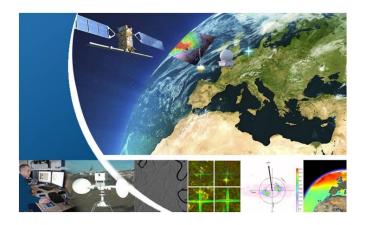






Adjustment of vTEC Scaling Factor for S-1 Orbit Altitude



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SHORT SUMMARY

This document presents the usage of a new overall TEC scaling factor for S-1 mission using up to 10 years of S-1 geolocation time series data over stable reference calibration sites. This technical note elaborates on the data adjustment performed and its validation results. We compare model-driven ionospheric bottom-side scaling factors, which are based on the three-dimensional electron model NEDM2020.



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1 Introduction

1.1 Background/Context

The ionization of Earth's upper atmosphere by particles of the solar wind and solar radiation is a known major source for data disturbance with Synthetic Aperture Radar (SAR) satellites, typically operating in the micro-wave regime between 1.2 GHz (L-band) and 9.5 GHz (X-band). Dominated by the approximately 11-years solar cycle, the impact of ionosphere dynamics on SAR satellites spans from minor degradation of precise orbit solutions to frequency-dependent path delays in the radar measurements. This causes significant errors of up to several meters when geolocating SAR image data, as well as errors in interferometric SAR processing [RD-1][RD-2][RD-3][RD-4].

The vertical Total Electron Content (vTEC) maps generated from Global Navigation Satellite System (GNSS) measurements of global geodetic station networks, see e.g. [RD-5], are a well-established data source for observing and modelling ionospheric delay effects in a wide range of applications, including the SAR. However, because the GNSS-based vTEC maps provide the total integrated effect of the entire ionosphere condensed into a thin spherical layer, additional considerations are required for the SAR satellites still operating within the upper layers of the ionosphere, which extends to approximately 1500 km above the Earth's surface. Consequently, total vTEC data has to be reduced to the relevant subsatellite vTEC part in order to reliably correct the SAR measurements.

For the Sentinel-1 (S-1) mission, operating a C-band SAR payload with 5.405 GHz center frequency and orbiting at an average 712 km altitude, we originally derived and tested a fixed scaling factor of 0.9 [RD-6], implying that 90 percent of a given total vTEC result are applicable to the SAR measurements. This method was sufficient to achieve a range geolocation accuracy with S-1 of better than 4 cm after calibrating the sensor timing offsets [RD-7].

However, with the onset of latest solar cycle #25 in 2022, we began to observe low cm-level systematic effects in our assessment of S-1 data geolocation quality with globally distributed test sites, which is performed on a regular basis within the framework of S-1 SAR Mission Performance Cluster (SAR-MPC) [RD-8][RD-9]. The systematic effects were attributed to limitations in the applied fixed scaling factor.

These systematic effects also impact the S-1 Extended Timing Annotation Dataset (ETAD), a supportive correction data product generated in S-1 ground segment for each SLC product with the exception of wave-mode data [RD-10]. Publicly disseminated since mid-2023, the product provides corrections for atmospheric path delays, for solid Earth deformation signals, and for the systematic effects in S-1 image generation, in order to improve the timing / localization accuracy of S-1 level 1 data. ETAD relies on the same TEC-map-based methods and a fixed scaling factor to compute ionospheric delay corrections [RD-11], and is impacted by the same limitation of having the factor set to 0.9 [RD-9]. Therefore, we decided to calibrate a new overall TEC scaling factor for S-1 mission using up to 10 years of S-1 geolocation time series data over stable reference calibration sites.

This technical note elaborates on the data adjustment performed and its validation results. We compare model-driven ionospheric bottom-side scaling factors, which are based on the three-dimensional electron model NEDM2020 [RD-12], with the newly determined empirical factor, showing that the latter attains more consistent long-term results with the S-1 SAR data. Moreover, we discuss implications of having introduced this updated factor to operational ETAD product generation in the S-1 ground segment, which took place in June 2025 with ETAD processor update version 3.0 and its corresponding auxiliary configuration product (AUX SCF) [RD-13].



It is important to note that S-1A ETAD products prior to processor version 3.0 will not be re-aligned for the changed TEC scaling factor. Users have to rescale the ionospheric path delay layer and the sum-of-range-corrections layer to avoid discontinuities in S-1 data time series. The applied TEC scaling factor is annotated to each ETAD product. This embedded scaling information makes it straightforward to align the ETAD products as required. Details on the necessary steps are described in chapter 5.2.

1.2 Purpose of this document

The ETAD product for S-1 is described in [RD-10]. The need for improving the TEC scaling factor underlying the ionospheric path delay correction provided with ETAD is discussed in the latest annual report of S-1 mission [RD-9].

The purpose of this technical note is to provide the S-1 users with background information on the updated TEC scaling factor, i.e., how it was determined and validated. Long-term geolocation results are shown and comparisons are made with results applying alternative scaling factors obtained from the physical model NEDM2020. Moreover, the document describes the updates performed in operational ETAD product generation, and how users have to modify the pre-v3.0 ETAD products to align existing data time series.

This document is organized as follows:

- Section 1: This introduction
- Section 2: Brief summary of the ionosphere and correction methods for SAR data, and an analysis of TEC scaling factor dynamics based on the NEDM2020 model
- Section 3: The method of computing instrument timing calibration and TEC scaling factor from SAR data, and computational results obtained for the S-1 mission
- Section 4: Geolocation validation results with the updated TEC scaling factor and comparison with results applying dynamic TEC scaling factors derived from NEDM2020.
- Section 5: Description of updated SETAP auxiliary product that provides the TEC scaling factor and instructions on how to align the already existing ETAD products
- Section 6: Validation results for a set of ETAD products that make use of the updated TEC scaling factor
- Appendix: Supplementary plots of the performed validation

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1.4 Acronyms and definition

ALE Absolute Location Error

AUX Auxiliary

CLS Collecte Localisation Satellites

CODE Center for Orbit Determination in Europe

CR Corner Reflector

DLR German Aerospace Center

ECMWF European Centre for Medium-Range Weather Forecast

ETAD Extended Timing Annotation Dataset

GIM Global Ionospheric Map

GNSS Global Navigation Satellite System

IGS International GNSS Service

INTA National Institute for Aerospace Technology

IOC In-orbit Commissioning

ITC Instrument Timing Calibration

IW Interferometric Wide (Sentinel-1 SAR mode)

JPL Jet Propulsion Laboratory

MAD Median absolute deviation

MPC Mission Performance Cluster

NEDM2020 Neustrelitz Electron Density Model 2020

RMS Root Mean Square
S-1 Sentinel-1 mission
S-1A Sentinel-1A satellite
S-1B Sentinel-1B satellite
S-1C Sentinel-1C satellite
SAR Synthetic Aperture Radar

SCR Signal-to-Clutter Ratio

SETAP Sentinel-1 Extended Timing Annotation Processor

TEC Total Electron Content

TECU TEC Unit

VCE Variance Component Estimation
vTEC vertical Total Electron Content
XML Extensible Markup Language



2 Considerations on S-1 Ionospheric Delay Correction

2.1 Brief introduction on Earth's lonosphere and Modelling

The ionosphere ranges from about 50 to 1500 km altitude and contains free electrons and charged particles, which cause disturbances in microwave signals. This ionization of the upper part of Earth's atmosphere is driven by solar radiation. The rate of ionization at a given location follows daily and seasonal patterns, as well as long-term solar activity cycles like the 11.5 year cycle. The ionospheric patterns usually show a maximum concentration at around 14:00 local solar time and an alignment with Earth's geomagnetic equator, while the peak concentration of particles typically oscillates between 300 km to 500 km altitude, following daily variations [RD-14].

A well-established method for observing and modelling the global ionospheric conditions is systematic analysis of GNSS data. Global ionospheric maps derived from GNSS observations of the global International GNSS Service (IGS) network describe the ionosphere as vertical Total Electron Content (vTEC) condensed to a global spherical layer, which is situated at a fixed assumed peak concentration height [RD-5]. Examples of TEC maps during different ionospheric conditions are shown in Figure 1. The data are given in TEC units (1 TECU = 10^{16} electrons/m²) and 1 TECU is equivalent to approximately 0.02m of slant path delay in Sentinel-1 C-band.

Another method to compensate for ionospheric disturbance in radio measurements are the partly physics-driven models such as GPS Klobuchar, Galileo NeQuick or BeiDou BDGIM, which can successfully mitigate about 50- 80% propagation delay for GNSS based positioning and navigation applications [RD-15]. Overall, these models are not considered an ideal choice when aiming for accurate SAR data corrections as their primary purpose is real-time GNSS positioning improvement.

There are also several physical ionosphere models, for example the International Reference Ionosphere model (IRI, [RD-16]) or the Neustrelitz Electron Density Model (NEDM2020, [RD-12]). Their aim is to model the complex physical characteristics of the ionosphere in 3-D space and time. In principle, they can output the relevant electron content applicable to a satellite orbiting within the ionosphere, but comparison studies show that the performance of the ionosphere models is, in most cases, better during quiet ionospheric and geomagnetic conditions, while during geomagnetic storms the performance gets worse independent of model selection [RD-12]. Generally, whilst they accurately show the effect of varying input conditions, it is still challenging to provide accurate absolute values of the ionospheric parameters unless one has an accurate starting point for the modelling.

