

## S-1 Mission Performance Centre

# Thermal Denoising of Products Generated by the S-1 IPF

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MPC-0392 DI-MPC-TN V1.1 2017,Nov.28



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#### Index Sheet:

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MPC-0392	DI-MPC-TN	V1.1	2017,Nov.28	i.2
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# List of tables and figures

### List of tables:

Table 4. Manning between variables and product appointing
Table 1: Mapping between variables and product annotation
List of figures:
Figure 1: NESZ measures for IW. Blue is the measured NESZ and the red lines are the predicted NESZ at minimum orbital altitude
Figure 2: NESZ measures for EW. Blue is the measured NESZ and the red lines are the predicted NESZ at minimum orbital altitudes
Figure 3: NESZ measures for IW. Blue is the measured NESZ and the red lines are the predicted NESZ at the minimum orbital altitude
Figure 4: NESZ measures for EW. Blue is the measured NESZ and the red lines are the predicted NESZ at the minimum orbital altitude
Figure 5: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ
Figure 6: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ
Figure 7: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ
Figure 8: Scalloping Gain versus Focused Burst Azimuth Time for IW Mode
Figure 9: Representation of the product folder tree, with in red the NADS, in blue the LADS and in green the CADS
Figure 10: Range denoising vector for EW GRD product
Figure 11: Azimuth denoising vector for EW GRD product
Figure 12: Azimuth noise vectors. Red the noise vector as written in the NADS (noiseAzimuthVector.noiseAzimuthLut), black the interpolated version representing the variable noiseAzimuthVector
Figure 13: IW Range intensity beta profile. Red line is the L1 product with thermal noise correction off, green line is L1 product with thermal noise correction on, blue line is noise corrected product using the provided NADS
Figure 14: EW Range intensity beta profile. Red line is the L1 product with thermal noise correction off, green line is L1 product with thermal noise correction on, blue line is noise corrected product using the provided NADS

MPC-0392 DI-MPC-TN V1.1 2017, Nov.28



# Applicable documents

- AD-1 S-1 Product Definition, S1-RS-MDA-52-7440, DI-MPC-PB, MPC-0239, version 2.6, 7/24/2015
- AD- 2 S-1 Product format specification, S1-RS-MDA-52-7441, DI-MPC-PB, MPC-0240, version 3.4, 5/9/2017
- AD- 3 TOPSAR: Terrain Observation by Progressive, De Zan, F., & Guarnieri, A. M., Geoscience and Remote Sensing, IEEE Transactions on, 2006 vol. 44(9), pp.2352-2360.
- AD- 4 Sentinel-1 SAR Performance Analysis, S1-TN-ARE-PL-0001, issue 1.7,01/03/2013
- AD- 5 Sentinel-1 Level 1 Detailed Algorithm Definition, S1-TN-MDA-52-7445, DI-MPC-IPFDPM, MPC-0307, version 2.1, 31/01/2017

#### **Reference documents**

**RD-1** Freeman, A. (1992). SAR calibration: an overview. *IEEE Transactions on Geoscience and Remote Sensing*, *30*(6), 1107–1121. http://doi.org/10.1109/36.193786

	MPC-0392	DI-MPC-TN	V1.1	2017,Nov.28
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# List of Contents

1. Introduction	1
<ol> <li>References and notations</li></ol>	
2.2. List of acronyms	2
2.3. List of variables	2
3. S-1 Noise Equivalent Sigma Zero	3
4. Impact of Noise on S-1 products	7
4.1. TOPS and azimuth descalloping	8
5. Denoising vectors	10
5.1. Range denoising vectors	11
E. 2. Animuth demoising vestors	12
5.2. Azimuth denoising vectors	12
5.2. Azimuth denoising vectors         6. Denoising procedure	
-	13
6. Denoising procedure	13 13
<ul><li>6. Denoising procedure</li><li>6.1. Denoising of TOPS (IW and EW) GRD products</li></ul>	13 13 13
<ul> <li>6. Denoising procedure</li></ul>	13 13 13
<ul> <li>6. Denoising procedure</li></ul>	13 13 13 14 14
<ul> <li>6. Denoising procedure</li> <li>6.1. Denoising of TOPS (IW and EW) GRD products</li> <li>6.1.1. Genetic variable description</li> <li>6.1.2. Computing the denoising matrix</li> <li>6.1.2.1. Step 1: Reading the azimuth denoising record</li> </ul>	13 13 13 14 14 15
<ul> <li>6. Denoising procedure</li> <li>6.1. Denoising of TOPS (IW and EW) GRD products</li> <li>6.1.1. Genetic variable description</li> <li>6.1.2. Computing the denoising matrix</li> <li>6.1.2.1. Step 1: Reading the azimuth denoising record</li> <li>6.1.2.2. Step 2: Reading the range denoising record and resampling</li> </ul>	13 13 14 14 14 15 17
<ul> <li>6. Denoising procedure</li> <li>6.1. Denoising of TOPS (IW and EW) GRD products</li> <li>6.1.1. Genetic variable description</li> <li>6.1.2. Computing the denoising matrix</li> <li>6.1.2.1. Step 1: Reading the azimuth denoising record</li> <li>6.1.2.2. Step 2: Reading the range denoising record and resampling</li> <li>6.1.2.3. Step 3: Generating range/azimuth denoising correction</li> </ul>	13 13 14 14 14 17 17
<ul> <li>6. Denoising procedure</li> <li>6.1. Denoising of TOPS (IW and EW) GRD products</li> <li>6.1.1. Genetic variable description</li> <li>6.1.2. Computing the denoising matrix</li> <li>6.1.2.1. Step 1: Reading the azimuth denoising record</li> <li>6.1.2.2. Step 2: Reading the range denoising record and resampling</li> <li>6.1.2.3. Step 3: Generating range/azimuth denoising correction</li> <li>6.1.3. Applying denoising</li> </ul>	13 13 14 14 14 15 17 17 18

