# Sea Ice Classification Using Edge AI for Synthetic Aperture Radar Satellite On-board Image Processing

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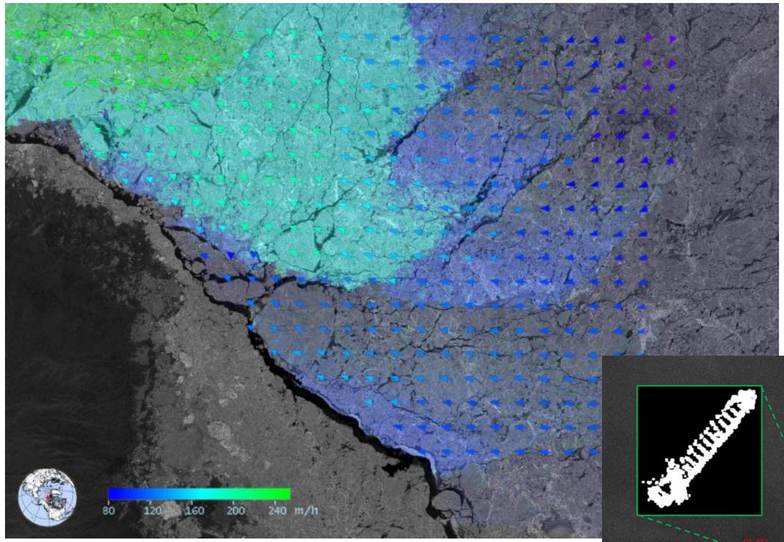
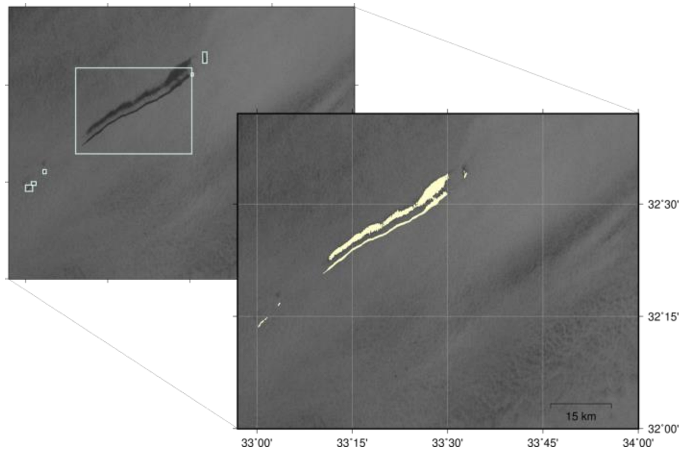
DLR

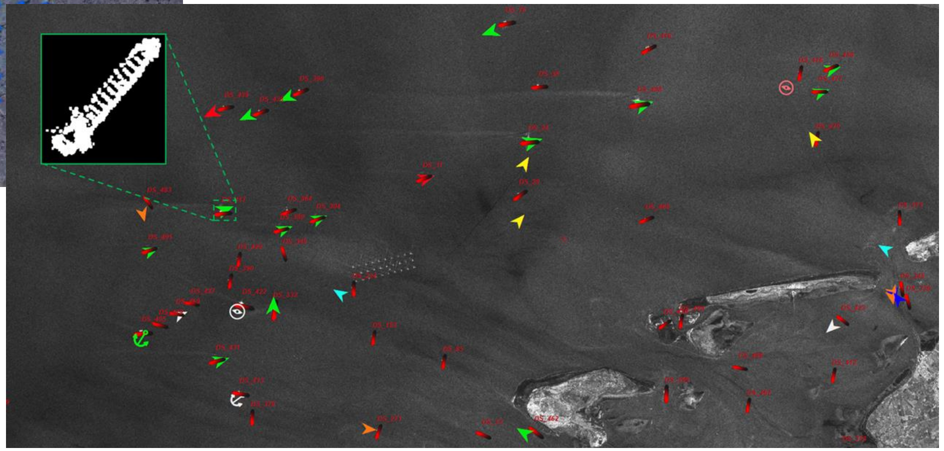
# Background

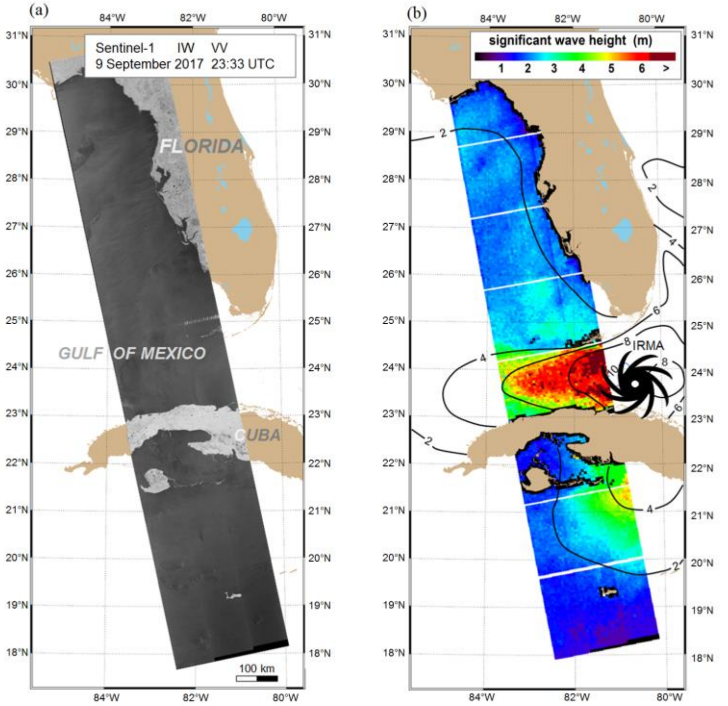


Sea ice drift



Oil spill


Maritime traffic



Wind speed & wave height

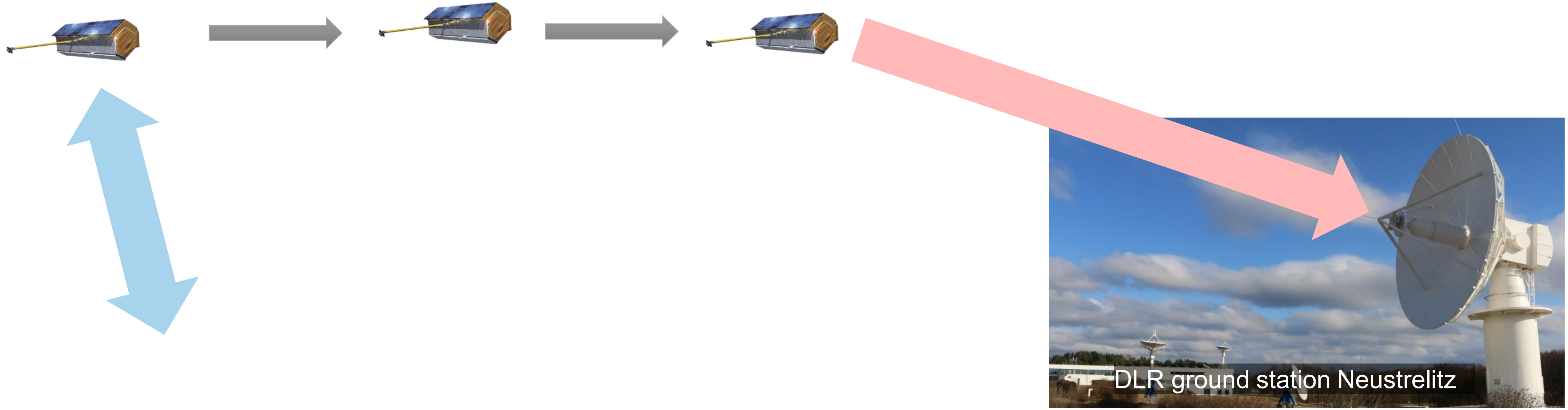
- State of the oceans changes constantly
- Satellite images record a point in time
- Derived information decays rapidly

