Thematic Area 1 – Session
Polarimetric and Multi-frequency SAR Applications

Ake Rosenqvist (JAXA) & Magdalena Fitrzyk (ESA)

TA1 breakout session topics

TA1: PolSAR & multi-ƒ applications

- Soil Moisture (Laura Frulla, CONAE) [*Virtual]
- Forest & Biomass (Paul Siqueira, UMass) [*Virtual]
- Wetlands (Ake Rosenqvist, JAXA)
- Agriculture & Crop monitoring (Heather McNairn, NRCan) [** by Ake]
- Sea Ice (Malin Johansson, Univ. Tromsø)

- Discussion

"White Paper" on observation requirements for current, near-future and next-generation SAR missions

Points for consideration for each science discipline

1. **State of the art & gap analysis** of limitations encountered using today's SAR missions

1. **Suggestions for current and near future SAR missions** (2020s) that address some of the shortcomings

1. Discuss the Holy Grail/Game Changer for the application. **Suggestions for brave mission solutions in the next decade** (2030s) that could resolve key uncertainties.

Observation requirements for Soil Moisture

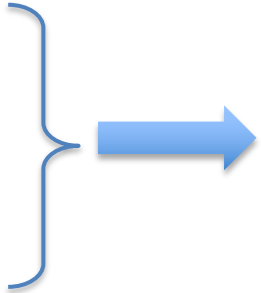
Laura Frulla (CONAE)

Information requirements / policy requirements

- High spatial and temporal resolution (because its high variability) → Accurate and timely estimates
- Large areas covered to obtain representative measurements and estimates at global and regional scales with an appropriate periodicity
- Long wavelength
- Polarimetric data, soil moisture affects both backscatter intensity and polarimetric phase
- SAR sensors must be well calibrated to improve the accuracy of the estimates
- High radiometric resolution
- Validation procedures for the estimates
- More in-situ data for good validation processes
- Appropriate acquisition plans to give continuity to the soil moisture estimates
- Easy availability of soil moisture values (in-situ/estimates)

The relevance of SAR

- Penetrates clouds
- Provides data regardless of weather conditions
- Are intrinsically sensitive to plant and soil moisture, which are directly correlated with crop development, stress and diseases
- Long wavelengths penetrate through the leaves and below the surface
- It may have the ability to perform polarimetric acquisitions



provide insight into vegetation structure and soil moisture

- By combining different acquisition times and using interferometric SAR and tomography, surface deformation (e.g. due to water extraction) and vegetation height can be measured

State of the Art (where are we today?)

- SAR missions provide soil moisture estimates with much better spatial resolution, fairly good temporal coverage and good quality

  Currently:

  - Sentinel 1, RCM, ALOS-4, SAOCOM 1
  - Unmanned Aerial Vehicles (UAVs) equipped with SAR sensors (very few)
  - machine learning techniques

  Future: NISAR, ROSE-L and Tandem-L satellites

Information gaps and short comings

- SM estimates from previous satellites are available but at a very coarse spatial resolution and do not necessarily have a continuous data set.
- **Temporal resolution**: data are not frequent enough for certain applications.
- High cost and heavy: SAR satellites are expensive to develop and launch.
- Complex technology: SAR systems require advanced technology and skilled operators.
- Data volume and processing: SAR generates large amounts of data that require large on-board storage, high bandwidth, large and powerful servers for storage and significant processing capabilities.
- User skills: not many.
- Ground infrastructure: at least two ground stations are needed to download data and command the satellites.
- Radio frequency interference: SAR signals can be affected by terrestrial services, leading to image artifacts.

Suggestions for current SAR missions

- Improve algorithms and software for faster and more accurate SAR data processing
- Improve algorithms to better reduce radio frequency interference
- Improve estimates of subsidence in agricultural areas in general to reduce economic and environmental risks, and promote sustainable agricultural practices
- Combine different SAR acquisitions from different sensors to reach higher temporal resolution
- Provide worldwide soil moisture estimates coordinating L-band acquisitions over areas with vegetation and dense vegetation, C-band over areas with sparse to no vegetation and X-band over areas with no vegetation
- Improve calibration techniques
- Obtain better estimation results based on AI
- Implement the use of cloud-based platforms to handle easily large SAR datasets, and provide soil moisture products.
- Develop super-resolution techniques to increase the spatial resolution in the final estimates.

Suggestions near future SAR missions

- Develop more affordable SAR technologies, including small satellites to reduce cost and time of development.
- Increase the frequency of SAR data acquisition to achieve higher temporal resolution.
- Increase the spatial resolution of the data sets.

Suggestions for brave mission solutions in the next decade (2030s)

- Set up a real constellation (by one or more agencies)
  - four full polarimetric SAR satellites operating at L band
  - not less than 3 or 4 days of repeat cycle
  - spatial resolution ~ 5 to 10 m
- At least two satellites can have a companion passive satellite to provide:
  - estimates of subsidence in agricultural areas in general reducing economic and environmental risks, and promoting sustainable agricultural practices.
  - detailed information on vegetation structure and identification of subsurface features by

SAOCOM 1 SAR Data Access

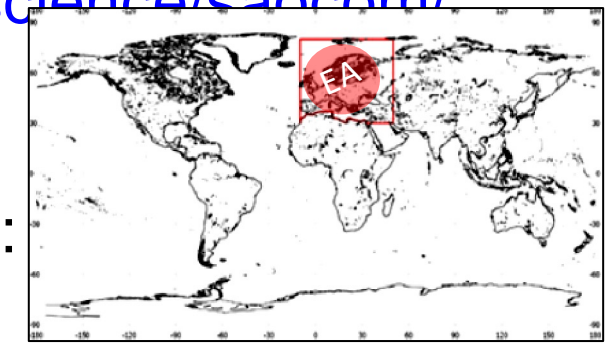
1. Catalogue

- inside ASI exclusivity area (ASI-CONAE cooperation):

  https://www.asi.it/en/earth-science/saocom/

- outside ASI exclusivity area:

  u_inter@conae.gov.ar



SAOCOM Catalogue can be navigated freely to identify already existing data:

https://catalog.saocom.conae.gov.ar/catalog/#/

Upon registration the quicklooks can be seen

agreement
project
→ Licence to Use

SAOCOM 1 SAR Data Access

2. One click

		non-commercial users		commercial users	
PERMISSIONS	REGIONS	argentines and residents	foreigns	argentines and residents	foreigns
archived: - L1, L2 download - L1 reprocess - interferometric products	Argentina	via One-click, checking that the area is within Argentina			
- L1, L2 download - L1 reprocessing - interferometric products - acquisition request	abroad (ASI AoE excluded)	atencion.usuario@conae.gov.ar (under some cooperation type)	atencion.usuario@conae.gov.ar (under some cooperation type)	via VENG www.saocom.com.ar (free access)	via VENG www.saocom.com.ar (comercial agreement)

https://registro.conae.gov.ar/registracion/view/

SAOCOM 1 SAR Data Access

3. Announcements of Opportunities

AO for SAOCOM ESA/CONAE

Promotion of Utilization and Mission Applications and Science (PUMAS)

Initiative under Earthnet's Third Party Missions Programme

For science and application developments (EO)

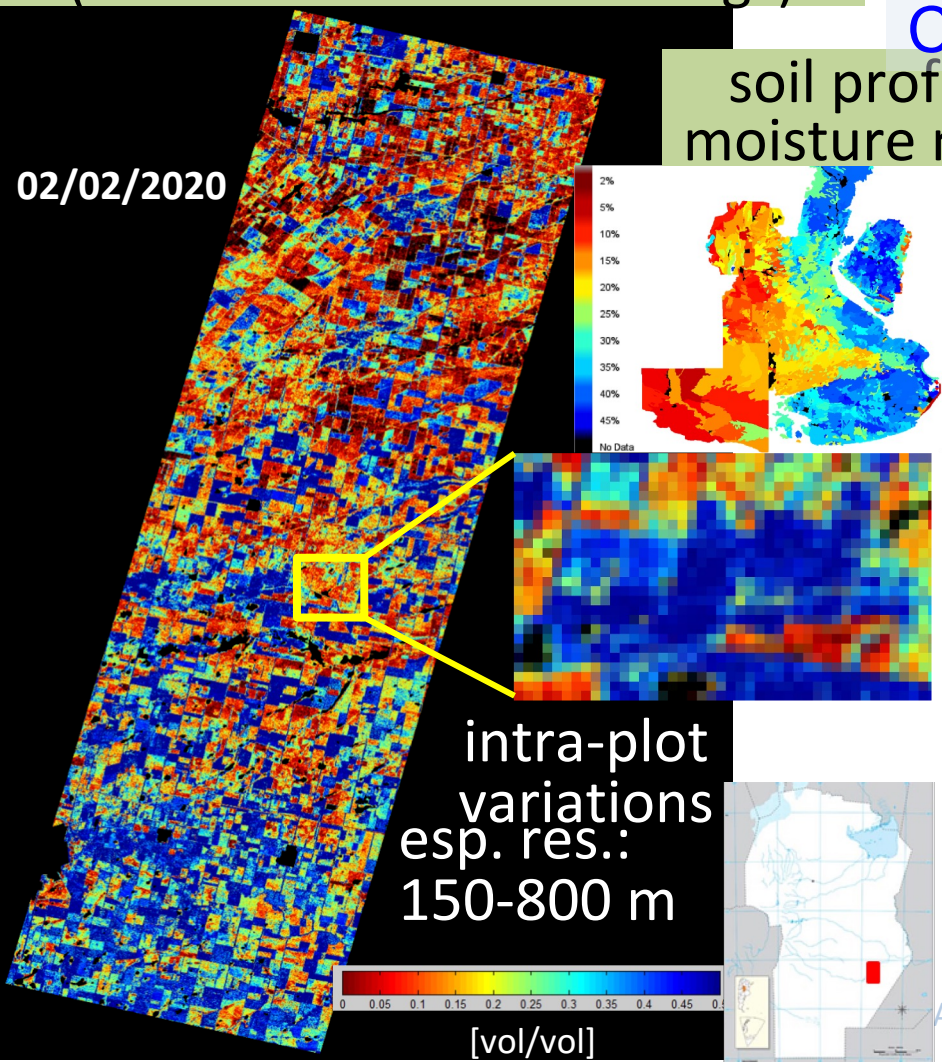
The call has been renewed regularly since 2023

Data available: ESA (EO), Copernicus and SAOCOM (Quota < 40 images, outside AoE)

- https://www.argentina.gob.ar/ciencia/conae/misiones-satelitales/ao-iniciativa-puma-esa-conae
- https://earth.esa.int/eogateway/announcement-of-opportunity/saocom

Access of soil moisture estimates from the SAOCOM 1 SAR acquisitions

SAOCOM 1 – Soil Moisture Map (Bell Ville and surroundings)