MPC-0392

DI-MPC-TN

V1.1 2017, Nov.28



#### 1. Introduction

The Sentinel-1 (S-1) Instrument Processing Facility (IPF) is responsible for generating the complete family of Level-1 and Level-2 operation products [AD- 1].

In many detected SAR satellite images, the presence of additive noise can be noticed, especially in areas of low backscatter (like calm sea, lakes, etc.). Unlike quantization noise, which is dependent upon the signal power itself, the thermal noise can hardly be noticed, and becomes relevant only where the signal mean is low. Furthermore, in multi-swath acquisition modes this noise has typically a different intensity in each sub-swath, causing an intensity step at inter-swath boundaries. During raw data focusing, data (including the noise contributions) are multiplied by several fast time-varying radiometric correction factors. The result is that noise contributions are re-shaped in a range-varying fashion.

In addition for TOPS mode, the so-called TOPS descalloping function also shapes the noise contribution in azimuth.

This technical note describes the approach for removing the thermal noise contribution (aka product denoising step).

This technical note also introduce the specific way to apply the denoising for products generated since IPF version 2.90 for which dedicated azimuth denoising annotation are provided in addition to already available range ones [AD- 2].

This document is composed as follows:

- Section 1: this introduction
- Section 2: list of references and notations used in the document
- Section 3: definition of Noise Equivalent Sigma Zero and performances
- Section 4: Impact of noise on S-1 products
- Section 5: Description of denoising vectors
- Section 6: Denoising procedure
- Section 7: Verification results

MPC-0392 DI-MPC-TN V1.1 2017, Nov.28



#### 2. References and notations

This section describes the references and notations used in the technical note.

#### 2.1. Documentation

Refer to the list of reference documents at the beginning of the technical note.

#### 2.2. List of acronyms

CADS	Calibration Annotation Data Set
LADS	L1 Annotation Data Set
NADS	Noise Annotation Data Set
DN	Digital Number

#### 2.3. List of variables

All the variables necessary to compute accurately the denoising are provided as a direct annotation of the product [AD- 2] or can be easily derived. The table below provides the mapping between the variables and the product annotations.

variable	annotations
kψ	/product/generalAnnotation/productInformation/azimuthSteeringRate
$f_{\eta_c}$	/product/dopplerCentroid/dcEstimateList/dcEstimate/dataDcPolynomial
k <sub>a</sub>	/product/generalAnnotation/azimuthFmRateList/azimuthFmRate
f <sub>c</sub>	/product/generalAnnotation/productInformation/radarFrequency
Vs	/product/generalAnnotation/orbitList/orbit/velocity [x,y,z]
Nl <sub>burst</sub>	/product/swathTiming/linesPerBurst
$\Delta ts$	/product/imageAnnotation/imageInformation/azimuthTimeInterval
t0	/product/imageAnnotation/imageInformation/productFirstLineUtcTime
$\Delta \tau_s$	1 / (/product/generalAnnotation/productInformation/rangeSamplingRate)
$\tau(0)$	/product/imageAnnotation/imageInformation/slantRangeTime
Nc	/product/imageAnnotation/imageInformation/numberOfColumns
Nl	/product/imageAnnotation/imageInformation/numberOfLines
	Table 1: Mapping between variables and product annotation

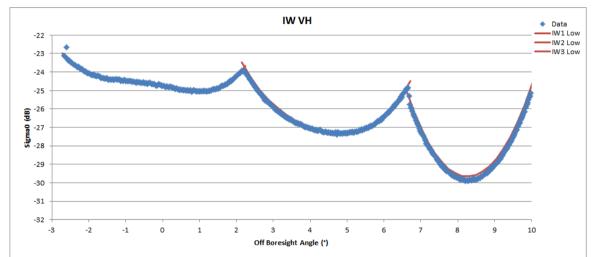




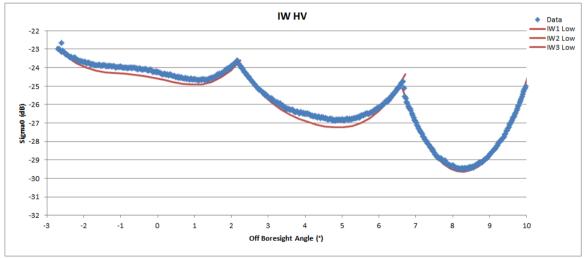
#### 3. S-1 Noise Equivalent Sigma Zero

The Noise Equivalent Radar Cross-Section (NESZ) is the radar cross-section of the thermal noise that is present in all S-1 imagery. The source of the thermal noise is the instrument itself and emissivity from the Earth's surface [RD- 1]. NESZ is a limit to the radar cross-section that can be measured. As S-1-A/B imagery has been corrected for the across-track variation in instrument gain, the elevation antenna patterns, the NESZ varies across the image. The largest NESZ is at near and far swath (in the case of IW and EW modes, at the near and far sub-swath). NESZ is more evident in cross-polarisation image (HV or VH) in dual-polarisation products due to the lower radar cross-section in these polarisations.

