Thermal Denoising of Cross-Polarized Sentinel-1 Data in Interferometric and Extra Wide Swath Modes

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Abstract—An updated algorithm for removal of thermal noise in Sentinel-1 synthetic aperture radar (SAR) Level-1 Ground Range Detected (GRD) data in cross-polarization is presented. The algorithm is comprised of two steps: correction of the annotated thermal noise magnitude (previously proposed in [1]) and a novel correction of the annotated thermal noise range dependence. The magnitude of the annotated thermal noise is corrected by applying scale and offset coefficients tuned on a few hundred of Sentinel-1 data acquired over surfaces with low backscatter in Interferometric Wide and Extra Wide swath modes in HV and VH polarizations. The values of coefficients for all modes and polarizations for data processed with Instrument Processing Facility (IPF) version 3.1 - 3.3 are provided. The range dependence is corrected by minimizing a cost function between the annotated range profiles of thermal noise and antenna pattern gain (APG).

An objective validation metric based on comparison of averaged backscatter at inter-swath boundaries is proposed. Validation is performed on hundreds of Sentinel-1 scenes acquired over open ocean, doldrums, deserts and sea ice. It shows that the new algorithm outperforms the standard thermal noise removal algorithm proposed by European Space Agency in almost all cases. Analysis shows that the new algorithm worsens noise correction in cases when the range dependence of the annotated APG does not match with the observed signal, indicating either problems with signal processing on IPF or imprecise annotation of APG.

Index Terms—Synthetic aperture radar, thermal noise, TOPSAR, remote sensing.

I. INTRODUCTION

THERMAL noise is present on Synthetic Aperture Radar (SAR) data and can be evident in areas with low backscatter and particularly in cross-polarization channels [1]. Thermal noise varies in both the range (across-track) and azimuth (along-track) direction, and in multiswath observation modes, different noise patterns in each subswath cause discontinuities in signal intensity at interswath boundaries [2]. Accurate radiometric correction of SAR imagery, including thermal noise removal, is needed before utilization of dual-polarization SAR observations for ocean or sea ice applications.

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The European Space Agency (ESA) Sentinel-1 mission is equipped with a C-band SAR instrument which can operate in Terrain Observation with Progressive Scans SAR (TOPSAR) mode and provide Extra Wide (EW) or Interferometric Wide (IW) observations useful for sea ice, ocean and land monitoring. The data in Level-1 Ground Range Detected (GRD) products consist of focused SAR data that has been detected, multi-looked and projected to ground range using the Earth ellipsoid model, and include both the SAR signal intensity and a look-up table (LUT) with values of noise power varying in the range (here and throughout the manuscript under "the range" we mean ground range unless slant range is specified) and azimuth direction. The Sentinel-1 documentation [2] recommends applying thermal noise correction by subtraction of noise equivalent sigma zero (NESZ) from radar backscatter:

\[ \sigma_{SN}^0 = \sigma^0 - \sigma_N^0 \]  \hfill (1)

where \( \sigma_{SN}^0 \) is the denoised radar backscatter, and \( \sigma^0 \) is the calibrated signal power provided in the S1 GRD file (\( DN \)) [3], [4]:

\[ \sigma^0 = DN^2/A_i^2 \]  \hfill (2)

where \( A_i \) is a calibration constant for each sub-swath \( i \). The choice of calibrated sigma zero (instead of e.g., beta zero) is dictated by scientific applications of Sentinel-1 SAR data requiring calibrated ground range data.

NESZ (\( \sigma_N^0 \)) is a calibrated product of the range (\( N^A_i \)) and azimuth (\( N_i^A \)) components of the noise power provided in the look-up table:

\[ \sigma_N^0 = N^A_i N_i^A / A_i^2 \]  \hfill (3)

In several studies [1], [5], [6], [7] it was shown that the magnitude of the provided noise values is not sufficiently precise because the noise dynamically depends on factors that are not included in the noise vectors, and even after noise subtraction the artefacts in the signal are still observed. A method for correction of the NESZ values by applying scaling and offset coefficient was proposed in [1]:

\[ \sigma_{SN}^0 = \sigma^0 - (K^{ns} \cdot \sigma_N^0 + K^{pb}) \]  \hfill (4)

where \( K^{ns} \) and \( K^{pb} \) are subswath dependent noise scaling and power balancing coefficients. Initially this method was developed for Level-1 GRD data from Sentinel-1 A and B.
satellites acquired in EW mode in HH/HV polarization and processed with Instrument Processing Facility (IPF) version 2.9 and earlier. Noise scaling is needed to eliminate range-varying artefacts in denoised signal within a sub-swath, and power balancing is needed to reduce discontinuities at interswath boundaries.

