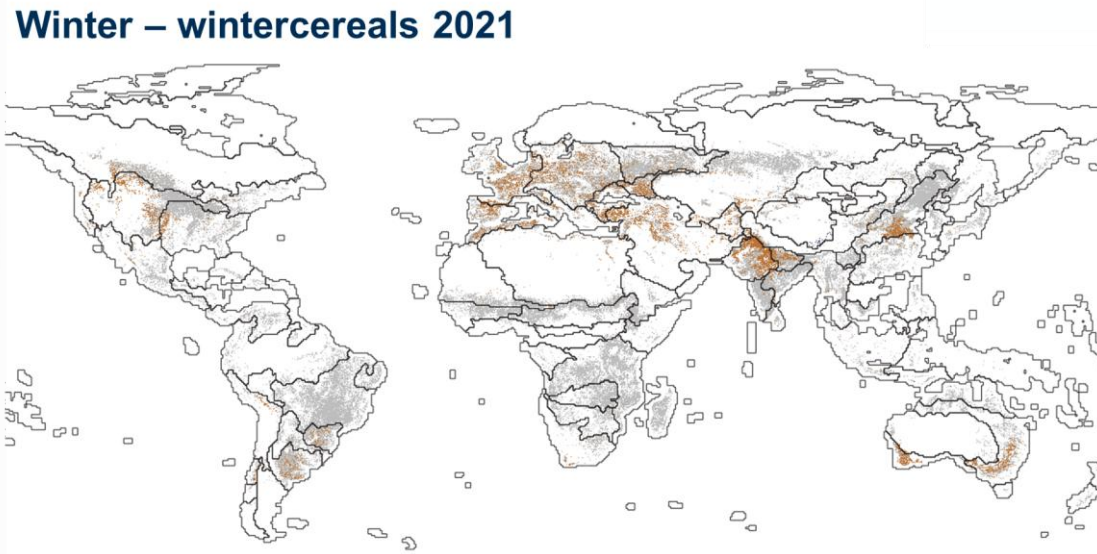
food security tep

Global Crop Mapping at Field Scale



Annual Cropland
Winter Cereals
Spring Cereals
Summer maize

WorldCereal



Demonstrate timely monitoring of global agricultural productive area for improved international & national reporting as well as market transparency.

- **mapping at 10 m** the global extent of **annual cropland** and two of the major staple crops **wheat and maize** on a seasonal basis
- **Core users:** FAO, GEOGLAM, AMIS
- Global release planned – November 2022

GEOGLAM Global Agricultural Monitoring

Where do we start?

No matter the application, no matter the sensor, 99.9% of the time you will:

- Get access to a remote sensing product
- Apply a model
- Interpret the results

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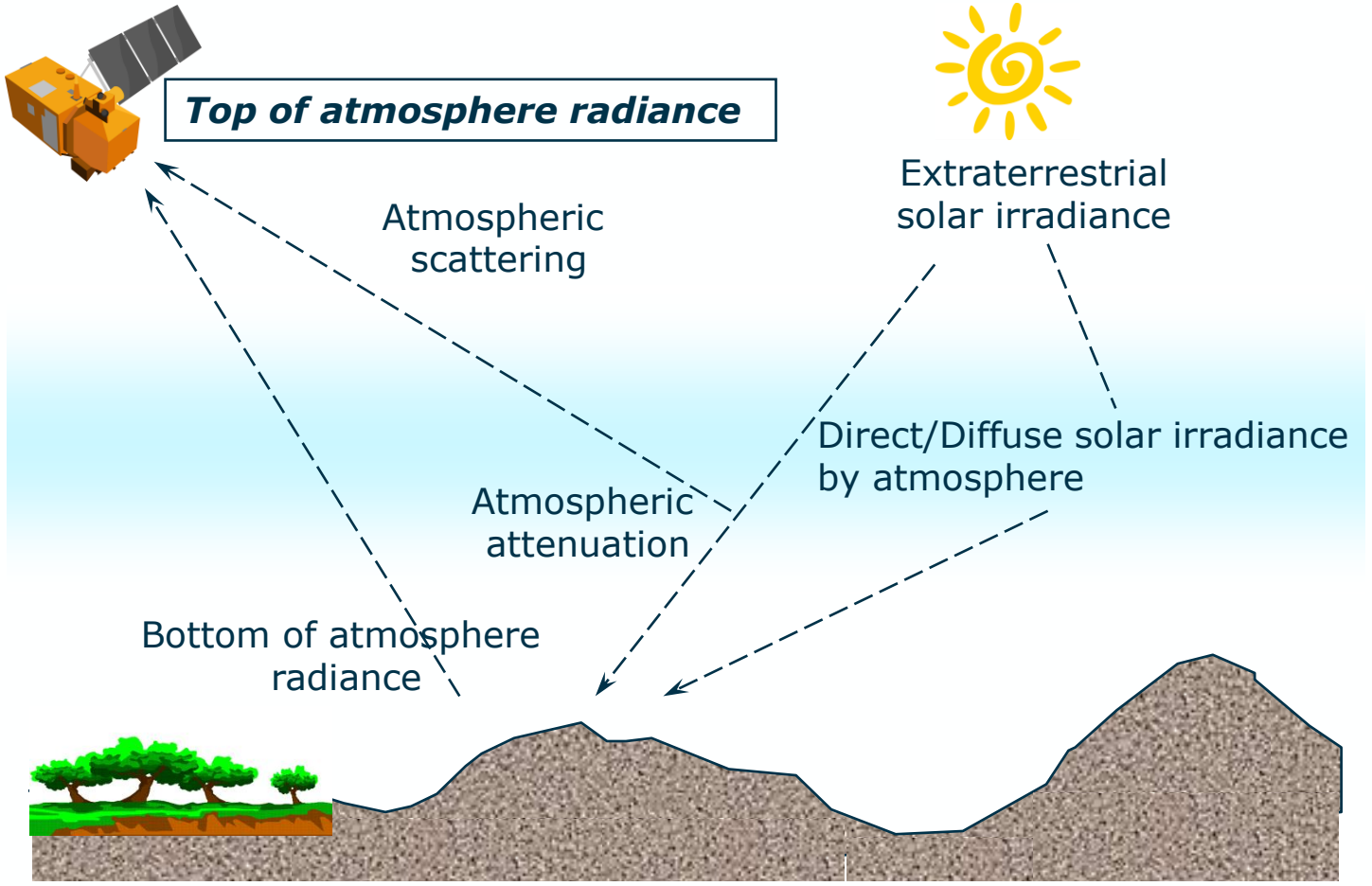

Where do we start?

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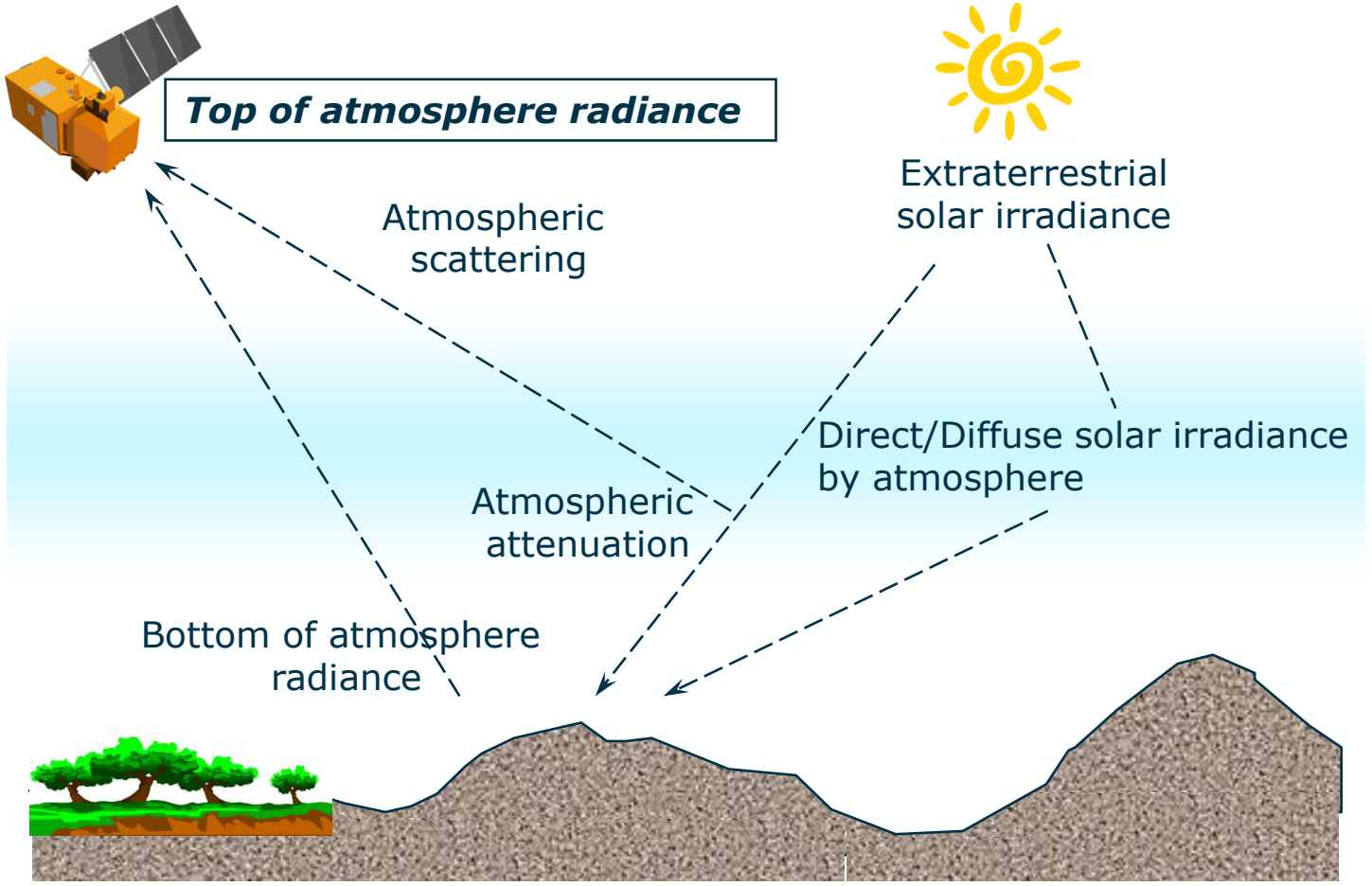
In optical satellite remote sensing (in general):

