TERRASCOPE SENTINEL-1

ALGORITHM THEORETICAL BASE DOCUMENT (ATBD)

S1 – SLC COHERENCE – V110

Reference: ***Terrascope Sentinel-1 Algorithm Theoretical Base Document S1 – COHERENCE – V110***
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LIST OF ACRONYMS

ACRONYM	EXPLANATION
ATBD	Algorithm Theoretical Base Document
COG	Cloud-Optimized GeoTIFF
DEM	Digital Elevation Model
DN	Digital Number
EO	Earth Observation
ESA	European Space Agency
GDAL	Geospatial Data Abstraction Library
GEOTIFF	Geospatial Tagged Image File Format
GIS	Geographical Information System
GRD	Ground Range Detected
IW	Interferometric Wide Swath
LUT	Lookup table
NRT	Near-real time
PDF	Product Distribution Facility
S1A/B	Sentinel-1A/B
SAR	Synthetic Aperture RADAR
SLC	Single Look Complex
SNAP	Sentinel Application Platform
SRTM	Shuttle RADAR Topography Mission
VV/VH	Vertical-Vertical/Vertical-Horizontal polarization mode

1. Introduction

1.1. Terrascope explained

Terrascope is the Belgian platform for Copernicus Sentinel, PROBA-V and SPOT-VEGETATION satellite data, products, and services. It provides easy, full, free and open access to all users without restrictions. This allows non-specialist users to explore the wealth of remote sensing information and build value-added products and services.

The following data are included:

- Sentinel-1 SAR data (sigma0 and coherence) over Belgium and its surroundings
- Sentinel-2 multispectral data over Europe and parts of Africa
- Sentinel-3 multispectral and thermal Synergy (SYN) – Vegetation (VGT) and Land Surface Temperature (LST) data
- Sentinel-5P atmospheric composition data
- The SPOT-VEGETATION archive
- The PROBA-V archive

For Sentinel-1, a sigma0 backscatter product is provided, obtained by further processing the Level-1 GRD products provided by the European Space Agency (ESA).

Users have the possibility to build derived information products to their own specification, using the Terrascope processing cluster through provided virtual machines or notebooks, and via OpenEO. This eliminates the need for data download (and consequential storage costs), because the cluster holds all of the data in a directly accessible, analysis-ready format. Integration of data or products in your own application is facilitated through catalog (opensearch and STAC) and Open Geospatial Consortium (OGC) web services.

Terrascope is user centered, so any suggestions for new or enhanced functionality are welcome. Feel free to contact us: info@terrascope.be.

1.2. Scope of Document

This ATBD (Algorithm Theoretical Base Document) describes the origin and generation of the Sentinel-1 (S1) Level-1 SLC Coherence data product.

The document is organised as follows:

- Section 2 provides an overview of the input data needed for the processing workflow.
- Section 3 explains the data available to users.

- Section 4 provides a detailed description of the different processing algorithms.
- Section 5 justifies the overall workflow with a quality assessment.

1.3. Description

The Sentinel-1 Level-1 SLC Coherence product provides the interferometric coherence between two Level-1 SLC images. Interferometric Coherence is the amplitude of the complex correlation coefficient between two images. Given two complex SAR images s1 and s2, coherence γ is defined as:

$$\gamma = \frac{|\langle s_1 s_2^* \rangle|}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}}$$

where |..| denotes as absolute value, <..> stands for average operation and * represents a complex conjugate product. Coherence is a unit-less metric with a range [0, 1]. High coherence values represent scatterers that were stable during the time between the two acquisitions, whereas low coherence values imply a change in backscatter intensity and/or mechanism. This can be caused by natural variations in the surface of the scatterer (e.g. water and vegetation) or changes to the scatterer itself (e.g. destruction of a building).

The processing workflow takes two ESA Level-1 SLC products as input. These images are first orbit corrected and co-registered through back-geocoding. Next, the coherence calculation takes place. Finally, the geometric distortions are removed through a Range Doppler terrain correction. All these steps are performed using the SNAP (the ESA Sentinel Application Platform) toolbox, more details are provided in the remainder of this document. The final product encompasses GeoTIFF files for the coherence in both the VV and VH polarization.