More recent studies proposed improvements upon the method in [1] by ad hoc removal of multiplicative noise [7], or segmenting the image into more azimuthal blocks using developed criterion on their homogeneity for the thermal noise as well as residual noise (i.e., multiplicative noise) removal [8], [9]. These adaptive algorithms, however, utilize radar signal as source of information for noise correction, and are potentially prone to over-correction in cases of strong signal contrast at interswath boundaries.

In addition to the imprecise magnitude of the annotated ground range noise vectors, we have discovered that there is a shift of these vectors in the range direction. As shown below, the range noise should be inversely proportional to the squared product of elevation antenna pattern (EAP) and range spreading loss (RSL) gains, but in many cases it is not so.

According to [10], the annotated slant range noise power is computed as:

\[ N_R^A(n_s; R, \eta) = \sigma^2(n_s, \eta) \cdot G_{tot}^2(n_s; R, \eta) \]  

where \( G_{tot}^2(n_s; R, \eta) \) is total gain computed as:

\[ G_{tot}(n_s; R, \eta) = \frac{G_{ds}(\eta)G_{pg}(n_s, \eta)}{G_{eap}(n_s, R)G_{rsl}(R)} \sqrt{k_{noise}k_{proc}} \]

where \( R \) is slant range, \( \eta \) is slow time, \( n_s \) is sub-swath number, \( G_{ds}(\eta) \) is de-scalloping gain, \( G_{pg}(n_s, \eta) \) is PG-correction factor, \( G_{eap}(n_s, R) \) is two-way elevation antenna pattern gain, \( G_{rsl}(R) \) is the range spreading loss, \( k_{noise} \) is the noise calibration factor, and \( k_{proc} \) is the processor scaling factor.

The only slant range-varying variables are \( G_{eap}^2(n_s; R) \) and \( G_{rsl}^2(R) \) and, therefore, the range component of the thermal noise should be proportional to a function that can be called "antenna range gain", \( G_{ar} \):

\[ N_R^A(n_s; R) \sim G_{ar} = \frac{1}{G_{eap}^2(n_s, R)G_{rsl}^2(R)} \]

However, it was observed that quite frequently there is an obvious shift between \( N_R^A(n_s; R) \) and \( G_{ar} \) in the range direction as shown on Fig. 1(a). Moreover, the same shift is observed when comparing the uncalibrated signal and uncalibrated noise as shown on Fig. 7(c) and Fig. 7(f) with light crosses. This leads to a situation where NESZ in near range is overestimated and NESZ in far range is underestimated. Subtraction of such NESZ from the signal results in an under-corrected signal in near range, and over-corrected signal in the far range, see Fig. 1(b). Analysis of both IW and EW data shows that the shift magnitude vary in the range of -70 to 200 pixels with mean and standard deviation of 30 and 36 pixels, correspondingly.

The goal of the present work is to improve the algorithm suggested in [1] for decreasing discontinuities of a signal after thermal noise reduction. Instead of adaptive correction using radar signal, the new algorithm for thermal noise removal utilizes extra information from the annotated metadata (i.e. thermal noise reduction). Instead of adaptive correction using radar signal, the new algorithm for thermal noise removal utilizes extra information from the annotated metadata (i.e. thermal noise reduction). Thus it combines both the range shift and the magnitude correction of thermal noise vectors.

In addition the algorithm was extended for application on Sentinel-1 A/B data acquired in EW and IW mode, in HV and VH polarization and IPF version 3.1, 3.2 and 3.3. We also suggest a new quantitative metric for comprehensive evaluation of the new algorithm performance. The improvements in thermal noise removal in several surface types including sea ice, ocean and deserts are illustrated.