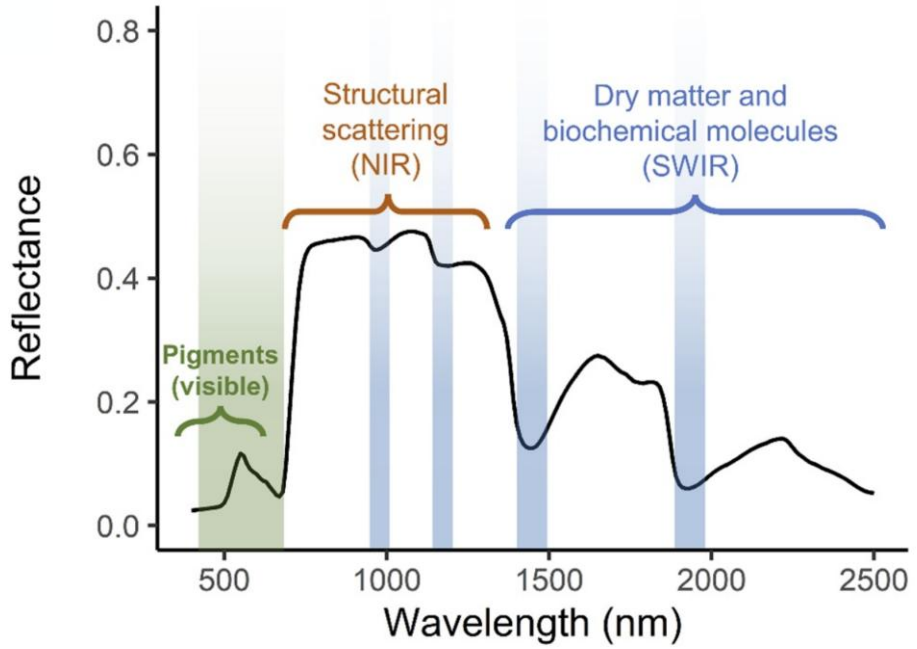
- Level 1 products are top-of-atmosphere (TOA; i.e. at sensor) products:
  - TOA radiance (e.g. S3 L1B)
  - TOA reflectance factors (e.g. S2 L1C)
- Level 2 products are bottom-of-atmosphere (BOA) products (i.e. geophysical surface properties):
  - BOA reflectance factors (e.g. S2 L2A)



BOA Reflectance Factors

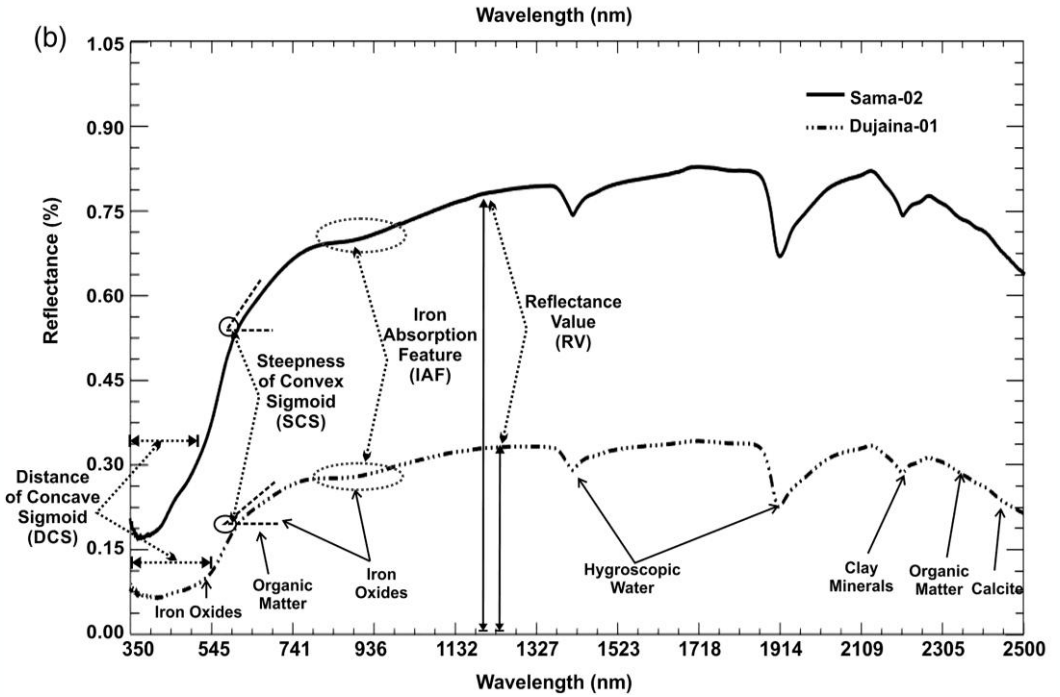
Arguably, the most relevant product level for the remote sensing of soil and vegetation monitoring (and much more) is **BOA hemispherical-directional reflectance factors (HDRF)**

N.B.: for simplicity, HDRF is often referred to as “reflectance”, but keep in mind not all “reflectances” are the same >> Schaepman-Strub et at. (2006) doi:10.1016/j.rse.2006.03.002



Poulter et al (2023)

https://doi.org/10.1029/2022JG006935

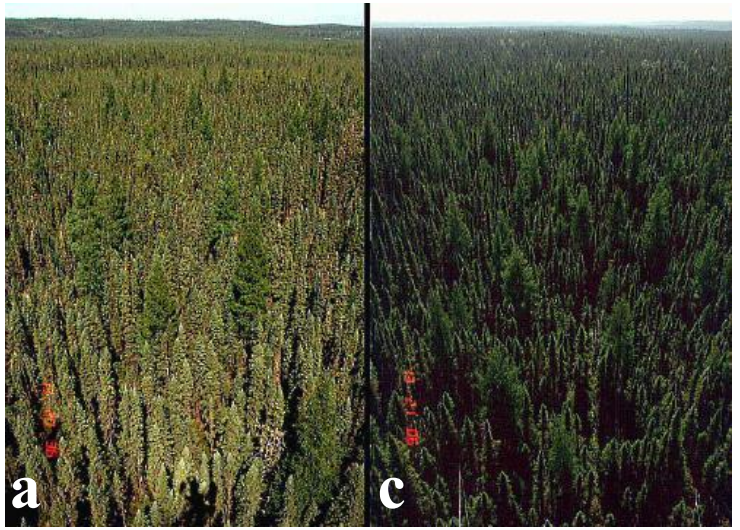


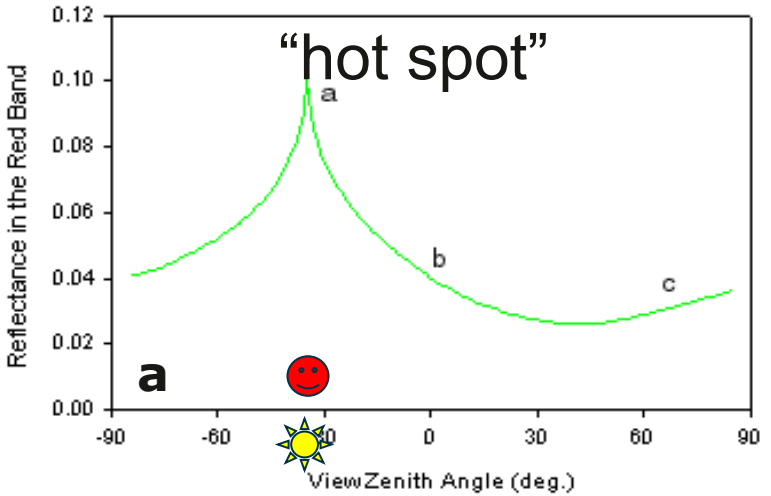
Sahwan et al (2020)

