

Update of S-1 Instrument Timing Calibration for ETAD



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1.2	27.10.2023	Update concerning the AUX ITC validity and S-1A	C.Gisinger (DLR) G.Hajduch (CLS)

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LIST OF CONTENTS/SOMMAIRE

1	Intro	oduction	4
	1.1	Background/Context	4
	1.2	Purpose of this document	4
	1.3	Reference Documents	5
	1.4	Acronyms and definition	5
2	Rec	alibration of Sentinel-1 sensor timing delays	7
3	Vali	dation of redefined instrument timing calibration	11
	3.1	Discussion of validation results	11
	3.2	Summary and conclusions	13
4	Upd	ate of AUX ITC products and ETAD application	17
	4.1	AUX ITC maintenance and updates	17
	4.2	How to apply the AUX ITC to ETAD	18
5	Vali	dation of ETAD product performance	21
A	opendi	x A - Additional ALE visualizations	22
A	opendix	x B - List of tables and figures	27



1 Introduction

1.1 Background/Context

The initial instrument timing calibration constants of Sentinel-1A and Sentinel-1B sensors applied with Extended Timing Annotation Dataset (ETAD) products [RD-15] stem from a calibration campaign that used 3 years of IW data from the Metsähovi Observatory calibration site in Finland. The information is stored in the Instrument Timing Calibration auxiliary product (AUX ITC) used by the ETAD processor [RD-1]. The initially derived timing calibration ensured fulfilment of ETAD geolocation requirements as confirmed in [RD-2], but centimeter-level offsets in absolute location error (ALE) can still be present when analyzing different globally distributed validation sites, as observed in the regular mission monitoring of SAR Mission Performance Center (SAR-MPC) [RD-4].

The reason for this may be the re-processed precise orbit solution [RD-2][RD-3], which was not available during determination of the initial instrument timing calibration, as well as possibly unknown residual biases in the atmospheric path delay corrections. In the case of S-1A, there is also the outage event with antenna tile #11 that occurred in June 2016 [RD-5], which is assumed to have an impact on the azimuth ALE for the different sub-swaths [RD-4][RD-6].

Therefore, SAR-MPC decided to perform an instrument timing re-calibration activity, focusing on the period after 06/2016 in order to have AUX ITC products for S-1A and S-1B that are suitable for ETAD product processing of said period. The goal was an update of the S-1A and S-1B overall range and azimuth calibration in AUX ITC, i.e., the 4 main values without any beam/mode/polarization specific offsets which are set to zero [RD-1].

It is important to note that the timing calibration information of AUX ITC does not impact the generation of the ETAD product and its individual correction layers. The applicable timing calibration is annotated in a user-friendly way (per burst) and added to summation layers of range and azimuth corrections for the sake of convenience [RD-15]. However, a user may readily exchange this information for any updated data of future AUX ITC releases. The details on the necessary steps are described in chapter 4.2.

1.2 Purpose of this document

The ETAD product for Sentinel-1 is described in [RD-15] and the need for an accurate S-1 instrument timing calibration is discussed in [RD-2].

The purpose of this document is to provide the Sentinel-1 product user with a summary of the latest instrument timing calibration that is used to generate ETAD products.

This document is organized as follows:

- Section 1: this introduction
- Section 2: summarizes the instrument timing calibration methods and data, and presents the results of the performed re-calibration
- Section 3: presents the validation of the updated instrument timing calibrations across several test sites and shows comparisons to the previous timing calibration
- Section 4: presents the updated auxiliary product that provides the instrument timing calibration and describes how to use the data with already existing ETAD products
- Section 5: presents the validation for a set of ETAD products that make use of the updated timing calibration

The appendix provides additional plots of the performed validation.

1.3 Reference Documents

[RD-1]	ESA-EOPG-CSCOP-TN-80, S-1 ETAD – Auxiliary Product Specification, iss. 1.17, 21.07.2023
[RD-2]	C. Gisinger et al., "The Extended Timing Annotation Dataset for Sentinel-1 - Product Description and First Evaluation Results," in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-22, 2022, doi: 10.1109/TGRS.2022.3194216.
[RD-3]	GMV-CPOD-MEM-0052, Sentinel-1 Full Mission Reprocessing 2021, issue 1.1, 13.04.2021
[RD-4]	SAR-MPC-0588, Sentinel-1 Annual Performance Report 2022, iss. 1.2., 13.03.2023
[RD-5]	MPC-0324, Sentinel-1A Tile #11 Failure, iss. 1.2, 12.10.2016
[RD-6]	C. Gisinger et al., "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, pp. 1154-1181, 2021 , doi: 10.1109/TGRS.20219.2961248
[RD-7]	C. Gisinger et al., "Precise Three-Dimensional Stereo Localization of Corner Reflectors and Persistent Scatterers with TerraSAR-X", in IEEE Transactions on Geoscience and Remote Sensing, vol. 53, pp. 1782-1802, 2015, doi: 10.1109/TGRS.2014.2348859
[RD-8]	X. Collilieux, et al, "Validation of a corner reflector installation at Côte d'Azur multi-technique geodetic observatory", in Advances in Space Research, vol. 70, iss. 2, pp. 360-370, 2022, doi: 10.1016/j.asr.2022.04.050
[RD-9]	T. Fuhrmann, J. Batchelor, T. McCall, M.C. Garthwaite.: Positions and orientations for the Queensland corner reflector array, Australia: Report on geodetic surveys conducted in May and June 2018. RECORD 2020/034, Geoscience Australia, Canberr, doi: 10.11636/Record.2020.034
[RD-10]	ETAD-DLR-DD-0008, Algorithm Technical Baseline Document, iss. 2.3, 09.03.2023
[RD-11]	J. Kouba, "Implementation and testing of the gridded Vienna Mapping Function 1 (VMF1)", in Journal of Geodesy, vol. 82, pp. 193-205, 2008, doi: 10.1007/s00190-007-0170-0
[RD-12]	D. Landskron and J. Böhm, "VMF3/GPT3: refined discrete and empirical tropospheric mapping functions", in Journal of Geodsy, vol. 92, pp. 349-360, 2018, doi: 10.1007/s00190-017-1066-2
[RD-13]	G. Petit G., B. Luzum B. (2010), IERS Conventions (2010), IERS Technical Note No. 36, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 2010. Online: https://www.iers.org/IERS/EN/Publications/TechnicalNotes/TechnicalNotes.html
[RD-14]	Leys et al., "Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median", in Journal of Experimental Social Psychology, vol. 49, iss. 4, pp. 764-766, 2013, doi: 10.1016/j.jesp.2013.03.013
[RD-15]	ETAD-DLR-PS-0002, S-1 ETAD Product Definition Document, iss. 2.4, 6.3.2023
[RD-16]	ETAD-DLR-PS-0014, S-1 ETAD Product Format Specification Document, iss. 1.8, 6.3.2023