S-1A imagery with low ocean backscatter has been used to estimate the NESZ as shown in Figure 1 and Figure 2 for IW and EW mode and cross-polarisation. The requirement that the NESZ should be below -22 dB is met at all sub-swaths. Measurements are similar to or slightly worse than the NESZ predictions (red curves).



S1A\_IW\_GRDH\_1SDV\_20170515T122159\_20170515T122227\_016592\_01B85F\_BB84.SAFE



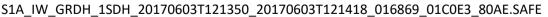
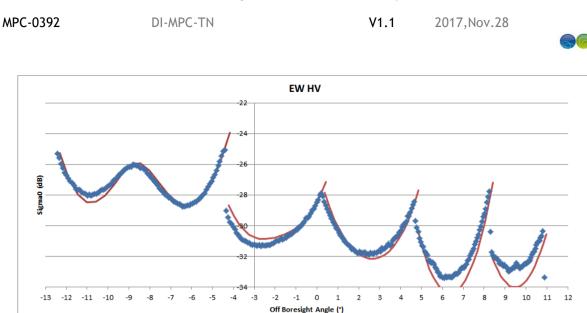
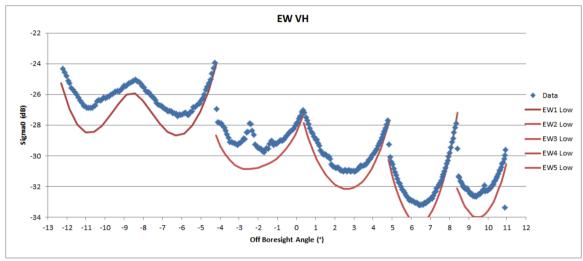


Figure 1: NESZ measures for IW. Blue is the measured NESZ and the red lines are the predicted NESZ at minimum orbital altitude.



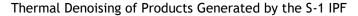
S1A\_EW\_GRDH\_1SDH\_20170129T181019\_20170129T181103\_015050\_018979\_AAFB.SAFE

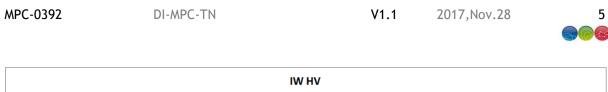


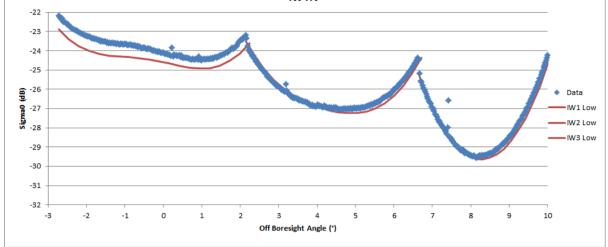
S1A\_EW\_GRDH\_1SDV\_20170608T122142\_20170608T122229\_016942\_01C330\_27F7.SAFE

Figure 2: NESZ measures for EW. Blue is the measured NESZ and the red lines are the predicted NESZ at minimum orbital altitudes.

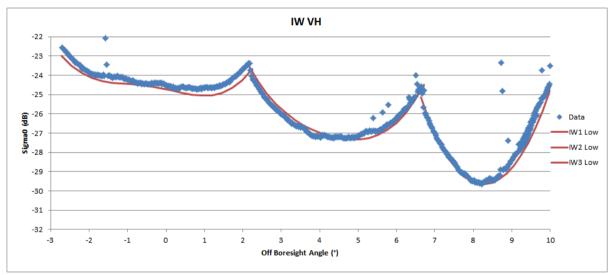
Examples of S1-B IW and EW imagery with low ocean backscatter have been used to estimate the NESZ as shown in Figure 3 and Figure 4. As for S-1A, the NESZ measurements are similar to or slightly worse than the NESZ predictions but are all better than the requirement of -22 dB.





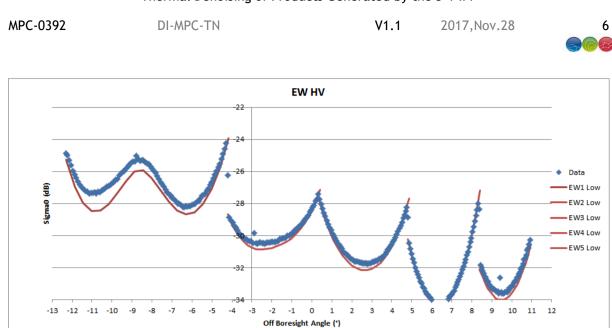


S1B\_IW\_GRDH\_1SDH\_20160824T173245\_20160824T173305\_001762\_002961\_F24D.SAFE

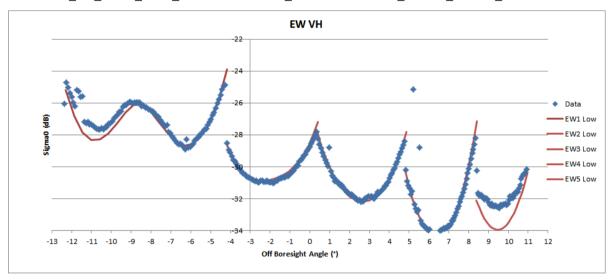


S1B\_IW\_GRDH\_1SDV\_20160822T174824\_20160822T174849\_001733\_002804\_6DD1

Figure 3: NESZ measures for IW. Blue is the measured NESZ and the red lines are the predicted NESZ at the minimum orbital altitude.



