Geometry- and Wavelength-Agnostic Highly efficient Forward and reverse SAR processor

(GAFA - Geometry- and Frequency-Agnostic)

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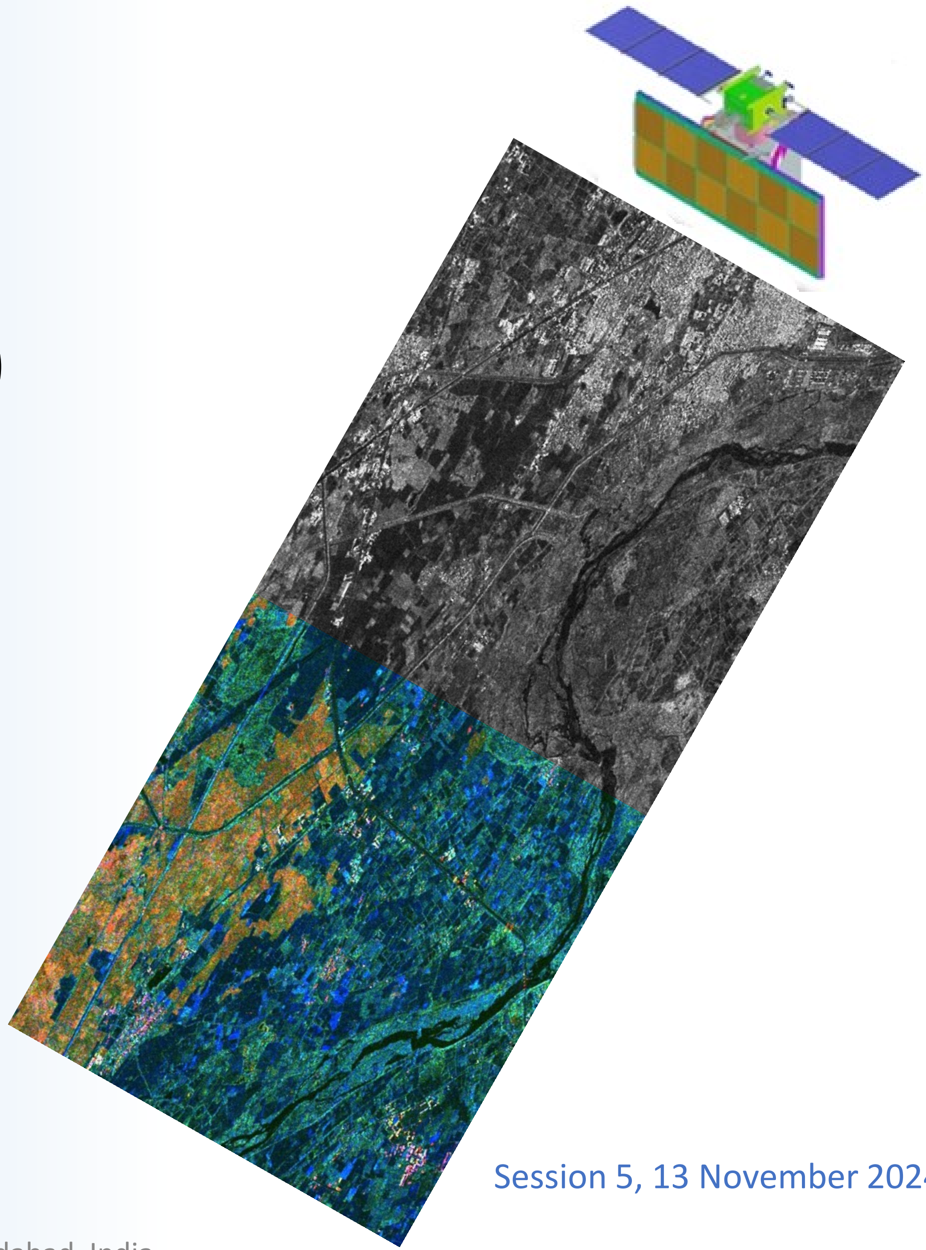


Session 5, 13 November 2024

GAFA development background and rationale

Within earlier ESA activities, forward and reverse kernels have been developed, e.g.

- During Sentinel-1A development
- During SAOCOM-CS (ESA companion satellite for SAOCOM) development (discontinued in 2017)

But: no common and open architecture existed

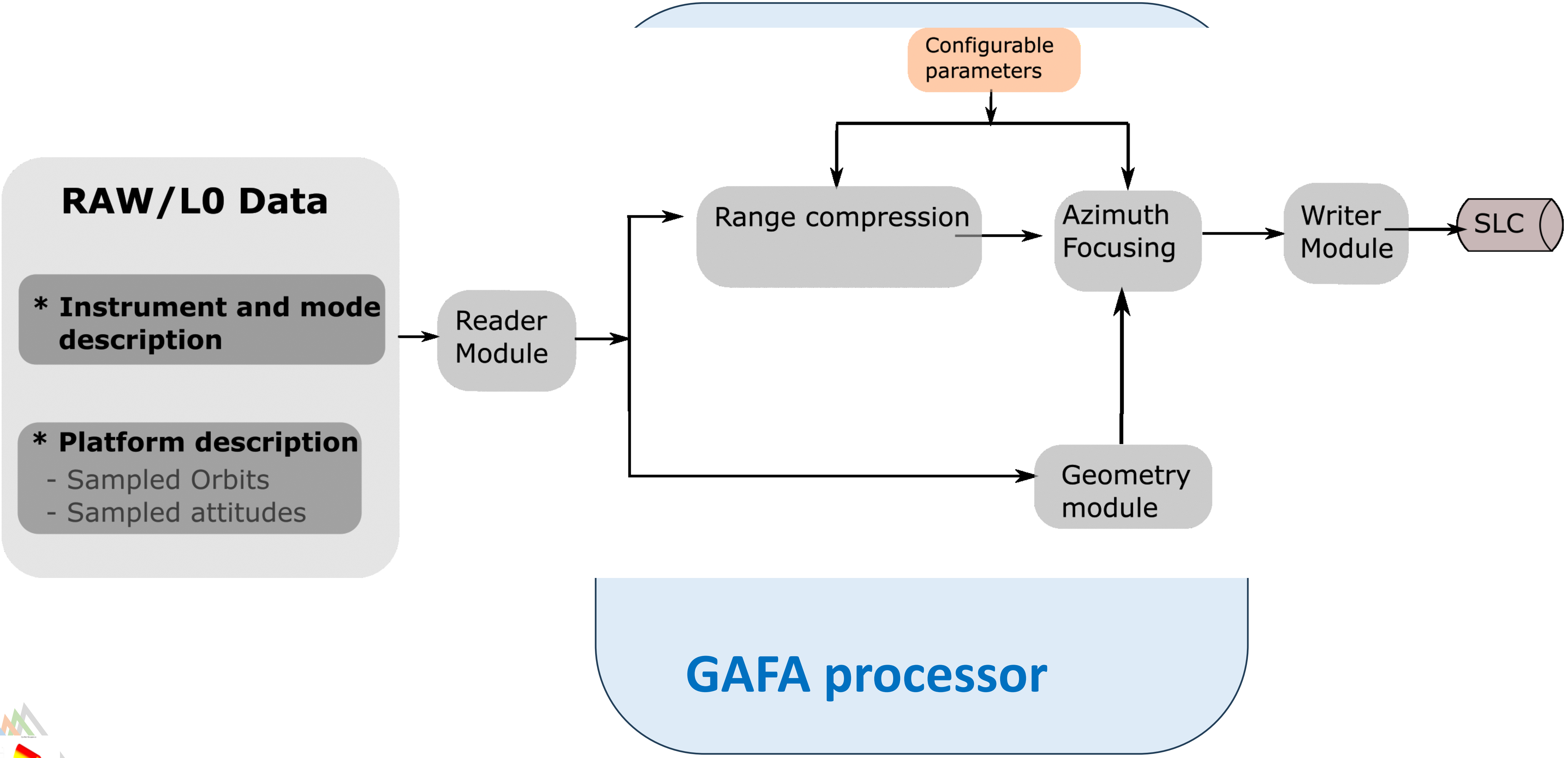
Rationale: To develop mission-agnostic SAR processing kernels configurable for forward and reverse operations:

- Focusing kernels of interest as (prototype) L1 processor for various use, e.g. integration in ground segment or application specific processing chains and for integration in end-to-end SAR performance simulator frameworks
- Reverse kernels of interest in end-to-end SAR performance simulator frameworks and large-scale raw/Level-0 dataset generation for ground segment testing

Implemented/considered scenarios:

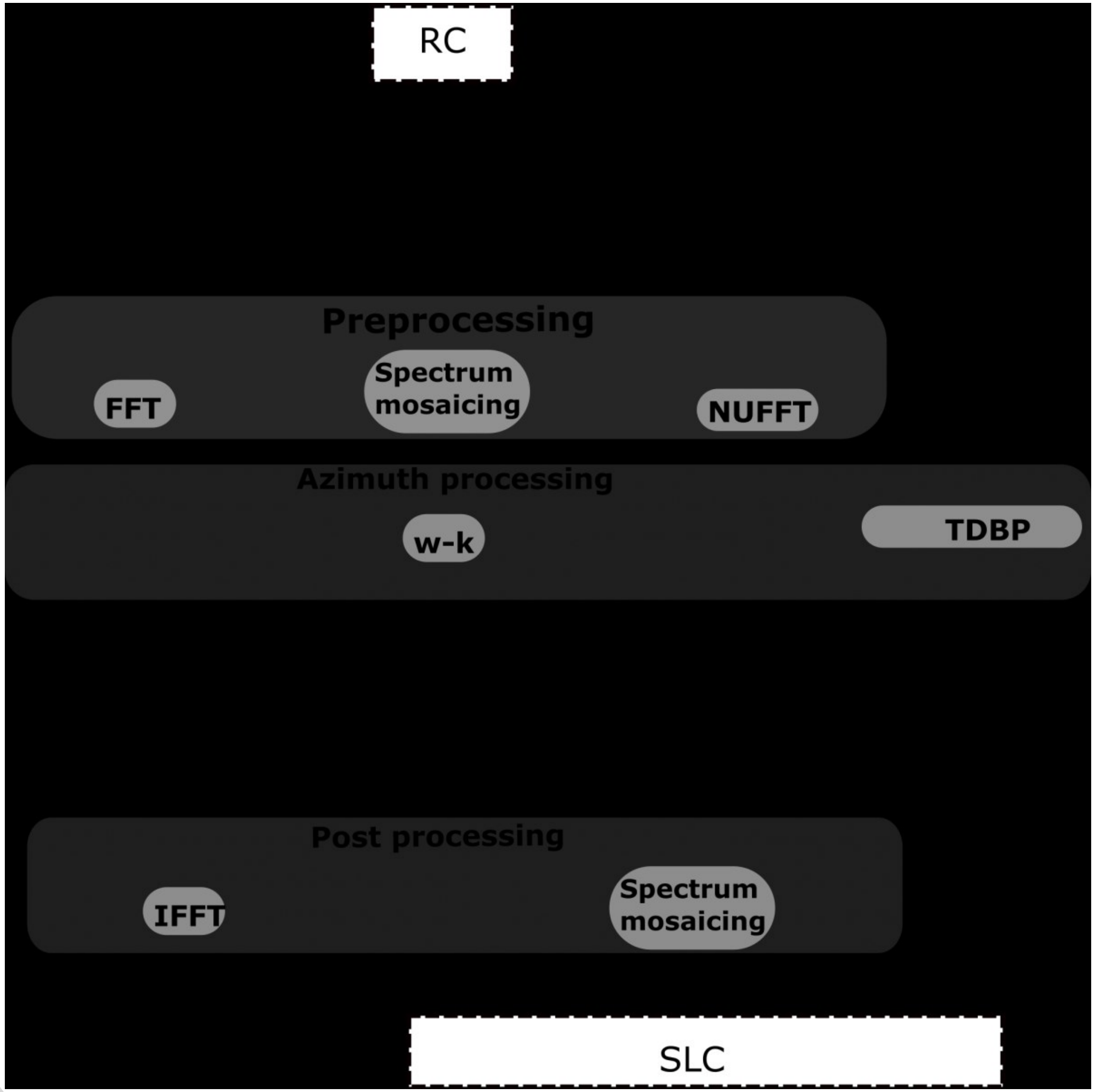
1) Monostatic (classic): Sentinel-1 (C-band);
2) Monostatic (HRWS): Sentinel-1NG (C-band) and ROSE-L (L-band);
3) Multistatic configurations: Harmony (C-band) + SAOCOM-CS (L-band);
4) GEO-SAR platforms (C-band, i.e. Hydroterra)