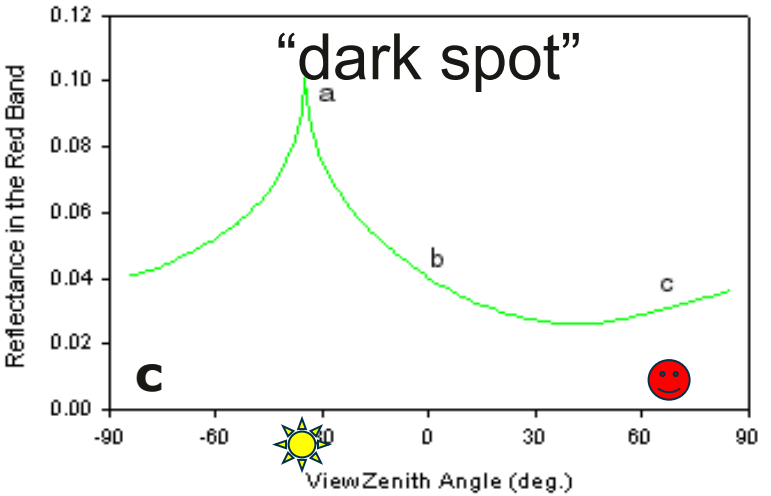
https://doi.org/10.1111/ejss.12986

BOA Reflectance Factors

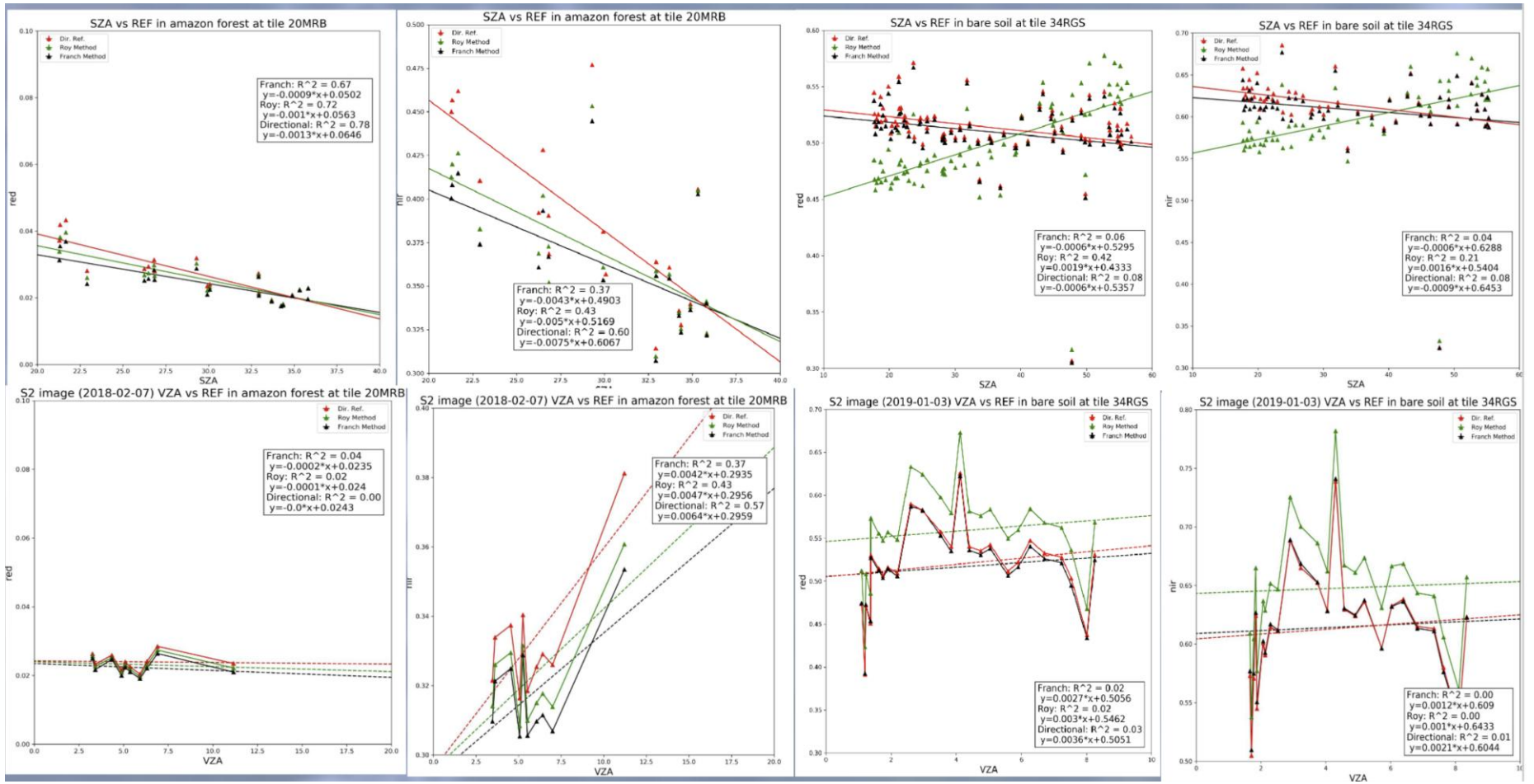
- Most surfaces, including vegetation, present a highly anisotropic behaviour >> the illumination and observation (view) angles impact heavily the remotely sensed radiance







Dealing with anisotropy: normalisation attempts



Moletto-Lobos et al. (2022) RAQRS'VI
Franch et al. (2019) https://doi.org/10.3390/rs11060632

Let’s talk about resolution(s)

- Spatial/Geometric Resolution
- Temporal Resolution
- Spectral Resolution
- Radiometric Resolution and SNR

The +1:

- Angular Resolution

The +2:

- Spectral coverage

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The +1:

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The +2:

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Spatial / Geometric Resolution

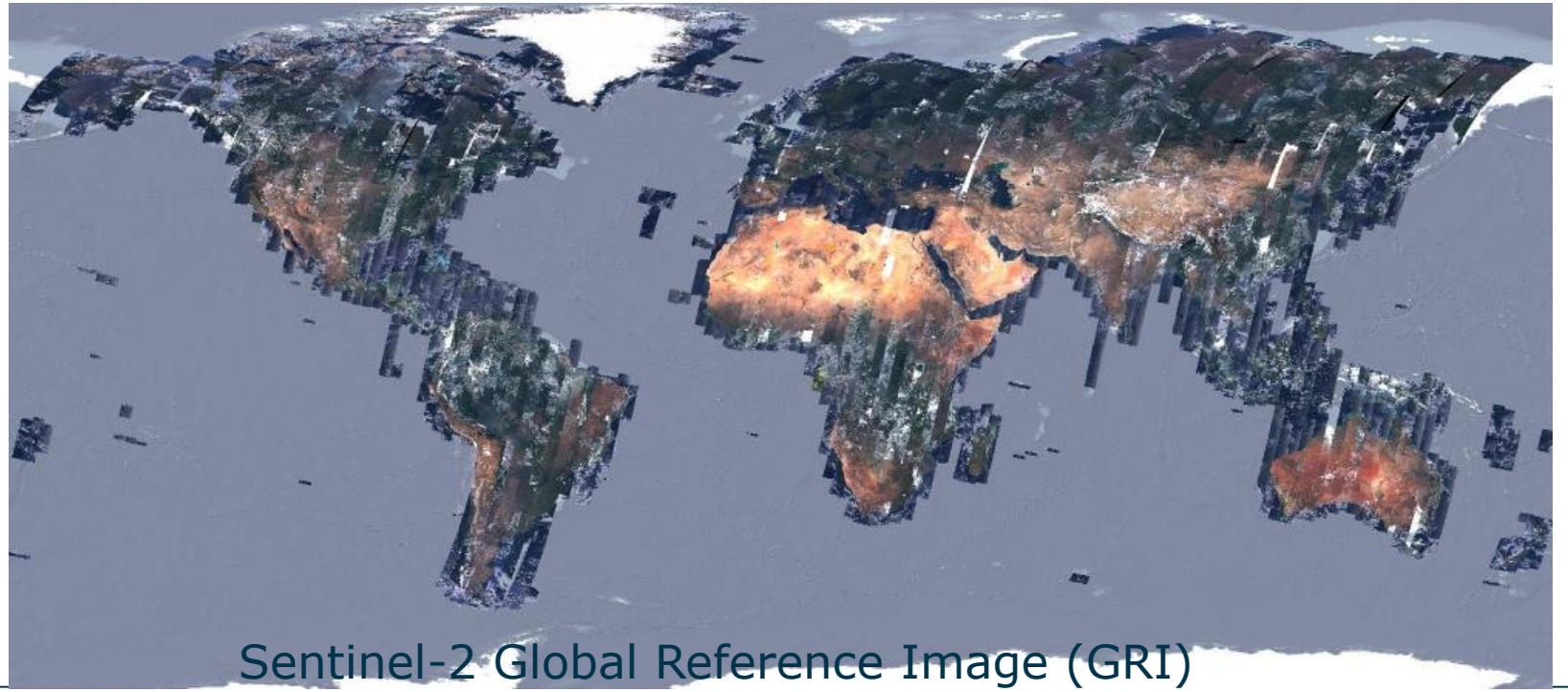
What is the spatial resolution of S2?

Spatial / Geometric Resolution

Spatial / Geometric Resolution

Important notes:

- The ground sampling distance (GSD) does not tell the whole story
- Modulation transfer function (MTF) at Nyquist frequency tells you how much spatial contrast the system can resolve
- Don’t forget about geolocation!