The paper is organized as follows: first we characterize the data used for training and validation, then we present the algorithms for the thermal range noise shift / magnitude correction and the new validation metric, and finally we provide the coefficients that can be used for implementation of our algorithm of NESZ modification and show and discuss the validation results.
II. DATA

A. Training data

For training the noise scaling and power balancing coefficients, a few hundred Ground Range Detected (GRD) products from Sentinel-1 A and B (S1A, S1B) acquired in Extra Wide (EW) and Interferometric Wide (IW) modes in HH/HV (1SDH) and VV/VH (1SDV) polarizations were used as specified in Table I.

TABLE I: Total number of S1A (and S1B in parenthesis) datasets for training

| Mode          | IW (GRDH) | IW (GRDM) | EW (GRDH) | EW (GRDM) |
|---------------|-----------|-----------|-----------|-----------|
| HV            | 50 (37)   | 47 (54)   | 67 (83)   | 93 (85)   |
| VH            | 50 (37)   | 47 (54)   | 67 (83)   | 93 (85)   |

B. Validation data

For validation of the thermal noise removal algorithm, independent Sentinel-1 data were used as specified in Table II.

The regions which represent various surface types, and where the data have been collected, are mentioned in the list below:

- Ocean: Norwegian Sea (65° – 75° N, -10° – 25° E).
- Desert: Sahara (17° – 18° N, 15° – 16° E), Arabian Desert (19° – 21° N, 50° – 55° E).
- Doldrums: Atlantic Ocean (-5° – 0° N, -40° – 0° E).
- Arctic: Laptev Sea (74° – 77° N, 115° – 122° E).
- Antarctic: Weddell Sea (-73° – -60° N, -50° – -20° E).

TABLE II: Validation sites and number of S1A (and S1B) scenes

| Surface          | Polarization | IW | EW | IW | EW |
|------------------|--------------|----|----|----|----|
| Mode             |              |    |    |    |    |
|                  | HH           | VH | HV | VH | HV |
| Ocean            | 33 (44)      | 38 (37) | 44 (38) | 38 (71) |
| Arctic Sea Ice   | 24 (113)     | 28 (16) | 16 (-) | 32 (48) |
| Doldrums         | 36 (20)      | 21 (30) | 30 (30) | 4 (-) |
| Desert           | 34 (14)      | 14 (-) | 8 (8) | 29 (-) |
| Antarctic Sea Ice| 4 (26)       | - (-) | - (-) | 60 (72) |

III. METHODOLOGY

A. Overall algorithm description

The overall scheme of the developed algorithm is presented in Fig. 2. It consists of two phases: training of noise scaling and power balancing coefficients, and correction of individual images. The new procedure for shifting thermal noise vectors in the range direction is used in both phases. It is described in detail in Section III-B below and presented in Algorithm 1. The procedure for finding the noise scaling and power balancing coefficients from [1] is briefly presented in Section III-C.

Four combinations of corrections are discussed in this paper: the default noise correction algorithm (Eq. 1) is referred to as the “ESA” algorithm. Note that the reference “ESA algorithm” applies only to correction of Sentinel-1 data processed with IPF versions 3.1 – 3.3. The noise shift correction applied alone (Eqs. 11 and 1) is referred to as the “ESA+SHIFT” algorithm, the noise scaling and power balancing algorithm applied alone (Eq. 4) is referred to as the “ESA+MAG”, and the full algorithm (Eqs. 11 and 4) is referred to as the “NERSC” algorithm.

B. Correction of shift of thermal noise vectors in the range direction

The correction is performed individually for each range noise vector from the look-up table (LUT) from the Noise Annotation Data Set (NADS) (see overview in Algorithm 1). The NADS LUT contains sub-sampled values of thermal noise and corresponding column and row (also called pixel and line) coordinates in the full size image system, hereafter referred to as destination coordinates and denoted as $x$ and $y$. The correction includes several steps of interpolation of annotation data.