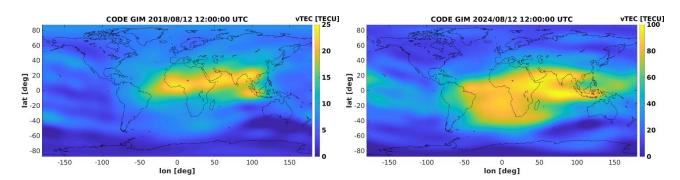


Figure 1: TEC map examples from CODE analysis center, showing global distribution of vertically integrated electron content at 12:00 UTC for solar quiet conditions (left) and for solar active conditions (right). Note the TECU scale which is four times larger during the active conditions. $1 \text{ TECU} = 10^{16} \text{ electrons/m}^2$.



Finally, there are the methods inherent to SAR data that can retrieve a high-resolution differential ionosphere result from repeat pass SAR images. The methods rely on the ionosphere's dispersive properties and partitioning of SAR signal bandwidth [RD-17]. Practical demonstration have been performed, see e.g. [RD-17][RD-18], but achieving reliable and wide-spread operational usage is still ongoing research. Moreover, the ionospheric compensation of single scene SAR data and the correction product of ETAD require an absolute ionospheric path delay, which has not yet been reliably retrieved with the SAR-data driven methods.

Considering the limitations of GNSS-related broadcast models and of physics driven models, as well as the current status of SAR data-driven methods, using the TEC maps is still considered the best option for absolute SAR data correction of S-1. Therefore, we concentrated on improving the usage of global ionospheric maps for S-1, which are the most consistent data source on ionospheric disturbance and are also used in operational ETAD products [RD-13].

Global TEC maps are available from different analysis centers contributing to the IGS, for instance CODE, UPC, JPL, or ESA [RD-5]. Most centers provide GIMs with a temporal resolution of 1 hour. For most of these GIMs, the spatial resolution is 2.5 degrees in latitude and 5 degrees in longitude. Consequently, they have only moderate spatial resolution and the grid spacing at the equatorial regions is larger than 500 km. For the ETAD, the products of CODE have been selected as baseline data. The products have a daily coverage of 00h to 24h and a temporal spacing of 1h. Each map is provided with its associated RMS map [RD-19].

lonospheric maps generated from ground station GNSS data provide the entire TEC up to GNSS orbit height of approximately 20,000km. Making use of the data in SAR applications therefore requires subtraction of the ionosphere part that lies above the radar satellite. Solutions to this problem have been discussed and investigated by the SAR community, which involve fixed scaling factors linked to SAR satellite orbit height, or scaling factors derived from series of SAR measurements, or accounting for an in-situ top-side vTEC observed by the GNSS receiver aboard the satellite [RD-4][RD-20].

After investigating spatio-temporal dynamics of the TEC scaling factor (see section 2.2) and performing a comparison to the more straightforward method of applying fixed scaling factor, we find that a fixed scaling factor is still adequate when considering present S-1 data quality (see section 4).

2.2 Impact and dynamics of bottom-side TEC Scaling Factor

The simplest solution is to reduce the TEC map data by a fixed percentage of 70% to 90%, equivalent to a bottom-side ratio of 0.7 to 0.9, depending on the SAR satellite orbit height. For S-1 orbiting at about 700 km altitude, this ratio has originally been set to 0.9 [RD-6]. The sensitivity of ionospheric path delays to different scaling factors is demonstrated by the time series given in Figure 2, showing a worst-case scenario of S-1 data acquired at an equatorial location. Assuming a continuous 6 day repeat pass time series of ascending and descending data at 0 degree latitude and 100 degrees longitude, i.e., Sumatra in Indonesia, the ionospheric slant path delay for each acquisition was computed from the CODE TEC maps according to ETAD methods [RD-11].

As expected, the impact of the TEC scaling factor is much more pronounced in S-1 late afternoon ascending data, for which the TEC levels can remain very high, see Table 1. Applying different scaling factors causes systematic differences of up to 0.25m during periods of high solar activity. Thus, even small deviations from the presently applied fixed factor of 0.9 could account for the systematic errors that were reported for the S-1 geolocation results of 2023 and 2024, which have been obtained at the Surat Basin calibration site located in Australia at 27 degree southern latitude [RD-8][RD-9].



Table 1: Average ionospheric path delay results computed from CODE TEC maps for S-1 data acquired at Sumatra, Indonesia (O degree latitude, 100 degrees longitude). Regular 6-day repeat pass series of ascending and descending data stacks are assumed for S-1 mission timeline, see Figure 2. Results show the impact of different TEC scaling factors α on ionospheric path delays in ascending and descending data during periods of low and high solar activity.

Pass	Period	Solar Activity Average Path Delay		Path Delay	Δ
			$\alpha = 0.9$	$\alpha = 0.7$	
Ascending	10/2016 10/2021	low	0.337 m	0.262 m	0.075 m
Descending 10/	10/2016 - 10/2021	low	0.068 m	0.053 m	0.015 m
Ascending	10/2021 00/2025	high	1.084 m	0.843 m	0.241 m
Descending	10/2021 - 09/2025	high	0.211 m	0.164 m	0.047 m

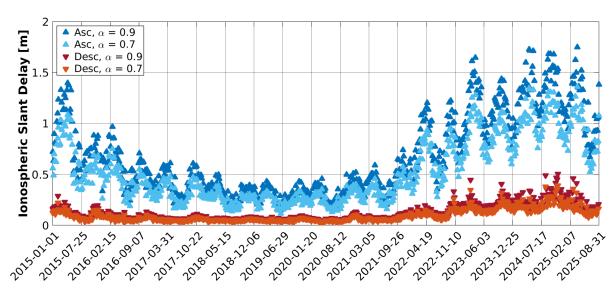


Figure 2: Ionospheric path delay results computed from CODE TEC maps for S-1 data acquired at Sumatra, Indonesia (0 degree latitude, 100 degrees longitude), applying different TEC scaling factors. Processing is based on existing stacks (one ascending stack, one descending stack), but regular 6-day repeat pass series were assumed for the entire S-1 mission timeline.

In reality, the shape of the ionospheric electron density profile varies during day, night, seasons, and solar activity and geomagnetic condition, as well geographic location, meaning that the ratio between bottom side and total ionosphere is equally variable. Possible modifications to a fixed ratio were investigated in a S-1 ETAD scientific evolution study, employing the 3-D ionospheric model NEDM2020 [RD-12]. Based on NEDM2020, we studied the dynamics of vTEC ratio between S-1 and GNSS altitude, i.e., TEC700km versus TEC20,000km.

The daily variation of the scale factor is shown in Figure 3 for January 1st, assuming quiet solar conditions. There is a strong variation between day-time and night-time hours, especially at lower latitudes where most of the ionization is taking place. Above 45 degrees latitude, daily variations tend to become more stable. For the sun-synchronous dusk-dawn orbit configuration used by Sentinel-1 mission, the important results are around 6:00 local time (descending passes) and 18:00 local time (ascending passes) because these local passing times stay fixed for any given location. The daily dynamics can therefore be safely neglected for S-1 and we restricted the analysis of other parameters to these particular local times.

The impact of solar activity can be shown in NEDM2020 by varying the F10.7 flux numbers, as shown Figure 4. Values between 60 and 220 flux units define a typical dynamic range of solar activity [RD-21]. For moderate and high solar activity, we find only small changes in the TEC scaling factors for both the ascending and descending passes. Low solar activity causes some variation which are more pronounced around 6:00 local time, i.e., the descending passes. Overall, the model suggests only a minor dependency of the S-1 TEC scaling factors on solar activity levels.

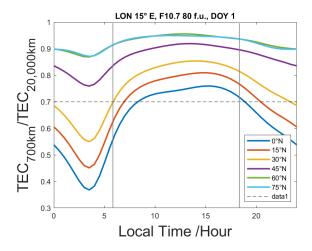


Figure 3: Daily variation of bottom-side TEC scale across different latitudes for the Sentinel-1 orbit height of 700km. Results from NEDM2020 model for January 1st, assuming a low solar activity of F10.7 = 80 flux units. Vertical lines mark the average S-1 passing times at 6h and 18h local time.

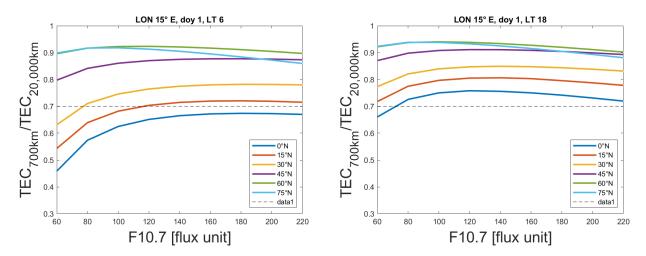


Figure 4: Variation of bottom-side TEC scale over solar activity defined by F10.7 flux numbers across different latitudes for the Sentinel-1 orbit height of 700km. Results from NEDM2020 for January 1st, showing 6h local time (left) and 18h local time (right).

Finally, we also investigated the impact of seasonal changes in the ionization on the scaling factor which is shown in Figure 5. There is a clear seasonality for the TEC scaling factors between the equator and the mid-latitudes for both analysis times. Depending on the geographic position, the values may deviate substantially from the factor of 0.9 currently used in ETAD generation, especially for 6:00 local time.

