Satellite Mission Development and Validation: Capabilities and uncertainties of aircraft campaigns

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My Background

Master from Bonn University, DE, Thesis on passive Microwave remote sensing

PhD from Wageningen, NL; Thesis on ground-based remote sensing

Joined ESA in 2009

- Campaign Scientist for FLEX, FORUM, EarthCARE, S5P
- Also work on Sentinel-3 (mainly Fire) and LSTM
- Mission Scientist for MICROWAVE Sounder (MWS) on board of MetOp Second Generation and Arctic Weather Satellite (AWS)
- Preparatory work for future precipitation mission including small sats

Today

- Introduction
- Earth Observation at ESA with a focus on airborne activities
- EO Campaigns Setup
- Campaigns for Satellite Mission Development
- EO Calibration/Validation Concepts
- Discussion on important aspects for airborne validation
- Summary & Conclusions

Why do we need satellites - the issue of scale ?

Polar Explorer or Polar Scientist

Speed: 20km/day

Measurements: Points or profiles along the way (cm resolution)

Endurance: 12h/day or approx 20km (depends on food, good health, holidays, equipment, weather conditions)

Twin Otter

Speed: 175km/hour

Coverage: Depends on instrument, generally swaths of 1m-1km with resolution from cm to meters

Endurance: 600 km or 5 flight hours before refueling (dependent on flight permissions, pilots, weather conditions)

CryoSat

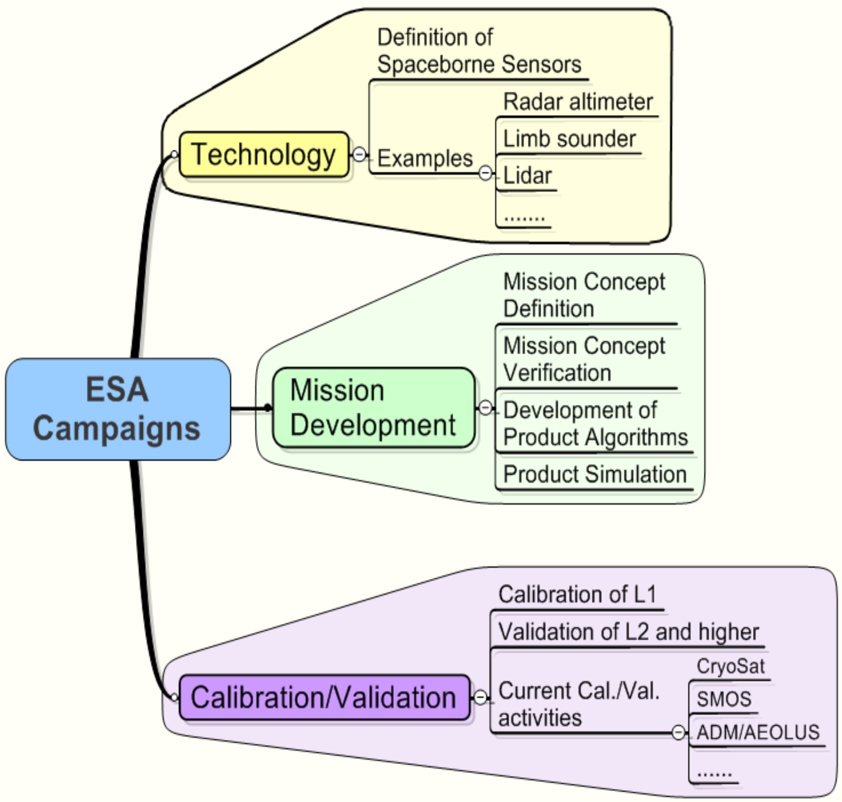
Speed and coverage: 23000 km/hour with resolution at 100s of meters

Endurance: 9 years and counting, operates 24 hours/day, no flight permission, don't care about weather…

Earth Observation Missions

Role of ESA Earth Observation campaigns

1. **ESA campaign activities started in 1981**
   1. 172 campaigns as of January 2021
   2. Typically 6-10 campaigns/year
2. **Strategic objectives:**
   1. Support strategic goals of EO Science Strategy
   2. Transnational access to airborne facilities in member states
   3. Foster partnerships with national and international organisations
3. **Campaign activities address:**
   1. Testing technology/Observing techniques
   2. Optimising requirements/design and reducing mission risk
   3. L1-L2 Algorithm prototyping/Product simulation
   4. Calibration/Validation
4. **Campaign data archive supporting science and application development**



Campaigns for different project phases

	Pre-Phase A	Phase A Feasibility	Phase B Design	Phase C/D Development	Phase E1 Commissioning	Phase E2 Operation	Data Archive
Technology	X	X					X
Mission Development (Geophysical)	X	X	X	X			X
Mission Development (Simulation)	X	X	X	X			X
Cal/Val				X	X	X	X
Science/ Applications						X	X

Earth Observation Data Levels

0	Unprocessed instrument data
1A	Unprocessed instrument data alongside ancillary information
1B	Data processed to sensor units, e.g. brightness temperatures
2	Derived geophysical variables, e.g. sea ice concentration
3	Variables that are mapped on a grid, e.g. data using EASE-Grid
4	Modelled output or variables derived from multiple measurements