This document applies to the Terrascope S1 coherence V110 processing chain. Table 1.1 summarizes the main characteristics of the different Terrascope product versions until V110. A comparison between both versions is included in Section 5.1.

Table 1.1: Summary of main characteristics of different Terrascope versions until V110.

Version	Main characteristics
V100	• Processing chain: SNAP 7.0
V110	• Processing chain: SNAP 11.0, GDAL 3.8.4, Python 3.11 • Scale and offset in metadata fixed • File naming corrected • Refactoring of code

1.4. Feature added value/use case

The calculation of interferometric coherence products requires expert knowledge, SAR processing software and considerable computation resources. On the other hand, these data have considerable potential for several downstream applications, including:

- change detection and disaster impact mapping
- agricultural monitoring (e.g. plowing detection)
- subsidence monitoring

The detection of landslides is only one of the potential applications. Figure 1.1 shows an example of landslide event. The left pane shows a picture from the ground while the right pane shows the coherence product, where high coherence values are shown in white and low coherence values in black. Here, the crack in the land surface can clearly be discriminated as the darker region.

By providing an operational, near-real time processing chain, the Terrascope platform reduces the barrier for users to explore coherence data for their downstream application.

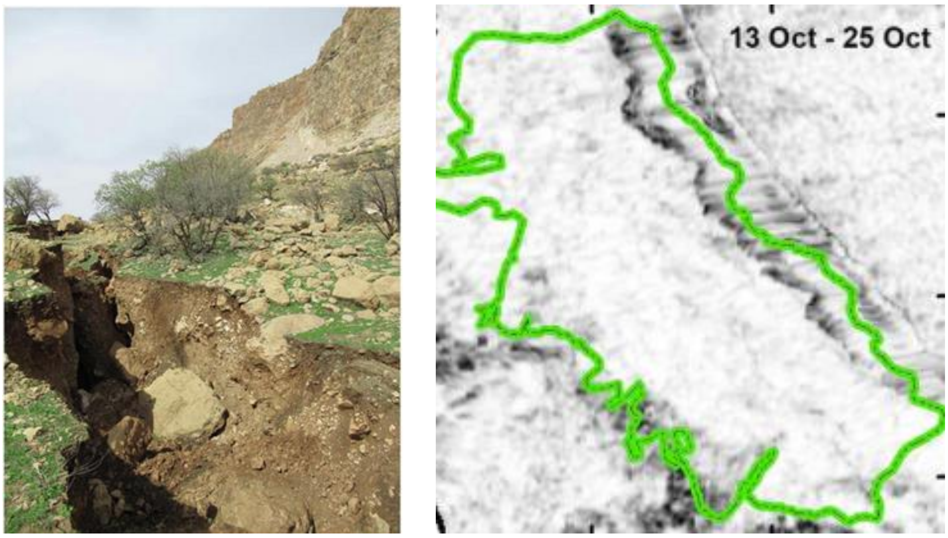

Figure 1.1: Example of a landslide as seen from the ground (left) vs. on a coherence product (right; low values in black, high values in white).

2. Input data

2.1. General

The Terrascope processing starts from the Sentinel-1 Level-1 SLC data products. These can be freely downloaded from the Copernicus Dataspace Ecosystem (https://browser.dataspace.copernicus.eu/).

2.2. Ancillary data

2.2.1. Orbit files

As the orbit state vectors provided in the metadata of a SAR product are generally not completely accurate, an orbit correction needs to be applied (cfr. Section 4.1). In order to allow for near-real time (NRT) processing, the Terrascope Sentinel-1 coherence V110 workflow uses restituted orbit files, which are auto-downloaded during the workflow.

