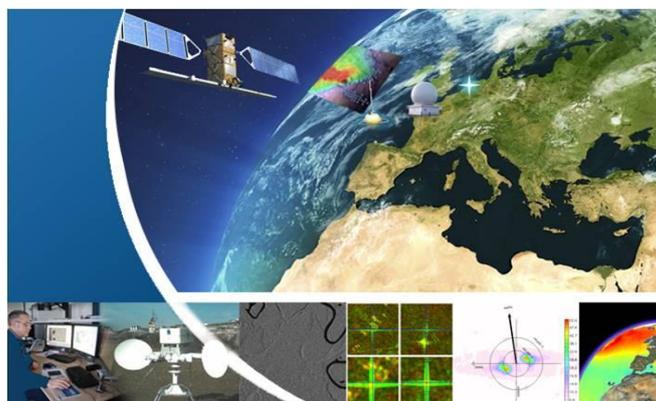




# Sentinel-1: Using the RFI annotations



Reference: MPC-0540

Nomenclature: DI-MPC-OTH

1.1 - 31/05/2023



Project funded under the European Union's Copernicus Program.

Copernicus, previously known as GMES (Global Monitoring for Environment and Security), is the European Programme for the establishment of a European capacity for Earth Observation.

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## CHRONOLOGY ISSUES/HISTORIQUE DES VERSIONS

Issue/ Version	Date	Object/Objet	Written by/ Rédigé par
1.0	11.02.2022	Includes description of RFI mitigation on product quality	G.Hajduch, N.Franceschi (ARESIS) M.Pinheiro (ESA) A.Valentino (ESA)
1.1	31.05.2023	Correction on the description of RFI mitigation activation in section 2.2.2. Starting with IPF 003.51, when an RFI is prescreened on one burst, the RFI mitigation is activated for all bursts and swath of the same polarization.	A.Cotrufo G.Hajduch

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# 1 Introduction

## 1.1 Background/Context

The Sentinel-1 products are generated using the Sentinel-1 Instrument Processing Facility (IPF). From one version of the IPF to another, the implemented processing evolves so as to improve the product performances.

Starting from version 3.40 of the IPF, specific processing is implemented into steps to (1) detect potential presence of Radio Frequency Interferences (RFI) and (2) optionally to mitigate their impact on product performances. The status of those two steps is annotated in the Sentinel-1 products.

## 1.2 Purpose of this document

The RFI detection and mitigation process is documented in the Sentinel-1 Level-1 Detailed Processing Model [S1-DPM].

The way the Sentinel-1 IPF is annotating the results of RFI detection and mitigation is documented in [S1-PS].

The purpose of this document is to guide the Sentinel-1 product user on how to use those RFI annotations depending on the various versions of the Sentinel-1 IPF.

This document is organised as follows:

- Section 1: this introduction
- Section 2: presents the behaviour of the S-1 IPF depending on its version for what concern the annotation of RFI
- Section 3: presents the main files of the product content to be considered for what concerns the RFI annotations
- Section 4: presents examples of RFI mitigation on the products

Two appendices provide example of RFI as observed and mitigated.

## 1.3 Applicable and Reference Documents

S1-DPM	Sentinel-1 Level 1 Detailed Processing Model (DPM), S1-TN-MDA-52-7445, MPC-0307, version 2.3
S1-PS	Sentinel-1 Product Specification, S1-RS-MDA-52-7441, MPC-0240, version 3.9

## 1.4 Acronyms and definition

DLR	Germany's national research centre for aeronautics and space
EW	Extra Wide
GRD	Ground Range Detected
IRF	Impulse Response Function
ISLR	Integrated side lobe ratio
IW	Interferometric Wide

PSLR	Peak side lobe ratio
RFI	Radio Frequency Interference
S-1 IPF	Sentinel-1 Instrument Processing Facility (Sentinel-1 processor)
SLC	Single-look complex
SM	Stripmap
TDS	Test Data Set
VH	Vertical Transmit-Horizontal Receive Polarisation
VV	Vertical Transmit-Vertical Receive Polarisation
WV	Wave
XML	Extensible Markup Language



## 2 Behaviour of the Sentinel-1 IPF with respect to RFI

This section describes the behaviour of the Sentinel-1 IPF depending on its version.

### 2.1 For S-1 IPF before version 3.40

For IPF before version 3.40, there is no specific processing related to RFI detection and mitigation.

The version of the S-1 IPF used to generate one product is annotated in its manifest.

```
<safe:facility country="France" name="Copernicus S1 Core Ground Segment - TLS" organisation="ESA" site="Airbus  
Defence and Space-Toulouse">  
    <safe:software name="Sentinel-1 IPF" version="003.31"/>  
</safe:facility>
```

Figure 1: Annotation of IPF version in the manifest of Sentinel-1 product.

The following XPath applied in the product manifest can be used to catch this value.

```
./xmlData/safe:processing/safe:facility/safe:software/@version
```

### 2.2 For S-1 IPF starting with version 3.40

The behaviour of the S-1 IPF for what concerns the RFI mitigation is based on three main successive steps:

- 1- A pre-screening of RFI evidence in noise measurements from specific pulses in the acquisition timeline. This pre-screening is performed (or not) depending on the availability of the required noise measurements
- 2- A detection of RFI from the measurement data. This detection step is configurable and can either be not applied at all, or only applied when RFI evidence are provided by the pre-screening step, or systematically applied
- 3- A mitigation of RFI applied on the measurement data depending on the results of the previous steps.

For IW and EW modes, the RFI pre-screening step can only be performed when the noise measurements are available. The noise measurements are always available in the nominal production scenario.

For SM and WV modes, the required noise pulses are not available, and no pre-screening step is performed and available.

Moreover, the behaviour of the S-1 IPF is configurable regarding the activation of the RFI correction step and regarding the mitigation type. The details on the RFI mitigation algorithm implemented in the S-1 IPF can be found in [S1-DPM]. A summary of the three steps depending on the mitigation strategy is provided in following figures.

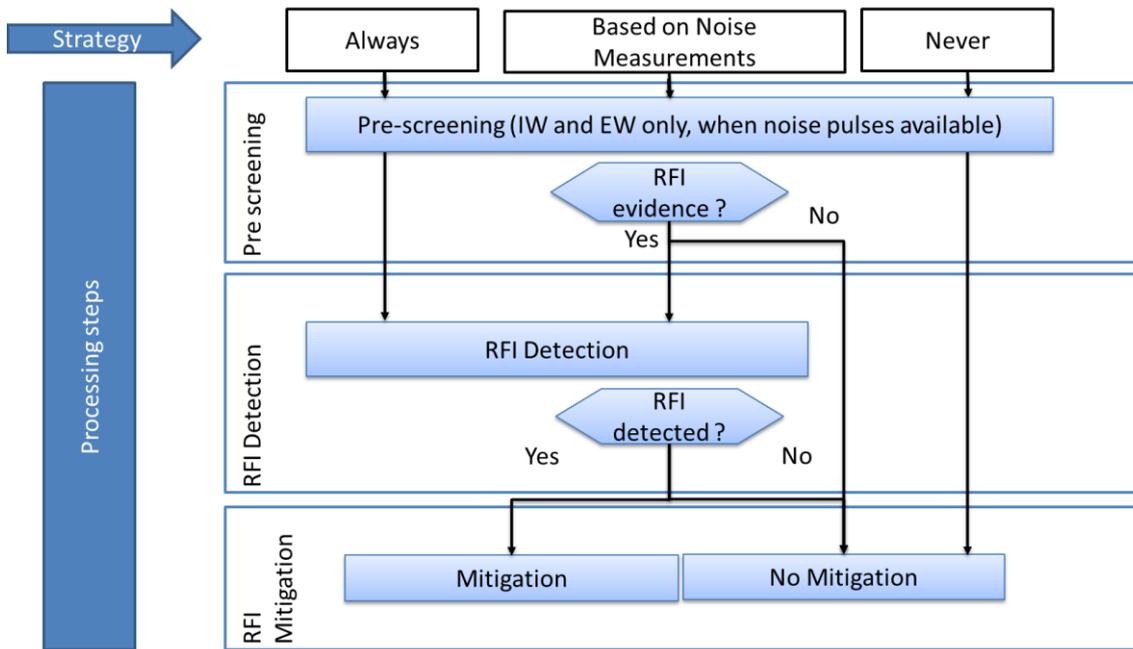


Figure 2: Rationale of the three steps of pre-screening / RFI Detection / RFI mitigation for EW and IW acquisition modes

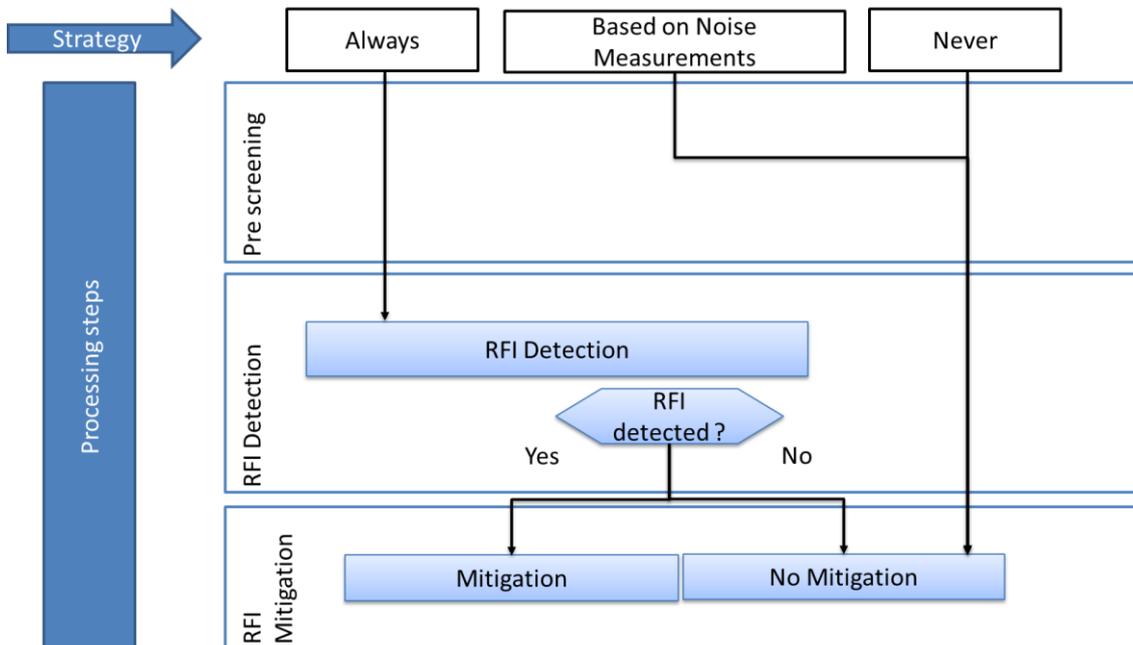


Figure 3: Rationale of the three steps of pre-screening / RFI Detection / RFI mitigation for SM and WV acquisition modes

## 2.2.1 Activation strategy

Three types of activations can be set as described in [S1-DPM] (see as well Figure 2):

- Either mitigation is never activated
- Or a mitigation is activated depending on analysis of noise echoes during the pre-processing (only applicable for Extra Wide Swath and Interferometric Wide Swath modes)
- Or the mitigation is activated systematically, not depending on the content of noise echoes.

The mitigation strategy is documented in the main annotation files of the product. There is one annotation file for each polarization and dataset. For instance:

- IW Single Polarisation GRD products contain one annotation file
- IW Dual Polarisation SLC products contain six annotation files (two polarisations and three sub swaths)
- EW Dual Polarisation SLC products contain ten annotation files (two polarisations and five sub swaths)

Below is an example of annotation of RFI activation in one annotation file (with no RFI mitigation activated).

```
<processingInformation>
  <rfiMitigationPerformed>Never</rfiMitigationPerformed>
  <rfiMitigationDomain>TimeAndFrequency</rfiMitigationDomain>
```

## 2.2.2 RFI annotation vs activation strategy

Depending on the activation strategy the RFI annotations does not contain the same information. This is summarized in following table.

rfiMitigationPerformed (value)	flag	Behaviour and content of RFI annotation
Never		<p>The RFI mitigation is not activated, regardless of actual the content of the noise pulses or the data.</p> <p><i>For EW and IW modes:</i></p> <p>Despite the fact that there is no mitigation, the pre-screening step is performed for the TOPS modes based on availability of noise measurements. Those noise measurements are always available in the nominal production scenario.</p> <p>Parameters of the pre-screening of RFI are annotated for each burst in the rfiDetectionFromNoiseReport element.</p> <p>However, as RFI detection is never applied, there is no single flag indicating the presence of RFI for the considered polarization (and sub swath for SLC products). An example is provided in Figure 4</p> <p><i>For SM and WV:</i></p> <p>For these modes, there is not sufficient noise information to perform the preliminary screening. Hence, this pre-screening step is not done and there</p>



	is no way to spot presence of RFI from screening the content of the RFI annotation file.
BasedOnNoiseMeasurement	<p>The noise measurements are used to perform a pre-screening of evidence of RFI contamination. When such evidence are detected further RFI detection is performed on the data. This data based detection may trigger the RFI mitigation on the impacted bursts.</p> <p><i>For EW and IW modes:</i> The results of RFI pre-screening is annotated for each burst in the rfiDetectionFromNoiseReport element.</p> <p>When RFI is pre-screened at least in one burst of a certain sub-swath and polarization:</p> <ul style="list-style-type: none"> <li>• Prior to IPF 3.51: the data based RFI detection is activated for the corresponding bursts of the same sub-swath and polarization only.</li> <li>• Starting with IPF 3.51: the data based RFI detection is activated for all the bursts of all the subswaths with the same polarization. It is not automatically triggered for possible bursts of other polarizations.</li> </ul> <p>This is documented in the rfiMitigationApplied flag of the RFI annotation file.</p> <p>If its value is <i>None</i>, there is no RFI pre-screened in the polarisation and/or subswath. For all other values, an RFI was pre-screened in the product. An example is provided in Figure 5</p> <p><i>For SM and WV:</i> This activation strategy does not apply to SM and WV.</p> <p>Whatever the value of this parameter the behaviour is equivalent to “Never”.</p>
Always	<p>The RFI detection is applied systematically, regardless of the availability and content of the noise pulses or the data.</p> <p>The rfiMitigationApplied flag in the RFI annotation file does not necessarily reflects the presence of RFI in the product.</p>

### 2.2.3 Example of RFI annotation (Never)

Following figure presents example of RFI annotation contents using the strategy “Never” for an IW product. This illustrates a part of RFI annotation XML file for the IW1 sub-swath of an IW product.