First, a vector of boresight angles is computed: $\theta$ = $\theta$elevation $- \theta$roll, where $\theta$elevation and $\theta$roll are vectors of elevation and roll angle interpolated from the Geolocation Grid Annotation Data Set (GGADS) on the destination coordinates. Then a vector of elevation antenna pattern gain ($G_{E,AP}$) from the Auxiliary Calibration Data Set (ACDS) is interpolated on the vector of boresight angle.

Next, a vector of range spread loss gain is computed:

$$G_{rsl} = \sqrt{\left(\frac{Rreli}{R}\right)^3}, R = T_{sr} \cdot c/2$$

where $Rreli$ and $T_{sr}$ are vectors of reference range and slant range time interpolated from the GGADS on the destination coordinates, and $c$ is the speed of light (see Eq. 9-20 in [10]).

Next, a one-dimensional linear spline interpolator using ‘interp1d’ class from the SciPy package (for details see http://docs.scipy.org) for the annotated range noise is trained on vectors of annotated range noise ($N^A_{R}$) and destination column coordinates ($x$) from the NADS LUT:

$$I_N = \text{Interpolator}(x, N^A_R)$$

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The shift of the annotated range noise vector ($\Delta X$) is found by minimizing the cost function:

$$
\epsilon_N = 1 - I_N(x + \Delta X) \times G_{ar}(x)
$$  
(10)

where ($G_{ar}$) is the vector of “antenna range gain” computed from vectors $G_{cap}$ and $G_{rad}$ using Eq. 7, $x$ denotes column coordinates, and $\times$ is the Pearson’s correlation coefficient between $G_{ar}$ and range noise values interpolated on the column coordinates offset by $\Delta X$.

Finally, the shifted noise is computed by applying the trained interpolator on the pixel coordinates with the offset:

$$
N_{Rs}^A = I_N(x + \Delta X)
$$  
(11)

As illustrated on Fig.1(a) the shifted noise matches better with $G_{ar}$. The signal corrected with shifted NESZ appears to be less varying with range, Fig.1(b).

**Input:** NADS, GGADS, ACDS, $x$

**Output:** $N_{Rs}^A$

**foreach** $i \in S$ do

**foreach** $y \in Y$ do

Interpolate $\theta_{elevation}$ and $\theta_{roll}$ from GGADS on the destination coordinates $x$;

Compute vector of $\theta_{boresight}$ on the destination coordinates;

Interpolate $G_{EAP}$ from ACDS on the vector of $\theta_{boresight}$;

Interpolate $R_{ref}$ and $T_x$ from GGADS on the destination coordinates;

Compute $G_{rsl}$ from $RR$ and $T_x$;

Compute $G_{ar}$ from $G_{EAP}$ and $G_{rsl}$;

Train the interpolator $I_N$ using $N_{Rs}^A$ and destination coordinates $x$;

Minimize $\epsilon_N$ and find $\Delta X$;

Compute $N_{Rs}^A$;

end

end

Algorithm 1: Algorithm for shifting annotated thermal noise vectors in the range direction. $S$ denotes sub-swaths, $Y$ denotes destination row coordinates and other notations are the same as in Section III-B.

**C. Finding the noise scaling and power balancing coefficients**

The training of the noise scaling ($K^{ns}$) and power balancing ($K^{pb}$) coefficients is presented in detail in [1] and is briefly explained here for clarity. The training is performed only once but on a sufficiently large sample of GRD Sentinel-1 A and B images collected in two acquisition modes (EW and IW) and in two polarizations (HV and VH) (see Table I). For each combination of the mode and polarization, lists of images from S1A and S1B satellites acquired over areas with low backscatter are created. Each image is split into sub-blocks 1000 pixels high (see Fig.3) and for each sub-block $i$ individual values of $k_{ns}^i$ and $k_{pb}^i$ are computed (as shown below) and saved in temporary files. After all images are processed, the averaged values of $K^{ns}$ and $K^{pb}$ are computed and the thermal noise removal step can be performed using Eq. 4 for any Sentinel-1 GRD data processed by the corresponding IPF version.