S1B\_EW\_GRDH\_1SDH\_20160904T054412\_20160904T054512\_001915\_002FF1\_35D0.SAFE



S1B\_EW\_GRDH\_1SDV\_20160721T060456\_20160721T060611\_001259\_0014E6\_9436.SAFE

Figure 4: NESZ measures for EW. Blue is the measured NESZ and the red lines are the predicted NESZ at the minimum orbital altitude.





#### 4. Impact of Noise on S-1 products

The impact of noise on image quality is on the detection of low radar cross-section features, especially in cross-polarisation (VH or HV) and on their measurement of radar cross-section. The presence of noise introduces a radiometric bias in any measured radar cross-section. This is illustrated in Figure 5 where the radiometric bias is shown for a range of measured radar cross-section as a function of NESZ from -22dB (the S-1A/B requirement) to -34dB (the lowest NESZ in Figure 1 to Figure 4). For example, if the NESZ were -32 dB (the red curve) and the measured radar cross-section were -22dB then the NESZ bias is 0.5dB. This means that the actual noise removed radar cross-section would be -22.5dB (i.e. actual radar cross-section = measured radar cross-section - radiometric bias).

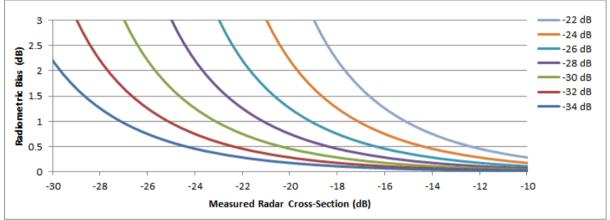


Figure 5: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ

The impact of the NESZ bias is further illustrated in Figure 6 and Figure 7 for IW and EW mode respectively for measured radar cross-sections of -10dB, -15dB and -20dB where the NESZ is the predicted NESZ shown in Figure 1 to Figure 4 (red curves). The impact of the elevation antenna patterns on the radiometric bias with swath position is clearly shown with a higher bias at the sub-swath edges introducing a radiometric jump at swath boundaries. Also there is reduction in the bias with increasing off-boresight angle and for EW mode compared to IW mode.

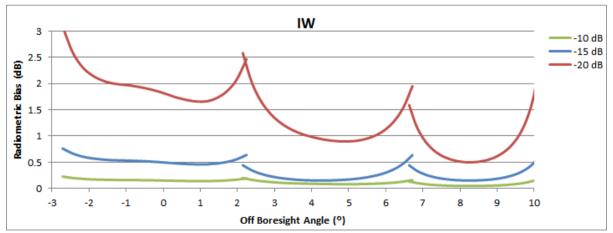


Figure 6: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ

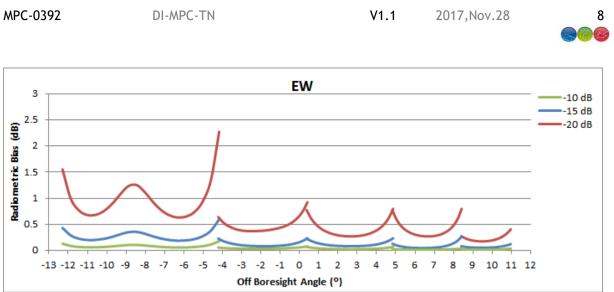


Figure 7: Radiometric Bias on Measured Radar Cross-Section as a Function of NESZ

#### 4.1. TOPS and azimuth descalloping

In TOPSAR modes, the steering of the antenna beam in the azimuth direction causes the weighting of the echoes to vary in the azimuth direction, inducing a scalloping effect: the area at the center of the burst is brighter than the ones at burst edges.

The azimuth scalloping for TOPSAR is shaped by the azimuth pattern of the element antennas that compose the antenna array. The scalloping extent depends on the maximum antenna steering angle within the burst and therefore it is sub-swath-dependent. The scalloping effect however, does not change from burst to burst within the same sub-swath.

The figure below shows an example of scalloping for the IW mode.

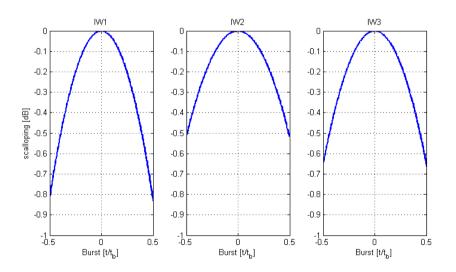


Figure 8: Scalloping Gain versus Focused Burst Azimuth Time for IW Mode

During raw data focusing, IPF compensates for this effect applying to the data the inverse of the scalloping gain function. This information is provided in input to IPF through dedicated LUTs in the AUX\_CAL file<sup>1</sup>, which contains the measured antenna element patterns for each swath/polarization combination. As said above, the correction is identical for all the bursts in a given swath and also

<sup>&</sup>lt;sup>1</sup> https://qc.sentinel1.eo.esa.int/aux\_cal/

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28



range invariant (the slight variation of the scalloping effect along range direction, in the order of magnitude of 10e-2dB, is not considered by IPF).