For this example:

- The strategy is “Never”, meaning that no RFI detection is performed and hence no RFI mitigation.
- The noise measurement being available, a pre-screening is performed, and the results of this step are annotated

```
<?xml version="1.0" encoding="UTF-8"?>
<rfi>
<adsHeader>
<missionId>S1A</missionId>
<productType>GRD</productType>
```

```

<polarisation>VH</polarisation>
<mode>IW</mode>
<swath>IW</swath>
<startTime>2021-11-29T05:59:54.071699</startTime>
<stopTime>2021-11-29T06:00:19.070668</stopTime>
<absoluteOrbitNumber>40782</absoluteOrbitNumber>
<missionDataTakeId>317244</missionDataTakeId>
<imageNumber>002</imageNumber>
</adsHeader>
<rfiMitigationApplied>None</rfiMitigationApplied>
<rfiDetectionFromNoiseReportList count="34">
  <rfiDetectionFromNoiseReport>
    <swath>IW1</swath>
    <noiseSensingTime>2021-11-29T05:59:50.936820</noiseSensingTime>
    <rfiDetected>true</rfiDetected>
    <maxKLDivergence>2.999700e+05</maxKLDivergence>
    <maxFisherZ>4.462828e+01</maxFisherZ>
    <maxRfiPsd>6.293523e+01</maxRfiPsd>
  </rfiDetectionFromNoiseReport>

```

Figure 4: Example of RFI annotation file . In this case, despite the detection of the RFI (*rfiDetected=True*), no mitigation was performed (*rfiMitigationApplied=None*) due to the content of the *rfiMitigationPerformed* flag, which was set to Never.

## 2.2.4 Example of RFI annotation (BasedOnNoiseMeasurements)

Following figure presents example of RFI annotation contents using the strategy “BasedOnNoiseMeasurement” for an IW GRD product. For GRD product the RFI annotations are Provided for each polarization (and not for each sub-swath).

This illustrates a part of RFI annotation XML file for the VV polarization of the IW GRD product.

For this example, the strategy is “BasedOnNoiseMeasurement”, meaning that

- a pre-screening is performed on noise measurements and the results are annotated. Some noise measurements are associated to RFI evidences and some other are not. They can be segregated by the rfiDetectionFromNoiseReport/rfiDetected elements;
- when evidence of RFI is present in the noise measurements, further RFI detections are performed on the impacted sub swath/polarisation and the results are annotated in the rfiBurstReport elements

```
<?xml version="1.0" encoding="UTF-8"?>
<rfi>
  <adsHeader>
    <missionId>S1B</missionId>
    <productType>GRD</productType>
    <polarisation>VV</polarisation>
    <mode>IW</mode>
    <swath>IW</swath>
    <startTime>2021-02-10T18:30:44.640033</startTime>
    <stopTime>2021-02-10T18:31:09.639286</stopTime>
    <absoluteOrbitNumber>25548</absoluteOrbitNumber>
    <missionDataTakeld>199510</missionDataTakeld>
    <imageNumber>001</imageNumber>
  </adsHeader>
  <rfiMitigationApplied>TimeFrequency</rfiMitigationApplied>
  <rfiDetectionFromNoiseReportList count="34">
    <rfiDetectionFromNoiseReport>
      <swath>IW1</swath>
      <noiseSensingTime>2021-02-10T18:30:41.379966</noiseSensingTime>
      <rfiDetected>false</rfiDetected>
      <maxKLDivergence>8.669438e+00</maxKLDivergence>
      <maxFisherZ>4.897439e+00</maxFisherZ>
      <maxRfiPsd>0.000000e+00</maxRfiPsd>
    </rfiDetectionFromNoiseReport>
    ....
    <rfiDetectionFromNoiseReport>
      <swath>IW3</swath>
```

```

<noiseSensingTime>2021-02-10T18:30:51.565025</noiseSensingTime>
<rfiDetected>true</rfiDetected>
<maxKLDivergence>3.199680e+05</maxKLDivergence>
<maxFisherZ>2.328487e+01</maxFisherZ>
<maxRfiPsd>2.272598e+01</maxRfiPsd>
</rfiDetectionFromNoiseReport>
.... </rfiDetectionFromNoiseReportList>
....
<rfiBurstReportList count="33">
<rfiBurstReport>
  <swath>IW1</swath>
  <azimuthTime>2021-02-10T18:30:40.254003</azimuthTime>
  <inBandOutBandPowerRatio>1.350108e+01</inBandOutBandPowerRatio>
  <timeDomainRfiReport>
    <percentageAffectedLines>6.855926e+01</percentageAffectedLines>
    <avgPercentageAffectedSamples>3.008939e-02</avgPercentageAffectedSamples>
    <maxPercentageAffectedSamples>1.929368e+00</maxPercentageAffectedSamples>
  </timeDomainRfiReport>
  <frequencyDomainRfiBurstReport>
    <numSubBlocks>3</numSubBlocks>
    <subBlockSize>537</subBlockSize>
    <isolatedRfiReport>
      <percentageAffectedLines>2.007356e+01</percentageAffectedLines>
      <maxPercentageAffectedBW>1.556925e+00</maxPercentageAffectedBW>
    </isolatedRfiReport>
    <percentageBlocksPersistentRfi>0.000000e+00</percentageBlocksPersistentRfi>
    <maxPercentageBWAffectedPersistentRfi>0.000000e+00</maxPercentageBWAffectedPersistentRfi>
  </frequencyDomainRfiBurstReport>
</rfiBurstReport>

```

Figure 5: Example of RFI annotation file with activation based on noise measurement and RFI detected on the second burst. Note that there is no RFI detected on the first burst.

## 2.2.5 Example of RFI annotation (Always)

Following figure presents example of RFI annotation contents using the strategy “Always” for an IW product. This illustrates a part of RFI annotation XML file for the IW1 sub-swath of an IW product.

For this example, the strategy is “Always”, meaning that

- The RFI annotation file contains the pre-screening report but its results have no impact in deciding whether the RFI detection/mitigation is activated.
- RFI detections are performed on every burst and the results are annotated for both time and frequency domain

```
<?xml version="1.0" encoding="UTF-8"?>
<rfi>
  <adsHeader>
    <missionId>S1A</missionId>
    <productType>GRD</productType>
    <polarisation>VH</polarisation>
    <mode>IW</mode>
    <swath>IW</swath>
    <startTime>2021-11-29T00:27:01.329972</startTime>
    <stopTime>2021-11-29T00:27:26.328008</stopTime>
    <absoluteOrbitNumber>40778</absoluteOrbitNumber>
    <missionDataTakeId>317215</missionDataTakeId>
    <imageNumber>002</imageNumber>
  </adsHeader>
  <rfiMitigationApplied>TimeFrequency</rfiMitigationApplied>
  <rfiDetectionFromNoiseReportList count="34">
    <rfiDetectionFromNoiseReport>
      <swath>IW1</swath>
      <noiseSensingTime>2021-11-29T00:26:58.244407</noiseSensingTime>
      <rfiDetected>>false</rfiDetected>
      <maxKLDivergence>2.719806e+00</maxKLDivergence>
      <maxFisherZ>3.338530e+00</maxFisherZ>
      <maxRfiPsd>0.000000e+00</maxRfiPsd>
    </rfiDetectionFromNoiseReport>
    <rfiDetectionFromNoiseReport>
      <swath>IW1</swath>
      <noiseSensingTime>2021-11-29T00:27:01.002677</noiseSensingTime>
      <rfiDetected>>false</rfiDetected>
      <maxKLDivergence>3.448161e+00</maxKLDivergence>
      <maxFisherZ>3.547025e+00</maxFisherZ>
      <maxRfiPsd>0.000000e+00</maxRfiPsd>
    </rfiDetectionFromNoiseReport>
  </rfiDetectionFromNoiseReportList>
</rfi>
```

```

</rfiDetectionFromNoiseReport>
...
</rfiDetectionFromNoiseReportList>
<rfiBurstReportList count="33">
  <rfiBurstReport>
    <swath>IW1</swath>
    <azimuthTime>2021-11-29T00:26:57.144723</azimuthTime>
    <inBandOutBandPowerRatio>1.024431e+00</inBandOutBandPowerRatio>
    <timeDomainRfiReport>
      <percentageAffectedLines>7.097232e-01</percentageAffectedLines>
      <avgPercentageAffectedSamples>6.528836e-02</avgPercentageAffectedSamples>
      <maxPercentageAffectedSamples>4.268854e-01</maxPercentageAffectedSamples>
    </timeDomainRfiReport>
    <frequencyDomainRfiBurstReport>
      <numSubBlocks>3</numSubBlocks>
      <subBlockSize>537</subBlockSize>
      <isolatedRfiReport>
        <percentageAffectedLines>9.633257e+01</percentageAffectedLines>
        <maxPercentageAffectedBW>3.466012e+00</maxPercentageAffectedBW>
      </isolatedRfiReport>
      <percentageBlocksPersistentRfi>0.000000e+00</percentageBlocksPersistentRfi>
      <maxPercentageBWAffectedPersistentRfi>0.000000e+00</maxPercentageBWAffectedPersistentRfi>
    </frequencyDomainRfiBurstReport>
  </rfiBurstReport>
...
</rfiBurstReportList>
</rfi>

```

Figure 6: Example of RFI annotation file with activation forced to "always".

### 3 Sentinel-1 product structure and RFI annotation

The following table describes the elements of Sentinel-1 product structure to consider for RFI annotation starting with version 3.40 of the IPF.

```

.
├── measurement
├── annotation
│   ├── calibration
│   └── rfi
│       ├── rfi-s1a-iw-grd-vh-20211129t055954-20211129t060019-040782-04d73c-002.xml -> rfi annotation
│       └── rfi-s1a-iw-grd-vv-20211129t055954-20211129t060019-040782-04d73c-001.xml -> rfi annotation
│   ├── s1a-iw-grd-vh-20211129t055954-20211129t060019-040782-04d73c-002.xml -> contains information on RFI mitigation strategy
│   └── s1a-iw-grd-vv-20211129t055954-20211129t060019-040782-04d73c-001.xml -> contains information on RFI mitigation strategy
├── manifest.safe -> contains version of the IPF
├── preview
└── support

```

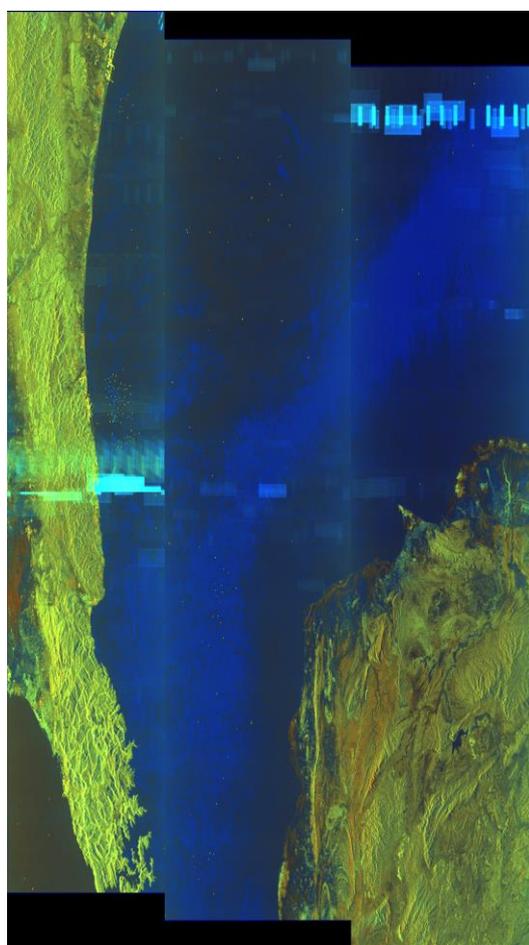
## 4 RFI mitigation and impact on product performance

### 4.1 Examples of RFI mitigation

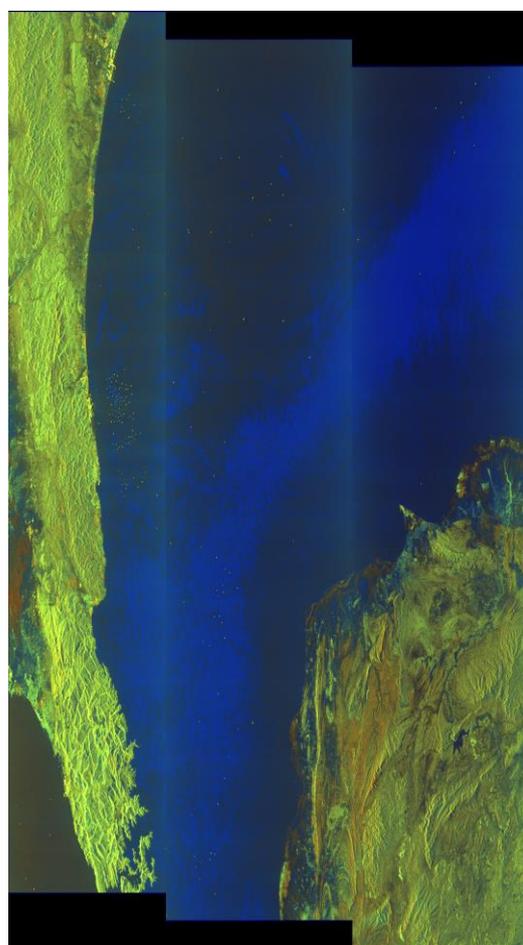
The RFI mitigation strategy applied in the IPF since 3.40 is designed to be conservative and not to produce degradation of the product performance beyond the portion of the image impacted by the interference. For this reason, the RFI observed in the Sentinel-1 products may not be completely suppressed.

The following figures present some illustrations:

- Figure 7: presents an example of efficient RFI suppression
- Figure 8: presents an example of incomplete RFI suppression
- Figure 9: presents an example where the RFI impacts the burst so much that it induces a significant power loss where the RFI was located (as expected), which cannot be compensated.
- Figure 10: presents a false alarm example where the pre-screening activates the RFI mitigation module even if no visible RFI is found in the quicklook.