![Fig. 3: Structure of an IW scene in a GRD product. A - swath boundaries, B - sub-block boundaries, C - quality computation patch boundaries.](image)

The individual coefficients $k_{ns}^j$ are found under the assumption that after thermal noise correction and in case of low signal, the signal can be approximated with a linear dependence on incidence angle: $\sigma_{SN}^2 \sim \alpha_i + \beta_i \cdot x$, where $\alpha$ and $\beta$ are linear regression coefficients, $x$ is a column coordinate.

Noise scaling coefficients are found by minimizing the following cost function, which is defined as a difference between a linear polynomial and denoised signal, computed as a difference between the total signal and scaled thermal noise:

$$
\epsilon_i = \sigma^0 - k_{ns}^i \cdot \sigma_{SN}^i - \alpha - \beta \cdot x
$$  
(12)

The minimization of $\epsilon$ yields not only $k_{ns}^i$ but also $\alpha$ and $\beta$ that are not used further in the computation of $K^{ns}$. Then an average scaling coefficient is calculated for each sub-swath:

$$
K_{ns}^j = \frac{1}{N} \sum_{i=0}^{N} k_{ns}^i
$$  
(13)

where $j$ is sub-swath index, and $N$ is number of sub-blocks from training images.

Power balancing aims to remove the discontinuities of signal intensity near sub-swath margins. The discontinuities are a signature of the noise power differences between sub-swaths. The training also comprises two major steps. First, values of power balancing coefficients and auxiliary statistics from individual sub-blocks from Sentinel-1 GRD images are computed by minimizing the cost function defined in Eq. 12 where $K^{ns}$ is fixed:

$$
\alpha, \beta = \arg\min_{\epsilon} \epsilon
$$  
(14)

Individual power balancing coefficients are then computed by finding the difference in signal power approximated at the boundary between two sub-swaths by linear regressions for these two sub-swaths:

$$
k_{pb}^i = \alpha_j + \beta_j \cdot x - (\alpha_{j+1} + \beta_{j+1} \cdot x), i = 2...N
$$  
(15)

Finally, the mean power balancing coefficient for all sub-swaths is computed:

$$
K_{pb}^j = \frac{1}{N} \sum_{i=0}^{N} k_{pb}^i
$$  
(16)
D. Quality metric

In order to evaluate the performance of the advanced thermal denoising algorithm, we propose a quality assessment metric in the range direction. We validate both ESA and NERSC approaches to estimate the relative improvement. Since the main problem in a range direction are steps in intensity at interswath boundaries, the range quality metric (RQM) indicates the degree of difference between small image patches in the neighboring sub-swaths (see Fig.3). RQM is closely related to the Fisher criterion score [11], [12] that measures the discriminability between two samples in one dimension and is given by:

$$RQM = \frac{\sigma_{M,j}^0 - \sigma_{M,j+1}^0}{\sigma_{M,j} + \sigma_{M,j+1}}$$

where $\sigma_{M,j}^0$ denotes the denoised signal, $j$ is sub-swath index, the $\hat{\cdot}$ operator denotes averaging and the $\cdot$ operator denotes computation of the standard deviation. The criterion gives the highest score to the samples with the largest relative difference between their means. Therefore, the lower value of the RQM corresponds to the less pronounced inter-swath intensity steps at the sub-swath boundary.

Our experiments with patch size for computing RQM showed that 100 x 100 pixels is optimal. Smaller patches result in noisier RQM estimates, whereas larger patch sizes are less sensitive to the relative difference between sub-swaths.

IV. RESULTS

The impact of the new thermal noise correction on visual appearance of individual Sentinel-1 images and profiles of backscatter is similar to the examples provided in [1] and we invite readers to inspect this open-access article. In this paper we would like to focus the Results section on the large scale validation performed on data acquired in different modes and polarizations, and over different surface types.