# Satellite Data Downlink

Data acquisition

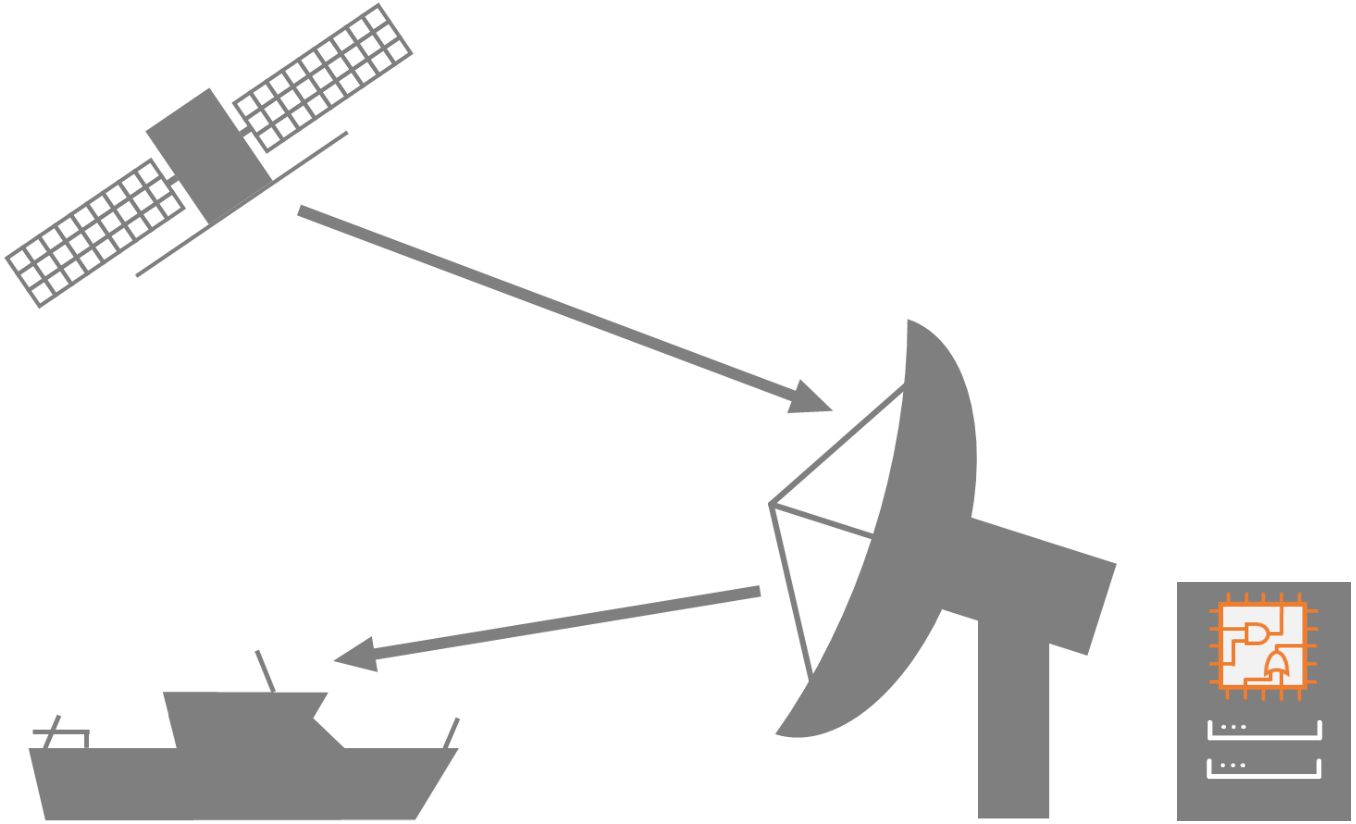
Continue flight

Data transfer to
ground station

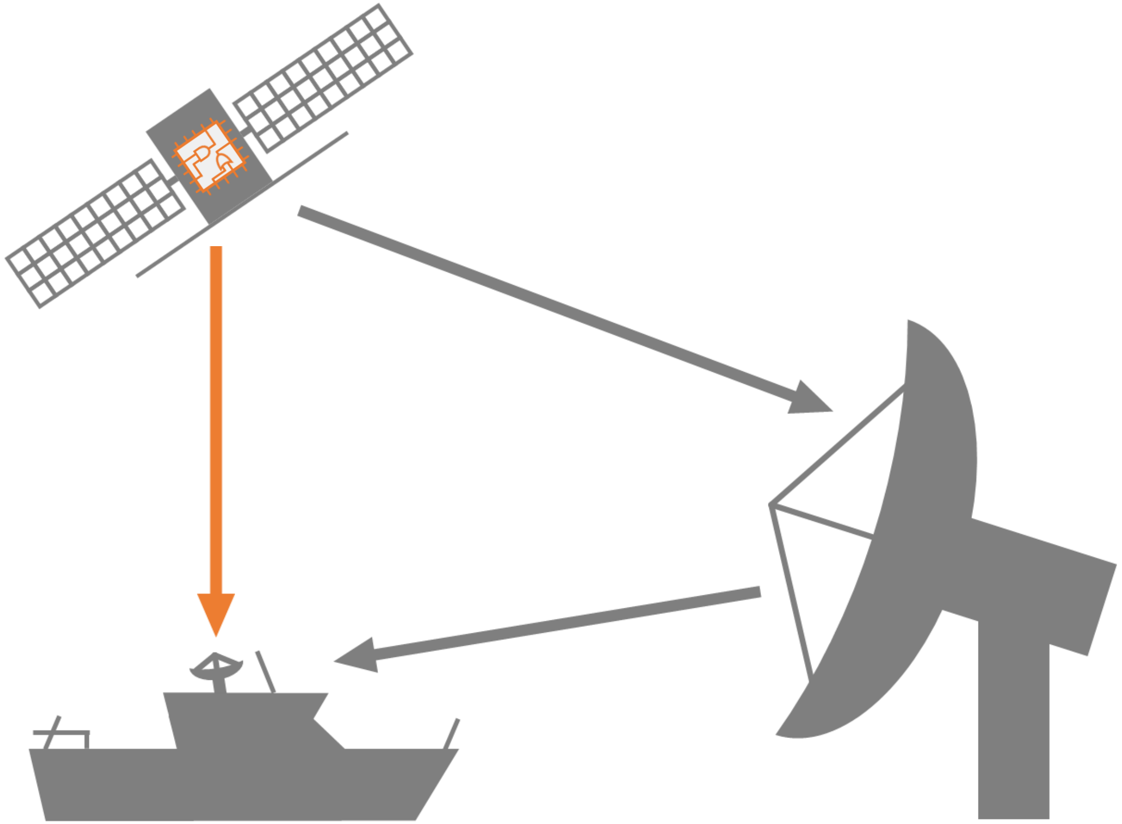



- Significant delay between acquisition and product delivery

# What if data is processed directly on the satellite?



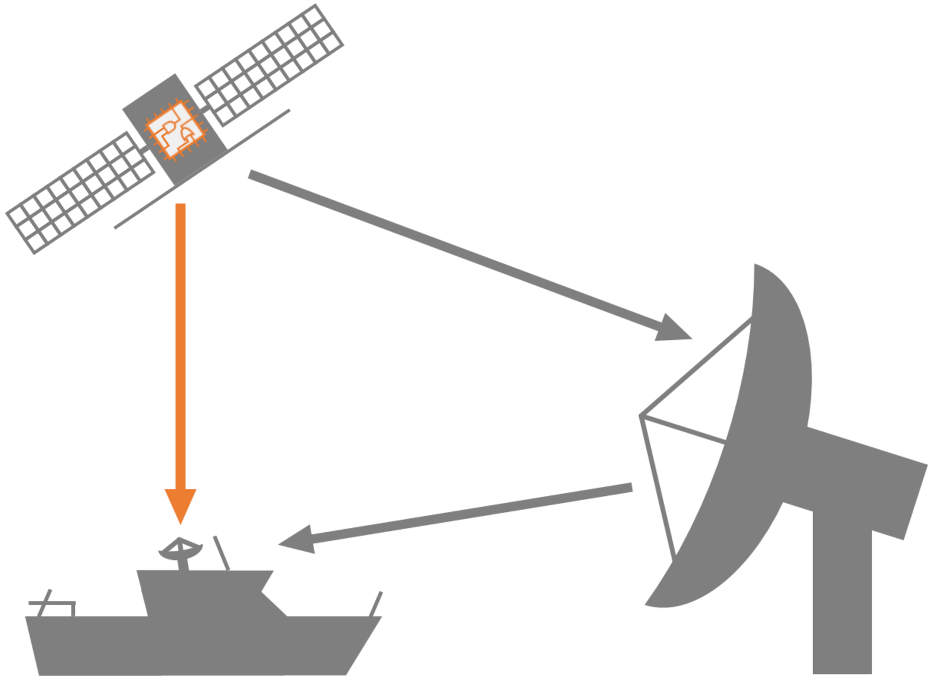
# What if data is processed directly on the satellite?



# What if data is processed directly on the satellite?

## On-board Data Processing

- Processing can begin right after acquisition
- Data volume significantly reduced
- Enables direct down-link to user (lower data rate required)
- Conventional down-link of full data still possible



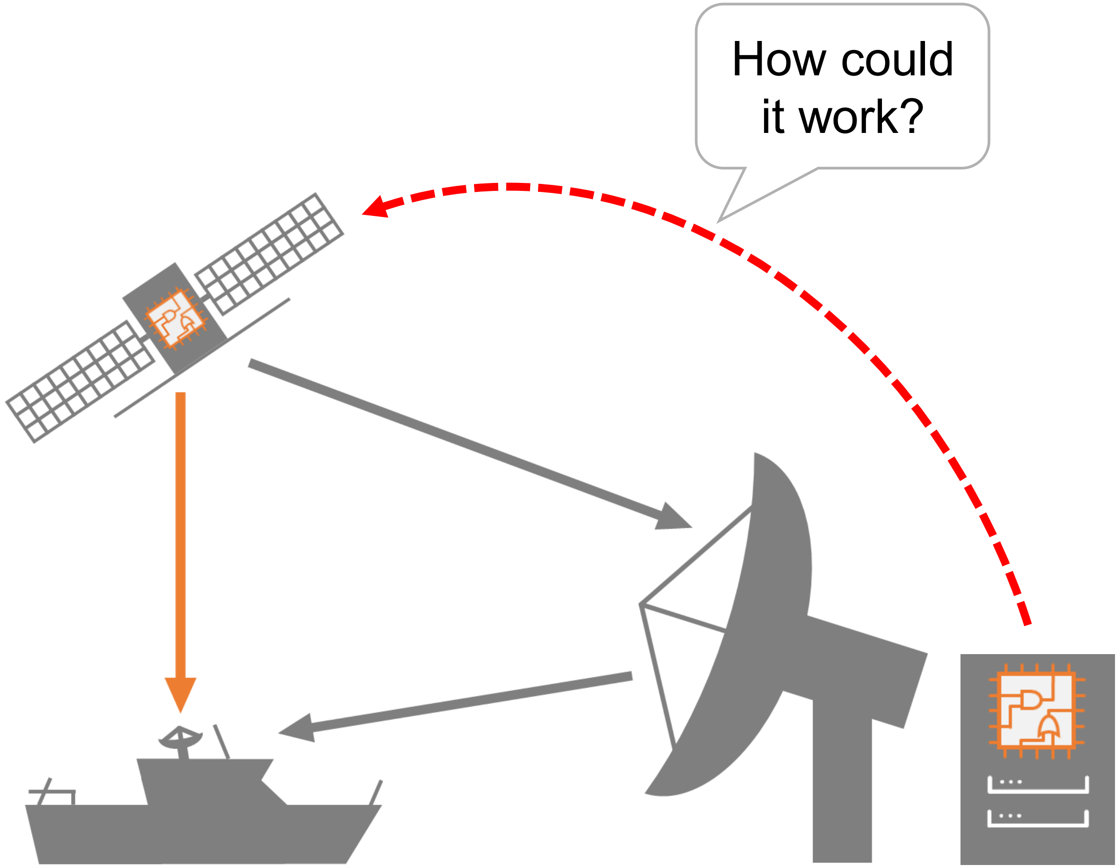
# What if data is processed directly on the satellite?