GAFA SAR: overview/summary



Introduction: GAFA SAR processor

A unifying framework based on agnostic frequency domain kernel



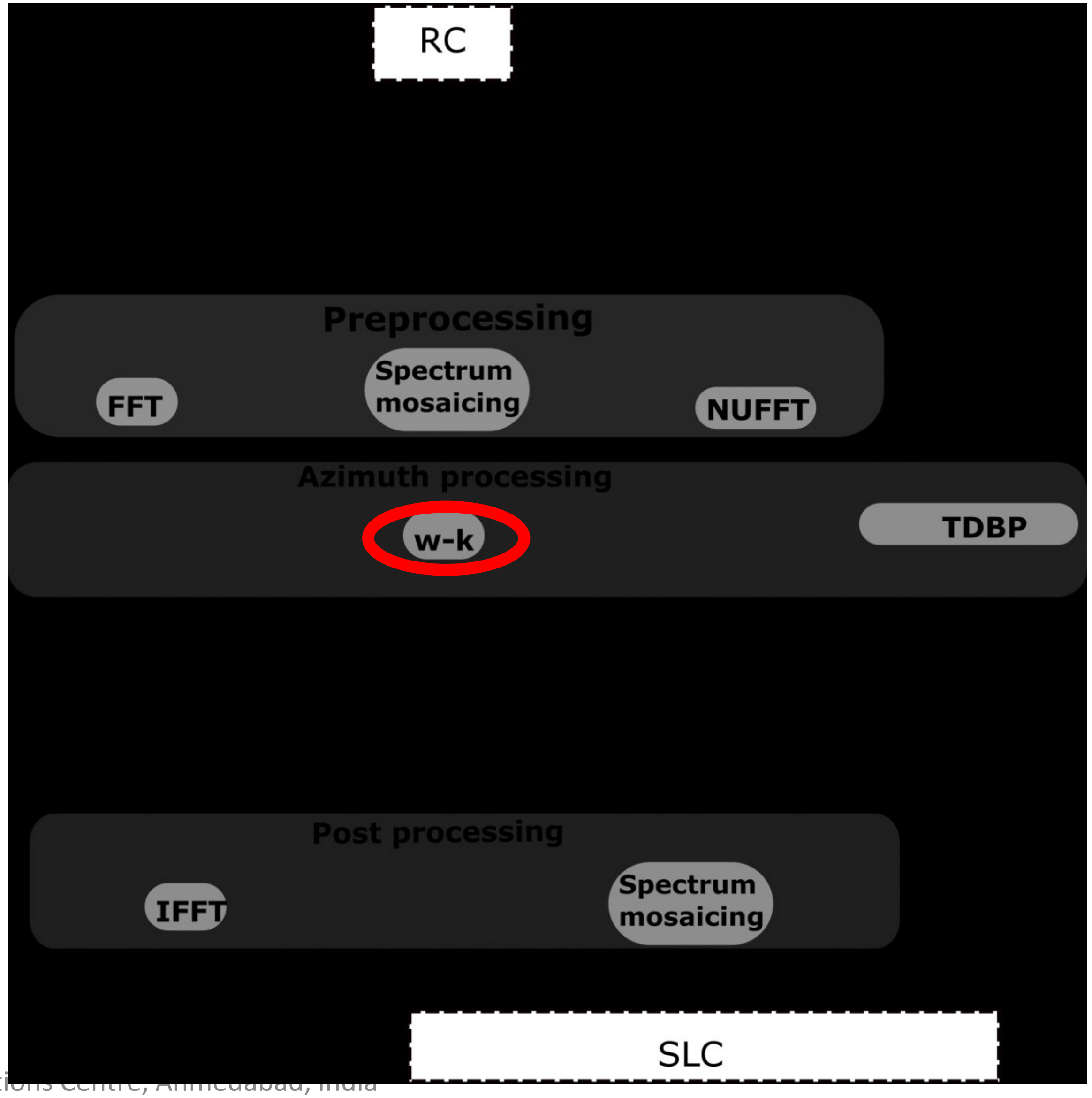
- A mode dependent preprocessing step:
  - Uniform sampling of range-Doppler domain
- An agnostic focusing kernel
- A mode dependent post processing step
- **One notable exception**: time domain focusing (TDBP)
  - GEOSAR
  - Independent implementation for validation

The agnostic frequency domain kernel

Some distinguishing features that made it possible for supporting a wide range of geometries including high-squint and bistatic

1. Range migration based on high order polynomial around specified doppler (zero or beam center doppler), instead of the commonly used hyperbolic approximation. Numerical focusing kernel based on series reversion.

2. Focusing grid is a generalized range-doppler coordinate system

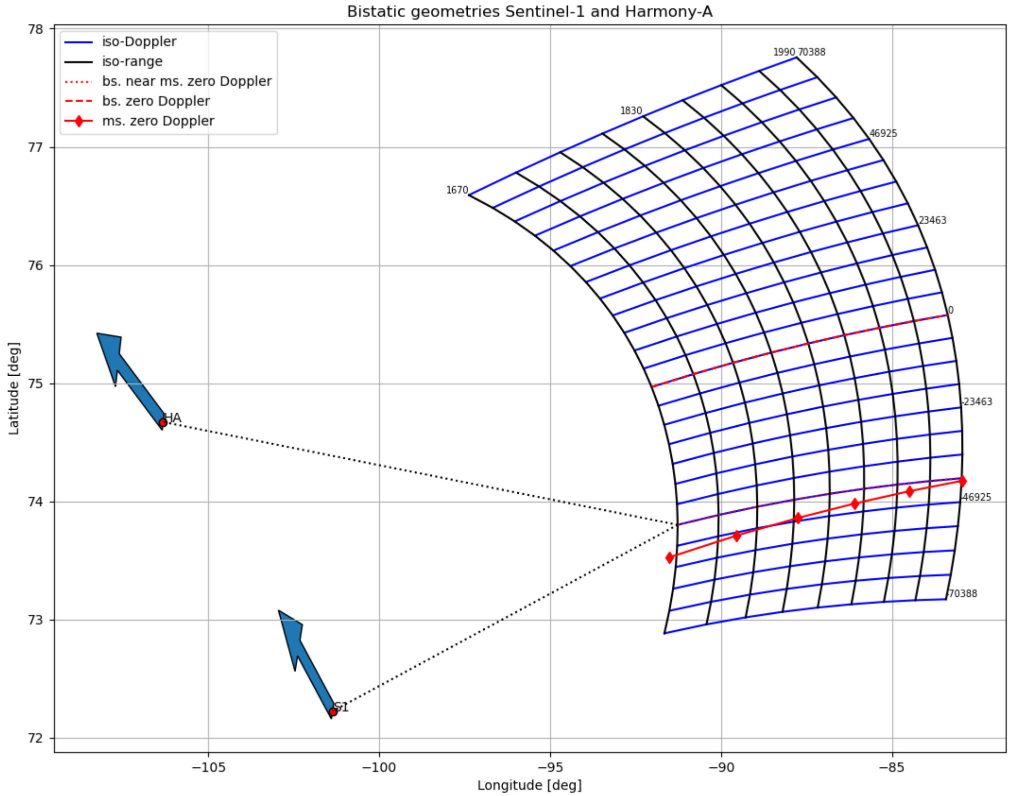


The agnostic frequency domain kernel

Some distinguishing features that made it possible for supporting a wide range of geometries including high-squint and bistatic

1. Range migration based on polynomial around specified doppler centroid (zero or beam center doppler), instead of the commonly used hyperbolic approximation. Numerical focusing kernel based on series reversion.

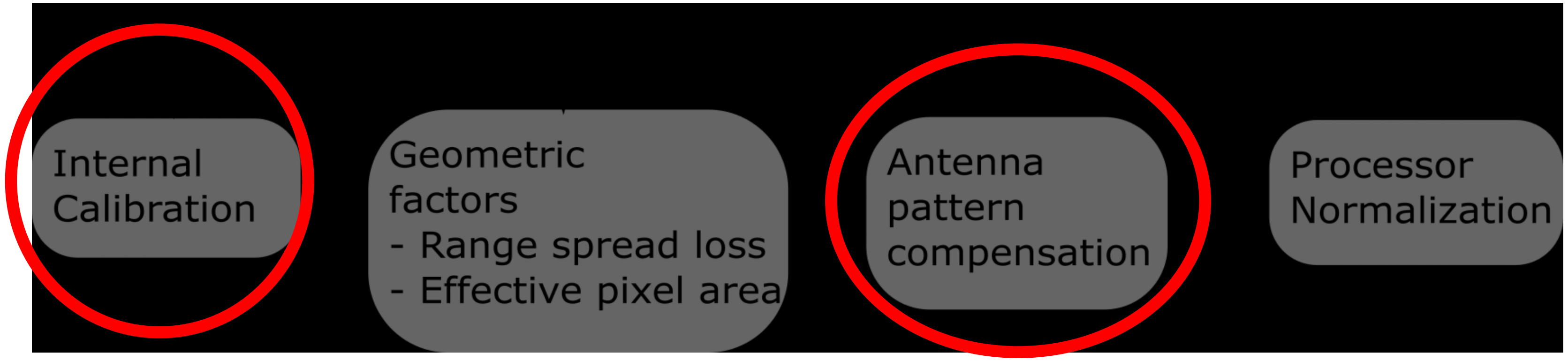
2. Focusing grid is a generalized range-doppler coordinate system
   - Azimuth (slow time)
   - Range (fast time)
   - Free choice of Doppler:
     - o Zero Doppler
     - o Beam center