A. Noise scaling and power balancing coefficients

Tables III and IV list the noise scaling and power balancing coefficients for Sentinel-1 GRD data processed with IPF 3.1 for all combinations of platforms, modes and cross-polarizations. These coefficients are used in the code for thermal noise removal [13].

| Satellite | S1A | S1A | S1B | S1B |
|-----------|-----|-----|-----|-----|
| polarization | HV | VH | HV | VH |
| GRDM EW1 | 1.0193 | 0.90676 | 0.90783 | 0.91562 |
| GRDM EW2 | 0.9853 | 0.84368 | 0.86959 | 0.88176 |
| GRDM EW3 | 0.97777 | 0.82888 | 0.83015 | 0.84638 |
| GRDM EW4 | 1.0608 | 0.92667 | 0.88949 | 0.95047 |
| GRDM EW5 | 1.0332 | 0.91996 | 0.88764 | 1.0045 |
| GRDH IW1 | 1.0336 | 1.0491 | 0.96597 | 0.98544 |
| GRDH IW2 | 0.99701 | 0.98434 | 0.9769 | 0.98805 |
| GRDH IW3 | 1.127 | 1.0787 | 1.0445 | 1.13 |

B. Range quality metrics

The range quality metric (RQM, see Section III-D) was computed for the images listed in Table II. The average RQM for each combination of mode and polarization for the ESA and NERSC methods and the average of the difference between $RQM_{ESA}$ and $RQM_{NERSC}$ were computed. Fig. 4 presents the average RQM and average RQM difference for each mode, whereas Tables V and VI provide details of the average RQM difference for each validation site.

![Range Quality Metric (S1A)](image)

![Range Quality Metric (S1B)](image)

Fig. 4: Range quality metric (RQM) values for the different imaging mode from the validation dataset of S1-A (upper plot) and S1-B (lower plot) data.

Both these tables and figures illustrate that in most cases the NERSC algorithm outperforms the default denoising procedure in almost every combination of mode and polarization. The only mode where the average RQM difference is slightly negative is S1A/IW/HV and mostly in the Desert validation.
V. Discussion

A. Why is the NERSC algorithm worse in some cases?

The reason for worse behaviour of the NERSC algorithm can be illustrated in an example of two scenes taken by Sentinel-1A over ocean and desert areas. Fig. 5(a) shows that in the ocean both the noise shift correction (profile 'ESA+SHIFT'), and then the noise magnitude correction (profile 'NERSC') progressively reduce the discontinuities in \( \sigma \) that are visible on the inter-swath boundaries. The 'ESA+MAG' profile illustrates that application of the noise magnitude correction alone (like in the previous algorithm) is not sufficient. Fig. 6 shows images with \( \sigma \) corresponding to the profiles on Fig. 5(a). From these images it is also clear that both the magnitude and the range shift corrections together are required for achieving optimal results.

Profile 'ESA+SHIFT' in Fig. 5(b) shows that in the desert case, the noise shift correction removes the discontinuities between sub-swaths in the \( \sigma \) profile. However, the shape of the profile in IW3 is obviously incorrect - values in the near range section of the profile are lower by 0.0005 than in the far range, whereas in the 'ESA' profile the values are almost equal. The magnitude correction (profile 'NERSC' on the same figure) flattens the \( \sigma \) profile but cannot correct the strong angular dependence and, therefore, introduces the discontinuity at the interswath boundary. In fact, the magnitude correction alone is sufficient in this case (see profile 'ESA+MAG').

We hypothesize that the reason for the different effect of the noise shift correction in the aforementioned two cases resides in the accuracy of the antenna pattern gain applied to the signal by the IPF (here and below only IPF versions 3.1 – 3.3 are considered). To prove it, we can compare the effect of the noise shift method for these two cases. Fig. 7(a), (d); (b), (e); (c), (f) compare various range profiles against each other on a scatter plot. Where there is good correspondence between the range profiles, the plot is close to a single line, indicating that one range profile is strictly proportional to another one. In the case of bad correspondence, the plot will resemble a stretched letter V, indicating that there is a shift in range direction between the compared profiles.

Comparison of the annotated noise with the antenna range gain \( G_{ar} \), see Eq. 7) before and after the noise shift is applied (grey crosses and black dots on Figures 7, A and D) shows that before the correction, there is a tangible difference between the annotated noise and ARG, and after the correction the difference is negligible. At the same time, if we compare the uncalibrated signal (DN) with the \( G_{ar} \) (see Figures 7, B and E) we can see very little difference for the first image and quite a significant scatter for the second image. The mismatch between \( G_{ar} \) and DN on the second image indicates that either the DN were produced at IPF with incorrect antenna pattern gain, or the annotated APG is incorrect. As a result, when we calibrate noise and signal and compare them (see Figures 7, C and F, crosses and dots) in the first case the shift correction improves the NESZ profiles but in the second case the NESZ profiles are deteriorated.