## Necessary Steps

- SAR acquisition
- Raw data focusing
- Information extraction
- Down-link

## On-board Constraints

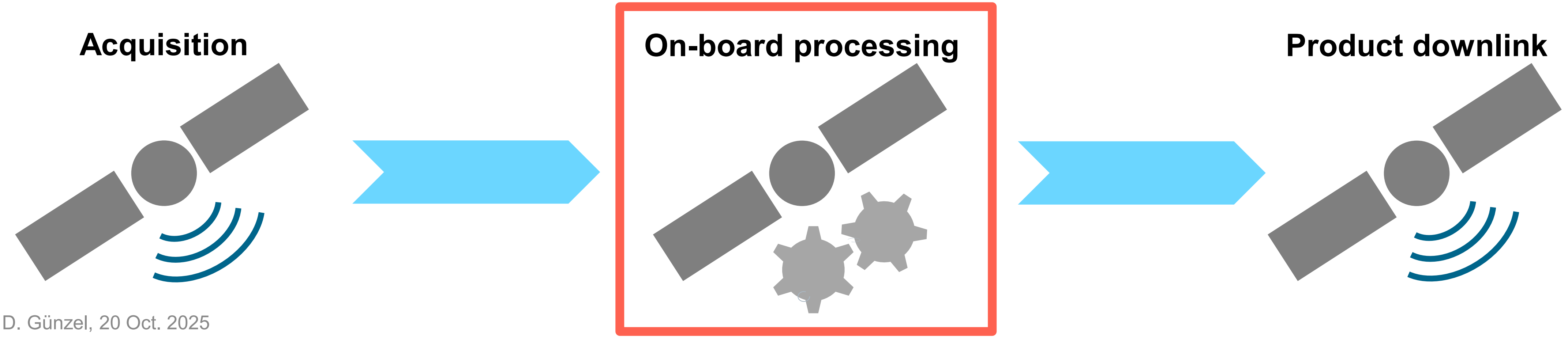
- Size, weight and power (SWaP)
- Radiation
- Technological
- Security



## Edge AI for Satellite On-board Image Processing

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101120726

- Implementation of (ground-based) demonstrator
- Application: Sea ice classification on Synthetic Aperture Radar (SAR) data
- Hardware comparable to satellite on-board devices



# Prototype Hardware

**Multi-Processor System-On-Chip (MPSoC)**

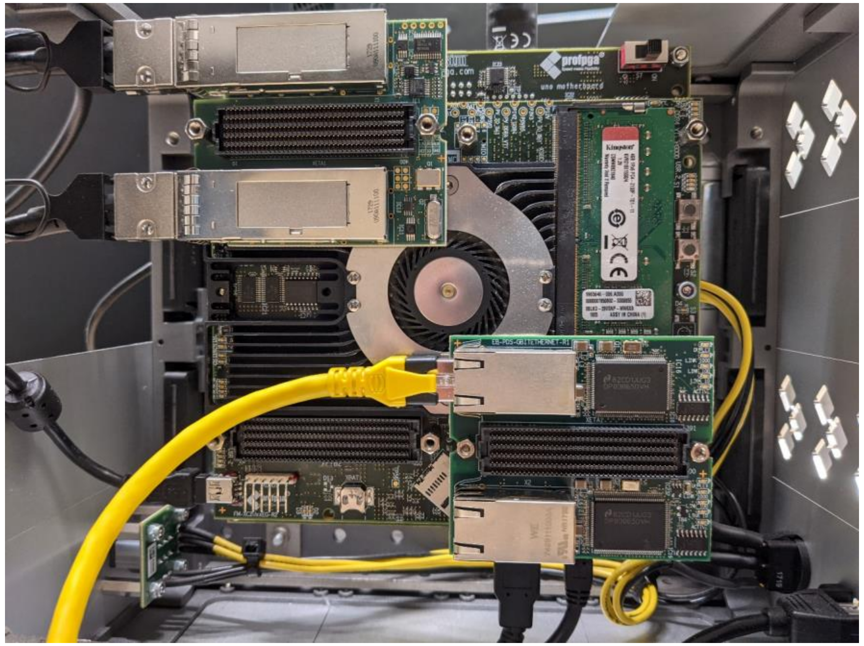
AMD Zynq UltraScale+ ZU19EG

- **Programmable Logic (PL)**

  FPGA 16nm FinFET+, 6.2M ASIC gates capacity; 5 GB DDR4

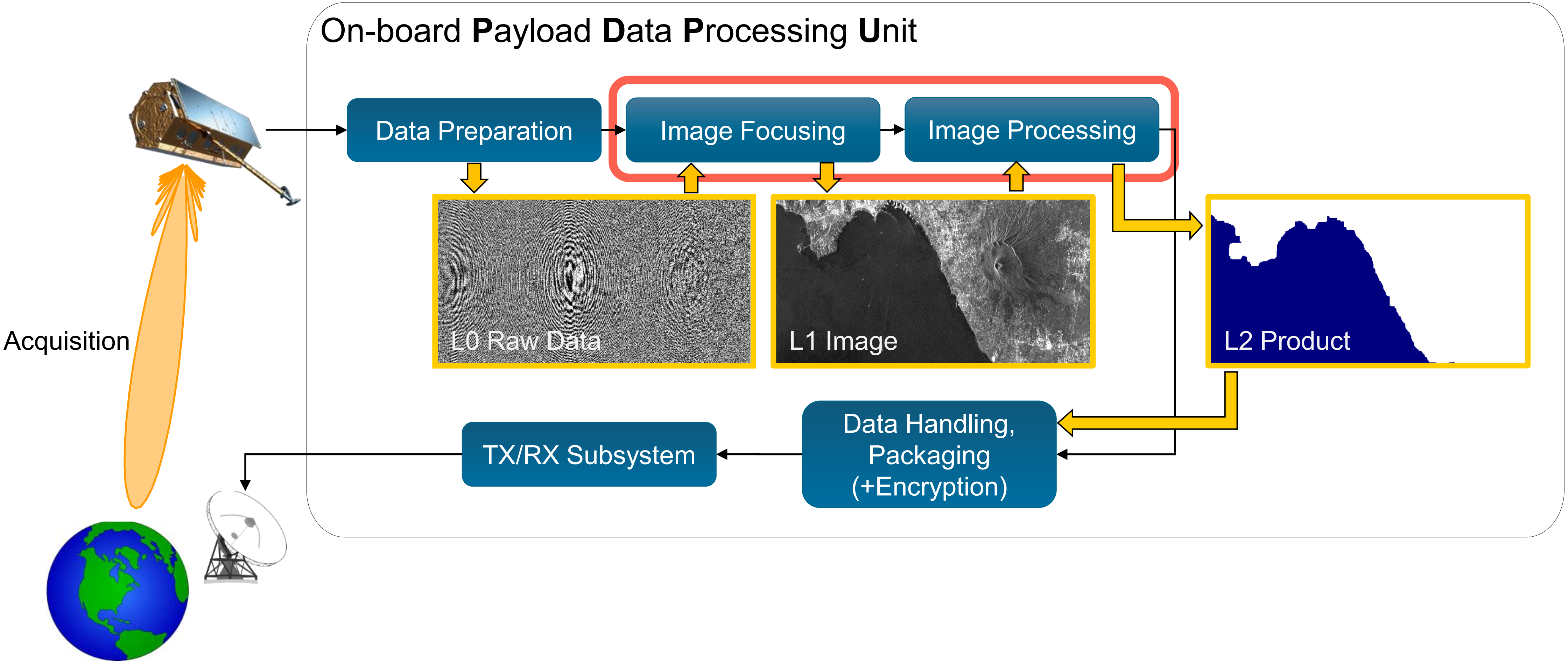
- **Processing System (PS)**

  Quad-core ARM Cortex-A53 CPU @ 1.2 GHz; 4 GB DDR4



Siemens Veloce proFPGA modular board

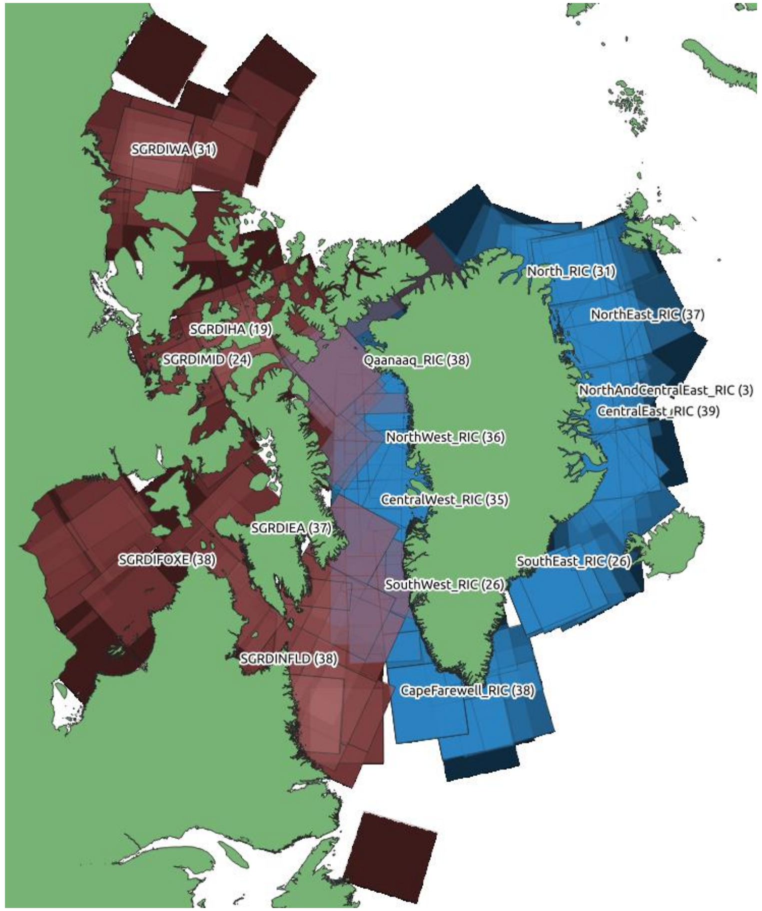
# SAR On-board Processing Chain



# Sea Ice Dataset

## AI4Arctic Challenge Dataset

- 533 manually labelled scenes
  - Canadian Ice Service
  - Danish Meteorological Institute
- Input data:
  - Sentinel-1 EW dual-pol (HH & HV)
  - SAR incidence angles grid
  - AMSR2 temperature data
  - ERA5 weather data
  - Distance to land
- Reference maps:
  - SIC: Total Sea Ice Concentration
  - SOD: Ice Stage of Development
  - FLOE: Floe size