2.2.2. Digital elevation model (DEM)

For both the back geocoding of the image pair (cfr. Section 4.3) and the Range Doppler terrain correction (cfr. Section 4.7), a DEM is required. The Terrascope Sentinel-1 coherence V110 uses the SRTM 1Sec DEM, which is available at a resolution of 30m. It is auto-downloaded during execution of the SNAP processing graph.

3. Output

3.1. Product layers

3.1.1. Product data

The coherence products generated and distributed by Terrascope include 2 outputs, each of which is formatted as a single layer compressed Cloud-Optimized GeoTIFF (COG) format. Each output is provided in a 10m resolution. Figure 3.1 shows the S1 coherence product file list.

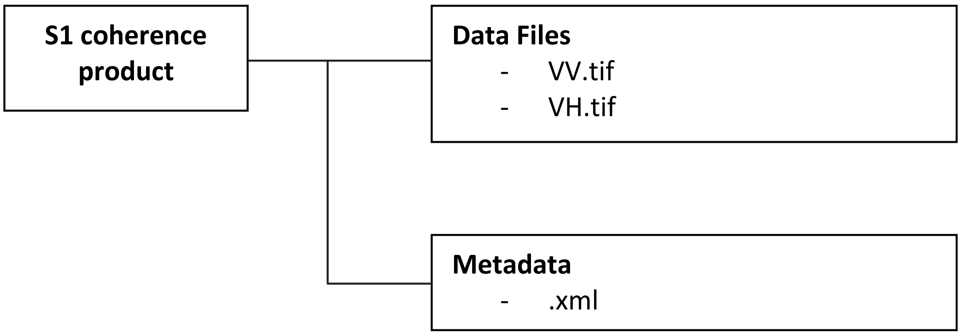

Figure 3.1: S1 coherence product file list.

3.1.2. Data collection structure and naming convention

All Terrascope Sentinel-1 coherence products are stored in the **SLC_COHERENCE** collection. In the Terrascope Virtual Machine environment, this data can be found in */data/MTDA/TERRASCOPE_Sentinel1/SLC_COHERENCE/<Year>/<Month>/<Day>/<Product_ID>.*

The <Product_ID> is constructed as follows:
<mission_identifier_1>_<mission_identifier_2>_<product_type>_<start_date_1>_<start_date_2>_<orbit_direction>_<relative_orbit>_<product_version>

Template	Description
mission_identifier_x	Mission identifier of product number x. Combination of S1A, S1B or S1C, e.g. S1A_S1B
product_type	Coherence
start_date_x	Start date of product number x. Product start date in the format yyyymmddThhmmss

orbit_direction	ASC or DSC, always the same for a given relative orbit
relative_orbit	relative orbit number
product_version	VITO product version

Example:

Input product 1:
S1A_IW_SLC__1SDV_20250320T055119_20250320T055147_058384_07382F_3FDE

Input product 2:
S1A_IW_SLC__1SDV_20250401T055120_20250401T055148_058559_073F32_D323

Coherence product:
S1A_S1A_Coherence_20250320T055119_20250401T055120_DSC_37_V110

3.1.3. Product metadata

The VV and VH coherence outputs are scaled and stored in uint8 format. The physical values are converted from floating point values into integers, mainly to reduce the file sizes. The physical number can be defined by using the following formula:

Physical Value = Scaling * Digital Number + Offset,

with Scaling set to 0.004 and Offset to 0.

The Scaling and Offset are stored in the GeoTIFF metadata, while other properties are provided in the accompanying xml file.

3.2. Product version

Terrascope products are produced in a controlled way. Every product has a version indicator, consistent with the Semantic Versioning 2.0.0 protocols (https://semver.org/). The version indicator has three digits: XYZ.

- X is 0 during prototyping and pre-operational use. X is 1 for the first operational setup, and increments when results are no longer backward compatible (i.e. any further processing will have to be adapted to deal with e.g. format changes, value scaling, etc.).
- Y is reset to 0 with an X increment. Y increments when functionality is added, but backward compatibility is guaranteed (e.g. when a different approach is taken for atmospheric or geometric correction).

- Z is reset to 0 when Y increments. Z increments when the software is patched (bug fixed) without any functional changes.

