MPC-SAR

S1-ETAD Project

Product Definition Document

European Union

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Document Change Control

This document is under configuration control. Latest changes to the document are listed first.

Issue	Date	Chapter	Changes
2.4	06.03.2023	All 2.1 4.4, 4.5 5, 5.1 5.2, 7.4 7.1 7.1, 7.2 8	Updates reflecting the introduction of the burstID in ETAD products and the change in the common grid definition and (polarization) calibration parameter dependencies introduced with SETAP v. 2.1 Applicable documents updated for latest versions Grid representation and reference times changed w.r.t. common grid burstID introduced Polarization dependency of instrument calibration changed burstID as identifying parameter for SLC-ETAD burst-matching Changes and corrections w.r.t. (burst) reference times and common gridding. Equations fixed on pp. 26 that describe the time calculation of the samples in the grid and the calculation of indices i,j; the burst:gridStartAzimuthTime and burst:gridStartRangeTime additions were incorrect and have been removed Gridding description and Table 3 changed w.r.t. to common grid
2.3	11.11.2022	Document 2	Cover updated for document release under SAR MPC maintenance contract Applicable documents updated for latest versions
2.2	24.10.2022	Annex A 2 7 7.2	Clarifications on sign of delay-to-phase conversion added Reference documents updated Reference added Data resampling clarified and references added
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2.0	11.05.2021	All 1 2 4 5 6 7 8 Annex A Annex B	Document completely restructured and revised. Previous chapters 6, 7, 8 and Annex A & C with format specifications moved to dedicated Product Format Specification document. Chapters 6 & 7 and Annexes replaced with information on product usage. Document re-purposed and product usage included. Reference documents updated Restructured and extended Minor editorial changes New chapter on summary of product format New chapter on product usage Formerly chapter 9; minor editorials New Annex on interferometric usage Annex on GRD applicability completed
1.1	27.02.2020	All All All 5 ff 6	Updated revision for CDR **General changes:** Restructuring and extension of chapters and annexes Clarifications and editorials Change to a hierarchical product structure without SLC slice level Detailed specification of NetCDF file content and annotation

		7, Annex C	Detailed specification of XML annotation elements
		6, 7, 7.1, Annex C	Redistribution of burst annotation elements from NetCDF to XML
		5.1 ff	Change of mapping grid format from XML to binary
		9	Inclusion of ETAD product tables on grid spacing, extent and product sizes
		8.1	Time tags in product naming refer to the first/last valid grid points and not to the focused data
		8.2	Definition of preview components
		8.3	Definition of orbit component
		Annex A	Introduction of annex for future specification of the manifest file
		2	Reference documents updated
			PDR-RIDs:
		Figure 2 4.3	PDR-PS-NM-01: Description of figure components updated. Additional explanation text added
		Figure 3 4.3	PDR-PS-NM-02: Figure 3 updated. Text added.
		4.4	PDR-PS-NM-04: Extent of grid margins explained
		Table 1 5.1	PDR-PS-NM-05, PDR-PS-NM-06: Mapping grid format changed. See also 6.1 for additional annotation of timing coordinates.
		7, 8.2, 8.3, Annex C	PDR-PS-NM-07: (Sub-)sections added on main annotation, previews and orbit.
		5	PDR-PS-NM-08: Burst index reference explained.
		4.3	PDR-PS-NM-09: Explanation on geo-referencing and geographic reference frames for mapping grid added
		6.1, Figure 7, Table 2, all	PDR-PS-NM-10: SLC slice structural elements removed from product. NetCDF attributes/variables detailed.
		9, 6, 7, 8.1, Annex A/C 5.2	PDR-PS-NM-11: NetCDF specified in detail, product tables on extent/size/volume added. Additional description of product elements. High level "placeholder" description for yet to be defined manifest file included. Section on polarization dependence of corrections added.
		8	PDR-PS-NM-12: Reference corrected. NetCDF file extension changed to .NC
1.0 draft	05.07.2019	All	First draft issue

Table of Contents

1 Introduction

1.1 Purpose

The document at hand defines the content and usage of the Extended Timing Annotation Dataset (ETAD) product for Sentinel-1. It outlines the rationale behind the product, its purpose, structure and format and specifies the usage of the annotated geo-physical and SAR system correction parameters. The grid of the correction layers, their coordinate system, applied map projections and units are explained.

1.2 Scope

This document is applicable to the S1-ETAD project. It reflects in this version the first results of ETAD product validation activities with external scientific users. Together with the Product Format Specification document it shall provide the user of the ETAD product with the necessary information to apply the ETAD corrections to Sentinel-1 products.

2 Applicable and reference documents

2.1 Applicable document

The following documents are fully applicable for this document.

	Document ID	Document Title	Issue
[A1]	ESA-EOPG-EOPGM-SOW-1	Sentinel-1 Auxiliary product for precise atmospheric and geodetic correction: Statement of Work	1.0 18.06.2018
[A2]	ETAD-DLR-DD-0008	Algorithm Technical Baseline Document	2.3 06.03.2023
[A3]	S1-RS-MDA-52-7441	Sentinel-1 Product Specification	3.7 27.02.2020
[A4]	ETAD-DLR-DD-0004	S1-ETAD Input/Output Description Document	2.4 08.02.2023
[A5]	PGSI-GSEG-EOPG-FS-05-0001	Standard Archive Format for Europe (SAFE) Control Book Volume 1 Core Specifications	1.8 28.06.2008
[A6]	ETAD-DLR-PS-0014	S1-ETAD Product Format Specification Document	1.8 06.03.2023

2.2 Normative references

The following standards have been used for preparing the plan on hand (e.g. ECSS).

	Document ID	Document Title	Issue
[N1]			
[N2]			
[N3]			

2.3 Informative references

The following documents are referenced in the present document.

	Document ID	Document Title	Issue
[I1]	GMES-GSEG-EOPG-FS-10-0075	Sentinels POD Service File Format Specifications	1.22 18.01.2018
[I2]	GEO.2018-1988-2	Copernicus Digital Elevation Model Product Handbook	1.0 28.11.2019
[I3]	EGM2008	https://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html	
[I4]	ESDS-RFC-022v1	netCDF-4/HDF5 File Format	V0.03 March 2011
[I5]	10.1109/TGRS.2019.2961248	Gisinger, C., Schubert, A., Breit, H., Garthwaite, M., Balss, U., Willberg, M., Small, D., Eineder, M., Miranda, N.: In-Depth Verification of Sentinel-1 and TerraSAR-X Geolocation Accuracy using the Australian Corner Reflector Array. IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 2, pp. 1154-1181, 2021.	
[I6]	S1-RS-MDA-52-7440	Sentinel-1 Product Definition	Issue 2, Rev. 7, 25/03/2016
[I7]	10.13140/RG.2.2.24577.51041	Hajduch, Guillaume & Vincent, Pauline & Meadows, Peter & Piantanida, Riccardo & Small, David & Mouche, Alexis & Johnsen, Harald & Niemeijer, Sander & Demange, Christophe. (2019). The Sentinel-1 Mission Performance Center Activities and Support for the End Users Community.	2019

[I8]	10.1109/TGRS.2022.3194216	Gisinger, Christoph and Libert, Ludivine and Marinkovic, Petar and Krieger, Lukas and Larsen, Yngvar and Valentino, Antonio and Breit, Helko and Balss, Ulrich and Suchandt, Steffen and Nagler, Thomas and Eineder, Michael and Miranda, Nuno: The Extended Timing Annotation Dataset for Sentinel-1—Product Description and First Evaluation Results. IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-22, 2022.	
[I9]	10.1109/TGRS.2015.2497902	N. Yagüe-Martínez et al., "Interferometric Processing of Sentinel-1 TOPS Data," in IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 4, pp. 2220-2234, April 2016.	
[I10]	10.1109/36.739168.	R. Hanssen and R. Bamler, "Evaluation of interpolation kernels for SAR interferometry," in IEEE Transactions on Geoscience and Remote Sensing, vol. 37, no. 1, pp. 318-321, Jan. 1999.	

3 Terms, definitions and abbreviations

3.1 Terms and Definitions

Term	Definition
Extended Timing Annotation Dataset	Timing corrections to be applied to standard SAR products timings
SAFE format	Format used by the Sentinel-1 data products

3.2 Abbreviations

Abbreviation	Meaning
CDR	Critical Design Review
CF	Climate and Forecast
DEM	Digital Elevation Model
ESA	European Space Agency
EW	Extra Wide-Swath (SAR mode)
FM	Frequency Modulation
GRD	Ground-Range Detected
HDF5	Hierarchical Data Format version 5
IW	Interferometric Wide-Swath (SAR mode)
KML	Keyhole Markup Language
KMZ	Keyhole Markup Language Zip File
L1	Level-1
NWP	Numerical Weather Prediction
PDGS	Payload Data Ground Segment
PDR	Preliminary Design Review
S-1	Sentinel-1
S1-ETAD	Extended Time Annotation Dataset for Sentinel-1
SAFE	Standard Archive Format for Europe
SAR	Synthetic Aperture Radar
SET	Solid Earth Tides
SLC	Single Look Complex
SM	Stripmap (SAR mode)
TEC	Total Electron Content
TOPS	Terrain Observation by Progressive Scans (SAR mode)
XML	Extensible Markup Language

4 Extended Timing Annotation

4.1 Introduction

Precise geolocation for geodetic measurements in the centimeter accuracy range with spaceborne SAR instruments has been demonstrated in the past years and yielded an emerging field of applications. This precision is not achieved out-of-the-box when using the orbit, the speed of light and the satellite velocity alone to transform the annotated timing parameters of a SAR product into geo-referenced positions.

On the contrary, the radar pulses transmitted and received by SAR satellites like Sentinel-1 are subject to signal propagation delay variations when passing through different layers of Earth's atmosphere (troposphere and ionosphere). These delays depend on the actual atmospheric conditions at a certain time and location and the specific geometry of the SAR acquisition.

The object on ground which is to be measured in its position is not stable with respect to its absolute geo-coordinates. The dominant effects are caused by the Solid-Earth Tides (SET) which induce temporal variations of the location with respect to the stable global reference coordinate frame.

Additionally, approximations are used in the SAR image formation and product time annotation process which do not fully take into account the change of position of the SAR instrument during the signal travel time, the squint angle/Doppler effects, and the distance variations to the surface during the TOPS observations.

All the geo-physical effects can be calculated based on the orbits and annotated timing information in the SAR product when evaluating tropospheric numerical weather prediction (NWP) models, ionospheric Total Electron Content (TEC) data and geodynamic models. The errors induced by the SAR processing approximations can be estimated by analyzing the SAR timeline and Doppler- plus FM-rate-parameters based on an accurate Digital Elevation Model (DEM).

Calculating these errors and creating a data set to efficiently correct them in post-processing is the task of the S1-ETAD (Extended Time Annotation Dataset for Sentinel-1) processor [A1][A2]. With the output of the processor, the S1-ETAD product [A6], which contains the correction data set, any user may thus achieve accurate geo-location from a S-1 standard SAR product.

4.2 Timing Correction

The ETAD provides corrections for the SAR timing parameters for the known individual effects in the SAR range and azimuth direction and for the sum of the combined delays and offsets on grids with pre-defined spacing on ground. The corrections offered by the ETAD are based on earlier studies performed with Sentinel-1 [I5].