In summary, our analysis performed with NEDM2020 suggests that the TEC scaling factor at Sentinel-1 orbit height is primarily driven by the geographic position (latitude) and the seasonal variation of the ionization. The long-term solar activity cycle has only a minor impact on the scaling factor, because its effect is only noticed during low activity periods. Daily variations are large, undergoing significant changes at night time hours, but this effect is not considered relevant for S-1 due to its sun-synchronous dusk-dawn orbit. The associated descending and ascending passing times of S-1 always remain around 6:00 and 18:00 local time, respectively

To test applicability of dynamic NEDM2020-based TEC scaling factors for S-1 data, we converted the results into two look-up-tables (LUTs), one for 6:00 and one for 18:00 local time, which can be queried for: day of year, solar activity (F10.7 flux number), and geographic position (latitude and longitude). The flux number applicable to a given date was taken from the Solar Radio Monitoring Program operated by the National Research Council and Natural Resources Canada [RD-22].



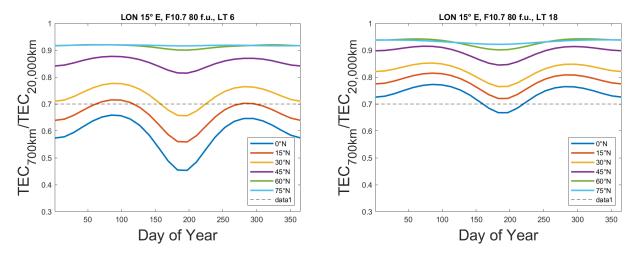


Figure 5: Seasonal variation of bottom-side TEC scale across different latitudes for the Sentinel-1 orbit height of 700km. Results from NEDM2020 for low solar activity of F10.7 = 80 flux units, showing 6h local time (left) and 18h local time (right).

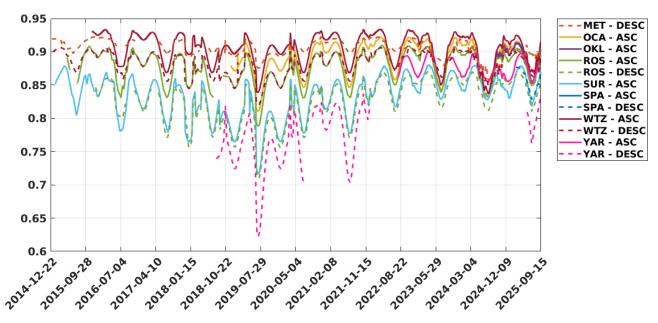


Figure 6: Dynamic bottom-side TEC scaling factors derived from NEDM2020 ionospheric model for the geolocation time series of S-1 data at different SAR calibration sites, see chapter 4.

For the global set of test sites used to verify S-1 geolocation performance, the dynamic modelling of the TEC scaling factor predicts values between 0.85 and 0.9 for most of the sites, see Figure 6. Details on the used sites and the actual geolocation results are presented in chapter 4. As expected, the dominating variation in the TEC scaling factors stems from the seasonal signal. There is also the moderate long-term signal caused by the solar activity cycle. For sites located closer to the equator, i.e., Surat Basin, Rosamond and Yarragadee, we find scaling factors as low as 0.65 during the solar minimum conditions of 2019, which is the largest deviation from the initially set fixed factor of 0.9. Overall, these NEDM2020 scaling factor results are still in good agreement with our initially chosen fixed factor, but this also means such dynamic scaling factors can only provide minor improvements for the systematic errors found in the geolocation results, see chapter 4. Because of these findings, we decided to calibrate and test a new overall TEC scaling factor which shall be based on data of S-1 mission.



3 Adjustment of S-1 Parameters from Geolocation Data

3.1 Estimating the TEC Scaling Factor and Instrument Timing Calibration

Our method of obtaining a S-1-tailored TEC scaling factor is based on solving the SAR range-Doppler equations in zero-Doppler configuration, which was already used to derive refined instrument timing calibration values for S-1A and S-1B [RD-7]. Relying on the assumption that a common set of parameters is involved in each measurement of known corner reflector (CR) reference targets, we can formulate an optimization problem that aggregates all our S-1 data of suitable calibration sites.

Given the range and azimuth radar timings (τ, t) of a point target, which can be extracted from complex SAR images by point target analysis [RD-6]. With these timings, we may define the range-Doppler equations, considering timing calibration offsets and a TEC scaling factor:

$$f_{Range}(\boldsymbol{X}_{\boldsymbol{s}}(t,\Delta t_{cal}),\boldsymbol{X}_{\boldsymbol{T}},\tau,\Delta \tau_{cal},\alpha): \qquad |\boldsymbol{X}_{\boldsymbol{s}}(t,\Delta t_{cal})-\boldsymbol{X}_{\boldsymbol{T}}| - \dots$$

$$\frac{c}{2} \cdot \left(\tau - \Delta \tau_{cal} - \Delta \tau_{ion,tot} \cdot \alpha\right) = 0$$

$$f_{Azimuth}(\boldsymbol{X}_{\boldsymbol{s}}(t,\Delta t_{cal}),\dot{\boldsymbol{X}}_{\boldsymbol{s}}(t,\Delta t_{cal}),\boldsymbol{X}_{\boldsymbol{T}}): \qquad \frac{\boldsymbol{X}_{\boldsymbol{s}}(t-\Delta t_{cal})\cdot(\boldsymbol{X}_{\boldsymbol{T}}-\boldsymbol{X}_{\boldsymbol{s}}(t-\Delta t_{cal}))}{|\boldsymbol{X}_{\boldsymbol{s}}(t-\Delta t_{cal})|\cdot|\boldsymbol{X}_{\boldsymbol{T}}-\boldsymbol{X}_{\boldsymbol{s}}(t-\Delta t_{cal})|} = 0$$
Eq. 1

where X_s , \dot{X}_s are the satellite orbit position and velocity vectors, X_T is the target position vector, (τ,t) are the measured radar timings of range and azimuth, and $(\Delta \tau_{cal}, \ \Delta t_{cal})$ are the respective timing calibration constants. The c denotes the speed of light in vacuum, and $\Delta \tau_{ion,tot}$ is the slant range delay due to the total ionosphere, which is scaled by α for the part applicable to S-1 SAR data. The ionospheric path delay is modelled from the vertical TEC, which is interpolated for time and location of the SAR measurements within the given GNSS-based global ionospheric maps:

$$\Delta au_{ion} = \Delta au_{ion,tot} \cdot lpha$$
 Eq. 2

with M defining the mapping function of vertical to slant TEC conversion, and f_{S1} is the nominal S-1 radar frequency. For more details on our ionospheric delay calculation method, we refer to chapter 6.2 of the ETAD algorithm baseline document [RD-11].

Deriving a solution of Eq. 1 by means of least-squares-methods requires a more generalized approach, also known as adjustment of conditions with additional parameters [RD-23]. Assuming radar timings (τ, t) of i targets obtained by j sensors, we can linearize Eq. 1 for the SAR measurements and the free parameters, and arrange the problem to the basic scheme of $B \cdot v + A \cdot x + w = 0$:

$$\begin{bmatrix} \frac{\partial f_{R,i,j}}{\partial \tau, i,j} & \frac{\partial f_{R,i,j}}{\partial t, i,j} & 0 & \cdots \\ \frac{\partial f_{A,i,j}}{\partial \tau, i,j} & \frac{\partial f_{A,i,j}}{\partial t, i,j} & 0 & \cdots \\ 0 & 0 & \ddots & \ddots \\ \vdots & \vdots & \ddots & \ddots \end{bmatrix} \cdot \begin{bmatrix} d\tau_{i,j} \\ dt_{i,j} \\ \vdots \\ d\tau_{i,j} \end{bmatrix} + \begin{bmatrix} \frac{\partial f_{R,i,j}}{\partial \Delta \tau_{cal,j}} & \frac{\partial f_{R,i,j}}{\partial \Delta \tau_{cal,j}} & 0 & \cdots & \Delta \tau_{ion,tot,i,j} \\ \frac{\partial f_{A,i,j}}{\partial \Delta \tau_{cal,j}} & \frac{\partial f_{A,i,j}}{\partial \Delta \tau_{cal,j}} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \end{bmatrix} \cdot \begin{bmatrix} d\Delta \tau_{cal,j} \\ d\Delta t_{cal,j} \\ \vdots \\ d\alpha \end{bmatrix} + \\ \vdots \\ d\alpha \end{bmatrix} + \\ \vdots \\ W_{f_{A,i,j}} \end{bmatrix} = \mathbf{0}$$
Eq. 3



The first part $B \cdot v$ contains the linearization of all the i = 1, n radar timing measurements of known targets provided by SAR images of the sensors j = 1, m. The second part $A \cdot x$ contains the linearization of the timing calibration constants $(\Delta \tau, \Delta t)$ of each sensor j, and the common TEC scaling factor α . The final part w denotes the overall discrepancies of each measurement equation.

The goal is to resolve discrepancies \boldsymbol{w} by minimizing the timing measurement residuals \boldsymbol{v} under the L2-norm and by estimating the free parameters \boldsymbol{x} at the same time. For the partial derivatives of the Jacobians and the solution of the system, please refer to [RD-24]. As it is shown in our publication, the problem ultimately can be converted into a standard case of non-linear least-squares parameter estimation, which is solved iteratively until the parameters have converged to stable results. To initialize the solution process, we set the calibration constants to zero, and the TEC scaling factor to 1.

For the given case of S-1 mission analysis, we use all three sensors S-1A/B/C, and data from 11 reference targets spanning up to 8.5 years (see next chapter 3.2). This yields some 11386 measurement equations, i.e., the dimension of $\bf \it B$ is 11386 x 11386. This system can be reliably solved for the 7 free parameters, i.e., the dimension of $\bf \it A$ is 11386 x 7: the 2 x 3 timing calibration constants of S-1A/B/C and the TEC scaling factor.