Due to this compensation, the noise contributions are re-shaped along azimuth direction. The denoising procedure shall then keep into account also this aspect in order to properly remove the thermal noise contribution from the data. In order to do this, starting from IPF 2.9.0 the noise vectors annotated in the L1 products have been improved adding to the range components the azimuth ones (see Sec. 5.2 for more details).



#### 5. Denoising vectors

The noise vectors are provided in the *annotation/calibration* folder in the *noise-\*.xml* file. In this document, they are referred as Noise Annotation Data Set **NADS**.

As usual with the S-1 products, there are as many noise XML files as there are measurement TIFF files. The number of TIFF files depends on the product type and on the polarisation configuration, for:

- SLC: Number Sub-swaths x Number of polarisations
- GRD: simply the number of polarisation (as the sub-swaths are merged in the case of TOPS)

The L1 Annotation Data Set (LADS) is the located in the main annotation folder.

For both *NADS* and *LADS*, the exact path can be retrieved from the product *manifest.safe* file contained in the product directory. Below is an example of reference to one of the noise annotation referenced by the manifest.

The Calibration Annotation Data Set (CADS) are provided next to the NADS, for example:



Figure 9: Representation of the product folder tree, with in red the NADS, in blue the LADS and in green the CADS

The noise vectors up to the IPF version 2.9.0 were provided only the range components. With the IPF 2.9.0 the azimuth variation has been introduced in order allow removing the noise in azimuth. The azimuth denoising record makes sense only for TOPS mode and thus is not provided for SM and WV modes.

The introduction of the azimuth denoising record also goes with an increase of the complexity for the denoising approach. This is because the:

- Range denoising vectors are varying with:
  - $\circ$   $% \left( Azimuth time, to take into account the change of geometry induced by the platform roll steering$
  - $\circ~$  Range, to accommodate for the changes of acquisition timeline and in particular the SWST changes
- Azimuth denoising vectors are sub-swath dependent as the burst belonging to different swaths are starting at different times and the antenna steering is different from a swath to another

MPC-0392 DI-MPC-TN V1.1 2017, Nov.28



For this reason the azimuth denoising vectors are provided in block-wise manner, where the blocks are delimited in range by the swath transition and in azimuth by changes in the swath merging, which follows the roll and SWST changes.

With the IPF 2.9.0, the swath merging strategy has been updated to limit the changes in the swath merging point, such that the number of azimuth denoising blocks is kept limited.

#### 5.1. Range denoising vectors

With the IPF 2.9.0 the range denoising record has been renamed from <code>noiseVectorList</code> to <code>noiseRangeVectorList</code> in order to introduce without ambiguity the <code>noiseAzimuthVectorList</code> (see next section).

However, the information provided is unchanged. It describes the evolution of the noise in range. For GRD, it covers the full swath (from IW1 to IW3 or from EW1 to EW5) while for SLC it provides the evolution only for the swath it belongs to.

```
...
<noiseRangeVectorList count="25">
    < noiseRangeVector >
        <azimuthTime>2015-03-11T07:39:27.860692</azimuthTime>
        <line>1268</line>
        <pixel count="210">0 40 80 ... 8330</pixel>
        <noiseRangeLut count="210">7.664914e+03 ... 7.603582e+03</noiseRangeLut>
        </ noiseRangeVector >
```

The vector is sub-sampled with typically a step of 40 samples. The sampling is however irregular as additional points have been introduced at swath transition. For example one extra point is added for the last pixel of swath n and one extra point is added for the first pixel of swath n+1.

This has been introduced in order to avoid interpolation errors at swath transition in the GRD case.

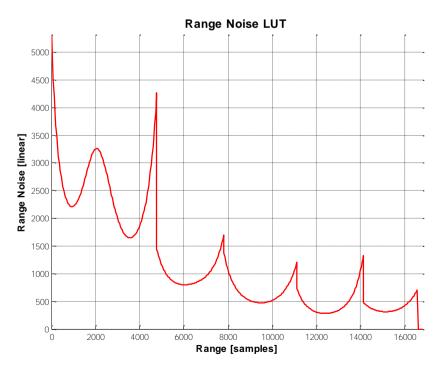


Figure 10: Range denoising vector for EW GRD product



#### 5.2. Azimuth denoising vectors

With the IPF 2.9.0 the azimuth denoising record noiseAzimuthVectorList has been introduced right after the noiseRangeVectorList.

It provides one azimuth-denoising vector for a portion of constant sub-swath merging transition point at near and far range.

```
...
<noiseAzimuthVectorList count="15">
    <noiseAzimuthVector>
        <swath>EW1</swath>
        <firstAzimuthLine>0</firstAzimuthLine>
        <firstAzimuthLine>0</firstRangeSample>
        <lastAzimuthLine>6242</lastAzimuthLine>
        <lastRangeSample>4773</lastRangeSample>
        line count="638">0 10 20 30 ...</line>
        </noiseAzimuthLut count="638">1.018141e+00 ...</noiseAzimuthLut>
        </noiseAzimuthVector>
```

The noiseAzimuthVector provides all the information (firstAzimuthLine. LastAzimuthLine, firstRangeSample, lastRangeSample) to identify the data block to which it applies.