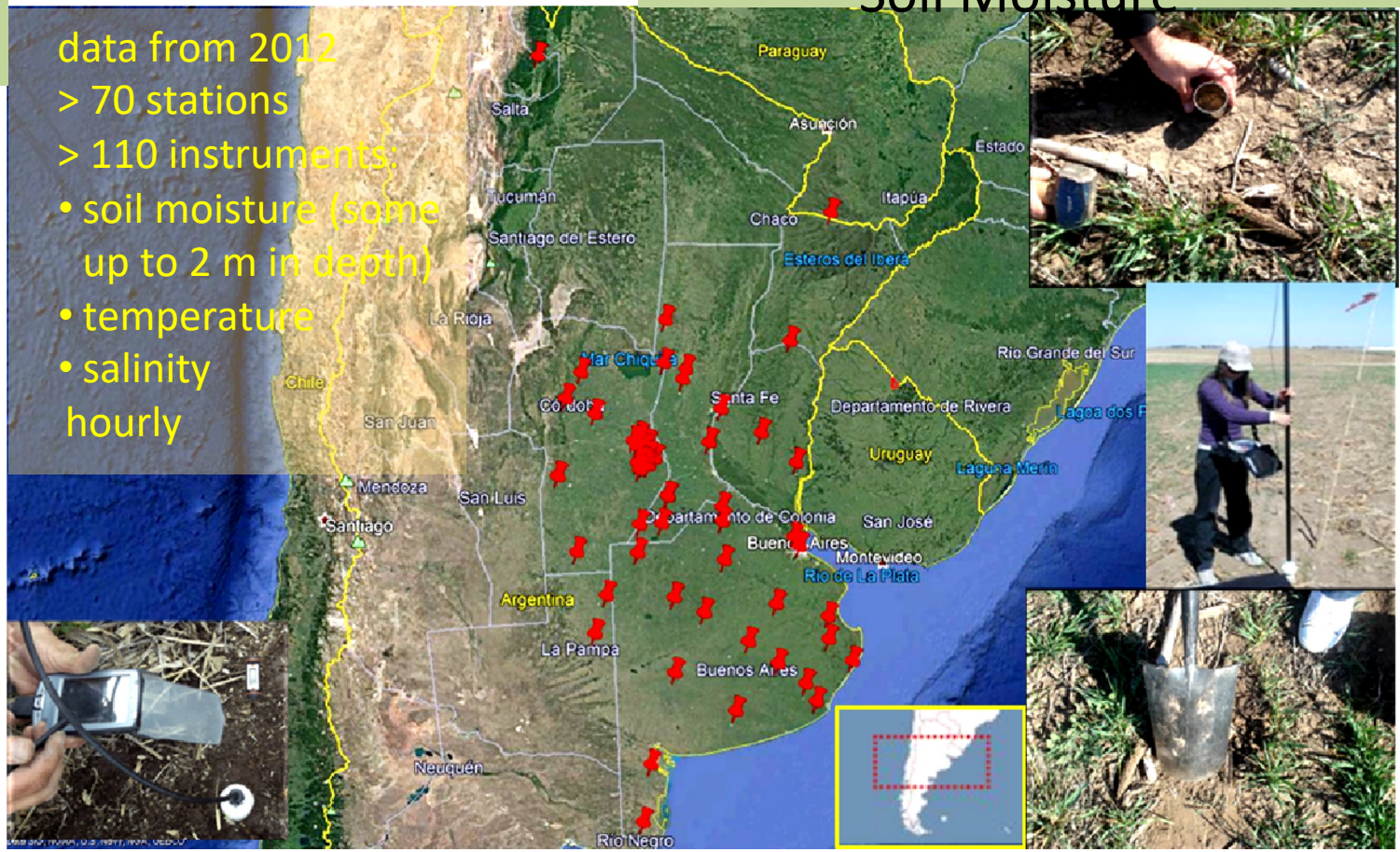
soil profile moisture map

SAOCOM Catalogue

CONAE´s GEOCatalogue

data from 2012
> 70 stations
> 110 instruments:
- soil moisture (some up to 2 m in depth)
- temperature
- salinity

hourly



Telemetric Sensor Network for *in-situ* Measurement of Soil Moisture

u_inter@conae.gov.ar

Observation requirements for Forest & Biomass

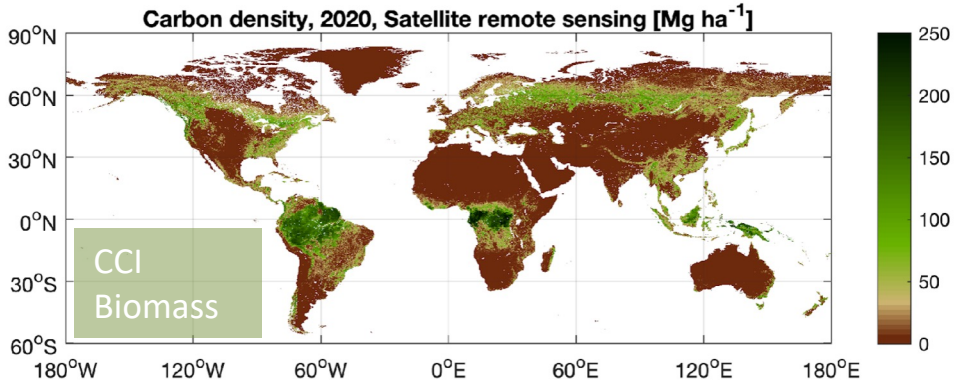
Paul Siqueira (UMass, USA)
Maurizio Santoro (Gamma RS, CH)

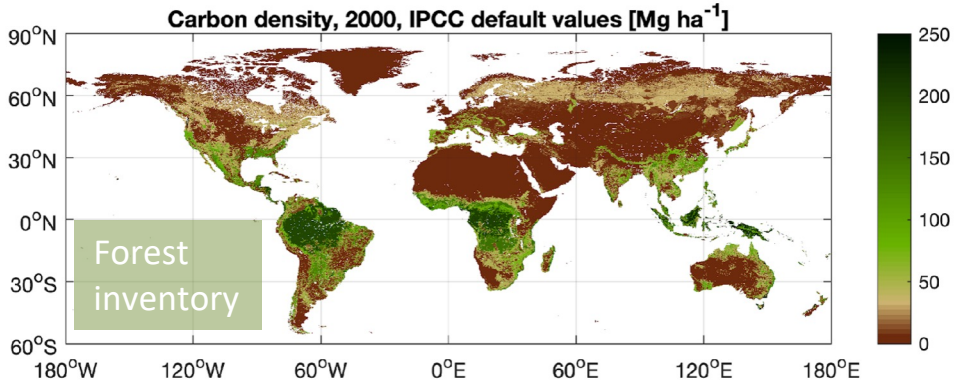
State of the Art & Gap analysis

- Like many Essential Climate Variables (**ECV**s), Forest Cover (**FC**) and Above Ground Biomass (**AGB**) are not directly observable from space, but rather observed through various remote sensing modalities (e.g. optical reflectance, lidar, SAR, InSAR, PolInSAR, TomoSAR)
- The availability of L-band data from from JERS-1, ALOS, and SAOCOM, have made inroads into using SAR for biomass and forest cover estimation.
- Dense time series of free and open C-band data from Sentinel-1 have changed the way that time-series can be used for forest characterization (RCS time series, interferometric coherence)
- Complemented by free and open lidar data from ICESAT and GEDI, which are used as the remote sensing standard for estimating forest height and inferring biomass. Difficulties remain in wall-to-wall coverage.

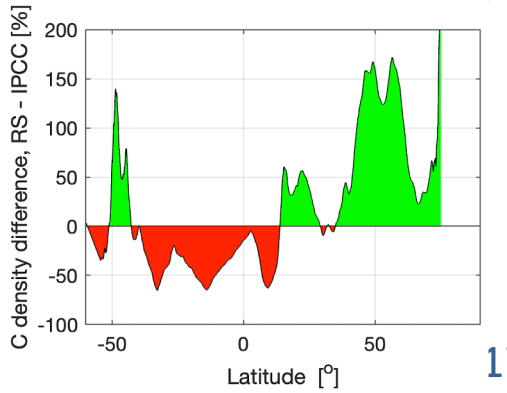
- The immediate future of satellite remote sensing for Forest and Biomass characterization is very promising

- Immediate needs are in algorithm development and coordination of observations.
- A dense time-series of **spaceborne quad-pol** is needed to better understand the use of Polarimetry and PolInSAR in Forest Characterization and Biomass Estimation. This is an opportunity for ALOS-4 and NISAR.
- Budgetary constraints are an ever-present problem. Hence community development is critical





differences in carbon density as determined by SAR versus forest inventory and biome analysis (Santoro, 2024)

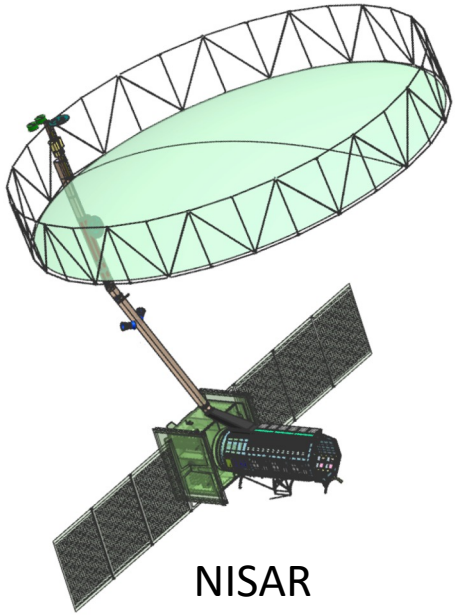


Suggestions for current and near future SAR missions

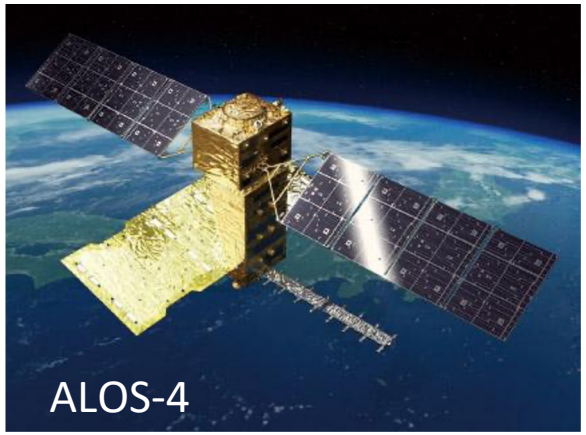
- There are a host of missions, either currently in orbit, or about to be in orbit
- These are complemented by resources such as GEDI, commercial X-band SARs, and other observing methods (ECOSTRESS, CHIME, MOLI, etc)
- High resolution SAR, over multiple observing modalities is an immediate opportunity.
- The immediate challenge is in learning how to cope with the enormous data volumes and instrument peculiarities.