To account for possible SAR data quality variation between the different targets and sensors, Variance Component Estimation (VCE) is applied for the range and azimuth data of each calibration target and sensor [RD-25]. The data quality may vary due to different CR sizes, variations in background clutter, or residual errors of atmospheric path delays. In other words, the VCE ensures an optimal estimation of the scaling factor and calibration constants while balancing non-homogenous data quality.

3.2 Summary of Input Data

Our processing applies S-1A, S-1B and S1-C IW data of the period 10/2016 to 04/2025 as available by the different sensors, i.e., S-1B data terminates by the end of 2021 while S-1C data start in 2025 with the in-orbit commissioning (IOC). Moreover, the final precise orbit solution was used which has a nominal accuracy of 5 cm but the distributed daily products are considered to be even more accurate [RD-26].

In order to involve globally distributed data of all three sensors, as well as various ascending and descending configurations that sample the IW-swath incidence angles, a set of well-established SAR calibration sites is used:

- Wettzell geodetic observatory, Germany, [RD-24]: 2 CRs (1.5m), 3 IW beams
- Metsähovi geodetic observatory, Finland [RD-24]: 1 CR (1.5m), 2 IW beams
- Côte d'Azur geodetic observatory, France (since Dec 2018) [RD-27]: 1 CR (1.44m), 2 IW beams
- Yarragadee geodetic observatory, Australia (since Aug 2018) [RD-28]: 1 CR from the 2 CRs (1.5m), 1 IW beam
- Surrat Basin SAR calibration site, Australia [RD-29]: selection of 4 CRs from the 40 CRs (1.5m or larger) to provide swath coverage, 2 IW beams
- Rosamond calibration site, United States [RD-30]: selection of 2 CRs from the 28 CRs (2.44m or 4.8m), 3 IW beams

The positions of all the targets are known from terrestrial survey with an accuracy of 5 cm or better. In case of the geodetic observatory sites, the coordinate accuracy is at the millimeter level. Table 2 summarizes the number of usable products per sensor, site, and configuration.

The processing is based on the DLR geometric calibration/validation tool chain which is documented in [RD-6][RD-24]. The data correction methods are identical to ETAD algorithms and products [RD-11], with the exception of:

Table 2: Sentinel-1 sites and SAR data between 10/2016 – 04/2025 used for determining the TEC scaling factor and instrument timing calibrations. The "All" columns refer to the acquisitions with an SCR of larger than 16 dB. The "Cleaned" columns refer 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. Rosamond 05 is located in a swath-overlap, yielding two beam measurements per pass.

Site			IW	IW Inc. beam Angle [°]	S-1	_A [#]	S-1	B [#]	S-1	C [#]	
	[°] size [m]	beam	All		Cleaned	All	Cleaned	All	Cleaned		
Metsähovi	60.2	1.50	Desc.	IW 1	34	180	173	73	70	6	5
				IW 2	41	181	169	72	62	5	5
Wettzell 1	49.1	1.50	Asc.	IW 2	40	476	463	264	257	n/a	n/a
Wettzell 2	49.1	1.50	Desc.	IW 1	31	239	234	135	133	1	1
				IW 2	41	475	450	298	291	6	6
Côte d'Azur	43.8	1.44	Asc.	IW 1	34	187	174	86	86	4	3
				IW 3	44	224	214	135	131	9	6
Yarragadee	-29.0	1.50	ASC	IW 3	42	63	60	n/a	n/a	4	3
Surat 03	-27.1	2.50	Asc.	IW 2	39	243	223	143	135	4	2
Surat 14	-27.4	2.50	Asc.	IW 2	37	244	219	143	134	4	4
Surat 26	-27.3	1.50	Asc.	IW 1	34	244	218	143	136	4	4
				IW 3	45	178	166	n/a	n/a	6	6
Surat 32	-27.4	1.50	Asc.	IW 1	32	244	221	143	130	4	3
				IW 3	44	178	174	n/a	n/a	6	4
Rosa 05	34.8	2.44	Asc.	IW 1	37	188	180	130	127	2	1
				IW 2	37	188	180	130	126	2	2
Rosa 27	34.8	4.80	Desc.	IW 2	41	244	233	72	68	1	1
Total						3976	3751	1967	1886	68	56

- The usage of Vienna Mapping Function data, version 3 [RD-31], to compute the tropospheric delay correction [RD-32]. Procurement of ECMWF data to use the ETAD tropospheric computation was not feasible for this analysis, given the amount of involved S-1 SAR data.
- Consideration of all solid Earth deformation correction, i.e., the solid Earth tides, the ocean tidal loading, the pole tides, atmospheric tidal loading, and ocean pole tide loading [RD-6][RD-33].

Data cleaning was performed to ensure that outliers are removed before computing the TEC scaling factor and the calibration constants for each sensor:

- Outlier detection per site and beam removing data with a signal-to-clutter ratio (SCR) of less than 16 dB. This detection is already performed as a part of the point target analysis. Therefore, the data summarized in Table 2 ("All" columns) only lists image data with clear CR signatures.
- Outlier detection per site and beam, analyzing the residuals of an initially computed raw Absolute Location Error (ALE) result. The detection applies the median absolute deviation (MAD) method with a cut-off criterium of 2.5 [RD-34]. For this ALE processing we solve equation (3) but without defining any free parameters x, which are simply set to a-priori values. This yields range and azimuth residuals that can be checked for potential outliers. The data remaining after outlier detection is summarized in Table 2 ("Cleaned" columns).



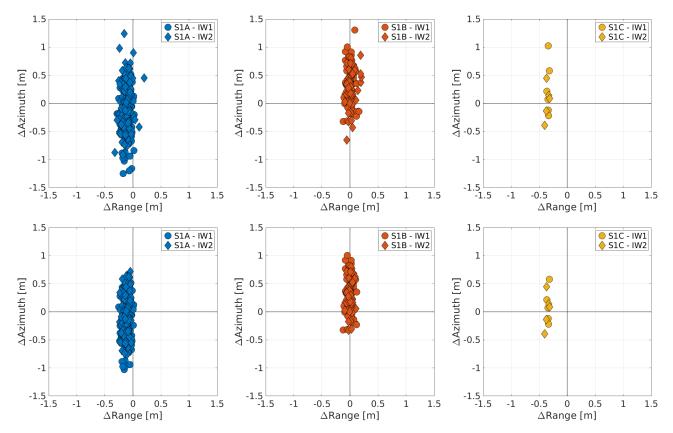


Figure 7: Outlier detection example on behalf of Metsähovi Descending CR for data as listed in Table 2. Uncalibrated ALE residuals of S-1A/B/C before applying the MAD outlier detection (top) and after applying the detection (bottom).

An example of raw ALE results before and after applying MAD outlier detection is shown in Figure 7. Overall, 6% of data was rejected for S-1A, 4% of data was rejected for S-1B, and 18% of data was rejected for S-1C. The relatively large percentage of eliminated S-1C data is due to the overall low amount of data, which makes statistical testing less reliable and eliminating 1-2 scenes already causes large changes in the relative percentage numbers of a site. Moreover, one should keep in mind that the goal for S-1C was an early IOC instrument calibration, which can be refined at a later stage if need arises.

3.3 Results and Discussion

The TEC scaling factor results and the timing calibrations obtained for S-1A/B/C are summarized in Table 3. The confidence intervals of the estimated parameters provided by the least-squares result are listed as well. This section only discusses the obtained results. Validation results are presented in chapter 4.

Based on the selected ranging data of S-1 mission, we find the best fitting TEC scaling factor of 0.78. The estimated precision is on the order of ± 0.01 , which indicates a reliable fixed factor result applicable to all data across the different sites. Interestingly, this TEC scaling factor is notably lower than the results of 0.8 to 0.9 predicted by NEDM2020 for the involved sites, see Figure 4. According to the model, the value of 0.78 obtained from S-1 data is more in line with the ionosphere conditions predicted at the low latitudes rather than the mid- to high-latitude ionosphere conditions of the calibration sites. The reason for this is not fully understood. There could be additional limitations in the ionospheric modelling of GIMs, for instance the vertical-to-slant-range mapping, or other yet unknown systematic effects of S-1 mission, which are better compensated for by this lower TEC scaling factor. Nevertheless, we think the result of 0.78 is still within a plausible numerical range, also because a similar factor of 0.76 has been reported for the ALOS-2 L-Band SAR satellite, which uses a slightly lower orbit height of 630 km [RD-20].



Table 3: Bottom-side TEC scaling factor and S-1A/B/C instrument timing calibration values estimated by least-squares methods from up to 8.5 years of IW data of 10 CR targets located at 5 calibration sites. Instrument timing values computed in units of seconds were converted to numbers in units of meters to help interpretation. The precision numbers mark the 95% confidence levels as provided by the least-squares solution.