Sentinel-2 Global Reference Image (GRI)

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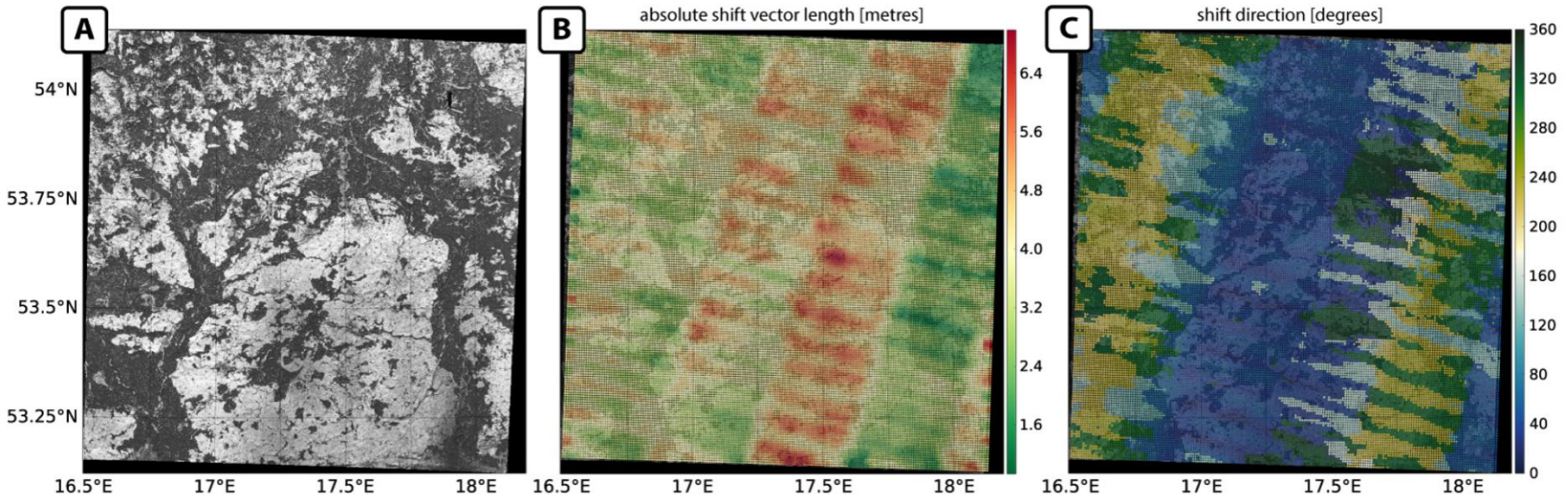


AROSICS

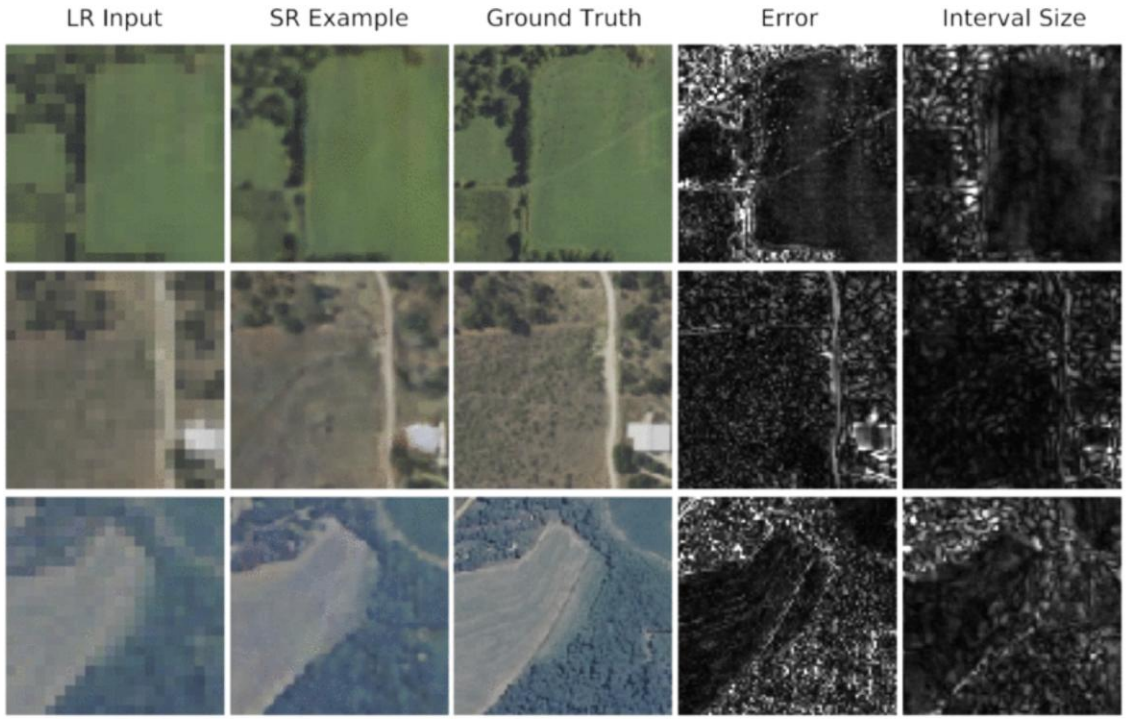
AROSICS repository

Scheffler et al. (2017) https://doi.org/10.3390/rs9070676

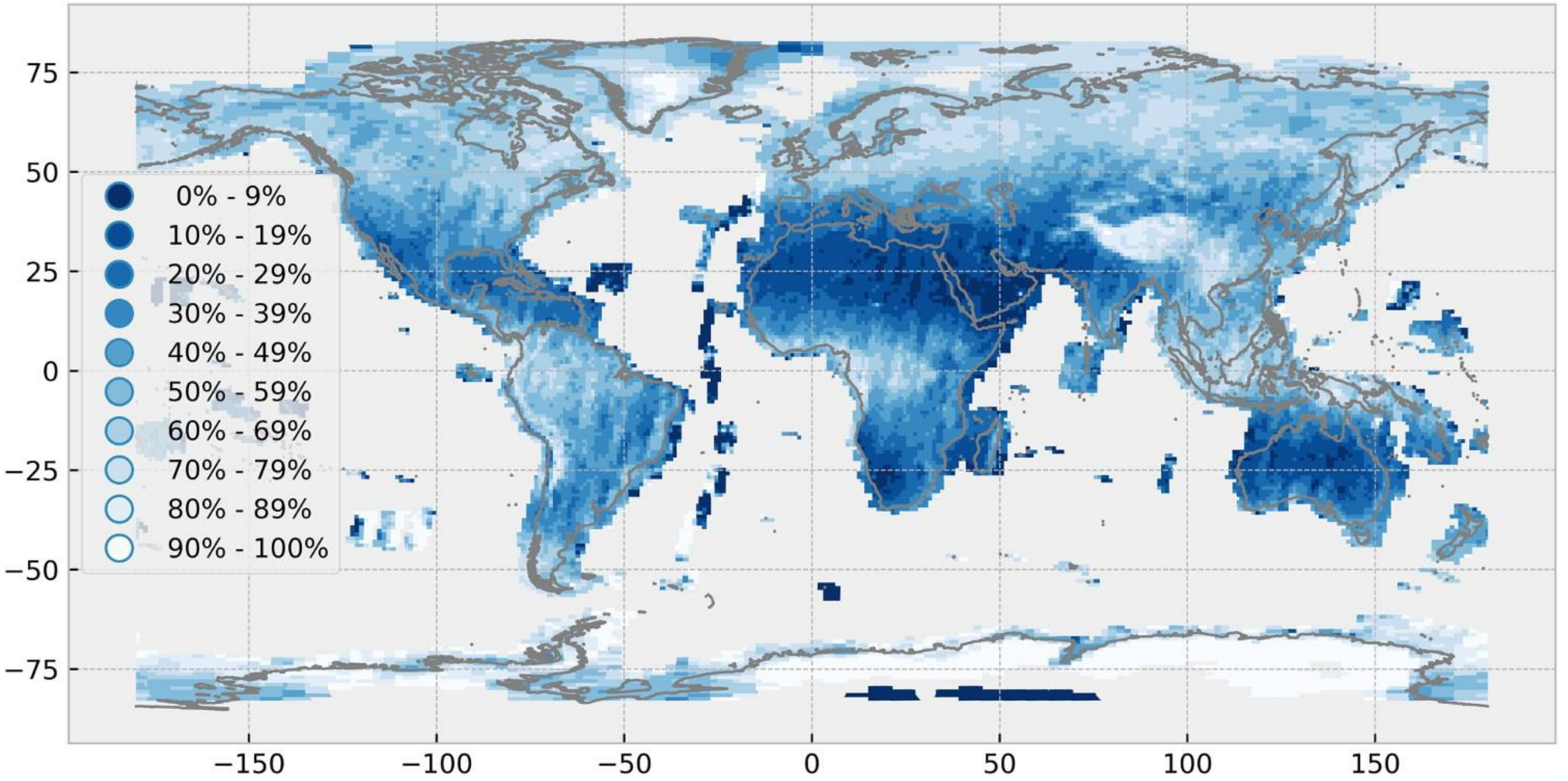
Spatial / Geometric Resolution

Important notes:

- Sharpening / super resolution techniques can be useful, particularly for target detection, but shall be used with care for quantitative retrievals
- Recently, SR techniques with associated uncertainties have been proposed >> more transparent, allows a more informed decision by the final user (see e.g. Donike et al, 2025; https://doi.org/10.1109/JSTARS.2025.3542220)