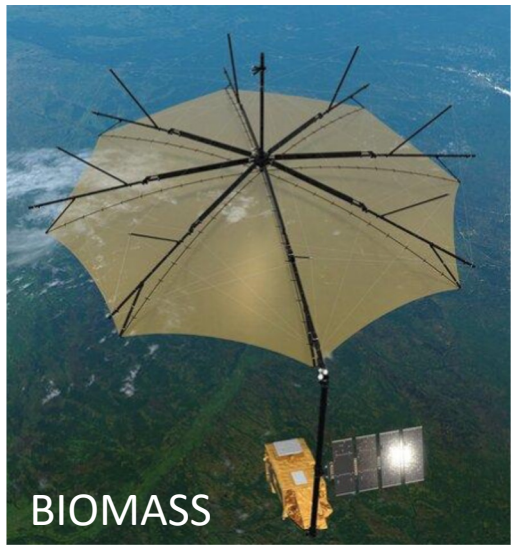
- JAXA's ALOS-4 could fill a unique gap for collecting a dense time-series of fully polarimetric data

- The challenge for the current and near future of SAR is in learning on how to make best use of these observing systems
  - Data fusion (polarimetry, interferometry, multi-frequency, etc.)
  - Bringing algorithms to the data rather than data to the algorithms (cloud computing)
  - Harnessing machine learning


NISAR

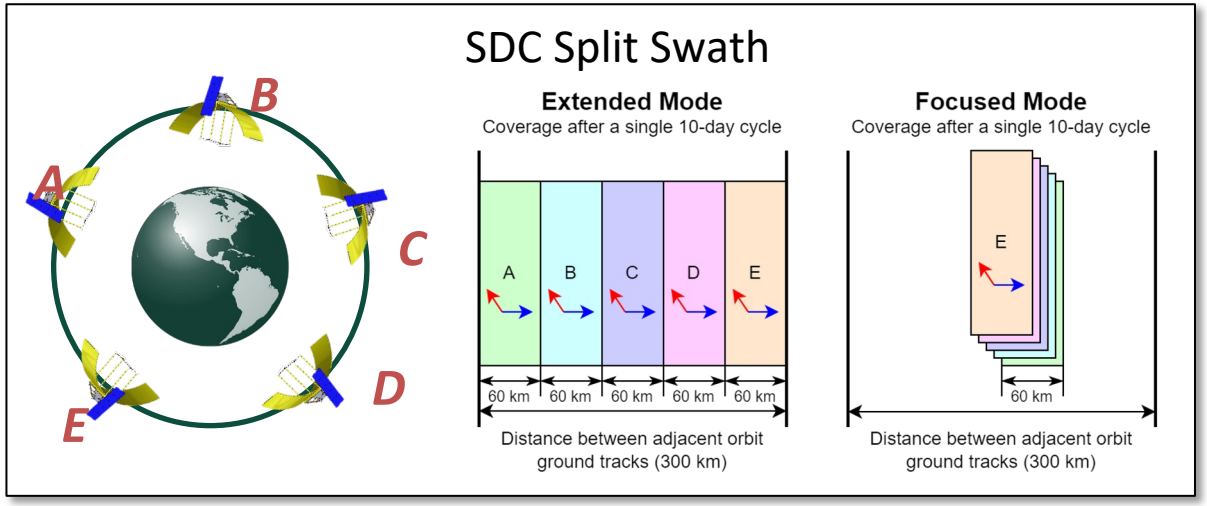


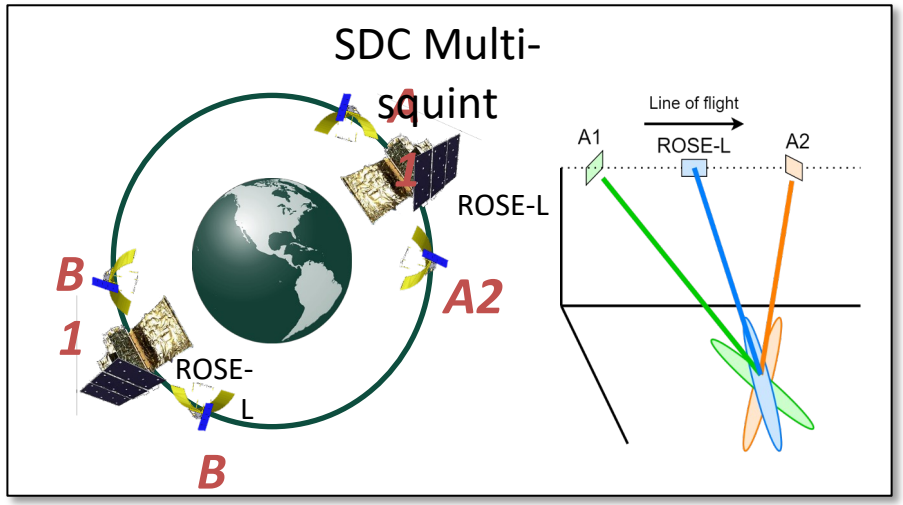




Suggestions for brave mission solutions in the next decade (2030s)

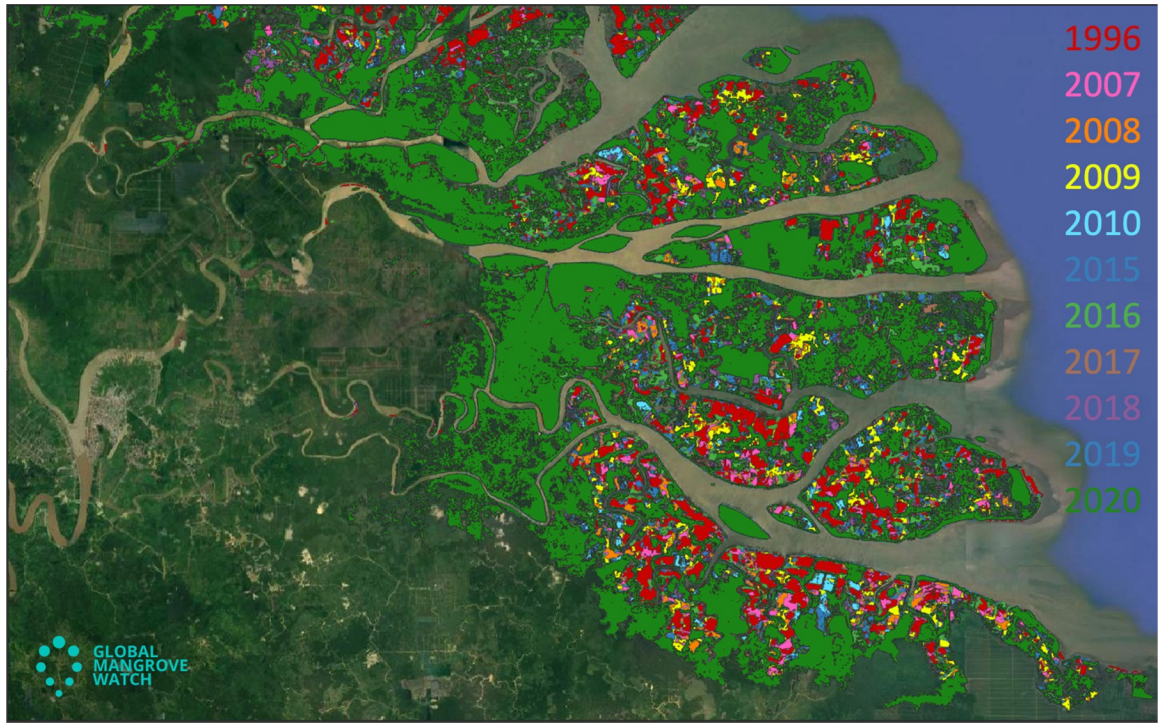
- ESA's ROSE-L and Sentinel-1 series, combined with BIOMASS and other such missions, will serve as a base of SAR data collections for building new and innovative systems for the future
- NASA currently has two relevant missions mentioned in the last decadal survey
  - Surface Deformation and Change (**SDC**) meant to be the follow-on mission for NISAR. Despite the name, an Ecosystems component is an essential part of the mission.
  - Surface Topography and Vegetation (**STV**) – intended to estimate vegetation vertical density profiles, likely using a combination of TomoSAR and Lidar
- Begin planning for a follow-on P-band mission
- Coordination with JAXA, CONAE, DLR, ISRO, to leverage resources and improve frequency of observations (e.g. 3-day repeat to capture weather variations.
- Keeping consistent time series over decades is fundamental, building on the 3-decade L-band data record by JERS-1, ALOS and ALOS-2.





Observation requirements for Wetlands

Ake Rosenqvist (JAXA, Japan)
Laura Hess (UCSB, USA)



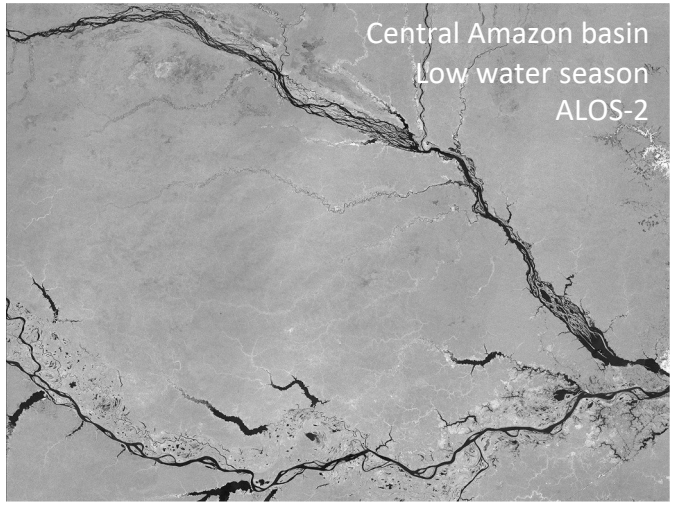
Policy Requirements

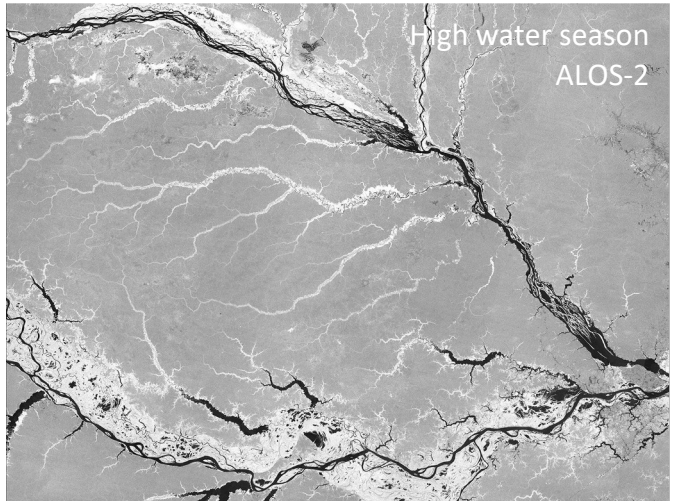
- **Ramsar Convention**: Use of EO to support wetland inventory (*location & type*), assessment (*condition*), monitoring (*changes over time*), and conservation (*sustained monitoring*)
- **UNFCCC/IPCC:** Wetlands as sources (CH4) and sinks (CO2) of Carbon
- **UN-CBD/GBF**: Wetlands hotspots for biodiversity
- **UN SDG Indicator 6.6.1:** "Change in the extent of water-related ecosystems over time"
- Seasonal inundation regime – characterised by its spatial and temporal variations – is an Essential Wetlands Variable (EWV) and a prime descriptor of wetland ecosystems.
- Climate Change is having a profound effect on the global water cycle and wetland inundation dynamics

State of the art

- Capacity to detect standing water below a closed vegetation canopy
- Penetration valid for all SAR frequencies, sensitivity depending on type of wetland vegetation (L: forested wtl. / C: herbaceous, sparse wtl.)
- Dense SAR time-series allow detailed mapping of wetlands spatial and temporal characteristics (key EWV) within and between years
- For all SAR frequencies, HH pol provides superior sensitivity to inundation