The ETAD product is specifically generated using the SAR products of each Sentinel-1 datatake as input, see the next chapter for details. The following correction layers are included:

- **Tropospheric delay in range:** the 4D operational analysis weather model data provided by ECMWF at discrete positions and time steps are interpolated to obtain the refractivity along the sensor to ground line-of-sight, which is then integrated to derive the tropospheric path delay in range. Impact can vary between 0.5m and 4.5m, depending on geographic location and atmospheric conditions.
- **Ionospheric delay in range:** the delay caused by the dispersive ionosphere is derived from total electron content (TEC) maps containing the integrated free electrons inferred from global GNSS observations. Impact can vary between 0m and 2m, depending on geographic location and solar activity.
- **Solid Earth tidal displacements in range and azimuth:** the tidal deformation of the Earth's crust by Sun and Moon is computed by the conventional geodynamic model associated with the geodetic reference frames and converted into timing corrections of range and azimuth. Impact

can vary between ±0.2m in range and ±0.05m in azimuth, depending on geographic location and the Sun and Moon constellation.

- **Bistatic azimuth shifts:** the corrections for the residual bistatic effects in azimuth stemming from the change of position of the satellite during the SAR acquisition are computed using the annotations of S-1 Single Look Complex (SLC) products. Impact is in the order of -5m to 0.5m, depending on the S-1 beam.
- **Doppler-induced range shifts:** the corrections for the range shifts caused by the focussing of Doppler-shifted radar pulses in Sentinel-1 TOPS modes are computed based on the annotations of S-1 SLC products. Impact varies between ±0.5m along the TOPS bursts.
- **FM-rate mismatch azimuth shifts:** the corrections for the azimuth shifts due to the mismatch of azimuth FM-rate, which is derived by the S-1 SAR IPF applying topographic assumptions, are computed using the accurate Copernicus 90m DEM and the annotations of the S-1 SLC products. Impact can reach up to 6m at the border of TOPS bursts if the scene contains large topographic height variation.

The latter three are the SAR system corrections which depend on approximations and algorithms used during SAR processing in the S-1 SAR IPF. The configuration of the SAR IPF may change and hence one or several of these shifts may not be required for future SAR products. The ETAD processor will be configured accordingly and the validity of each correction is indicated in the ETAD product by flags and annotation parameters. Only the applicable corrections are summed up for the standard correction grids of the ETAD products. Thus, the application of the ETAD product by the user will not change with such a potential evolution in SAR product generation.

When applying these correction grids by interpolating their information for each SAR image position, the “true” position in range and azimuth time of that image sample or detected object may be derived. The annotated ETAD delays/offsets are to be subtracted from the times annotated in the SAR product to estimate the position based on the “geometric” range, i.e. when using the constant speed-of-light in vacuum and the time-to-position relation of the precise orbit data. Figure 1 illustrates this relation. The details on applying the corrections are described in chapter 7 of this document.

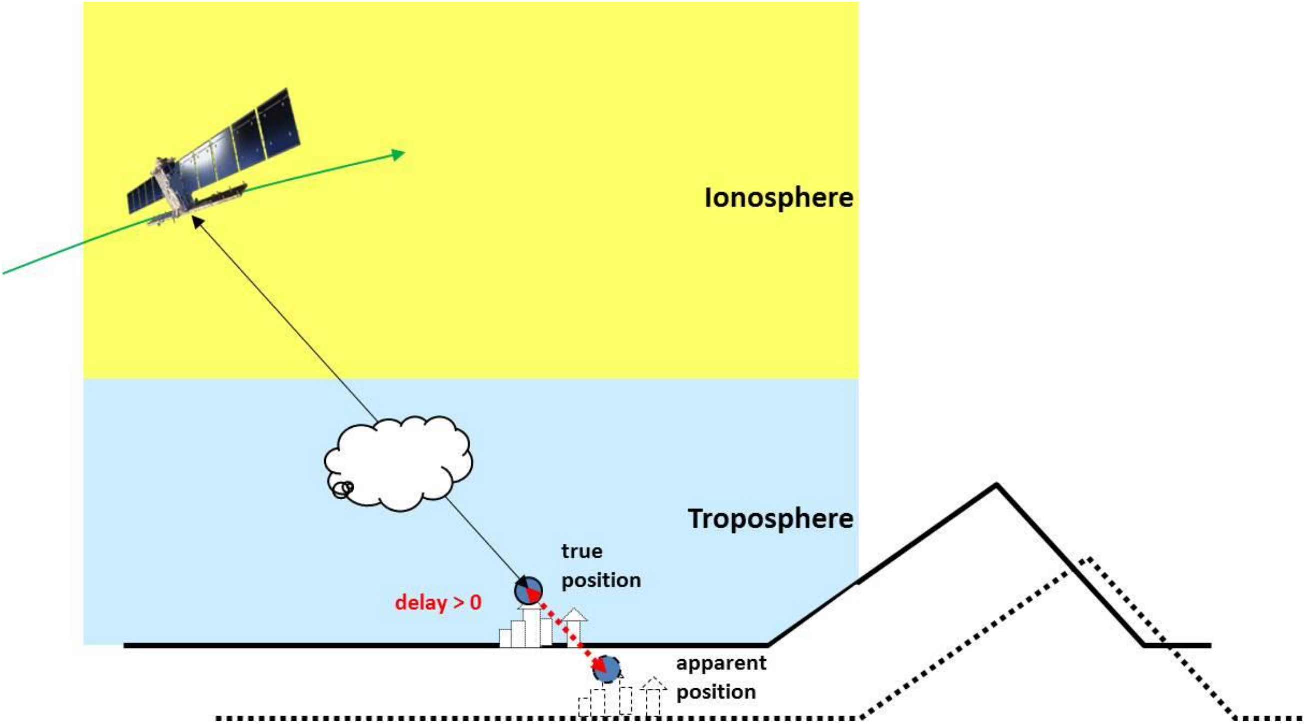

Figure 1: Illustration of the effect of signal propagation delays on the apparent range location of an object when not compensating for the signal propagation delays encountered during the image acquisition in the geo-location calculation.

The annotated delays are given in time units (i.e. seconds) representing two-way slant-range times. The delays and time offsets are interpreted as position shifts in meters at a given image location when converting them with the speed-of-light and the SAR beam velocity on ground. Note that the minuscule difference in position shift for the speed of light in vacuum and the one on ground level are to be neglected, since the discrepancies are smaller by several orders of magnitude than the accuracy of the corrections. The achievable accuracy in ETAD correction is specified in Table 1.

Table 1: ETAD and Sentinel-1 SLC Geometric Accuracies

Uncertainty of the ETAD product (1 sigma) in meter			Uncorrected S-1 SLC products	
	Range	Azimuth	Range	Azimuth
TOPS IW (spec.[(a),(b)])	0.2	0.1	7.0	7.0
Stripmap (spec.[(a),(b)])	0.2	0.1	2.5	2.5
First ETAD Validation results TOPS IW[(c),(d)]	<0.05	<0.4	3.15 +/- 0.32	-2.74 +/- 0.69
First ETAD Validation results Stripmap[(d)]	<0.03	<0.05	3.32 +/- 0.14	-2.09 +/- 0.05

(a): Note that the specified ETAD uncertainty is the composition of the product layer uncertainties and the error of the precise orbit solution; the latter is assumed with 5 cm (absolute, 3-D).

(b): Geolocation accuracy requirement of the SLC product at 3 sigma in meters [I6].

(c): Measuring calibration targets involves the entire S-1 SAR system with its additional errors (e.g. residual SAR focusing and product annotation errors, higher order geodynamics; SAR antenna phase centre offset; atmospheric gradients in azimuth; finite azimuth time quantization) and the error stemming from the SCR vs. image resolution limit. Estimates for these additional errors have been made in order to assess the performance of the ETAD product in the validation. For the available data of calibration targets in IW mode, the additional contributions do not allow a more accurate error determination.

(d): Preliminary measurements for a subset of calibration sites given here. The geometric performance of Sentinel-1 SAR products is measured and monitored by the ESA MPC [I7]

Additionally, the delays also correspond to phase offsets in complex data when converting them with the Radar wavelength of the Sentinel-1 system, yielding an (absolute) phase screen between two interferometric acquisitions. However, the residual uncertainty after correction is in the order of the phase cycles of the SAR wavelength and therefore limited in this respect. Additionally, the differences between phase delays and the annotated group delays have to be considered (see Annex A for details).

4.3 Product Generation and Extent

The ETAD product is generated by the S1-ETAD processor from the information extracted from the annotation of a set of SLC input product slices belonging to one single data take. Input SLCs of IW TOPS mode and stripmap mode datatakes can be processed to ETAD products. The auxiliary data used are the precise orbit, numerical weather data, ionospheric TEC data and auxiliary instrument information for timing calibration [A4]. Internal resources of the processor are a global DEM data set and the planetary ephemerides used to calculate the geo-dynamic Earth tides. The DEM data set used operationally is the Copernicus 90m DEM [I2] along with EGM2008 geoid undulations [I3]. The details on computation can be found in the dedicated ETAD algorithm technical baseline documentation [A2] .

The output product is the combined set of grids covering the area defined by the individual input product slices – usually a full S-1 data take or a single slice. Figure 2 illustrates this generation process.

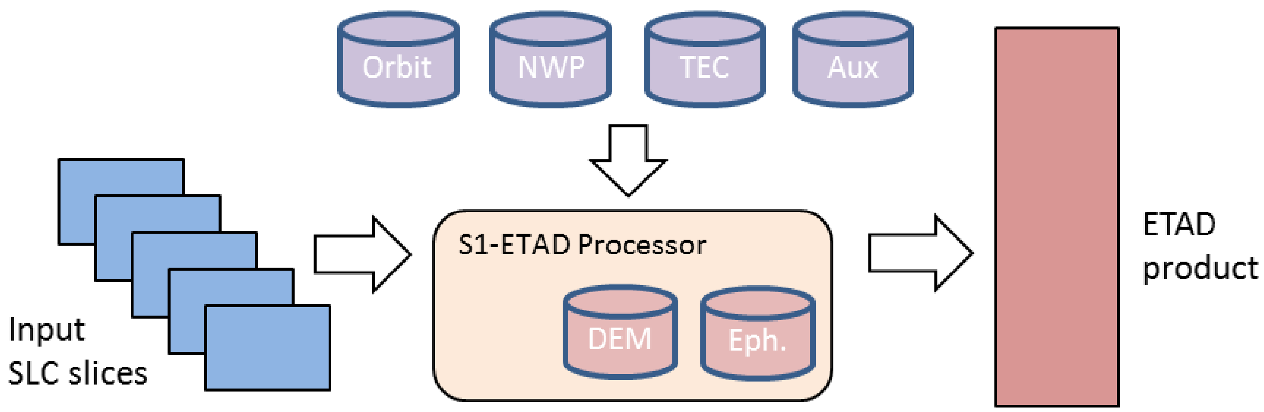

Figure 2: Outline of the ETAD product generation process and its in- and outputs.

The output product's temporal and spatial coverage is thus governed by the minima and maxima of the range and azimuth times of the combined inputs. Note however that there are always grid points in the correction layers, which extend beyond the extent of the input product SAR data coverage to avoid extrapolation for the user. These time boundaries are used for the naming of the product and are annotated in the metadata of the individual grid layers.

In case one or more of the SLC slices of the specific data take are not available to the S1-ETAD processor at time of ETAD product generation, those segments in the output product will remain empty. Accordingly, missing products at the beginning or end of a data take will yield a "shorter" ETAD product compared to the original data take. In short, ETAD annotation is only available where SLC input annotation is available to the S1-ETAD processor.

Note that stripmap data are handled by the S1-ETAD processor equivalently to one single TOPS burst in one single swath. The TOPS SAR specific layers are hence also present in the ETAD product and the grid representation is identical to the one for TOPS data.