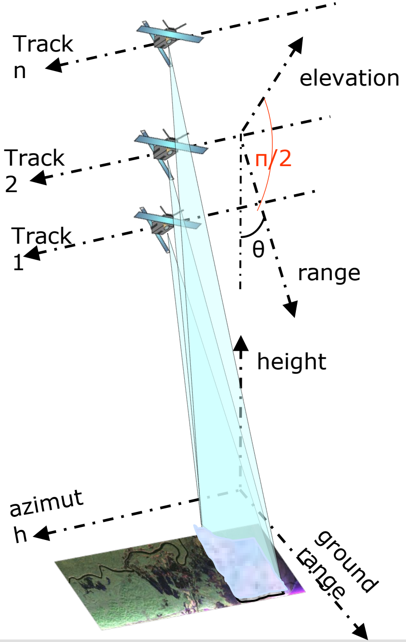
Early Developments: TOMOSENSE

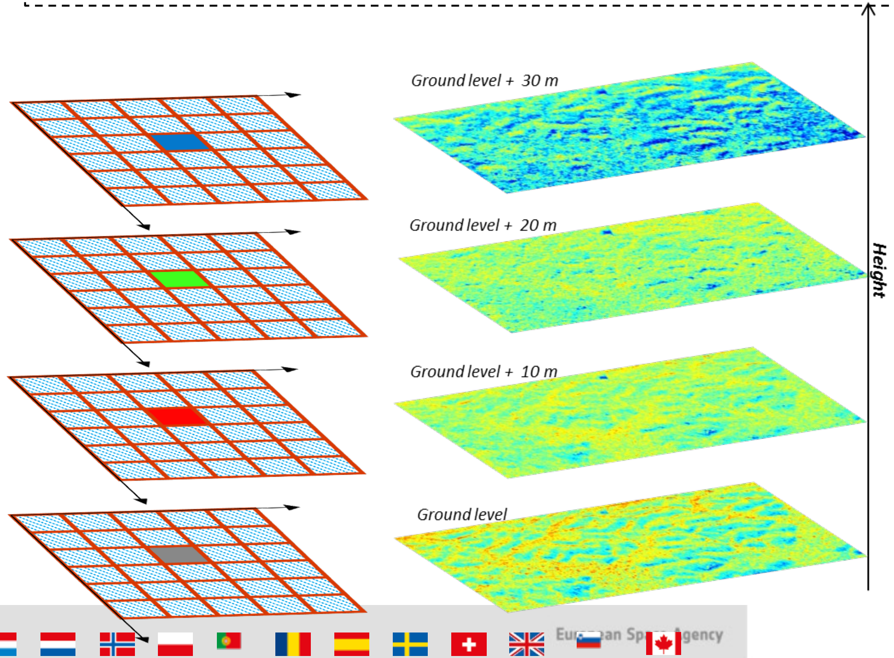
TomoSAR systems employ a RADAR sensor flown along multiple trajectories

○ Image formation by Digital Processing techniques

⇒ *Three dimensional representation* of Radar intensity at a given wavelength

SAR produces pixels TomoSAR produces voxels !!!





Flight Configuration

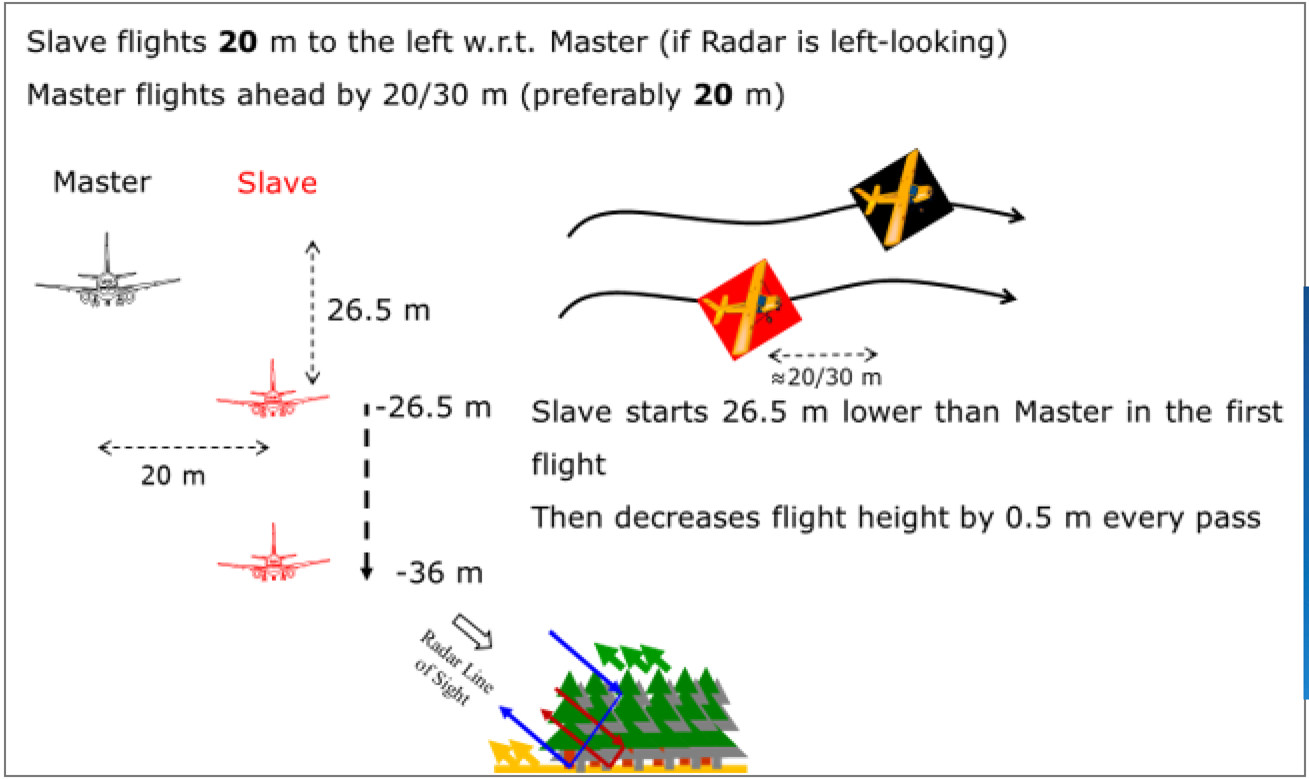
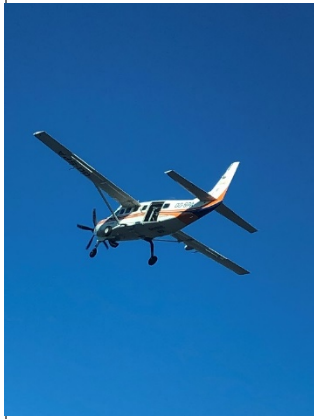