GAFA supports end-to-end radiometric calibration

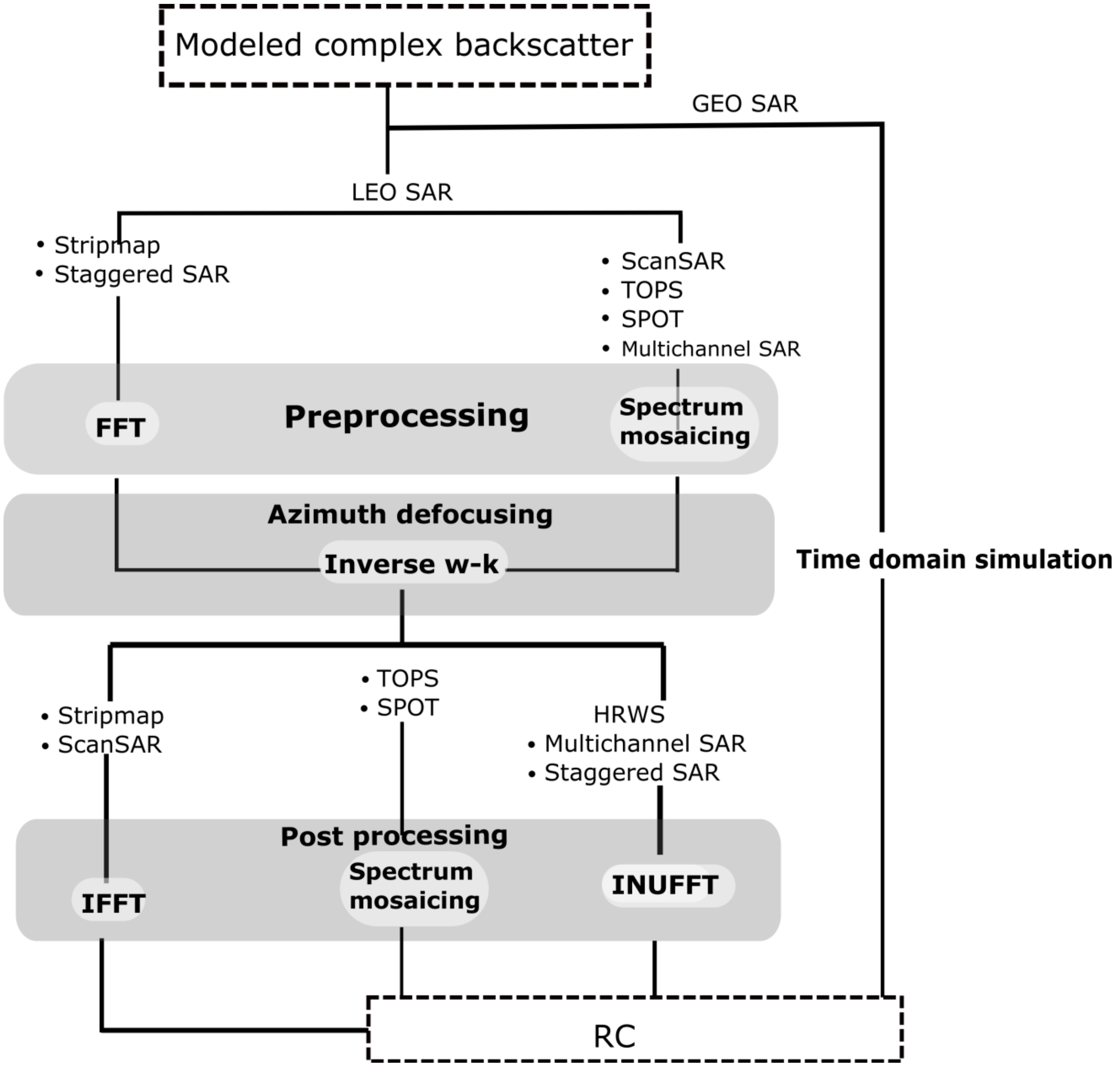
- Starting point: radar equation
- Requires sensor specific annotations of raw data
  - Example: Sentinel-1
  - Implementation closely follows the calibration steps from Sentinel-1 **SAR Instrument Calibration and Characterisation procedures**

Components in GAFA



GAFA SAR: The reverse processor

- Simulation of SAR raw data based on reverse kernel
- A generic building block for E2E simulators
- Required configuration
  - Input from a scene generator (randomized phase to simulate fully developed speckle, unless scene generator already generates phase)
  - Mission parameters, including
    - Orbit / attitude
    - SAR mode parameters
      - SWST/SWL
      - Pulse parameters
      - Antenna patterns
      - Imaging mode
      - Mode specific parameters, e.g.
        - Antenna sweep rate (TOPS/spot)
        - Burst duration (scanSAR/TOPS)
        - Phase center layout (MAPS)
        - ...

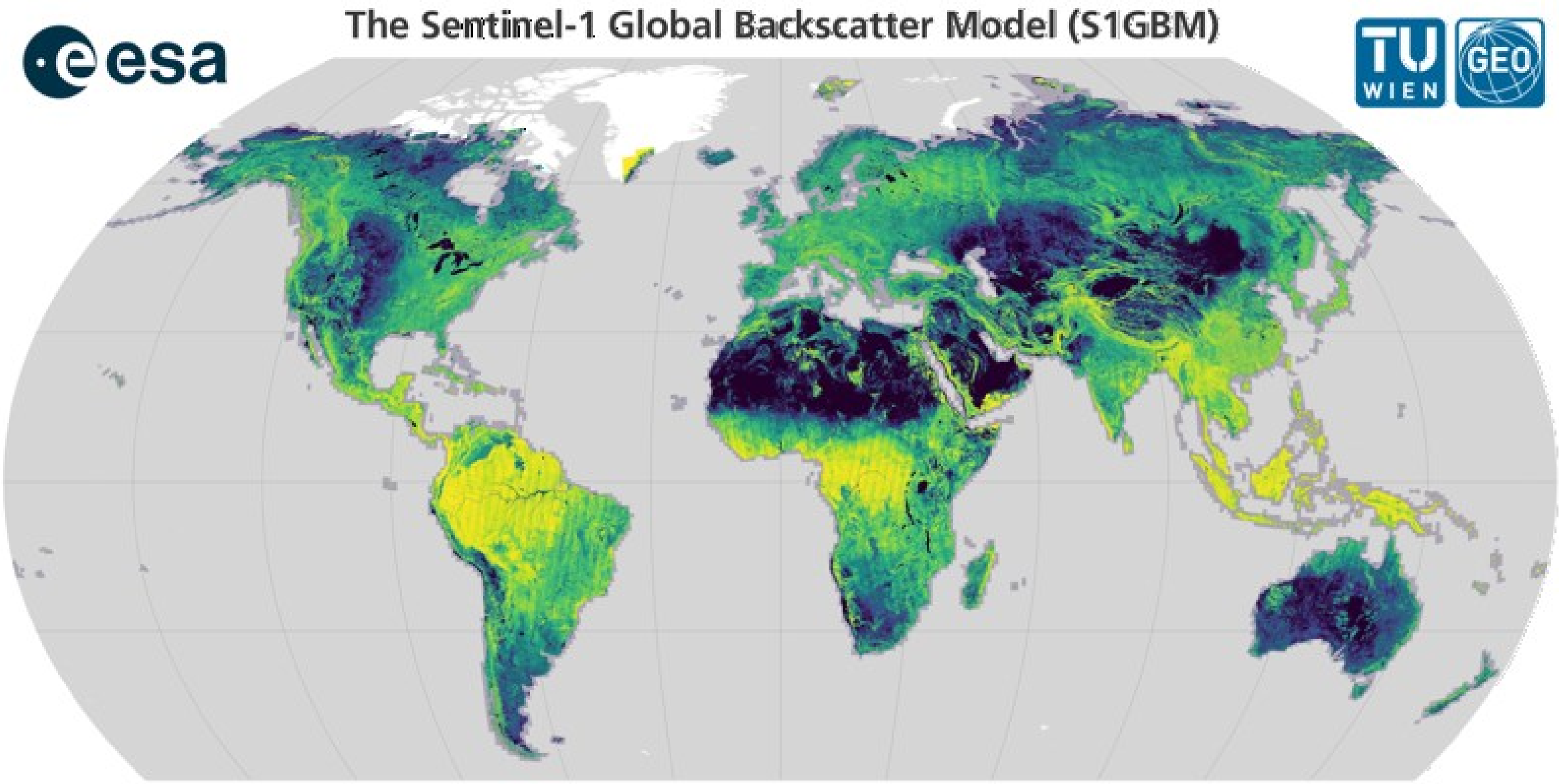


GAFA SAR: The reverse processor – scene generation

C-band – S1 Global Backscatter Model[1]

- https://researchdata.tuwien.ac.at/doi/10.48436/94y79-r2d09

- 10m posting
- σ^0 linear model as function of incidence
  → 2 parameters per pixel, i.e. slope and intersect