4.4 Grid Representation

The ETAD product is aiming at accurate geodetic geolocation, which is only possible with the exact timing and sampling of the S-1 level 1 SLC products [A3]. Hence the ETAD grid is represented in a matching but coarser grid, regularly sampled in azimuth and range time (t, τ) to avoid inaccuracies from projection and scaling. The grid is thus equidistant in (t, τ) time dimensions, but irregularly sampled when projected on ground.

The sampling in azimuth direction is approx. 200 m, whereas the ground range sampling varies depending on incidence angle and topography. The spacing in slant- range is approx. 120 m, which corresponds typically to 160 to 250 m on the ground. The ETAD sampling is decoupled from the sampling of the SLC since SETAP version 2.1. It is linked to the time annotation only and uses fixed integer dividers of a 10 second time span as sampling in azimuth. This allows to maintain a consistent grid for all SLCs of a datatake even if they are processed independently from each other. Thus the sampling for different ETAD products is now identical (in azimuth time) for different types of SAR input data in all their configurations (i.e. stripmap, TOPS) with their individual instrument samplings. See Chapter 8 for details on the actual grid spacing for different modes.

The ETAD is primarily designed for S-1 SLC products, but along with the correction layers a mapping grid is also provided, which yields the corresponding geographic coordinates of each azimuth/range time grid point. The mapping grid locations are the DEM-derived geocentric ITRF positions converted to geodetic latitude, longitude and ellipsoidal height referring to the WGS-84 ellipsoid. With the help of this auxiliary layer, the corrections can be applied to ground-projected products like the S-1 GRD product or derived for a specific location on ground (see chapter 7.5 and Annex B for details). Note that the mapping grid is regularly sampled in time but irregularly sampled on ground and that - due to the SAR specific projection problem of layovers - the transformation is not unique. The accuracy of this approach is limited since the ETAD mapping grid is based on the DEM and is calculated *before* the correction parameters are derived in order to ensure that overlapping grid points from different bursts yield consistent coordinates for the correction reference. Consequently, the geodetic accuracy of the ETAD product refers to the exact interpolation of the time-based corrections at a given position in the SAR image, not on the coordinates given in the mapping grid or spatial coverage annotation.

Applying the (regularly gridded) corrections to the regularly sampled SAR image actually "warps" this into an irregularly sampled image as sketched in Figure 3. However, please keep in mind that the primary application of ETAD is to calculate the delays and offsets at the location of a specific object in the image (e.g. a calibration target) and to submit this specific object to a corrected geo-location.

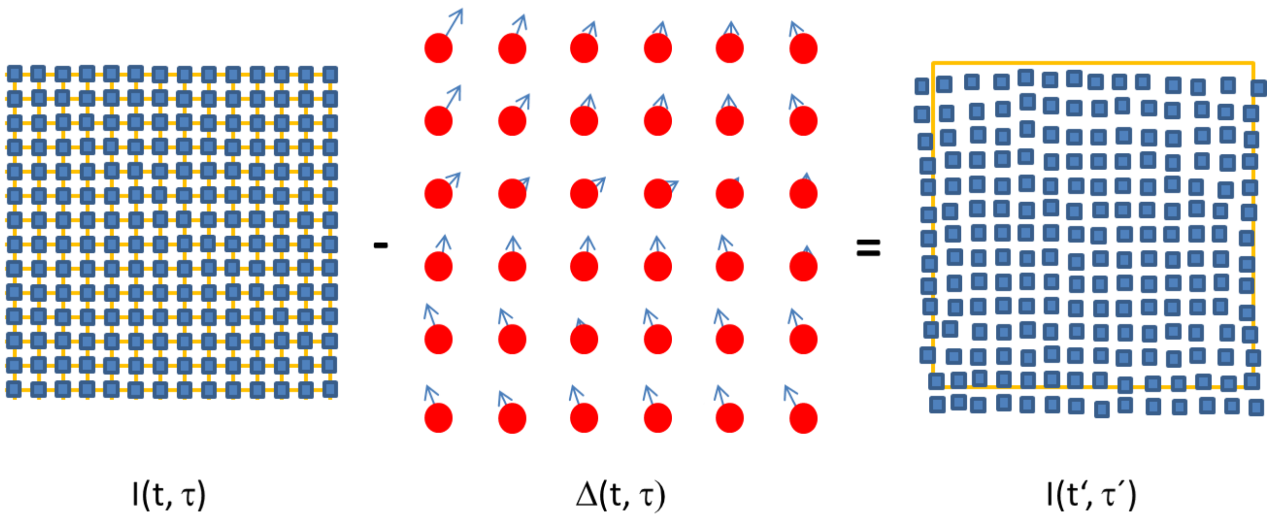

Figure 3: Sketch of the application of the delay parameters (arrows) of the ETAD grid (red dots) to an SLC image (left; each blue box represents a SAR pixel), which results in an image with corrected timing (blue boxes on the right) on an irregular grid.

4.5 Bursts and Sub-Swaths

Sentinel-1 uses as SAR mode the TOPS burst mode for the majority of its acquisitions. The TOPS mode yields a more homogeneous radiometric performance but at the price of strongly varying SAR parameters within a burst, from burst to burst, and for each of the sub-swaths used. While the geophysical corrections are independent from the burst layout and only depend on time, location on Earth and in orbit position, the SAR system specific corrections do however depend on the position within the focused burst. That is specifically important for the topographically induced azimuth FM-rate mismatch shift, which may yield several meters of location error at burst borders and the Doppler shift on the range pulses, which may amount to +/-0.4 m.

The focused TOPS bursts do overlap in azimuth – hence the SAR system specific correction parameters in the overlap region are different (actually mostly opposing) for the individual bursts and cannot be combined into one correction. Additionally, the sub-swaths overlap in range. Therefore, the ETAD corrections have to be provided burst-wise, based on the SAR processing parameter information given in the input products. The SLC products of an S-1 data take are generated in slices. These slices have individual sets of processing parameters used for the SAR processor approximations (e.g. assumed height of the scene in FM-rate calculation), which have to be taken into account as well.

The ETAD product structure is thus based on separate correction layers for the individual bursts, grouped with a common annotation component with segments referring to the individual slices of a data take. The ETAD product does not have to rely on actual focused data at the grid position for calculating the correction parameters. This is obvious for the geo-physical data but also holds true for the SAR specific corrections which can be derived from extrapolating the SAR annotations.

In order to relief the user from extrapolating the ETAD product, the product grids are covering the full bursts plus a margin extending beyond the focused burst image, see Figure 4. This margin is variable since the grid itself is based on a fixed and consistent spacing in time domain (see Chapter 8 for details on the actual spacing for different modes) and the burst boundary times are not necessarily aligned with the grid elements. The grid for each burst starts with the grid lines and rows preceding the first/nearest valid samples of a burst and ends with the first grid lines and rows right after the last/most far valid samples.

Despite being organized in layers for each of the bursts, the consistency of ETAD over a full data take is given by one (virtual) common timing grid for all bursts, maintaining a constant sampling for all layers. Depending on the generation of the ETAD product (e.g. when based on individual SLCs instead of entire data takes), the bursts may have different reference times in azimuth. Nevertheless, the grids are consistent and the reference time in slant range is identical (using 0s as start value; i.e. the position of the satellite). The mapping grids also provide the exact same geographic location information for the overlapping points of the different grids since they are derived from the common "master" grid used for processing.

At any given point on the common ETAD output grid, there may thus be several different correction parameters for the different swaths and bursts. The correction at overlapping grid locations are equal for the physical timing corrections but system correction values vary, as the same grid point is imaged at late azimuth and early azimuth in subsequent bursts and near range and far range in neighbouring swaths. This is sketched in Figure 4.

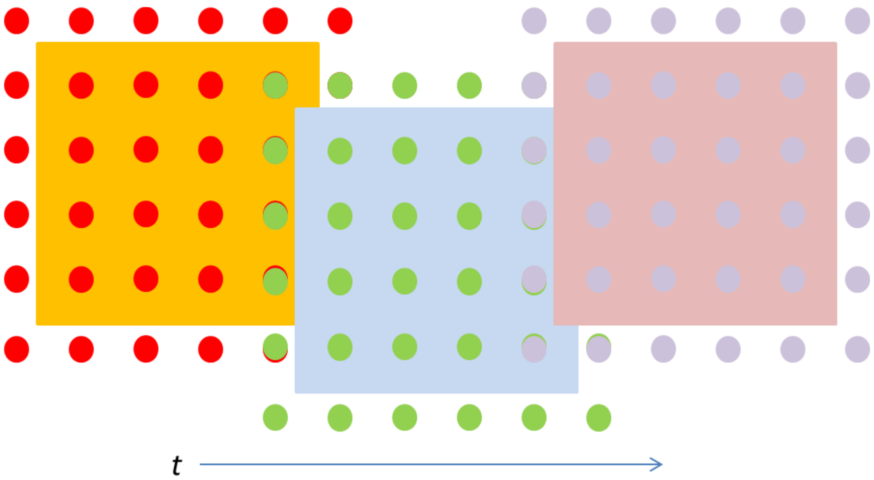

Figure 4: Sketch of the individual grids (colored dots) for three overlapping focused burst images (colored rectangles) of one beam using a common grid reference time and spacing.

5 ETAD Product Structure and Format

As already pointed out in the previous chapter, the basic structural element of the ETAD product is the burst (respectively the stripmap image). The sub-swaths are not *required* as hierarchical element but kept for convenience to mirror the organizational structure of the input per sub-swath. Bursts and the burst indices in the ETAD product are numbered according to their sequence in azimuth time - they are not referenced to any absolute positional orbit or acquisition scheme. Figure 5 sketches the logical structure of the ETAD product for one data take.

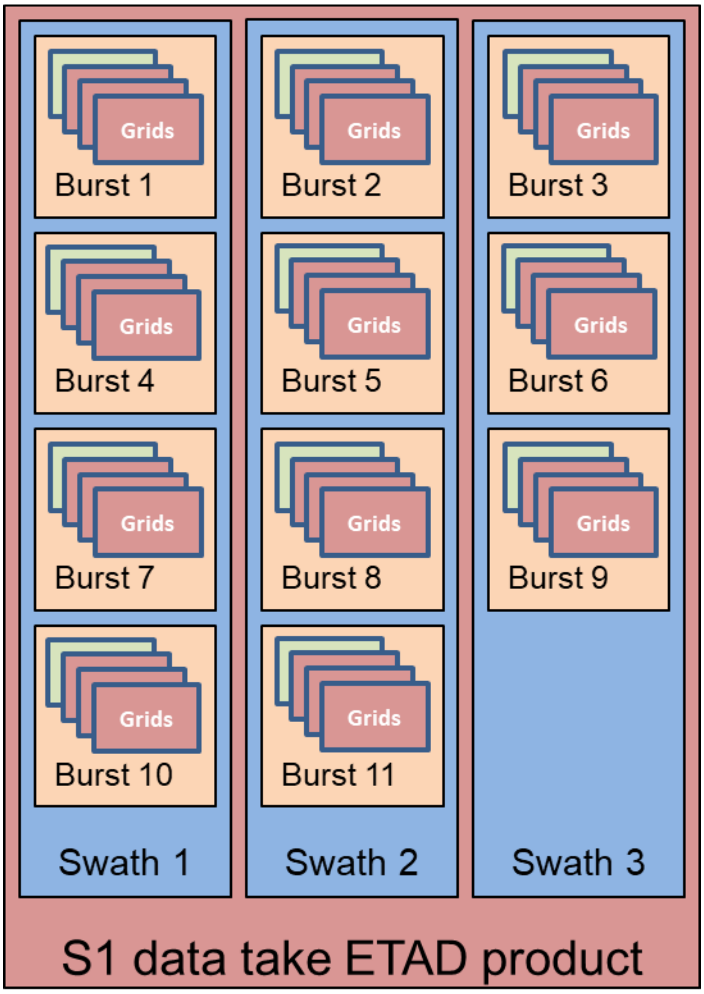

Figure 5: Logical structure of the ETAD product hierarchy for a hypothetical S-1 TOPS data take with 3 sub-swaths and 11 bursts in total.