- Fully polarimetric data:
  - Sensitivity to peat and bog wetness and water table depth through polarimetric decomposition. Different wavelengths different penetration depths
  - Polarimetric phase – improved mapping of Wetland vegetation structure and condition (e.g. degradation)
  - Compact polarimetry – R&D required to understand usefulness





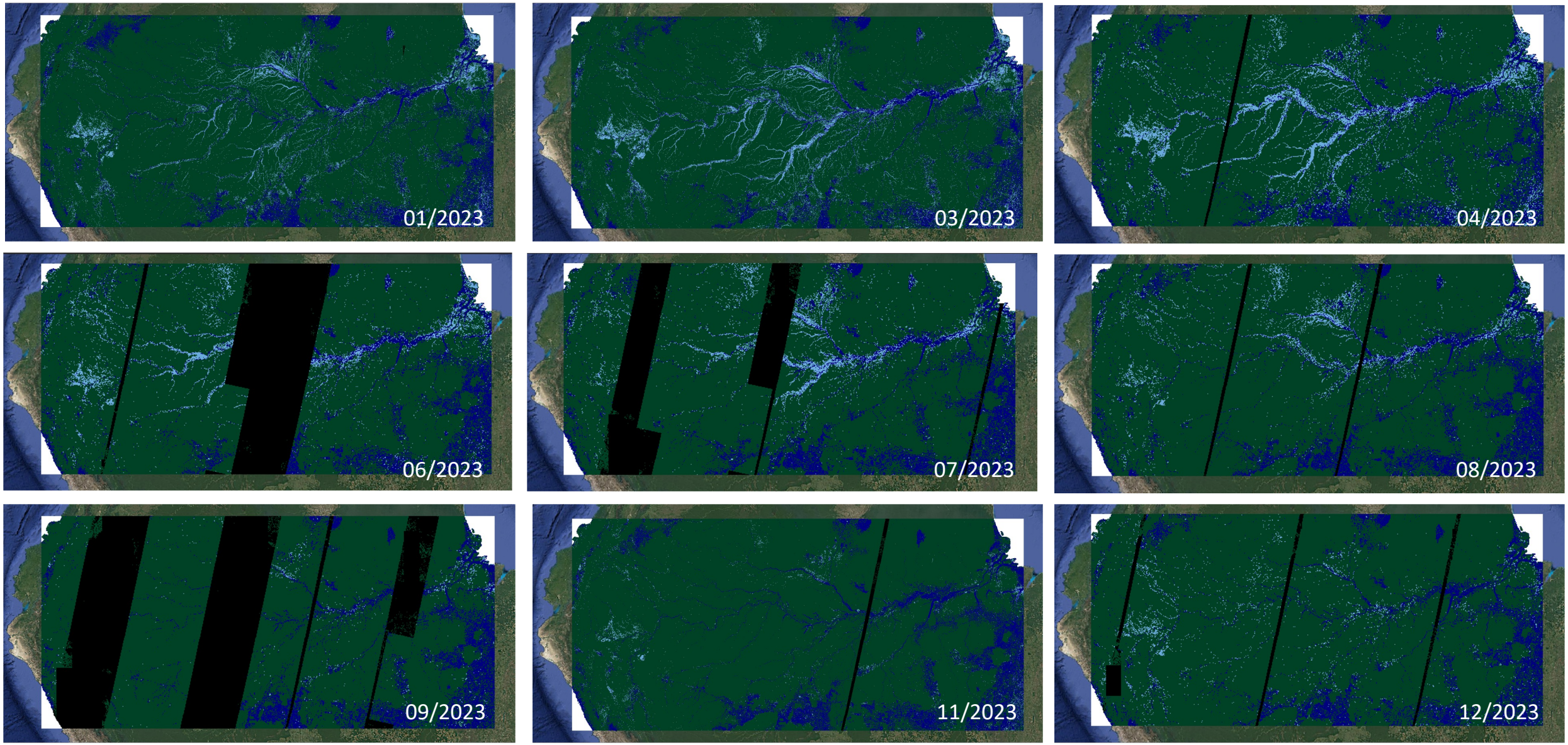
State of the art

- Systematic observations of pantropical wetlands by L-band (JERS-1, ALOS & ALOS-2) since 1990s
- C-band time series (Sentinel-1) widely used for boreal and herbaceous wetland mapping.
- Operational use of L-band for global mangrove monitoring (Global Mangrove Watch)

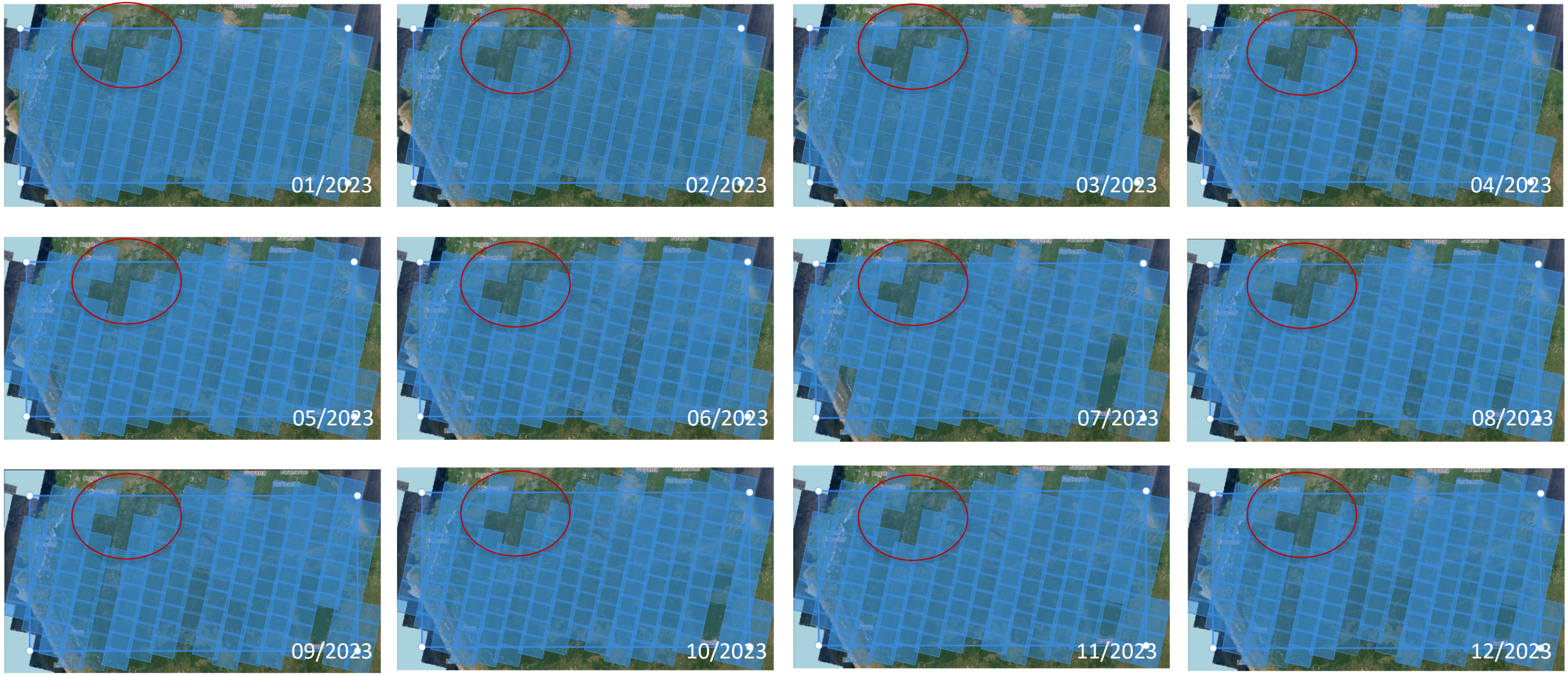
Gaps:

- L-band focus on tropical wetlands. Lack of data over temperate and boreal wetlands.
- Temporal sampling (~1.5 months) insufficient to capture flood dynamics
- Time series is everything. Gaps in the acquisition coverage – severe detriment to the value of the archive
- Lack of freely available C-HH data
- Canopy penetration is limited even at L-band for some wetland types (mangroves); Interest in P-band capability (R&D)
- Systematic Polarimetric observations required for water table monitoring in peatlands

Amazon Basin monthly inundation extent – derived from ALOS-2 PALSAR-2

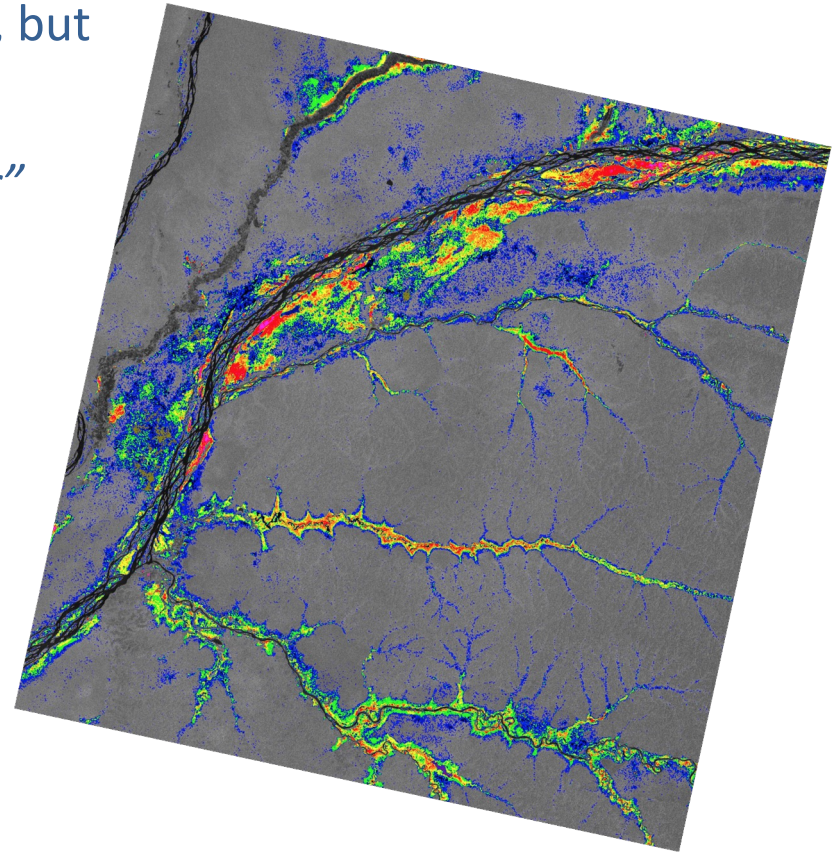


Amazon Basin monthly observations by Sentinel-1A



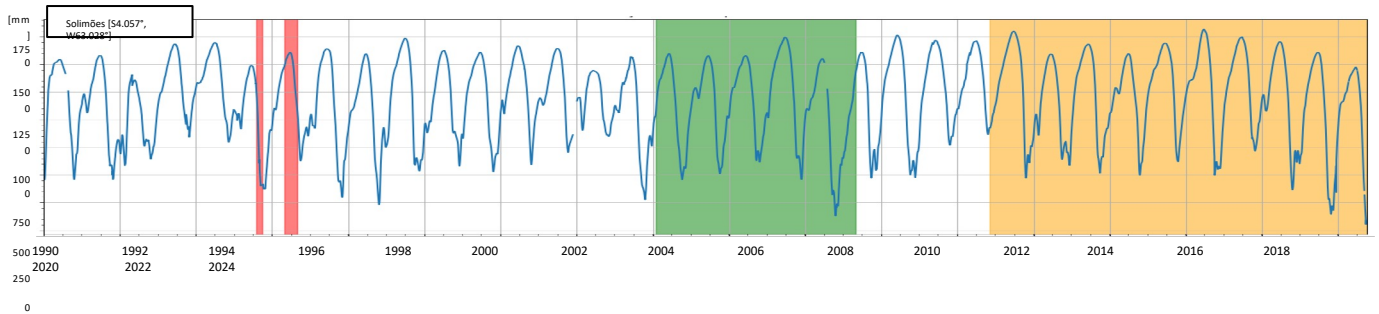
Recommendations for current and near future SAR missions
(ALOS-4, NISAR-L, NISAR-S, SAOCOM-1, Sentinel-1, RADARSAT)