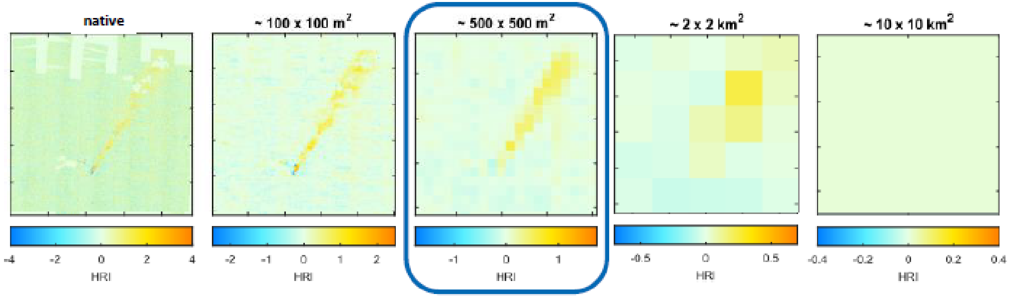
Figure 13 – C-Band flight formation.

Airborne picture of the master plane from the slave in acquisition formation



Mission Development: Example EE11 Nitrosat

- Nitrosat is an ESA Earth Explorer 11 candidate which aims to measure NO2 and NH3 at a spatial resolution of 500 meters or below
- Airborne campaigns started in 2021 and will proceed in 2022 focussing on point and area sources
- Currently no airborne instrument available with the suitable specs

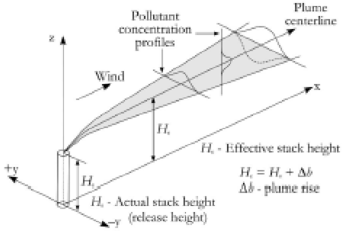


Fluxes estimates

- The traverse method enables one to retrieve fluxes from small plumes
- Results dependent on assumed plume altitude:

$$4000 \pm 3000 \text{ t } NH_3/\text{yr}$$

compared to 400 t NH_3/yr emissions reported in the European Pollutant Release and Transfer Register (E-PRTR)



A. Leelossy, et al. (2014). Dispersion modeling of air pollutants in the atmosphere : a review. Open Geosciences, 6(3).

Aircraft observations of NO2 and NH3 over selected locations in Germany Lara Noppen et al 2021

What is an inverse or retrieval Problem?

Almost any measurement you make...

- When you measure some function of the quantity you really want, you have a retrieval problem.
- Sometimes it's trivial, sometimes it isn't.

Various aspects:

- Formulate the problem properly:

  - Describe the measurement in terms of some Forward Model

  - Don't forget experimental error!

- Finding a solution, inverting the forward model

  - Algebraic, Numerical, No unique solution, No solution at all

- Finding the 'best' solution

  - Uniqueness - a unique solution may not be the best..., Accuracy, Efficiency

- Understanding the answer

https://earth.esa.int/atmostraining2008/Wed_C_rodgers.pdf

Things to think about!

- Why isn't the problem trivial?

  - Forward models which are not explicitly invertible

  - Ill-conditioned or ill-posed problems

  - Errors in the measurement (and in the forward model) can map into errors in the solution in a non-trivial way.

- What to measure?

  - Does it actually contain the information you want?

- Updating existing knowledge

  - You always have *some* prior knowledge of the 'unknown'

  - the measurement improves that knowledge

  - the measurement may not be enough by itself to completely determinethe unknown

- Ill-posed problems

  - You cannot solve an ill-posed problem. You have to convert it into a well-posed problem.