In terms of annotation, the parameters required for application to the S-1 SAR products are all provided with the correction grid data file. Additionally, the information on the input products, auxiliary data and parameters used for product generation are given in detail in a dedicated XML file. Since parameters for SLC slice generation in SAR processing may differ between the individual input products, the annotation also provides the required identification of those bursts belonging to a specific input SLC slice and vice-versa. Each burst has an individual index number and a reference to the swath and the input product it stems from. The common product annotation lists all input SAR products and the corresponding bursts it contained. This allows a two-way identification and referencing between SAR image and ETAD product. Additionally, the burstID annotated in the IW and EW SLC products is also annotated in the ETAD product, helping to identify the corresponding correction grid of an individual SLC burst. Note that this relative burstID is only unique within one swath of the IW or EW product. It is not provided for stripmap mode data.

While the main parameters for the geophysical corrections apply to the entire data take, the SAR specific system corrections depend on SAR (processing) parameters of the different input products and the individual bursts. The SAR parameters relevant for the calculation of the SAR system correction parameters are detailed for each burst in this XML file.

5.1 Burst-Wise Correction Layers

For each burst all the individual correction layers are provided to allow the users to leave out single corrections if required by their application – e.g. for measuring single geo-physical effects instead of compensating them. Also, the users might have specific in-situ data which allows better corrections. The nominal use case is however to apply the sum layers, i.e. the accumulated corrections in range and azimuth. These two layers give one single correction parameter for each grid point, i.e. offsets in azimuth time t or delays in slant range time τ. The annotated layers are listed in Table 2.

Table 2: The correction and gridded annotation layers for each burst

ETAD Correction and Annotation Grids for each Burst / SM image				
No.	Name	Parameter	Unit	Type
1	Tropospheric Delay Correction Layer	$\Delta\tau_{tro}$ @ $(t,\tau)_i$	[s]	Double
2	Ionospheric Delay Correction Layer	$\Delta\tau_{ion}$ @ $(t,\tau)_i$	[s]	Double
3	Geodetic Range Correction Layer	$\Delta\tau_{SET}$ @ $(t,\tau)_i$	[s]	Double
4	Geodetic Azimuth Correction Layer	Δt_{SET} @ $(t,\tau)_i$	[s]	Double
5	Bistatic Azimuth Shift Correction Layer	Δt_{BA} @ $(t,\tau)_i$	[s]	Double
6	Doppler Range Shift Correction Layer	$\Delta\tau_{DRS}$ @ $(t,\tau)_i$	[s]	Double
7	FM-Mismatch Azimuth Shift Correction Layer	Δt_{FMM} @ $(t,\tau)_i$	[s]	Double
8	**Range Correction Sum Layer**	$\Delta\tau_{sum}$ @ $(t,\tau)_i$	[s]	Double
9	**Azimuth Correction Sum Layer**	Δt_{sum} @ $(t,\tau)_i$	[s]	Double
Gridded Annotation				
10	Mapping Grid - Geodetic Latitude	lat @$(t,\tau)_i$ in WGS84	[deg]	Double
11	Mapping Grid - Geodetic Longitude	lon @$(t,\tau)_i$ in WGS84	[deg]	Double
12	Mapping Grid - Ellipsoidal Height	h @$(t,\tau)_i$ in WGS84	[m]	Double

In the current ETAD framework, the geodetic corrections are synonymous with the solid Earth tide (SET) corrections. These layers belonging to one burst all share the same extent and sampling in time. The start and stop times for the grids in range and azimuth and their sampling are thus provided once in the common annotation per burst.

The extended XML annotation for each burst also contains the burst-Index, the burstID, the coverage of the actual burst and the burst-specific SAR parameters used for correction. Additionally, statistics on the corrections are provided in the XML and given both in time domain (in seconds) and distances (in meters).

5.2 Polarization Channel Dependence

Bursts of different polarizations are subject to the same geo-physical and SAR-systematic timing effects. The correction layers are hence valid for all polarization layers of one burst. Nevertheless, a residual instrumental delay or azimuth time tagging offset may be present in the different polarization layers (which are provided by the AUX_ITC input product of the S1-ETAD processor [A4]). Therefore, the main co-polar polarization channel (i.e. HH or VV) is selected and identified as reference channel. All polarization dependent delays and shifts of the reference channel are included in the calibration. I.e. the "residual" delays and shifts of the reference channel are zero while the other channels are given as offset values to the reference channel.

Azimuth and range offsets are annotated for the reference polarization as well (i.e. as 0.0 seconds) in order to allow an automatic evaluation of all channels in the same manner by always adding the respective annotated offset value to all correction grid values.

Possible instrument or processing-related characteristics that influence geometric accuracies of the different polarization channels are given as offsets for each burst individually within the grid data. This also reflects possible swath-dependencies of the instrument delay calibration.

6 ETAD Product Format Overview

The ETAD product is provided in a SAFE product container similar to the Sentinel-1 SAR products. The selected format for the ETAD product files is XML for metadata annotation and the NetCDF-4 framework using the Hierarchical Data Format version 5 (HDF5) file format [I4] for the correction grids and parameters. *For details on structure, naming and format refer to the **Product Format Specification document** [A6] – here only an overview is provided.*

The main component of the ETAD product is the NetCDF file. All information required for a nominal application of the corrections by the user is provided in this file. The XML annotation file and the additional extracted orbit product is for further information. Figure 6 provides an overview of the product structure.

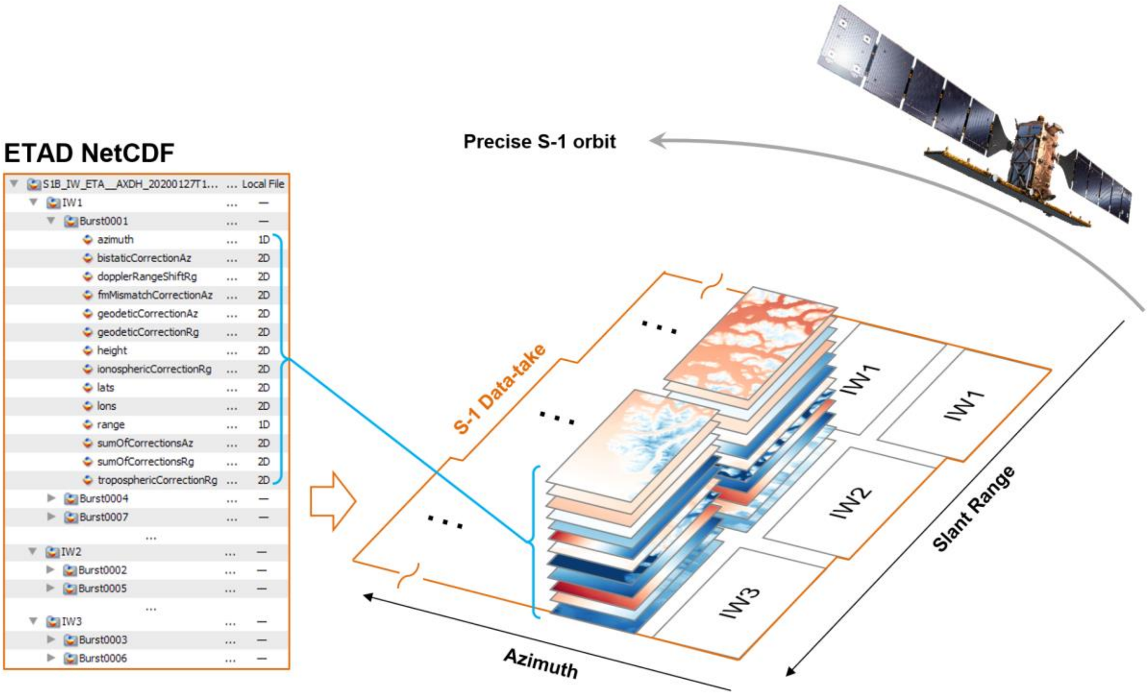

Figure 6: Sketch of the ETAD product NetCDF structure.

Preview files in KMZ format are provided for an assessment of the scale of the summary corrections in range and azimuth. These display the coarsely geo-referenced burst images in slant-range and are thus limited in the geometric accuracy. An example for such an KMZ preview is shown in Figure 7.

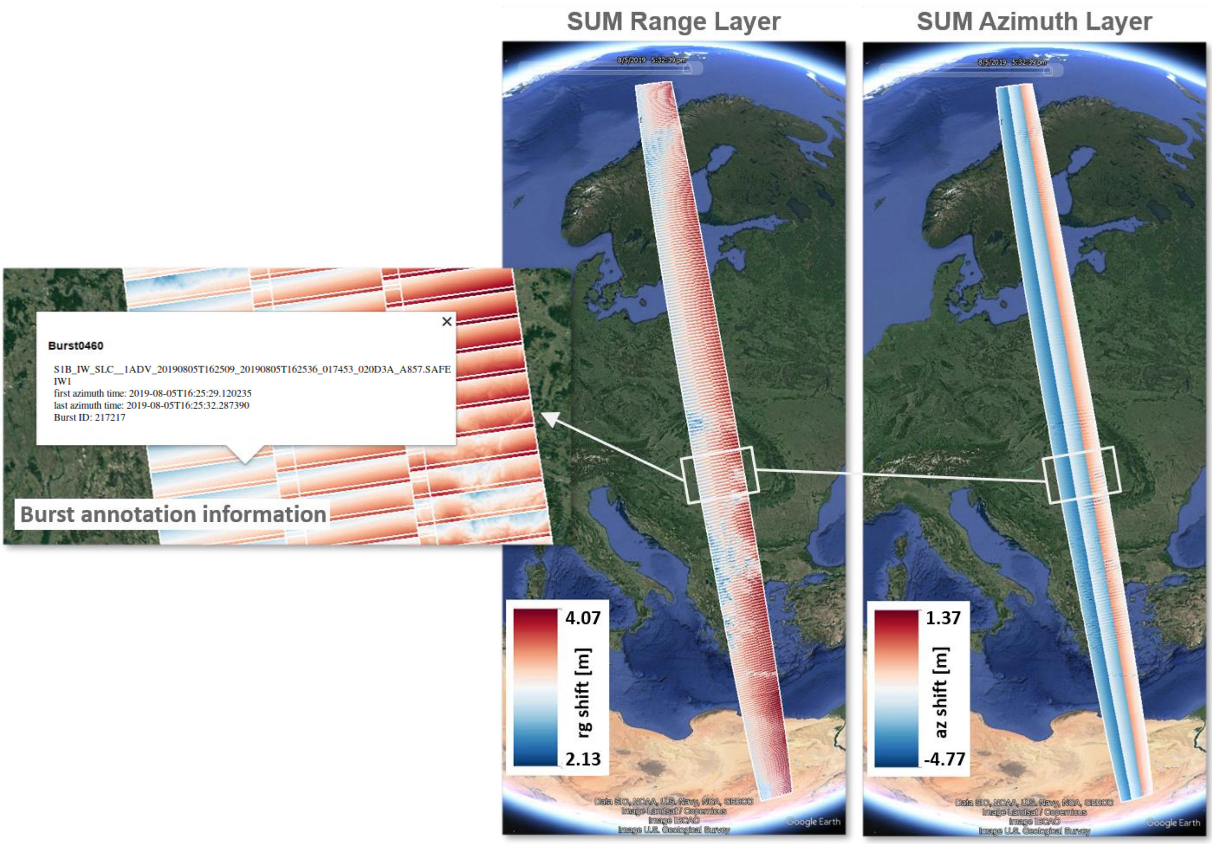

Figure 7: Example of KMZ preview file for the correction summary layers for an IW dataset over Europe in Google Earth™.