In the second case the NESZ profile becomes shifted incorrectly and the noise is overestimated in the near range and underestimated in the far range, leading to the increased discontinuity in the denoised \( \sigma \) on Fig. 5(b). The noise scaling procedure is then applied to the incorrectly shifted NESZ vector and is not capable of adequately reducing the discontinuity. Another suggestion on the cause of the shift found between range-dependent corrections and noise vectors is the interpolation of the range noise vector to project it from slant range to ground range geometry. In particular, possibly, the IPF chooses the interpolation starting time incorrectly, taking into account the 'invalid samples’ occurring at the beginning of each sub-swath. From the end-user perspective, this inconsistency is heavily data-dependent and burst-dependent. It affects both GRDM and GRDH data in all polarizations. Further analysis of mismatch between range spread loss, signal and annotated noise vectors can in future be performed by comparing the radiometric retrievals from GRD products to those from SLC products from the same image acquisition, but goes out of scope of the present publication. The identified problems are accounted for in development of the future IPF versions.

B. Visual evaluation

As many improvements on thermal noise reduction have been made in Sentinel-1 ground segment processing facilities in IPF 3.1 and its later versions, one important question here is whether or not the NERSC algorithm still performs better than the ESA-recommended noise vectors subtraction. To give the reader a visual impression of the algorithm performance, a pair of representative examples over different surfaces are given below. A comparison of the noise removal performance of the ESA and NERSC algorithms is shown in Fig. 8 on a Sentinel-1B GRD image acquired in IW mode in VH polarization over the Laptse Sea. The figure shows clear sub-swath discontinuities for the ESA algorithm. Adding noise shift and magnitude correction in the new algorithm clearly helps in reducing the discontinuities, Fig. 8(b).

Another example is for a Sentinel-1A image acquired in EW mode over sea ice in the Weddell Sea as shown in Fig. 9, and is a good illustration demonstrating the difference in the thermal noise appearance in the presence of a mixture
of different surfaces. Fig.9 can give an impression of how the differences in backscatter from the sea ice surface of different types affect the thermal noise appearance on SAR images. Over the younger and saltier sea ice we have a weaker backscatter signal, while it is significantly stronger for older ice and is characterized by the mixed behaviour of surface and volume scattering. In the case of younger ice, the noise is dominating (well-pronounced stripes at sub-swath boundaries), while over the older ice type the noise appearance is almost negligible. In this case, the proposed algorithm gives a better result compared to raw ESA noise vector subtraction.

Therefore, the visual comparison also confirms that the modified NERSC algorithm still has potential for advanced noise removal for IPF versions later than 3.1.

C. Comparison with the previous version of the algorithm

Direct comparison of the new algorithm with the previous version [1] is not possible due to the absence of publicly available data processed with both IPF 2.9 and IPF 3.1. Nevertheless, we evaluated the performance of both algorithms and compared them with the ESA algorithm by processing several Sentinel-1 scenes taken over relatively calm water in the Greenland Sea in June 2019 (IPF 2.9, old algorithm) and June 2021 (IPF 3.2, new algorithm) as shown in Fig.10. The scenes (as shown on Fig.10(a, d)) were acquired from ascending and descending orbits within one week and the time difference between acquisitions did not exceed 2 days. The choice of time and area is dictated by availability of archived images. Profiles of denoised $\sigma^0$ were extracted from the processed scenes by a moving average window 100 × 100 pix. Understandably, the profiles contain $\sigma^0$ values from the same geographical positions but from different incidence angles.

Comparison of the profiles clearly shows that both the old and the new versions of the NERSC algorithm enhance the thermal noise removal procedure by reducing the spread of the profiles and improving their shape. For IPF 2.9, see Fig.10(b) and Fig.10(c), the old NERSC algorithm removes clearly wrong high values of $\sigma^0$ in the range of 8 - 13 $^\circ$E from profiles 0, 1 and 2. Other NERSC profiles (e.g., 3, 4 and 5) show less longitudinal variations (corresponding to the range variations) than the ESA ones. Overall the spread of NERSC profiles in Fig.10(c) is less than in Fig.10(b).