  - Which of an infinite manifold of solutions do you want?

https://earth.esa.int/atmostraining2008/Wed_C_rodgers.pdf

Summary so far

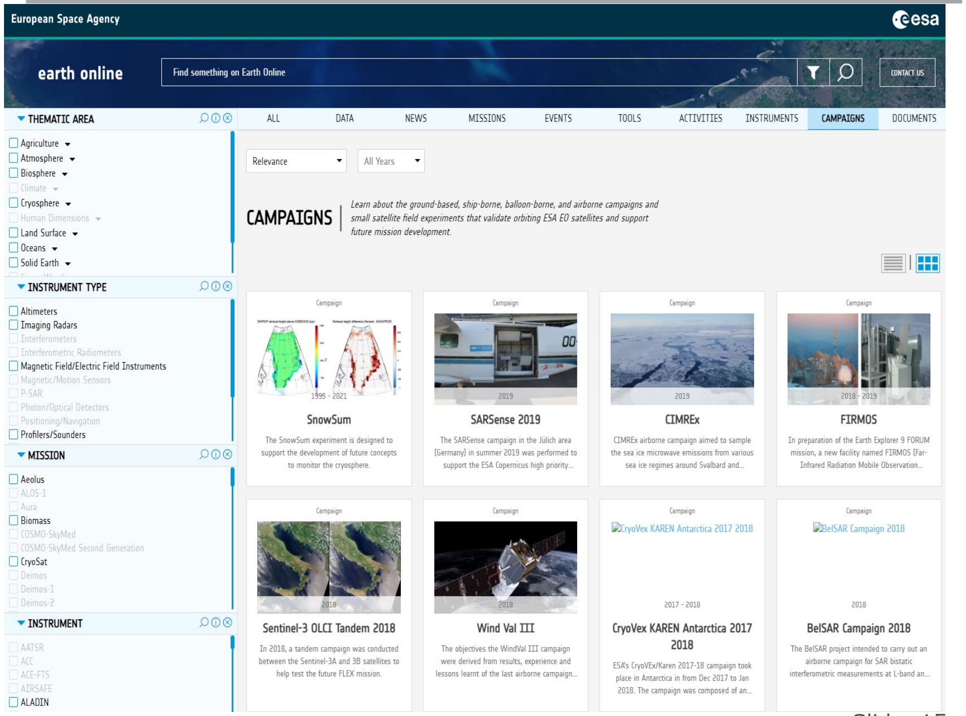
- General setup for Campaigns at ESA
- Scales matter
- Balance between best quality and fit for purpose
- Retrieval as a challenge

Things to keep in mind when working on these topics

Access to ESA Campaign Data

1. ESA campaign data available to interested PIs
    a. Formatted and documented datasets including DOIs
    b. Data Inventory
    c. Final report with full description of campaign activity and analyses
2. Final report accessible directly through web
3. Access to datasets provided through Category 1 mechanism (short proposal incl. identification of desired datasets)
4. Currently **more than 80** campaign datasets available

https://earth.esa.int/eogateway/search?category=Campaigns&filter=



CAL/Val ???

Why Calibration ***and*** Validation?

Calibration is "*quantitatively defining the system response to known controlled signal inputs" (http://calvalportal.ceos.org/)*

Instrument Calibration is the responsibility of Mission management

- Instrument gains/offsets, etc
- Spectral calibration
- Vicarious calibration (e.g. Sentinel-3 SLSTR fire channels...)

Calibration is a well managed process

Calibration is specific and requires dedicated activities and teams with clear reporting lines and often mission/financial implications.

Validation Definitions:

- Validation is “the process of assessing, by independent means, the quality of the data products derived from the system outputs” (CEOS Definition)

- Rodgers (2000) defined the purpose of validation as the confirmation that the theoretical characterization and error analysis actually represent the properties of the real data.

- In the metrology (i.e., “measurement science”) community, validation is understood to be a verification against requirements which ensure that the data are adequate for an intended use

How to Validate?

Type 0: Quality Assurance

- Analyze data on means (expected) and extremes (outliers)
- Visual inspection of data plotted on global maps

Type 1: Statistical Comparisons to Standard

- Ground based systems and networks, balloons, …Validated satellite instruments on same and other platforms
- Perform statistical comparisons, focus on differences

=> Yields statistics on mean, median, variance, correlation, …Plots of difference versus measurement geometry parameters

Type 2: Different Algorithm Statistical Comparisons

- Run different algorithms on same level 1 data. Perform statistical comparisons, focus on differences

=>Yields statistics on mean, median, variance, correlation, …Benchmark effect of different assumptions and approaches

https://earth.esa.int/atmostraining2008/

Type 0 validation (Quality Assurance)will tell you:

- Whether satellite data values make sense (min, mean, max),
- Whether its spatial distributions (global maps) make sense,
- Under which circumstances (clouds, dust storms, high sza) and over which geographical regions (land, ocean, desert, snow) there are problems,
- To what aspect these problems are related (algorithmic, surface, measurement geometry, polarization)

- Feed-back to algorithm developers,
- Feed-forward to scientific users!

Type 1 validation will provide you with:

- Qualitative agreement of satellite and reference data,
- Qualitative differences between satellite and reference data,
- To what aspect these differences are related (algorithmic, surface, measurement geometry, polarization),
- Feed-back to algorithm developers,
- Feed-forward to scientific users!

Type 1 validation quantifies the data quality but only under those circumstances covered!

- airborne and balloon observations supplement fixed position ground based observations to a certain extent
- same platform satellite instrument extends global coverage

Type 2 validation will provide you with:

- a test bed for algorithmic assumptions (cloud heights, types of surface, ghost columns, aerosols, interfering gases, …),
- a qualitative assessment of the influence of such assumptions (apply various approaches and benchmark effects) ,
- feed-back to algorithm developers (best choice),
- feed-forward to scientific users (optimal choice)!

Concept of Fiducial Reference Measurements?

