ERS SAR CALIBRATION

DERIVATION of
the BACKSCATTERING COEFFICIENT σ^o
in ESA ERS SAR PRI PRODUCTS

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Issue 2	Revision 3	22 January 1997	Appendix D1, p.24: *VMP processor installed at UK-PAF.*
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	Revision 5b	7 September 1998	Appendix D (p.25), Appendix J (p. 42-43-44), Appendix K (p. 45): *Corrections needed.*
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List of acronyms and abbreviations

ADC	Analogue to Digital Convertor
AOI	Area Of Interest
CEOS	Committee on Earth Observation Satellites
MPH	Main Product Header
PAF	Processing and Archiving Facility
PCS	Product Control Service
PRI	Precision Image
RMS	Root Mean Square
SAR	Synthetic Aperture Radar
SPH	Specific Product Header

1. Introduction

The scope of this technical note is to describe the derivation of the radar backscattering coefficient σ^o in ERS-1 and ERS-2 SAR PRI data products generated by ESA.

The ERS SAR PRI products are generated by different processors at ESA/ESRIN and at the following Processing and Archiving Facilities (PAFs):

- the German PAF (D-PAF),
- the Italian PAF (I-PAF),
- the United-Kingdom PAF (UK-PAF).

The Precision Image (PRI) product is the ESA standard product for SAR radiometric precision analysis. The specifications of the PRI product are described in document [ESA,'ERS-1 Product Specifications', ESA SP-1149, issue 3, June 1992]. These specifications impact upon the radiometric characteristics of the data product as follows:

- the pixel value in the image is proportional to the square root of the intensity,
- the intensity value is proportional to the radar brightness β^o,
- the radar brightness β^o is proportional to the backscattering coefficient σ^0 divided by the sine of the pixel incidence angle,
- the image is corrected for the in-flight elevation antenna pattern,
- the image is compensated for the range spreading loss.

Therefore, a direct and "simple" derivation scheme allows to provide measurements of the backscattering coefficient using the PRI data product. However, during the over nine years of exploitation of the ERS-1 SAR instrument and the first six years of exploitation of the ERS-2 SAR instrument, various sources of radiometric accuracy and stability errors have been identified that are related to either the on-board instrument (e.g. ADC non-linearities or replica pulse power variations) or the PAF processors (e.g. inaccuracies in the implementation of the elevation antenna pattern). For each of these sources of radiometric errors a correction method is proposed in this technical note.

Two derivation methods of the backscattering coefficient σ^0 are described in Chapter 2:

1- the simplified derivation method allows a rough estimate of the backscattering coefficient,

2- the comprehensive derivation method includes a set of equations for accurate derivation of the backscattering coefficient to remove the sources of radiometric errors mentioned above.

In addition, both methods include a method to provide suitable radiometric resolution i.e. to reduce statistical uncertainties of the backscattering coefficient measurements due to speckle. This method is based on intensity averaging.

In Chapter 3, a correction method is presented that accounts for radiometric errors due to ADC non- linearities.

In addition and as an example of the application of the comprehensive derivation method, Chapter 4 presents the set of equations applicable in the case of an ERS-2 SAR PRI product.

The parameters used to derive the backscattering coefficient from an ERS SAR PRI image are available in the appendices of this document and within the product annotations (CEOS header) - these are indicated by *italics* throughout this document. The location of the parameters within the product annotations can be found in Appendix A.

This document supersedes the earlier issue of this document (ref. [1]).

Note that summaries of the performance of the ERS-1 and ERS-2 SARs can be found in refs. [11- 16].

2. Calibration of the ERS SAR PRI data product

2.1 General principles and assumptions

In the next chapters, the following ***assumptions on the local incidence angle*** α are made:
- a flat terrain is considered, i.e. there is no slope. The incidence angle α is depending only on the ellipsoid and varies from about 19.5$^\text{o}$ at near range to about 26.5$^\text{o}$ at far range.
- any change in incidence angle across a distributed target is neglected, i.e. a distributed target corresponds to one average value of the incidence angle.

The radar backscattering coefficient σ^0 is related to the radar brightness β^0 as follows:

$$\sigma^0 = \beta^0 . \sin \alpha,$$

where α is the local incidence angle.

For illustration of look angle and local incidence angle α in SAR illumination geometry, please refer to Appendix B.

To derive measurements of the radar backscattering coefficient σ^0, detailed knowledge of the local terrain slope (i.e. the local incidence angle α) is needed. As the local incidence angle is usually not known or partially known if a flat terrain is assumed, ESA decided to present the Precision Image (PRI) as an image of the radar brightness β^0 of the scene. Consequently, pixel intensity values in ERS SAR PRI products are directly proportional to the radar brightness β^0 of the illuminated scene. The digital number giving the value of a pixel in PRI products, say DN, is directly related to β^0 and to σ^0 by the following relations:

$$[DN]^2 = \text{Constant} \cdot \beta^\text{o} = \text{Constant} \cdot \frac{\sigma^\text{o}}{\sin \alpha} = \text{Constant}(\alpha) \cdot \sigma^\text{o}$$

Constant (α) is a function depending on the local incidence angle and can be decomposed as follows:

$$\text{Constant}(\alpha) = K \cdot \frac{\sin \alpha_\text{ref}}{\sin \alpha}$$

where ***K is the calibration constant*** and α_ref the reference incidence angle, 23 degrees, i.e. the ERS SAR mid-range incidence angle. K is specific to the type of data product and to *the processing centre*. The value of K is given in Appendix D.

The backscattering coefficient σ^0 is usually expressed in decibels:

$$\sigma^0_{(dB)} = 10 \cdot \log_{10} \sigma^0$$

However, in the next chapters, the backscattering coefficient σ^o is expressed as a linear value, i.e. not in decibels.

A simplified version of the calibration method is given with equation (1) in Chapter 2.2. A comprehensive version that accounts for various sources of radiometric accuracy and stability errors is given in Chapter 2.3 with equation (2a) and equation (2b).