Note that HDF5 refers to these folder-like hierarchies as "groups". Groups may contain subgroups and/or datasets (or "variables") and associated metadata. For ETAD, separate NetCDF groups have been assigned for the product-, swath- and burst-level. The different groups inside the NetCDF files use the "attributes" data structural element for identifying parameters (e.g. indices and timing parameters). The only "variables" are the correction and mapping grids inside the individual burst groups. These two-dimensional matrices all share the same azimuth and range dimensions, see Figure 6. For convenience, the azimuth and range times are also provided as one-dimensional vectors, so to say spanning the X- and Y-axis of the grids. This facilitates the data representation in NetCDF readers and viewers.

A driving rationale in product design was to provide a standardized access to the data and a consistent calculation of the sums and statistics even if the corrections may be configured differently or may not be applicable anymore. E.g. in case one or more of the individual correction grids has not been calculated the corresponding grids are provided nevertheless and filled with zeros. This is the case for stripmap data, where the Doppler Range Shift and the FM Mismatch Azimuth Shift are not applicable or relevant. In such circumstances the Boolean attribute flags of each grid indicate the validity of the specific grid matrix.

7 ETAD Product Application

The ETAD product is designed to correct the timing information of Sentinel-1 SLC products in order to achieve a significantly improved geometric accuracy of these data sets. First examples for the use of the ETAD product in different applications may be found in [I8]. There are different approaches the user might follow to achieve this. Either aiming at more precise geo-location information for individual positions/objects (e.g. Corner Reflectors (CRs)) in the SLC product or using a more general approach to resample the SLC image pixels to their accurate positions in time. In both cases, the crucial step is to access the ETAD data relevant for the specific image data – i.e. the specific burst.

ESA maintains a python API under the URL https://gitlab.com/s1-etad/s1-etad for the users to access the ETAD data. This section explains the generic higher-level approach of product usage. The IW product is used here but the access to stripmap data is identical – just with reduced swathes (i.e. one swath) and bursts.

7.1 Timing Correction of Individual Targets

The ETAD product itself covers the entire datatake and the geophysical corrections only depend on location and time within this datatake but the SAR system related corrections are variable for each burst. Figure 8 shows the coverage of an ETAD IW product.

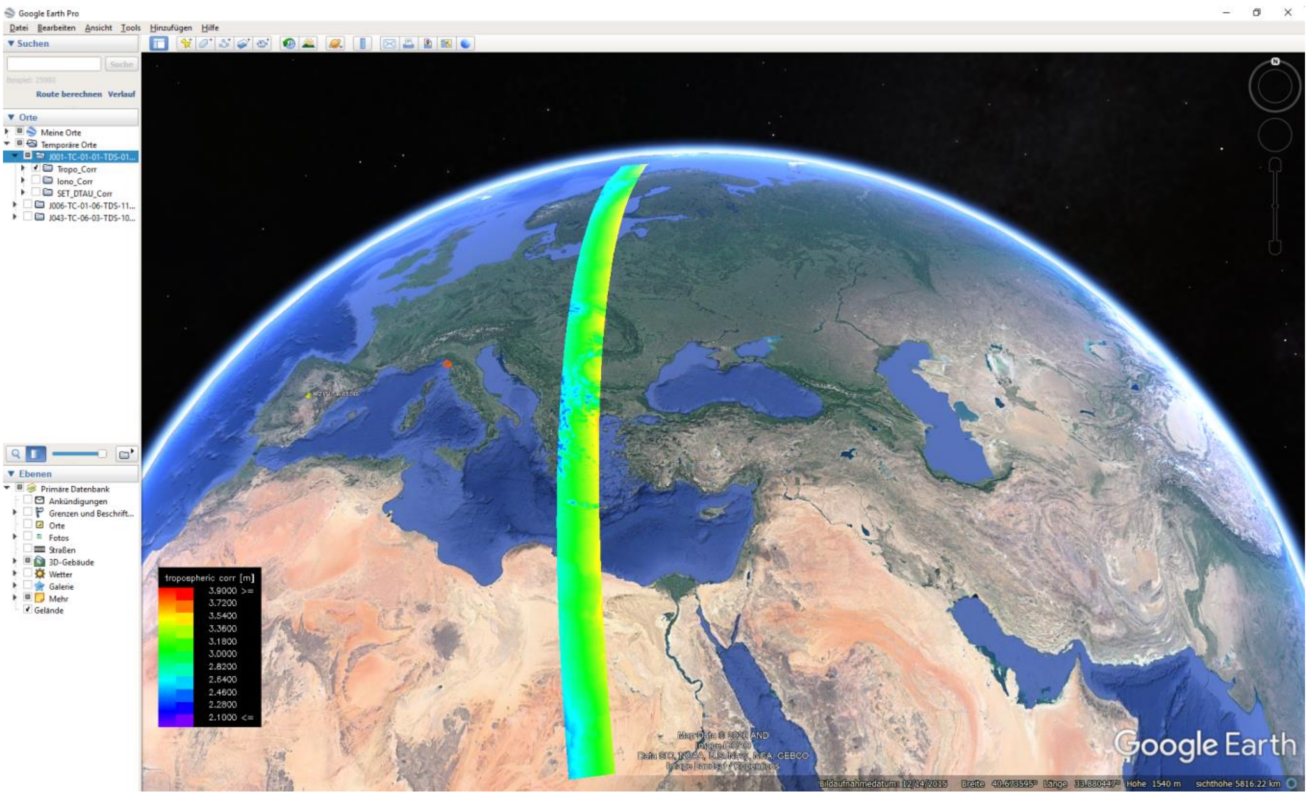

Figure 8: Example of the extent of an IW ETAD product, displaying the tropospheric range correction layer only in Google Earth™

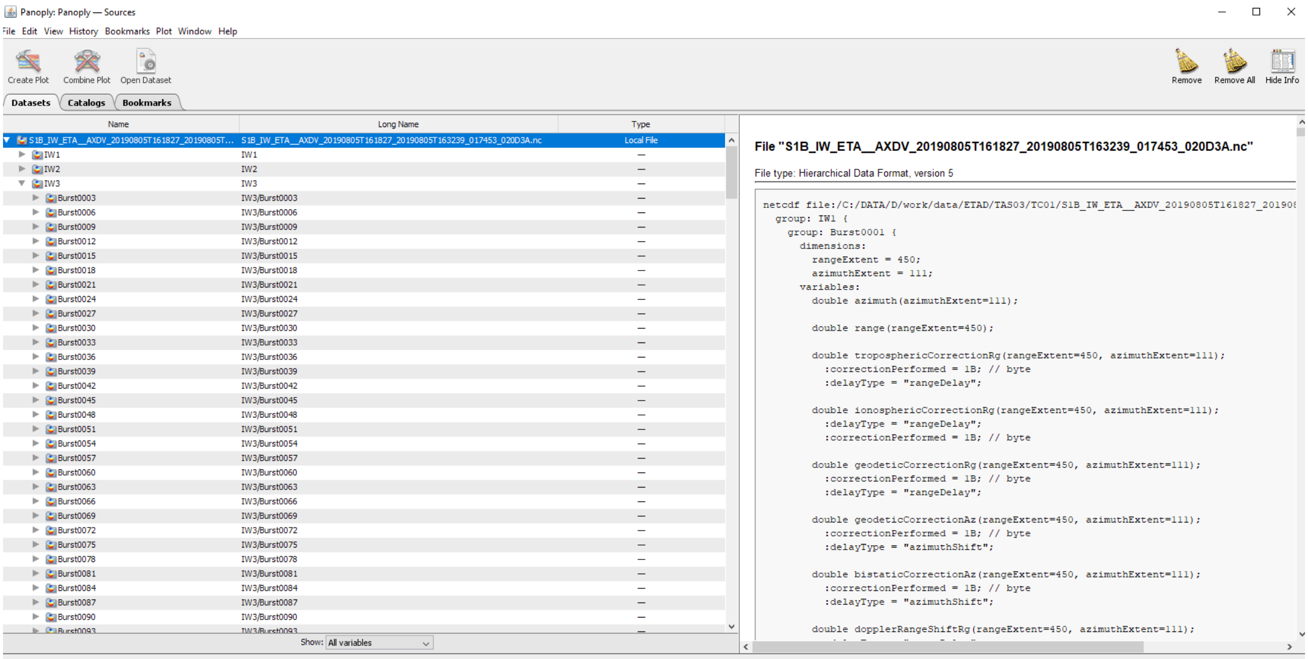

Figure 9: Example of the NetCDF file structure accessed with the NASA/GISS NetCDF-viewer Panoply[1].

The first step is to navigate within the ETAD product to find the burst grids for the burst of interest. The reference times of an ETAD dataset are the start time parameters of the entire product annotated in the NetCDF root group – corresponding to one datatake.

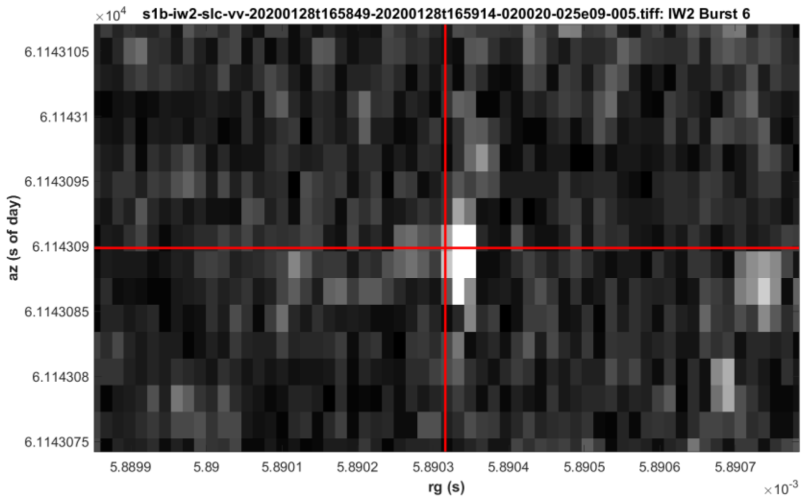

Figure 10: Example of a CR target located at a specific position in range and azimuth time in an uncorrected SLC burst image (the red cross indicates the expected "true" position).

Assuming the target position in time domain is derived from (point target) analysis of the SLC, the corresponding burst group can be derived from the timing information of each burst group. In order to restrict the search, the *burst:productID* string in each NetCDF burst group may be inspected for a product name which corresponds in time to the SLC product name at hand. Note however that components of

[1] https://www.giss.nasa.gov/tools/panoply/

that name may differ due to different product variants. Also, the search may be restricted to one specific swath-group only if desired. More convenient is the search with the help of the burstID annotated in the SLC. It uniquely identifies a burst in a specific IW or EW swath relative to the start of one 12-day repeat cycle of the Sentinel-1 mission. Since SETAP version 2.1, this burstID is also annotated in the ETAD correction grids. Specifically for repeated acquisitions and stack processing, the user may use the same set of burstIDs to identify the region of interest in the SLC and the matching ETAD correction grids.