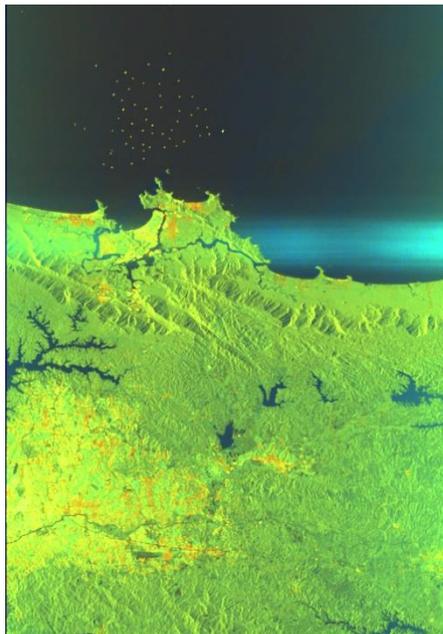


With previous RFI

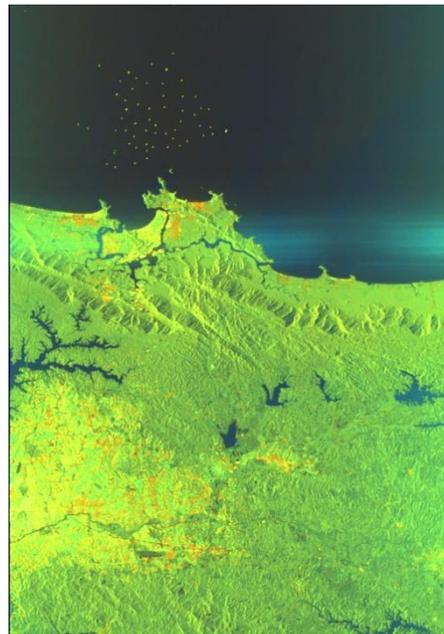


With RFI 3.4.0 (RFI suppressed)

Figure 7: Example of RFI mitigation (IW product acquired on 2019-11-24T14:16:38)



With previous RFI



With RFI 3.4.0 (RFI suppressed)

Figure 8: Example of RFI mitigation (Stripmap 6 product acquired on 2020-11-22T21:43:58).

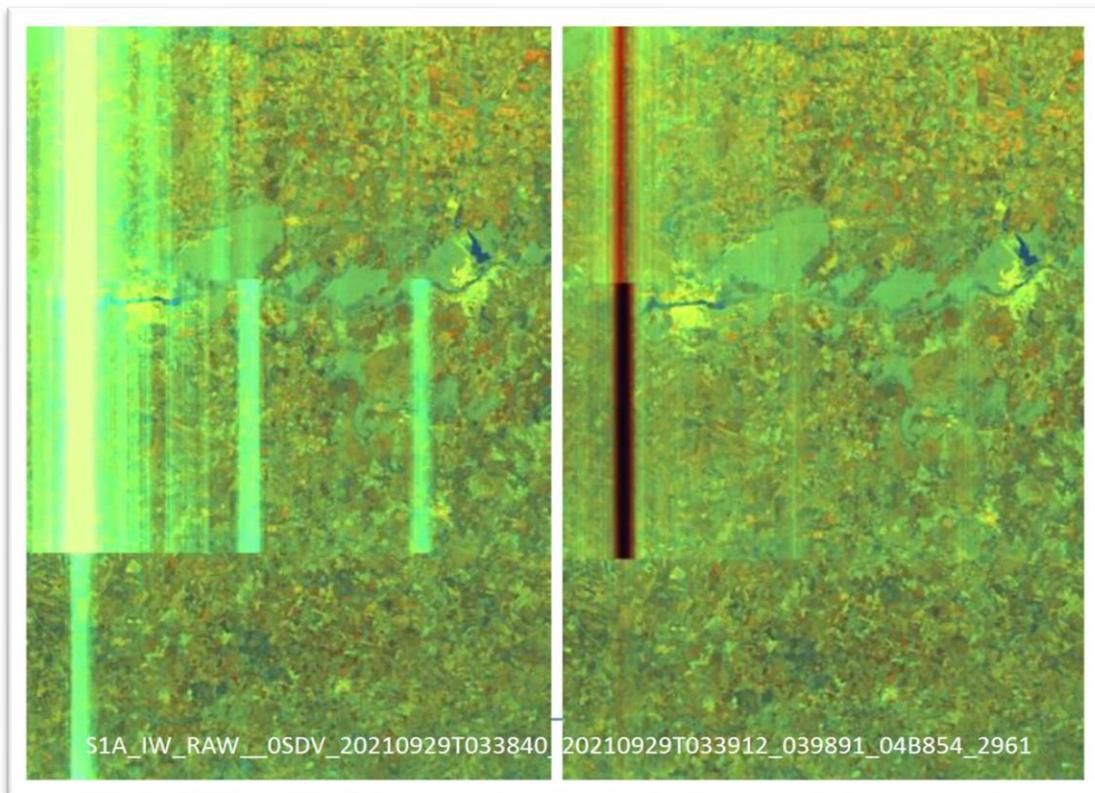


Figure 9: Example of RFI mitigation (IW 6 product acquired on 2021-09-29) left without mitigation, right with mitigation.

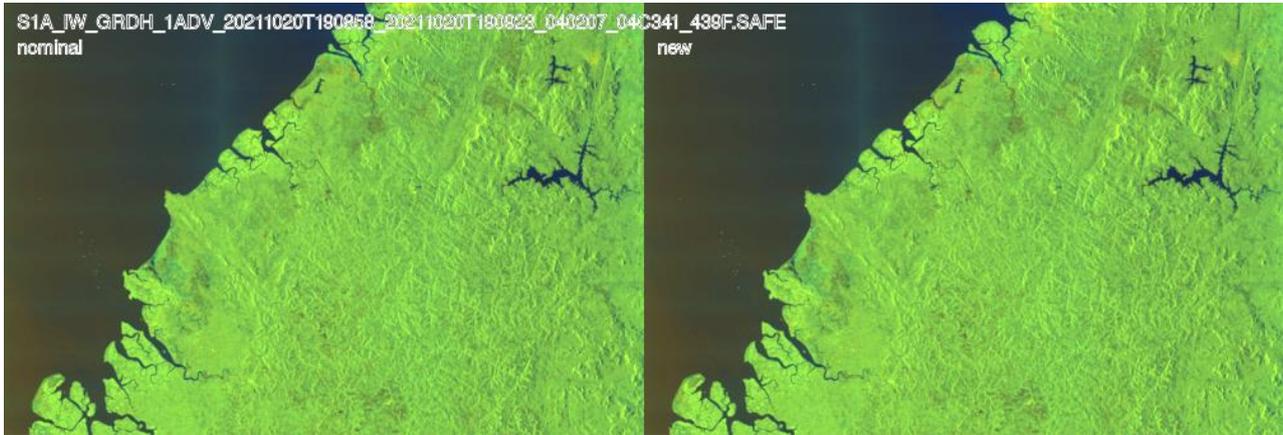


Figure 10: Example of false alarm in the pre-screening RFI mitigation (IW product acquired on 2021-10-20T19:08:58). The pre-screening commands to activate the mitigation module on the VH channel even if no evident artifact is present.

## 4.2 Impact on product performance

The impact of the RFI mitigation on product performance was assessed using simulated data and considering three indicators:

- **Interferometric coherence:** the interferometric coherence between the original SLC image (i.e., without RFI) and the impacted SLC image is computed in the area where the RFI artefacts were removed. The interferometric coherence measures the cross-coherence between the two images and, in case of perfect reconstruction should be equal to 1.
- **Azimuth transects** comparing the mean radiometric intensity in the azimuth direction between the original image and the corrected one is helpful to understand if the radiometric level of the image was altered by the mitigation algorithm.
- **Impulse response function:** the impulse response function (IRF) of a transponder placed in an area affected by RFI is studied before and after the mitigation and compared to the original IRF of the target. The goal of this analysis is evaluating the impact of the mitigation process in the image resolution.

These quantities are studied for both time-domain and frequency-domain mitigation approaches.

The detailed description of the two approaches is provided in [S1-DPM]. The approach effectively considered for the mitigation depends on the content of the AUX\_PP1 auxiliary file (configuration file of the level 1 processor), being either a time-domain, frequency-domain, or time and frequency domain.

### 4.2.1 Simulated RFI

The impact of RFI mitigation algorithm on product performance is assessed using simulated data. By injecting artificial interferences into known data, the efficiency of the algorithm in removing the RFI can be assessed at a quantitative level.

The test data set consists of two acquisitions:

- **DLR-TDS:** an IW DH scene over the DLR transponders and corner reflectors in the German Alps. It is used for analysing the impact of the mitigation on the impulse response function.  
S1A\_IW\_RAW\_\_OSDH\_20140624T170903\_20140624T170935\_001195\_0012C2\_5B9E.

- **RF-TDS:** an IW DV acquisition on the Amazon rain forest. This data set is used for studying the impact of the mitigation on radiometry and interferometric coherence. S1A\_IW\_RAW\_\_OSDV\_20200226T102109\_20200226T102141\_031422\_039E0C\_4608.

In both cases, the injected RFI is modelled by means of a stationary complex Gaussian process. Four types of interfering signals have been simulated:

- **RFI-TD-NB:** High power signal concentrated in the time domain with a duration  $30\mu\text{s}$  pulsating with a frequency of 4kHz. The RFI-to-signal ratio is 50dB.
- **RFI-TD-WB:** Signal concentrated in the time domain with a duration of  $200\mu\text{s}$  pulsating with a frequency of 500Hz. The RFI-to-signal ratio is 30dB.
- **RFI-FD-NB:** Signal concentrated in the frequency domain and spanning a bandwidth of 10kHz, with a persistence of 1ms. The RFI-to-signal ratio is 50dB.
- **RFI-FD-WB:** Signal concentrated in the frequency domain and spanning a bandwidth of 1MHz, with a persistence of 100ms. The RFI-to-signal ratio is 20dB.

## 4.2.2 Time domain mitigation

In this section, the time-domain algorithm is applied to correct RFIs of the following types: RFI-TD-WB and RFI-TD-NB. They are both concentrated in time domain but differ in terms of duration ( $200\mu\text{s}$  vs  $30\mu\text{s}$ ), repetition frequency (500Hz vs 4kHz) and RFI-to-signal ratio (50dB vs 30dB).

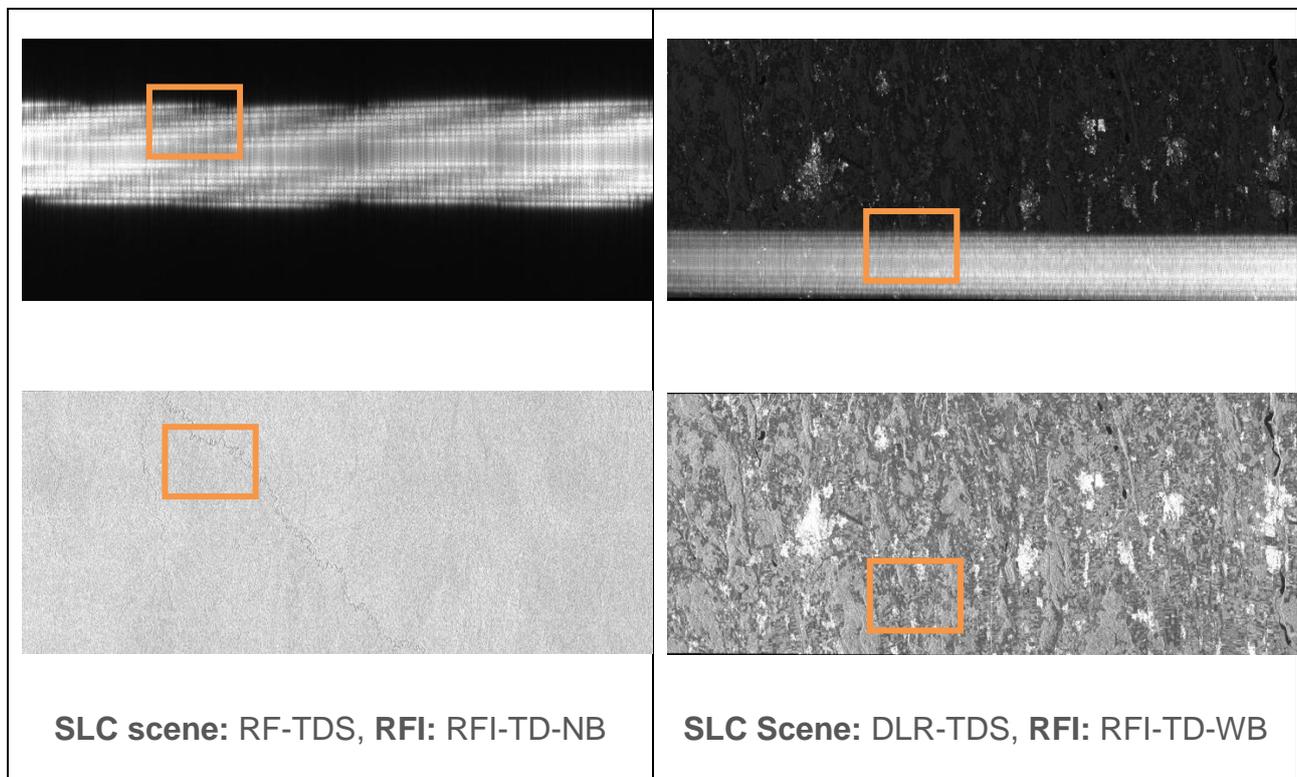


Figure 11: Comparison between mitigated (bottom) and interfered (top) SLC images; Circle: transponder D39

Firstly, the Amazon rain forest TDS is considered. Following figures show the interferometric coherence with respect to the original image without RFI in two cases: uncorrected and time-domain mitigated. If the mitigation is used, a drastic improvement of the coherence can be found, and the resulting coherence level remains above 0.95 for the whole image patch under analysis. This means that a good preservation of the original radiometric level is guaranteed.