1.4 Acronyms and definition

ALE	Absolute Location Error
AUX	Auxiliary
CR	Corner Reflector
DLR	German Aerospace Center (Germany's national research centre for aeronautics and space)
ECMWF	European Centre for Medium-Range Weather Forecast
ETAD	Extended Timing Annotation Dataset



EW	Extra Wide (Sentinel-1 SAR mode)
НН	Horizontal Transmit-Horizontal Receive Polarization
HV	Horizontal Transmit-Vertical Receive Polarization
ITC	Instrument Timing Calibration
IW	Interferometric Wide (Sentinel-1 SAR mode)
MAD	Median absolute deviation
MPC	Mission Performance Center
S-1	Sentinel-1
S-1A	Sentinel-1A satellite
S-1B	Sentinel-1B satellite
SAR	Synthetic Aperture Radar
SCR	Signal-to-Clutter Ratio
SLC	Single-look complex
SM	Stripmap (Sentinel-1 SAR mode)
VCE	Variance Component Estimation
VH	Vertical Transmit-Horizontal Receive Polarization
VV	Vertical Transmit-Vertical Receive Polarization



2 Recalibration of Sentinel-1 sensor timing delays

The re-calibration summarized in the report at hand applies S-1A and S-1B IW data of the period 10/2016 to 12/2021 and the latest reprocessed precise orbit solution. The following well-established calibration sites are used for largely comparable numbers of products for both sensors and regular sampling of the IW swath:

- Wettzell geodetic observatory [RD-7]: 2 CRs (1.5m), 3 IW beams
- Metsähovi geodetic observatory [RD-7]: 1 CR (1.5m), 2 IW beams
- Côte d'Azur geodetic observatory (since Dec 2018) [RD-8]: 1 CR (1.44m), 2 IW beams
- Surrat Basin SAR calibration site [RD-9]: selection of 4 CRs from the 40 CRs (1.5m or larger) to provide a homogeneous swath coverage, 2 IW beams

The number of usable products per sensor, site, and configuration is summarized in Table 1.

Table 1: Sentinel-1 sites and SAR data between 10/2016 - 12/2021 used for the instrument timing re-calibration. All refers to the acquisitions with an SCR of larger than 15 dB. Cleaned refers to the usable acquisitions after applying a MAD outlier detection, see details in text. Note that Wettzell 1 IW2 and Wettzell 2 IW2 are located in a burst-overlap area and are measured twice per pass, doubling the data rate.

Site	CR	Pass	IW-	Inc.	S-14	\ [#]	S-1E	3 [#]
	eage-size		beam	Angle [*]	All	Cleaned	All	Cleaned
Metsähovi	1.50 m	Desc.	IW 1	34	104	95	73	70
			IW 2	41	101	90	72	65
Wettzell 1	1.50 m	Asc.	IW 2	40	293	281	264	257
Wettzell 2	1.50 m	Desc.	IW 1	31	149	145	135	132
			IW 2	41	298	281	299	292
Côte d'Azur	1.44 m	Asc.	IW 1	34	91	73	86	86
			IW 3	44	111	106	135	130
Surat 03	2.50 m	Asc.	IW 2	39	145	137	143	134
Surat 14	2.50 m	Asc.	IW 2	37	145	141	143	134
Surat 26	1.50 m	Asc.	IW 1	34	145	137	143	138
			IW 3	45	82	75	n/a	n/a
Surat 32	1.50 m	Asc.	IW 1	32	145	138	143	130
			IW 3	44	82	78	n/a	n/a
Total				·	1891	1777	1636	1568

The processing is based on the existing DLR geometric calibration/validation tool chain which is documented in [RD-6][RD-7]. The data correction methods are identical to ETAD algorithms and products [RD-10], with the exception of:

- The usage of Vienna Mapping Function data, version 3 [RD-12], to compute the tropospheric delay correction [RD-11]. Procurement of ECMWF data to use the ETAD tropospheric computation was not feasible for this recalibration activity, given the amount of involved S-1 SAR data.
- Consideration of all solid Earth deformation correction, including the solid Earth tides, the ocean tidal loading, the pole tides, atmospheric tidal loading, and ocean pole tide loading [RD-6][RD-13].