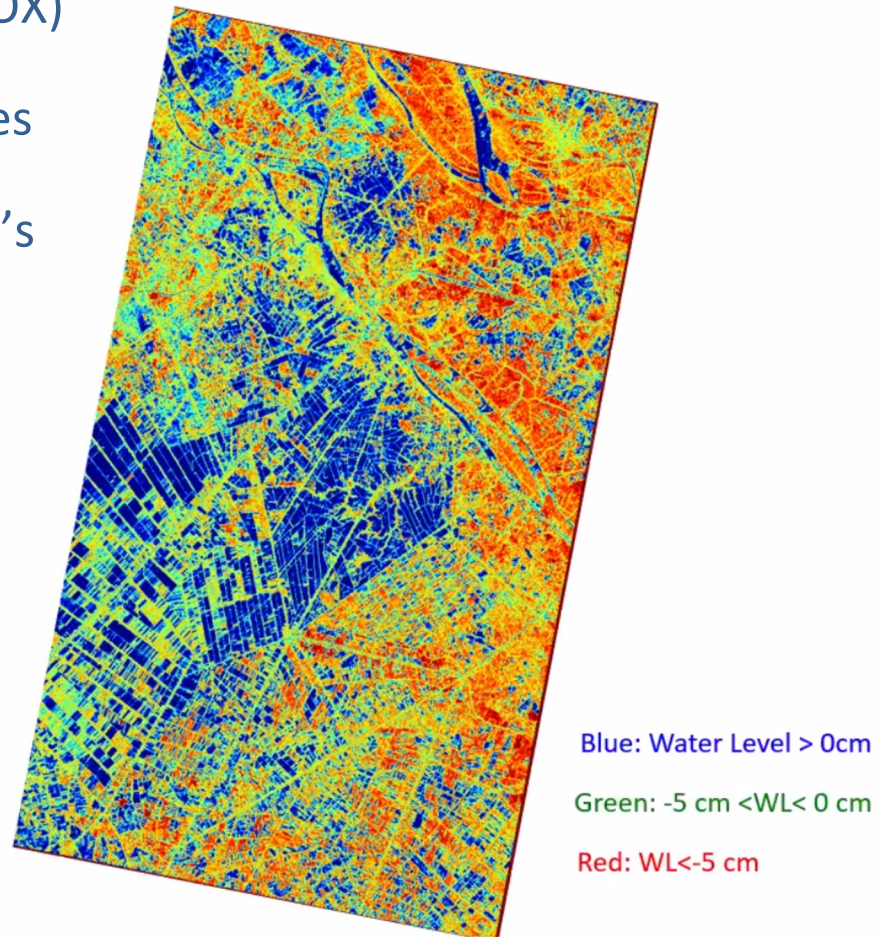
- Continued uninterrupted systematic L-band wide-swath time-series observations (DP or QP) over the world's wetlands. L-band critical, but all frequencies useful
- Minimise acquisition gaps!! *"Data not acquired is data lost forever"*
- Spatial resolution of missions (10-25 m) is adequate.
- L-band mission complementarity
  - NISAR Dual-pol weekly observations
  - ALOS-4 Quad-pol multi-seasonal observations
  - Access to SAOCOM-1A/B systematic archive
- Access to systematic C-HH or S-HH data



Suggestions for brave mission solutions in the next decade (2030s)
(ALOS-NG; SAOCOM-2, ROSE-L, Sentinel-1NG; SDC/SVT; TerraSAR-FOX)

- Future missions to consider wetlands as part of mission objectives
- Continuity of systematic time-series observations over the world's wetlands at all SAR frequencies
- Temporal revisit: ~weekly
- Spatial resolution: 10-25 m
- Polarimetric observations at C-band for irrigated rice (CH4)

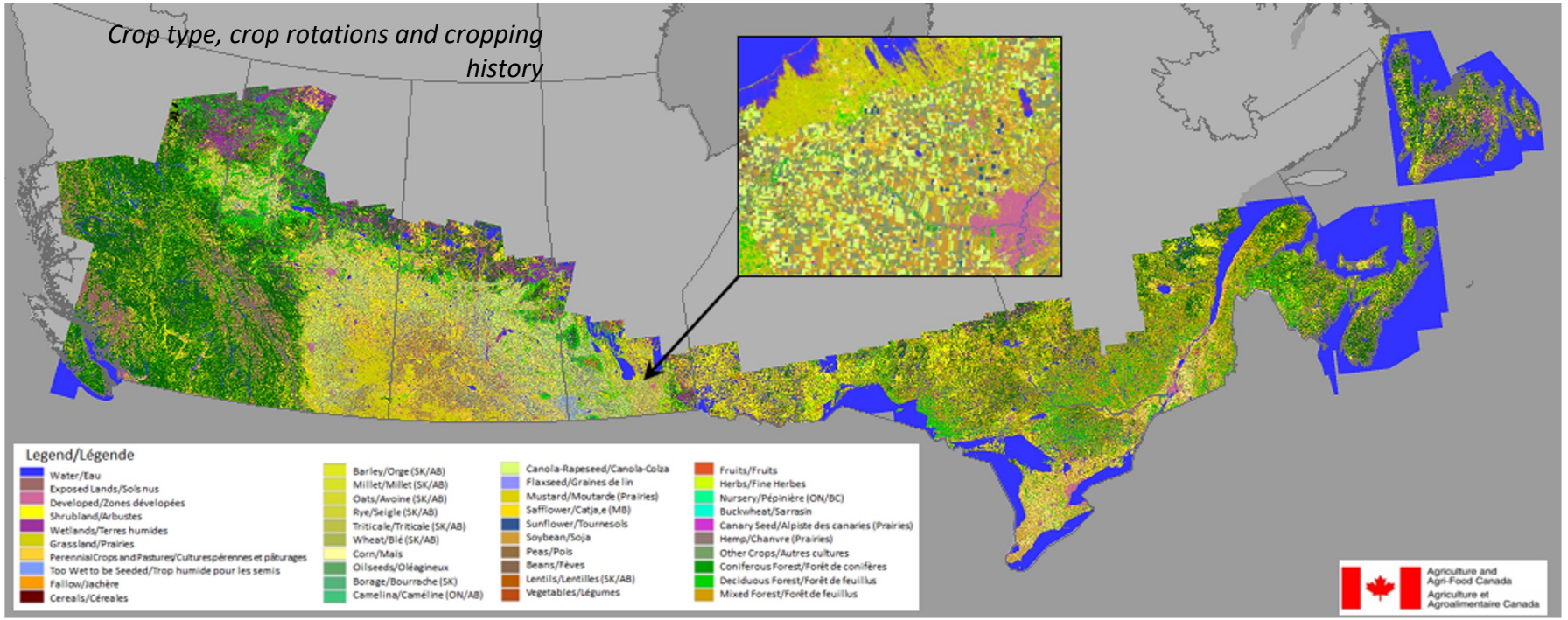




[Arai et al. 2022]

Agriculture & Crop Monitoring

Heather McNairn (Agriculture Canada)

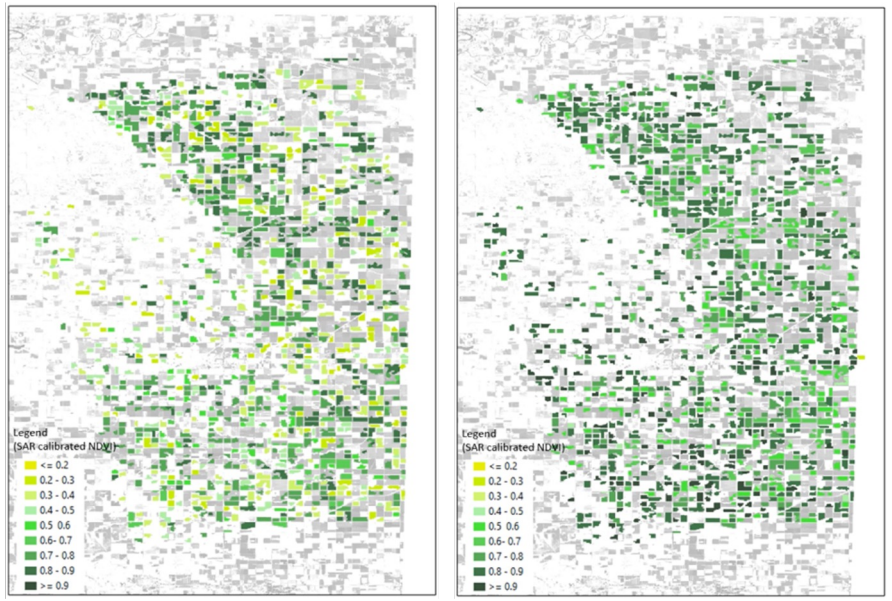


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State of the Art & Gap analysis

- Accuracies needed for crop classification, to feed operational needs (not research), have required the integration of SAR + optical primarily due to lack of multi-frequency and high temporal coverage over all agricultural regions
- Machine Learning models and semi-empirical modelling have demonstrated that SAR can estimate crop bio-physical parameters including LAI, biomass and phenology, and can track crop development over the season (primarily still in research/demonstration phase)
- Greatest limitation is the limited access to multi-frequency and high temporal repeat over the geographies needed to move from demonstration and to support operational needs (these feed downstream users and thus products must be robust, repeatable and dependable)

Crop productivity and crop condition

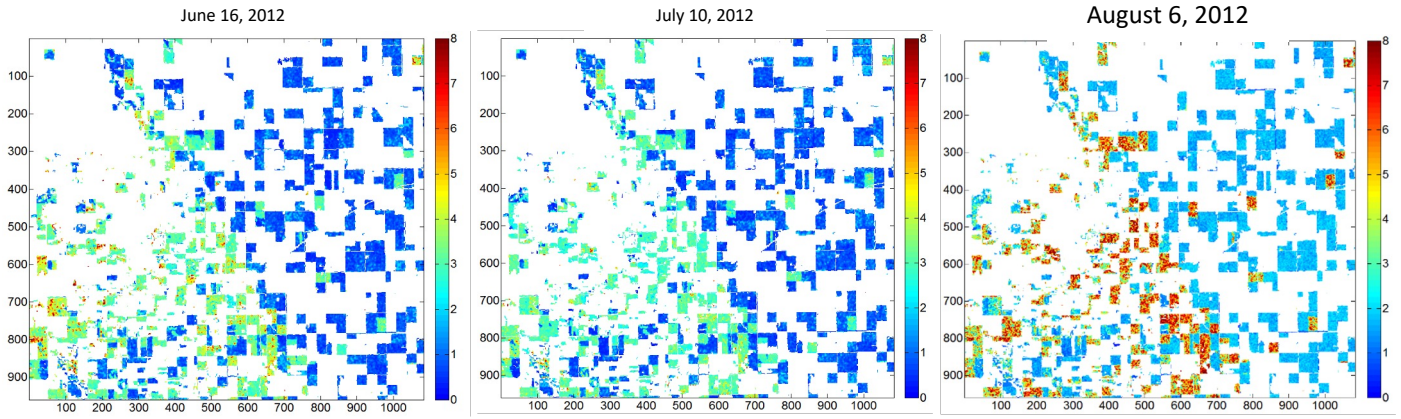


Tracking crop development for corn, soybeans, wheat and canola using a Sentinel-1 derived vegetation index

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Suggestions for current and near future SAR missions

- Coordination of virtual constellations to improve temporal coverages and access to multi-frequency datasets beyond research sites and localized monitoring. Uptake in operations requires coverages that are predictable, repeatable and dependable.
- Consider use of Compact Polarization modes on current and near future missions.