The coverage of each burst is given by the NetCDF parameters:

in Azimuth:
rootGroup:azimuthTimeMin + burst:gridStartAzimuthTime
to
rootGroup:azimuthTimeMin + burst:gridStartAzimuthTime + (azimuthExtent * gridSamplingAzimuth)

in Range:
rootGroup:rangeTimeMin + burst:gridStartRangeTime
to
rootGroup:rangeTimeMin + burst:gridStartRangeTime + (rangeExtent * gridSamplingRange)

Note that a target in the SLC product may be covered by more than one burst grid of the ETAD product due to overlaps between swaths or adjacent bursts. The target may not even be imaged in all the bursts but yet covered in the extended grid area. All the grids for the bursts are relevant and may yield very different corrections. This is specifically relevant in the TOPS burst overlaps were different SAR acquisition and processing parameters result in discrepant corrections. The correction from each burst has to be applied to the image data of the corresponding burst.

The standard timing correction grids are named in the NetCDF file:
sumOfCorrectionsRg
sumOfCorrectionsAz

Those two grids contain the timing corrections $\Delta_\tau(t,\tau)$ and $\Delta_t(t,\tau)$ – i.e. the time correction values in range (τ) and azimuth (t) to be applied at the position in time at t,τ. A visualization of the content of a burst grid is displayed in Figure 11.

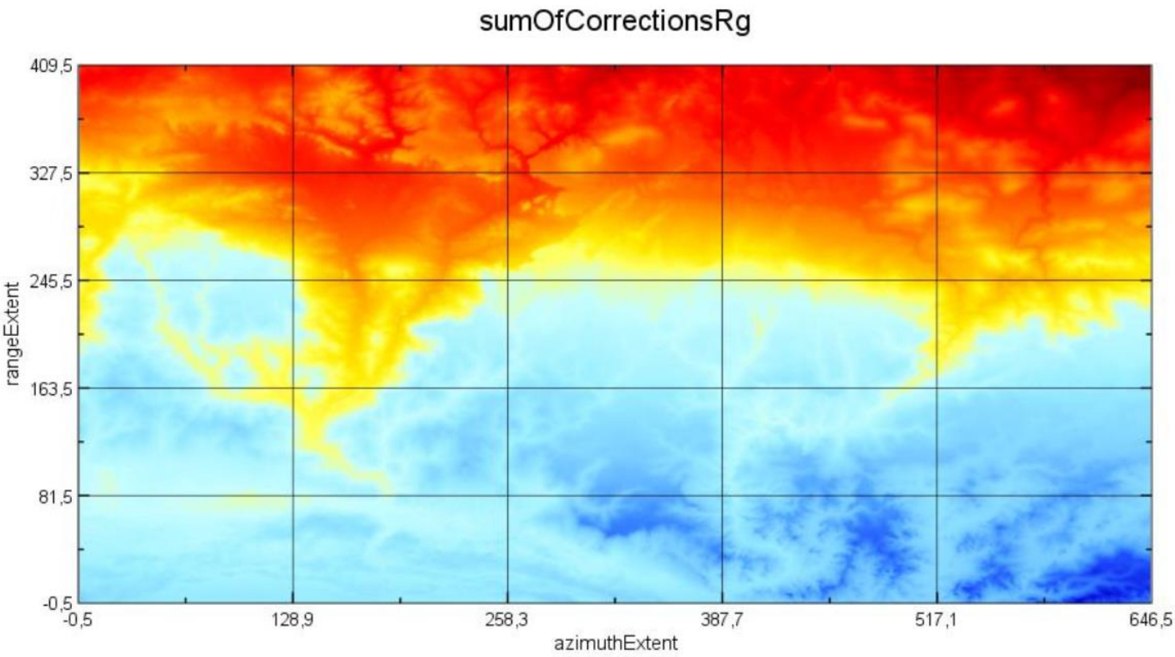

Figure 11: Example of the NetCDF grid content for one burst. Here, the burst has an extent of 410 range samples and 647 azimuth samples.

As explained before, SLC and the ETAD grids have a different sampling in time and the application of the correction values requires bilinear interpolation of the grid values to the SLC sample position.

The positions in time of the samples in the grid are given by the reference times and the azimuth and range vectors:

t_{grid} = rootGroup:azimuthTimeMin + burst:azimuth(i)
τ_{grid} = rootGroup:rangeTimeMin + burst:range(j)

The indices *i* and *j* of the relevant grid samples for the target have to be identified when dealing with individual objects in the images. There is a simple way to derive the correction grid samples at time (t, τ) near the SLC time position; using the start times and the gridSampling[Range|Azimuth]:

i = (t - rootGroup:azimuthTimeMin) / gridSamplingAzimuth
j = (τ - rootGroup:rangeTimeMin) / gridSamplingRange

The four neighboring samples indexed with the nearest integer values of i and j have to be interpolated with a simple bilinear interpolation scheme following

$$f(x,y) = \frac{1}{(x_2-x_1)(y_2-y_1)} \begin{bmatrix} x_2 - x & x - x_1 \end{bmatrix} \begin{bmatrix} f_{1,1} & f_{1,2} \\ f_{2,1} & f_{2,2} \end{bmatrix} \begin{bmatrix} y_2 - y \\ y - y_1 \end{bmatrix}$$

The resulting interpolated Δ correction values in t and τ have to be subtracted from the measured SLC time positions of the target to derive the "true" positions in time:

$t_{corr} = t - \Delta_t$
$\tau_{corr} = \tau - \Delta_\tau$

These corrected times may be used for a precise geolocation of the specific target based on the precise orbit segment provided in the ETAD product.

A quick assessment of the applicable shifts in meters Δ_{rg}, Δ_{az} may be derived from conversion of Δ_τ with the speed of light c for the (slant-)range shift and the average azimuth beam velocity v_{beam} on ground for Δ_t using the NetCDF parameter *burst:averageZeroDopplerVelocity* (in m/s).

$$\Delta_{rg} = \Delta_\tau \frac{c}{2}$$

$$\Delta_{az} = \Delta_t v_{beam}$$

Depending on the physical conditions, the observed shifts should not exceed the range of a few meters.

Note that starting with SETAP version 2.1, the "min" times annotated in the root group may actually be set to zero. Nevertheless, the algorithm above is still valid for all ETAD products.

7.2 Generalized Approach

As explained in Chapter 4, the apparently regular timing in the SAR instrument frame is actually not regular on physical scales due to the geophysical, signal propagation and SAR effects. The ETAD grids may thus be used to warp the regular SLC raster into irregularly sampled data in the physical "true" time domain. The steps to identify the corresponding bursts and grids are analogue to the ones described in the previous section.

The difference in the process is:

1. Resample the ETAD burst grids on the denser SLC raster at times (t, τ) analogue to the previous section but for each SLC sample.
2. Subtract the resampled range corrections Δ_τ from the SLC range times
3. Subtract the resampled azimuth corrections Δ_t from the SLC azimuth times

The result is an irregularly spaced burst sample raster with corrected timings for the S1 SLC data, i.e., an irregular corrected SLC image as sketched in Figure 3.

In order to resample this irregularly spaced raster back to a regular grid, SLC data interpolation has to be applied. If the application at hand uses only the SAR amplitude information, straightforward bi-linear or bicubic resampling methods are sufficient. If the application relies on the phase information, phase preserving complex interpolation has to be used [I9][I10].

Obviously, the resampled ETAD corrections may also be understood as a map of shifts to be applied at the (regular) sample positions of the SLC without actually correcting those positions. This is not fully correct but depending on the user's application, sufficient to derive partially geometrically corrected information.

As an example, an uncorrected measured ground motion of correlated objects between two repeat pass acquisitions may be corrected from calculating the difference in the interpolated ETAD shifts at the two acquisition times at the given locations. A very similar approach for interferometric corrections is detailed in Annex A.

7.3 Correction with Specific Grids

Assuming the user wants to correct only specific effects on the SLC data timing to measure or substitute the omitted ones, the sums of the individual selected grids instead of the two sum-grids have to be applied.

The individual timing corrections in the NetCDF are named:

- troposphericCorrectionRg
- ionosphericCorrectionRg
- geodeticCorrectionAz
- geodeticCorrectionRg
- bistaticCorrectionAz
- dopplerRangeShiftRg
- fmMismatchCorrectionAz

The user may combine these different but equidistantly sampled grids to sums of the required corrections according to the specific needs of the application. Consider in the following as an example a user who wants to measure the geodetic shifts in an image and hence to leave out these grids.

The specific correction grid for a burst without the geodetic grids then results from

Δ_τ = troposphericCorrectionRg + ionosphericCorrectionRg + dopplerRangeShiftRg + burst:instrumentTimingCalibrationRange

Δ_t = bistaticCorrectionAz + fmMismatchCorrectionAz + burst:instrumentTimingCalibrationAzimuth

This correction is then applied the same way as outlined in the previous sections.

It is important to note that the two sumOfCorrections[Az|Rg] grids already contain the instrument timing calibration parameters configured for the ETAD processor that are added to the summation corrections. These contain for each burst the delays and offsets used to calibrate the system in order to remove offset values from a biased (or incomplete) instrument calibration.

The calibration parameters are also provided in the NetCDF as instrumentTimingCalibrationRange and instrumentTimingCalibrationAzimuth and need to be included in the sum. Note that these parameters are provided for the reference polarization (i.e. the co-polar data). A correction for other polarization than the reference polarization is outlined in section 7.4.

If the user has e.g. ground truth data of better quality for a specific effect, the grid may be substituted with own measurements. It has to be stressed, that the ETAD calculations are performed for the specific acquisition conditions and sensing times. Nevertheless, if a data set is available at a specific location for the time of the acquisition in the instrument geometry, the new grid values may be derived from these data and added accordingly to the sum of the selected grids following the approach above.

7.4 Polarimetric Data

The geo-physical effects, signal propagation effects and SAR-system effects corrected by ETAD do not depend on the polarisation and one single data set for correction is thus sufficient. However, the instrument calibration parameters may yield different delays and shifts for the acquired polarisation channels not accounted for in the sum grids of the "reference polarisation". Currently the instrument parameters per polarisation are identical but they may be refined in the future or altered due to changes in the instruments. These delay calibration parameters may also depend on the specific swath and might thus differ in the different bursts.

The user should check the burst:referencePolarisation value to identify which channel is the reference (it is nominally the co-polar one) and then if the (second) polarisation channel with a polarisation identifier not matching the referencePolarisation string (i.e. the cross-polar one of a Sentinel-1 dual-pol SLC) has a different calibration from the polarisation offsets rangeOffset[HV][HV] and azimuthOffset[HV][HV] annotated in the NetCDF burst group.

If these values differ from 0.0, the respective rangeOffset[HV][HV] and azimuthOffset[HV][HV] values of the specific burst have to be added to the correction. For an HV channel as example:

$\Delta_{\tau,HV}$ = sumOfCorrectionsRg + burst:rangeOffsetHV
$\Delta_{t,HV}$ = sumOfCorrectionsAz + burst:azimuthOffsetHV

7.5 Additional Mapping Data

The ETAD product contains the coordinates of the grid samples in geographic coordinates *(Lat,Lon,h)* as additional grid layers. This data may be used as additional information for data evaluation - e.g. as a coarse DEM of the local terrain in a burst projected in slant range geometry as visualized in Figure 12. Note however that the posting of this data is relatively coarse.