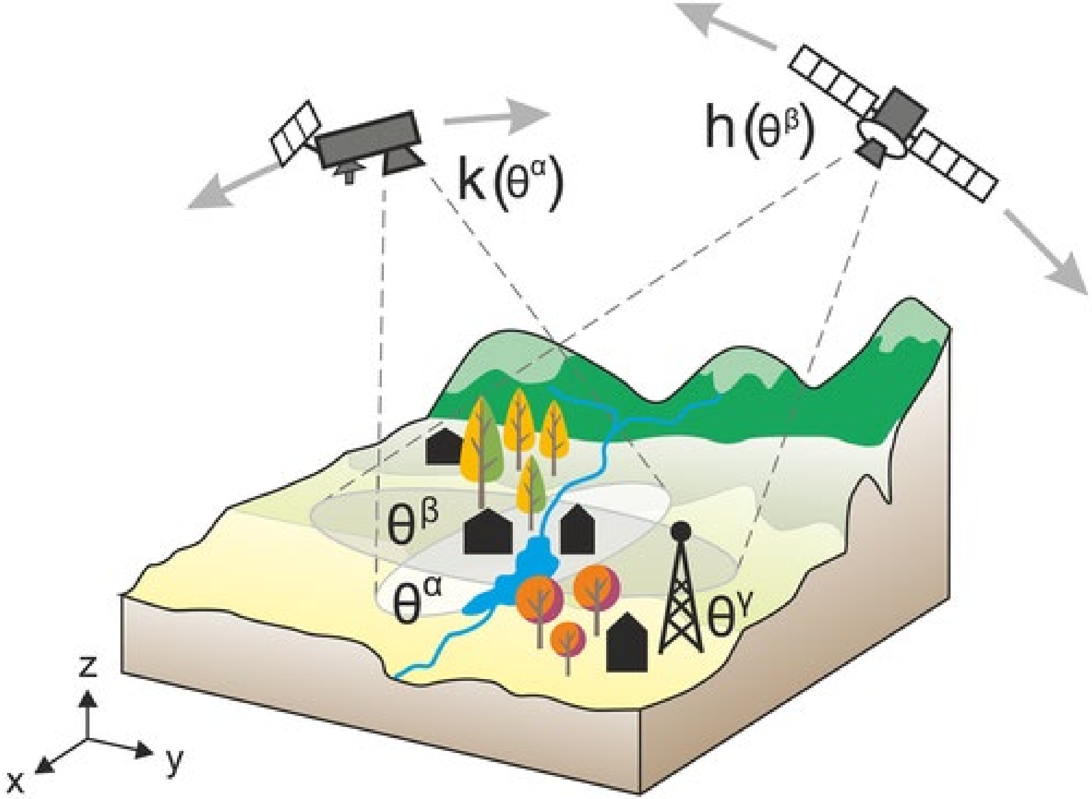
FRM are the suite of **independent ground measurements** that provide the maximum scientific utility/return on investment for a satellite mission by **delivering, to users, the required confidence in data products**, in the form of independent validation results and satellite measurement uncertainty estimation, over the duration of the mission (*Donlon et al, 2014*)

IF we have **no FRM** then we cannot really use the mission as we have no idea how accurate data products are

IF we have **many FRM** this is great scientifically (statistical significance, geographic coverage, robust network…) but incurs additional costs with reducing ROI

There is a balance between these two extremes to deliver a satellite mission with a KNOWN product quality that is "fit for Purpose"