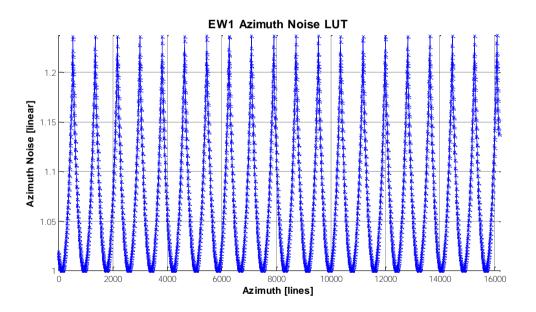


Figure 11: Azimuth denoising vector for EW GRD product

Similarly to the range vectors, the azimuth vectors are sub-sampled to limit the volume of the XML annotations.

In the GRD, the azimuth block includes several bursts and thus specific points are introduced at burst transition to avoid interpolation issues.

In the SLC case, only one record is provided. It represents the azimuth variation within one burst and the same record can be used for all the bursts within the same sub-swath.

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28



#### 6. Denoising procedure

As described in [AD- 5], the IPF provides by default the denoising vectors in the **NADS**. However, it is also able to actually apply the denoising as described in section 7.3.1. The native application of the denoising can be checked by using in the **LADS** the field:

/product/imageAnnotation/processingInformation/thermalNoiseCorrectio
nPerformed

Since the beginning of the mission, the denoising is not applied by the IPF as it is a destructive correction (not possible to revert the original pixel value) and to maintain a consistency with ERS and Envisat/ASAR data where this correction wasn't applied.

Before the application of the denoising by the user, it is a good practice to check the value of this Boolean in first place.

As defined in the L1 product specification [AD- 2], the application of thermal denoising consists in subtracting the noise LUT to the pixel <u>intensity</u>. Therefore, for SLC products it is applied after detection (going from complex to amplitude) and raising to square (amplitude to intensity)  $|DN|^2$ .

$$DN(i,j)^{2}_{denoised} = (|DN(i,j)|^{2} - \eta(i,j)) < O$$
[Eq-1]

Subtracting the noise can lead to negative values. It is therefore necessary to set negative values to zero. This is denoted in the above equation by the "< 0" operator, clipping all negative to 0.

The denoising procedure described in this section consists in simply applying this formula. The complex part being for TOPS GRD to use the proper denoising vectors for each block into which the image is divided by the noise annotations.

The sections below describe the approach for denoising for the following two cases:

- TOPS GRD products;
- SM SLC/GRD and TOPS SLC products.

#### 6.1. Denoising of TOPS (IW and EW) GRD products

The denoising approach described in this document, is not meant to be efficient computationally wise. It is meant to provide a clear understanding of the annotation provided in the *NADS* and how to use them. In the section 6.3 tips are provided for users looking for an efficient implementation.

The document describes a two-step approach that consists in:

- 1- Computing a denoising correction image that would represent the noise matrix  $\eta(i,j)$ . This is the most complex part that is performed block-wise;
- 2- Denoising, which is simply the application of the equation [Eq- 1].

#### 6.1.1. Genetic variable description

```
swathList \rightarrow list of swaths covered by the NADS. In the IW GRD case it is ['IW1', 'IW2', 'IW3']
```

```
swath \rightarrow is the current swath for which the correction matrix \eta is computed it takes sequentially the value of swathList
```

```
numberOfAziDenoiseBlocks \rightarrow number of azimuth denoising vectors belong to the subswath swath_
```

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28



#### 6.1.2. Computing the denoising matrix

The denoising matrix is computed for each sub-swath (even for GRD) and for each azimuth denoising block. This means that steps 1 to 3 are encapsulated into two for loop statements as shown below:

```
For ss=0, n_elements(swathList)-1 do begin
    swath_ = swathList[ss]
    #getting the number of azimuth block belonging to swath_
    numberOfAziDenoiseBlocks =
count(/noise/noiseAzimuthVectorList/noiseAzimuthVector/swath eq swath_)
    for b=0, n_elements(numberOfAziDenoiseBlocks) -1 do begin
        step 1
        step 2
        step 3
    endfor
endfor
```

#### 6.1.2.1. Step 1: Reading the azimuth denoising record

Put into a memory structure the b<sup>th</sup> azimuth record belonging to the *swath*. This is made by the (not described) function *getNoiseAzimuthRecord*.

Note that the azimuth records are not ordered by swath. Consequently, the b<sup>th</sup> record of *swath*\_ is not necessarily the b<sup>th</sup> record of the full XML *noiseAzimuthVectorList*.

noiseAzimuthVector \_ → getNoiseAzimuthRecord(b, swath\_)

<code>noiseAzimuthVector\_</code> is the memory image of the XML <code>noiseAzimuthVector</code> as described in section 5.2.

noiseAzimuthVectorStart  $\rightarrow$  t0+ (noiseAzimuthVector.firstAzimuthLine) \*  $\Delta$ ts noiseAzimuthVectorStop  $\rightarrow$  t0+ (noiseAzimuthVector.lastAzimuthLine) \*  $\Delta$ ts

Create the list of range samples belonging to the  $b^{th}$  block defined by noiseAzimuthVector\_.

MPC-0392 DI-MPC-TN V1.1 2017, Nov.28



The azimuth denoising record is sub-sampled and requires to be resampled to provide one correction for each line of the b<sup>th</sup> block. This is done using the (not described) function *interpol*. The result of such interpolation is shown in Figure 12.

At the end of this step, *noiseAzimuthMatrix* is an array of the same dimension of the current b<sup>th</sup> azimuth block *numberOfSamples x numberOfLines* containing the azimuth correction matrix for all samples of the block.