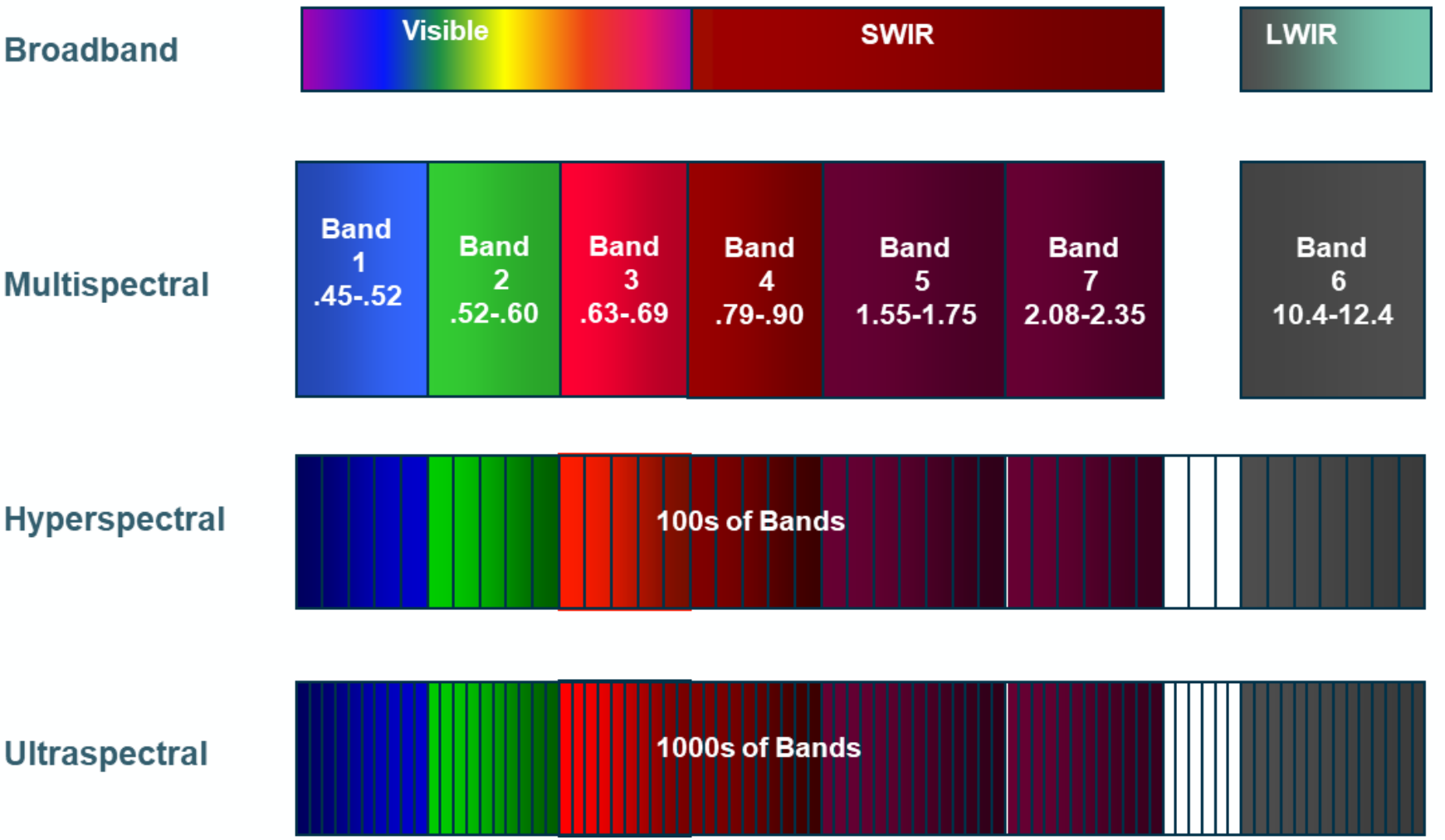


Temporal Resolution



Sudmanns et al. (2019) https://doi.org/10.1080/17538947.2019.1572799

Spectral Resolution



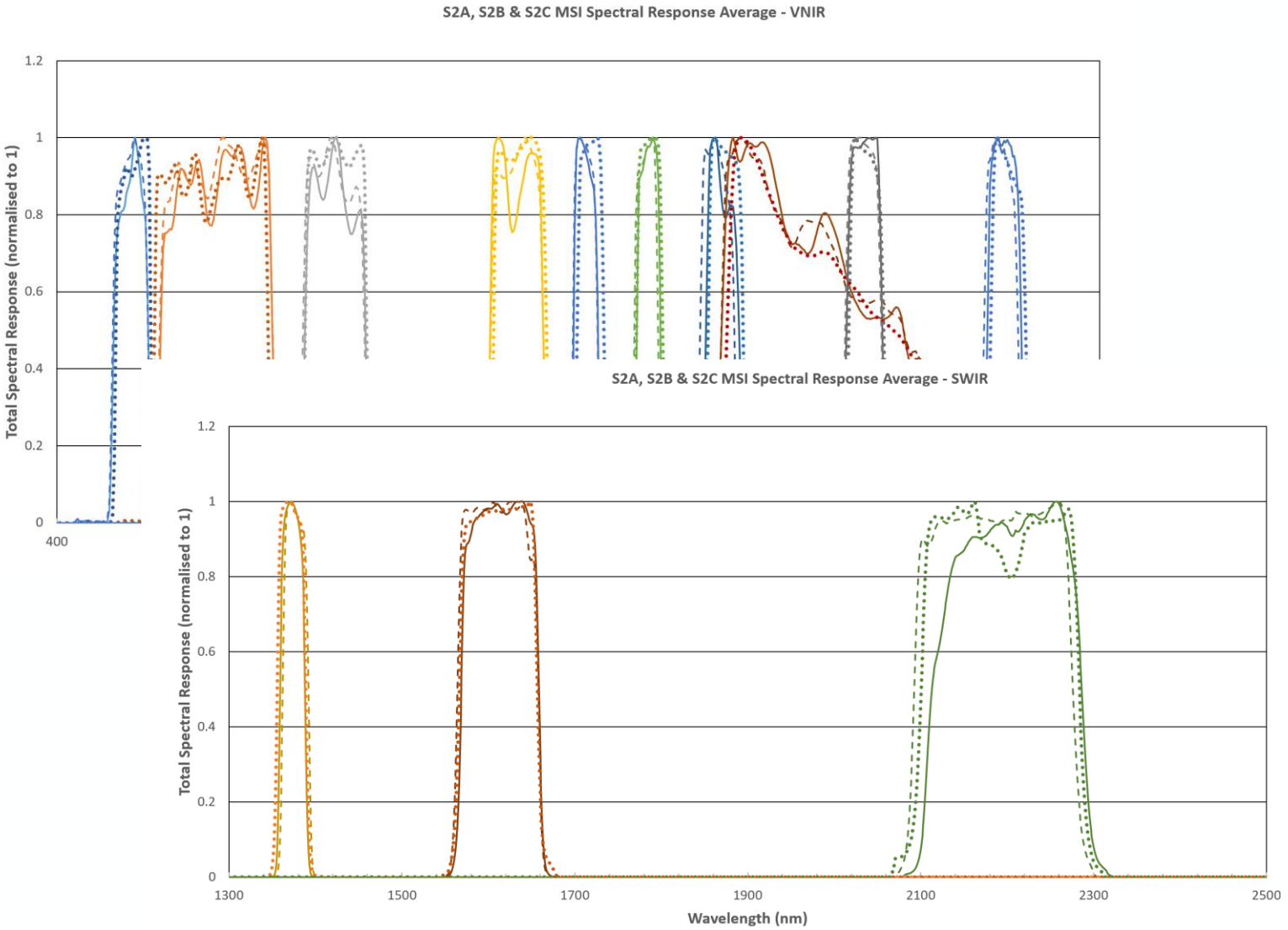
Spectral Resolution

What is the spectral resolution of S2?