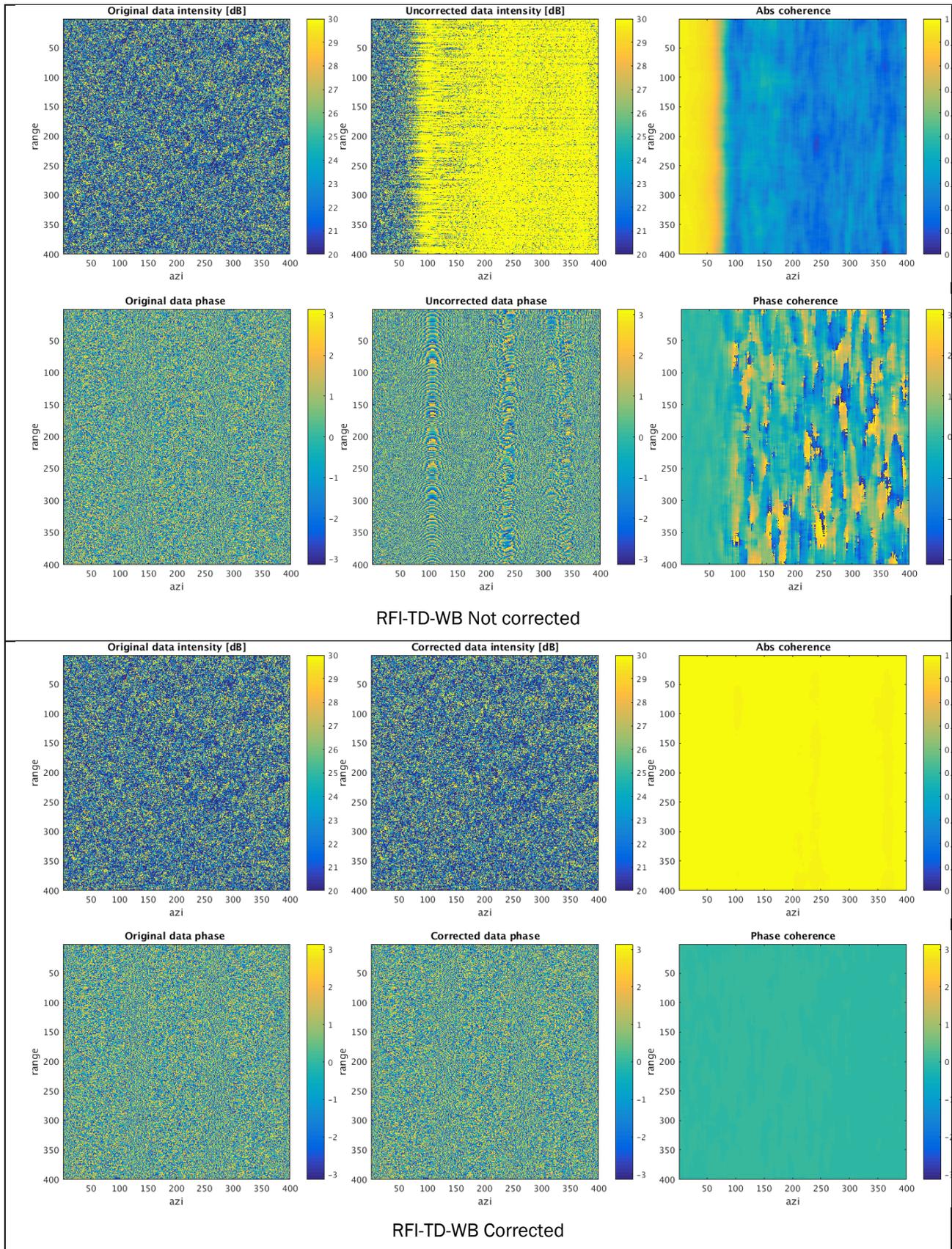


Figure 12: Scene: RF-TDS, RFI: RFI-TD-WB. Interferometric coherence. The first two rows show the results of the coherence without applying the mitigation, whereas the last two rows show the result after RFI mitigation.

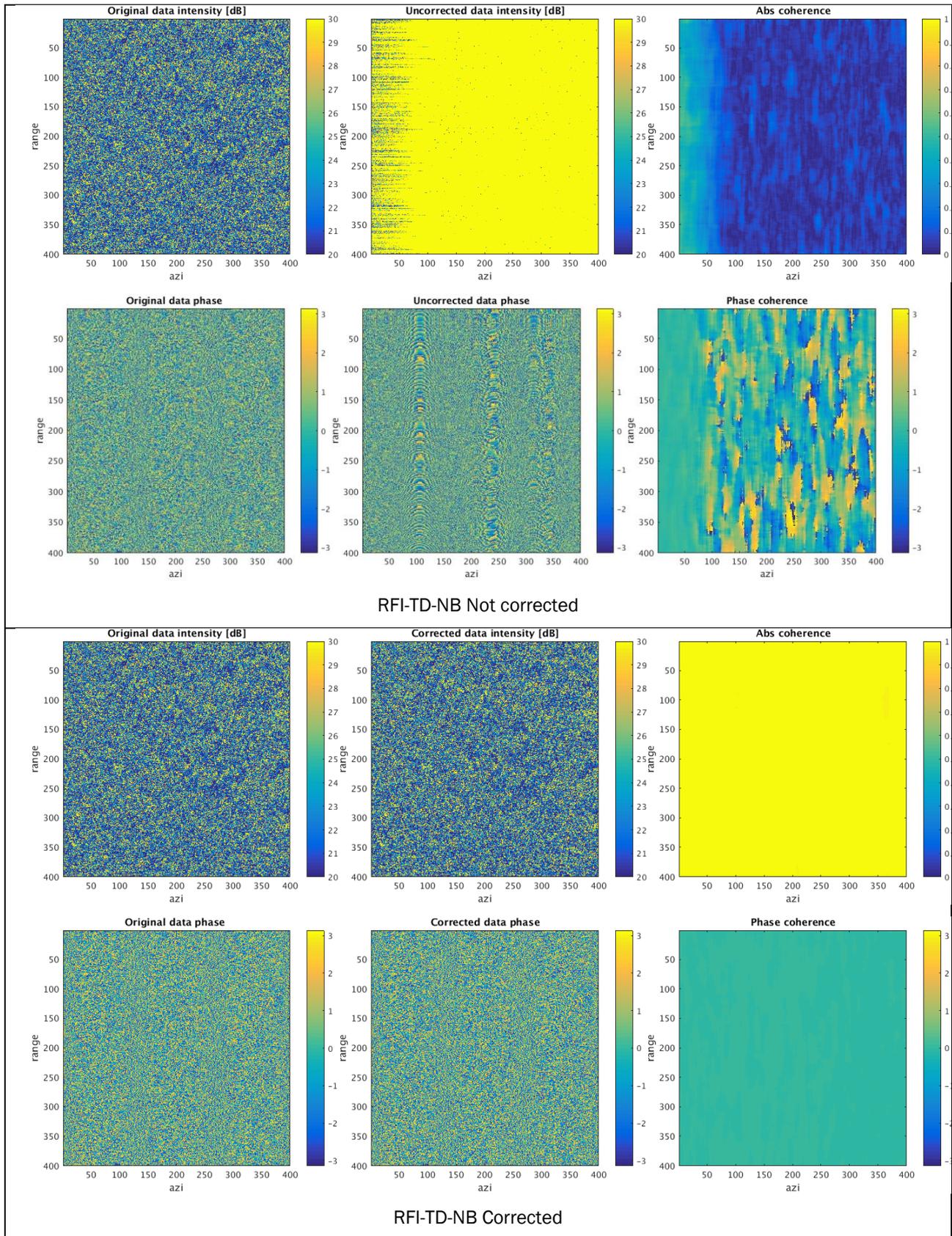
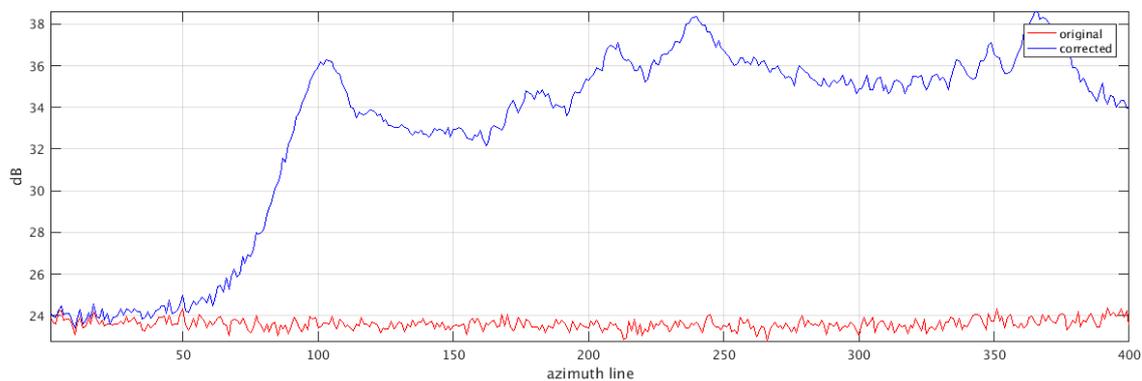


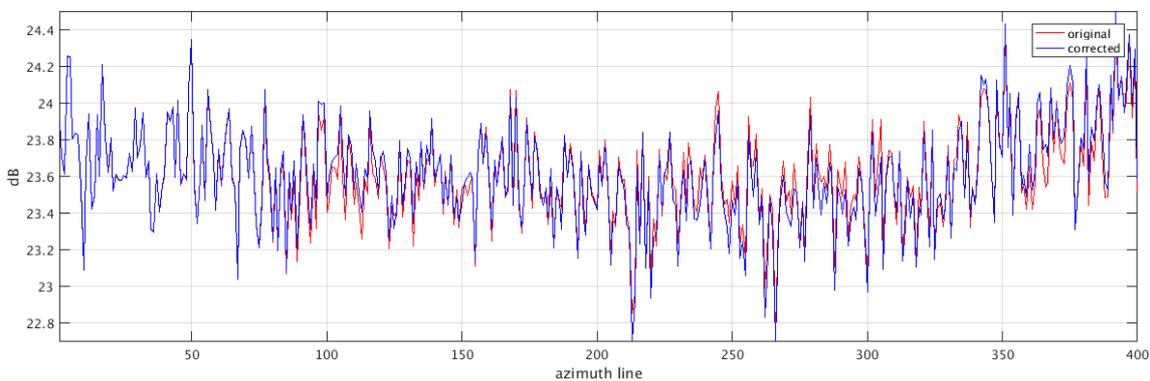
Figure 13: Scene: RF-TDS, RFI: RFI-TD-NB. Interferometric coherence. The first two rows show the results of the coherence without applying the mitigation, whereas the last two rows show the result after RFI mitigation.

Similarly, when comparing the azimuth transect of the rain forest image with and without the RFI mitigation, a great improvement is registered. In the mitigated case, the distance between the beta

profiles of the original image and the corrected one is around 0.1dB. The transects shown in Figure 14 and Figure 15 correspond to the average of the patches above along the range dimension.

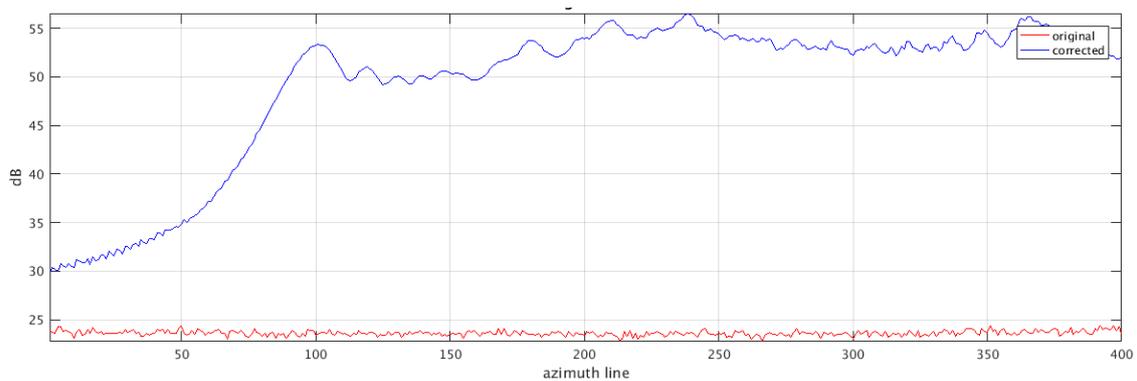


RFI-TD-WB Not corrected

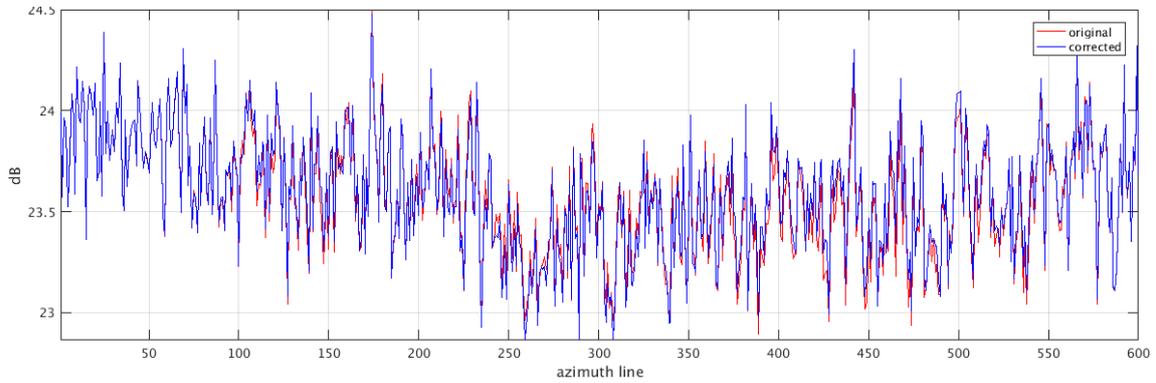


RFI-TD-WB Corrected

Figure 14: Scene: RF-TDS, RFI: RFI-TD-WB. Azimuth transect. On the top, the overplot of (red) original and (blue) interfered transects are shown, whereas on the bottom the overplot of (red) original and (blue) RFI mitigated transects can be seen.



RFI-TD-NB Not corrected



RFI-TD-NB Corrected

Figure 15: Scene: RF-TDS, RFI: RFI-TD-NB. Azimuth transect. On the top, the overplot of (red) original and (blue) interfered transects are shown, whereas on the bottom the overplot of (red) original and (blue) RFI mitigated transects can be seen.

Finally, using the RF-DLR dataset, the impulse response function of the DLR transponder D39 is evaluated before and after the RFI mitigation; as reference, the original IRF in case no RFI was injected can be seen in Fig.11. The IRF analysis provided in Fig.13 and Fig.12 proves that, even if the transponder was severely affected by RFI, an IRF very close to the original can still be restored, with a resolution near to the original and only a small degradation in terms of PSLR (0.05dB range, 0.5dB azimuth) and ISLR (0.02dB range, 0.3dB azimuth).