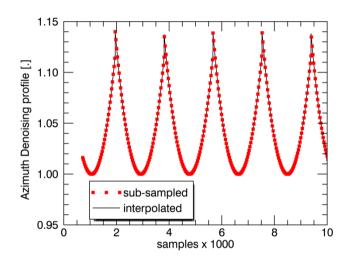


Figure 12: Azimuth noise vectors. Red the noise vector as written in the NADS (noiseAzimuthVector.noiseAzimuthLut), black the interpolated version representing the variable noiseAzimuthVector

#### 6.1.2.2. Step 2: Reading the range denoising record and resampling

The range denoising vectors are indexed by azimuth time. It is this therefore necessary to identify which range vectors belong to this block. This is done thanks to the (not described) functions:

- getNoiseRangeRecordsInInterval(): returns the range vectors within a valid azimuth time interval.
- getNearestRangeRecordInInterval(): given an azimuth time interval and a valid azimuth time, the function returns the nearest range vector falling inside the interval.
- getNoiseRangeRecordByIndex():function returning the range noise record by its index

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28 10

16

As mentioned earlier, several range vectors are expected to fall into the block due to the variation of the roll steering.



noiseRangeVectorFirstIndex and noiseRangeVectorLastIndex represent the index
of the record from the XML list /noise/noiseRangeVectorList/noiseRangeVector.

In case the azimuth block is too small and does not contain any range vectors, we have to choose a range vector outside of the azimuth block. This means that its merge points are different from those of the azimuth block being processed. In this special case, selecting two range vectors with different merge points and interpolating between them is not recommended. The preferred strategy is choosing the range vector belonging to the current subswath that is closest to the center of the azimuth block. In case this vector has a range extent that is smaller than the current azimuth block, extrapolation will be performed in the following step. Note that it is important that the chosen range vector stays in the extents of the current subswath, because otherwise it would contain null values instead of valid range samples. For better performances, the start and end time of each sub swath can be calculated before looping through the azimuth blocks.

The next step consists in reading and interpolating all the range vectors belonging to the block. This is done by the code shown below. Note that the interpolation of each range vector is not performed on its full extent, but only on the region of interest of the current azimuth block: this helps in case there is no range vector in the current azimuth block, and the closest range vector belongs to an azimuth block with smaller range extension. For this reason, the interpol() function must perform extrapolation in case it is necessary.

```
noiseRangeVectorList - create_array(numberOfSamples_, numberOfNoiseRangeVector)
noiseRangeVectorLine - create_array(numberOfSamples_, numberOfNoiseRangeVector)
for index - 0, numberOfNoiseRangeVector-1 do begin
rangeRecordIndex - index + noiseReangeVectorFirstIndex
rangeRec_ - getNoiseRangeRecordByIndex (rangeRecordIndex)
```





noiseRangeVectorList contains numberOfNoiseRangeVector vectors belonging to the azimuth block. Those have been properly resampled in range using the (not described) function *Interpol*, but are still sub-sampled in azimuth.

#### 6.1.2.3. Step 3: Generating range/azimuth denoising correction

This step consists in performing the azimuth resampling and the generation of the full azimuth and range noise correction.

The *numberOfNoiseRangeVector* vectors are associated with a line number located in *noiseRangeVectorLine*. The vectors need to be resampled in azimuth to provide one range correction at each line belonging to the block.

At the end of this step *noiseRangeMatrix* is a matrix of the same dimension of the current azimuth block that contains the range noise correction for each.

The full (range and azimuth) denoising matrix is obtained by element-multiplication of the *noiseRangeMatrix*\_ with the *noiseAzimuthMatrix*\_.

 $noiseCorrectionMatrix \rightarrow noiseRangeMatrix * noiseAzimuthMatrix$ 

#### 6.1.3. Applying denoising

The application of the denoising correction to the selected block of data is performed according to equation [Eq- 1], i.e. simply subtracting the *noiseCorrectionMatrix*\_ computed at the previous step to the corresponding portion of data, after having computed its intensity and clipping to 0 negative values.



#### 6.2. Denoising of SM SLC/GRD and TOPS SLC products

SM SLC, GRD and TOPS SLC have the particularity that specific annotations are provided for each (sub-)swath (i.e. product channel).

The SM SLC and GRD denoising step simply consist in:

- 1- retrieving the denoising vector closest to the (block of ) lines to be denoised;
- 2- interpolating to get a value per sample;
- 3- in the case of SLC, doing detection of the complex Digital Number  $(|DN|^2)$ ;
- 4- subtracting the denoising LUT.

For TOPS SLC the denoising needs to be done prior sub-swath merging, i.e. on each single burst of data. In addition, also the azimuth contribution shall be kept into account, as described in the section 4.1. For these reasons the procedure above is modified as follows:

- 1- retrieving the range denoising vector closest to the burst to be denoised;
- 2- interpolating to get a value per sample;
- 3- retrieving the azimuth denoising vector;
- 4- interpolating to get a value per line;
- 5- combining the range and azimuth contributions multiplying them together;
- 6- doing detection of the complex Digital Number  $(|DN|^2)$ ;
- 7- subtracting the denoising LUT.