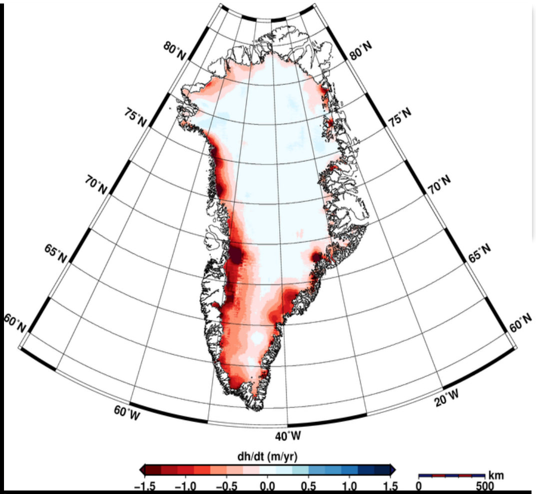
General sketch of validation

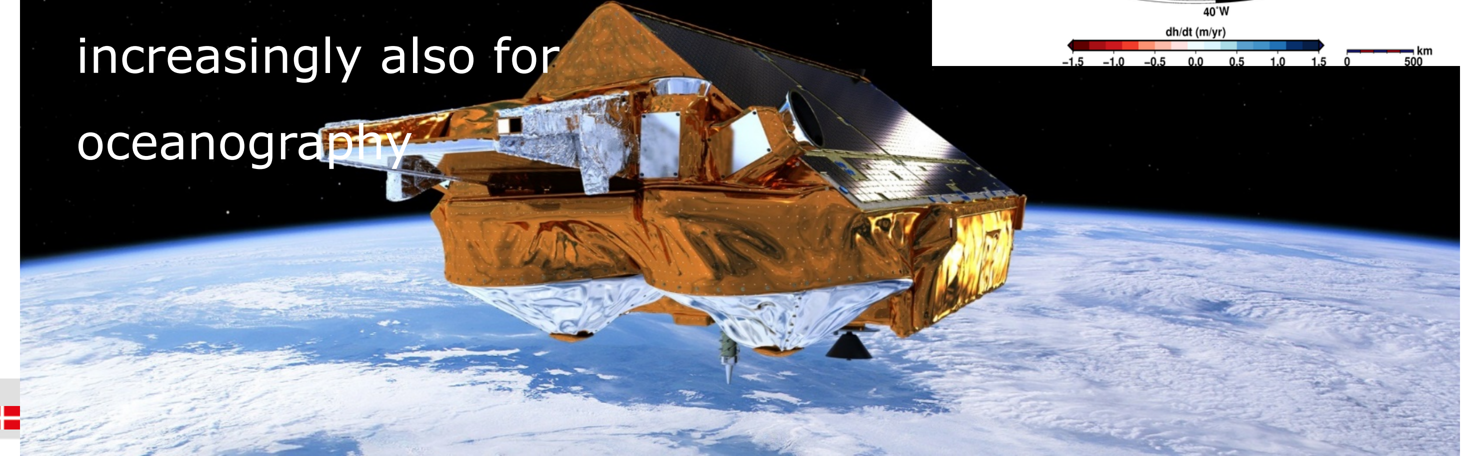


Validation practices for satellite-based Earth observation data across communities, Loew et al 2017

Example CryoSat: The Ice Mission

- First interferometric altimeter in space
- Global sea ice thickness measurements
- Data used for ice research, but increasingly also for oceanography



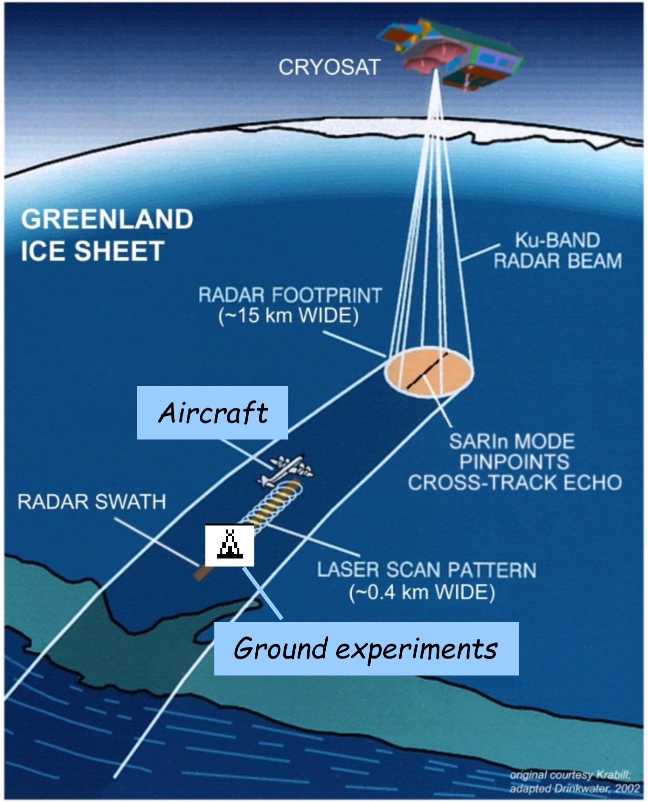


Overall experimental concept

Coordinated airborne and ground measurements required to bridge the spatial scales between ground and satellite measurements

Airborne instrumentation configuration:

- ASIRAS – airborne radar altimeter which serves as a proxy for SIRAL on-board Cryosat
- Laser scanner – to address error sources due to penetration
- Support instruments (DGPS, data recorders, cameras)



Uncertainty Concept for validation campaigns

The validation of satellite-based products with varying spatial resolution against point-like ground-based measurements (fixed or mobile) or against airborne measurements with a different spatial resolution involves uncertainties.

Uncertainty satellite:

Uncertainty Instrument, L1, and L2 processing

$$\sigma_{Sat}^2 = \sigma_{Ins\&L1}^2 + \sigma_{L2}^2$$

Uncertainty independent measure:

Uncertainty Instrument, L1, and L2 processing, and **representativity**

$$\sigma_{Ind}^2 = \sigma_{Ins\,\&\,L1}^2 + \sigma_{L2}^2 + \sigma_{representativity}^2$$

Uncertainty Instrument, L1, and L2 processing, and representativity

$$\sigma^2_{Ind} = \sigma^2_{Ins\,\&\,L1} + \sigma^2_{L2} + \boldsymbol{\sigma^2_{representativity}}$$

- The actual $\boldsymbol{\sigma^2_{repres}}$ depends on the actual variable to measure
- $\boldsymbol{\sigma^2_{repres}}$ related to spatial variability and temporal variability

- Satellite-based products are routinely validated against ground-based reference data
- Usually the ground-based data are not available on a spatial scale relevant to the validation
- **Fortunately, there are campaigns that can provide data with (sufficient) spatial resolution**
- Accurate airborne measurements with sufficient spatiotemporal coverage are available
- ESA Experience in this context with light-weight sensor below 5kg e.g. AirFLOX, SWING
- To a smaller extent with hyperspectral, thermal and also SAR

=> This enables recurrent spatial mapping by means of combined satellite, airborne and ground-based observations