The current Terrascope Sentinel-1 coherence workflow version is V110.

Whenever X or Y changes, the impact of the updates will be reported. Users are informed about version changes through the Terrascope newsletter (to subscribe: https://terrascope.be/en/stay-informed).

3.3. Product data access

The Terrascope S1 data products can be accessed through:

- Web services: Web Map Service (WMS) and Web Map Tile Service (WMTS):
  https://bit.ly/TerrascopeFAQ_WMTS
  Protocols for downloading images and integrating them into GIS software

- Notebooks (login required): https://notebooks.terrascope.be/hub/login
  Programming environment to quickly access and edit data

- Virtual Machines (VM) (login required): https://terrascope.be/en/form/vm
  External computer used to view data and process it in the cloud

- OpenEO API (login required): https://openeo.org/documentation/1.0/python/
  Python API to automate satellite data processing in the cloud

The details of each of these access points are described on https://terrascope.be/en/services.

4. Methodology

In order to product the coherence product, a set of processes needs to be executed. All of these are performed using SNAP, more specifically using the command line "gpt" tool of SNAP. An overview of the SNAP processing graph is provided in Figure 4.1. For each process in the workflow, the following sections describe what the operator in SNAP does, what it needs as input, and what it delivers as output. A more in-depth algorithmic description is provided in [1]. Following these SNAP algorithms, a few more gdal steps are required to save the result to GTIFF, apply the scaling, correctly set the nodata value, add overviews and provide the metadata.

The following sections describe the different SNAP process used. Part of the information provided below is taken from operator descriptions in SNAP. We refer the reader to these documents for additional information on the processes involved.

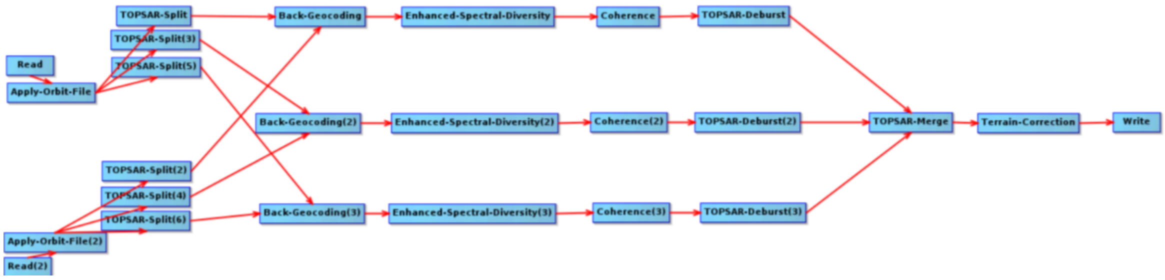

Figure 4.1: SNAP processing graph for the Terrascope SLC coherence product.

4.1. Orbit correction

The orbit state vectors provided in the metadata of a SAR product are generally not completely accurate and can be refined with the precise orbit files which are available days-to-weeks after the generation of the product. The orbit file provides accurate satellite position and velocity information. Based on this information, the orbit state vectors in the abstract metadata of the product are updated.

For Sentinel-1, Restituted orbit files and Precise orbit files may be applied. Precise orbits are produced a few weeks after acquisition. Orbit files are automatically searched and downloaded from https://qc.sentinel1.copernicus.eu/. To refine the orbit state vectors, the following steps are performed by SNAP:

- Get the start time of the source product;
- Find orbit file with user specified type and the product start time;
- For each orbit state vector, get its zero Doppler time;
- Compute new orbit state vector with 8th order Lagrange interpolation using data for the 9 nearest orbit positions around the zero Doppler time.

The Sentinel-1 precise orbit determination operations provide restituted orbit information within 3 hours from sensing which is nominally used for the systematic processing of Fast24 products. The quality of the restituted orbits has proven to be better (twice as good) than expected in 95% of the cases, resulting in the very good absolute geolocation accuracy of Sentinel-1 products. Given the timeliness of the product, the high absolute accuracy already with restituted orbits, and the high additional load and complexity of reprocessing every image once the precise orbit becomes available, we provide our coherence product based on restituted orbit files.