Describing spectral bands (multispectral)

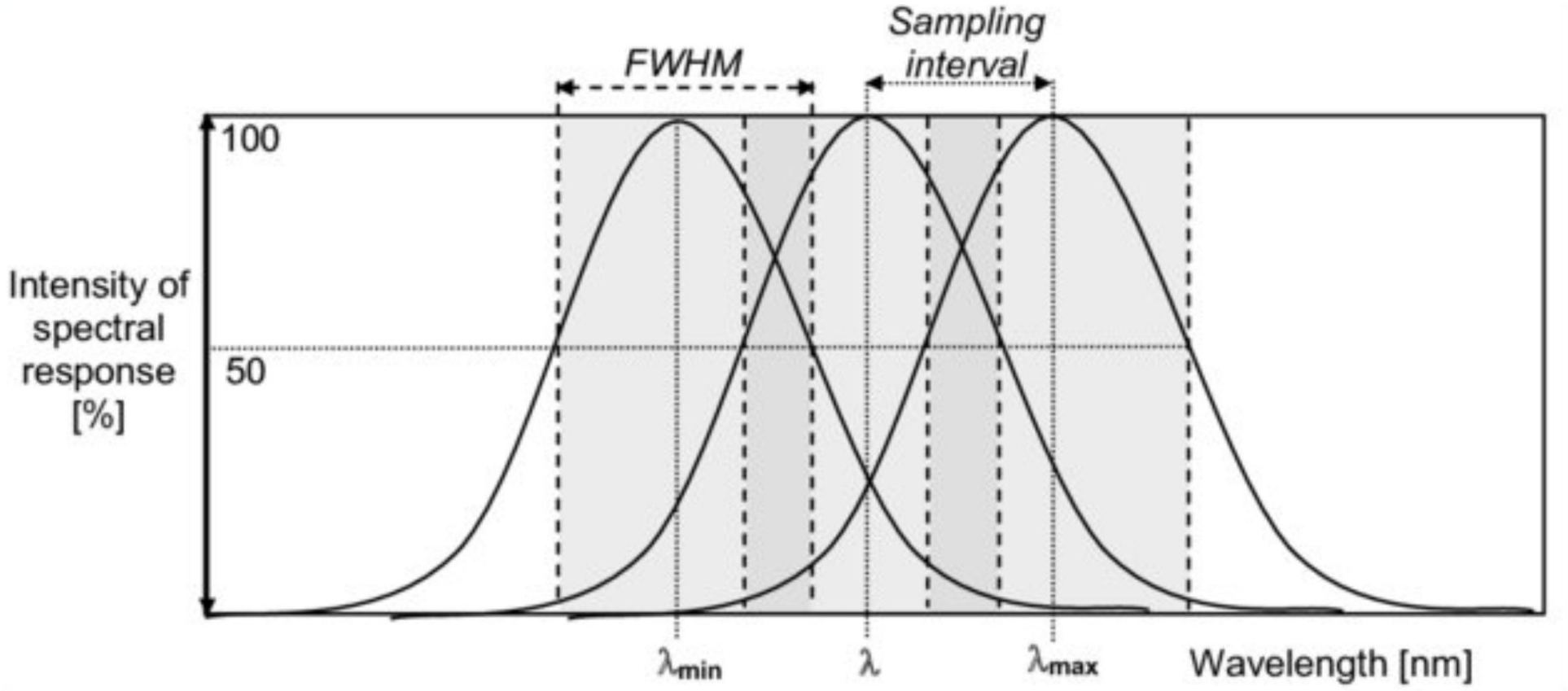
Spectral Response Functions (SRFs) are (often) provided by space Agencies >> use them!

Bandwidth and central wavelength alone do not represent the actual sensitivity of the instrument to the different wvl.



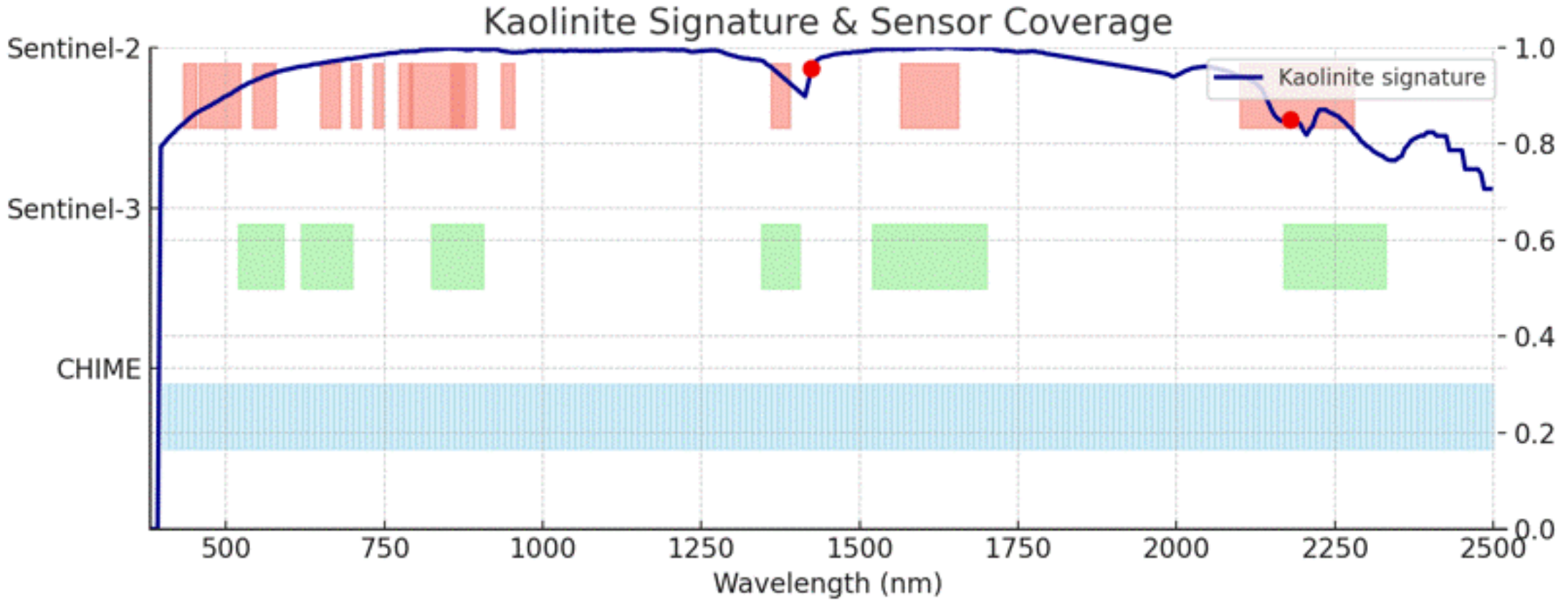
Describing spectral bands (hyperspectral)

Full-width at half maximum (FWHM) and spectral sampling interval (SSI) are often used to describe SRFs in hyperspectral data >> often assumed to be gaussian

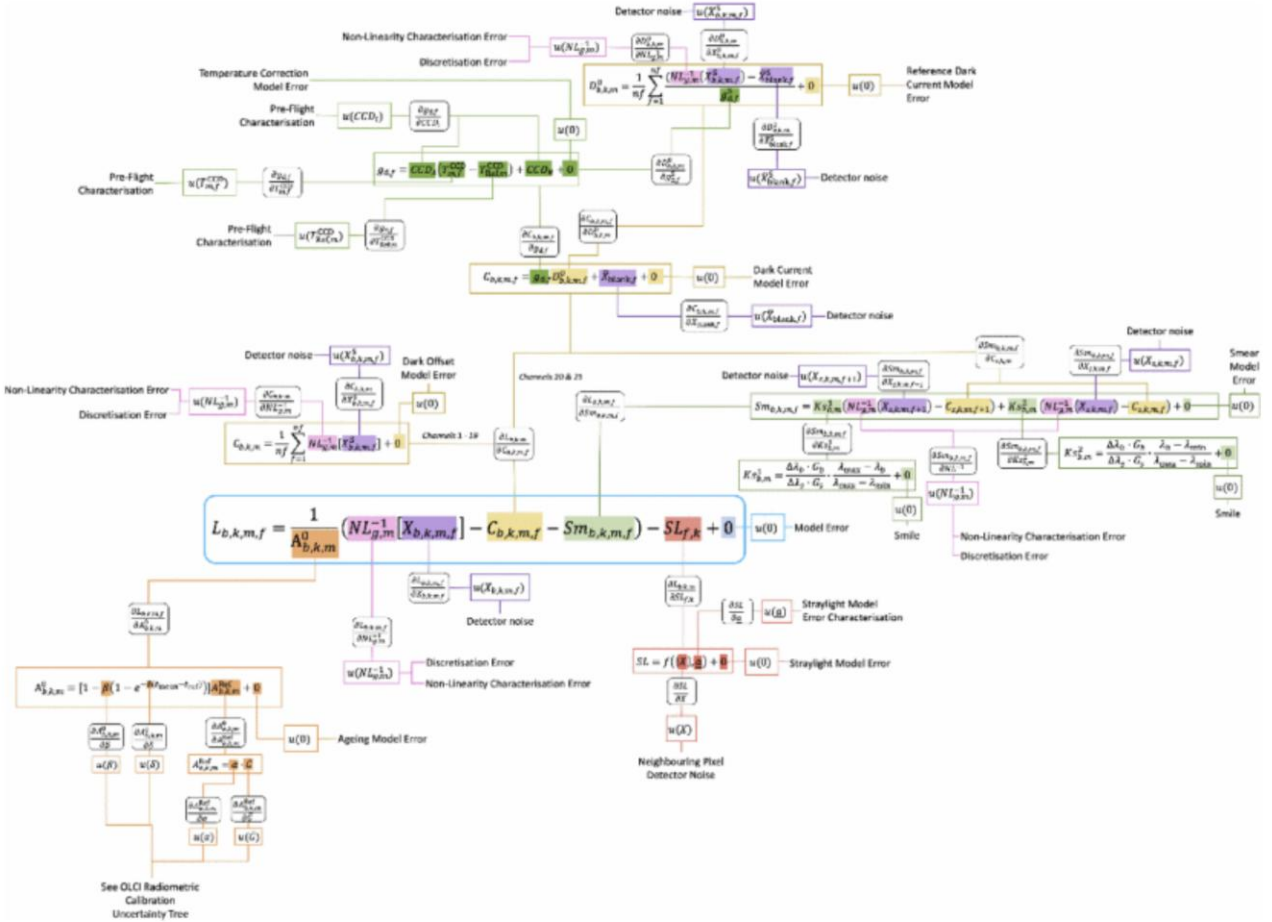


Malenovsky (2006) PhD Thesis

Hyperspectral reflectance



Uncertainties in RS Products: let's start early on!