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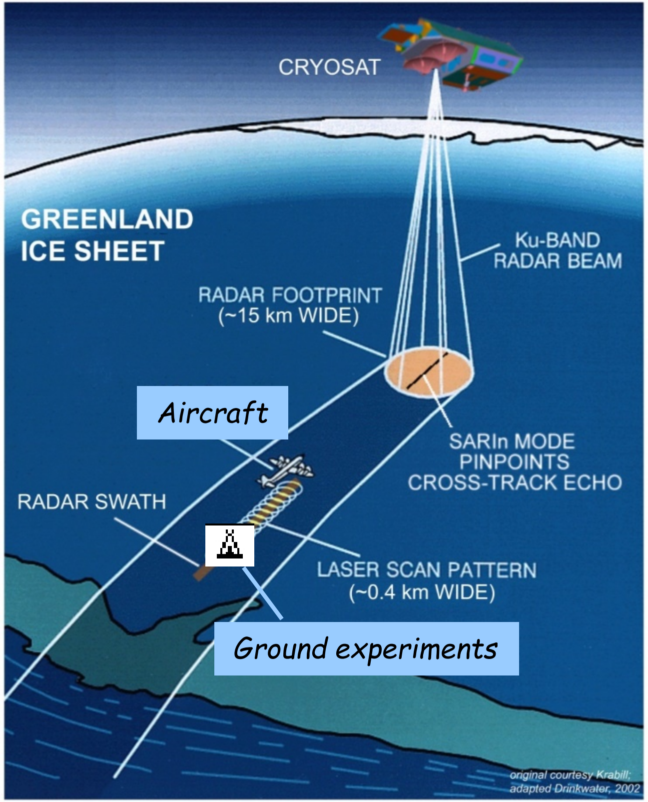
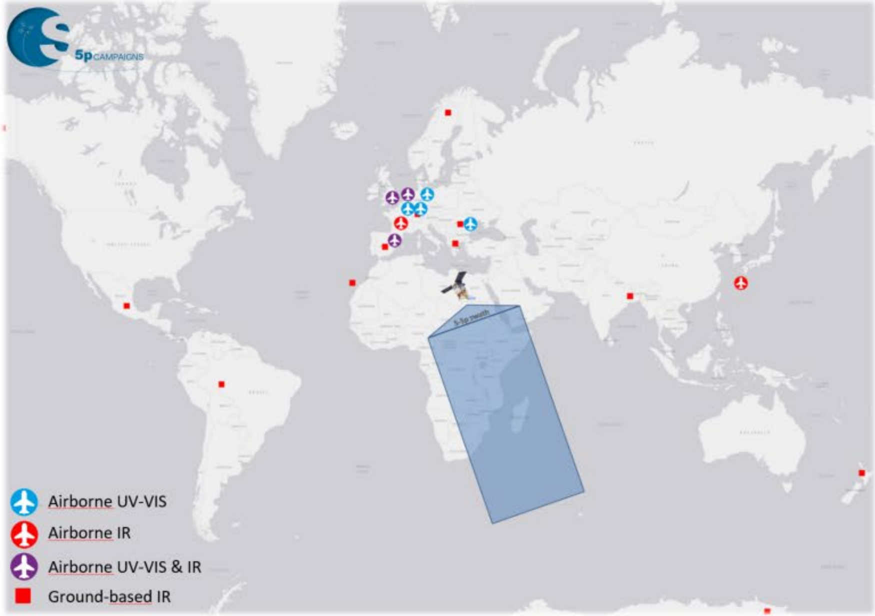


Sentinel-5p Validation Campaigns – Activities in 2021-2022



S5PVAL-DE-RUHR
S5PVAL-DE-BERLIN
S5PVAL-RO
S5PVAL-BE
NET-Sense

NO_2
SO_2
HCHO

MAGIC
ACCLIP
S5PVAL-KOLKATA
S5PVAL-PORTOVELHO
COCCON

CO
CH_4

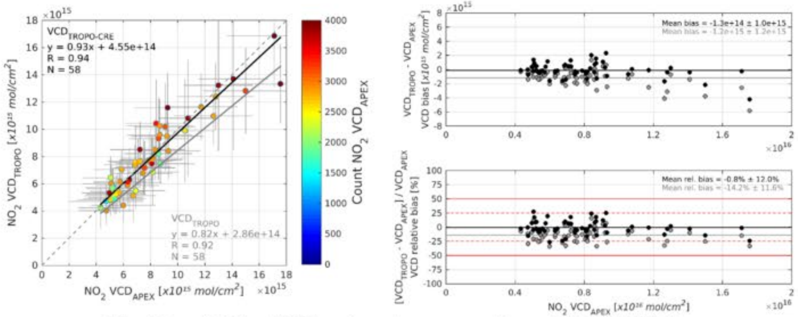
https://s5pcampaigns.aeronomie.be

Validation requirements

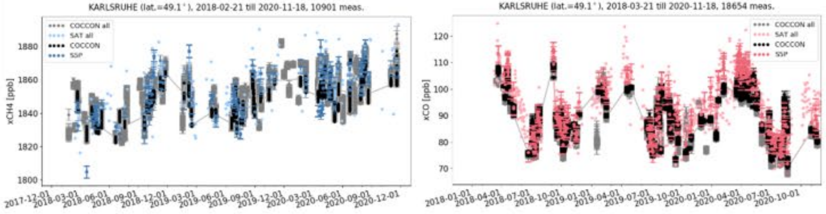
L2 product accuracy + precision → Spatial validation → Temporal validation → Algorithm parameter → Special validation requirements