Data cleaning was performed to ensure that outliers are removed before computing the calibration for each sensor:

- Outlier detection per site and beam removing data with a signal-to-clutter ratio (SCR) of less than 15 dB. This detection is already performed as a part of the point target analysis. Therefore, the data summarized in Table 1 (All) only lists image data with clear CR signatures.
- Outlier detection per site and beam, analyzing the residuals of an initially computed raw ALE result by applying the median absolute deviation (MAD) method with a cut-off criterium of 2.5 [RD-14]. The data remaining after outlier detection is summarized in Table 1 (Cleaned).

An example of results before and after applying MAD outlier detection is shown in Figure 1. Overall, 6% of data was rejected for S-1A, and 4% of data was rejected for S-1B.



Figure 1: Outlier detection example on behalf of Wettzell Descending CR for data as listed in Table 1. ALE before applying the MAD outlier detection (left) and after applying the detection (right).

From this cleaned S-1A and S-1B geolocation data, refined calibration values can be derived by fitting an optimal global average to center the ALE. The calibration calculation makes use of the generalized least squares methods, solving the SAR range-Doppler equations in zero-Doppler configuration as described in [RD-7]:



$$\begin{split} f_{Range}(X_s(t,\Delta t_{cal}),X_T,\tau,\Delta \tau_{cal}) &: \qquad |X_s(t,\Delta t_{cal}) - X_T| - c/2 \cdot (\tau - \Delta \tau_{cal}) = 0 \\ f_{Azimuth}(X_s(t,\Delta t_{cal}),\dot{X}_s(t,\Delta t_{cal}),X_T) &: \qquad \frac{X_s(t-\Delta t_{cal}) \cdot (X_T - X_s(t-\Delta t_{cal}))}{|X_s(t-\Delta t_{cal})| \cdot |X_T - X_s(t-\Delta t_{cal})|} = 0 \end{split}$$
 Eq. 1

where X_s , \dot{X}_s are the satellite orbit position and velocity vectors, the X_T is the target position vector, t, τ are the radar timings of azimuth and range, and Δt_{cal} , $\Delta \tau_{cal}$ are the respective timing calibration constants.

Because the accurate reference positions of the involved targets are known from terrestrial geodetic survey, the parameter model $A \cdot x$ of the generalized adjustment $B \cdot v + A \cdot x + w = 0$ can be modified for estimation of calibration constants:

$$\begin{bmatrix} \frac{\partial f_{R,i}}{\partial \tau, i} & \frac{\partial f_{R,i}}{\partial t, i} & 0 & \cdots \\ \frac{\partial f_{A,i}}{\partial \tau, i} & \frac{\partial f_{A,i}}{\partial t, i} & 0 & \cdots \\ 0 & 0 & \ddots & \ddots \\ \vdots & \vdots & \ddots & \ddots \end{bmatrix} \cdot \begin{bmatrix} d\tau, i \\ dt, i \\ \vdots \end{bmatrix} + \begin{bmatrix} \frac{\partial f_{R,i}}{\partial \Delta \tau_{cal}} & \frac{\partial f_{R,i}}{\partial \Delta t_{cal}} \\ \frac{\partial f_{A,i}}{\partial \Delta \tau_{cal}} & \frac{\partial f_{A,i}}{\partial \Delta t_{cal}} \end{bmatrix} \cdot \begin{bmatrix} d\Delta \tau_{cal} \\ W_{f_{A,i}} \\ \vdots \end{bmatrix} = \mathbf{0}$$
Eq. 2

The first part $B \cdot v$ contains the linearization for all the i = 1, n radar timing measurements of the target(s) as provided by the SAR images of a sensor, the second part $A \cdot x$ contains the linearization for the sensor's unknown timing calibration constants, and the final part w denotes the discrepancies that are resolved by minimizing the residuals v under the L2-norm and by estimating the calibration parameters x. For the partial derivatives of the Jacobians and the solution of the system please refer to [RD-7].

The equation Eq. 2 is solved for all available data of a particular sensor, i.e., S-1A or S-1B. Variance Component Estimation (VCE) is applied for the range and azimuth data of each calibration site, as data quality may vary because of CR sizes, the different background clutter, or the impact of atmospheric path delays. The VCE ensures an optimal estimation of the calibration constants while accounting for the non-homogenous data quality.

The redefined timing calibrations for S-1A and S-1B are summarized in Table 2. The confidence intervals of the estimated calibration parameters as given by the least-squares result are listed as well. For the range, the timing calibrations are determined equivalent to 0.002 m (95% confidence level) and for the azimuth equivalent to 0.010 m (95% confidence level). These numbers are in close agreement with our expectations from the basic law of averaging, σ/\sqrt{n} , when assuming typical S-1 precisions of 0.04 m in range and of 0.25m in azimuth, and accounting for the number of available data (Table 1).

Table 2: Redefined S-1A and S-1B instrument timing calibration estimated by least-squares methods from 5.5 years of data of 8 CR targets located at 4 calibration sites. Result values in units of seconds and converted numbers in units of meters. The precision numbers mark the 95% confidence level as provided by the least-squares solution.

Sensor	Δτ _{cal} [s, 2-way]	Δt _{cal} [s]	Rg [m, 1-way]	Az [m]
S-1A	7.4103e ⁻¹⁰ ± 1.3962e ⁻¹¹	6.3522e ⁻⁶ ± 1.2914e ⁻⁶	0.1111 ± 0.0021	0.0432 ± 0.0088
S-1B	-1.2855e ⁻¹⁰ ± 1.3673e ⁻¹¹	-3.5523e ⁻⁵ ± 1.5402e ⁻⁶	-0.0193 ± 0.0020	-0.2416 ± 0.0105

The results of current and redefined S-1A and S-1B timing calibrations are compared in Table 3. With regards to the previous solution, the range timing calibrations change by 6 cm and 3 cm for S-1A and S-



1B, respectively, mostly due the usage of the re-processed S-1 precise orbit solution and the usage of more data across multiple test sites. The S-1A and S-1B azimuth timing calibrations change by 4 cm and 10 cm, respectively. In summary, the large amount of data allowed for a reliable re-definition of S-1 sensor timing calibration constants with an estimated precision of 0.2 cm in range and 1 cm in azimuth.