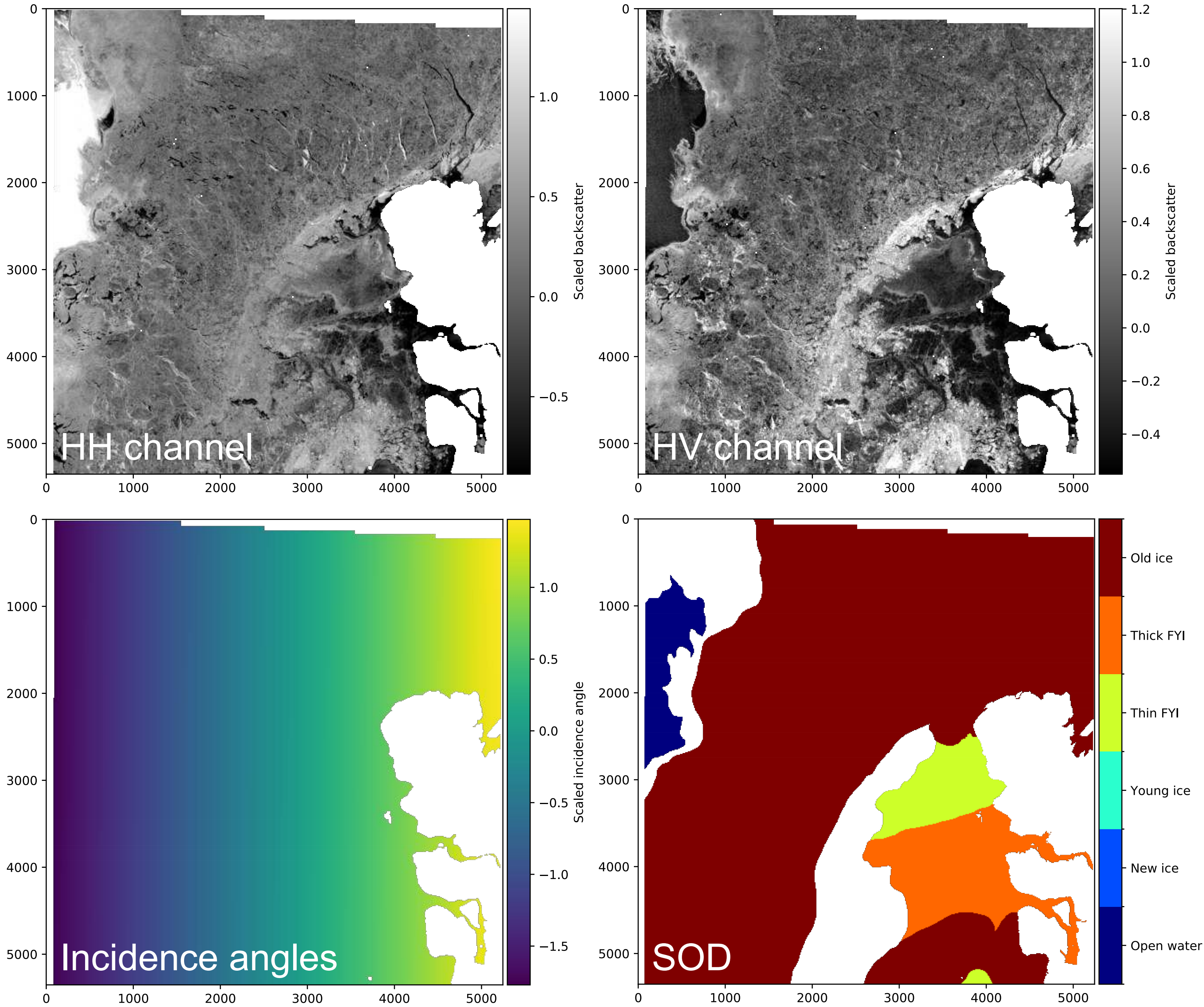



Coverage of the AI4Arctic Dataset*

* J. Buus-Hinkler et al., "AI4Arctic sea ice challenge dataset." https://doi.org/10.11583/DTU.c.6244065.v2 (Nov 2022)

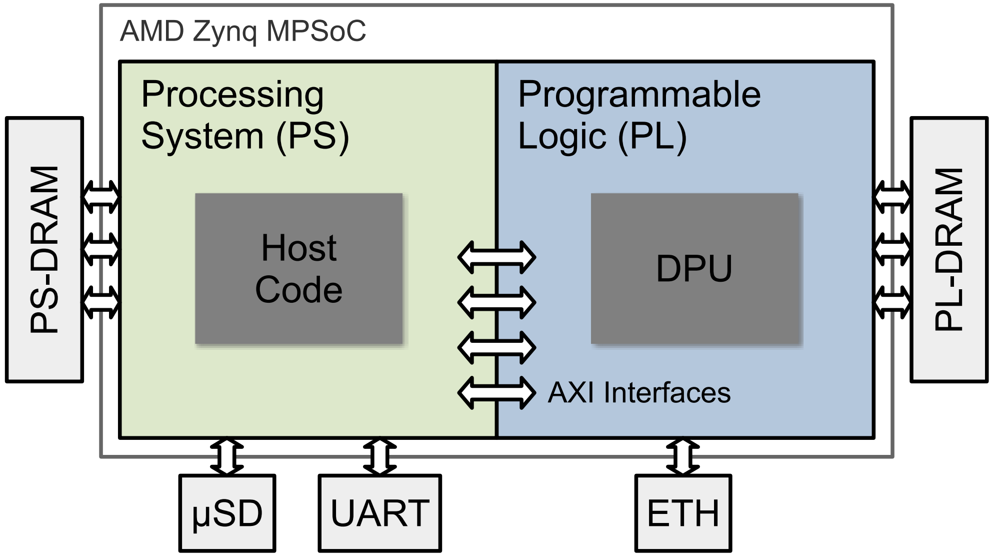
# Sea Ice Classifier

- U-Net
  - VGG13 encoder
  - Input size 512 x 512 pixels
  - 18.4 mil parameters
  - PyTorch framework
- Inputs
  - Sentinel-1 EW dual-pol HH & HV
  - Incidence angle of each pixel
  - ➢ Sliced into 512 x 512 px. patches
- Output: Segmentation map
  - Stage of Development (SOD)
  - Proxy for ice thickness
  - 6 classes



# CNN Implementation on MPSoC

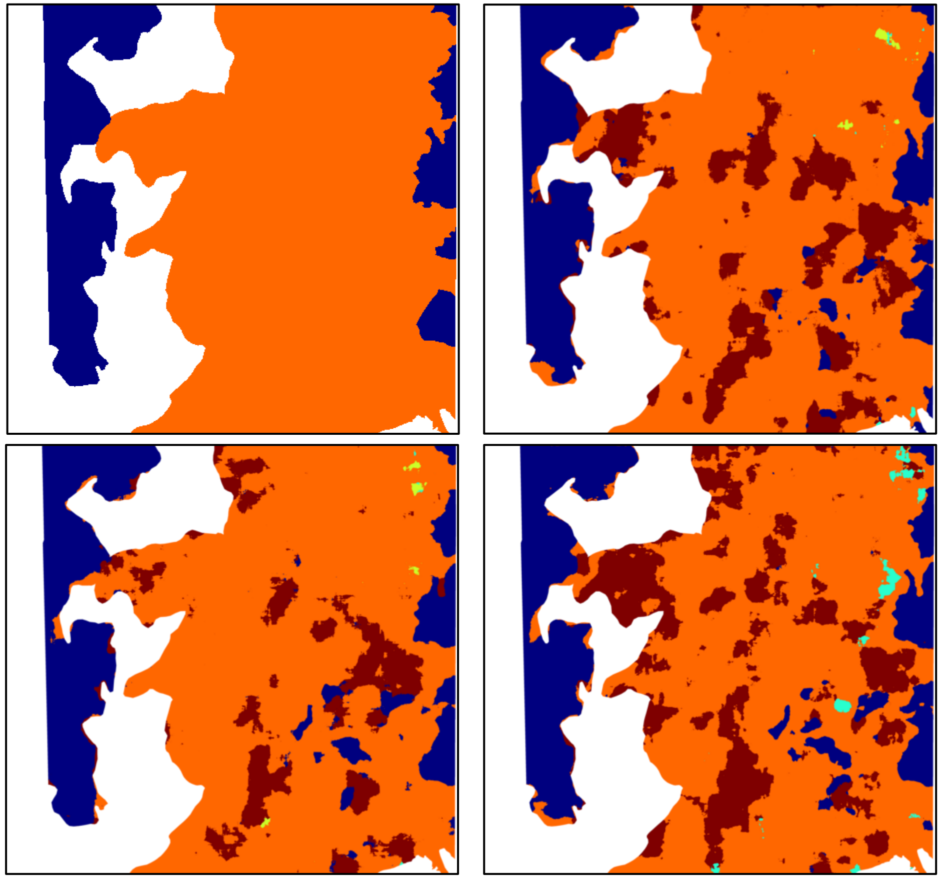
- AMD Deep Learning Processor Unit (DPU) for Zynq UltraScale+
  - Implemented in PL logic
  - Offers set of common operators
  - Programmed via Python/C++ API
- Vitis AI toolchain for model porting
  - Inspection
  - Pruning
  - Quantization
  - Compilation