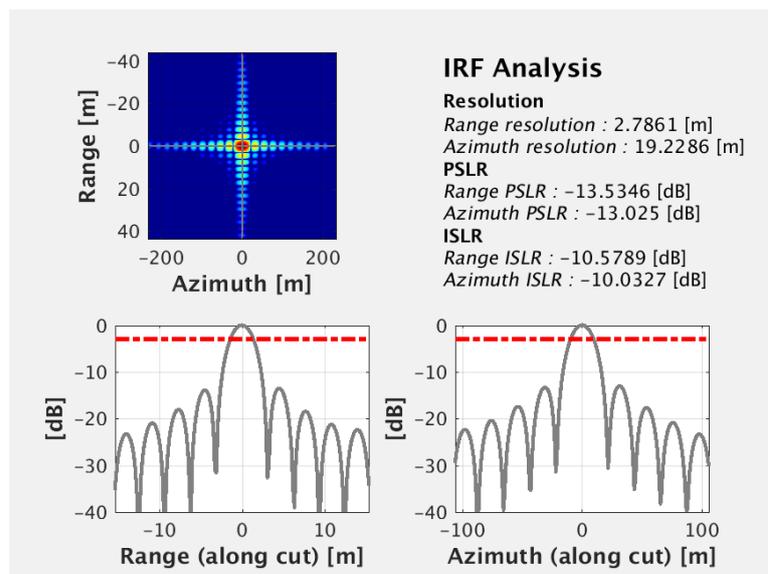


Figure 16: Scene: RF-DLR, original impulse response function of the RFI-free image.

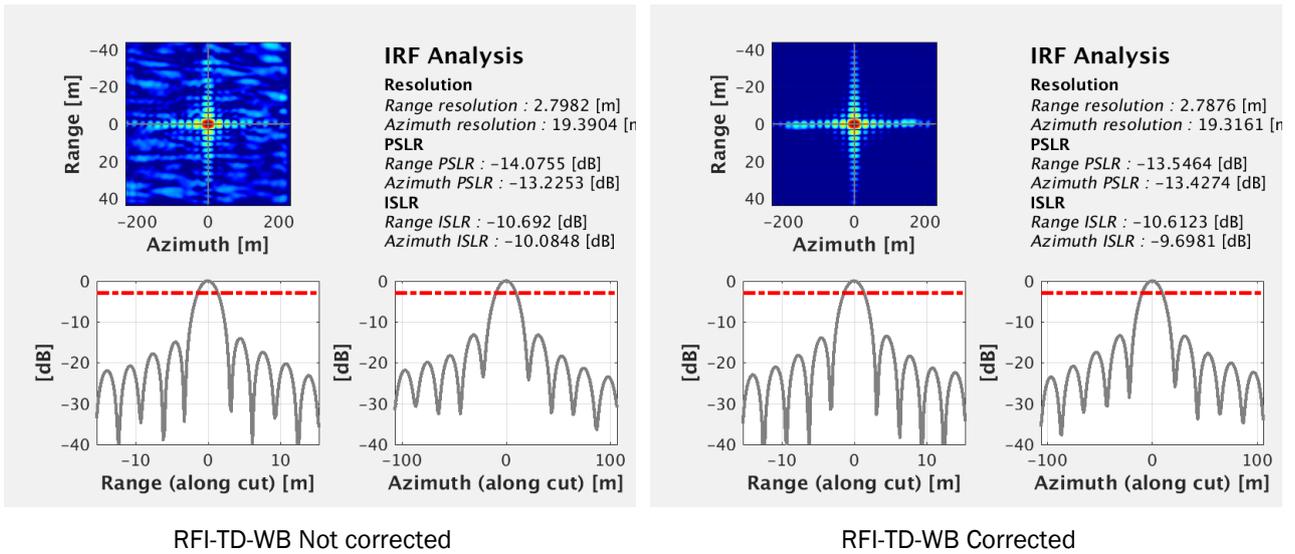


Figure 17: Scene: RF-DLR, RFI: RFI-TD-WB. Impulse response function.

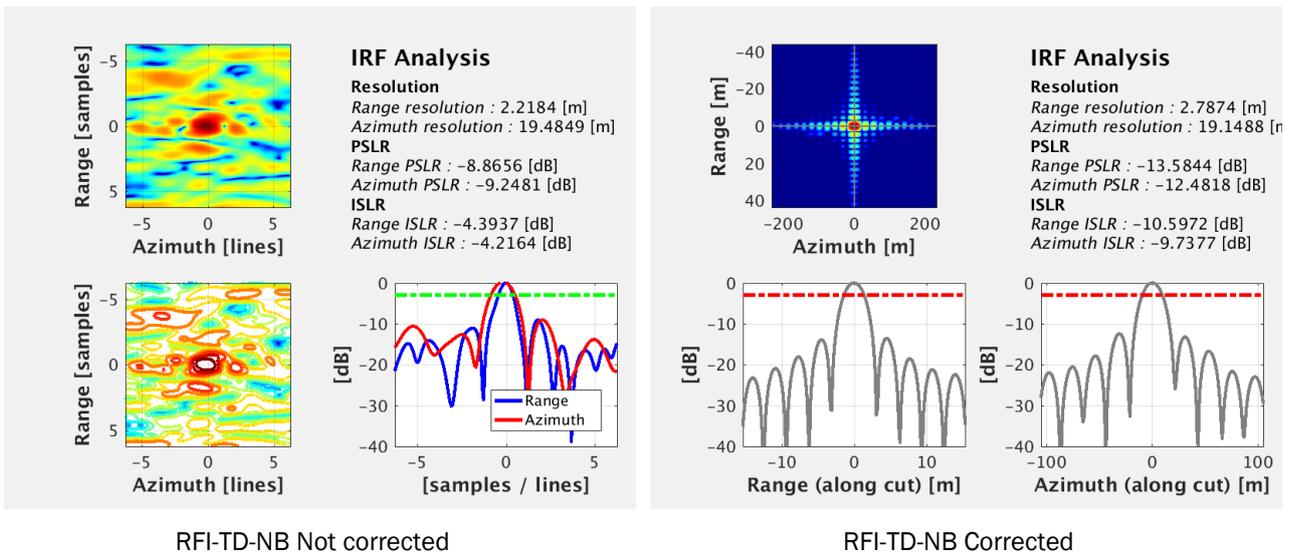


Figure 18: Scene: RF-DLR, RFI: RFI-TD-NB: Impulse response function. For this type of interference, the IRF was severely impacted, but the mitigation strategy was able to restore an IRF very close to the original one.

### 4.2.3 Frequency domain mitigation

The same analysis performed in the time-domain is repeated here for the frequency-domain mitigation algorithm. In this case, the artificially injected RFIs are RFI-FD-WB and RFI-FD-NB: they are both concentrated in the frequency domain but differ in terms of bandwidth (1MHz vs 10KHz) persistence (100ms vs 1ms) and RFI-to-signal ratio (50dB vs 20dB).

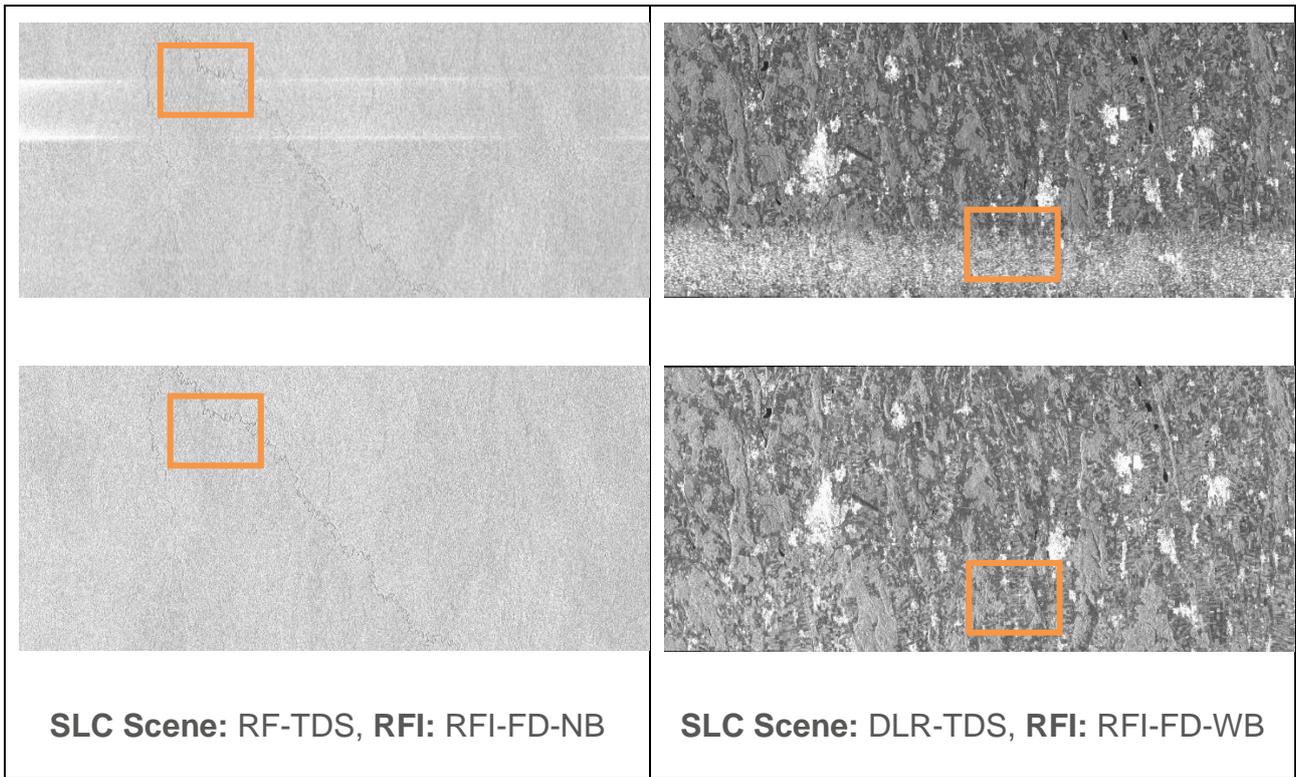
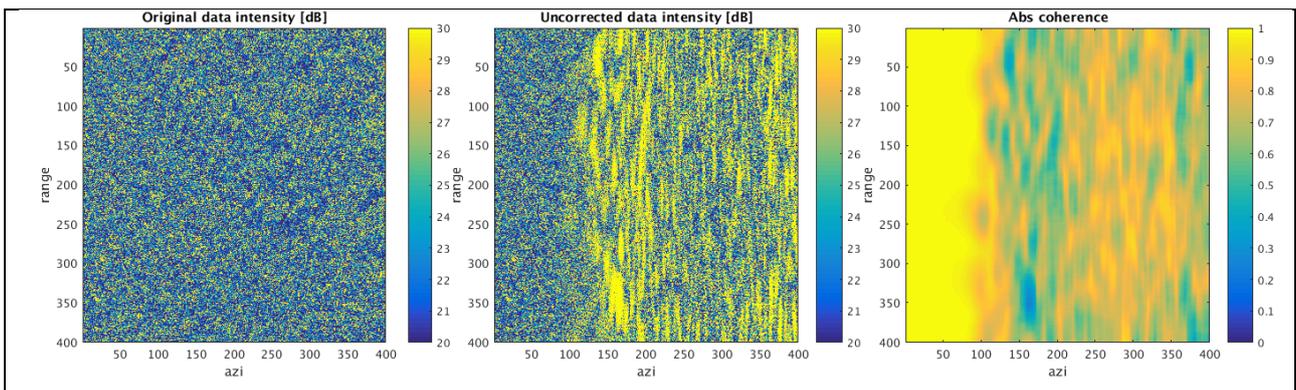


Figure 19: Comparison between mitigated and interfered SLC images. Circle: Transponder D39

Firstly, the Amazon rain forest TDS is considered. Figure 19 and Figure 20 show the interferometric coherence with respect to the original image in two cases: uncorrected and frequency-domain mitigated. If the mitigation is used, a drastic improvement of the coherence can be found, and the resulting coherence level remains above 0.96 for the whole image patch under analysis. This means that a good preservation of the original radiometric level is guaranteed.



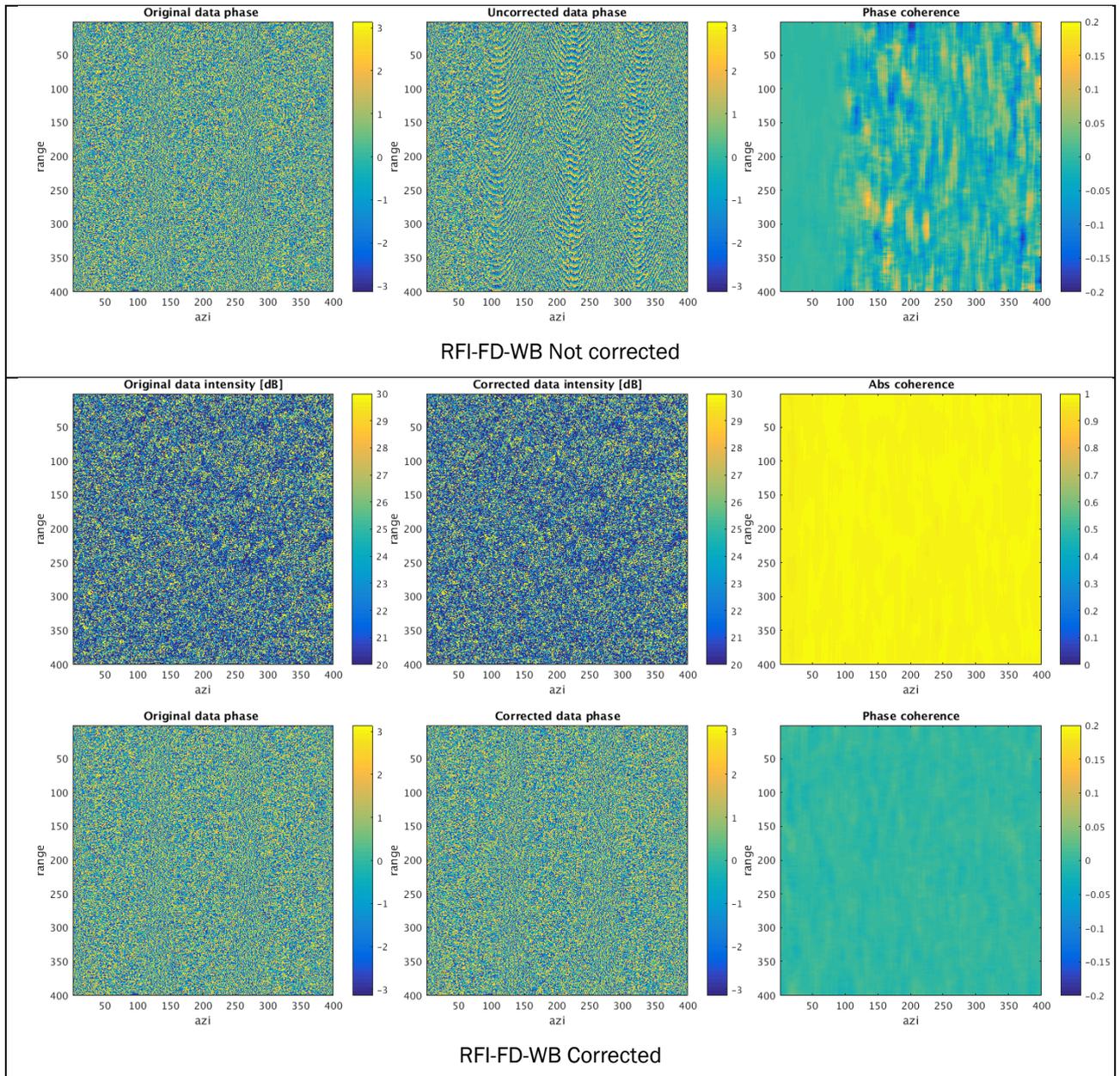


Figure 20: Scene: RF-TDS, RFI: RFI-FD-WB, interferometric coherence. . The first two rows show the results of the coherence without applying the mitigation, whereas the last two rows show the result after RFI mitigation.