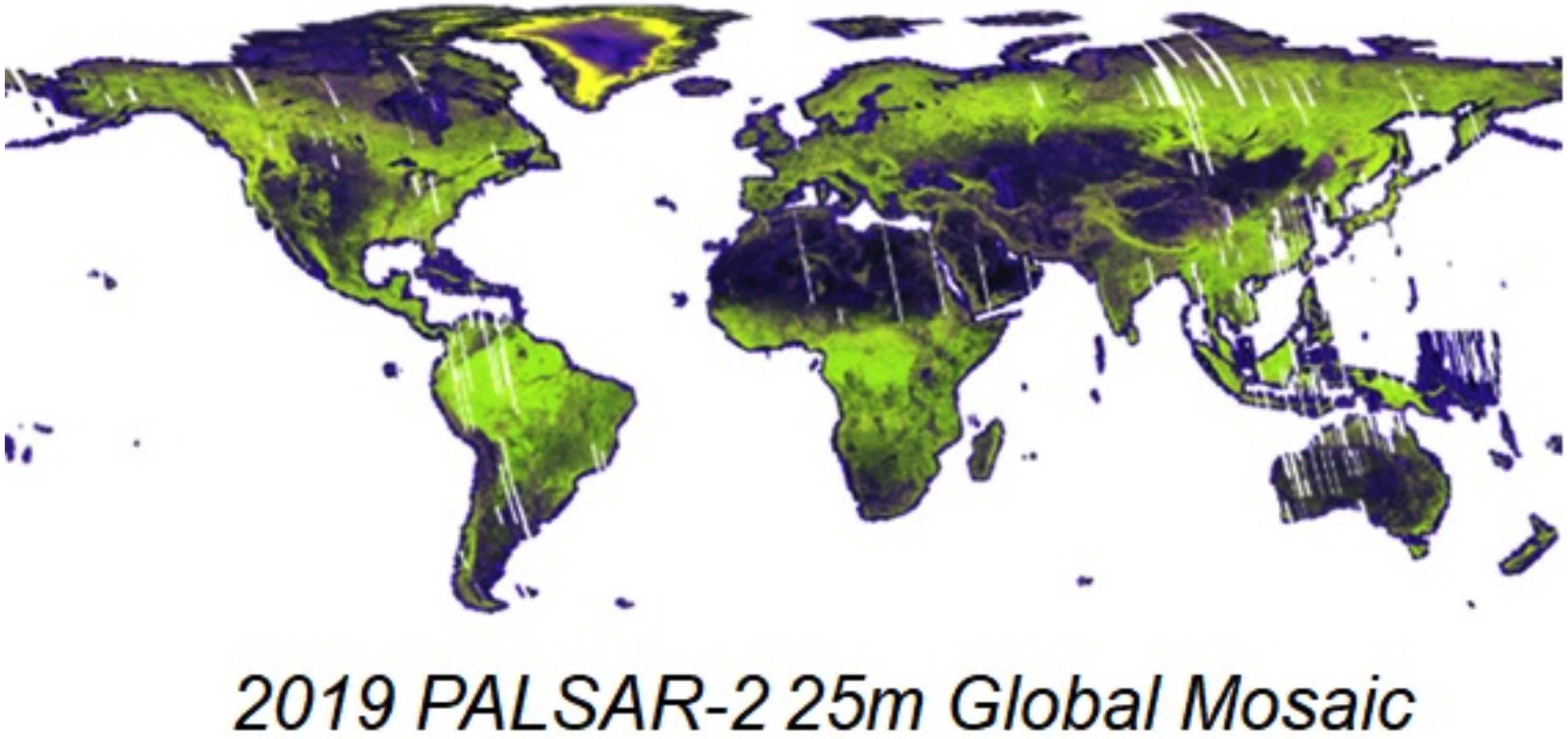


[1] Bauer-Marschallinger, B., Cao, S., Navacchi, C. et al.
The normalised Sentinel-1 Global Backscatter Model, mapping Earth's land surface with C-band microwaves.
Sci Data ***8****, 277 (2021). https://doi.org/10.1038/s41597-021-01059-7*

GAFA SAR: The reverse processor – scene generation

L-band – PALSAR backscatter mosaic

- https://www.eorc.jaxa.jp/ALOS/en/dataset/fnf_e.htm
- 25m posting
- Terrain corrected ("flattened") $\gamma0$
- Gap filled using low-resolution scanSAR data



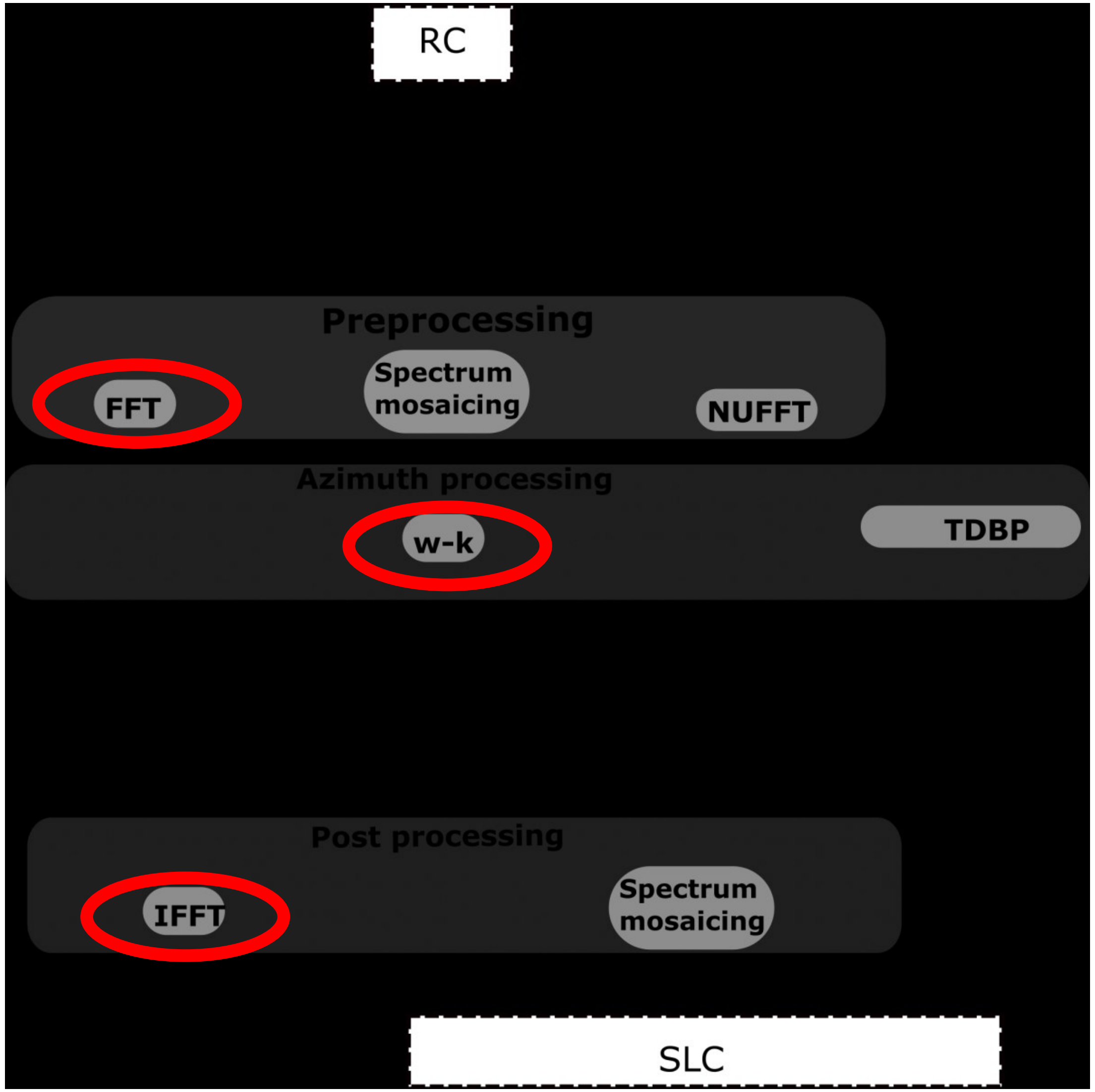
Supports / Examples/ Use-cases

Sentinel-1

Harmony

GEO-SAR

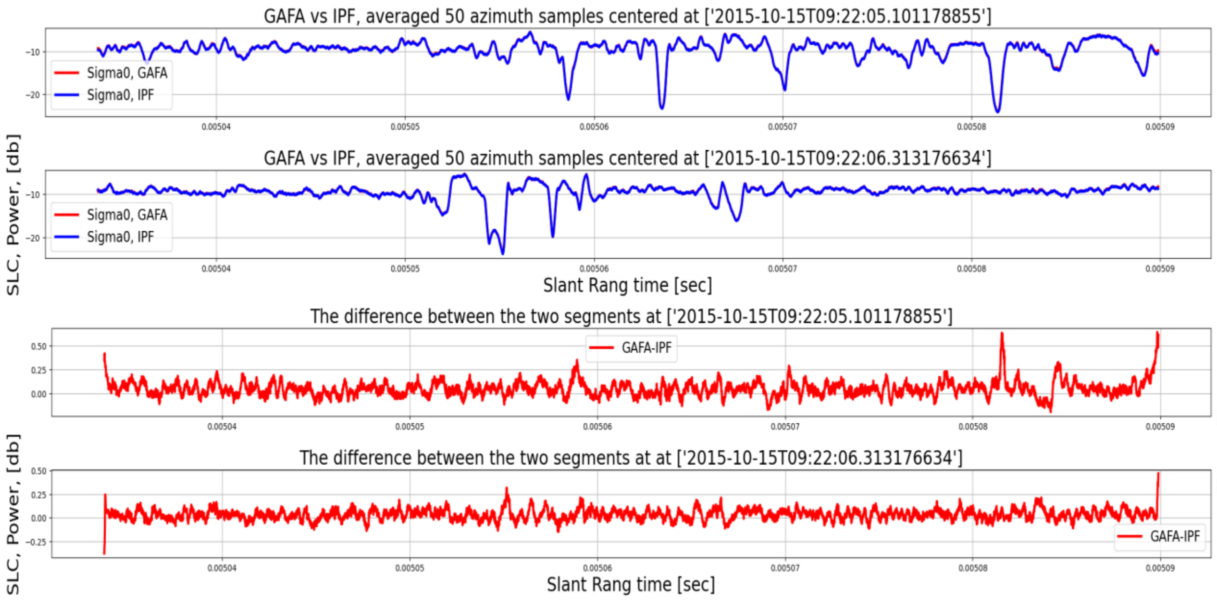
Support for Stripmap – Monostatic



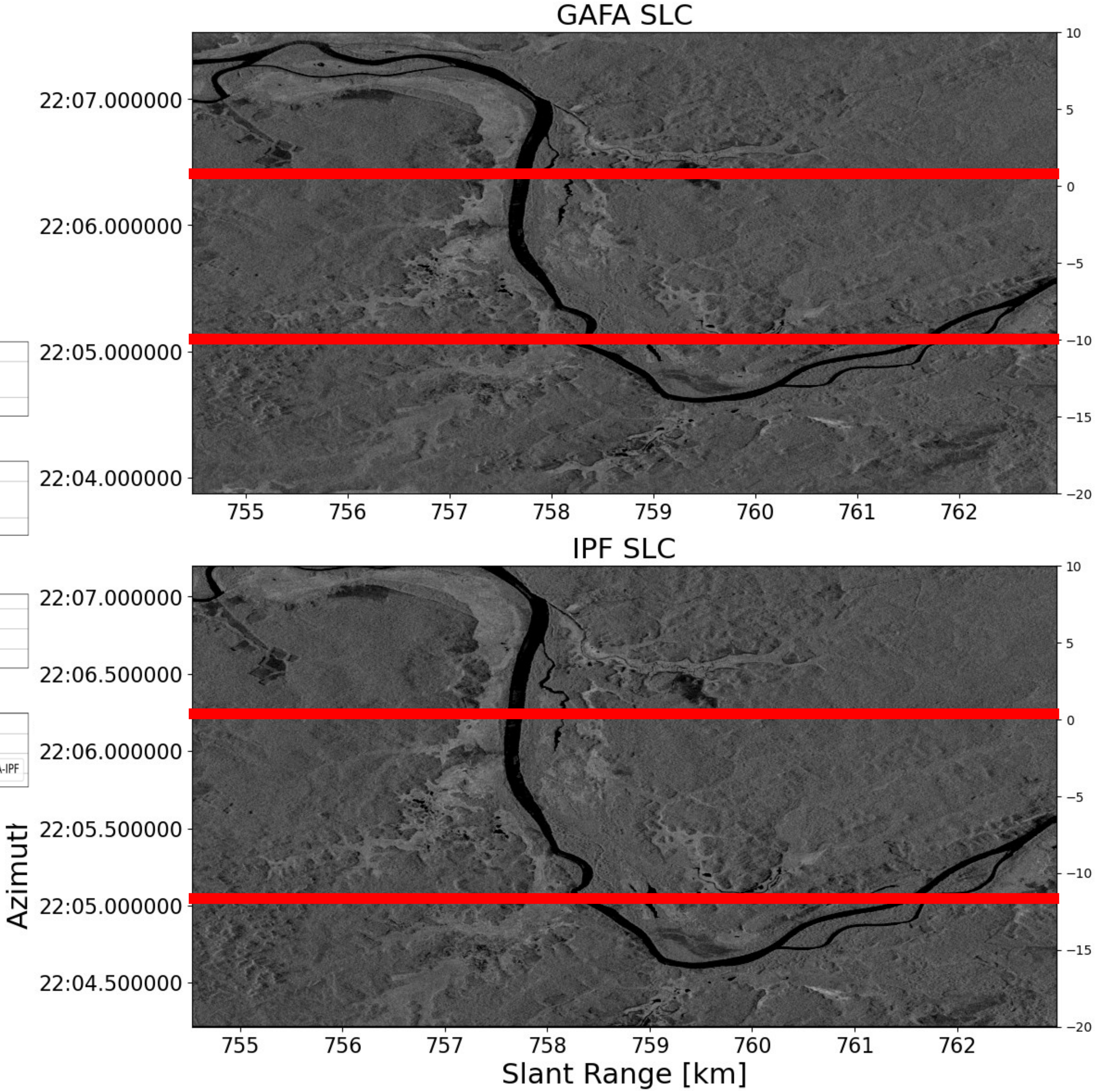
- Preprocessing:
  - None (FFT does the job)
- Focusing:
  - Support for High-squint
- Post processing:
  - None (IFFT)