Uncertainties in RS Products: let's start early on!

remote sensing

MDPI

Article

A Radiometric Uncertainty Tool for the Sentinel 2 Mission

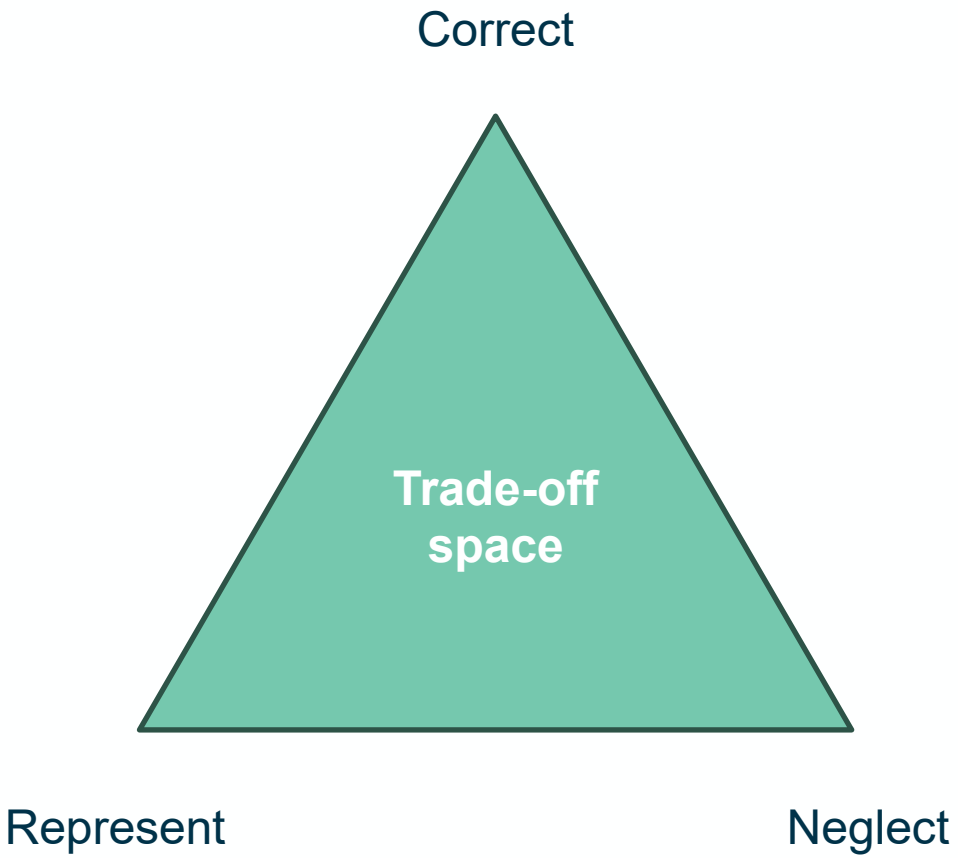
Javier Gorroño [1,2,*], Norman Fomferra [3], Marco Peters [3], Ferran Gascon [4], Craig I. Underwood [2], Nigel P. Fox [1], Grit Kirches [3] and Carsten Brockmann [3]

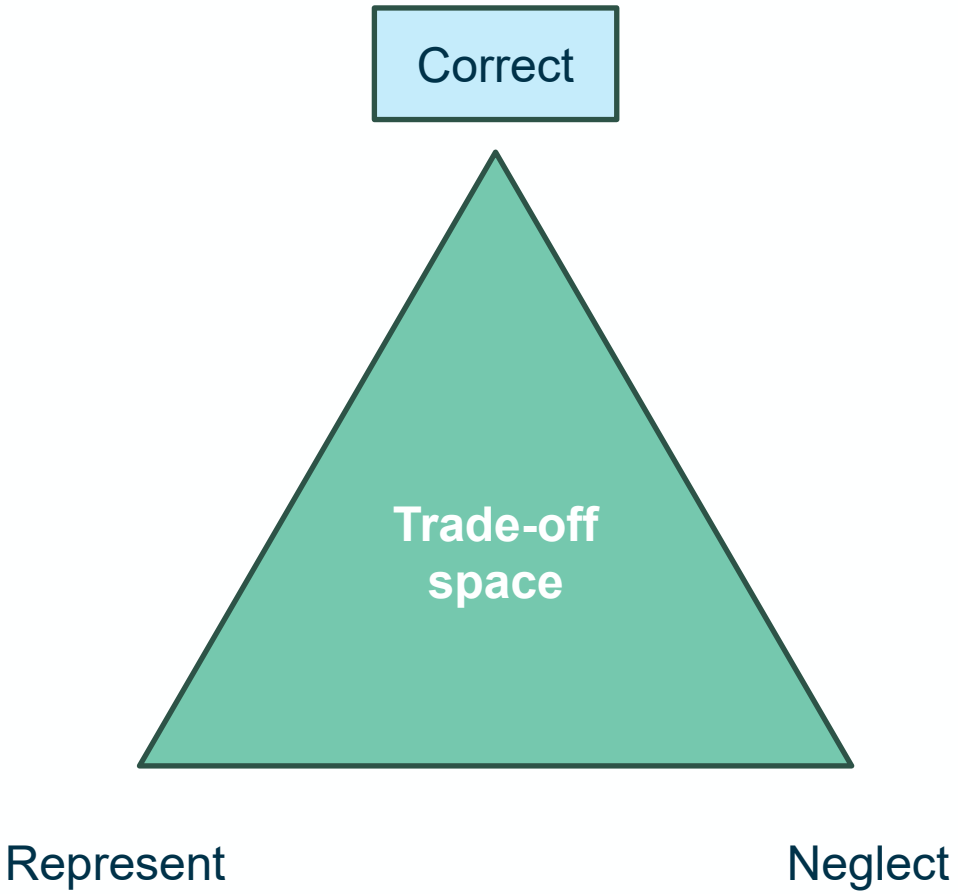
[Sentinel-3 OLCI Products]

Element Name	Description
Manifest.safe	Sentinel-SAFE product manifest
Oa##_radiance.nc	Radiance for OLCI acquisition bands 01 to 21
Oa##_radiance_unc.nc	TOA Radiance uncertainty for OLCI acquisition bands 01 to 21

Important message:

- If uncertainty is provided together with a product, at least consider using it ☺


Correct
Trade-off space
Represent
Neglect

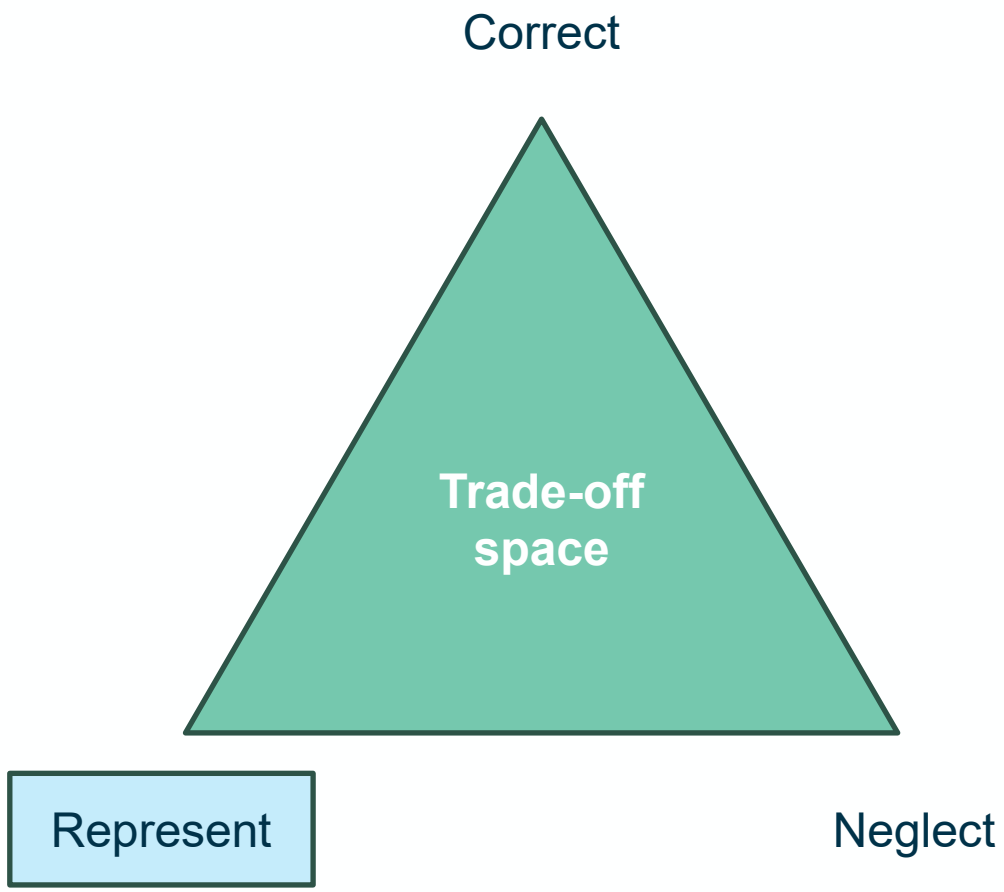


Differences in e.g. illumination and observation geometries, spectral response function, spatial resolution, geolocation, atmospheric correction are corrected for to the maximum extent possible