2.2   Simplified equation for the derivation of σ^o in PRI products

With the assumptions made in the previous chapter, and without taking into account for various sources of radiometric accuracy and stability errors, the backscattering coefficient σ^o of a distributed target is given by the following simplified equation:

$$\sigma^o = \left(\frac{1}{N} \cdot \sum_{i,j=1}^{i,j=N} DN_{ij}^2 \right) \cdot \frac{1}{K} \cdot \frac{\sin\alpha}{\sin\alpha_{ref}} \qquad \textit{Equation (1)}$$

- N is the number of pixels within the Area Of Interest (AOI) i.e. the group of pixels corresponding to the distributed target in the image,
- i and j are the range and azimuth locations of the pixels within the distributed target containing N pixels,
- DN_{ij} is the digital number corresponding to the pixel at location (i,j),
- α is the average incidence angle within the distributed target,
- α_{ref} is the reference incidence angle, i.e. 23.0 degrees.

2.3   Comprehensive equation for the derivation of σ^o in PRI products

The calibration method is achieved via the following expressions:

$$\sigma^o = \left(\frac{1}{N} \cdot \sum_{i,j=1}^{i,j=N} DN_{ij}^2 \right) \cdot \frac{1}{K} \cdot \frac{\sin \alpha}{\sin \alpha_{ref}} \cdot C \cdot \frac{ProductReplicaPower}{ReferenceReplicaPower} \cdot Powerloss$$

Equation (2)

- σ^o is a measurement of the backscattering coefficient corresponding to all the N pixels DN_{ij} for a distributed target within the Area Of Interest (AOI),

- α is the average incidence angle corresponding to the AOI. It is calculated from the image geometry in Appendix B.

The components of equation (2), as given as average values for the AOI, are as follows:

$\frac{1}{K} \frac{\sin \alpha}{\sin \alpha_{ref}}$: is the factor that relates the pixel value to the backscattering coefficient,

C : is the factor that accounts for updating the gain due to the elevation antenna pattern implemented in the processing of the ERS SAR PRI data products,

$\frac{ProductReplicaPower}{ReferenceReplicaPower}$: is the replica pulse power variations correction factor, *[for ERS-1 only]*

Power Loss: is the Analogue to Digital Convertor (ADC) power loss.

Equation (2) arises as the combination of equation (2a) and equation (2b) as follows:

$$A_{ij}^2 = DN_{ij}^2 \frac{1}{K} \frac{\sin \alpha_i}{\sin \alpha_{ref}} C_i \frac{ProductReplicaPower}{ReferenceReplicaPower} \, Power\,Loss_{ij}$$

Equation (2a)

$$\sigma^o = \frac{1}{N} \sum A_{ij}^2 \quad \text{for all pixels within the AOI}$$

Equation (2b)

Equation (2a) is the application of equation (2) at the pixel scale.
- A_{ij} is the amplitude corresponding to the pixel at location (i,j) in the product.
- α_i is the incidence angle of a pixel at range coordinate i. It is calculated from the image geometry as given in Appendix B.

The different components of equation (2a) are detailed in chapter 2.3.1.

Equation (2b) is the application of intensity averaging to reduce radiometric resolution errors due to speckle. Equation (2b) provides a measurement of the backscattering coefficient of a distributed target that corresponds to a certain Area Of Interest (AOI) i.e. a group of N pixels in the radar image. It is detailed in chapter 2.3.2.

Note: compared to the expression given in the earlier issue of this document (ref. [1]), equation (2a) includes corrections for replica pulse power variations and the problem of the saturation of the Analogue to Digital Convertor (ADC). Further discussion of these corrections is given in (ref. [2], ref. [3], ref. [4] and ref. [5]).

2.3.1 Equation (2a) accounts for the following steps as part of the method to apply to the data product:

$$A_{ij}{}^2 = DN_{ij}{}^2 \frac{1}{K} \frac{\sin \alpha_i}{\sin \alpha_{ref}} C_i \frac{ProductReplicaPower}{ReferenceReplicaPower} \, Power \, Loss_{ij} \qquad \textit{Equation (2a)}$$

- i) Application of the calibration constant as a function of the pixel range location:

$\dfrac{1}{K} \dfrac{\sin \alpha_i}{\sin \alpha_{ref}}$ is the calibration constant value as a function of the range location

K is the calibration constant. The value of K is specific to the type of data product and to *the processing centre* and is given in Appendix D. α_i is the distributed target incidence angle. α_{ref} is the reference incidence angle, i.e. 23.0 degrees.

- ii) Application of the correction factor for the elevation antenna pattern:

Ci is a PAF and product processing date dependent correction factor for the elevation antenna pattern

Ci accounts for updating the gain due to the elevation antenna pattern implemented in the processing of the ERS SAR PRI data products with refined measurements as provided in Appendix G1, Appendix G2 and Appendix G3. The value of Ci is given in Appendix C.

- iii) Application of the replica pulse power variations correction (<u>ERS-1 only</u>):

$\dfrac{ProductReplicaPower}{ReferenceReplicaPower}$ is the replica pulse power variations correction

ProductReplicaPower is the power of the replica pulse used to generate the product (see CEOS Header). ReferenceReplicaPower is the replica pulse power of the reference image. It is given in Appendix D. In addition, the case of products processed at ESRIN is mentioned in Appendix D as they require the provision of the chirp average density for the correction.

The replica pulses are part of the internal calibration system of the ERS SAR and are copies of the transmitted pulses. In the case of the ERS-1 SAR, the highest observed variation of the

power of the replica pulse was of 1.8 dB from imaging sequence to imaging sequence, even though for an individual imaging sequence variation bounds are up to only 0.1 dB (ref. [3]).

In the case of the ERS-2 SAR, there is no variation of the replica pulse power (until May 1997) with respect to the calibration pulse power. **<u>Consequently the replica pulse power variations correction shall not be applied for ERS-2 SAR products</u>**.

Note that routine measurements are provided to the user (*) including monthly averages of the replica pulse power. The ESA SAR processors use a complete replica pulse from the raw data corresponding to the required SAR image to scale the raw data during processing. To perform automatic internal calibration successfully, the replica pulse power should be directly proportional to the transmitter pulse power. Because this is not so (ref. [6]), the replica pulse power variations introduced by the SAR processor need to be removed.