The ESA algorithm on data from IPF 3.2, see Fig.10(e) has a clearly better performance than IPF 2.9 Fig.10(b). Nevertheless, a few profiles (e.g. 1 and 5) show strong artificial range
Fig. 7: Scatterplots comparing (A, D) $G_{ar}$ with uncalibrated noise for two cases: before (crosses) and after (dots) shift correction; (B, E) $G_{ar}$ with uncalibrated signal; (C, F) calibrated signal and calibrated noise equivalent sigma zero (NESZ) for two cases: before (crosses) and after (dots) shift correction. Comparison is performed for range profiles averaged over 1000 rows from the source profiles on Fig. 5.

Fig. 10(f), resulting in a better match between profiles acquired in different days (e.g. profiles 4 and 5).

VI. CONCLUSION

An updated thermal noise removal algorithm comprising the correction of the annotated noise magnitude and range dependence is presented. The magnitude correction described in [1] is extended to more Sentinel-1 operational modes and polarizations. New noise scaling and power balancing coefficients are trained for both Sentinel-1 A and B, for Interferometric Wide and Extra Wide modes, for HV and VH polarizations. These coefficients are presented in the paper and in the denoising software [13].

The range dependence is corrected by identifying and reducing a mismatch between the range profiles of the annotated thermal noise and the annotated “antenna range gain” ($G_{ar}$), computed as the inverse squared product of the elevation antenna pattern (EAP) and the range spreading loss (RSL) gains. $G_{ar}$ is the only range-dependent component of the antenna pattern gain (APG) and modulates the range variations of both signal and noise powers. Ideally there should be no mismatch and noise profiles should be strictly proportional to $G_{ar}$. In practice, however, a mismatch of 10 - 100 pixels is observed in most of the scenes leading to a situation where the noise profile is overestimated on one side of a sub-swath and underestimated on the other side. That, in turn, leads to over- or under-correction of thermal noise at inter-swath boundaries and creates discontinuities and obvious stripes on Sentinel-1 images after thermal noise correction. The correction of the noise range dependence is very effective in most of the cases in removing these discontinuities. In a few cases, however, the annotated $G_{ar}$ is obviously incorrect - its range dependence does not match with the signal power. In such cases the quality of annotated noise, fitted to the incorrect $G_{ar}$, deteriorates and the combined noise removal algorithm provides worse results than the standard one.

While the magnitude correction is based on the scale/offset coefficients tuned on many images, the range dependence correction is performed individually for each SAR scene. Thus the combined algorithm addresses the problem of universal vs. individual correction raised in [7], but instead of an empirical
fitting of noise to signal, a more robust fitting of noise to the \( G_{ar} \) is proposed.

A quantitative quality metric is developed for estimating the signal discontinuities at inter-swath boundaries in the range direction. Extensive validation of the proposed combined algorithm is performed in several sites including open ocean, desert, Arctic and Antarctic sea ice and doldrums and shows that the new denoising largely improves the quality of SAR data in most cases and makes it more valuable for applications. As explained above, the new denoising algorithm deteriorates the SAR image quality only in the few cases when the annotated APG does not match the signal. These cases should be further investigated by ESA and the S-1 IPF maintainer to make sure that the SAR signal is in agreement with the annotated de-noising vectors and the antenna pattern. The results of this study should help to solve the problem in the future versions of the Sentinel-1 IPF.

The denoising software is available as an open-source Python code [13] which provides a convenient Application Programming Interface for performing thermal noise removal from Sentinel-1 data, training the noise scaling and power balancing coefficients, and validation. The repository hosting the code also provides documentation how to install and use the developed software.

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Fig. 10: Comparison of $\sigma^0$ profiles computed with ESA (B, E) and NERSC (C, F) algorithms applied to IPF 2.9 (B, C) and IPF 3.2 (E, F) Sentinel-1 data. Maps (A, B) show locations of Sentinel-1 scenes (thin lines) and position of the profiles (thick lines).

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