Sensor	α	Δτ _{cal} [s, 2-way]	Δt _{cal} [s]	Rg [m, 1-way]	Az [m]
S-1A		$7.0771e^{-10} \pm 2.4897e^{-11}$	6.3208e ⁻⁶ ± 9.8439e ⁻⁷	0.1061 ± 0.0037	0.0430 ± 0.0067
S-1B	$0.78 \pm 1e^{-2}$	-1.2209e ⁻¹⁰ ± 2.1485e ⁻¹¹	-3.1978e ⁻⁵ ± 1.3352e ⁻⁶	-0.0183 ± 0.0032	-0.2175 ± 0.0091
S-1C		2.2916e ⁻¹⁰ ± 8.7259e ⁻¹¹	-1.9685e ⁻⁵ ± 6.3372e ⁻⁶	0.3435 ± 0.0131	-0.1339 ± 0.0431

Table 4: Comparison of S-1A and S-1B instrument timing calibration values in units of seconds and corresponding numbers in units of meters. Recomputed ITC results of Table 3 versus the AUX ITC values currently used in ETAD processing [RD-7].

Sensor		Recompute	ed ITC			Curren	t ITC	
	Δτ [s]	Δt [s]	Rg [m]	Az [m]	Δτ [s]	Δt [s]	Rg [m]	Az [m]
S-1A	7.0771e ⁻¹⁰	6.3208e ⁻⁶	0.1061	0.0430	7.4103e ⁻¹⁰	6.3522e ⁻⁶	0.1111	0.0432
S-1B	-1.2209e ⁻¹⁰	-3.1978e ⁻⁵	-0.0183	-0.2175	-1.2855e ⁻¹⁰	-3.5523e ⁻⁵	-0.0193	-0.2416

For the large amount of data available with S-1A and S-1B, the range timing calibrations are determined with precisions equivalent to 0.003 m in range and equivalent to 0.010 m in azimuth, considering a confidence level of 95%. These numbers are in good agreement with the basic law of statistical averaging, σ/\sqrt{n} , if we assume typical S-1 precisions of 0.04 m in range and of 0.25 m in azimuth, and accounting for the number of available data (Table 2) and the fact that there is a correlation between the scaling factor and the range calibration constants. Obviously, the precision of S-1C calibration is worse due to the much lower amount of only 3 months of commissioning phase data. The instrument timing can be resolved within ± 0.013 m in range and ± 0.043 m in azimuth.

The S-1C instrument timing biases as given in Table 3 were inserted to AUX ITC of ETAD to provide timing calibration for the publicly released data of commissioning phase 2, i.e., March 25, 2025 to Mai 19, 2025 [RD-35]. For the regular S-1C data release, the timing calibration became integrated to the AUX INS which is applied to level 1 data by the SAR processor [RD-36]. As to the instrument timing constants obtained for S-1A and S-1B, no changes were made to the AUX ITC products currently used in operational ETAD product processing, because the existing numbers are still in good agreement with our recomputed results.

The currently used instrument timing calibrations of S-1A and S-1B were derived from IW data of the ionospheric quiet period of 2016 to 2018 [RD-7]. Therefore, the applied TEC scaling factor of 0.9 was less critical, and we have already obtained comparable results. The results of the current and the recomputed S-1A and S-1B timing calibrations are compared in Table 4. The recomputed range timing calibrations only differ by a few millimeters. In case of S-1A, the azimuth timing calibrations are basically identical, whereas for S-1B we note a minor difference of 0.024 m. When recalling the typical geolocation accuracy of S-1 IW data, i.e., centimeter-level in range and decimeter-level in azimuth [RD-8][RD-9], these timing calibration differences are considered acceptable and we decided to keep the existing AUX ITC products of S-1A and S-1B.



4 Validation of TEC Scaling Factor

4.1 Discussion of validation results

In order to analyze the TEC scaling factor results, ALE comparisons were performed applying the current factor of 0.9, the dynamic factors predicted by NEDM2020, and the refined factor of 0.78 computed from S-1 data. The processing follows our standard geolocation analysis method and considers all the timing corrections of known perturbation effects: troposphere, ionosphere, solid deformation signals, and S-1 systematic bistatic effects [RD-6][RD-37]. The instrument timing calibrations of S-1A and S-1B are set to the current AUX ITC values, as discussed in chapter 3.3. For the uncalibrated S-1C data before May 19, 2025, we use the values given in Table 3, whereas regular S-1C data already include the instrument timing calibration and can be used as is.

The sites involved are mostly identical to the calibration sites (see chapter 2) but in this case all available targets and total available IW data between January 2015 and September 2025 were used. Additionally, the JPL calibration site in Oklahoma and the INTA calibration site in southern Spain were used because both host arrays of CRs that are distributed over wide areas. The coordinates of the targets have been measured with GNSS and their accuracy is given with 5 cm or better. The used S-1 data from these sites covers 1 year, starting with September 2024 when availability was reconfirmed as part of the S-1C IOC preparation activities. In summary, overall configuration for our validation covers 8 test sites that span 3 continents and host a total of 102 CR reference targets:

- Wettzell geodetic observatory, Germany, [RD-24]: 2 CRs (1.5m), 3 IW beams
- Metsähovi geodetic observatory, Finland [RD-24]: 1 CR (1.5m), 2 IW beams
- Côte d'Azur geodetic observatory, France (since Dec 2018) [RD-27]: 1 CR (1.44m), 2 IW beams
- Yarragadee geodetic observatory, Australia (since Aug 2018) [RD-28]: 2 CRs (1.5m), 1 IW beams
- Surrat Basin SAR calibration site, Australia [RD-29]: 40 CRs (1.5m or larger), 2 IW beams
- Southern Spain calibration site, Spain (since Sep 2024) [RD-38]: 15 CRs (1.5m), 7 IW beams
- Rosamond calibration site, United States [RD-30]: 28 CRs (2.44m or 4.8m), 3 IW beams
- Oklahoma calibration site, United States (since Sep 2024) [RD-30]: 13 CRs (2.8m), 4 IW beams

Note that CR signatures with a SCR lower than 16 dB were removed, and additional MAD outlier detection was applied for statistical data cleaning. By convention, all offset results are presented as "predicted minus measured", which is in line with the regular S-1 mission geolocation reports of the SAR-MPC.

The dynamic TEC scaling of NEDM2020 yields very similar range geolocation results as the fixed factor of 0.9, see Figure 8 (left) and Figure 9 (top). The periods of strong solar activity, i.e., 2014 – 2015 and 2020 – 2025, only show minor differences when comparing the scaling methods visually, see Figure 9 (top). However, during these periods we can clearly see a change of results when applying the refined scaling factor of 0.78, see Figure 8 (right) and Figure 9 (bottom). The corresponding geolocation statistics are summarized in Table 5.

The azimuth geolocation results are not in the scope of this technical note. The geometric characteristics and status of S-1 IW data were already discussed in our previous publications [RD-7][RD-8][RD-9]. The residual biases of 0.1-0.3 m are typical for the results of S-1A. They are mostly considered to be a S-1A specific limitation because the azimuth results obtained with S-1C and S-1B are generally much more homogeneous for same time periods and sites, see for instance Table 5 and Table 6.

The likely reason is the outage of tile #11 of S-1A SAR antenna that occurred in June 2016 [RD-39], changing the azimuth antenna pattern characteristics. Therefore, these offsets are not related to the calibration sites. It has to be emphasized that these biases are considered non-critical with respect to the 10m (3 sigma) accuracy requirement of the IW products [RD-40].



Table 5: Impact of bottom-side TEC scaling factors α on overall S-1 range geolocation results and the results of each sensor. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model versus TEC scaling factor of 0.78 estimated from S-1 data. Results computed with Sentinel-1A/B/C IW data of 01/2015 – 09/2025 as available at the SAR calibration sites in Europe, Australia, and North America (see details in text). Numbers are the average geolocation error and standard deviation.

		Range ALE [m]		Azimuth ALE [m]
	α0.90	α NEDM2020	α0.78	
Sentinel-1	0.020 ± 0.059	0.006 ± 0.059	-0.014 ± 0.055	-0.059 ± 0.274
S-1A	0.024 ± 0.062	0.010 ± 0.062	-0.012 ± 0.057	-0.085 ± 0.283
S-1B	0.002 ± 0.046	-0.010 ± 0.048	-0.019 ± 0.047	0.002 ± 0.237
S-1C	0.050 ± 0.055	0.036 ± 0.055	-0.003 ± 0.054	-0.030 ± 0.274

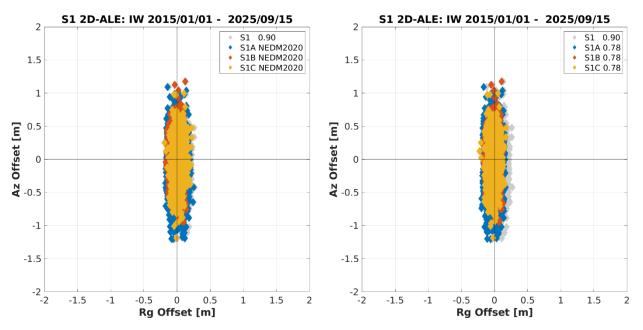


Figure 8: Sentinel-1 IW data geolocation residuals across CRs from 8 different test sites, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (left). Nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (right). Offsets are predicted minus measured.

Looking only at the overall range ALE numbers of Sentinel-1 mission in Table 5, the change is difficult to quantify because the results are dominated by large amount of ionospheric quiet data of the joint S-1A and S-1C data period. Nevertheless, we note a small improvement in the overall standard deviation from 0.59m to 0.55m. The actual impact of the different scaling factors is best seen in the results of S-1C, comprising recent data of January to September 2025, see Table 5. The systematic change amounts to 0.05m and 0.04m when comparing the fixed factor of 0.9 and dynamic NEDM2020 factors with the adjusted factor of 0.78. In other words, if we would have calibrated the S-1C with a different factor, this would be the order of systematic discrepancy to be found in S-1C data, eventually.