Table 3: Comparison of S-1A and S-1B instrument timing calibration values in units of seconds and corresponding numbers in units of meters. The current ITC is based on 3 years of data and at Metsähovi calibration site, whereas the redefined ITC makes use of 5.5 years of data and 8 CR targets located at 4 calibration sites.

	Current ITC				Redefined ITC			
Sensor	Δτ [s]	∆t [s]	Rg [m]	Az [m]	Δτ [s]	Δt [s]	Rg [m]	Az [m]
S-1A	1.1281e ⁻⁹	1.2873e ⁻⁵	0.1691	0.0875	7.4103e ⁻¹⁰	6.3522e ⁻⁶	0.1111	0.0432
S-1B	0.0646e ⁻⁹	-4.9701e ⁻⁵	0.0097	-0.3380	-1.2855e ⁻¹⁰	-3.5523e ⁻⁵	-0.0193	-0.2416



3 Validation of redefined instrument timing calibration

3.1 Discussion of validation results

In order to validate the timing calibration results, ALE comparisons of the existing versus the redefined timing calibration were carried out for S-1A and S1B at several test sites. The sites involved are mostly identical to the calibration sites (see chapter 2) but in this case all available targets and all available mission data between October 2016 and December 2022 were used. The rationale for the overlap between calibration and validation sites lies in the overall larger amount of data and the much higher number of targets at the Surat Basin site which are used to validate the calibration results. Note that CR measurements with an SCR lower than 15 dB were removed as outliers but additional detection with MAD was not applied.

Figure 2 shows the validation for the Surat Basin site, including all the 40 CRs and all data from 10/2016 – 12/2022. Figure 3 shows the ALE results for the same 10/2016 – 12/2022 period for the geodetic observatories of Wettzell, Metsähovi, and Côte d'Azur, hosting a total of 4 CRs. Result numbers are compared in Table 4 and Table 5. Detailed comparisons in terms of incidence angle and time series are given in the Appendix A - (Figure 5 to Figure 8).

Further analysis was performed at Yarragadee geodetic observatory, Australia, that provides two 1.5m CRs. The site allows for an independent verification of timing calibration constants with Sentinel-1 SM data, but only for the S-1B satellite which acquired a 1-year data series between June 2019 and August 2020. Moreover, S-1B acquired IW data between July 2018 and December 2021 that was analyzed as well. The 2D ALE results are shown in Figure 4 and the numbers are summarized in Table 6. The corresponding ALE time series is shown in the Appendix A - (Figure 9).

	Range	ALE [m]	Azimuth ALE [m]		
	Current ITC	Redefined ITC	Current ITC	Redefined ITC	
Sentinel-1A	0.040 ± 0.051	-0.018 ± 0.051	-0.093 ± 0.289	-0.138 ± 0.289	
IW-1	0.035 ± 0.046	-0.023 ± 0.046	-0.228 ± 0.267	-0.272 ± 0.267	
IW-2	0.025 ± 0.045	-0.033 ± 0.045	0.054 ± 0.234	0.010 ± 0.234	
IW-3	0.083 ± 0.051	0.025 ± 0.051	-0.013 ± 0.275	-0.058 ± 0.275	
Sentinel-1B	0.011 ± 0.043	-0.018 ± 0.043	-0.103 ± 0.250	-0.006 ± 0.250	
IW-1	0.012 ± 0.043	-0.017 ± 0.043	-0.084 ± 0.261	0.013 ± 0.261	
IW-2	0.009 ± 0.042	-0.020 ± 0.042	-0.128 ± 0.231	-0.031 ± 0.231	
IW-3	N/A	N/A	N/A	N/A	

Table 4: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin calibration site hosting 40 CRs. Results with the current instrument timing calibration (ITC) and the redefined ITC as listed in Table 1.



Table 5: ALE computed with S-1A and S-1B IW data of 10/2016 - 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Results with the current instrument timing calibration (ITC) and the redefined ITC as listed in Table 1.

	Range	ALE [m]	Azimuth ALE [m]		
	Current ITC	Redefined ITC	Current ITC	Redefined ITC	
Sentinel-1A	0.077 ± 0.049	0.019 ± 0.049	0.007 ± 0.345	-0.038 ± 0.345	
IW-1	0.078 ± 0.050	0.019 ± 0.050	-0.005 ± 0.353	-0.049 ± 0.353	
IW-2	0.073 ± 0.048	0.015 ± 0.048	0.042 ± 0.310	-0.002 ± 0.310	
IW-3	0.100 ± 0.051	0.042 ± 0.051	-0.156 ± 0.449	-0.201 ± 0.449	
Sentinel-1B	0.046 ± 0.046	0.017 ± 0.046	-0.063 ± 0.322	0.034 ± 0.322	
IW-1	0.047 ± 0.045	0.018 ± 0.045	-0.048 ± 0.317	0.049 ± 0.317	
IW-2	0.044 ± 0.045	0.015 ± 0.045	-0.067 ± 0.296	0.030 ± 0.296	
IW-3	0.057 ± 0.051	0.028 ± 0.051	-0.078 ± 0.435	0.019 ± 0.435	

Table 6: ALE computed with S-1B IW data of 08/2018 - 12/2021 and S-1B SM data of 06/2019 - 09/2020 acquired at the geodetic observatory Yarragadee, hosting 2 CRs. Results with the current instrument timing calibration (ITC) and the redefined ITC as listed in Table 1.