Support for Stripmap – Monostatic

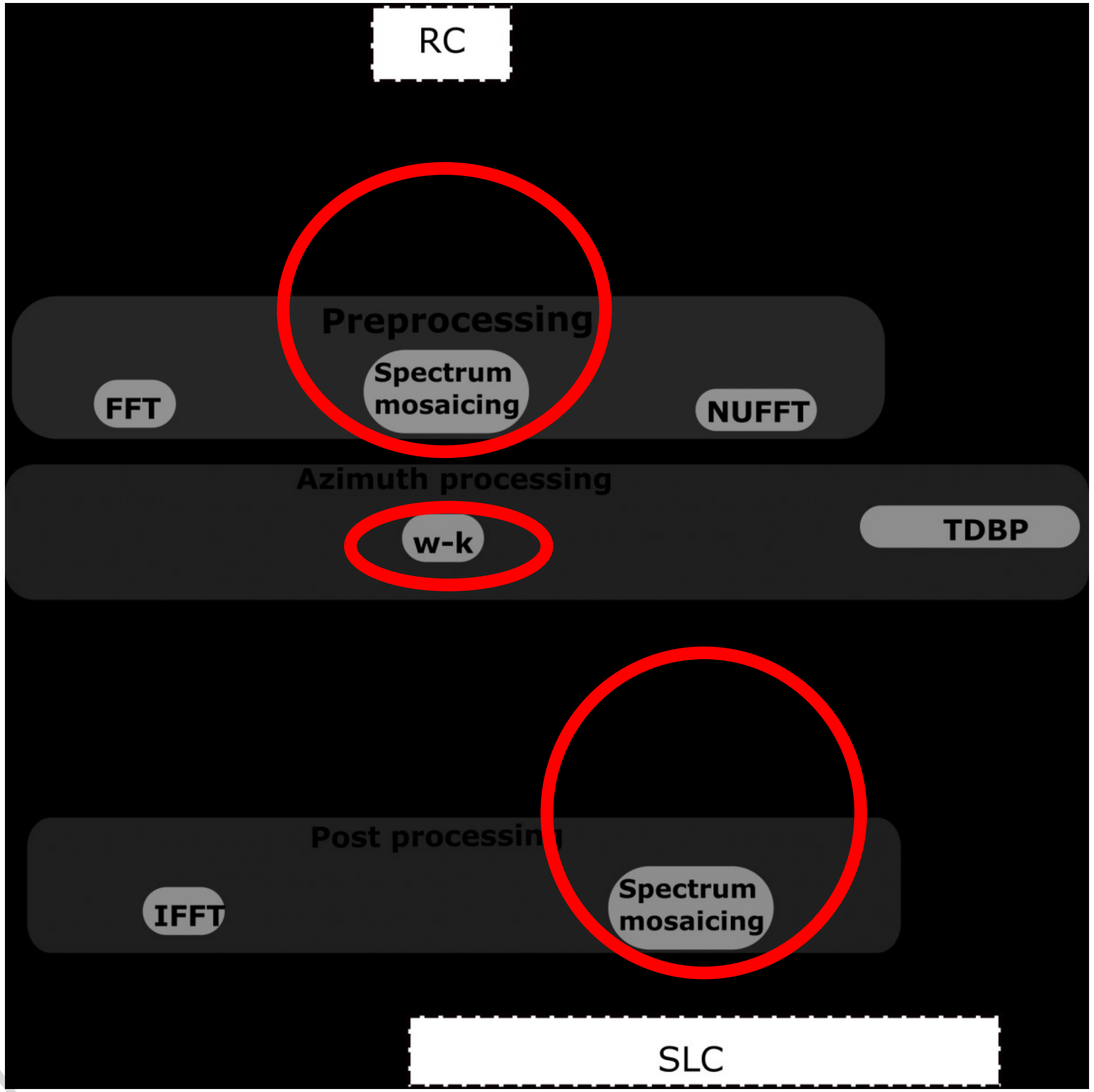
- Example:
  Sentinel-1, WV mode, rainforest (GAFA vs IPF)
  WV1, HH



Timestamp	Mean difference [dB]	Std [dB]
09:22:05.101179	0.050	0.080
09:22:06.313177	0.035	0.058



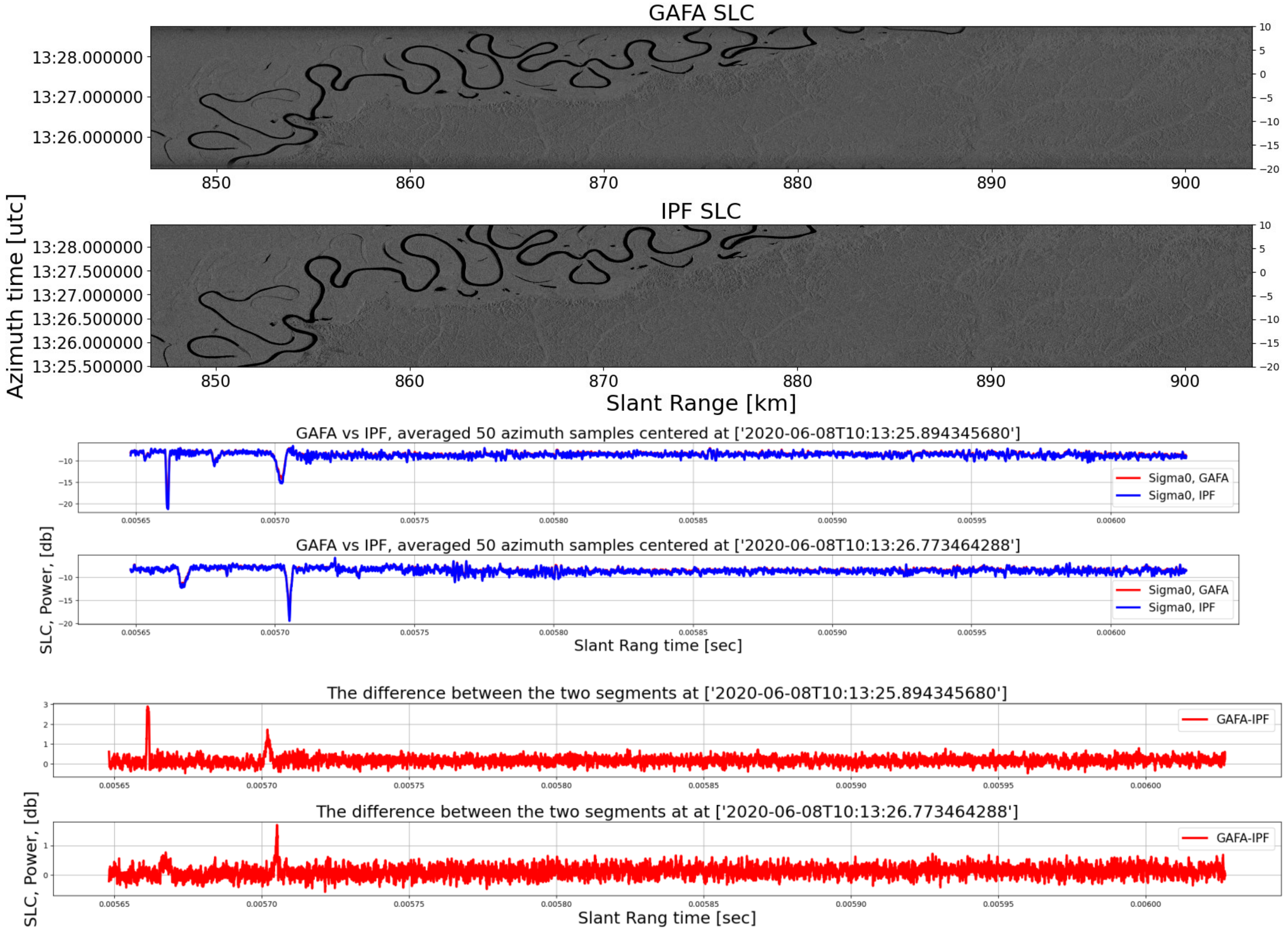
Support for TOPS/spotlight - Monostatic



- **Preprocessing:**
  - Spectral mosaicking
- **Focusing:**
  - Common kernel
- **Post processing:**
  - Spectral mosaicking
- **Note:**
  - Spotlight and inverse TOPS can be focused with same processing flow
  - ScanSAR can be focused with no postprocessing and same postprocessing