This interpretation is supported by the reduced statistics given Table 6, which compares the results of the solar quiet period 2016 – 2021 and of the solar active period of 2021 – 2025. Note the offset of 0.044 m for S-1A for the scaling factor of 0.9 during the solar active period, which is in line with the offsets discussed in the yearly mission reports [RD-8][RD-9]. The numbers of S-1A for the solar active period are in close agreement with the results of S-1C, confirming an overall improved consistency between the two periods when applying the adjusted factor of 0.78.

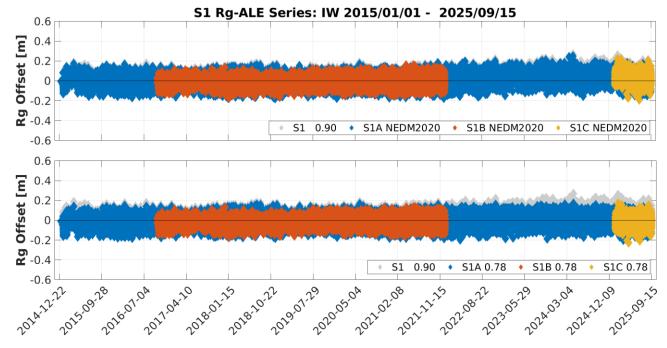


Figure 9: Sentinel-1 IW data range geolocation residual time series across CRs from 8 test sites, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (top). Nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (bottom).

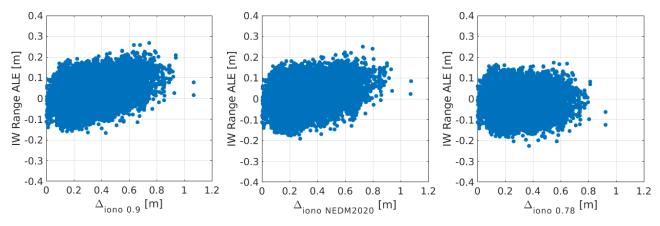


Figure 10: Sentinel-1 IW data range geolocation residual from the 8 different test sites versus the corresponding ionospheric path delay correction shifts, when applying the different TEC scaling factors. Nominal TEC scaling factor of 0.9 (left), dynamic TEC scaling factors of NEDM2020 model (middle), and TEC scaling factor of 0.78 estimated from S-1 data (right).

The improved consistency is also seen in Figure 9, where S-1A data after 2021 shows a slight positive trend for both the fixed factor of 0.9 and the dynamic NEDM2020 factors, which is largely mitigated when applying the factor of 0.78, see Figure 9 (bottom). The trade-off for this improved long-term range ALE balance is the small bias of -0.02 m during the solar quiet period, indicating the limits of having only one fixed value for the entire S-1 mission.

A complementary analysis is shown in Figure 10, which displays the range geolocation residuals versus the applied ionospheric path delay corrections, considering the different scaling factors. There is a clear systematic effect in the results with the fixed factor of 0.9 and the dynamic NEDM2020 factors, which cannot be mitigated by instrument timing calibration constants. If one would attempt to calibrate the sensors for these two configurations to center the overall range ALE, there would still remain a systematic distortion between solar active and solar quiet periods. Therefore, we consider the factor of 0.78 to be more suitable for S-1 SAR data.

To study the changes per calibration site, individual geolocation results were compiled as well. The outcomes are summarized in Table 7. Figures of the underlying range geolocation series can be found in the appendix A. In accordance with the model analysis discussed in chapter 2.2, the impact of the TEC scaling factors on the range ALE is less critical for the mid to high-latitude sites (Metsähovi, Wettzell), but it becomes more notable for the lower latitudes. The largest changes of 0.05-0.07 m are observed at the sites of Spain and Oklahoma, which are only covered by the recent S-1A and S-1C data. For the estimated factor of 0.78, the results become more homogenous. This is indicated by the average range biases, which become closer to zero and in most cases also decrease in magnitude. Also the standard deviations improve slightly for almost all the sites, but again the short-term improvement during solar active periods is somewhat masked by the larger amount of solar quiet data, see figures in appendix A.

Table 6: Impact of bottom-side TEC scaling factors α on overall S-1 range geolocation results and the results of each sensor. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model versus TEC scaling factor of 0.78 estimated from S-1 data. Results computed with Sentinel-1A/B/C IW data, comparing the data from the solar quiet years and the solar active years over the SAR calibration sites in Europe, Australia, and North America (see details in text). Note that S-1B data during the solar active period stops at Dec 2021, while S-1C data starts at Jan 2025. Numbers are the average geolocation error and standard deviation.

		Range ALE [m]		Azimuth ALE [m]
	α0.90	α NEDM2020	α0.78	
	Sol	ar quiet period 2017 - 20	021	
Sentinel-1	-0.001 ± 0.050	-0.014 ± 0.051	-0.020 ± 0.051	-0.050 ± 0.255
S-1A	-0.002 ± 0.054	-0.015 ± 0.056	-0.021 ± 0.055	-0.091 ± 0.266
S-1B	0.000 ± 0.044	-0.012 ± 0.046	-0.019 ± 0.045	-0.002 ± 0.233
S-1C	n/a	n/a	n/a	n/a
	Sola	ar active period 2021 - 2	025	
Sentinel-1	0.040 ± 0.060	0.026 ± 0.060	-0.005 ± 0.056	-0.087 ± 0.280
S-1A	0.044 ± 0.061	0.029 ± 0.060	-0.004 ± 0.057	-0.113 ± 0.279
S-1B	0.008 ± 0.051	-0.002 ± 0.052	-0.014 ± 0.052	0.026 ± 0.251
S-1C	0.050 ± 0.055	0.036 ± 0.055	-0.003 ± 0.054	-0.030 ± 0.274

Table 7: Impact of bottom-side TEC scaling factors α on overall S-1 range geolocation results for the different calibration sites. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model versus TEC scaling factor of 0.78 estimated from S-1 data. Results computed with Sentinel-1A/B/C IW data of 01/2015 – 09/2025 as available at the SAR calibration sites in Europe, Australia, and North America (see details in text). Numbers are the average geolocation error and standard deviation.

Site	Lat [°]		Range ALE [m]		Azimuth ALE [m]
		α _{0.90}	α NEDM2020	α _{0.78}	
Metsähovi	60.2N	0.007 ± 0.055	0.007 ± 0.054	-0.011 ± 0.050	0.005 ± 0.333
Wettzell	49.1N	0.033 ± 0.047	0.031 ± 0.046	0.011 ± 0.044	0.023 ± 0.313
Côte d'Azur	43.8N	0.045 ± 0.049	0.041 ± 0.050	0.008 ± 0.048	-0.149 ± 0.358
Spain	39.5N	0.033 ± 0.068	0.020 ± 0.070	-0.021 ± 0.064	-0.109 ± 0.338
Rosamond	34.8N	0.063 ± 0.043	0.052 ± 0.041	0.033 ± 0.043	-0.007 ± 0.219
Oklahoma	34.5N	0.042 ± 0.039	0.040 ± 0.041	-0.029 ± 0.039	-0.036 ± 0.187
Yarragadee	29.08	0.011 ± 0.041	0.001 ± 0.040	-0.013 ± 0.038	-0.004 ± 0.254
Surat Basin	27.0S	0.003 ± 0.057	-0.014 ± 0.055	-0.031 ± 0.049	-0.082 ± 0.274



4.2 Summary and conclusions

In order to assess the different bottom-side TEC scaling factors, we compared the originally defined fixed scaling factor of 0.9, the dynamic scaling factors predicted by NEDM2020, and the newly adjusted fixed scaling factor of 0.78. The comparison was performed by geolocation analysis of SAR reference targets, which evaluated the performance of S-1 IW data when applying GIM-based ionospheric path delay corrections and the different TEC scaling factors. We used S-1A/B/C data from 8 different test sites that span 3 continents and a total of 102 CR reference targets for this validation. The data covers the entire S-1 mission timeline, i.e., January 2015 to September 2025.

Our theoretical analysis performed with NEDM2020 suggests that the bottom-side TEC scaling factor at Sentinel-1 orbit height is largely dominated by geographic position (latitude) and seasonal variation of the Earth's atmosphere ionization. According to the model, the long-term solar activity cycle has only a minor impact on the scaling factor and thus the path delay corrections, because its impact is mainly noticed during periods of low solar activity. For most of the used validation sites, NEDM2020 predicted typical factors between 0.85 and 0.9 over the mission timeline, which is more in line with the fixed scaling factor of 0.9. Interestingly, a factor of 0.78 was obtained from S-1 data with a precision of ± 0.01 that is notably lower. However, we find that this fixed factor improved range ALE results, giving more balanced results between the solar active and solar quiet periods.

The reason for this is not entirely clear. It could be additional limitations in the ionospheric modelling of GIMs such as the vertical-to-slant-range mapping, or other yet unknown systematic effects of S-1 mission, which are better compensated for by this lower TEC scaling factor. Nonetheless, the geolocation results show improvements by about 0.05 m and 0.04 m when comparing the fixed factor of 0.9 and dynamic NEDM2020 factors with the readjusted factor of 0.78 during solar active periods. This largely removes the systematic range biases which have been found during the solar active periods. The trade-off for this improved long-term range ALE balance is a small bias of about -0.02 m during the solar quiet period, indicating the limits of having only one fixed value for the entire S-1 mission.