Example: HLS or sen2like

Pro: the resulting harmonised / fused products are very convenient to handle for the user

Cons: relevant information may be lost in the process, as it involves a number of assumptions and inter- and extrapolation steps. This can be particularly true for weak absorptions / emissions captured by hyperspectral measurements

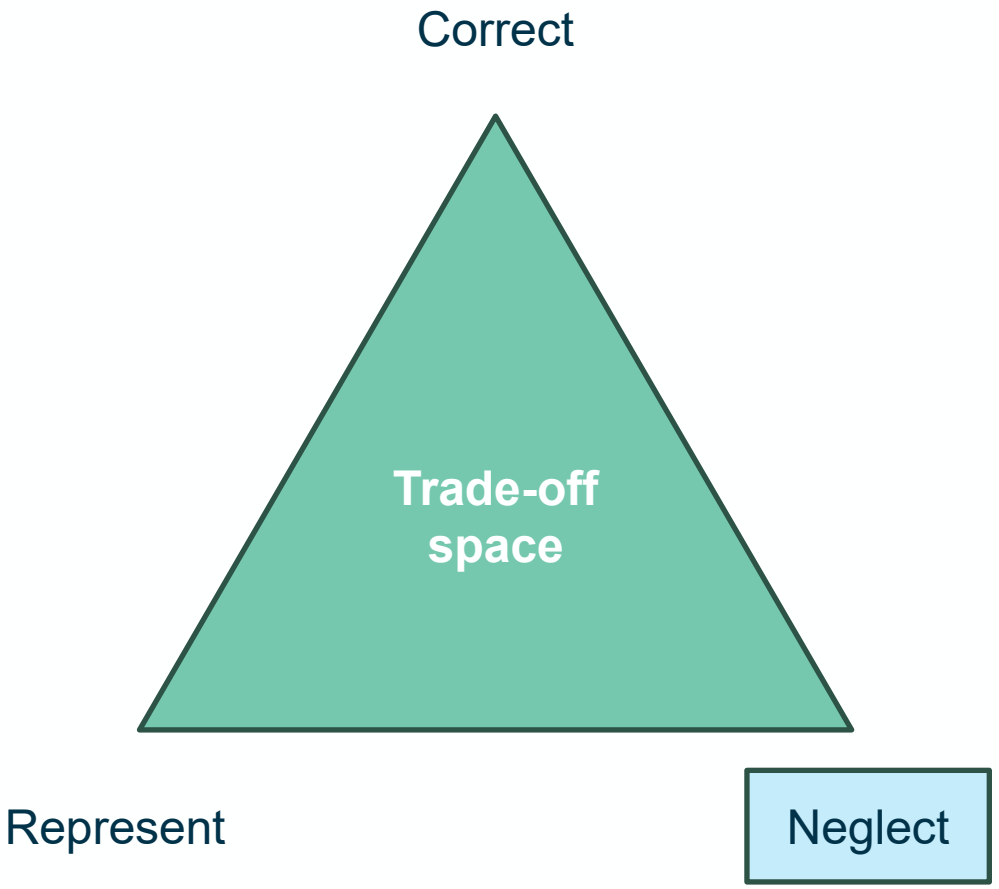


Differences in e.g. illumination and observation geometries, spectral response function, spatial resolution, geolocation, atmospheric correction are represented in the forward / retrieval model in a physical or statistical way to the maximum extent possible

Example: physically based RT models, physics-aware gaussian processes

Pro: each sample / instrument can be represented with a high degree of fidelity

Cons: complexity can grow indefinitely and become very soon impractical



Differences in e.g. illumination and observation geometries, spectral response function, spatial resolution, geolocation, atmospheric correction are neglected to a very large extent

Example:

Pro: data pre-processing is minimal

Cons: the downstream products can potentially include biases or increased uncertainty

A working example: Sen2like

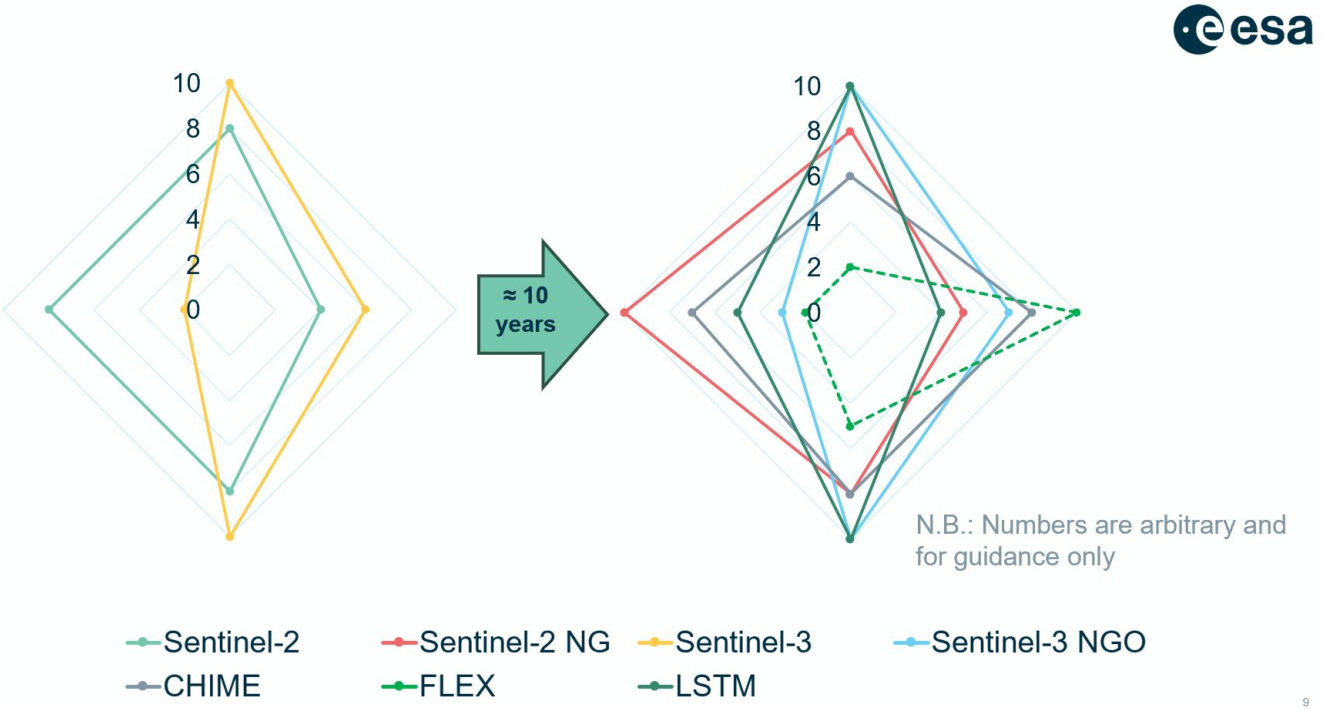
[Sen2like timelapse]

[Sen2like at ESA Phi-week 2020]

[Sen2like repository]

Saunier et al. (2023) https://doi.org/10.57780/esa-4862e7e

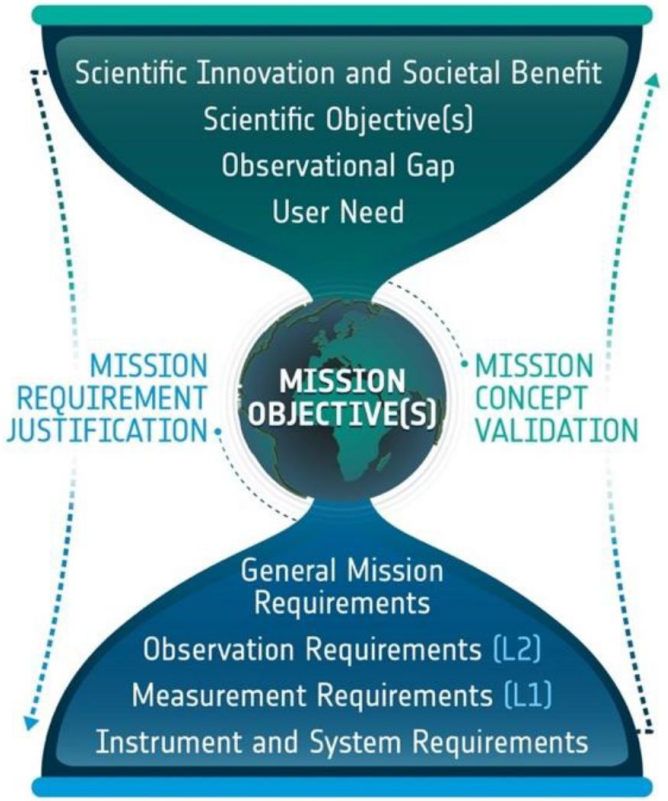
How can you get ready for this?



- Stay tuned
- Master the basics
- Get engaged through preparatory studies
- Don’t be shy to ask for opportunities

Shape the future of European EO!

- On ESA side only, 12 Earth Explorer calls and two Scout calls have already been issued
- There is room for innovation in science and policy driven mission concepts
- Two NEOMI calls already issued for innovative concepts with low maturity



Thank you very much for your attention!

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