Support for TOPS – Monostatic

- Example:
  - Sentinel-1, IW mode
  - rainforest (GAFA vs S1 IPF)
  - IW1, HH

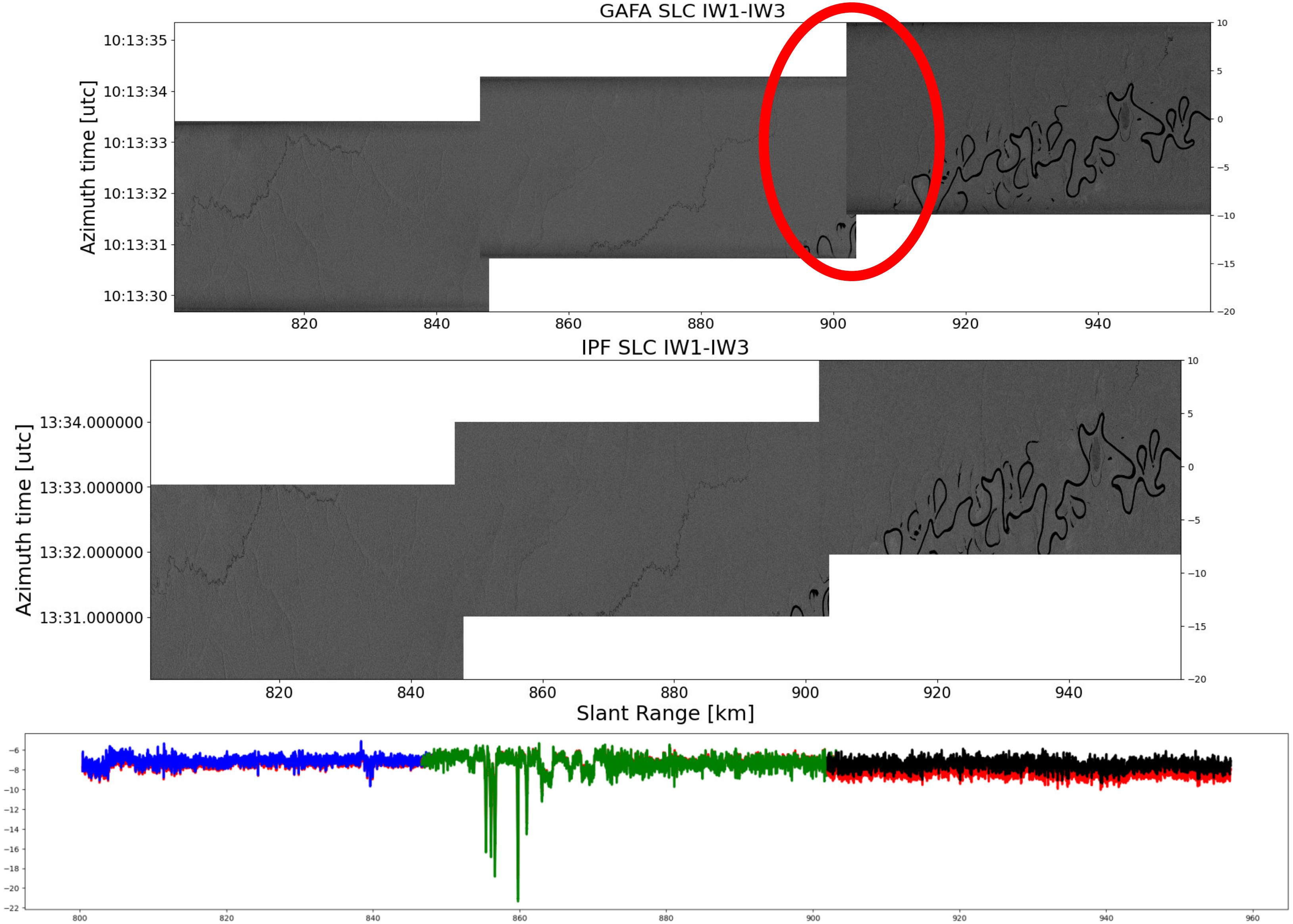


Timestamp	Mean difference [dB]	Std [dB]
13:25.894345	0.151	0.213
13:26.773464	0.118	0.176

Support for TOPS – Monostatic

Issue: Small, swath dependent bias when compared to ESA IPF

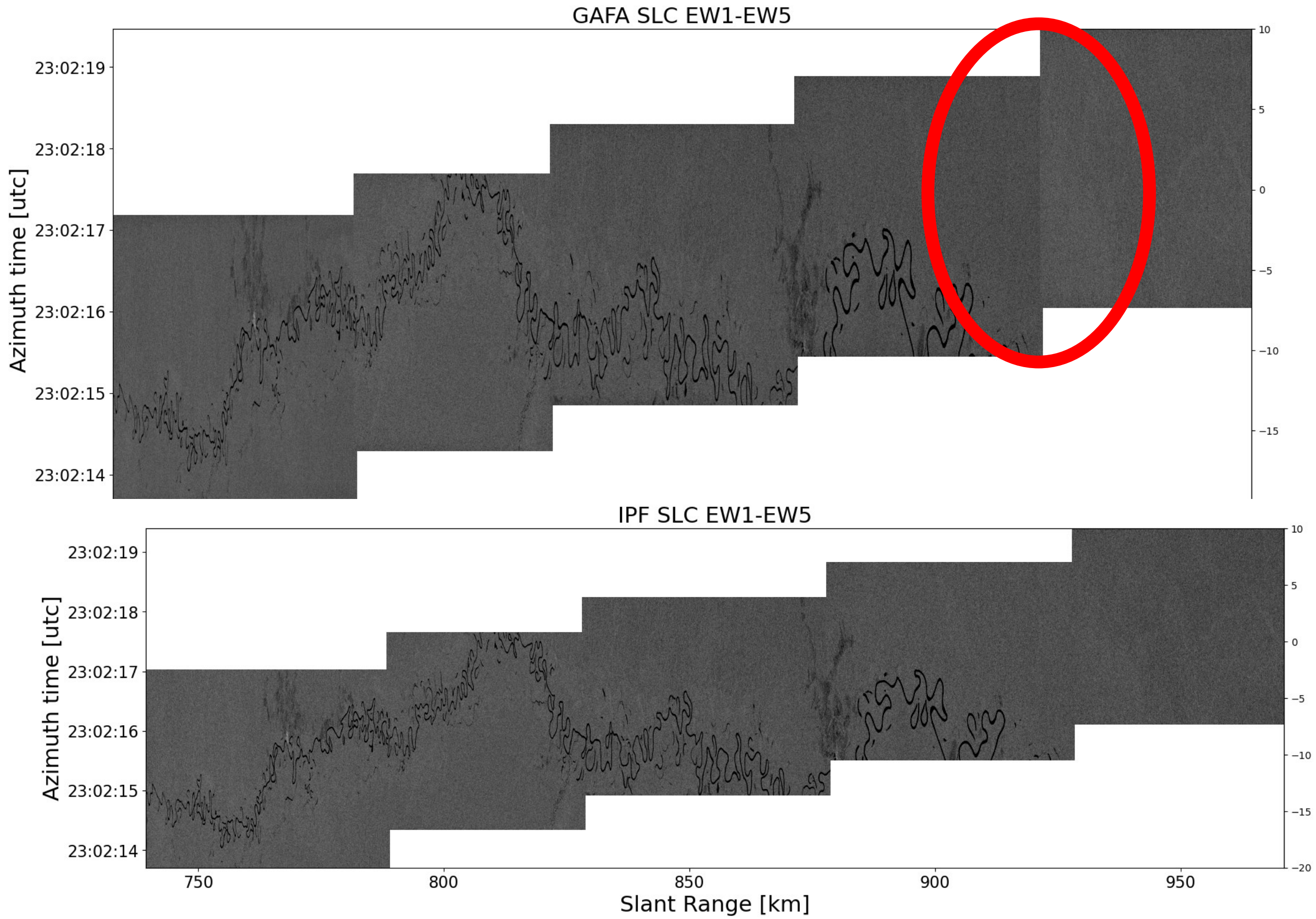
- Known effect likely to be due to imperfect antenna model
- IPF corrects this using swath dependent "processing gain" factors, GAFA currently does not

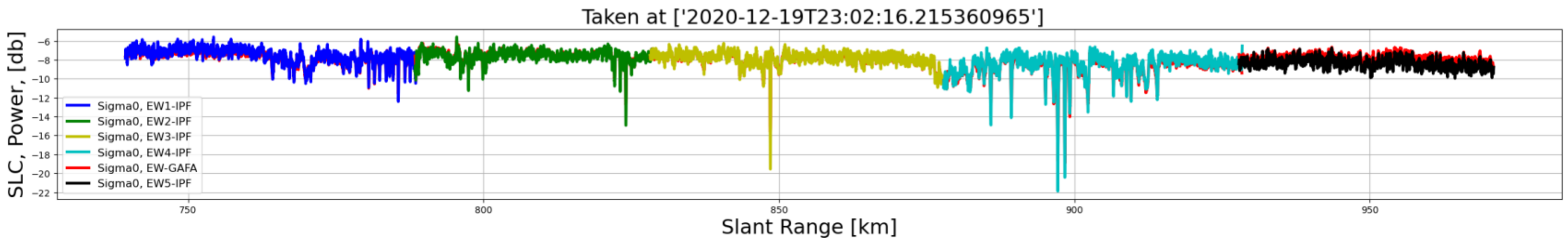


Support for TOPS – Monostatic

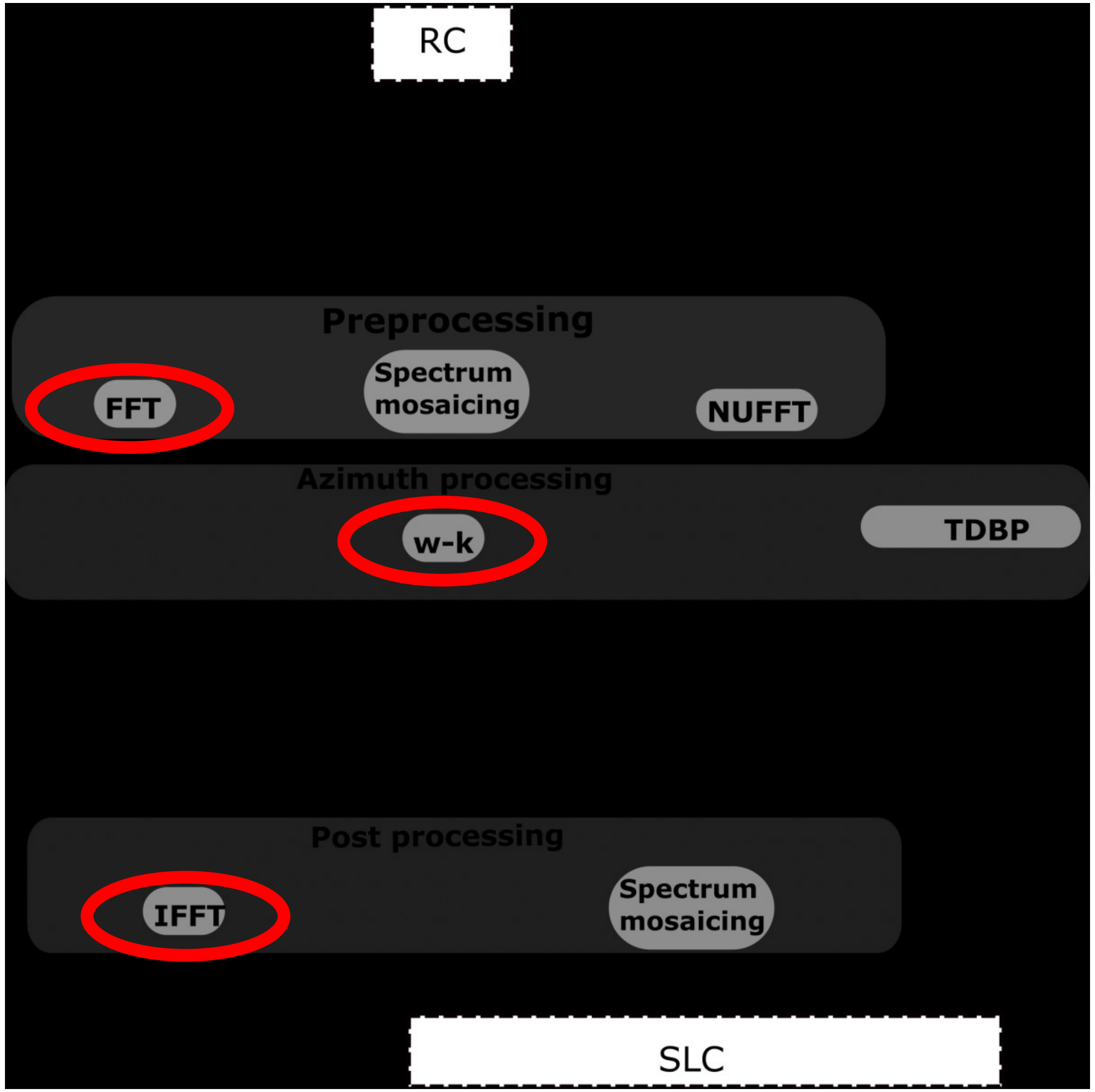
Swath dependent bias
when compared to ESA IPF