Moreover, the range ALE results confirm the very high geometric fidelity of S-1 mission across the individual sensors S-1A, S-1B, and S-1C. With a fixed scaling factor of 0.78, the remaining ALE offsets for IW range data are generally better than 0.04 m across the global verification data, and more comparable results are achieved by each sensor. Regarding temporal stability, the mission performs equally well over the analyzed data period of 01/2015 - 09/2025. No degradation of range ALE or change in sensor behavior was observed during this period. This also means the instrument timing calibrations, which are currently specified for range data of each sensor, can be considered valid over the full mission timeline as of today .Nevertheless, SAR MPC will continue to actively monitor geometric quality of S-1 mission and adjust the calibration of each sensor as required.

Based on these findings, we recommend users to apply a bottom-side TEC scaling factor of 0.78 when using GIMS to correct for the ionospheric path delays in S-1 data. We also decided to change the bottom-side TEC scaling factor from 0.9 to 0.78 for the operational production ETAD products, see the chapters 5 and 6 for further details. Not only does this offer a relatively simple method to improve the long-term stability of ionospheric corrections in ETAD products, it also allows to retain the current instrument timing calibrations of S-1A and S-1B. This makes the change straightforward, and users can readily update existing ETAD products by accounting for the new scaling factor, see section 5.2.



5 Update of AUX SCF products and ETAD application

5.1 AUX SCF maintenance and updates

The SETAP configuration auxiliary product (AUX SCF) is part of the auxiliary products which are used by the ETAD processor to generate the products [RD-13]. It provides the processor configuration and defines a set of external parameters that are required for ETAD correction computation algorithms [RD-11]. The product is maintained by the SAR-MPC and can be accessed via the SAR-MPC website¹. The website hosts all the auxiliary products related to S-1 SAR processing and provides a RestAPI to identify and download particular products².

There is only one AUX SCF product with a validity completely covering the S-1 mission lifetime. For the update to SETAP version 3.0 performed in June 2025, a new release of AUX SCF product was put in place, which contains the modified TEC scaling factor of 0.78 as *ionosphereScalingFactorOrbitHeight* [RD-36]:

S1__AUX_SCF_V20140406T133000_G20250624T073745.SAFE/data/s1-aux-scf.xml

```
<setapConf schemaVersion="1.21" xsi:noNamespaceSchemaLocation="../support/s1--aux-scf.xsd">
  <generalProcessorConf>
     <listOfGlobalParams>
        <troposphericDelayCorrection>true</troposphericDelayCorrection>
        <ionosphericDelayCorrection>true</ionosphericDelayCorrection>
        <solidEarthTideCorrection>true</solidEarthTideCorrection>
        <oceanTidalLoadingCorrection>true</oceanTidalLoadingCorrection>
        <orbitStateVectorExtractionExtension>10</orbitStateVectorExtractionExtension>
        <ionosphereScalingFactorOrbitHeight>0.78</ionosphereScalingFactorOrbitHeight>
        <troposphereIntegrationStepSizeTropopause unit="m">50.0</troposphereIntegrationStep
         SizeTropopause>
        <troposphereIntegrationStepSizeStratosphere unit="m">100.0</troposphereIntegrationStep</pre>
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        <fDcRmsThreshold unit="Hz">30.0</fDcRmsThreshold>
     </listOfGlobalParams>
     IistOfCorrectionQualityLimits>
     /listOfCorrectionQualityLimits>
  </generalProcessorConf>
  <modeRelatedConf>
  </modeRelatedConf>
</setapConf>
```



¹ https://sar-mpc.eu/

² https://sar-mpc.eu/doc/api/

During ETAD processing, the TEC scaling factor is used in the computation of the ionospheric path delay in range, and it is also annotated as *scalingVTECOrbitHeight* in the XML annotation file of each ETAD product [RD-41]. Thus, the applied TEC scaling factor is immediately visible from any given ETAD product and completely transparent to the end users.

Updates to AUX SCF are controlled by SAR-MPC and products are ingested into the S-1 ground segment, where they are accessed by the operational ETAD production service. Because there is only one valid AUX SCF product, an updated TEC scaling factor takes precedence over any previously applied value. However, the application of a new TEC scaling factor to existing products is straightforward and can be performed by the user in order to align the previously generated ETAD products, see next chapter 5.2.

The adjusted TEC scaling factor of 0.78 discussed in the document at hand is considered as the new baseline for S-1 ETAD ionospheric delay corrections. Future updates are not foreseen at this point, but we recommend the users monitor the changes to AUX SCF published by SAR-MPC.

5.2 How to align the TEC scaling factor in ETAD products

The bottom-side TEC scaling factor used in ETAD processing is a fixed parameter that is applicable to all ETAD products. At the time of writing this document, there is only the change from 0.9 to 0.78 that was introduced with SETAP version 3.0, together with the public dissemination of S-1C data. Thus, only the ETAD products of S-1A before version 3.0 have to be aligned, and users may want to check for the change in processor version that is annotated in ETAD products. Nevertheless, this section describes a generic procedure which is valid for any number of changes made to the TEC scaling factor.

There are two strategies of aligning ETAD products which can be referred to as "relative" and "absolute" method. Given a set of ETAD products, one may take the latest product and use its annotated TEC scaling factor to check if any of the ETAD products have to be modified (= relative alignment between given ETAD products). As an alternative approach, the latest valid AUX SCF can be retrieved from SAR-MPC website and used as an overall baseline to check the products (= absolute alignment of given ETAD products).

Regardless of the method, there will be the currently applicable TEC scaling factor $\alpha_{current}$, which has to be applied to a product if $\alpha_{product} \neq \alpha_{current}$ in order to prevent discontinuities in time series of ETAD ionospheric delay correction data.

Let $\alpha_{current}$ be the last applicable TEC scaling factor that was extracted from an AUX SCF product or an up-to-date ETAD product annotation:

- AUX SCF: data/s1--aux-scf.xml
 - → generalProcessorConf/listOfGlobalParams/ionosphereScalingFactorOrbitHeight
- ETAD product: annotation/S1*_*_ETA__AX**_*.xml
 - → processingInformation/processingParameters/ionosphericCorrectionMethod/ scalingVTECOrbitHeight

If a non-current product has to be aligned, the sum of range correction layer and the actual ionospheric correction layer have to be updated.

When working with individual ETAD layers, the ionospheric path delay layer ionosphericCorrectionRg of a non-current ETAD product has to be modified as follows:

```
ionosphericCorrectionRg * \alpha_{current}/\alpha_{product}
```

In case the sum of range correction layer sumOfCorrectionsRg shall be used, the layer of a non-current ETAD product can be updated as follows:

 $sumOfCorrectionsRg - ionosphericCorrectionRg * (1 - \alpha_{current}/\alpha_{product})$



6 Validation of ETAD product performance

Computation of the redefined TEC scaling factor (see section 3) was performed with correction data and methods that are compatible but not identical to the ETAD correction grids. A generation of ETAD products for all the data used in the processing was considered out of scope for this activity. In order to assess the basic ETAD applicability of updated AUX SCF in SETAP version 3.0, we carried out a geolocation validation for a selection of publicly available S-1A and S-1C ETAD data of the Surat Basin calibration site.

All the 40 CR targets are used in the assessment. The temporal data coverage is August 2023 to August 2025 for S-1A, and March 2025 to August 2025 for S1-C. Note that an alignment of non-current S-1A ETAD products was performed as described in section 5.2.

The numerical results are listed in Table 8 and corresponding graphical results are shown in Figure 11 and Figure 12, respectively. We recall that this ALE analysis of S-1A and S-1C data from Surat Basin site applies only the ETAD corrections. Therefore, the improved range geolocation results clearly confirm the updated TEC scaling factor provided in AUX SCF. The range biases between 0.06 to 0.10 m, which are reported in S-1 mission reports of 2023 and 2024 for S-1A ETAD geolocation results [RD-8][RD-9], are successfully mitigated if the existing ETAD products of S-1A are modified for the new TEC scaling factor. In case of S-1C, all publicly released ETAD products have been generated with SETAP version 3.0, making use of the latest AUX SCF and the instrument timing calibration discussed in section 3.3. Thus, the S-1C results already are fully consistent if ETAD products are used as is.

In summary, we find the ETAD products of processer version 3.0 to be in good agreement with the overall validation results shown in chapter 4. Even during the periods of strong solar activity, the best attainable geolocation accuracy in range is now better than 0.05 m if applying the ETAD products.

Table 8: ALE computed with IW ETAD products of S-1A and S-1C as of August 2025 for S-1 SAR data acquired at Surat Basin calibration site hosting 40 CRs, see Figure 11. Only public ETAD products available from Copernicus Data Space Ecosystem (CDSE) were used in the processing. The S-1A ETAD products before SETAP version 3.0 were adjusted for the refined TEC scaling factor, following section 5.2.