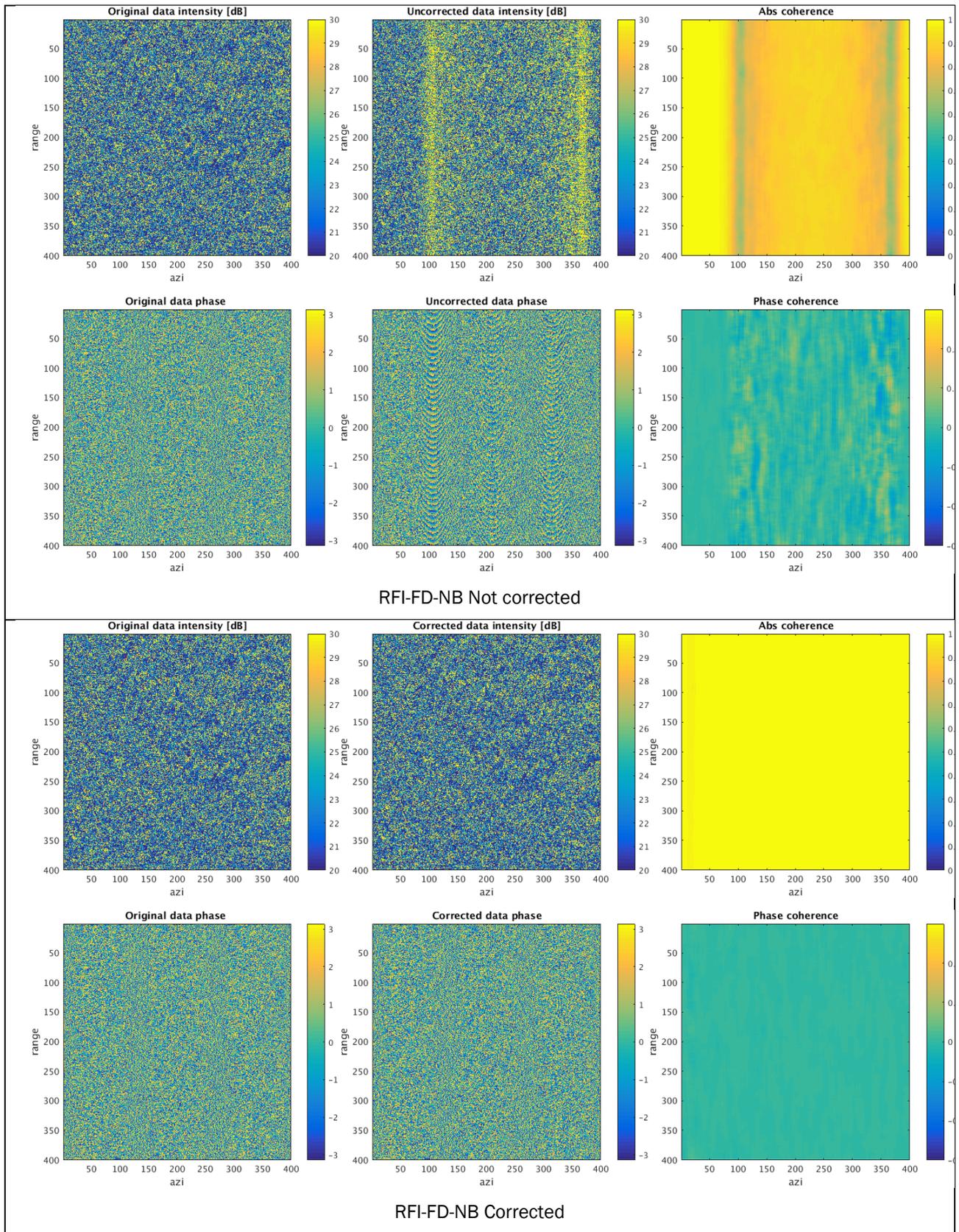
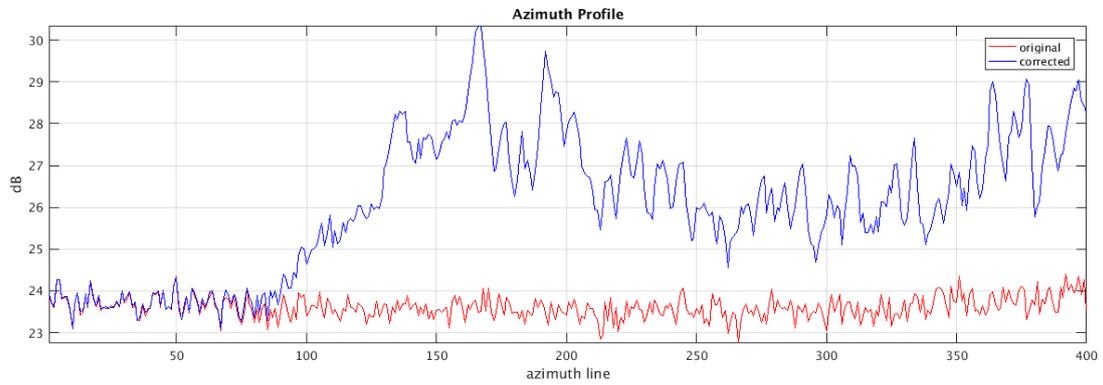
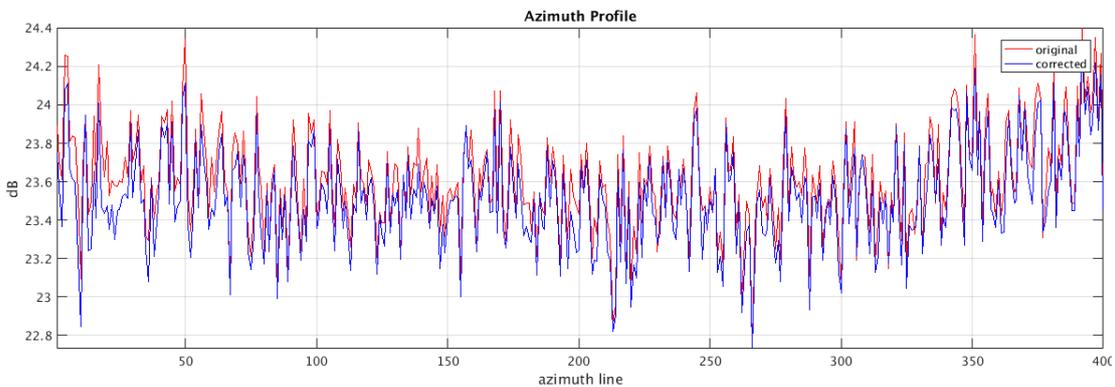


Figure 21: Scene: RF-TDS, RFI: RFI-FD-NB: Interferometric coherence. The first two rows show the results of the coherence without applying the mitigation, whereas the last two rows show the result after RFI mitigation.

Similarly, when comparing the azimuth transect of the rain forest image with and without the RFI mitigation, a great improvement is registered. In the mitigated case, the maximum distance between the beta profiles of the original image and the corrected one is around 0.15dB. The transects shown in Figure 22 and Figure 23 correspond to the average of the patches above along the range dimension.

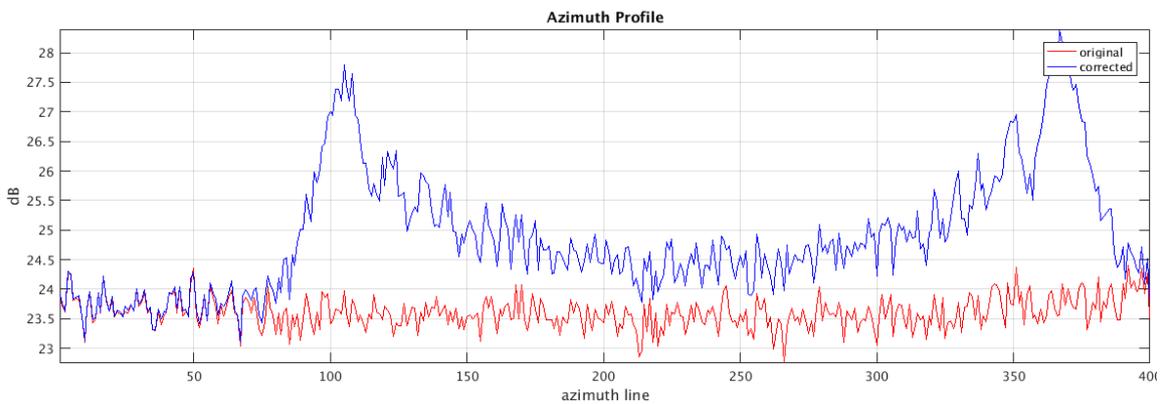


RFI-FD-WB Not corrected

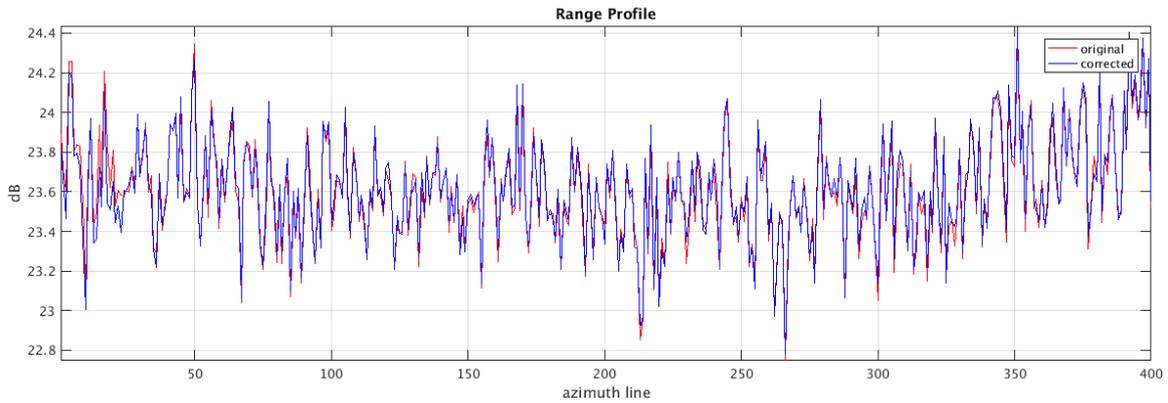


RFI-FD-WB Corrected

Figure 22: Scene: RF-TDS, RFI: RFI-FD-WB. Azimuth transect. On the top, the overplot of (red) original and (blue) interfered transects are shown, whereas on the bottom the overplot of (red) original and (blue) RFI mitigated transects can be seen.



RFI-FD-NB Not corrected

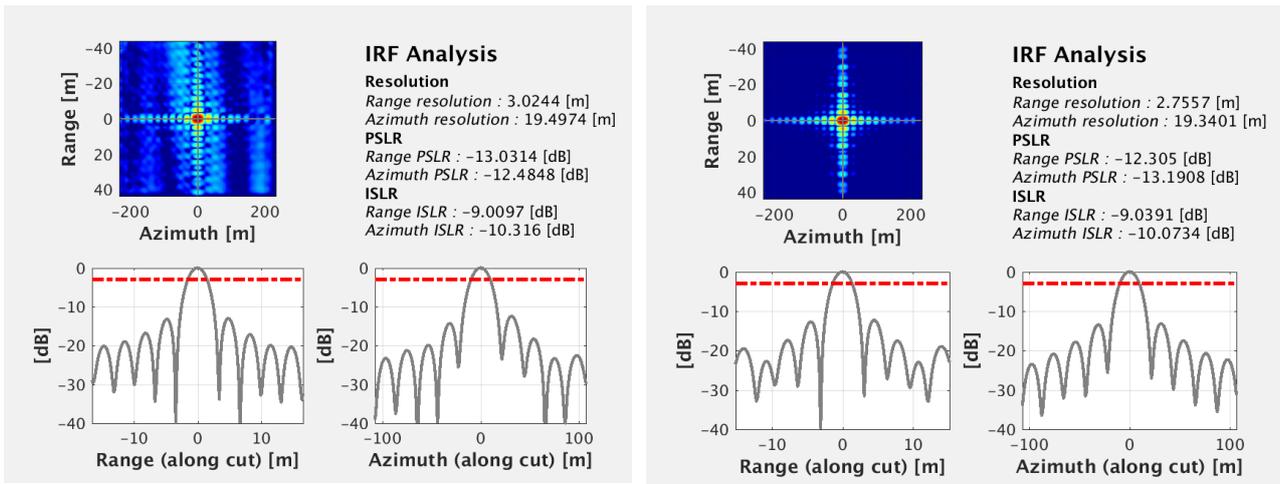


RFI-FD-NB Corrected

Figure 23: Scene: RF-TDS, RFI: RFI-FD-NB. Azimuth transect. On the top, the overplot of (red) original and (blue) interfered transects are shown, whereas on the bottom the overplot of (red) original and (blue) RFI mitigated transects can be seen.

Finally, using the RF-DLR dataset, the impulse response function of the DLR transponder D39 is evaluated before and after the RFI mitigation; as reference, the original IRF in case no RFI was injected can be seen in Figure 16.