Coordinated validation

S-5p tropospheric NO_2 validation based on airborne APEX remote sensing

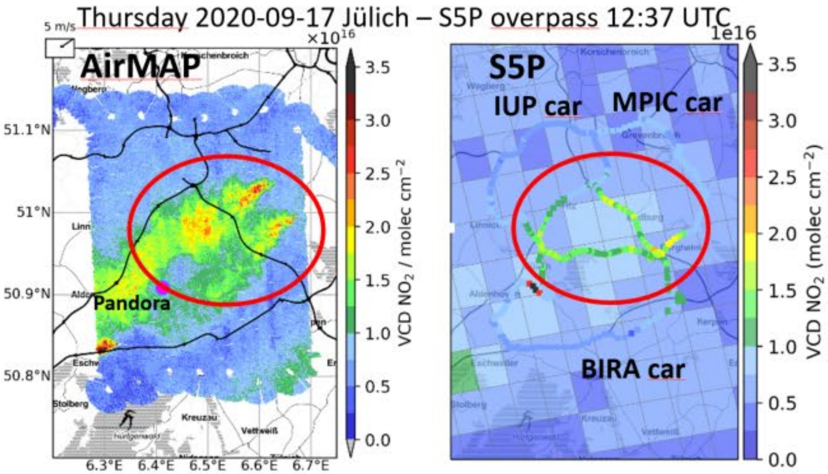


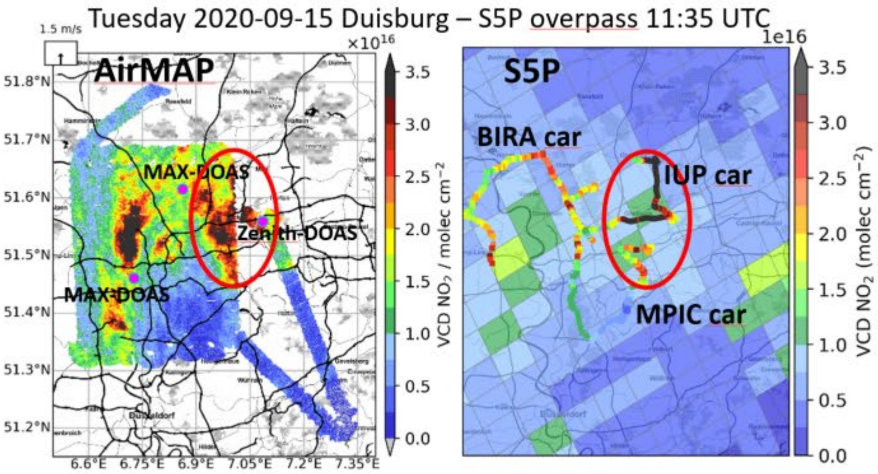
S-5p CO and CH_4 validation based on ground-based COCCON FTS

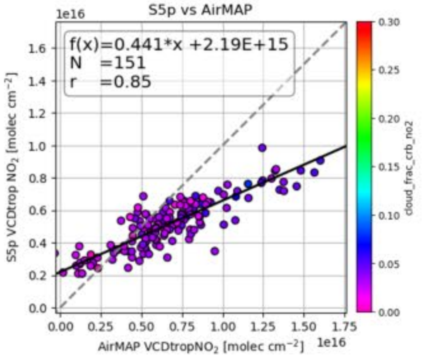


Coordinated by: aeronomie.be · inoe 2000 · esa · copernicus

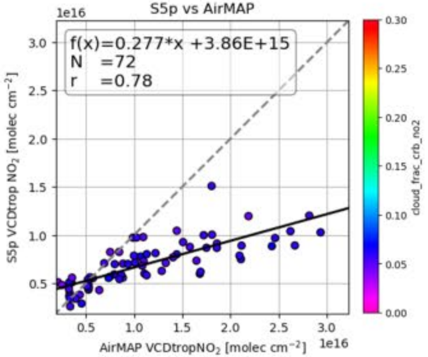
S5P Airborne & Ground-based Validation







- Measurements of AirMAP and car DOAS are consistent
- Good correlation of S5P and AirMAP measurements
- Low biased S5P TROPOMI NO_2 data of around 30% to 45%, with varying magnitude for different days and areas



Kezia Lange et al. 2021 - klange@iup.physik.uni-bremen.de

Capabilities, Challenges and Limits

- By underflying satellites one can obtain spatial and temporal high collocated measurements but only for smaller areas
- In general one might expect larger uncertainties for faster processes in the atmosphere compared to the land surface
- Capabilities and uncertainties of aircraft data still need to be studied
- For example, Lammert & Ament (2015) used a perfect model approach to study uncertainties. They excluded temporal aspects!

Question: How to perform regional validation by means of airborne observations? (e.g. Latin Hypercube sampling?)

Some general summary comments

- ESA campaign activities responding directly needs of the EO programmes in efficient and effective way and play a key role in
    - preparing future EO missions
    - supporting mission development
    - Cal/val for missions in orbit
    - supporting wider science community through the ESA campaign database on the EOPI portal
- Expanding international collaboration (NASA, EC e.g. EUFAR, National Agencies) leading to pooling of resources and enhanced science and mission related return (e.g. enabling campaign activities not possible in isolation)
- No dedicated airborne programme at ESA at present (i.e. no regular calls for industry or similar). Requirements and implementation solutions usually through advisory mechanisms, PIs and knowledge of opportunities.
- Expanding industrial interest in airborne sensors and activities in the context of UAVs/Drones and medium and high altitude platforms

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Thanks again!