	Range ALE [m]	Azimuth ALE [m]
Sentinel-1A	0.010 ± 0.060	-0.160 ± 0.295
IW-1	0.010 ± 0.060	-0.278 ± 0.283
IW-2	-0.003 ± 0.061	-0.035 ± 0.248
IW-3	0.027 ± 0.052	-0.145 ± 0.276
Sentinel-1C	0.022 ± 0.051	-0.042 ± 0.299
IW-1	0.041 ± 0.046	-0.122 ± 0.319
IW-2	0.015 ± 0.045	-0.026 ± 0.243
IW-3	-0.006 ± 0.053	0.108 ± 0.272



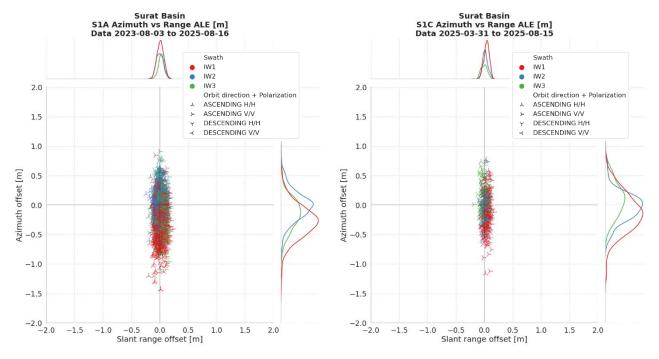


Figure 11: ALE computed with S-1A and S-1C ETAD data of 08/2023 – 08/2025 for the SAR data acquired at the Surat Basin calibration site hosting 40 CRs. Geolocation residual results of S-1A (left) and of S-1C (right).

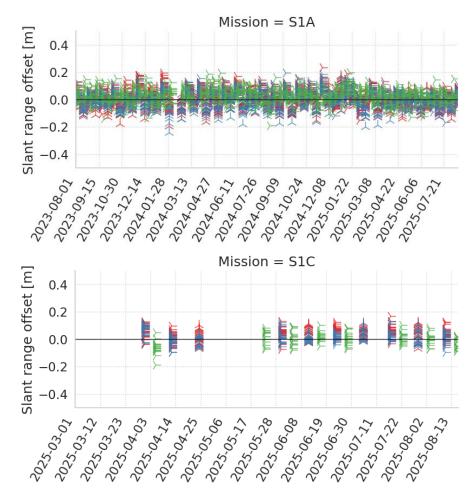


Figure 12: Range ALE time series of the S-1A and S-1C geolocation results applying ETAD corrections. Results obtained with S-1A (top) and S-1C (bottom) at Surat Basin calibration site hosting 40 CRs.



Appendix A - Additional ALE visualizations

This section contains additional visualizations for the TEC scaling factor validation results that are discussed in chapter 4.1. The range ALE residual time series are shown for each of the 8 involved SAR calibration sites: Metsähovi (Finland), Wettzell (Germany), Côte d'Azur (France), southern Spain (Spain), Rosamond (United States), Oklahoma (United States), Yarragadee (Australia), Surat Basin (Australia).

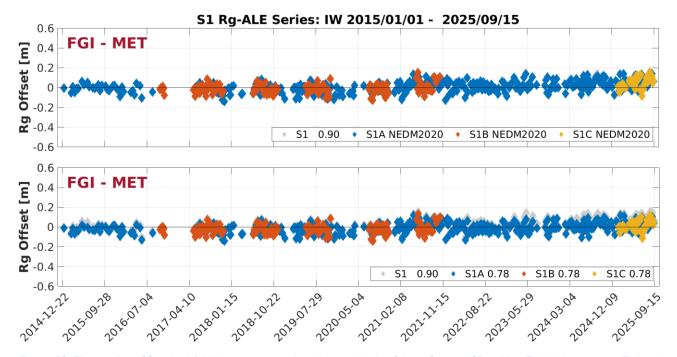


Figure 13: Time series of Sentinel-1 IW data range geolocation residuals of the reference CR at Metsähovi observatory, Finland, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (top), and nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (bottom).



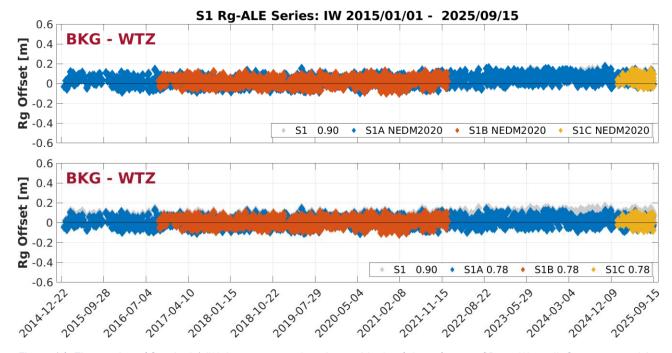


Figure 14: Time series of Sentinel-1 IW data range geolocation residuals of the reference CRs at Wettzell, Germany, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (top), and nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (bottom).

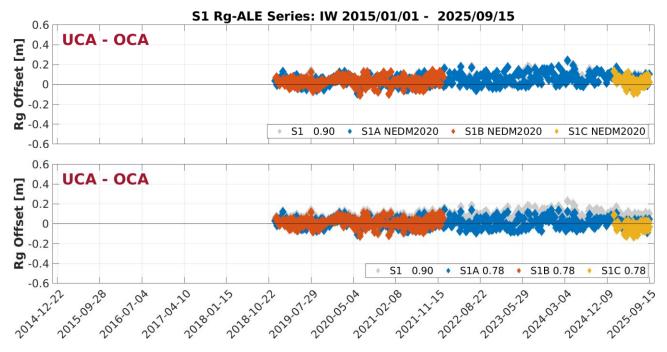


Figure 15: Time series of Sentinel-1 IW data range geolocation residuals of the reference CR at Côte d'Azur observatory, France, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (top), and nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (bottom).



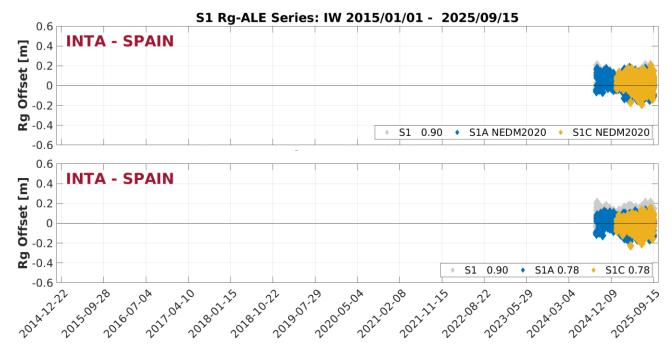


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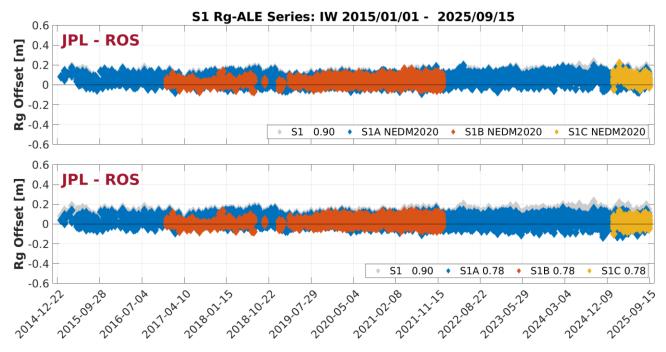


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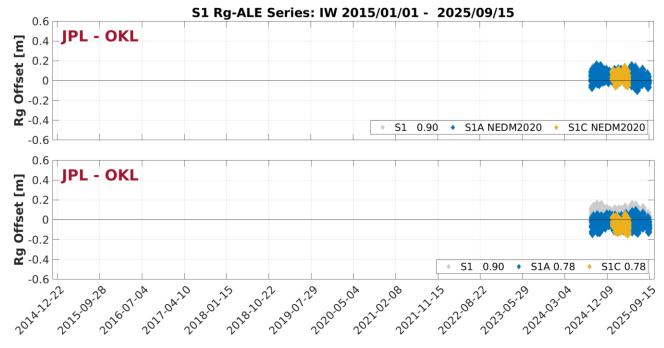


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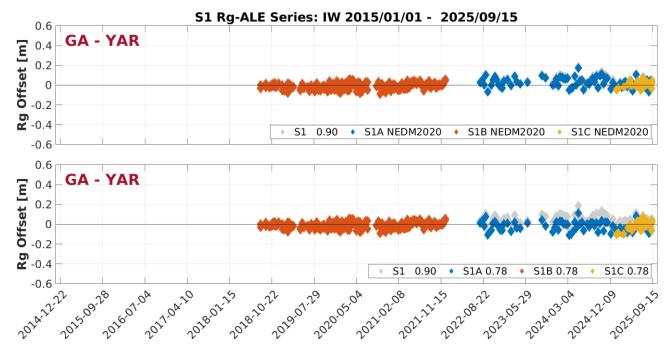


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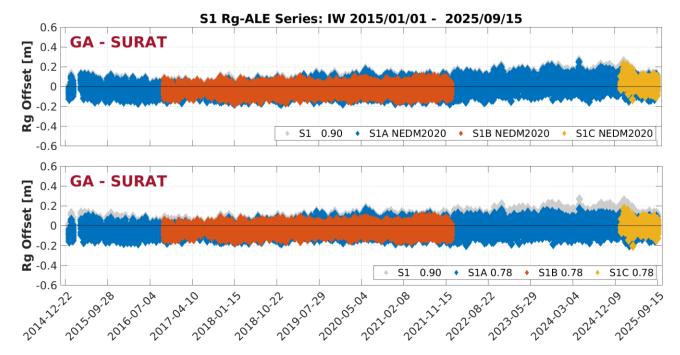


Figure 20: Time series of Sentinel-1 IW data range geolocation residuals of the reference CRs at Surat Basin site, Australia, applying different bottom-side TEC scaling factors. Nominal TEC scaling factor of 0.9 versus dynamic TEC scaling factors of NEDM2020 model (top), and nominal TEC scaling factor of 0.9 versus TEC scaling factor of 0.78 estimated from S-1 data (bottom).



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