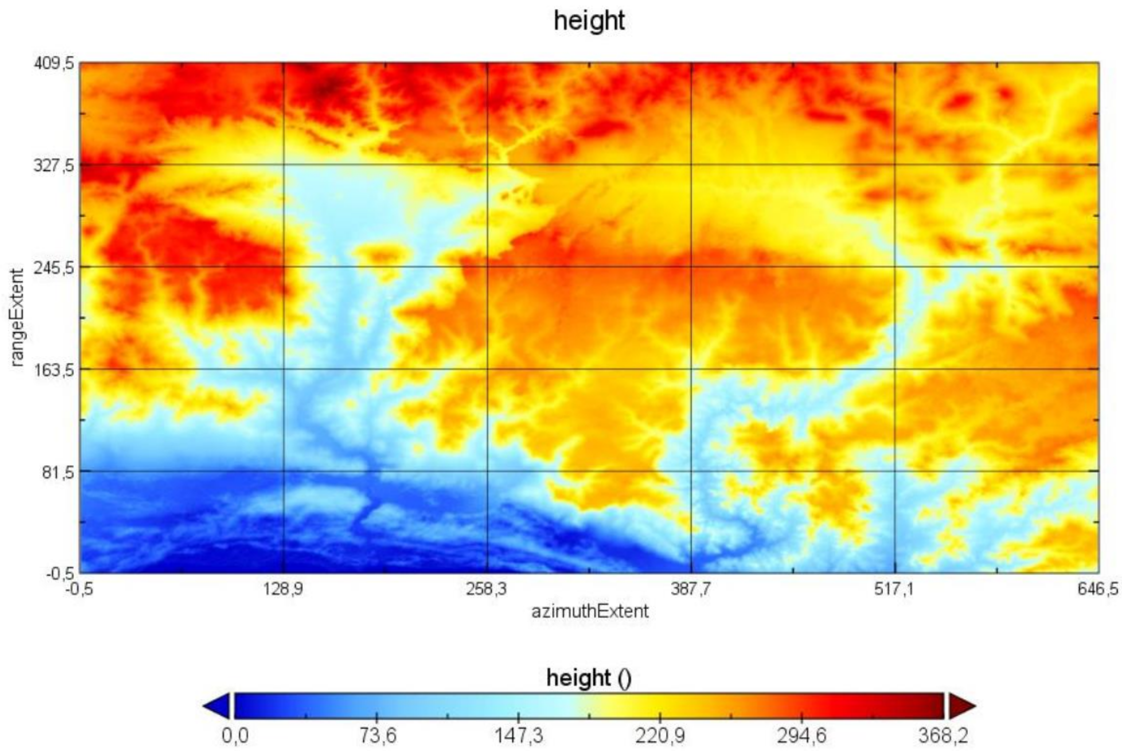

Figure 12: Example of the DEM of a SLC burst from the mapping grid data.

Another approach is to use the mapping information to derive the correction values for a specific geographic location. Note that the location data is not sampled regularly in geographic coordinates, it is thus more complicated to search and identify the relevant grid points close to the desired location in order to derive the grid indices i, j for interpolation of the correction data (see previous sections). Figure 13 shows a sketch of this relation. $\Delta(t,\tau)$ stands for the timing correction at a given grid point (gridded radar timing) which is translated to the timing correction at a given geo-location by the mapping-grids (lat,lon,h)@(t,τ) which give the location for each grid point (gridded radar timing). That way, the timing correction Δ is known at discrete but irregularly distributed positions on ground as Δ(lat,lon,h). This application of the mapping-grids to derive correction at geographic positions (e.g. for use with GRDs or terrain corrected data) is illustrated in Figure 13.

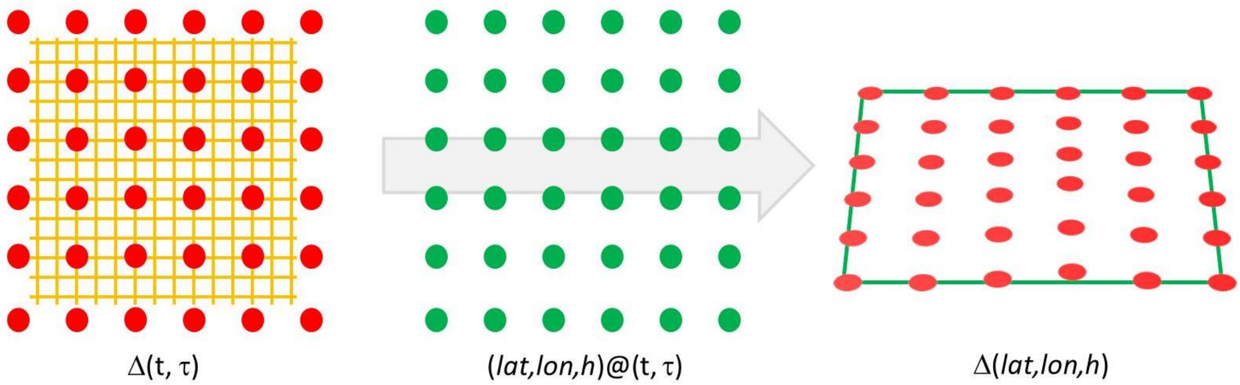

Figure 13: The mapping grid (green dots) provides the geographic coordinates (lat, lon, h) for each grid point in time. It may be used to evaluate the ETAD timing corrections (Δ, red dots superimposed on the finer SAR timing grid) given at positions in time domain (t,τ) on an irregular geographic grid (red dots at lat, lon, h).

8 ETAD Product Tables

This section provides the tables detailing the sampling, spacing on ground, extent and data volume of the ETAD output product in dependence of the acquisition SAR modes SM and IW (with the extension to EW), the (SM-)swaths and the length of the data take. Note that the polarization mode is not relevant in this case.

The ETAD processor is nominally configured to achieve constant grid spacing in time domain which corresponds to approximately 200 m on ground for the entire data take. A ground sampling of the order of 300 m is sufficiently accurate to reflect significant changes in ground topography and the corresponding signal propagation effects. The uniform sampling is complicated by the fact that the TOPS modes span a wide incidence angle range and thus yield very different ground range projections.

The processor uses an integer divider of a 10s time interval in azimuth to achieve a sampling close to the configured one (i.e. the 200m) for the entire grid. In range, the 200m ground sampling is achieved near the center of the full swath coverage. A typical IW mode datatake with a SLC sampling in time domain of 1.55411655E-08 *s* in slant range and 2.0555563E-03 *s* in azimuth has a grid sampling of approx. 249 m in near range and 168 m in far range on ground and 200 m in azimuth (assuming an average beam ground velocity) with a time spacing of approx. 8.1E-07s in slant range and 0.029240s in azimuth. This corresponds approximately to sub-sampling factors of 52 x 14 between the original SLC timing and the ETAD grid. Note however that the sub-sampling factors are not integer anymore starting with SETAP version 2.1. Since the ground velocity and orbit height varies slightly, the projected ground spacing in meters is not fixed but the sampling dividers and the corresponding spacing in time domain are.

Table 3 provides an overview on the ETAD grid sampling for the different modes. Note however that the target grid ground spacing is configurable and may change for testing purposes or depending on resources and algorithmic improvements.

Table 3: ETAD product grid sampling.

	spacing [m]			**ETAD grid sampling (time domain) [s]**	
Mode	**ground-range near**	**ground-range far**	**azimuth on ground**	**slant-range**	**azimuth**
IW	249	168	200	8.0814061E-07	0.029240
EW	333	147	200	7.1933395E-07	0.029240
S1	238	169	200	4.9953747E-07	0.029240
S2	232	175	200	5.7546716E-07	0.029240
S3	223	181	200	6.8936170E-07	0.029240
S4	215	183	200	7.8149861E-07	0.029240
S5	215	189	200	8.7918594E-07	0.029240
S6	215	193	200	9.3779833E-07	0.029240
targeted grid spacing on ground = 200 [m] with average zero-Doppler velocity (ground velocity): 6.84E+03 m/s					

The average incidence angle ranges for the different modes used in the ground projection and sub-sampling factor definition are given in Table 4.

Table 4: Incidence angle ranges.

Incidence angles [deg]			
Mode	**min**	**max**	**mid**
IW	29.1	46	37.55
EW	18.9	47	32.95
S1	18.32	26.31	22.32
S2	21.78	29.5	25.64
S3	27.64	34.85	31.25
S4	33	39.72	36.36
S5	37.89	44.12	41.01
S6	40.79	46.73	43.76

The ETAD output data volume is measured relative to the input SAR data volume due to the flexible length of the input product coverage. A single grid layer of an IW data take has thus only about 1/(52*14)=0.001374 times the number of samples *of one polarization channel* of a single SLC. However, since there are 12 grid layers, the total amount of samples amounts to about 0.017 times the number of samples.

All grids are stored as double precision float values in the NetCDF file to host the very large dynamic range of the different corrections which comprise several magnitudes in numerical range. The grids are thus using 8 bytes per sample while a L1 SLC image is stored in 32-bit signed integer hosting the two interleaved I&Q 16-bit signed integer complex samples. The data volume of each ETAD sample is thus twice the one of a SLC sample which yields a data volume ratio of 0.033. The NetCDF-4/HDF5 data format contains very small overhead resulting from the grids extending beyond the focused image data and the range and azimuth vectors provided for each burst (equivalent to one additional grid line and row). The format allows however for data compression if required.

The overall data volume of the IW ETAD NetCDF file is thus lower than 4% of the corresponding SAR product data volume (<2% for dual polarization data). An ETAD product of one IW SLC data segment of 25 seconds length contains approximately 1.16 million grid points times 12 layers resulting in 106 MB NetCDF file size for all (overlapping) swathes, bursts and grids. The factors and approximated extents & file sizes for slice products and the resulting (uncompressed) NetCDF files of different modes are provided in the following Table 5 in units of typical slices. Note however that the SLC products are not homogenous in their data representation due to the different swathes with different start/stop times and individual numbers of focused bursts.

Table 5: ETAD product extent and NetCDF file size for SLC slices of the different modes

		SLC input slice (single polarization data only, approximation)				ETAD product NetCDF (approximations only)			
Mode	**length [s]**	**lines**	**samples**	**size [MB]**	**scaling factor**	**lines**	**samples**	**number of points**	**Size [MB]**
IW	25	13135	64106	3212	**3.297E-02**	938	1233	1.16E+06	**106**
EW	60	22198	31058	2630	**1.333E-01**	2220	1725	3.83E+06	**351**
S1	25	46766	19656	3507	**8.889E-03**	866	393	3.40E+05	**31**
S2	25	40320	18870	2902	**1.042E-02**	840	393	3.30E+05	**30**
S3	25	48124	18218	3344	**9.317E-03**	859	396	3.40E+05	**31**
S4	25	41254	17688	2784	**1.136E-02**	859	402	3.46E+05	**32**
S5	25	47479	17426	3156	**9.740E-03**	848	396	3.36E+05	**31**
S6	25	41587	17255	2737	**1.136E-02**	866	392	3.40E+05	**31**

A. ETAD for Interferometric Applications

The ETAD product is not specifically designed for interferometric phase corrections and verified only for *geometric* corrections. However, the annotated range delays may be converted to phase offsets to derive phase screens between two repeat pass acquisitions specifically to account for tropospheric and ionospheric effects. Nevertheless, it has to be emphasized that the resolution of the ETAD product and specifically the one of the tropospheric corrections is not suitable to evaluate small scale atmospheric disturbances which do play an important role in interferometry.

Even if not verified for accurate phase correction, the residual interferometric phase estimate from two ETAD products may be very useful to assess the degree of disturbance – e.g. to select well suited master-secondary interferometric pairs in stacks of data. A first example for an ETAD InSAR application is given in [I8]. Note however that the ETAD grids are optimized for the individual data takes of interferometric pairs. Thus, they are evaluated at different locations and terrain heights on ground and – even after co-registration – steeper terrain variations will hence imprint artefacts on local scales in these differential phase estimates.

One of the main differences of the ETAD correction to one specific for interferometry is the fact that ETAD considers the group delays of the radar signals (i.e. changes in the speed of light) in the dispersive ionospheric medium and not the corresponding phase delays which act in the opposite direction.

It also depends on the InSAR processing approach which of the SAR system corrections are to be considered in the calculation of the differential correction phase. Some geometric shifts or bistatic offsets may be compensated already or cancel in co-registration and resampling of the secondary acquisition to the master image.