(*): in 'SAR Performance', of 'ERS SAR' as provided by the ESA Earthnet Online service on the web:
   http://earthnet.esrin.esa.it/

- iv) Application of the correction for ADC non-linearities:

Power Loss$_{ij}$ is the Analogue to Digital Convertor (ADC) power loss

The Analogue to Digital Convertor (ADC) quantizes each of the two raw data channels to 5 bits thus each using 32 quantization levels. **If the input signal level to the ADC is high,** a large number of data values will occupy the lowest and highest quantization levels, i.e. non-linearities due to **saturation** have occurred. Any saturation will lead to the situation where the output power from the ADC will be less than the input power (i.e. there is a power loss). A detailed description of ADC saturation is given in ref. [2], ref. [4] and ref. [5]. In addition, **if the input signal level to the ADC is low, quantization noise** has occurred leading to the situation where the output power from the ADC will be more than the input power (i.e. there is a power gain).

A method for ADC non-linearities correction i.e. a correction for power loss due to ADC saturation and power gain due to quantization noise is given in Chapter 3. The method provides an evaluation of the power loss due to ADC saturation that is directly inferred from the PRI data. As an output, the power difference Power Loss$_{ij}$ used in equation (2a) is provided via a look up table.

2.3.2 Equation (2b) accounts for the reduction of radiometric resolution errors in the backscattering coefficient measurements:

$$\sigma^o = \frac{1}{N} \Sigma A_{ij}^2 \quad \text{for all pixels within the AOI} \qquad \text{Equation (2b)}$$

After the amplitude A_{ij} has been derived using equation (2a), a further operation may be applied to enhance radiometric resolution i.e. to reduce speckle in the measurement of the backscattering coefficient σ^o of a distributed target. To reduce radiometric resolution errors, the backscattering coefficient can be calculated by simply using the average intensity value in the PRI image of a distributed target using equation (2b) i.e. by averaging the intensity values of a certain amount of pixels within the group of pixels that corresponds to the target.

Radiometric resolution errors as a function of N are given in Appendix I based on (ref. [8]).

Impact of the Area Of Interest extent N, in pixels, on the accuracy of the backscattering coefficient measurements: applying intensity averaging to an AOI corresponding to 80 resolution cells i.e. N ~240 pixels in the image of a distributed target leads to 90% confidence interval bounds of +/-0.5 dB i.e. using N ~ 240 the probability that the measured intensity lies between resolution error bounds of +/- 0.5 dB is 90%.

3. Correction method for Analogue to Digital Convertor non-linearities

3.1 Introduction

As shown in Figure 3.A) below, the impact of quantization noise is very limited and the impact of saturation is much reduced for the ERS-2 SAR PRI data product with respect to the ERS-1.
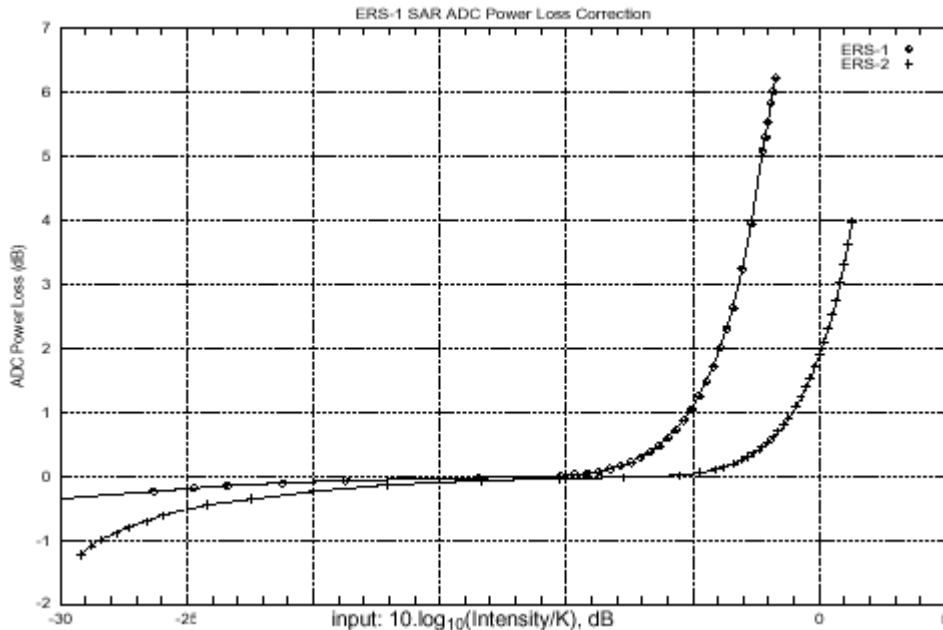
Figure 3(A) ADC non-linearities look up tables for ERS-1 and ERS-2 data. X-axis represents the value of intensity/K (as expressed in dB) inferred from the PRI data following the method presented in Chapter 3.2; Y-axis represent the power loss, in dB. Note that Figure 3.A) indicates slight power gains due to quantization noise for measured backscattering coefficients lower than ~-22 dB. As it is close to the noise equivalent sigma-nought of the ERS SAR PRI data product, the impact of quantization noise can be considered as negligible.

In order to avoid a complex and time-consumimg procedure, the user shall make sure that the ADC non-linearities correction method needs to be applied before implementing it. The following paragraphs indicate the occurrence and impact of ADC saturation for ERS-1 and ERS-2 data.

ERS-1 SAR data and ADC saturation:

ERS-1 SAR ADC saturation occurs mainly for **large distributed targets having high backscattering coefficients** (ref. [2]), e.g. the rough sea or large towns. As an indication of the occurrence of saturation for imagery over Europe, the Atlantic and Greenland, approximately 45% will have a power loss of more than 0.25 dB at the near range position. Of these approximately 36% will also have a power loss greater than 0.25 dB at far range. The highest power losses have been found for Greenland where these are up to 5.5 dB (ref. [4]). In practice, in the case of large distributed targets, if the backscattering coefficient as roughly

measured using the approximation of equation (1) presented hereafter, is greater than -7 dB then correction for saturation should be applied.

$$\text{(Approximation of Equation 1):} \quad \sigma^o = \left(\frac{1}{N} \cdot \sum_{i,j=1}^{i,j=N} DN_{ij}^2 \right) \cdot \frac{1}{K}$$

Note: following the method presented in Chapter 3.2.1, the averaging procedure above to derive σ⁰ must be applied using a window of extent 1200 pixels in range and 400 pixels in azimuth.