Jumps observed between swaths





Support for Bistatic – Future missions



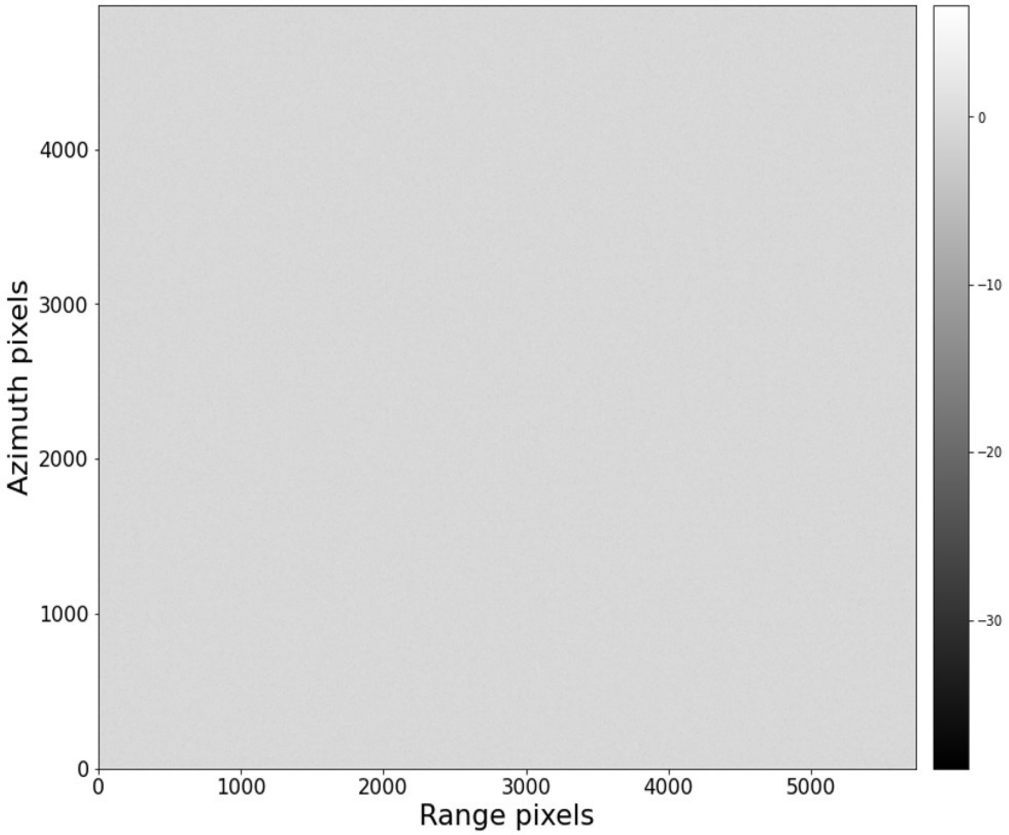
Bistatic/Multistatic handled same way as high-squint monostatic, but with adapted geometry calculations – due to separate Tx/Rx parameters

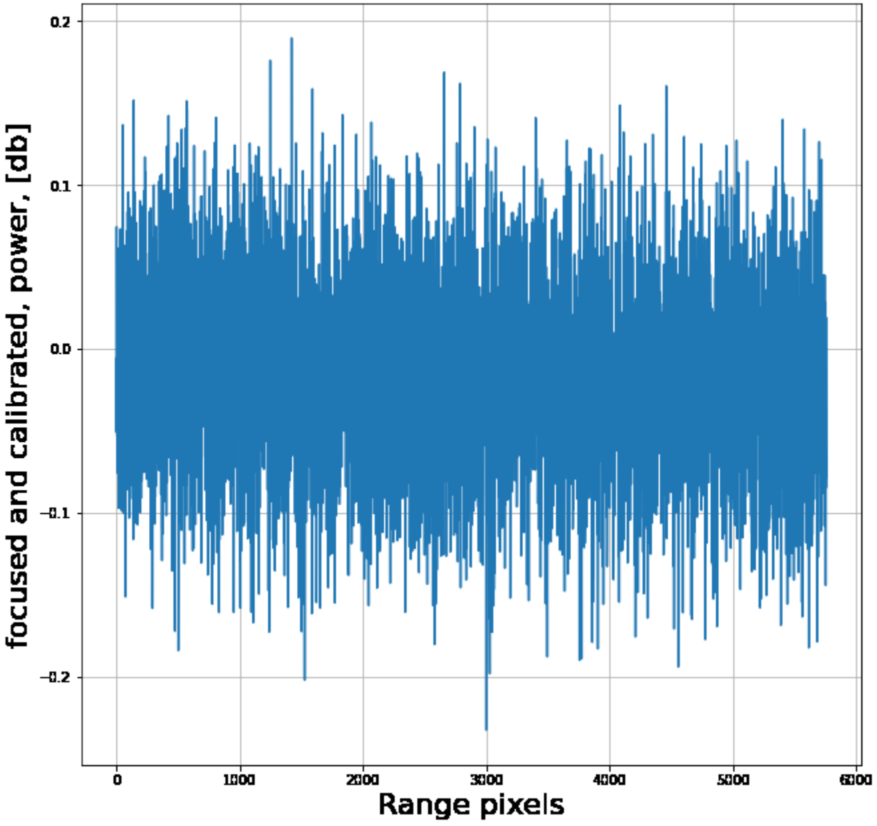
- Preprocessing:
  - None (FFT does the job)
- Focusing:
  - Support for High-squint
- Post processing:
  - None (IFFT)

Support for Bistatic – Future missions

- Validation of the processor with flat scene simulations
  - Focused and radiometrically corrected
- Also validated using point target responses