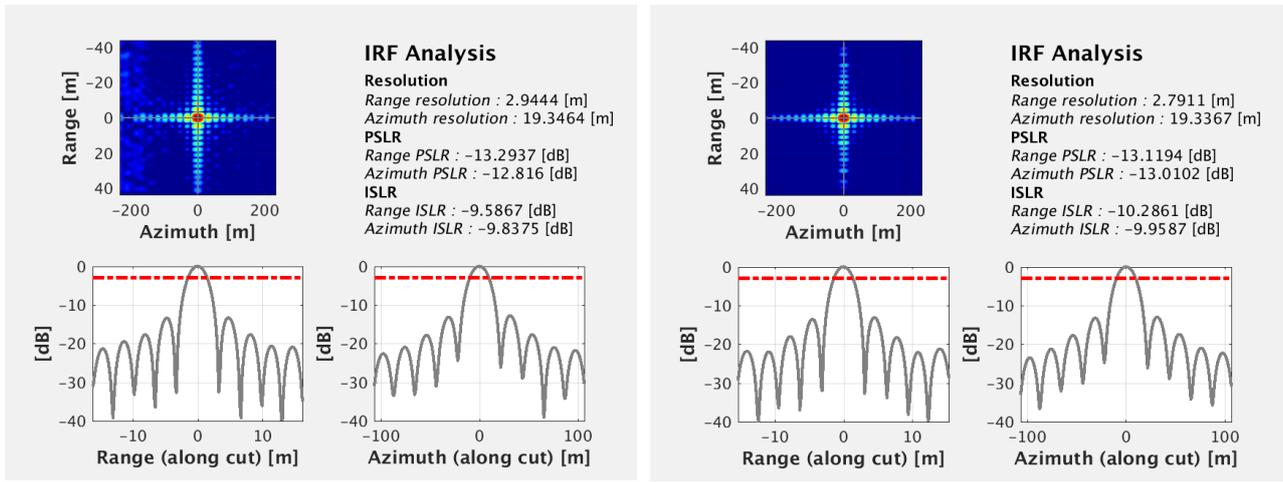
The IRF analysis provided in Figure 17 and Figure 18 proves that, even if the transponder under analysis was severely affected by RFI, an IRF very close to the original can still be restored, with a maximum change in resolution in the order of 0.2m (azimuth) and 0.04m (range); a maximum deterioration in terms of PSLR equal to 1.2dB range / 0.2dB azimuth and ISLR equal to 1.5dB range and 0.05dB azimuth.



RFI-FD-WB Not corrected

RFI-FD-WB Corrected

Figure 24: Scene: RF-DLR, RFI: RFI-FD-WB. Impulse response function



RFI-FD-NB Not corrected

RFI-FD-NB Corrected

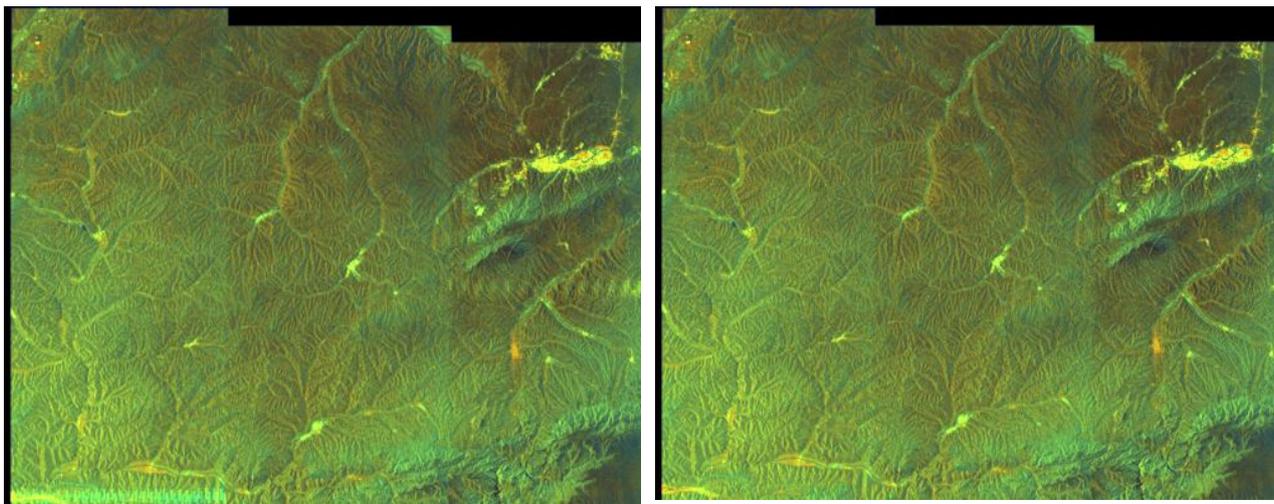
Figure 25: Scene: RF-DLR, RFI: RFI-FD-NB. Impulse response function

# Appendix A - Catalogue of RFI examples

In this section a partial catalogue of typical interference occurrences and, for each example, the corresponding image after mitigation are provided. Comparing the original (unmitigated) product and the mitigated one makes especially clear how the RFI looks like in the focused image and what are the potential limitations of IPF RFI mitigation module.

The RFI mitigation algorithms implemented in the S-1 IPF are generally successful at removing most of the interference from the L1 products, even though results strongly depend on the characteristics of the interfering signal, like bandwidth, transmitted power or repetition frequency.

The example shown in the figure below shows a case where the joint time-domain and frequency-domain mitigation achieves good results and the strong artifacts seen in the original image are completely filtered.

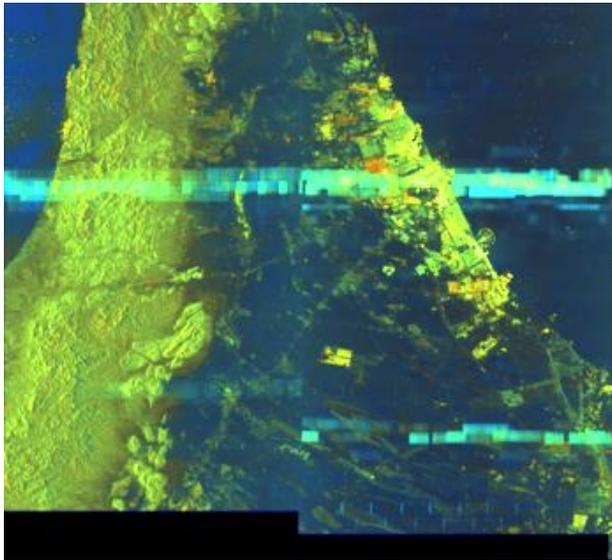


RFI mitigation off

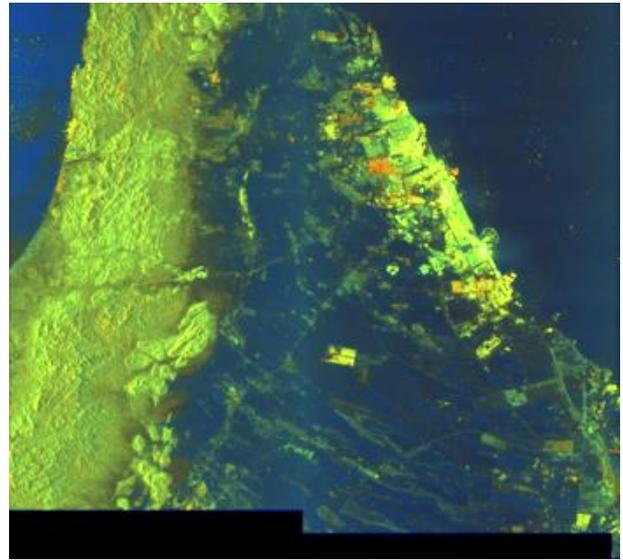
RFI mitigation on

*Figure 26 S1A\_IW\_GRDH\_1SDV\_20211020T230331\_20211020T230400\_040209\_04C354\_24CB*

Another example of joint time-domain and frequency-domain mitigation is shown below. The RFI-related artifacts are correctly removed from both the sea and land. Please note that the remaining pattern is related to the contamination of sea backscatter at very low wind in VV and VH by strong scatterers near the coast.



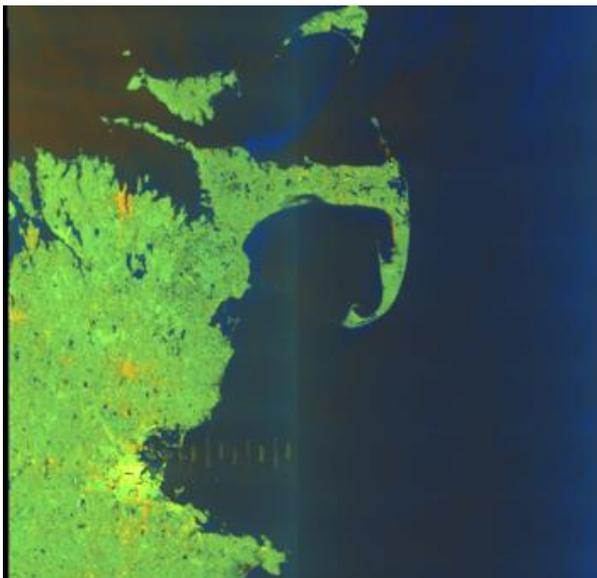
RFI mitigation off



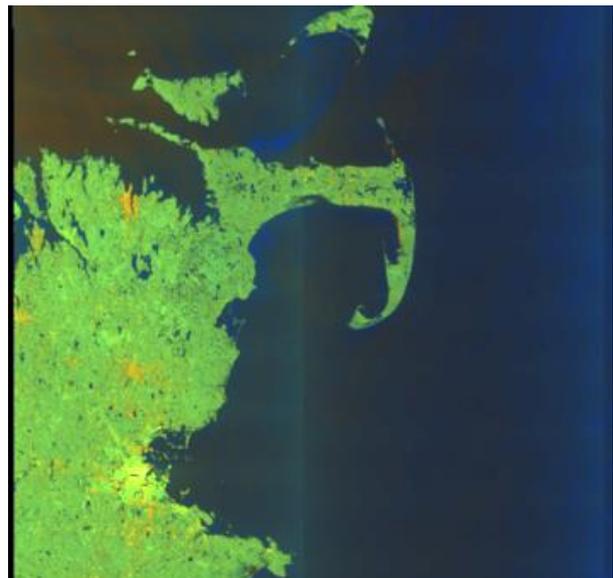
RFI mitigation on

*Figure 27 S1A\_IW\_GRDH\_1SDV\_20210922T021545\_20210922T021608\_039788\_04B4BE\_02A0*

The image below shows an example of RFI occurring over an urban area and well confined in the time domain. The time-domain algorithm is very efficient in removing this type of interferences from the raw echoes, resulting in a clean image after focusing.



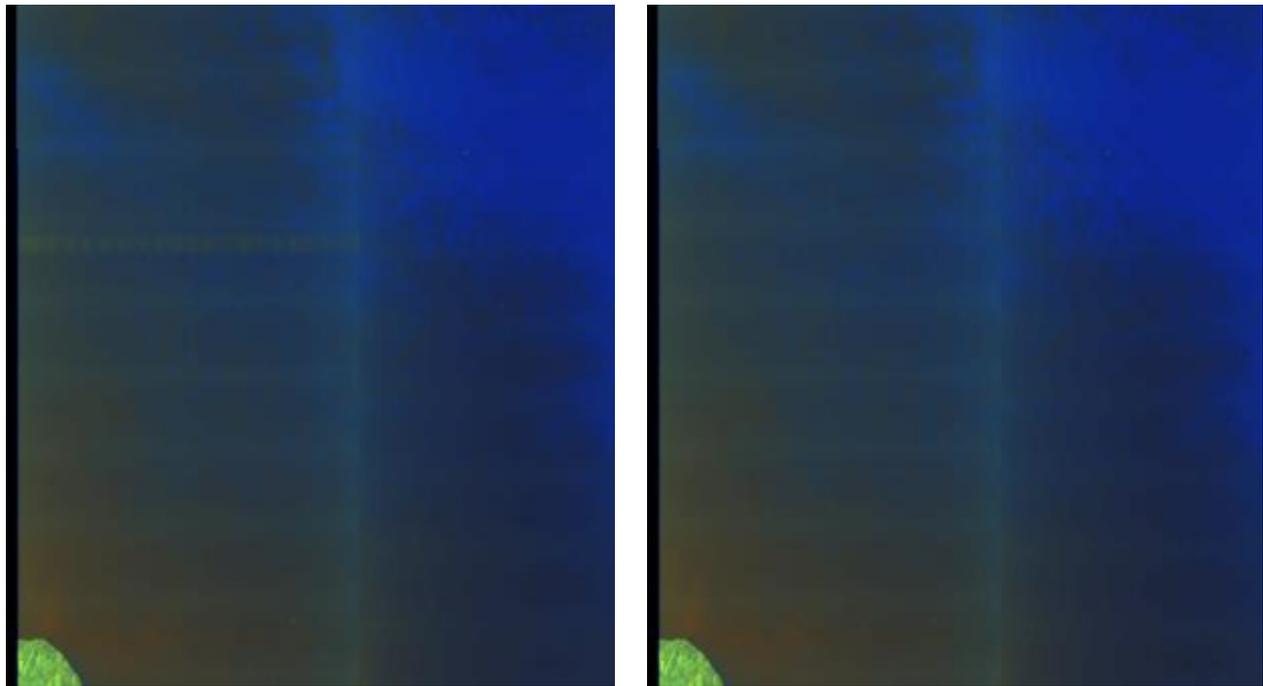
RFI mitigation off



RFI mitigation on

*Figure 28 S1A\_IW\_GRDH\_1SDV\_20211020T223511\_20211020T223536\_040209\_04C353\_611E*

In the following example the RFI is successfully removed only using the frequency domain algorithm. The interference visible in IW1 is quite spread in the time-domain but it is confined in a relatively small portion of the raw spectrum, making it easy to suppress by the frequency-domain algorithm.