Leaf Area Index for corn and soybeans using a semi-empirical model and RADARSAT-2

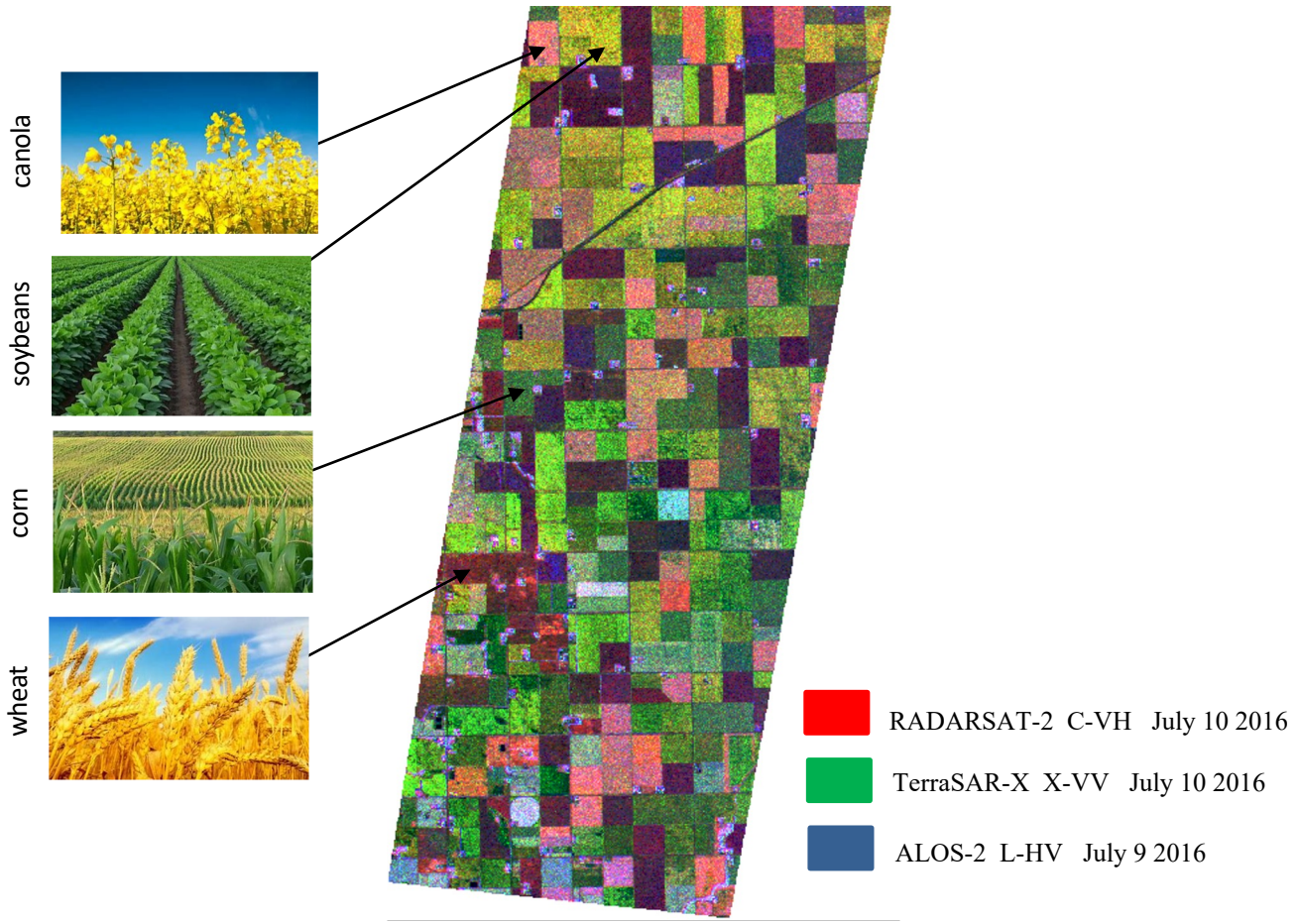
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Mission Solutions In the Next Decade

- Multi-frequency with improved polarization diversity beyond dual-pol (Compact Polarimetry, for example). Ideally multiple frequencies are on the same satellite. No single polarization is best.

- We need to fill the gap for X-band large area coverage.

Integration of data from RADARSAT-2, ALOS-2 and TerraSAR-X
Manitoba (Canada)



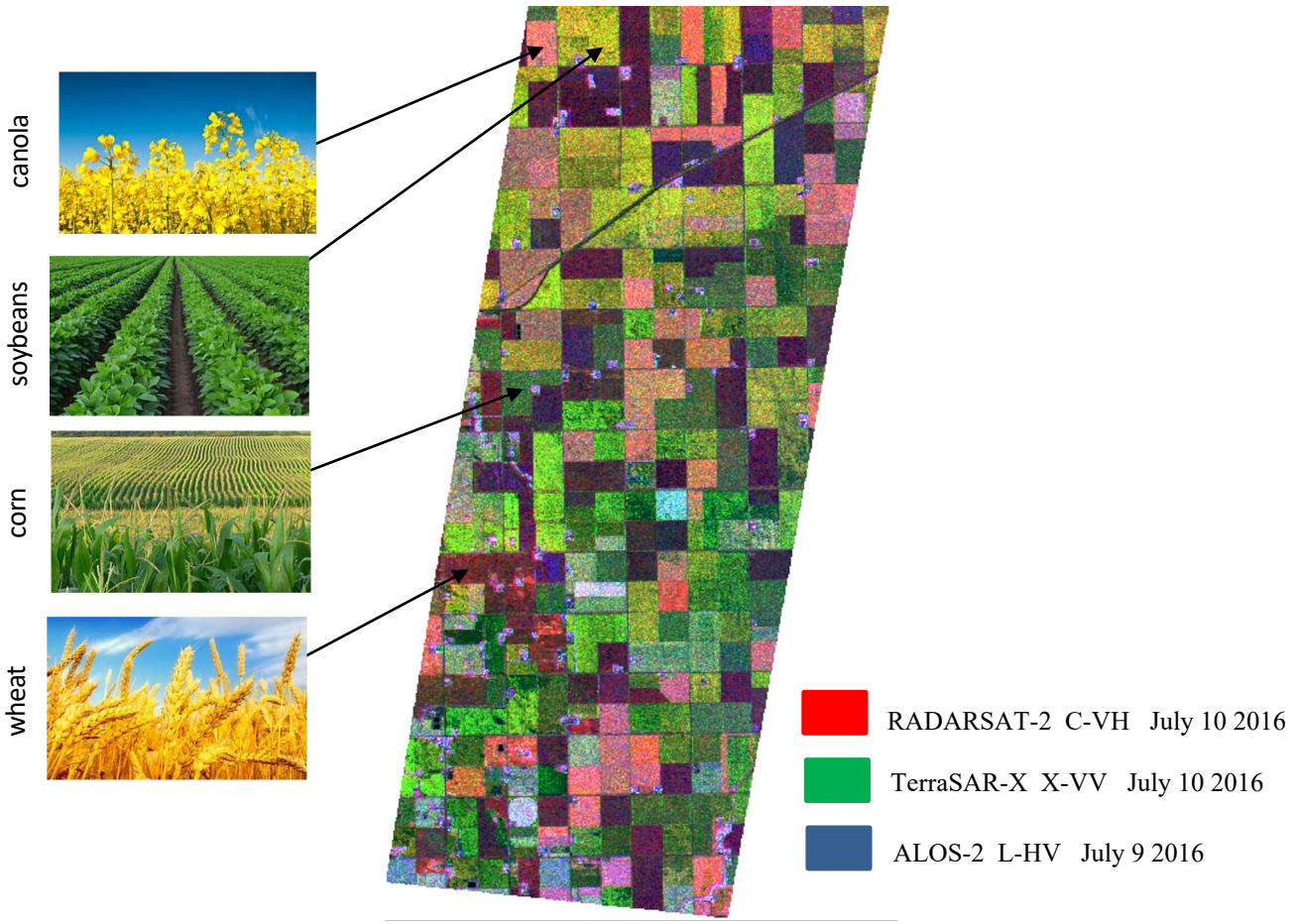
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Mission Solutions In the Next Decade

- Temporal domain is key to success and requires that these rich data sets are available as a dense time series over large geographies. For example, outside of Europe, the repeat coverage of Sentinel-1 is not enough to drive many operations (every 12 days is insufficient).

- There is no exact temporal repeat recommendation as this varies depending on application (crop mapping versus crop condition monitoring) but keep in mind that most crop canopies change quickly over just a few days. In research, we consider observations >3 days apart to likely be different due to changing crop structures.