Otherwise, equation (2a) may be used without ADC saturation correction i.e. Power Loss$_{ij}$ is 1 in equation (2a) for all pixel coordinates i and j in the Area Of Interest.

ERS-2 SAR data and ADC saturation:

ERS-2 SAR ADC saturation is much reduced compared to the ERS-1 SAR due to a reduction in on-board gains on 13th July 1995. For example, if the measured intensity as derived using the method presented in Chapter 3.2 is:

(Intensity / K)$_{dB}$ = 10.log$_{10}$ (Intensity / K) = -2.5 dB as given by Figure 3(A).

then a power loss of 4.0 dB has to be considered for ERS-1 SAR PRI imagery and the corresponding ERS-2 SAR PRI power loss is only 0.4 dB (but only for data acquisition dates after 13th July 1995). In practice, in the case of large distributed targets, if the backscattering coefficient as roughly measured using the approximation of equation (1) presented above, is greater than -2 dB then correction for saturation should be applied. Otherwise, equation (2a) may be used without ADC saturation correction i.e. Power Loss$_{ij}$ is 1 in equation (2a) for all pixel coordinates i and j in the Area Of Interest.

A method (ref.[4]) for ADC power loss correction in the case of ERS SAR PRI data products is given hereafter. The method provides the value of the power loss due to ADC saturation via a look up table applied in a post-processed version of the PRI image.

3.2 The ADC saturation correction method

3.2.1 Presentation of the method

For the ADC saturation correction several steps are required in order to identify and estimate, if any, power loss due to saturation by using the processed ERS SAR PRI data to give a representation of the raw data:

Firstly, the ERS SAR PRI image must be root mean square (RMS) block averaged (i.e. squaring the pixel values within a block, averaging and then taking the square root) in order to reduce computation load. This is achieved using a block size of b x b pixels. The recommended block size, b, is at least 8 by 8 pixels (i.e. using block size of 100 m by 100 m or more). For an ERS SAR PRI image of size n in range and m in azimuth, DN_{uv} is the pixel amplitude of the RMS block averaged data product of size n/b in range and m/b in azimuth; u and v are the RMS block averaged range and azimuth pixel coordinates:

$$\overline{DN}_{uv}^{2} = \frac{1}{N} \sum_{\substack{(u-1) \times b < i < u \times b-1 \\ (v-1) \times b < j < v \times b-1}} DN_{ij}^{2} \qquad (u = 1 \text{ to } n/b \text{ ; and } v = 1 \text{ to } m/b)$$

Equation (3a)

Secondly, various factors must be removed to give a representation of the original raw data and infer the level of saturation: removal of any elevation antenna pattern that may have been applied, removal of the range spreading loss and replica pulse power variations. These three steps following RMS block averaging can be combined to calculate a power loss amplitude, $DNpl_{uv}$, for the image:

$$DNpl_{uv}^{2} = \overline{DN}_{uv}^{2} \frac{1}{rsl_u} C_{pl} \frac{ProductReplicaPower}{ReferenceReplicaPower} \quad [u = 1 \text{ to } n/b \text{ ; and } v = 1 \text{ to } m/b]$$

Equation (3b)

rsl_u is the range spreading loss (see Appendix B) and C_{pl} is a correction factor that accounts for power loss due to the elevation antenna pattern. The value of C_{pl} is given in Appendix E.

Note: The replica pulse power correction is required for both ERS-1 and ERS-2. In the case of ERS-2 this is the only occasion that the replica pulse correction is used.

Thirdly, smoothing using a large window is then used on the power loss amplitude image DNpl. The smoothing window extent must correspond to an extent of 15 km in range and 5 km in azimuth on the ground i.e. for 12.5 m pixels, the window size must correspond to 1200 pixels in range and 400 pixels in azimuth (the window extent is determined by the antenna synthetic

aperture length in azimuth and the replica length in range). The pixel at location (u,v) in the DNpls image corresponds to b times b pixels in the PRI data product such that i is ranging from $(u-1)_xb+1$ to u_xb and j is ranging from $(v-1)_xb+1$ to v_xb. The smoothing operation for a pixel at range and azimuth coordinates (u, v) for an image of size n/b in range and m/b in azimuth is given by:

$$DNpls_{uv} = \frac{b^2}{1200 \times 400} \sum_{u-600/b+1 < k < u+600/b} \sum_{v-200/b+1 < l < v+200/b} DNpl_{kl}$$

$[u=600/b \text{ to } (n-600)/b , v=200/b \text{ to } (m-200)/b]$ *Equation (3c)*

Note: due to edge effects in the smoothing operation the procedure will reduce the size of image DNpls compared to DNpl (by 600/b pixels at near and far range and 200/b pixel at early and late azimuth positions).

<u>Finally</u>, the power loss is determined for each block averaged pixel of the resultant image via a look-up table: each pixel in the resultant smoothed power loss amplitude image, $DNpls_{uv}$, is converted to:

<div align="center">

Intensity / K   (i.e. $DNpls_{uv}^2$ / K)
</div>

    where K is the calibration constant (given in Appendix D)
    for i ranging from $(u-1)_xb+1$ to u_xb and j ranging from $(v-1)_xb+1$ to v_xb.

The corresponding **Power Loss values can be determined via the look-up tables** displayed in Figure 3.A), page 10, and given in Appendix F.

It is estimated that the ADC power loss can, in general, be estimated to a precision of better than 0.5 dB (ref. [3]). Exceptions to this are regions consisting of numerous bright point targets (such as e.g. cities).

3.2.2 Diagram of the method

- DN_{ij}: digital number corresponding to pixel at location (i,j) in the PRI product (amplitude).

- i and j: range and azimuth pixel coordinates for an image of size n in range and m in azimuth.

- b: block size in RMS (root mean square) block averaging operation.