DPU integration on AMD Zynq MPSoC

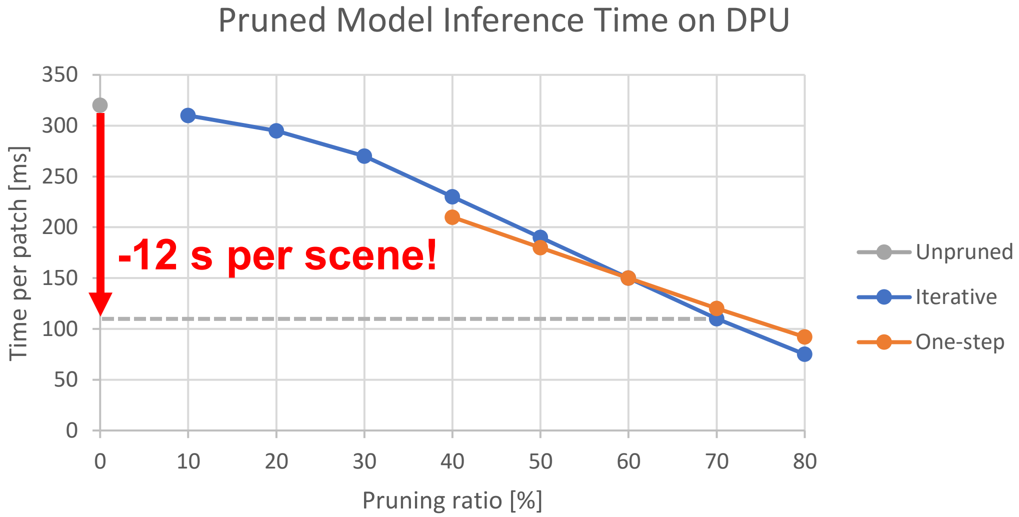
# Model Pruning

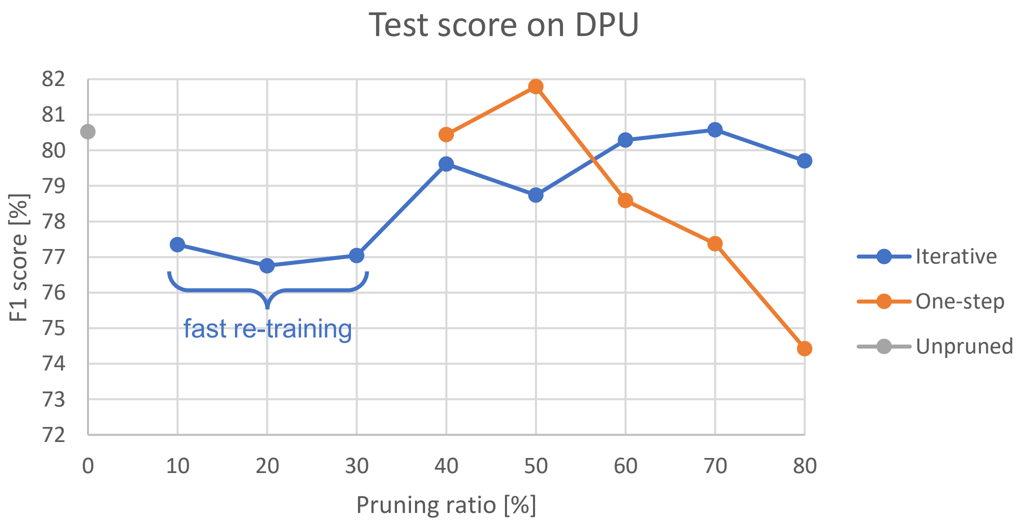
Reference map | Unpruned



One-step 50% | Iterative 70%

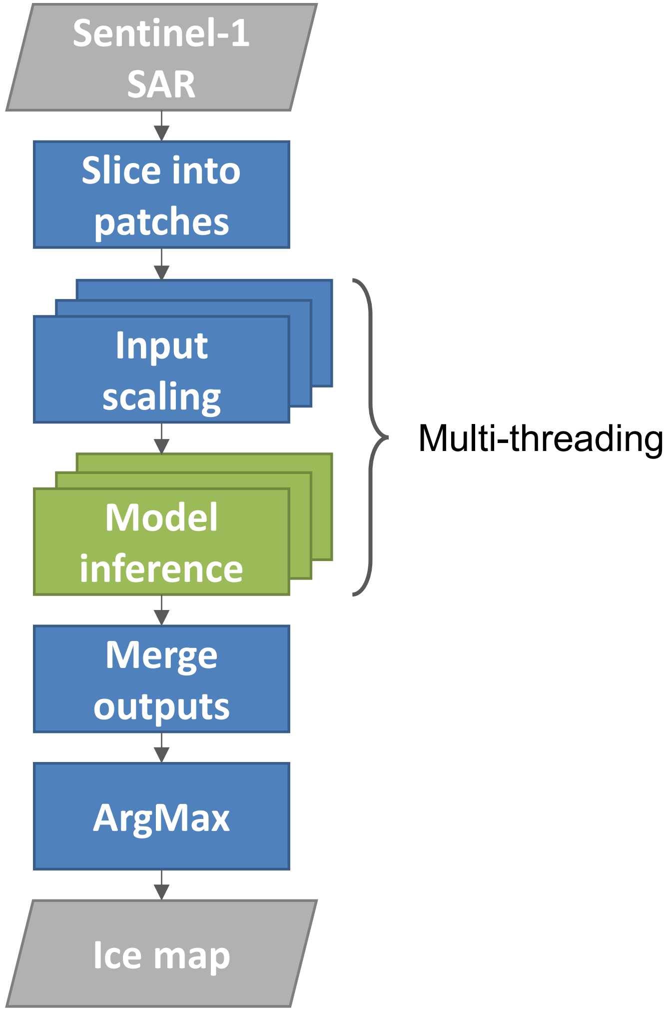
Scene: 20180716T110418_cis




**One-step pruning F1 score degraded rapidly at >50% sparsity, where iterative pruning maintained high score**

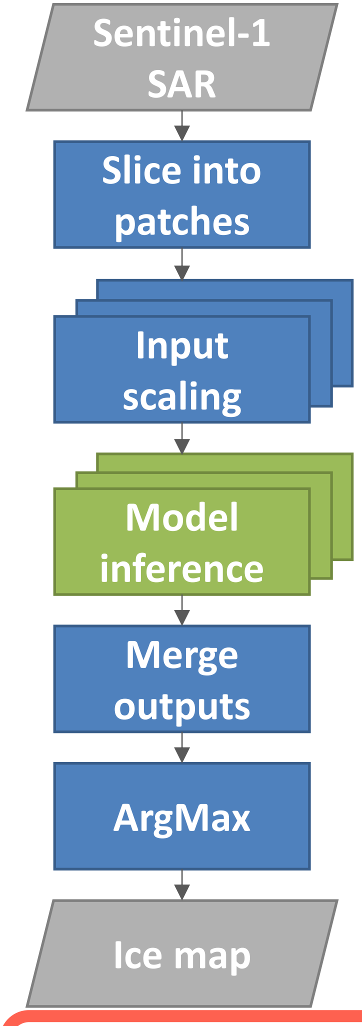
# On-board Integration




MPSoC inference steps

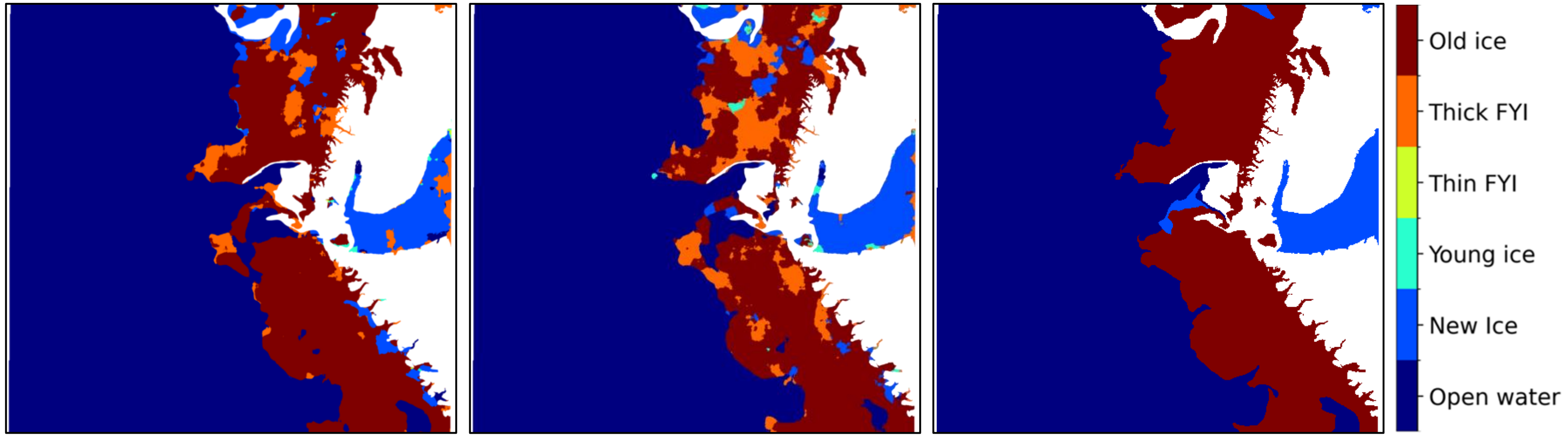
- Model inference on **PL (FPGA)**
  - Multi-core DPU execution
- Pre- and post-processing on **PS (ARM CPU)**
  - Slicing into patches
  - Input scaling
  - Merging inference results
  - ArgMax to find dominant class

# Results (1)



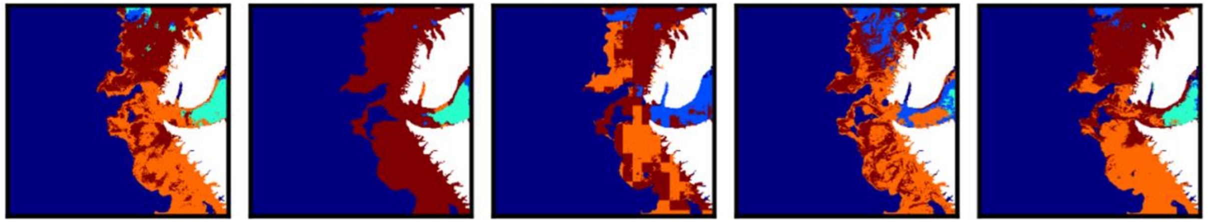

19.9–44.1 s
(average 38.0 s)

Scene: 20201013T080448_dmi




GPU MPSoC Reference

UW PWGSN crissy sim jff

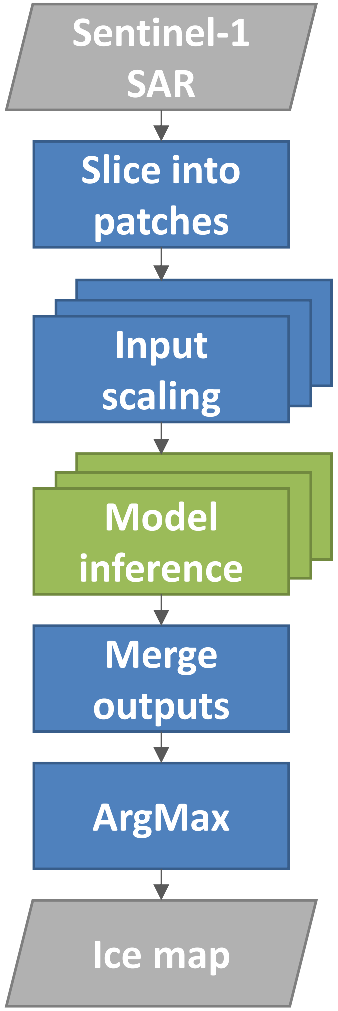


Results of top 5 AutoICE challenge participants*

Power consumption: ~21 W (peak 38 W)