Integration of data from RADARSAT-2, ALOS-2 and TerraSAR-X
Manitoba (Canada)



Sea Ice

Malin Johansson (U. Tromsø)

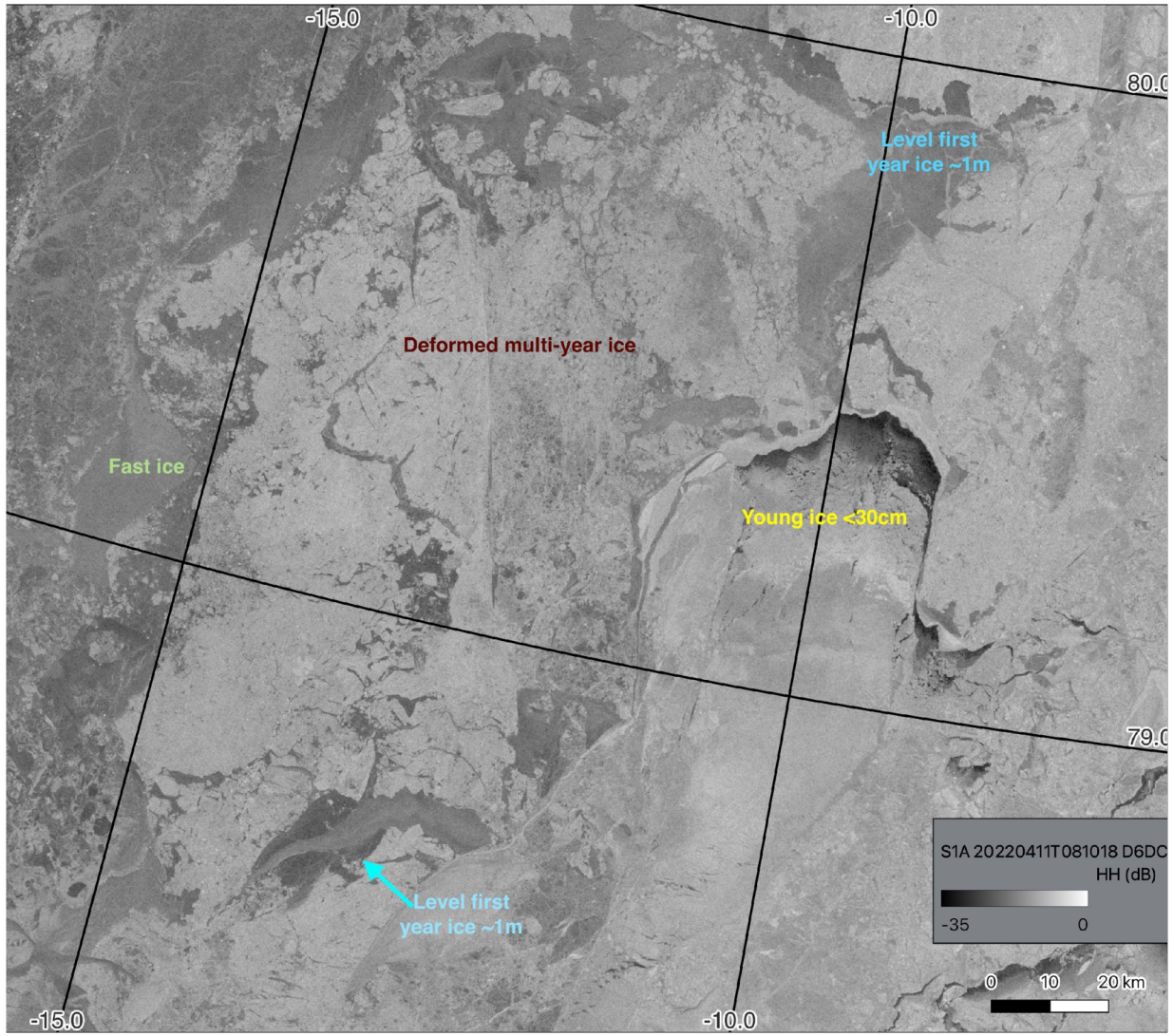
1. State of the Art

- Monitor sea ice extent, concentration and type -> provided operationally by ice centres
- SAR
  - High spatial resolution combined with a wide areal coverage -> Local and regional sea ice processes, 100–1000 m
  - Near real time delivery of the ice conditions -> safe maritime operations
  - Improve our understanding of the interaction between atmosphere, sea ice, and ocean
  - Ridges, leads and polynyas
- Can aid monitoring of heat, gas and light exchange on a Pan-Arctic Scale
- More data is collected than used -> machine learning, AI etc

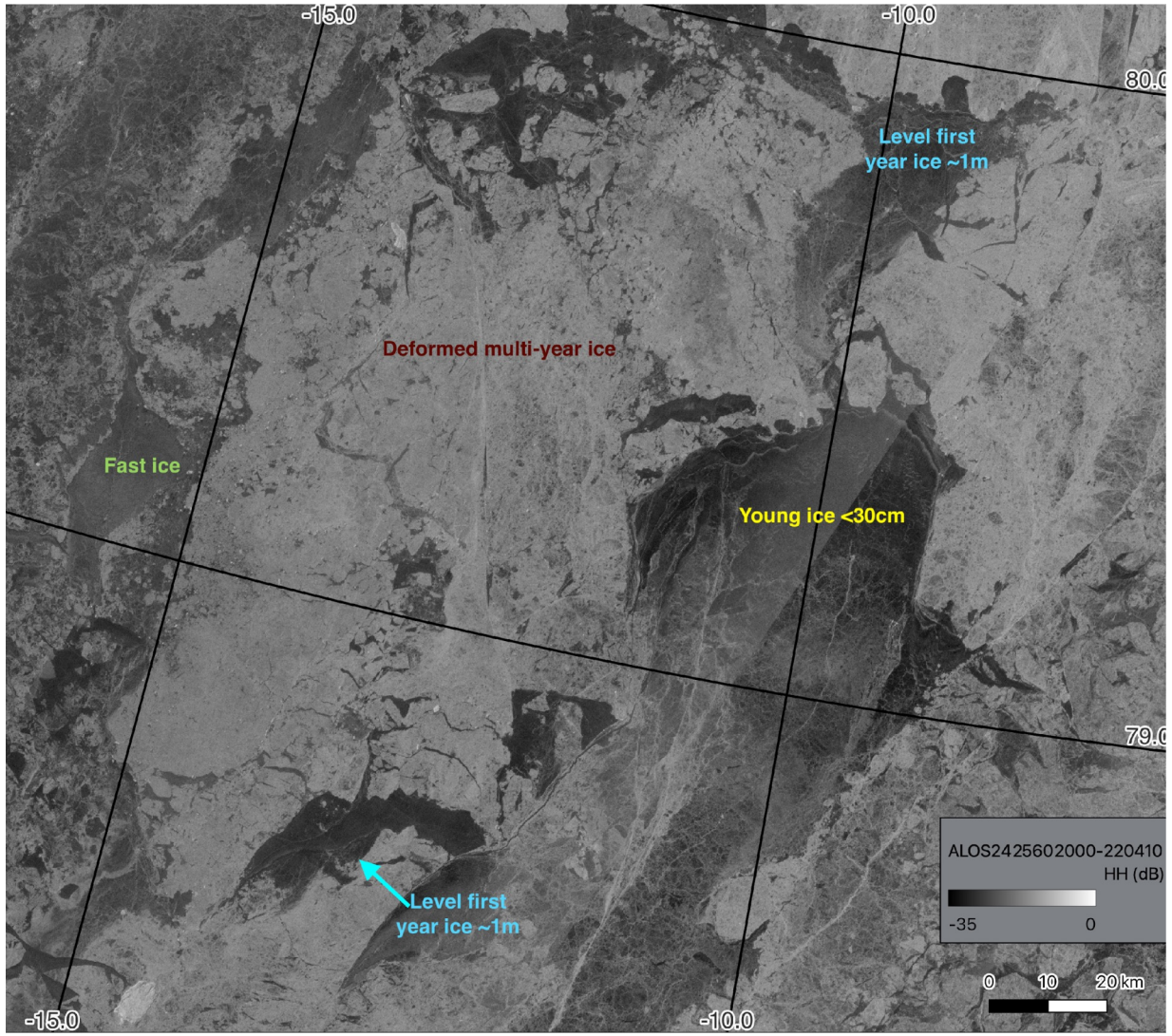
Gap analysis

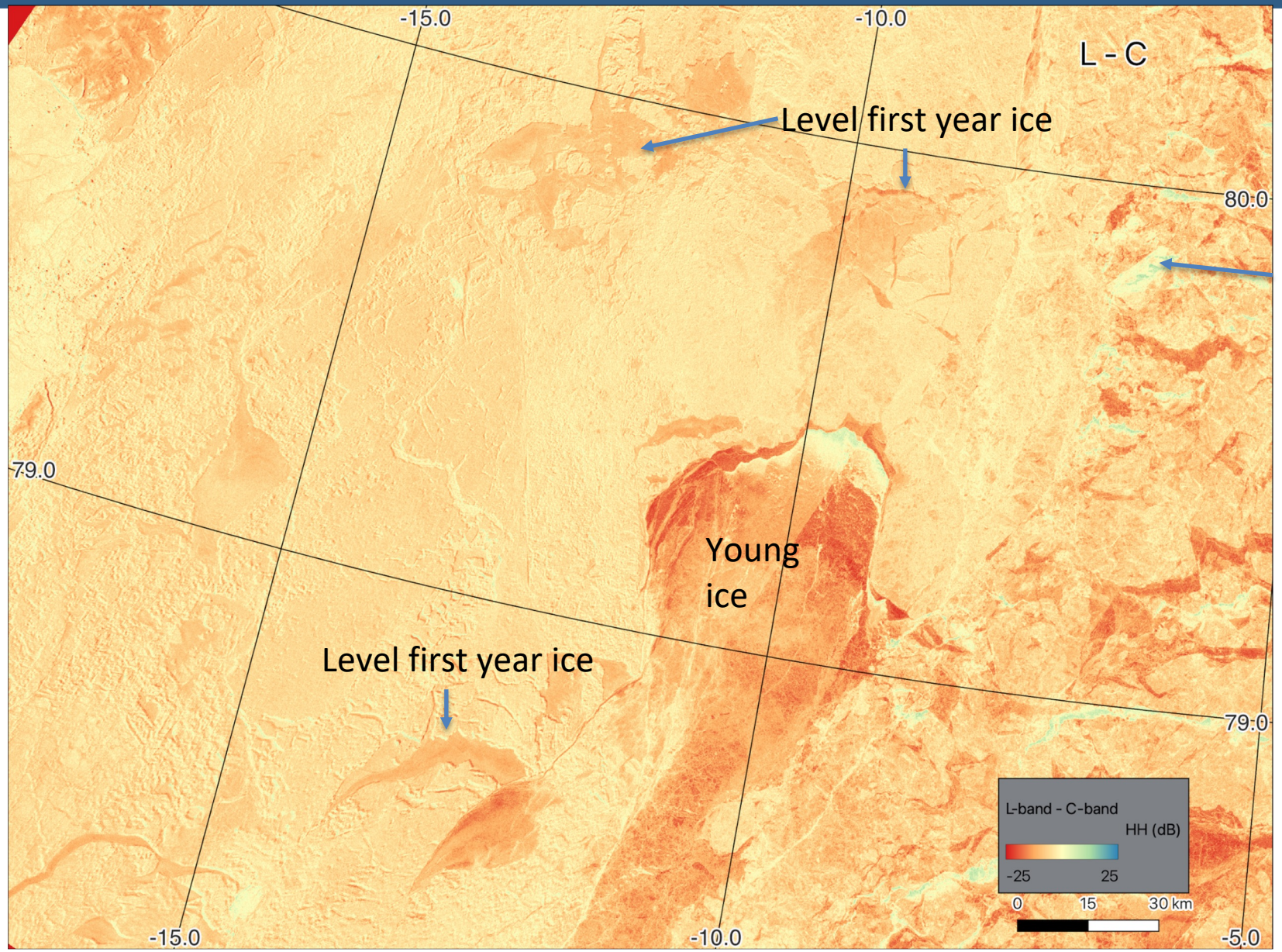
- Poor Antarctic coverage -> NISAR will address this
- Separation between open water and sea ice areas
  - Open water areas roughened by strong winds -> look like thick sea ice
  - Calm water surfaces and thin ice -> good noise floor is essential
  - Noise level (NESZ) for cross-polarization often is too high for separating water and thinner ice classes
  - Snow on sea ice is a challenge -> rain on snow events, ice lenses, wind compacted lenses
  - Snow is a larger problem during the melt season, in the marginal ice zone and on flooded Antarctic sea ice.