- u and v: pixel coordinates in block averaged image (DNpl) and in smoothed image (DNpls).
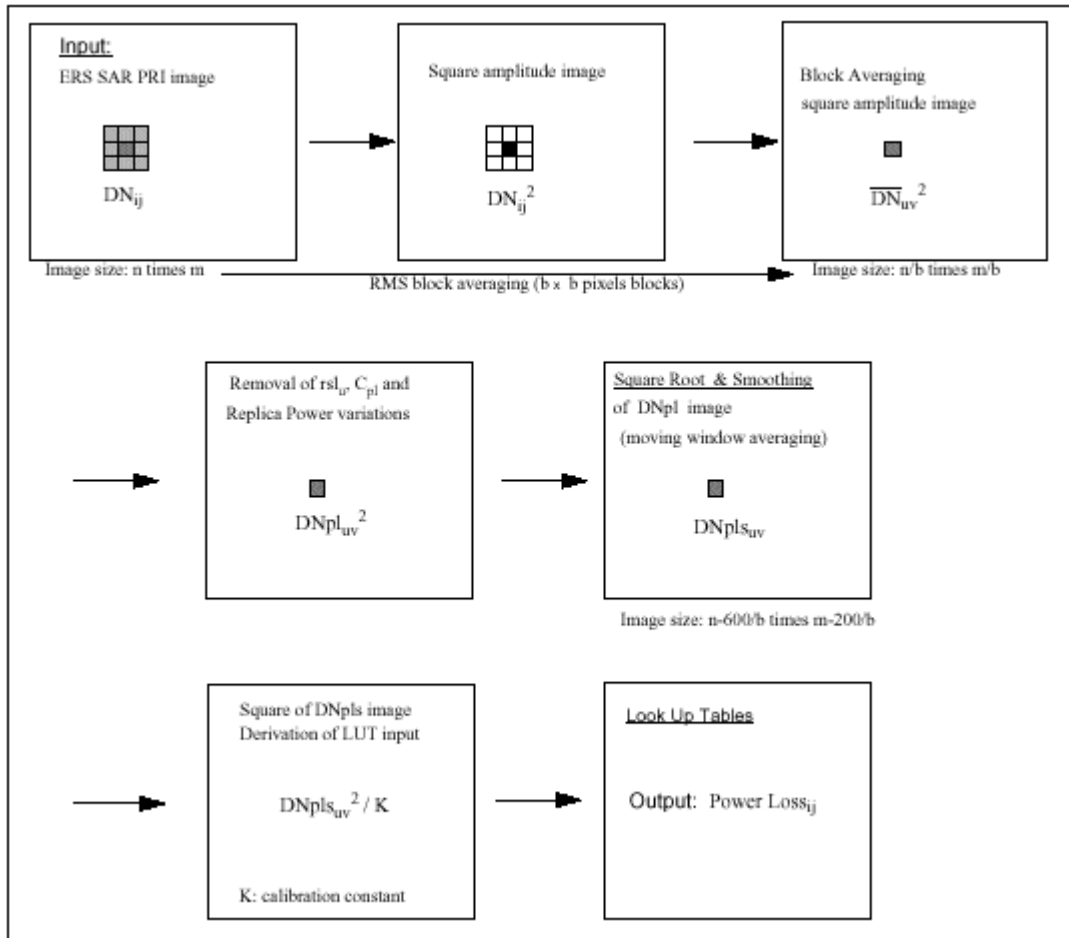
<u>Figure 3.B) The ADC non-linearities correction method</u>: input is the PRI data ; output is: Power Loss$_{ij}$ given for the computed intensity value (DNpls$_{uv}^2$ / K) via the look up table.

4. Interpretation: the case of ERS-2 SAR PRI products processed after 17th October 1995

4.1 Set of equations for the comprehensive derivation method

In the case of ERS-2 SAR PRI products processed after 17th October 1995, the method to derive measurements of the backscattering coefficient σ^o is as follows:

Equation (2a) becomes:

$$A_{ij}^2 = DN_{ij}^2 \; \frac{1}{K} \; \frac{\sin \alpha_i}{\sin \alpha_{ref}} \; \frac{ProductReplicaPower}{ReferenceReplicaPower} \qquad \textit{Equation (2a')}$$

Equation (2b) for the backscattering coefficient, in intensity, remains:

$$\sigma^o = \frac{1}{N} \; \Sigma \; A_{ij}^2 \quad \text{for all pixels within the AOI} \qquad \textit{Equation (2b')}$$

Indeed, because the implementation of the elevation antenna pattern was done using the definitive ERS-2 pattern (see Appendix C), no correction factor is needed. In addition, because the on-board gains of the ERS-2 SAR instrument have been reduced, no correction factor for ADC non- linearities is needed in equation (2a). The users shall ensure that there is no occurrence of ADC non- linearities due to saturation in their data product by deriving rough measurements of backscattering coefficient over a large area covering their AOI to verify that it is lower than -2 dB (e.g. no large cities, no rough sea within 5 km in azimuth and 15 km in range).

4.2 Example of application

> *Measurement of the backscattering coefficient σ^o for a distributed target*
> *in an ERS-2 PRI product generated at UK-PAF and processed on 25th April 1996*

Let us consider an AOI containing 11 range pixels times 12 azimuth pixels with centre pixel range coordinate 2000. The mean intensity in the AOI is: $I_{mean} = 475000$ (average value over N=132 pixels $P_1,..,PN$).

A rough measurement of σ^o using a window of extent 1200 pixels in range (15 km) and 400 pixels in azimuth (5 km) covering the AOI (following the method presented in Chapter 3.2.1) and using the approximation of equation (1) below gives:

(Approximation of Equation 1): $\sigma^o = \left(\dfrac{1}{N} \cdot \displaystyle\sum_{i,j=1}^{i,j=N} DN_{ij}^2 \right) \cdot \dfrac{1}{K}$

$\sigma^o = 0.3548$ from the average intensity over 1200 times 400 pixels and with K=1000000 (calibration constant in ERS-2 SAR PRI products as given in Appendix D).

$\sigma^o{}_{dB} = 10.\log_{10}(\sigma^o) \sim -4.5$ dB

As $\sigma^o{}_{dB} < -2$ dB there is no ADC saturation thus equations (2a') is valid.

From Appendix B (first method) and using the CEOS annotations from the product header, we obtain:

Measured earth angle ψ_i for pixel i =2000 is: ψ_i =2.45654 deg.