4.2. TOPSAR Split

This operator splits each sub-swath with selected bursts into a separate product.

4.3. Sentinel-1 Back Geocoding

This operator co-registers two Sentinel-1 SLC split products (reference and secondary) of the same sub-swath using the orbits of the two products and a Digital Elevation Model (DEM). The SRTM 1sec DEM is used at this step. It is an essential step to ensure that the two images are perfectly aligned for coherence calculation.

4.4. Sentinel-1 Enhanced Spectral Diversity

This operator performs the joint coregistration of the Sentinel-1 stack. First, it estimates a constant range offset for the whole sub-swath of the split S-1 SLC image using incoherent cross-correlation. Next, it estimates a constant azimuth offset for the whole sub-swath using the Network Enhanced Spectral Diversity (NESD) method, which exploits the data in the overlap areas of adjacent bursts. By applying the range and azimuth shift corrections to the secondary bands, the required fine azimuth coregistration accuracy can be obtained.

4.5. Coherence estimation

This operator is the core module that estimates the coherence value between two images on a pixel-by-pixel basis. We do not subtract the topographic phase, which is a necessary step to calculate the InSAR phase.

4.6. TOPSAR Deburst and Merge

Sentinel-1 IW products have 3 swaths and each sub-swath image consists of a series of bursts, where each burst was processed as a separate SLC image. For Sentinel-1 IW, a focused burst has a duration of 2.75 sec and a burst overlap of ~50-100 samples. An example IW SLC image with different sub-swaths and bursts is provided in Figure 4.2. As can be seen from this figure, the imaged ground area of adjacent bursts only marginally overlaps in azimuth.

The TOPSAR Deburst operator combines the images for all bursts in a sub-swath by re-sampling them to a common pixel spacing grid in range and azimuth. The TOPSAR Merge operator merges the debursted split product of different sub-swaths into one complete product. It should be noted that merging the bursts does not eliminate artefacts. This could be done in a later phase e.g. by applying multilooking.

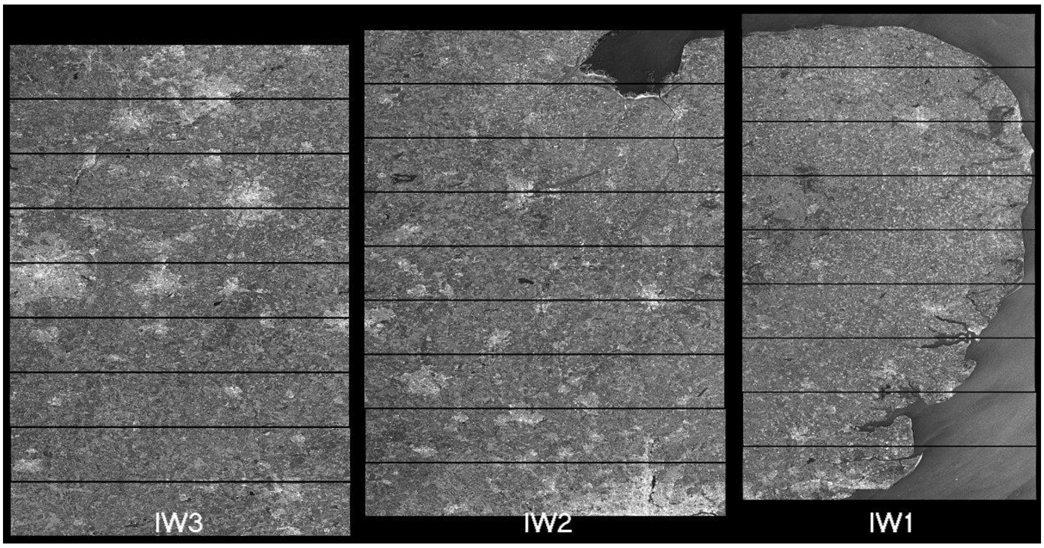

Figure 4.2: Example Sentinel-1 IW SLC image with different sub-swaths and bursts.