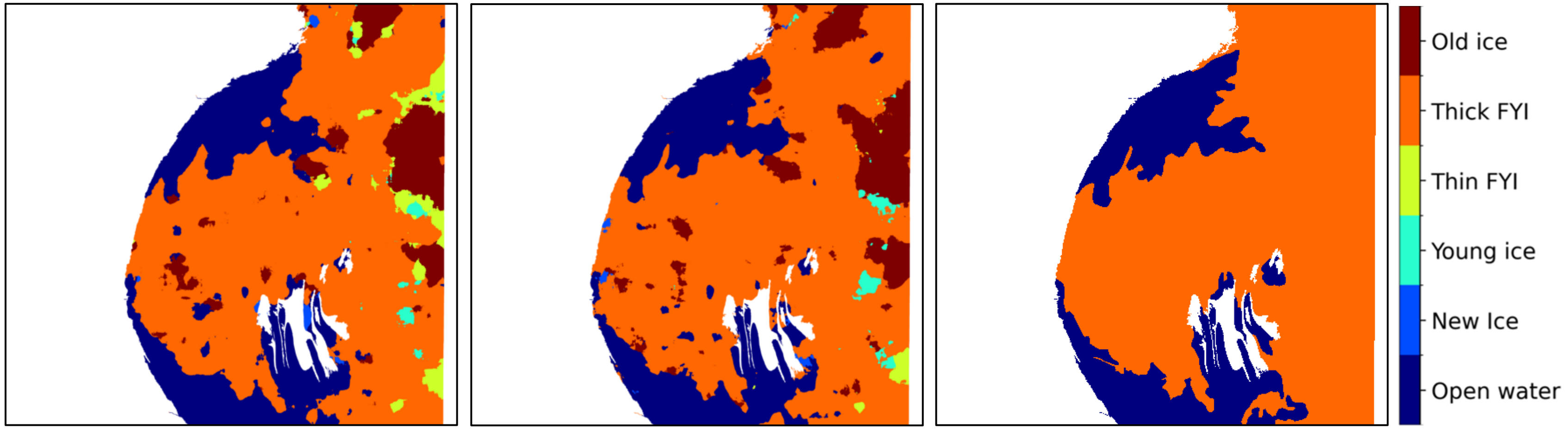
*A. Stokholm et al., “The AutoICE challenge,” *The Cryosphere* **18**(8), 3471–3494 (2024)

# Results (2)

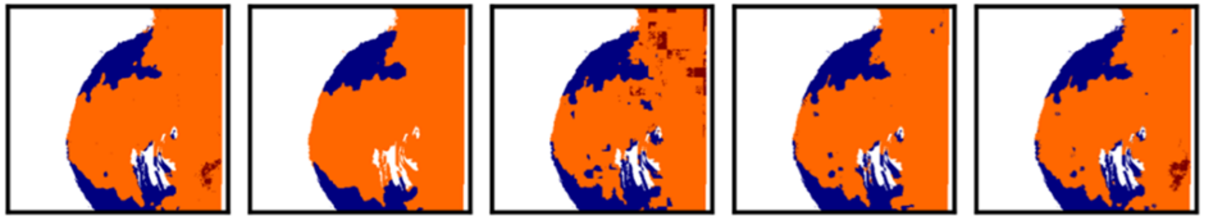



19.9–44.1 s
(average 38.0 s)

Scene: 20180707T113313_cis




GPU MPSoC Reference




Results of top 5 AutoICE challenge participants*

→ F1 score on MPSoC: 80.6 %

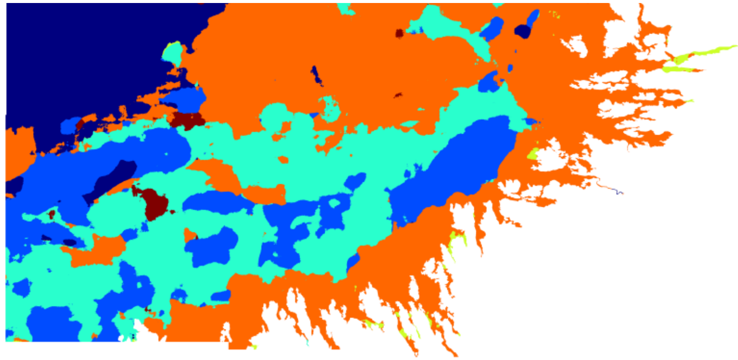
*A. Stokholm et al., "The AutoICE challenge," *The Cryosphere* **18**(8), 3471–3494 (2024)

# Conclusion

**On-board SAR Processing Chain**

Sentinel-1 TOPSAR Image Focusing

Edge AI Use Case: Sea Ice



- Enable near real-time product delivery
- Can be ported to hardware for low Earth orbit
- Possible implementation in future missions?

**Maritime Safety and Security Lab Bremen**

**Recent Publications**

elib
Publications of the DLR

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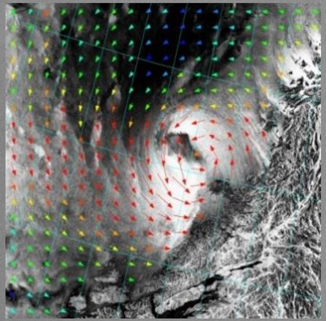
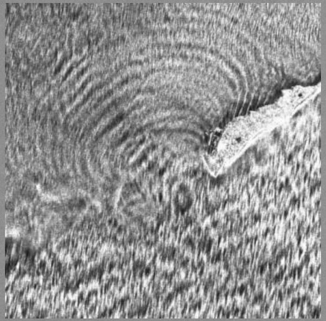
Remote Sensing Technology Institute | SAR Signal Processing
Maritime Safety and Security Lab Bremen | Germany

# Maritime Safety and Security Lab Bremen

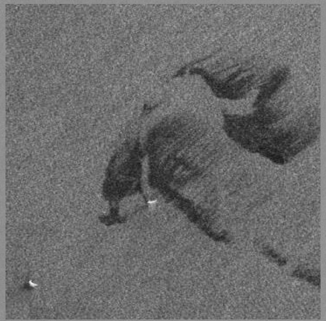
Development of algorithms to derive **maritime information** from **spaceborne SAR data** in **near real-time** on…



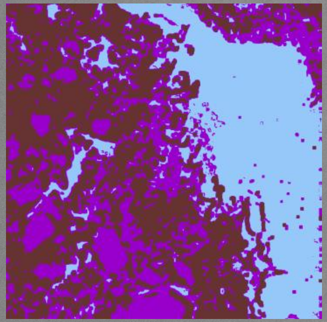
…wind



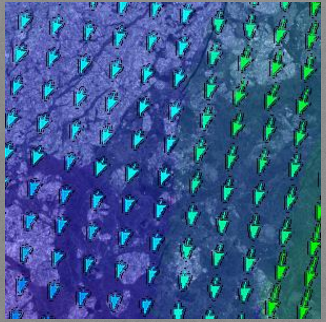
…sea state



…oil spills



…sea ice types



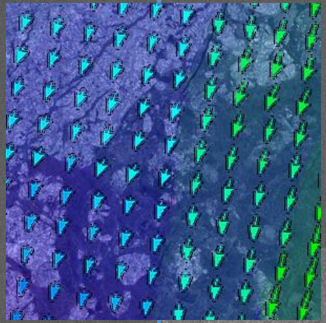
…sea ice drift


Support of campaigns

TerraSAR-X

Sentinel-1

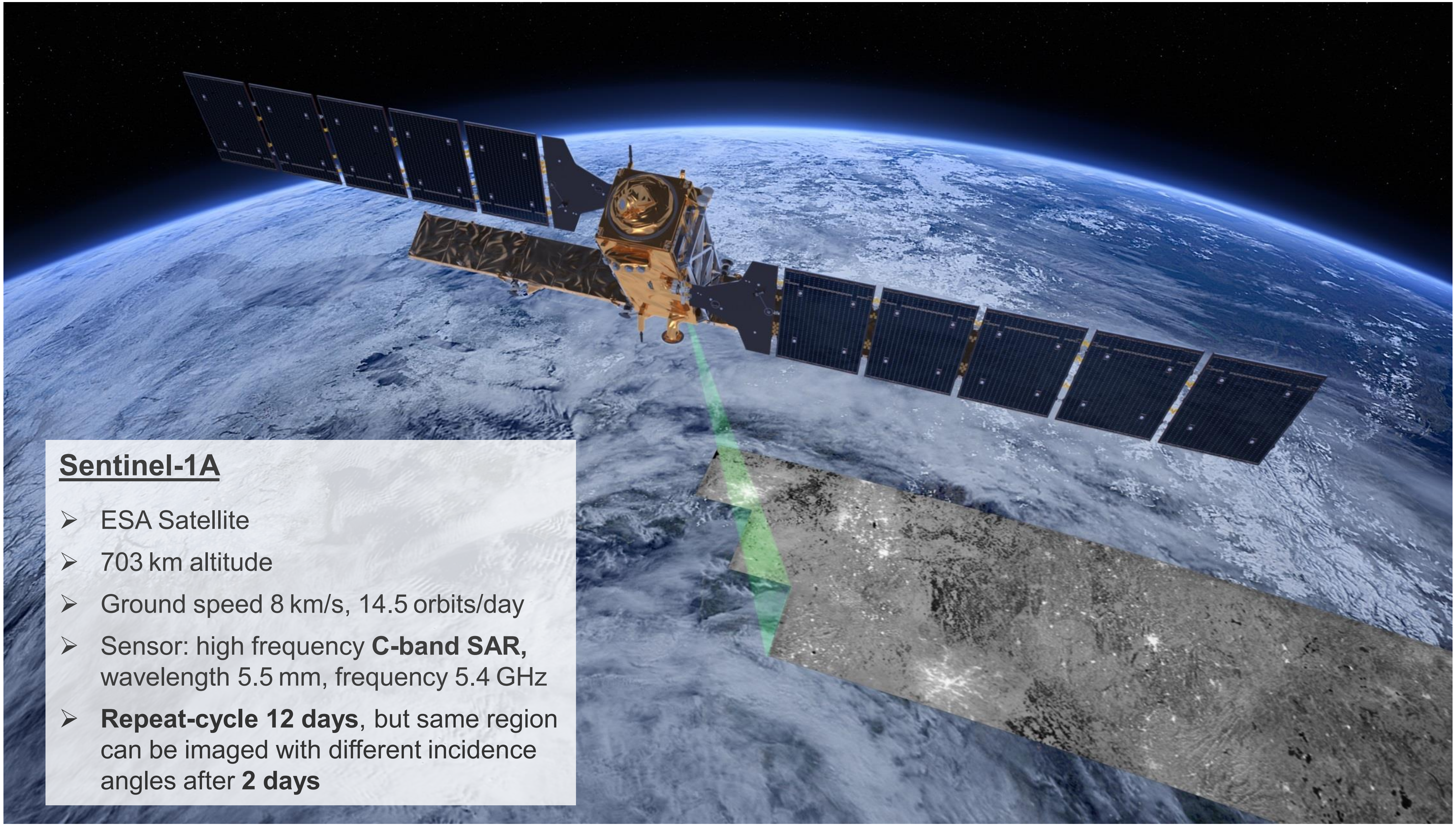
Downlink at DLR ground segment Neustrelitz