#### 6.3. Efficiency

As previously said, the procedure described in the section 6.1 is not meant to be efficient computationally wise, but just a clear description of how to apply denoising on L1 products generated by IPF. In particular, the block-wise approach described could result inefficient for bigger products. In this section is briefly presented an alternative method that operates on the data in a column-wise manner, following the way they are physically written to disk.

The pre-requirements of this method are that:

- all the *NADS* information (range and azimuth vectors and blocks coordinates) are read once and for all at the beginning of the procedure, in order to avoid continuous accesses to these files;
- all the noise range and azimuth vectors are interpolated once and for all at the beginning of the procedure to have respectively one value per samples and per line of the selected product.

Then the detailed procedure consists in:

- 1- reading one complete line of data;
- 2- using its azimuth time to select the corresponding noise range vector (see section 6.1.2.2);
- 3- using the information in the **NADS** to select the blocks intersected by the noise range vector and divide it in correspondence of the swath transitions, obtaining a number of subvectors equals to the number of sub-swaths;
- 4- using the current line to select, for each sub-vector, the corresponding noise azimuth correction;
- 5- combining the noise range and azimuth contributions;
- 6- reconstructing the complete noise range vector;
- 7- applying it to the line of data;
- 8- moving to the next line.

#### 7. Verification Results

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28

19

In order to validate the IPF noise annotation and the proposed denoising procedure, the NADS was used to denoise a GRD product independently from IPF.

The validation was executed on two Doldrums scenes, where the backscatter is low and the impact of the thermal noise is dominant:

- S1B\_IW\_RAW\_\_0SDV\_20170515T005157\_20170515T005229\_005602\_009D01\_4C55.SAFE
- S1B\_EW\_RAW\_\_0SDV\_20160802T003514\_20160802T003622\_001431\_001B7D\_175E.SAFE

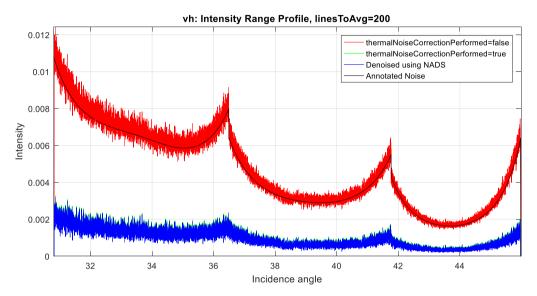


Figure 13: IW Range intensity beta profile. Red line is the L1 product with thermal noise correction off, green line is L1 product with thermal noise correction on, blue line is noise corrected product using the provided NADS. Natural values are used.

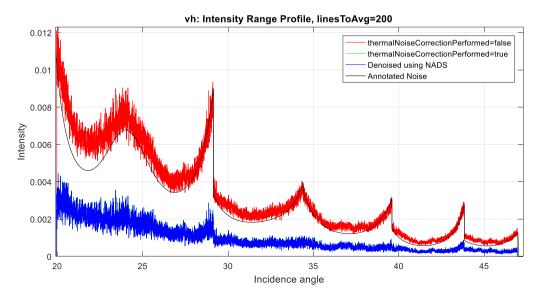


Figure 14: EW Range intensity beta profile. Red line is the L1 product with thermal noise correction off, green line is L1 product with thermal noise correction on, blue line is noise corrected product using the provided NADS. Natural values are used.

MPC-0392 DI-MPC-TN V1.1 2017,Nov.28



The figures above display the average range profiles of the scene using a window of 200 azimuth lines.

The red line is the profile with the *thermalNoiseCorrectionPerformed* flag is set to *false*, the green line is the profile with the *thermalNoiseCorrectionPerformed* flag is set to *true*. The blue line is a product obtained applying the noise map calculated from the NADS on a GRD product where the noise was not removed by IPF (*thermalNoiseCorrectionPerformed=false*). The black line is the noise annotation.

It can be seen that the green line and blue line are really close to each other: this means that the actual thermal noise correction can be properly reconstructed from the NADS. A residual small bias (0.2dB worst case) between the correction obtained using NADS and the one applied by IPF is observed and ascribed mainly to the quantization error introduced by L1 SAFE product generation step.

In Figure 13 and Figure 14, the de-noising is performed in two steps: firstly, subtracting from the L1 GRD image the noise map generated using the procedure in section 6; then, all negative values are clipped to zero. This is the same procedure performed internally by IPF. However, when averaging over multiple lines to generate plots like those in Figure 13 and Figure 14, the resulting de-noised profile are slightly biased due to the fact that, since the negative values were clipped, only non-negative pixel values are taken into account when averaging. To improve such kind of visualization, negative values can be clipped *after* computing the average, resulting in profiles much closer to zero as can be seen comparing Figure 13 and Figure 15.

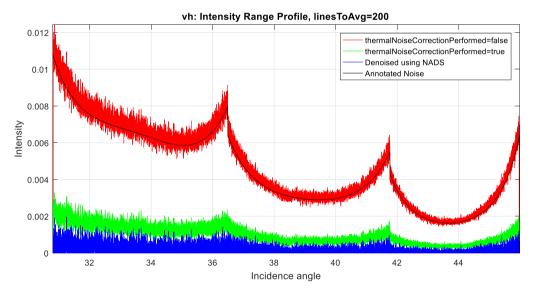


Figure 15: IW Range intensity beta profile. Red line is the L1 product with thermal noise correction off, green line is L1 product with thermal noise correction on, blue line is noise corrected product using the provided NADS and clipping negative values after the average. Natural values are used.

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