Slant range to a pixel at range coordinate i, is: R_i = 846.89 km

Incidence α_i angle at pixel coordinate i is: α_i = 21.29 deg.

Look angle θ_i at pixel coordinate i is: θ_i = 18.83 deg.

From Appendix D and using the annotations, the needed correction factors can be derived and applied:

K=1000000 (i.e. 60 dB)

$\sin \alpha_i = 0.3631$

$\sin \alpha_{ref} = 0.3907$

$\sin \alpha_i / (K \cdot \sin \alpha_{ref}) = 1 / 1076131.6$

ProductReplicaPower / ReferenceReplicaPower: *not applicable for ERS-2.*

The measurement of the backscattering coefficient gives:

Using equation (2a') and using equation (2b') over the AOI of N=132 pixels:

$\sigma^o = \Sigma A_{ij}{}^2 / N = 475000 \times (1 / 1076131.6) = 0.4414$ in linear scale

i.e. in decibel: $\sigma^o{}_{dB} = 10.\log_{10}(\sigma^o) = -3.5$ dB

Note: using 132 pixels at pixel location 2000, $\sigma^o{}_{dB}$ is a measurement of the backscattering coefficient with 80% confidence for ±0.5 dB radiometric resolution error bounds (see Appendix I)

5. Summary

This document has given the steps whereby users can derive measurements of the backscattering coefficient σ^o from their ERS SAR PRI products. A simplified and a comprehensive σ^o derivation methods have been presented.

The steps for the comprehensive derivation method include corrections for the implementation of the elevation antenna pattern, for the backscattering coefficient dependence on incidence angle, for any replica pulse power variations (ERS-1 only) and finally for Analogue to Digital Convertor (ADC) non-linearities. The correction for ADC non-linearities, when needed (specific to certain conditions in the imaged scene, in particular with ERS-1 data), is the most complex correction and requires users to perform image analysis of their products following the method proposed in the document.

The backscattering coefficient σ^o measurements have radiometric resolution errors that are given using confidence intervals as presented in Appendix I, Figure I-B and Table I-2.

It has been estimated that the backscattering coefficient σ^o value derived with the comprehensive method is accurate to within ±0.4 dB.

ERS SAR CALIBRATION

Appendices

ERS SAR Calibration:
Derivation of σ°
in ESA ERS SAR PRI products

ES-TN-RS-PM-HL09

Issue 2.f 05 November 2004

Appendix A. Location of CEOS Header Parameters

The location of relevant header parameters for the derivation of σ° in ESA ERS SAR PRI products is given in Table A below.

Parameter	File	Record	Field	Bytes	Units/Format
product processing date	VDF	TR	10	78 - 85	YYYYMMDD
acquisition date	LF	DSSR	11	69-76	YYYYMMDD
scene centre time (UTC)	LF	DSSR	11	69 - 100	YYYYMMDDhhmmsstt
processed scene centre geodetic latitude	LF	DSSR	13	117 - 132	degrees
processing system identifier	LF	DSSR	82	1063 - 1070	-
processing version identifier	LF	DSSR	83	1071 - 1078	-
zero Doppler azimuth time of centre azimuth pixel	LF	DSSR	126	1839 - 1862	DD-MMM-YYYY hh:mm:ss.ttt
zero Doppler range time	LF	DSSR	126	1767 - 1782	millisec
number of pixels per line	LF	MPR	9	61 - 76	pixels
number of lines	LF	MPR	10	77 - 92	lines
pixel size (range direction)	LF	MPR	11	93 - 108	m
pixel size (azimuth direction)	LF	MPR	12	109 - 124	m
ellipsoid semi-major axis	LF	MPR	21	269 - 284	m
ellipsoid semi-minor axis	LF	MPR	22	285 - 300	m
number of orbit state vectors	LF	PPDR	14	141 - 144	-
date of the first orbit state vector	LF	PPDR	15,16,17	145 - 156	DD
time of the first orbit state vector	LF	PPDR	19	161 - 182	seconds
time interval between state vectors	LF	PPDR	20	183 - 204	seconds
orbit state position vector (X,Y,Z)	LF	PPDR	29,31,..	387-452, 519-584, ..	m
Replica Pulse Power	LF	FRDR	55	567 - 582	-
near range incidence angle	LF	FRDR	56	583 - 598	degrees
Processor range compression designator	LF	DSSR	123	1719-1734	-
reference slant range	LF	FRDR	59	631 - 646	km
absolute calibration constant, K	LF	FRDR	62	663 - 678	-
number of valid pixels per line	LF	FRDR	125	1723-1726	pixels

File VDF = Volume Directory File

Record TR = Text Record

File LF = Leader File

Record DSSR = Data Set Summary Record

Record MPR = Map Projection Record

Record PPDR = Platform Position Data Record

Record FRDR = Facility Related Data Record (General Type)

YYYY=year

MM = month (eg. 12)

DD = day

MMM = month (eg. DEC)

hh = hour

mm = minutes

ss = seconds and ttt = milliseconds

Table A. Location of CEOS Header Parameters for ERS SAR PRI products (based on ref [9]).

Appendix B. Image Geometry

This appendix describes how the slant range, incidence angle, look angle and range spreading loss can be calculated for any pixel within a PRI product. It is assumed that the incidence angle α of the imaging surface can be represented by an ellipsoid. This <u>excludes</u> any local surface slope which can be important for hilly or mountainous regions. The derivation of the actual incidence angle requires the use of a Digital Elevation Model (DEM).

Appendix B1: First method

To derive the incidence angle α_i, the look angle θ_i and the slant range R_i, to a pixel at ground range coordinate i, the user needs to retrieve from the product header CEOS annotations the values of:

- the *zero Doppler range time* t_1 of the first range pixel.
- *the near range incidence angle,* α_1.
- *the processed scene centre latitude* (geodetic), λ.

The Earth radius, R_T, is calculated using:

$$R_T = a \ [\ \cos^2\lambda + (b/a)^4 \times \sin^2\lambda\ ]^{1/2} \times [\ \cos^2\lambda + (b/a)^2 \times \sin^2\lambda\ ]^{-1/2}$$

where
a = equatorial Earth radius (6378.144 km)
b = polar Earth radius (6356.759 km)

a and b values correspond to the ERS reference ellipsoid: GEM6 (Goddard Earth Model 6). GEM6 oblateness coefficient is 1/298.257.