L0 processing and value adding

Delivery in NRT

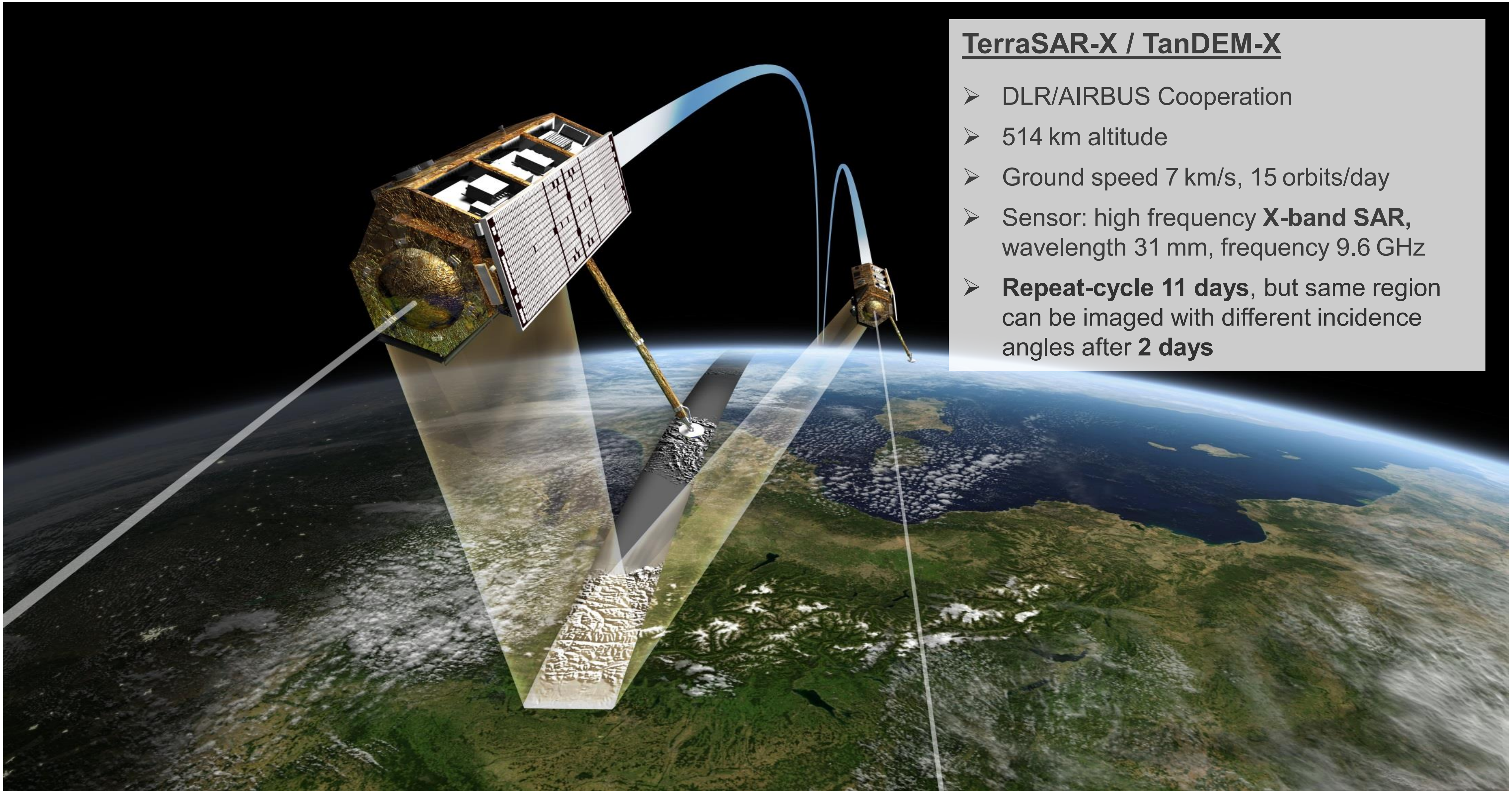
# SAR Satellites: C-band



**Sentinel-1A**

- ESA Satellite
- 703 km altitude
- Ground speed 8 km/s, 14.5 orbits/day
- Sensor: high frequency **C-band SAR,** wavelength 5.5 mm, frequency 5.4 GHz
- **Repeat-cycle 12 days**, but same region can be imaged with different incidence angles after **2 days**

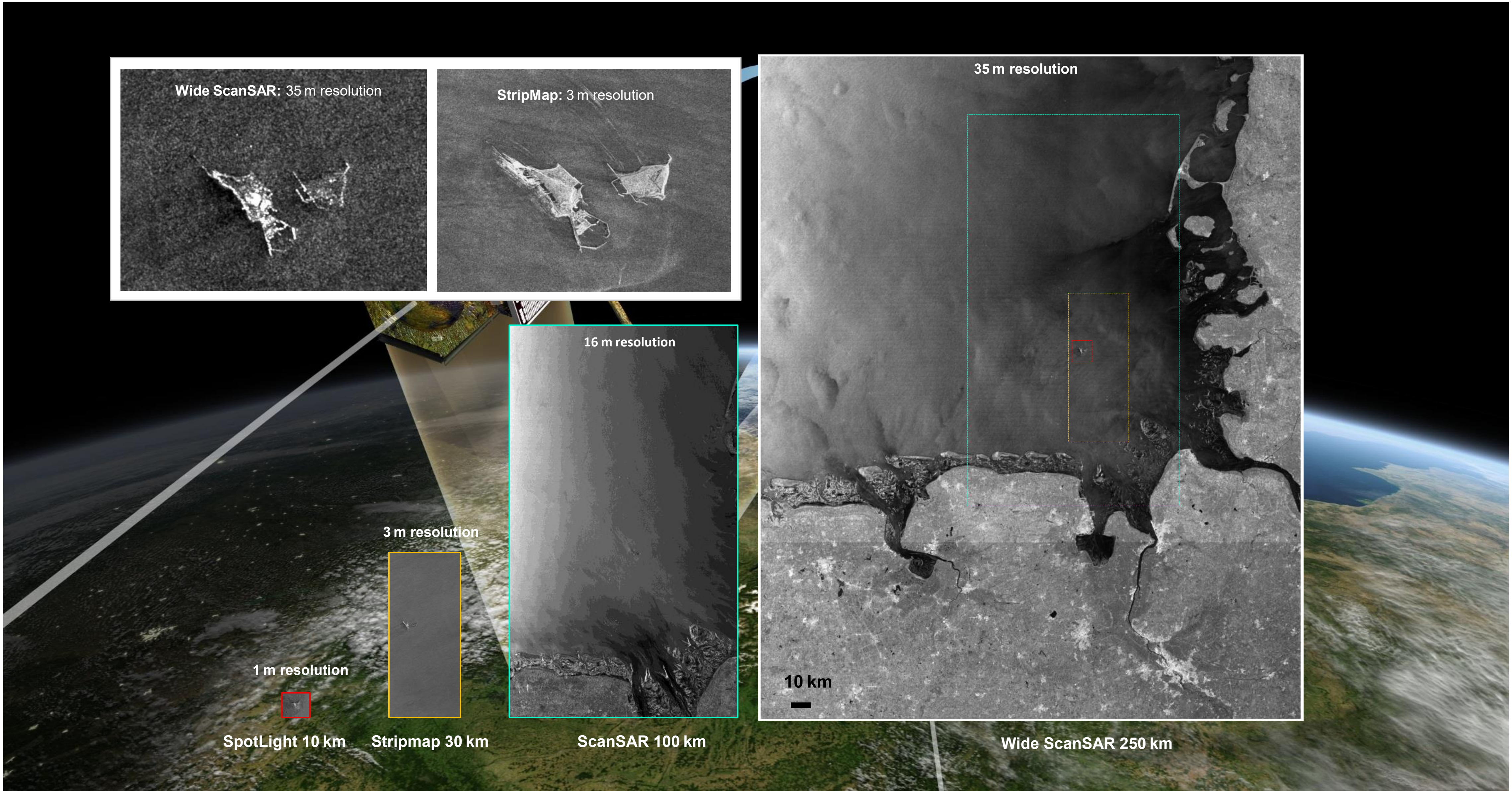
# SAR Satellites: X-band



**TerraSAR-X / TanDEM-X**

- DLR/AIRBUS Cooperation
- 514 km altitude
- Ground speed 7 km/s, 15 orbits/day
- Sensor: high frequency **X-band SAR,** wavelength 31 mm, frequency 9.6 GHz
- **Repeat-cycle 11 days**, but same region can be imaged with different incidence angles after **2 days**