4.7. Range Doppler Terrain Correction

Due to relief variations of a scene and the tilt of the satellite sensor, distances can be distorted in the SAR images. Image data which is not directly at the sensor's nadir location will have some distortion. Terrain corrections are intended to compensate for these distortions so that the geometric representation of the image will be as close as possible to the real world.

The process needs a DEM based on which the correction is applied. The more accurate the DEM, the better the correction. For the Terrascope Sentinel-1 coherence V110 product, the SRTM 1Sec DEM is used. Furthermore, we can define the map projection (~ellipsoid) based on the which the correction will be done. Here we use WGS 84 / UTM zone 31N with a pixel spacing of 10m, in accordance with the Sentinel-2 data in Belgium as also provided by Terrascope.

5. Quality assessment

5.1. Terrascope V110 vs. V100

In the latest update of the Terrascope Sentinel-1 coherence workflow, the SNAP software was updated and some important bugs related to the band naming and metadata were fixed. In the V100 version the polarization was inconsistently switched in the file name, though correct in the metadata. Besides this correction, no product differences are expected.

To quantify the differences between both versions, as well as the impact on downstream analysis, a statistical consistency analysis was performed for all imagery obtained in October 2024. Figure 5.1 and Figure 5.2 show the comparison between V100 and V110 for VH coherence and VV coherence respectively. A subsampling of 1/100th points was used.

In each figure, the first row and second row of subplots show the comparison when matching based on file name and metadata respectively. As can be seen from the first row of each figure, important deviations prevail when matching on file name, caused by the bug present in V100. When comparing the correct bands (cfr. second row of each figure), a perfectly linear relation is shown.