	Range	ALE [m]	Azimuth ALE [m]		
	Current ITC	Redefined ITC	Current ITC	Redefined ITC	
Sentinel-1B	0.026 ± 0.033	-0.003 ± 0.033	0.006 ± 0.218	0.103 ± 0.218	
IW-1	0.018 ± 0.034	-0.011 ± 0.034	0.002 ± 0.213	0.099 ± 0.213	
IW-2	0.035 ± 0.029	0.006 ± 0.029	0.011 ± 0.225	0.108 ± 0.225	
IW-3	N/A	N/A	N/A	N/A	
Sentinel-1B	-0.013 ± 0.016	-0.042 ± 0.016	-0.104 ± 0.038	-0.007 ± 0.038	
S1	N/A	N/A	N/A	N/A	
S2	N/A	N/A	N/A	N/A	
S3	N/A	N/A	N/A	N/A	
S4	N/A	N/A	N/A	N/A	
S5	-0.013 ± 0.016	-0.042 ± 0.016	-0.104 ± 0.038	- 0.007 ± 0.038	
S6	N/A	N/A	N/A	N/A	

The results applying the redefined timing calibration values are in line with our anticipated outcome of this re-calibration activity. For the IW range data, the sensors can achieve a typical ALE of better than 4 cm (S-1A) and 3 cm (S-1B), with very homogenous results across the total of 44 CR targets located at 4 calibration/validation sites, see Table 4 and Table 5. There are only small variations in the individual IW sub-swaths. The same holds true for the S-1B IW azimuth data, for which the attainable ALE is now 5 cm or better. The S-1A IW azimuth data is limited by the variation observed in the results of the different sub-swaths. The redefined azimuth timing calibration gives an improvement for central IW2 sub-swath, but the overall azimuth ALE is slightly worsened by the inhomogeneous azimuth characteristics of the different sites and swaths. This is considered to be a S-1A specific problem because the azimuth results obtained with S-1B are generally much more homogeneous for the very same time period and sites. The



likely reason is the outage of tile #11 of S-1A SAR antenna that occurred in June 2016, changing the sensor characteristics.

Regarding temporal stability, the redefined timing calibration constants perform equally well over the analyzed data period of 10/2016 - 12/2022, see Figure 6 and Figure 8. No degradation or change in terms of the above described sensor behavior is observed during this period when using the redefined timing calibration.

The analysis performed with S-1B IW data at Yarragadee test site is in close agreement with the range results obtained at the other sites, see Table 6. The redefined timing calibration improves the range offset from 2.6 cm to 0.3 cm. The azimuth ALE, however, shows a discrepancy with regards to the other calibration site. The azimuth offsets are close to zero when applying the current timing calibration, whereas the redefined timing calibration introduces an offset of 10 cm. The reason for this is not clear but when inspecting the S-1B azimuth ALE results of individual targets at the Surat calibration site, see Figure 5b, there are a few targets with a larger azimuth offset of more than 5 cm.

When comparing the redefined timing calibration for S-1B SM data, see Table 6, the results from Yarragadee are in close agreement with the overall results of the IW ALE, indicating a largely consistent time delay behavior of S-1B for both SAR modes. There is a small degradation in the range ALE offset when applying the redefined timing calibration (-1.3 cm versus -4.2 cm), but for the azimuth ALE the previously observed bias of -10 cm is now removed, and the results are almost perfectly centered.

3.2 Summary and conclusions

In conclusion, the redefined timing calibration values of S-1A and S-1B offer an improvement over the existing timing calibration used with ETAD AUX ITC. The remaining ALE offsets in IW range data are generally reduced to 4 cm or better in the global verification data set covering both sensors and more than 5 years of data from 4 calibration sites, hosting in total 44 CRs. For the azimuth ALE of S-1B, the offsets observed in certain targets can remain as large as 10 cm but are generally 5 cm or better. For S-1A, the overall azimuth timing calibration is limited by the sensor's known inhomogeneous azimuth characteristics with the different IW sub-swaths. Therefore, ALE offsets of up to 30 cm can still be present in S-1A azimuth IW data when using the redefined timing calibration. There is limited availability of SM acquisitions at calibration sites, but the results obtained with S-1B indicate a good compatibility of the redefined timing calibration with SM data.

SAR MPC will continue to actively monitor geometric quality of S-1 mission and adjust the AUX ITC of each sensor as required. Moreover, archived data of additional test sites are studied with regards to calibration of the S-1A IW sub-swath effects. Compensating for any swath-related effect is already supported by the design of AUX ITC and SAR MPC will consider such refinements if conclusive results can be obtained.





Figure 2: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin calibration site hosting 40 CRs. Results with the current ITC (top) and the redefined ITC (bottom).





Figure 3: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Results with the current ITC (top) and the redefined ITC (bottom).





Figure 4: ALE computed with S-1B SM data of 06/2019 - 09/2020 (left) and S-1B IW data of 08/2018 - 12/2021 (right) acquired at the geodetic observatory Yarragadee, hosting 2 CRs. Results with the current ITC (top) and the redefined ITC (bottom).



4 Update of AUX ITC products and ETAD application

4.1 AUX ITC maintenance and updates

The S-1 instrument timing calibration information for ETAD is part of an auxiliary product required by the processor to generate the ETAD products. It is maintained as AUX ITC by the SAR MPC and can be accessed via the SAR MPC website¹ that hosts the auxiliary data products related to S-1 SAR processing. This website provides a RestAPI to identify and download the auxiliary data products².