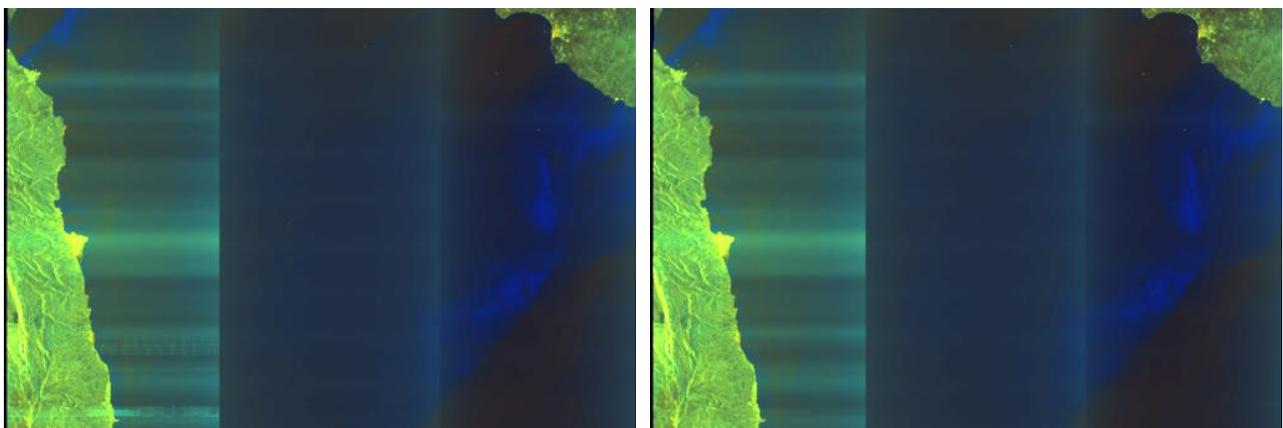


RFI mitigation off

RFI mitigation on

Figure 29 S1B\_IW\_GRDH\_1SDV\_20211020T164738\_20211020T164803\_029222\_037CCF\_3CA8

In the following example the RFI mitigation is not satisfactory. The image presents two forms of RFI: one very prolonged and spread all over IW1, the other more concentrated in time domain. Only the second type is successfully filtered out by the processor.

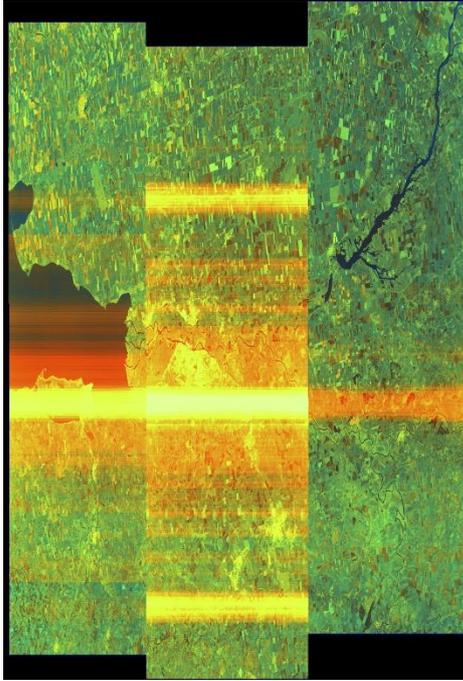


RFI mitigation off

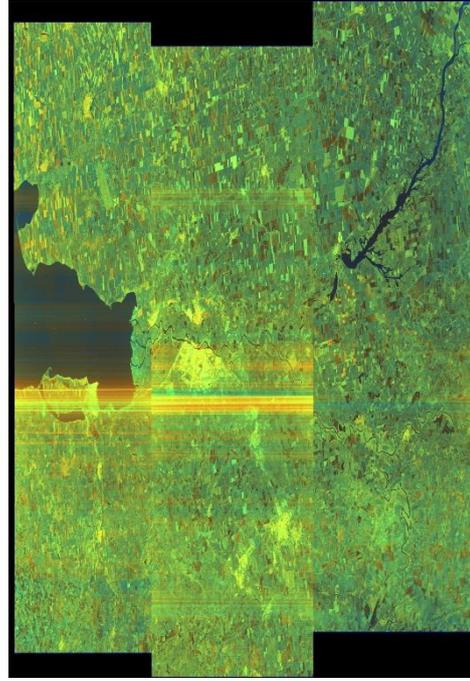
RFI mitigation on

Figure 30 S1A\_IW\_GRDH\_1SDV\_20211023T034344\_20211023T034409\_040241\_04C474\_01DC

The RFI in the image below is extremely powerful and extended: its spectrum consists of multiple peaks located 63kHz apart for a total bandwidth as large as the transmitted radar chirp. In cases like these, the mitigation module can only partially recover the imaged scene.



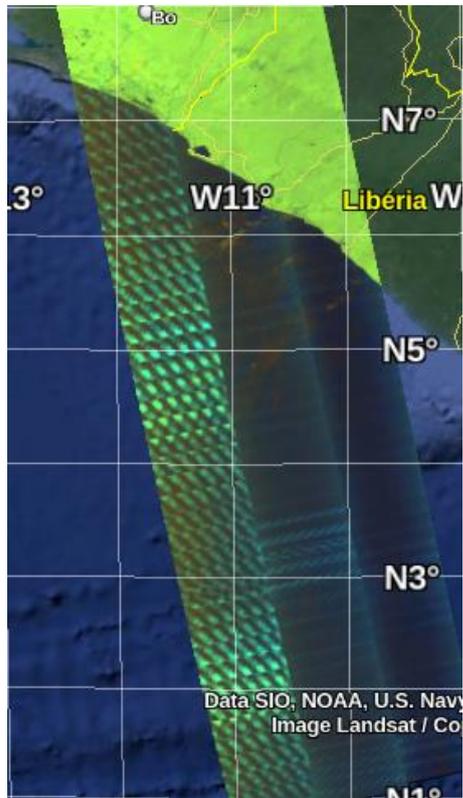
RFI mitigation off



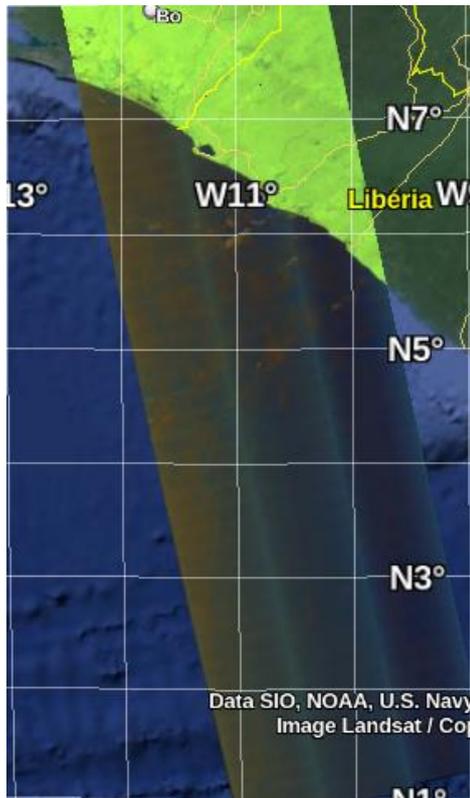
RFI mitigation on

Figure 31: S1A\_JW\_RAW\_\_OSDV\_20210604T151207\_20210604T151239\_038192\_0481E1\_18B2.SAFE

In some cases, the interference is not originated from a ground emitter, but from another satellite, e.g. another C-band imaging satellite acquiring in the same region. Despite their strength and duration, these types of interference can be efficiently removed as shown in the pictures below.



RFI mitigation off



RFI mitigation on

Figure 32 South Liberia on 09/09/2021 - S-1A orbit 39609

# Appendix B - Catalogue of problematic RFI mitigation

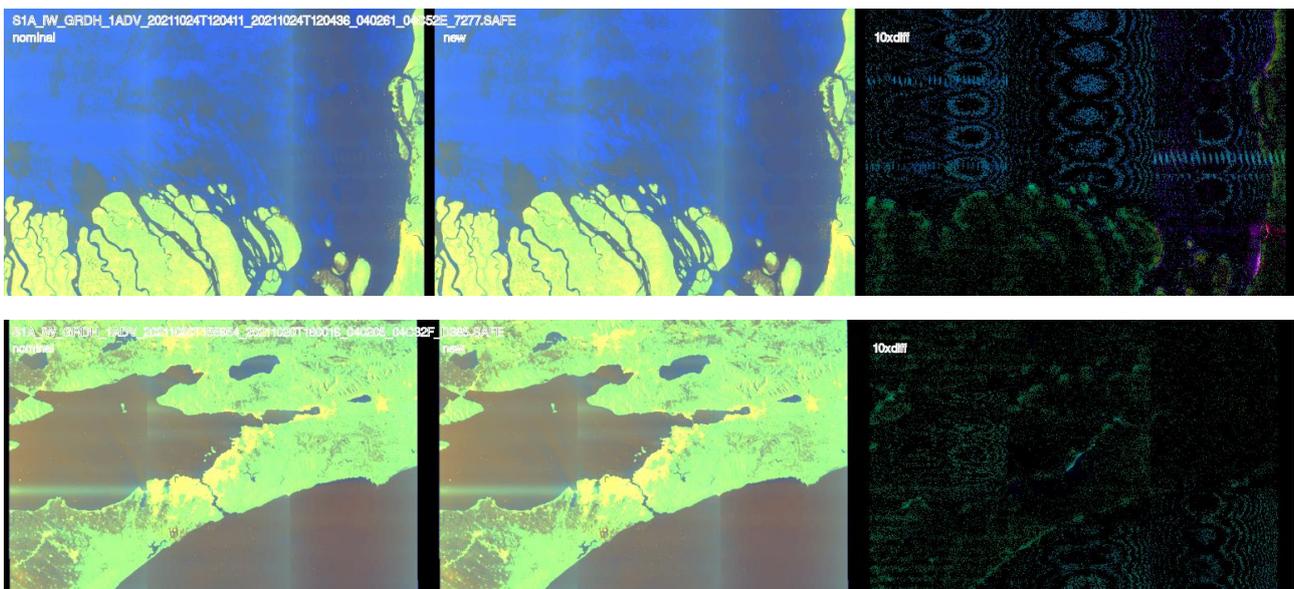
In this section a (partial) catalogue of cases where the RFI detection and/or mitigation algorithms show undesired behaviour is given. Note that these effects are at least partially related to thresholds used for pre-screening and detection and might or might not be present depending on the adopted thresholds for operations and on signal characteristics.

For each of them an illustration is provided by: 1) The quicklook of original product without RFI mitigation (on the left), 2) The quicklook of the product with RFI mitigation applied (centre) and 3) The magnified difference of quicklooks with/without mitigation illustrating the impact of the RFI mitigation (right).

## Radiometric change in transition to low-backscatter areas

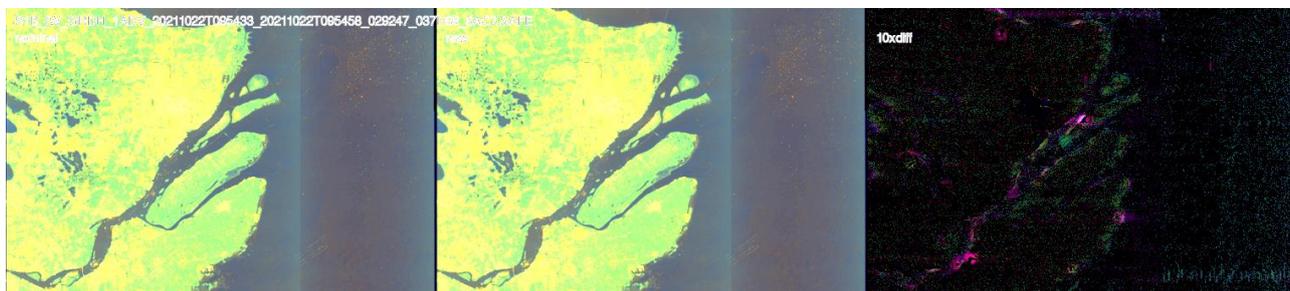
The examples below show areas of transition between water (low-backscatter) and land (high-backscatter). Looking at the magnified difference plot on the right, a few effects can be identified:

- RFIs were properly detected and at least partially removed
- Circular pattern on low backscatter areas: This are small radiometric jumps of around 0.1 to 0.3 dB which are caused by the removal of spurious tones (i.e., not caused by RFI but not an undesired effect). These spurious tones are usually well below the backscatter level, but in calm sea conditions they can have an impact on cross-polarization channel. In these cases, they can have enough energy to trigger the frequency-domain detection.
- Radiometric bias in transition areas: for the cross-pol channel, small biases are visible in transition from low to high backscatter areas, due to false positives clustered around the transition areas. This is a limitation of the algorithm, since the hypothesis assumed for the statistical distribution of backscatter might not be fulfilled over transition areas. The extent of the bias varies from 0.01 to 0.2dB depending on the chosen time-domain detection threshold.



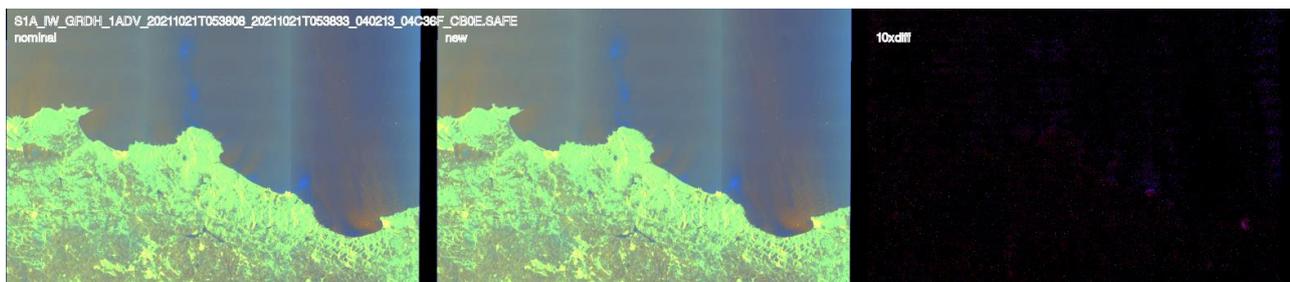
Very bright areas causing false positives in time-domain

Very bright targets w.r.t, their surroundings might be falsely identified as RFI in time-domain, causing a small radiometric bias. This is typically observed in transitions from low to high backscatter areas (see examples above), but also around some smaller targets within land, as observed by the pink artefacts in the image below. As for the other examples in this appendix, this effect strongly depends on the configurable detection thresholds set for the algorithms. With a proper calibration of the algorithm, this effect should remain below 0.02dB.



## False positives in pre-screening

The example below shows a case where the pre-screening indicates the presence of RFI, but the analysis of the raw data and of the quick-looks indicates no presence of RFI. In these cases, the contamination is only present in the noise measurement but is absent or very weak in the imaging echoes. As a result, the RFI detection/mitigation module does not produce substantial changes.



## Miss-detection in pre-screening

The example below shows a case where the pre-screening fails to identify RFIs and the data-driven detection and mitigation are not performed. As the pre-screening step only considers a small number of echoes, it is expected that in some cases the RFI may be present in the data but not found in the noise measurements.



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