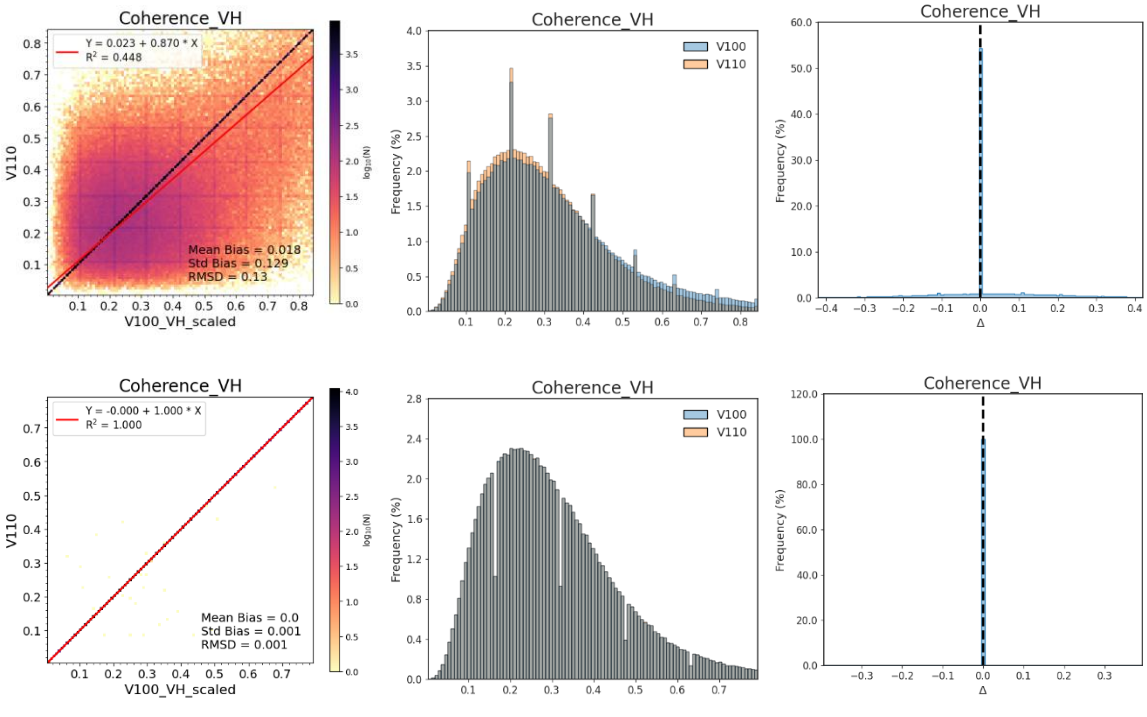

Figure 5.1: Comparison of V110 and V100 versions for VH coherence: scatter density plot (left), histogram overlay (center) and histogram of absolute differences (right). Upper and lower row show results for matching based on file name and metadata respectively.

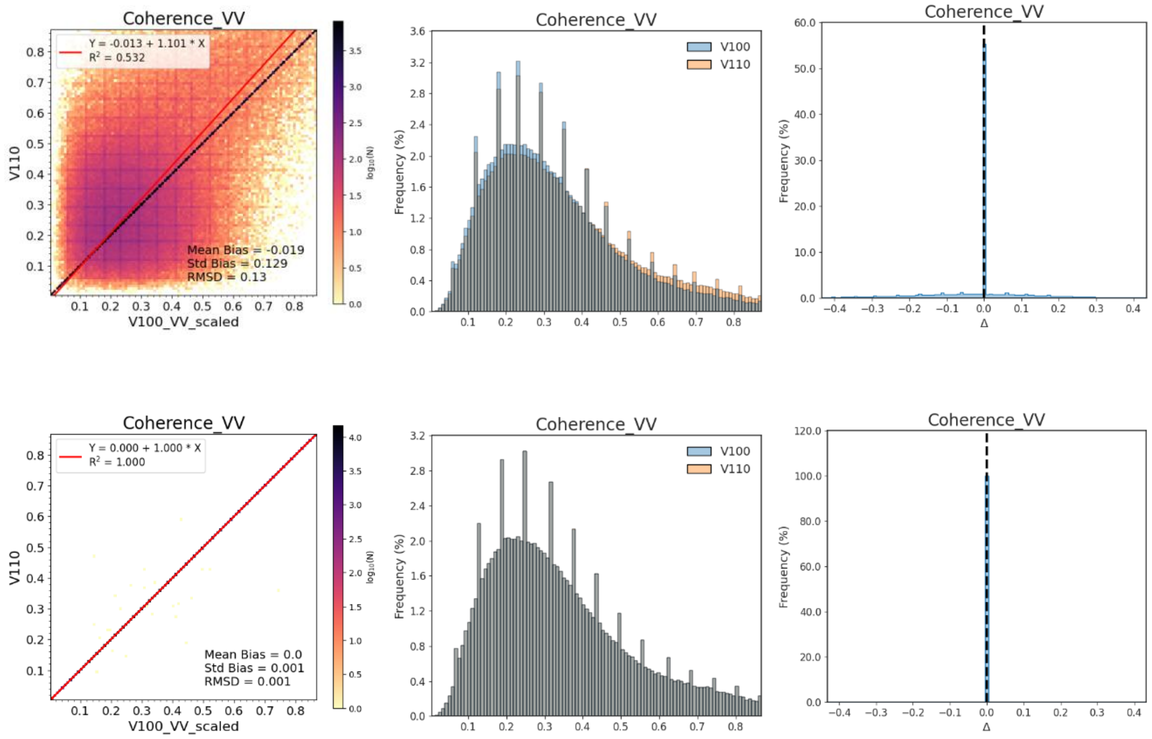

Figure 5.2: Comparison of V110 and V100 versions for VV coherence: scatter density plot (left), histogram overlay (center) and histogram of absolute differences (right). Upper and lower row show results for matching based on file name and metadata respectively.

6. References

[1] Yagüe-Martínez, Néstor, et al. "Interferometric processing of Sentinel-1 TOPS data." IEEE Transactions on Geoscience and Remote Sensing 54.4 (2016): 2220-2234.