The AUX ITC is defined for each S-1 sensor (S-1A, S-1B, S-1C, S-1D) and contains reference timing calibration values for range and azimuth, as well as specific offset numbers for the different combinations of mode, swath and polarization. Accounting for the S-1 SAR-modes (SM, IW, EW) and their respective number of beams (S1-6, IW1-3, EW1-5) and the four polarization channels (HH HV, VV, VH), the total amount of sub-calibrations supported by AUX ITC is 56 [RD-1]. Presently, all these specific offsets are set to zero, because the possibility of calibrating and validating specific timing offsets is still being investigated by SAR MPC.

During ETAD processing, the AUX ITC calibration information is applied to the range and azimuth correction summation layers, and it is annotated in the ETAD products [RD-15]. Thus, the calibration values as well as any potential future update are completely transparent for the users. The application of the calibration data is straightforward and may be performed by the user to align previously generated ETAD products for a new AUX ITC, see next chapter 4.2. In April 2023, new AUX ITC versions of S-1A and S-1B were generated that include the latest numbers of the performed re-calibration (see Table 2):

S1A_AUX_ITC_V20160627T000000_G20230406T084701/data/s1a-aux-itc.xml

<auxiliarysetap schemaversion="1.6" xsi:nonamespaceschemalocation="/support/s1-aux-itc.xsd"></auxiliarysetap>
<instrumenttimingcalibrationreference></instrumenttimingcalibrationreference>
<rangecalibration unit="s">7.4103e-10</rangecalibration>
<azimuthcalibration unit="s">6.3522e-06</azimuthcalibration>
<instrumenttimingcalibrationoffsetlist count="56"></instrumenttimingcalibrationoffsetlist>
<instrumenttimingcalibrationoffset></instrumenttimingcalibrationoffset>
<swath>S1</swath>
<pre><polarisation>HH</polarisation></pre>
<rangeoffset unit="s">0.0</rangeoffset>
<azimuthoffset unit="s">0.0</azimuthoffset>
<instrumenttimingcalibrationoffset></instrumenttimingcalibrationoffset>
<swath>S1</swath>

² https://sar-mpc.eu/doc/api/



¹ https://sar-mpc.eu/

<auxiliarysetap schemaversion="1.6" xsi:nonamespaceschemalocation="/support/s1-aux-itc.xsd"></auxiliarysetap>
<instrumenttimingcalibrationreference></instrumenttimingcalibrationreference>
<rangecalibration unit="s">-1.2855e-10</rangecalibration>
<azimuthcalibration unit="s">-3.5523e-05</azimuthcalibration>
<instrumenttimingcalibrationoffsetlist count="56"></instrumenttimingcalibrationoffsetlist>
<instrumenttimingcalibrationoffset></instrumenttimingcalibrationoffset>
<instrumenttimingcalibrationoffset></instrumenttimingcalibrationoffset>
<swath>S1</swath>
<pre><polarisation>HH</polarisation></pre>
<rangeoffset unit="s">0.0</rangeoffset>
<azimuthoffset unit="s">0.0</azimuthoffset>
<instrumenttimingcalibrationoffset></instrumenttimingcalibrationoffset>
<swath>S1</swath>

Please note the validity start time of the AUX ITC products. For S-1B, the product is considered valid for the full mission period, whereas for S-1A the validity start date aligns with the recovery of the SAR antenna tile #11 failure which was observed in June 2016 [RD-5]. This failure was found to change the azimuth geolocation behavior of S-1A [RD-6] and a separate calibration will be performed for the earlier data.

Updated AUX ITC versions are ingested into the S-1 ground segment and are accessed by the operational ETAD production service. The first officially distributed ETAD products will be based on the calibration outlined in the document at hand. It is therefore considered the new baseline for any future timing calibration updates. Refinements of the AUX ITC will be published by SAR MPC.

4.2 How to apply the AUX ITC to ETAD

In the ETAD product, the instrument timing calibration information is annotated to the product XML file as well as applied in the NetCDF data file. The NetCDF file contains the actual corrections and is sufficient to make use of ETAD, but for completeness we describe the update for new AUX ITC information in both of the ETAD files.

The ETAD product XML file cross-references the AUX ITC and its data that were used to generate a product [RD-16]. This information may serve as baseline for applying an updated calibration and can be exchanged for the values of a newer AUX ITC, see Table 7. The values can be directly replaced with the information of the AUX ITC data file [RD-1].

The burst-related annotation in the ETAD product XML file summarizes the application of AUX ITC data with regards to the range and azimuth summation layers, see Table 8. The sum of the AUX ITC reference calibration plus the offset value of the respective mode, swath, and polarization channel is already added by the ETAD processor to the sum of correction layers:

- Range: instrumentTimingCalibrationReference/rangeCalibration +
 instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/rangeOffset
- Azimuth: instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/azimuthOffsetList/instrumentTimingCalibrationOffset/azimuthOffset



The two summation layers (one for range and one for azimuth) refer to the co-polarised channel (VV or HH). In order to convert these layers to the cross-polarisation channel, the user has to account for the relative offsets between VV and VH or between HH and HV, for which the information is already computed by the ETAD processor and annotated at burst level (Table 8). This means the polarization-dependent offset in the ETAD XML file is either zero (co-polarization channel) or the difference between the applicable offset values of the AUX ITC [RD-15]:

- Range: instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/rangeOffset[co] instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/rangeOffset[cross]
- Azimuth: instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/rangeOffset[co] instrumentTimingCalibrationOffsetList/instrumentTimingCalibrationOffset/rangeOffset[cross]