From the ERS reference geometry, the ERS altitude H is given by:

$$R_T + H = [\ R_T{}^2 + R_1{}^2 + 2 \times R_T \times R_1 \times \cos\alpha_1\ ]^{1/2}$$

where R_1 is the slant range distance to the first range pixel: $R_1 = c \times t_1 / 2$

c is the velocity of light, t_1 is the *zero Doppler range time* of the first range pixel.

The near range look angle is given by:

$$\cos\theta_1 = (R_1 + R_T \times \cos\alpha_1) / (R_T + H)$$

The Earth angle ψ_1 for first range pixel is given by: $\pi = \psi_1 + \theta_1 + (\pi - \alpha_1)$ thus: $\psi_1 = \alpha_1 - \theta_1$

ψ_1 is the angle between the vertical of the satellite and the vertical of the first range pixel.

The Earth angle ψ_i for pixel i can be estimated using:

$$\sin(\Delta\psi_i) = (i-1) \times \Delta r / R_T, \text{ where } \Delta r \text{ is the } pixel\ spacing \text{ (along ground range).}$$

$\Delta\psi_i$ being small ($\Delta\psi_i = 0.9$ degree for 100 km swath width), ψ_i is given by:

$$\psi_i = \psi_i + \Delta\psi_i = \psi_1 + (i-1) \times \Delta r / R_T \text{ (expressed in radians)}$$

The slant range to a pixel at range coordinate i, R_i, is given by:

$$R_i = [\ R_T^2 + (R_T+H)^2 - 2 \times R_T \times (R_T + H) \cos\psi_i\ ]^{1/2}$$

The incidence α_i angle at pixel coordinate i is given by:

$$\cos\alpha_i = [\ (R_T+H)^2 - R_i^2 - R_T^2\ ] / (2 \times R_i \times R_T)$$

and the look angle θ_i at pixel coordinate i is given by:

$$\cos\theta_i = (R_i + R_T \times \cos\alpha_i) / (R_T + H)$$
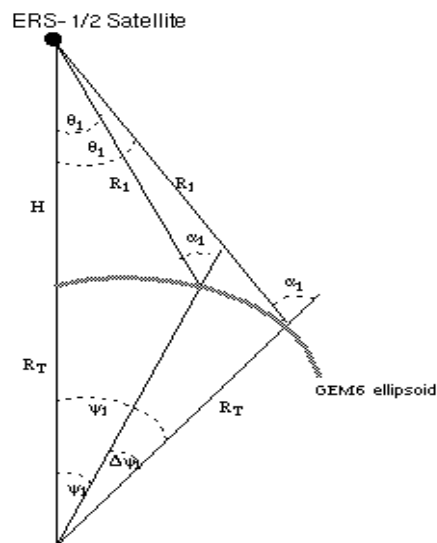
The range spreading loss compensation (already applied in PRI products) at pixel coordinate i is given by:

$$rsl_i = R_i^3 / R_{ref}^3$$

where R_i is the slant range at range pixel coordinate i,

and R_{ref} is the *reference slant range*, 847.0 km.

Appendix B2: The second method

> *This method shall be applied only for UK-PAF products*
> *processed prior to 8th April 1993 (see ref. [7]).*

First, the Earth radius and satellite radius are to be calculated. The Earth radius, R_T, for a given *processed scene centre latitude* (geodetic), λ, is given by:

$$R_T = a \ [\ \cos^2\lambda + (b/a)^4 \times \sin^2\lambda \ ]^{1/2} \times [\ \cos^2\lambda + (b/a)^2 \times \sin^2\lambda \ ]^{-1/2}$$

where a and b are respectively the reference *ellipsoid semi-major* and *semi-minor axis*.

The satellite radius, $R_T + H$, is calculated using the nearest *orbit state position vector* (x, y, z coordinates) to the *zero Doppler azimuth time of centre azimuth pixel*. This needs the *number of orbit state vectors, time of the first orbit state vector* and the *time interval between state vectors*.

Once the nearest state vector has been extracted the satellite radius is calculated thus:

$$R_T + H = [\ x^2+y^2+z^2 \ ]^{1/2}$$

The slant range to a pixel at range coordinate i, R_i, is given by:

$$R_i = [\ R_T{}^2+(R_T+H)^2 - 2 \times R_T \times (R_T + H) \cos\psi_i \ ]^{1/2}$$

where ψ_i is the earth angle for range pixel coordinate i.

ψ_i is given by:

$$\psi_i = \alpha_1 - \theta_1 + \sin^{-1}[\ (i-1) \times \Delta r / R_T \ ]$$

α_1 is the *near range incidence angle*, θ_1 is the near range look angle,

and Δr is the *pixel spacing*.

The near range look angle is given by: $\sin \theta_1 = R_T / (R_T + H) \times \sin \alpha_1$

α_i incidence angle at pixel coordinate i is given by: $\cos \alpha_i = [\ (R_T+H)^2 - R_i{}^2 - R_T{}^2 \ ] / (2 \times R_i \times R_T)$

and the look angle θ_i at pixel coordinate i is given by: $\sin \theta_i = R_T / (R_T + H) \times \sin \alpha_i$

Finally, the range spreading loss compensation (already applied in PRI products) at pixel coordinate i is given by:

$$rsl_i = R_i{}^3 / R_{ref}{}^3$$

where R_i is the slant range at pixel coordinate i, and R_{ref} is the *reference slant range*, 847.0 km.

Appendix C.   Correction Factor Ci

The correction factor Ci is given below for the various processing centres and *product processing dates*:

g^2Init (θ_i) is the standard ERS-1 antenna pattern (Appendix G1),
$E_c(\theta_i)$ is the UK-PAF ERS-1 antenna pattern correction (Appendix H),
g^2Im (θ_i) is the improved ERS-1 antenna pattern (Appendix G2),
θ_i is the look angle at range pixel coordinate i (Appendix B).