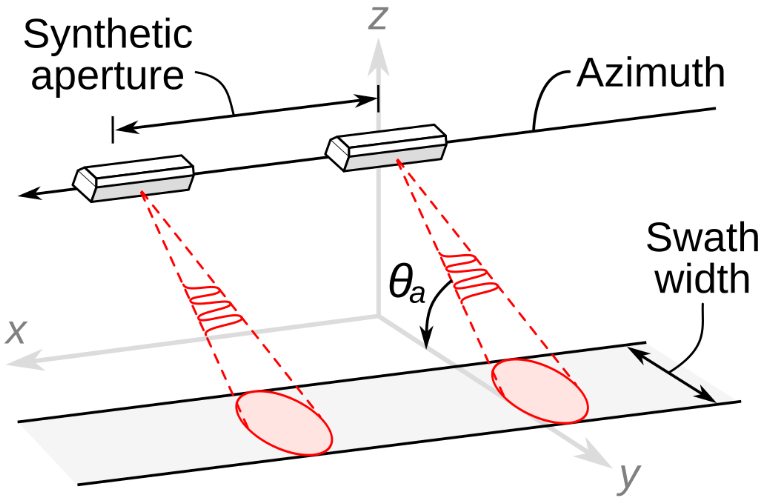
# TerraSAR-X Acquisition Modes



# SAR: Synthetic Aperture Radar

- Transmit pulses of electromagnetic waves
- And receive echoes of each pulse (amplitude & phase)
- Satellite moves at constant speed
  - ➢ Synthetic aperture much longer than physical antenna width
- Side-looking antenna: Discrimination of objects along ground-range
  - ➢ Two-dimensional imaging
- Always trade-off between spatial resolution and coverage

Synthetic aperture radar



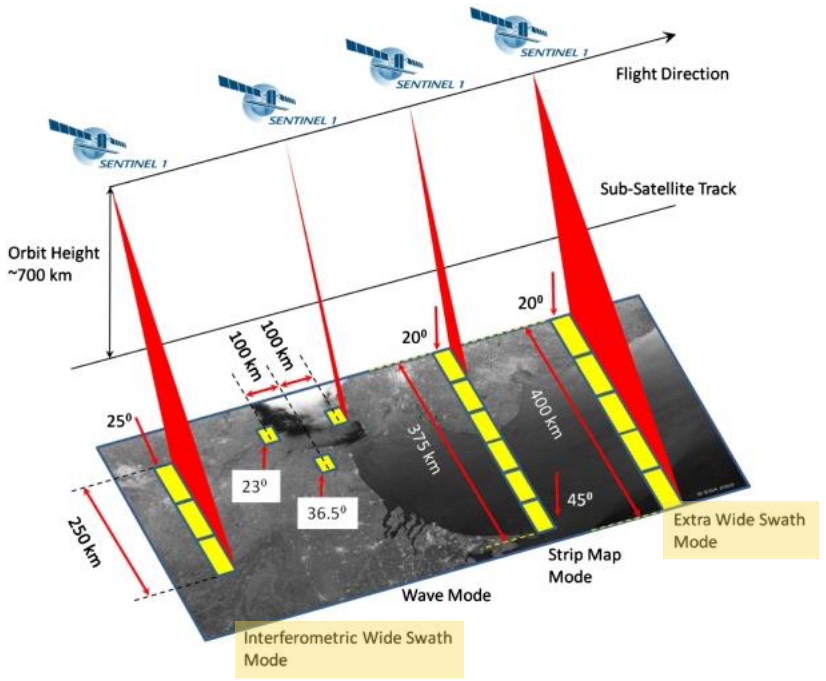
# Sentinel-1 Image Focusing

## Processor Specifications

- Support two TOPSAR modes
  - Interferometric wide (IW): 250 km swath width
  - Extra wide (EW): 400 km swath width
- L0 raw data downloaded from Copernicus Data Space Ecosystem
- Chirp scaling algorithm

## Preliminary Results

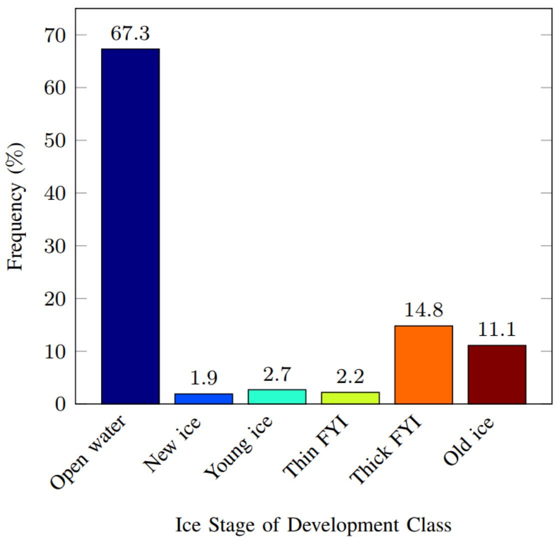
- Full image latency: 26 seconds
- Latency dominated by PS
- Expect 15 seconds after software optimization



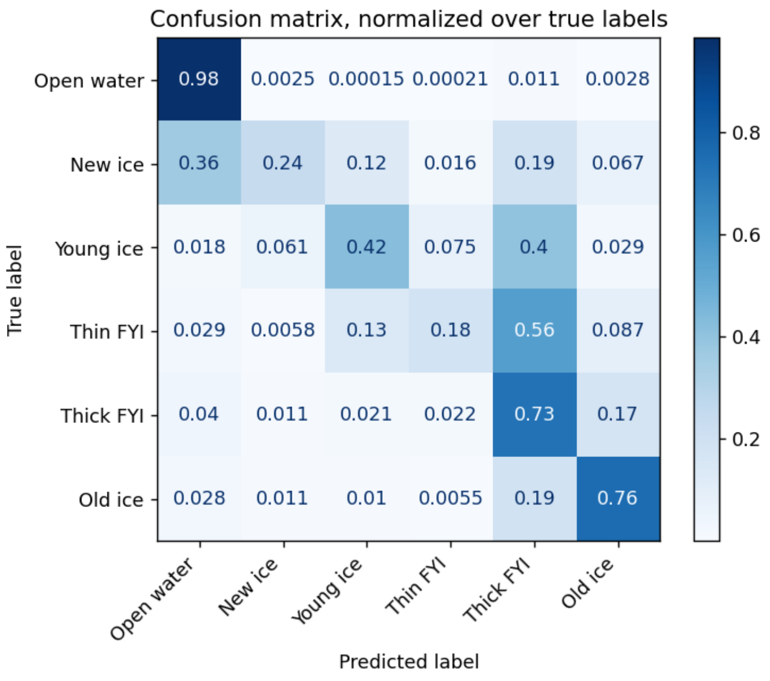

Sentinel-1 acquisition modes (Source: ESA)

# Classifier Prediction Results

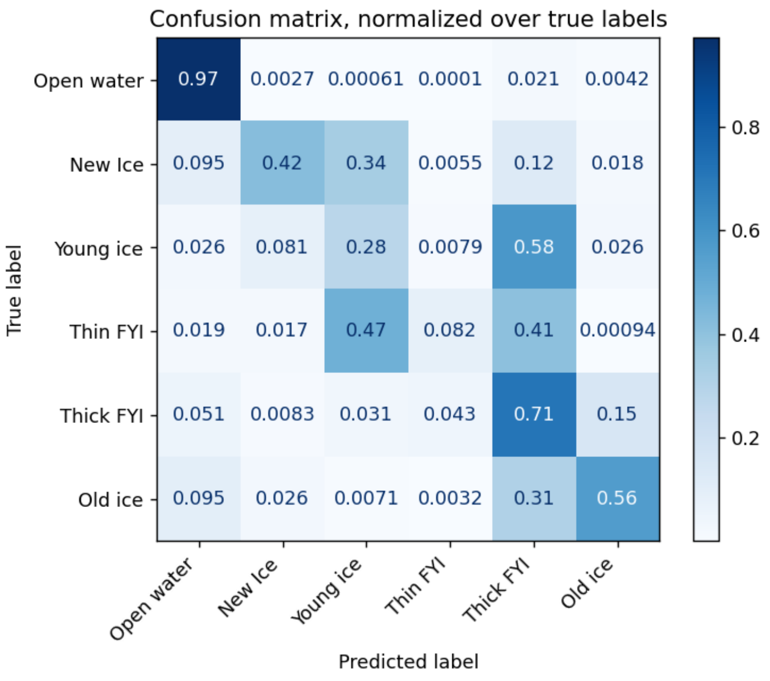
- Dataset highly imbalanced
- Training with weighted Cross-Entropy loss
- Evaluation with weighted average F1 score




Training dataset class distribution




Validation




Test

# CNN Implementation on FPGA

## Dataflow Architecture

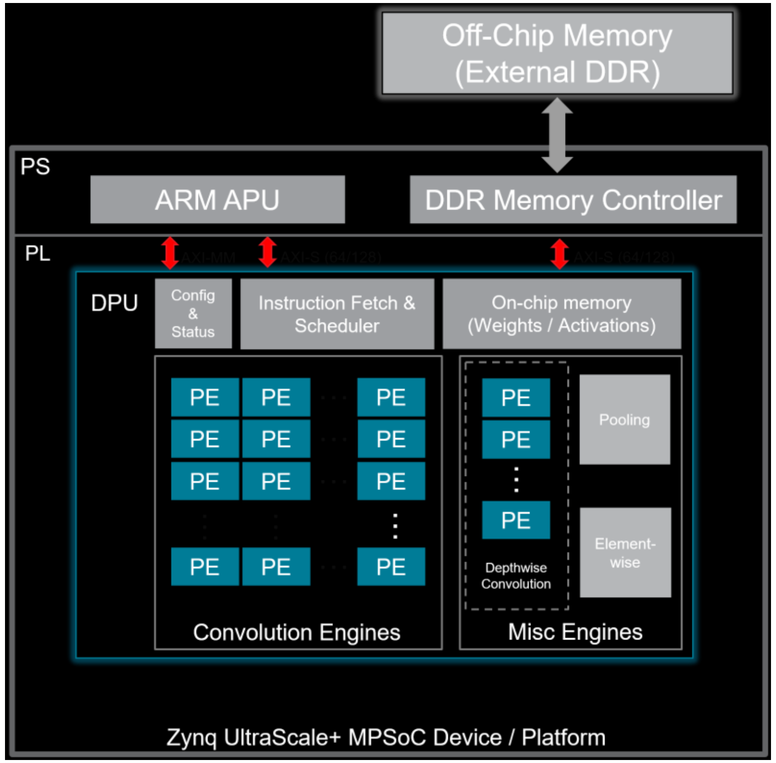
- Map each layer to FPGA fabric
- Dedicated circuit compiled for specific model
- Beneficial for deterministic inference latency

## Accelerator

- Implements set of common operators
- Programmed via instruction set
- Supports larger models
- More comprehensive toolchains

FINN

hls4ml




AMD Deep Learning Processor Unit (DPU) for Zynq US+
Source: AMD