Harmony – A: WV

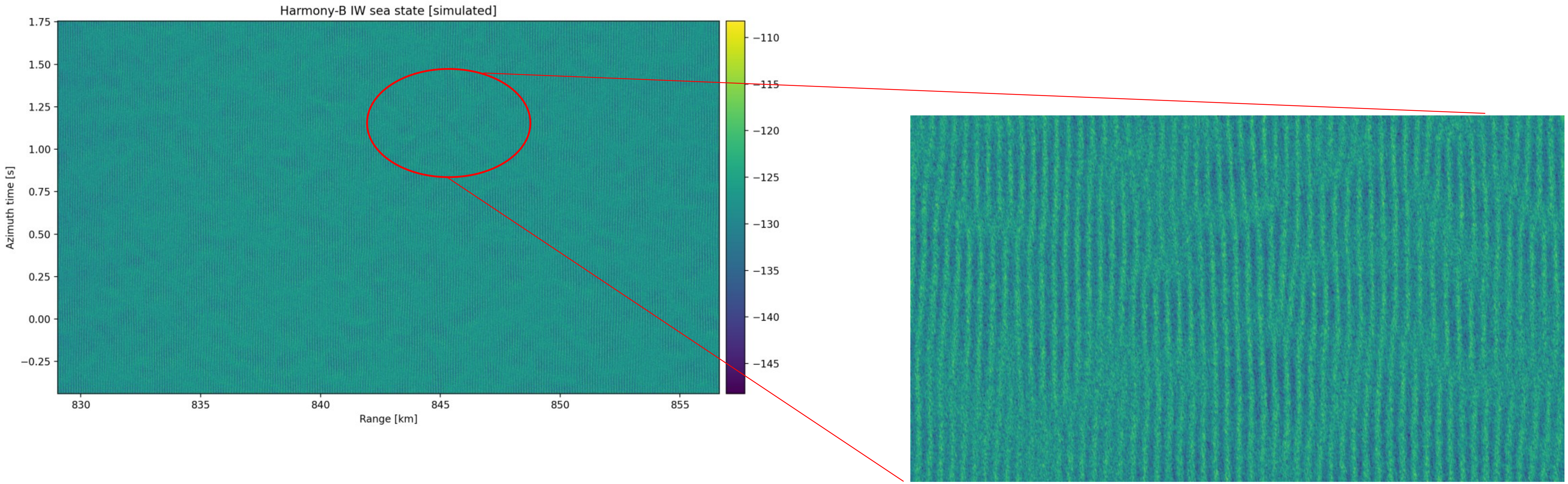




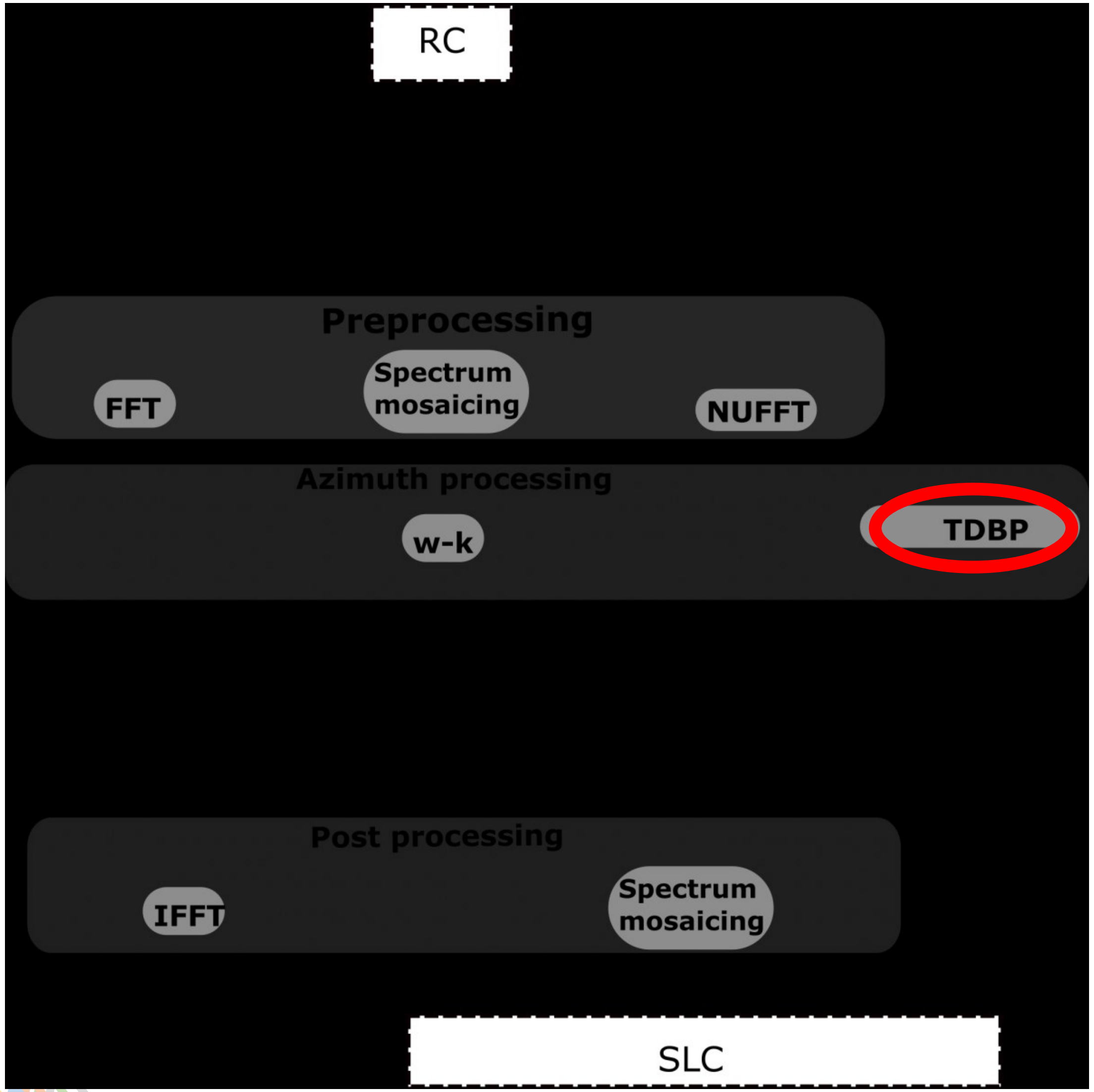
Support for Bistatic – Future missions

Validation of the processor with **sea-state simulations**

Bistatic-TOPS for Harmony



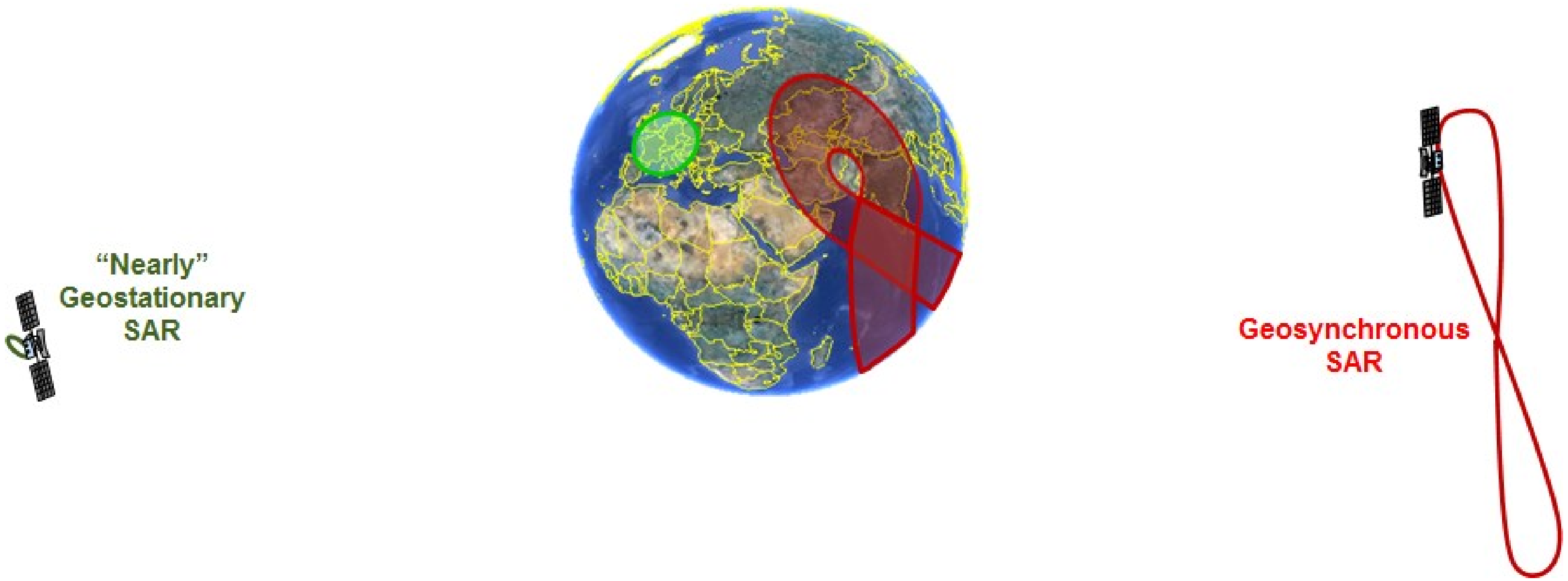
Support for GEO-SAR – Future missions



- Time domain processing (TDBP)

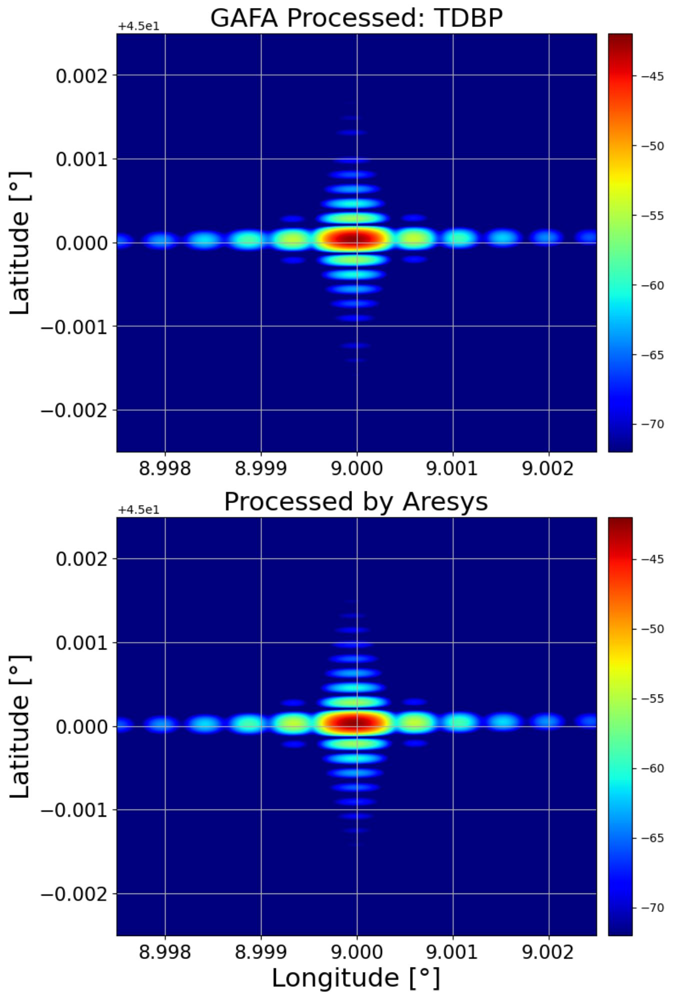
Support for GEO-SAR – Future missions

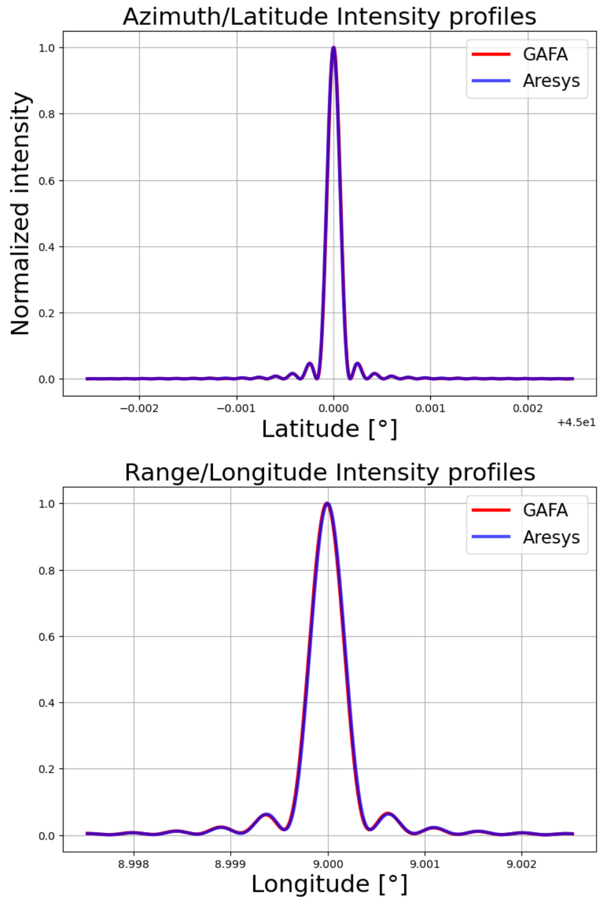
- GEO-SAR concept introduced since eighties
- Technological and processing constraints prevented the implementation so far
- Hydroterra mission selected as one of the three EE10 candidates
- Hydroterra+ (evolved concept) selected as EE12 candidate
- Frequency domain processing approach limited by:
  - Non-straight orbit
  - Limited azimuth invariance
  - Large azimuth blocks size



System	Geostationary SAR	Geosynchronous SAR	LEOSAR [Sentinel-1]
Antenna size	3-6 m	15-30 m	12 m
Average Tx Power	400 W	3000 W	250 W
PRF	50 Hz	200 Hz	1700 Hz
Max velocity	5 m/s	2600 m/s	7500 m/s
Integration time	20 mins. - 8 hrs.	< 2 mins.	< 1 s

Example: Validation of TDBP in GAFA using GeoSAR simulations





Orbit time (P1)	05:47:00

Summary

- Main scenarios have been covered and demonstrated during GAFA development:
  - LEO Monostatic, multistatic, L- and C- band + GEO-SAR
  - HRWS capability (ROSE-L) currently being verified
- A versatile kernel implemented in a generic way: heavy lifting has been taken care of
  - Typically, only minor pre- and post-processing steps are needed.
- Adaptation for any current or future SAR mission with minor re-configuration
- GAFA currently used for:
  - Harmony end-to-end performance activities
  - Independent processor verification S-1C IOC
    - Including radiometric calibration
- Standardisation of data model for range/azimuth SAR data (L0 and L1)???