ETAD product XML annotation	Description		
/etadProduct/processingInformation/auxInputData/auxSetap /inputProduct	The used AUX ITC product		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingCalibrationReference/rangeCalibration	The range time reference calibration of the AUX ITC		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingCalibrationReference/azimuthCalibration	The azimuth time reference calibration of the AUX ITC		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingOffsetList/	List of AUX ITC offset data as applicable to a given product, i.e., for mode, swath(s) and polarization(s)		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingOffsetList/instrumentTimingCalibrationOffset /swath	Swath of the calibration offset, e.g. IW1		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingOffsetList/instrumentTimingCalibrationOffset /polarisation	Polarisation of the calibration offset, e.g. VV		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingOffsetList/instrumentTimingCalibrationOffset /rangeOffset	Range time offset value of the AUX ITC		
/etadProduct/processingInformation/auxInputData/auxSetap /instrumentTimingOffsetList/instrumentTimingCalibrationOffset /azimuthOffset	Azimuth time offset value of the AUX ITC		

Table 7: Cross-reference of applicable AUX ITC data in the ETAD product XML annotation file.

Table 8: Summary of AUX ITC data in the ETAD product XML annotation file as applied at burst level.

ETAD product XML annotation	Description	
/etadProduct/etadBurstList/etadBurst/gridInformation /polarisationChannels	List of AUX ITC calibration data applied to the range and azimuth summation layers of a given burst	
/etadProduct/etadBurstList/etadBurst/gridInformation /polarisationChannels/relativePolarisationOffsets /referencePolarisation	Marks the reference polarisation for which the AUX ITC data was applied in the ETAD, i.e., the HH or the VV channel.	
	Important: the applied timing calibration consists of the AUX ITC <i>instrumentTimingCalibrationReference</i> + <i>instrumentTimingCalibrationOffset</i> for the given mode / swath / polarization	
/etadProduct/etadBurstList/etadBurst/gridInformation /polarisationChannels/relativePolarisationOffsets/rangeOffset	relative range offset which has to be applied by the user for the given mode / swath / polarisation	
	Important: the range summation layer already contains the calibration of the reference polarisation and thus its	



	offset value is zero; the entry is only non-zero for the cross-polarisation channel.	
/etadProduct/etadBurstList/etadBurst/gridInformation /polarisationChannels/relativePolarisationOffsets/azimuthOffset	relative azimuth offset which has to be applied by the user for the given mode / swath / polarisation	
	Important: the azimuth summation layer already contains the calibration of the reference polarisation and thus its offset value is zero; the entry is only non-zero for the cross-polarisation channel.	

For the ETAD NetCDF, the relevant AUX ITC information is directly annotated to each burst group. Every burst contains the attributes [RD-16]:

- instrumentTimingCalibrationRange
- instrumentTimingCalibrationAzimuth
- rangeOffsetVV (or rangeOffsetHH); always zero
- azimuthOffsetVV (or azimuthOffsetHH); always zero
- rangeOffsetVH (or rangeOffsetHV)
- azimuthOffsetVH (or azimuthOffsetHV)

The numbers rely on the methods as described for the ETAD product XML file (Table 7, Table 8) and can be easily exchanged for the data of the AUX ITC. These calculations are normally performed by the ETAD processor but when there is an update of AUX ITC the user must perform the steps to align the previous products.

ETAD sum of correction layers

In order to update the existing NetCDF summation layers for a new AUX ITC, perform the following steps at the burst level. Please note the correct selection of mode, swath and polarization offsets from AUX ITC as applicable to a given burst, because in principle AUX ITC and ETAD allow for swath- and polarisation-dependent instrument timing calibration:

- (sumOfCorrectionsRg instrumentTimingCalibrationRange)_{NetCDF} + (rangeCalibration + rangeOffset)_{AUX ITC}
- (sumOfCorrectionsAz instrumentTimingCalibrationAzimuth)_{NetCDF} + (azimuthCalibration + azimuthOffset)_{AUX ITC}

If the correction layers shall be applied to the cross-polarisation channel, account for the corresponding calibration offset as provided in the AUX ITC.

Individual ETAD correction layers

When working with individual ETAD correction layers, the new AUX ITC data is simply added to account for the latest instrument timing calibration. Please note the correct selection of mode, swath and polarization offsets from AUX ITC as applicable to a given burst, because in principle AUX ITC and ETAD allow for swath- and polarisation-dependent instrument timing calibration:

- (troposphericCorrectionRg + ionosphericCorrectionRg + ...)_{NetCDF} + (rangeCalibration + rangeOffset)_{AUX ITC}
- (bistaticCorrectionAz + fmMismatchCorrectionAz + ...)_{NetCDF} + (azimuthCalibration + azimuthOffset)_{AUX ITC}

If the correction layers shall be applied to the cross-polarisation channel, account for the corresponding calibration offset as provided in the AUX ITC.

5 Validation of ETAD product performance

Computation of the redefined timing calibration was performed with correction data and methods that are compatible but not identical to the ETAD correction grids, because a generation of ETAD products for all the data used in re-calibration was considered out of scope for this activity. To assess basic ETAD applicability for the updated AUX ITC, a cross-comparison was carried out for a small subset of S-1A and S-1B data of Surat Basin calibration site, i.e., 01/2021 - 04/2021 (S-1A/B) and 02/2022 - 04/2022 (S-1A) and all the 40 CR targets. The numerical results are listed in Table 9.

The ALE analysis of S-1A and S-1B data from Surat Basin site using only the ETAD corrections confirms applicability of the new timing calibration values of AUX ITC in ETAD. The impact on the ALE offsets is in close agreement with the findings of the overall Surat Basin results listed in Table 4: In range the typical ALE is around 4 cm or better, with only small variations in the individual IW sub-swaths. In azimuth the offset for S-1B is considerably reduced, whereas for S-1A there remains a variation in the offsets of the different sub-swaths.