C-band SAR



L-band SAR

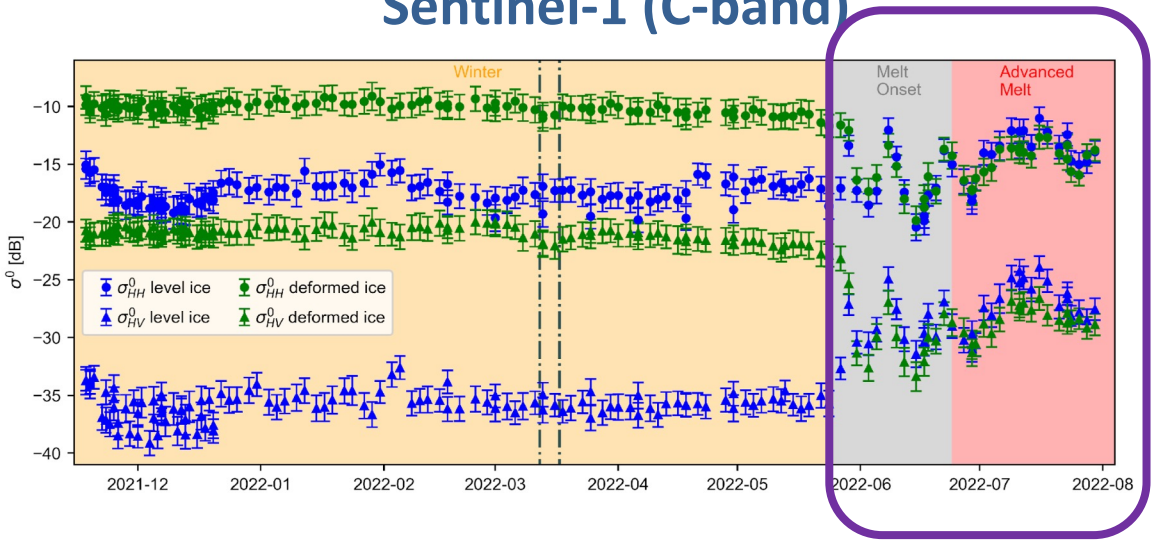



L - C
Level first year ice
Deformed multi-year ice
Young ice
Level first year ice
-15.0
-10.0
80.0
79.0
79.0
-15.0
-10.0
-5.0
L-band - C-band
HH (dB)
-25
25
0
15
30 km

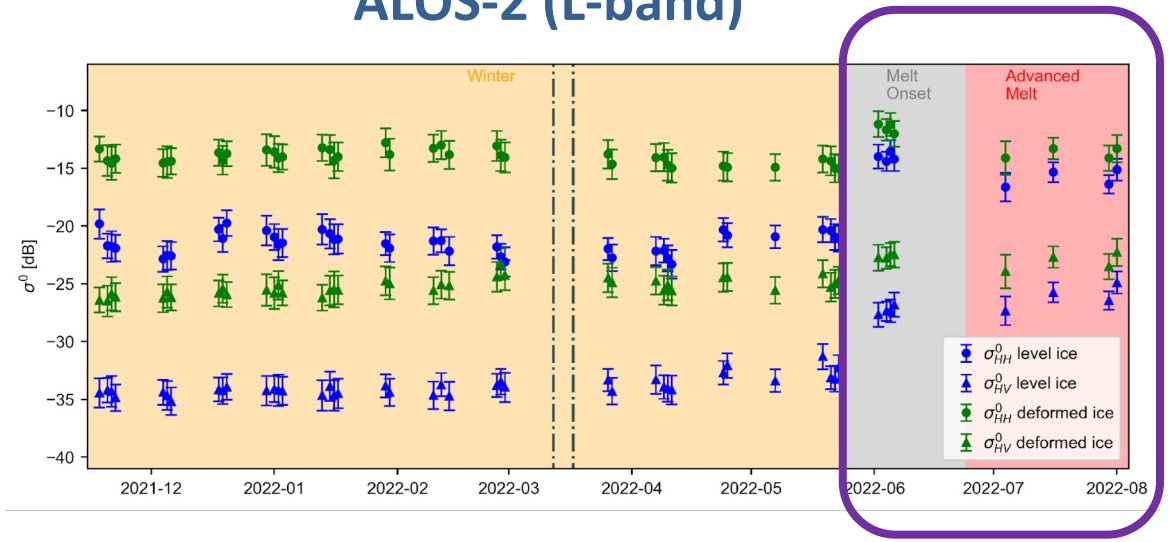
2. Suggestions for current and near future SAR missions

- Multi-frequency and polarimetric SAR data can help to overcome these ambiguities
  - L-band SAR coverage essential during early melt season -> separation of rough and deformed ice from smooth level ice
  - L-band data preferable for deformation
  - High temporal resolution data during the melt season can address some of these shortcomings.

Sentinel-1 (C-band)



ALOS-2 (L-band)

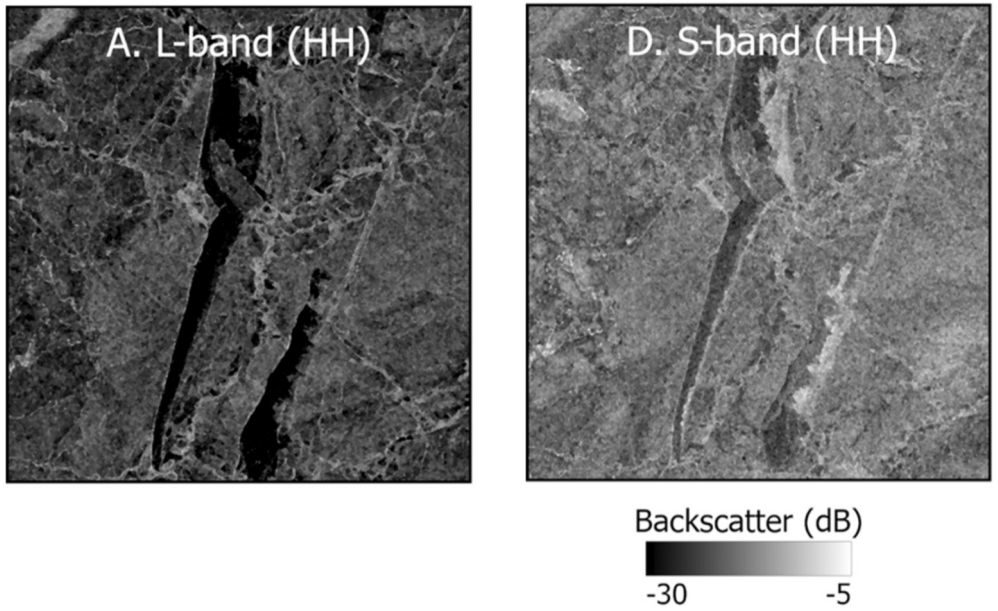


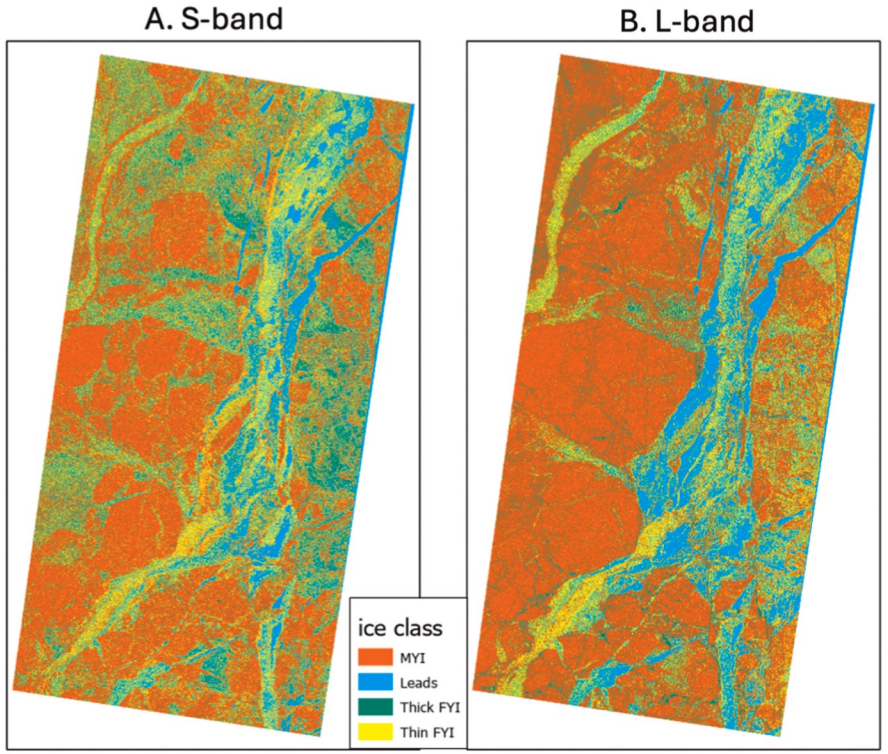
Karlsen et al, 2024

2. Suggestions for current and near future SAR missions

•Data with temporal gaps 10s minutes – hours is difficult for drifting sea ice. -> Solution tandem constellations consisting of L- and C- or X-band satellites

•NISAR will offer simultaneous S- and L-band SAR over Beaufort Sea -> showcase the usefulness of multi-frequency SAR without the need to drift correct the data.





Mahmud et al, 2024

2. Suggestions for current and near future SAR missions

•High temporal resolution -> improved ice motion, deformation (convergence/divergence)

•Multi-frequency data can help overcome issues with snow retrievals -> in particular for X- and C-band





Photos: T. Karlsen

Snow Thickness	Penetration Depth		
	Ku-Band	X-Band	C-Band
14 cm	2 cm	4 cm	6 cm
8 cm	2 cm	3 cm	4 cm
4 cm	1 cm	2 cm	3 cm

Nandan et al, 2017

3. Suggestions for brave mission solutions in the next decade (2030s)

- L-band SAR constellation mission

- Nearly simultaneous C- and L-band observations
  - Tandem flight pattern for ROSE-L and Sentinel-1
  - Braver -> one satellite platform with C- and L-band

- Combine two SAR for increased detection of icebergs (i.e. resolution <10m) and wide spatial coverage (>400km)
  - Convoy of sensors is possible easier option, fly in parallel and cover adjacent swath

- Use RCM HH+VV mode in summer over the Arctic
  - Better for melt ponded time period
  - “Avoids” the low return signal issue

- Low noise floor
- Derive instantaneous surface motion from Doppler shift -> Done using simulated Harmony data (Kleinherenbrink et al. (2021)) –> SNR not good enough

- Coordination also with passive microwave, altimeter, optical sensors etc -> which sensor combination is most needed?