It is thus advised to select the range correction layers relevant for the specific processing approach. In the following example, the Doppler shift in range is omitted and the range shift is calculated from the individual range correction grids.

Taking this into account, an estimate for a phase screen between two acquisitions where the interferometric phase is $\phi = \phi_{master} - \phi_{sec}$ using ETAD can be derived with simple steps analogue to the ones from chapter 7 which have to be performed for each TOPS burst:

1. Resample the selected ETAD layers to SLC resolution applying bilinear interpolation for t and τ
2. Apply the SAR SLC master to secondary co-registration parameters from the interferometric processing to the selected ETAD correction layers
3. Compute the differential range delay correction Δ_{delay}:

   For the reference polarization channels (i.e. the co-polar ones) this results from
   (troposphericCorrectionRg + geodeticCorrectionRg **–** ionosphericCorrectionRg + burst:instrumentTimingCalibrationRange)*master*

   – (troposphericCorrectionRg + geodeticCorrectionRg **–** ionosphericCorrectionRg + burst:instrumentTimingCalibrationRange)*secondary*

   In case the non-reference polarization channels are used (i.e. the cross-polar ones), a possible change in the polarization channel calibration has to be considered additionally:
   (troposphericCorrectionRg + geodeticCorrectionRg **–** ionosphericCorrectionRg + burst:instrumentTimingCalibrationRange + burst:rangeOffset[HV|VH])*master*

   – (troposphericCorrectionRg + geodeticCorrectionRg **–** ionosphericCorrectionRg + burst:instrumentTimingCalibrationRange + burst:rangeOffset[HV|VH])*secondary*

4. Convert the differential range delay correction to interferometric phase correction with
   $\phi_{etad} = - \Delta_{delay} * c_{light} * 2\pi / \lambda_{S-1}$
   and subtract it from the interferogram to obtain a corrected interferometric phase
   $\phi_{corr} = \phi - \phi_{etad}$

Please note the important points:

a. The ionosphericCorrectionRg has to be subtracted to account for the phase delay.
b. The instrumentTimingCalibrationRange has an effect on the absolute phase difference if the ETAD configuration or instrument calibration changed between the SLC data acquisition or the generation of the two ETAD products (also required if acquisitions of S1-A and S1-B are combined for the interferogram)
c. Despite using only "physical" grid parameters - which are not influenced by the SAR burst processing - the corrections have to be applied on burst level prior to any mosaicking to account for those possible changes in the instrument calibration parameters – including those of different swathes. Otherwise discontinuities may be observed.

An example for such a derived interferometric phase difference (in the original ETAD resolution) is depicted in Figure 14.

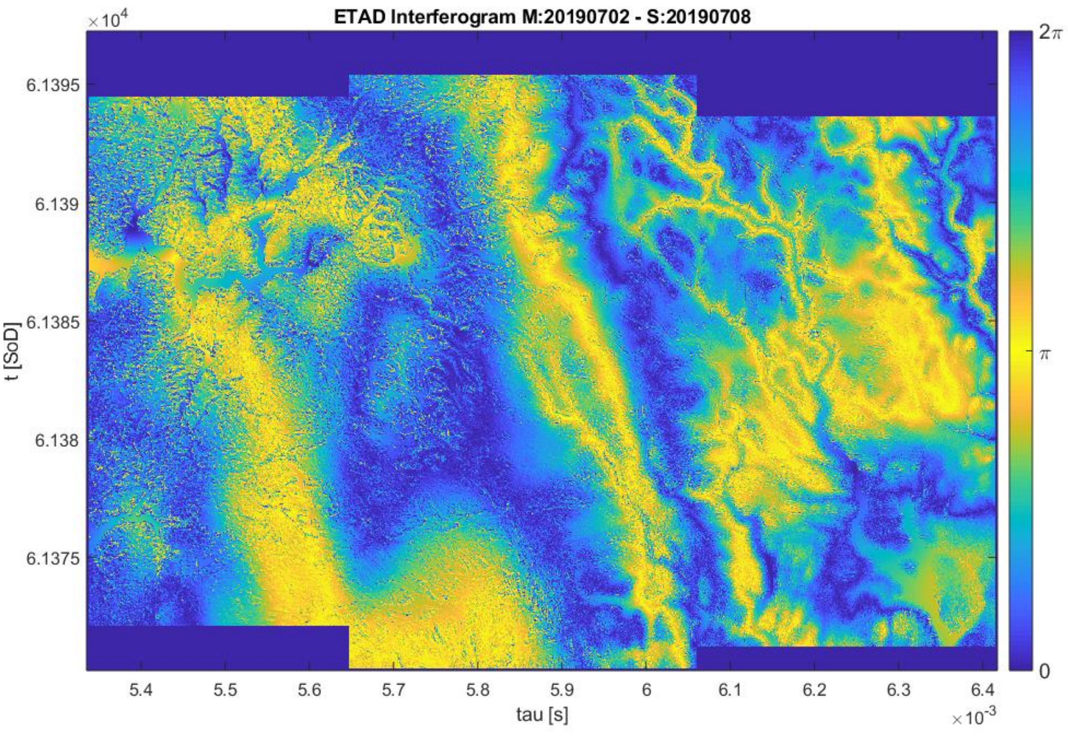

Figure 14: Example of an interferometric phase estimate using the ETAD products of two acquisitions.

B. ETAD Application to GRD Products

This section contains an instruction on the application of the ETAD grid annotation associated with the L1 SLC products to the standard ellipsoid-projected L1 Ground Range Detected (GRD) product variants of those SLCs.

Since 100% of IW and SM data acquired over land masses worldwide are systematically produced to level 1 SLC products[2], an ETAD product for each of those acquisitions should be available when systematically generated. In consequence, such a "SLC"-ETAD product is available for each GRD product of those data sets. This section hence provides the necessary information to access an ETAD product based on SLC products of a datatake for the corresponding GRD product(s).

In principle, each location on ground covered by a Sentinel-1 acquisition can be corrected using the approach to locate the corresponding grid indices from geographic coordinates of the mapping grids as indicated in section 7.5. The mapping grids and other annotation components are the direct source for the calculation of the corrections at the individual ground positions for a specific azimuth and range time. The correction grids then refer to an irregular grid on ground. This way any point in a GRD or even a terrain corrected product derived from a SLC dataset may be corrected.

It is however not very sensible to perform this approach of point-wise correction in a product which has been projected on an ellipsoid using straight-forward slant to ground range polynomials.

An alternative and more accurate approach is hence to recreate the slant-range timing information for the GRD product by inverting the slant-to-ground projection that has been applied in order to assign the correction grid values to the specific image matrix locations. This approach is outlined here. *Note however that the GRD is never suited for accurate geometric assessment since the projection cannot revert the mosaicking of the burst data to correctly handle the burst overlaps. It is strongly advised to use SLCs only for geometric evaluation.*

The *standard* GRD product is derived from focused SAR data in SLC geometry that has been detected, multi-looked and projected to ground range using an Earth ellipsoid model. The ellipsoid projection of the GRD products is corrected using the terrain height specified in the product general annotation. The terrain height used varies in azimuth but is constant in range. The orientation of the data is still in SAR orientation (i.e. azimuth/range). Figure 15 sketches the GRD range projections.

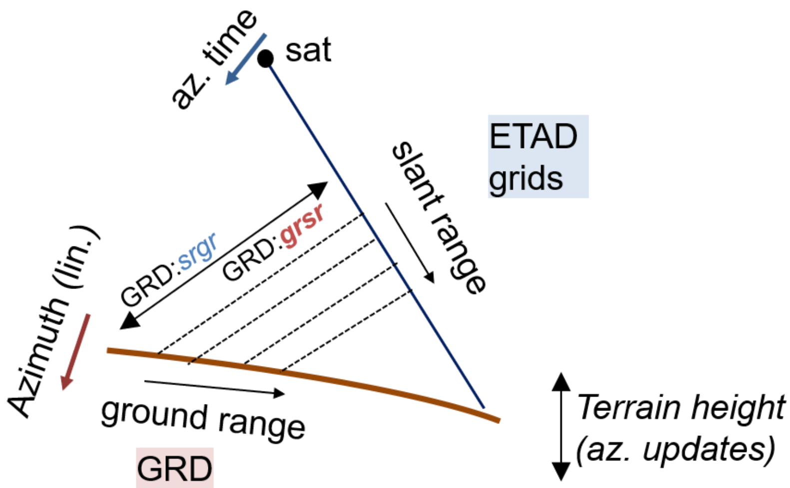

Figure 15: Sketch of GRD projections in range.

[2] https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/production-scenario

The product contains annotated information on the slant-to-ground range forward and backward projection polynomials within the coordinateConversionType in the XML product file of the GRD (S1A_IW_GRDH_*.SAFE/annotation/s1a_iw_grdh*.xml) under the

/product/coordinateConversion/coordinateConversionList/coordinateConversion/grsrCoefficients

nodes for a specific segment in azimuth. The polynomials are time-stamped with the zero Doppler azimuth and two-way slant range times to which they apply. The coefficients used on range lines between updates are found by linear interpolation between the updated and previous values.

The polynomial of interest is defined by the grsrCoefficients and the gr0 parameter (the ground range origin used for slant range calculation [m]). The polynomial calculated from the provided s_i coefficients is then

$slantRange = s_0 + s_1 (gr - gr0) + s_2 (gr - gr0)^2 + \ldots + s_{n-1} (gr - gr0)^{n-1}$

where gr is the ground range at which we are evaluating and n is the "count attribute" -1.

The constantly scaled azimuth times corresponding to the individual range lines can be derived from the annotated start time and the azimuthTimeInterval (in seconds) in the imageInformation node of the imageAnnotation segment in the XML file and the line number.

The procedure is then

1. Evaluate for each range line in the GRD image the ground-to-slant-range re-projection by linear interpolation of the adjacent grsrCoefficient-polynomials between the updated azimuthTime tags.
2. Convert the derived slant-ranges to times using *c/2* and use the derived range times and the GRD azimuth times to access the ETAD grids.
3. Evaluate for each sample (or the required image segment) the correction grids as outlined in chapter 7 by bilinear interpolation. Note that the bursts and swathes are now undistinguishable in the mosaicked GRD and the burst applicable to the relevant (t, τ) time pair has to be selected. This issue of handling the overlaps is discussed below.
4. Assess the timing correction for the GRD samples and apply them accordingly.

In case the user is only interested in the "physical" correction grids (e.g. the tropospheric ones), the overlapping parts of those specific grids of different bursts yield identical correction results and the first applicable burst-grid may be used.

If both the SLCs and GRDs were generated by a SAR IPF which takes the SAR system effects into account, this simple approach also holds for the sum-grids. Otherwise, the handling of overlaps is more complex for the SAR system corrections or sum-grids since the GRD product does not contain sufficient information on the exact position of the boundaries of the bursts in the mosaicked image. An approximative approach is to evaluate the extent of the relevant grids and to split the overlap area in two halves. However, due to the merged nature of the GRDs, an exact reconstruction is not possible with the current GRD product annotation.

It is theoretically possible to *correct* the GRD in slant-range projection using the method detailed above and to re-project the corrected slant-range image back to ground range using the opposite slant-to-ground-range polynomial from the srgrCoefficients annotated in the same XML node to obtain a "corrected GRD". It is however not really useful to do this given the fact that the GRD itself is only coarsely geo-located.

Correcting with ETAD a "terrain corrected" product is even less meaningful since the (uncorrected) timing information has already been used in geocoding / DEM projection and hence the errors are already "burnt-in" in the orthorectified image. In order to obtain an accurate terrain corrected product, an ETAD-corrected SLC should be used as input for geocoding / projection.