Table 9: ALE computed with S-1A and S-1B IW data of 01/2021 – 04/2021 (both sensors) and of 02/2022 – 04/2022 (only S-1A) acquired at the Surat Basin calibration site hosting 40 CRs. Results with ETAD corrections and the current instrument timing calibration (ITC) and the redefined ITC as listed in Table 1.

	Range ALE [m]		Azimuth ALE [m]	
	Current ITC	Redefined ITC	Current ITC	Redefined ITC
Sentinel-1A	0.029 ± 0.058	-0.029 ± 0.058	-0.092 ± 0.324	-0.137 ± 0.324
IW-1	0.047 ± 0.049	-0.011 ± 0.049	-0.214 ± 0.323	-0.259 ± 0.323
IW-2	0.023 ± 0.047	-0.035 ± 0.047	0.040 ± 0.241	-0.005 ± 0.241
IW-3	0.012 ± 0.076	-0.046 ± 0.076	-0.012 ± 0.344	-0.057 ± 0.344
Sentinel-1B	0.018 ± 0.044	-0.011 ± 0.044	-0.109 ± 0.266	-0.012 ± 0.266
IW-1	0.019 ± 0.045	-0.010 ± 0.045	-0.087 ± 0.284	0.001 ± 0.284
IW-2	0.017 ± 0.043	-0.012 ± 0.043	-0.140 ± 0.236	-0.043 ± 0.236
IW-3	N/A	N/A	N/A	N/A



Appendix A - Additional ALE visualizations

This section contains additional visualizations of ALE validation results discussed in chapter 3.1. The range and azimuth ALE residuals are arranged per target incidence angle and as time series. The colors mark the different IW beams: red = IW1, blue = IW2, green = IW3.



Figure 5: ALE computed with S-1A and S-1B IW data of 10/2016 - 12/2022 acquired at the Surat Basin Calibration site hosting 40 CRs. Range results (a) and azimuth results (b) with regards to target incidence angle applying the current ITC (top) and the redefined ITC (bottom).





Figure 6: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin Calibration site hosting 40 CRs. Range results (a) and azimuth results (b) over time applying the current ITC (top) and the redefined ITC (bottom).





Figure 7: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Range results (a) and azimuth results (b) with regards to target incidence angle applying the current ITC (top) and the redefined ITC (bottom).





(b)

Figure 8: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Range results (a) and azimuth results (b) over time applying the current ITC (top) and the redefined ITC (bottom).





Figure 9: ALE computed with S-1B SM data of 06/2019 – 09/2020 (left) and S-1B IW data of 08/2018 – 12/2021 (right) acquired at the geodetic observatory Yarragadee, hosting 2 CRs. Range results (a) and azimuth results (b) over time applying the current ITC (top) and the redefined ITC (bottom).



Appendix B - List of tables and figures

LIST OF FIGURES

Figure 1: Outlier detection example on behalf of Wettzell Descending CR for data as listed in Table 1. ALE Figure 2: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin calibration site hosting 40 CRs. Results with the current ITC (top) and the redefined ITC (bottom).14 Figure 3: ALE computed with S-1A and S-1B IW data of 10/2016 - 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Results with the current ITC (top) and the redefined ITC (bottom)......15 Figure 4: ALE computed with S-1B SM data of 06/2019 – 09/2020 (left) and S-1B IW data of 08/2018 - 12/2021 (right) acquired at the geodetic observatory Yarragadee, hosting 2 CRs. Results with the Figure 5: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin Calibration site hosting 40 CRs. Range results (a) and azimuth results (b) with regards to target incidence angle applying the current ITC (top) and the redefined ITC (bottom)......22 Figure 6: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin Calibration site hosting 40 CRs. Range results (a) and azimuth results (b) over time applying the current Figure 7: ALE computed with S-1A and S-1B IW data of 10/2016 - 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Range results (a) and azimuth results (b) with regards to target incidence angle applying the current ITC (top) and the redefined ITC Figure 8: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the geodetic observatories Metsähovi, Wettzell, and Côte d'Azur, hosting in total 4 CRs. Range results (a) and azimuth Figure 9: ALE computed with S-1B SM data of 06/2019 – 09/2020 (left) and S-1B IW data of 08/2018 - 12/2021 (right) acquired at the geodetic observatory Yarragadee, hosting 2 CRs. Range results (a) and azimuth results (b) over time applying the current ITC (top) and the redefined ITC (bottom)......26

LIST OF TABLES

Table 1: Sentinel-1 sites and SAR data between 10/2016 - 12/2021 used for the instrument timing recalibration. All refers to the acquisitions with an SCR of larger than 15 dB. Cleaned refers to the usable acquisitions after applying a MAD outlier detection, see details in text. Note that Wettzell 1 IW2 and Wettzell 2 IW2 are located in a burst-overlap area and are measured twice per pass, doubling the data rate......7 Table 2: Redefined S-1A and S-1B instrument timing calibration estimated by least-squares methods from 5.5 years of data of 8 CR targets located at 4 calibration sites. Result values in units of seconds and converted numbers in units of meters. The precision numbers mark the 95% confidence level as provided Table 3: Comparison of S-1A and S-1B instrument timing calibration values in units of seconds and corresponding numbers in units of meters. The current ITC is based on 3 years of data and at Metsähovi calibration site, whereas the redefined ITC makes use of 5.5 years of data and 8 CR targets located at 4 Table 4: ALE computed with S-1A and S-1B IW data of 10/2016 – 12/2022 acquired at the Surat Basin calibration site hosting 40 CRs. Results with the current instrument timing calibration (ITC) and the redefined ITC as listed in Table 1......11