PRI products generated at ESRIN, D-PAF and I-PAF:

product processing date	Ci	Explanation
ERS-1 PRI product		
1st August 1991 to 31st August 1992	$1 / g^2$Im (θ_i)	No antenna pattern applied.
1st September 1992 to 15th July 1995	g^2Init $(\theta_i) / g^2$Im (θ_i)	Standard antenna pattern applied.
After 16th July 1995	1	Improved antenna pattern applied.
ERS-2 PRI product		
After 16th October 1995	1	Antenna pattern applied.
Note: Before 16th October 1995, no ERS-2 SAR PRI products have been distributed to users.		

PRI products generated at UK-PAF (see ref. [6]):

product processing date	Ci	Explanation
ERS-1 PRI product		
1st August 1991 to 31st August 1992	$1 / g^2$Im (θ_i)	No antenna pattern applied.
1st September 1992 to 8th April 1993	$E_c(\theta_i)$ x g^2Init $(\theta_i) / g^2$Im (θ_i)	Standard antenna pattern applied incorrectly.
8th April 1993 to 15th July 1995	g^2Init $(\theta_i) / g^2$Im (θ_i)	Standard antenna pattern applied correctly.
After 16th July 1995	1	Improved antenna pattern applied.
ERS-2 PRI product		
After 16th October 1995	1	Antenna pattern applied.
Note: Before 16th October 1995, no ERS-2 SAR PRI products have been distributed to users.		

Appendix D.   Calibration Constant and Reference Replica Power

Appendix D1: PRI Calibration constant K

ERS-1	**Calibration Constant K**	
	in linear scale	**in Decibels**
Product processing date		
D-PAF and ESRIN:		
before 1st September 1992	678813	58.32 dB
since 1stSeptember 1992	666110	58.24 dB
I-PAF:		
from 28th June 1993 to 6th December 1994	625228	57.96 dB
from 7th December 1994 to 16th March 1995	370016	55.68 dB
Since 17th March 1995	686379	58.36 dB
UK-PAF:		
before 1st September 1992	890107	59.49 dB
from 1st September 1992 to 20th January 1997	1072611.2	60.30 dB
since 20th January 1997	666110	58.24 dB
Acquisition date		
D-PAF, ESRIN and UK-PAF:		
before 24th February 1998	as above	as above
since 24th February 1998	799000	59.03 dB
I-PAF:		
before 24th February 1998	as above	as above
since 24th February 1998	822245	59.15 dB

ERS-2		Calibration Constant K	
		in linear scale	in Decibels
Product processing date			
D-PAF, I-PAF and ESRIN:			
since 13th July 1995		944000	59.75 dB
UK-PAF:			
from 13th July 1995 to 20th January 1997		1000000	60.00 dB
since 20th January 1997		944061	59.75 dB
Acquisition date			
D-PAF, ESRIN, I-PAF and UK-PAF:			
before 13th July 1995		not calibrated	not calibrated
since 13th July 1995		as above	as above
From 4th September 2004 10:04:14 to 14th October 2004 14:37:11		2371374	63.75 dB
From 14th October 2004 14:37:11		944061	59.75 dB

The calibration constant values given above should be used in preference to those in the CEOS header, <u>except</u> that the ERS-2 SAR PRI calibration constant is only valid for *data acquisition dates* after 13th July 1995. Before this date ERS-2 SAR PRI images are considered uncalibrated. For data acquisitions between 4th September and 14th October 2004, the replica pulse power was lower than expected; to compensate for this the calibration constant has to be increased by 4dB.

Appendix D2: SLCI Calibration constant K

ERS-1		Calibration Constant K	
		in linear scale	in Decibels
Product processing date			
UK-PAF:			
from 1st September 1992 to 20th January 1997		56662.5	47.53 dB
since 21st January 1997		65026.0	48.13 dB
I-PAF, D-PAF and ESRIN:			
from 21st January 1997		65026.0	48.13 dB
Acquisition date			
UK-PAF:			
before 24th February 1998		as above	as above
since 24th February 1998		78000.0	48.92 dB

ERS-2		Calibration Constant K	
		in linear scale	in Decibels
Product processing date			
UK-PAF:			
from 13th July 1995 to 20th January 1997		445656.2	56.49 dB
since 20th January 1997		93325.3	49.70 dB
I-PAF, D-PAF and ESRIN:			
since 20th January 1997		93325.3	49.70 dB
Acquisition date			
UK-PAF, I-PAF, D-PAF and ESRIN:			
From 4th September 2004 10:04:14 to 14th October 2004 14:37:11		234422.55	53.70 dB
From 14th October 2004 14:37:11		93325.3	49.70 dB

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Appendix D3: Reference Replica Power

ERS-1	Reference Replica Power
PRI generated at D-PAF, I-PAF and UK-PAF	205229.0
PRI generated at ESRIN	*Chirp average density reference* (see below)
ERS-2	
generated at D-PAF, I-PAF, UK-PAF and ESRIN	*156000.0*

- *Chirp average density reference*: in the case of data products processed at ESRIN (and at D-PAF if the product replica power value is not annotated), the ratio between ProductReplicaPower and ReferenceReplicaPower using equation (2a) shall be replaced by the ratio between first chirp average density measured during image acquisition and chirp average density of reference:

$$\frac{\text{ProductReplica Power}}{\text{ReferenceReplicaPower}} \quad \text{shall be changed into:} \quad \frac{\text{Chirp average density image}}{\text{Chirp average density reference}}$$

Chirp average density reference:

> **267.20 for ERS-1** (measured on reference image of 13/10/1991).

Chirp average density image: this parameter can be found in the Facility Data Record, PCS type, at byte location: 77+176+3196 = 3449 in the 'ESA reserved' record area. At that location is recorded the first chirp average density over a series of records corresponding to the image acquisition. Because of the low variability of the chirp average density measurements, the first value provides a suitable measurement.

Appendix E.   Correction Factor Cpl

The factor Cpl is given below for the various processing centres and *product processing dates*:

g^2Init (θ_i) is the standard ERS-1 antenna pattern (Appendix G1),

$E_c(\theta_i)$ is the UK-PAF ERS-1 antenna pattern correction (Appendix H),

g^2Im (θ_i) is the improved ERS-1 antenna pattern (Appendix G2),

g^2ERS2 (θ_i) is the ERS-2 SAR antenna pattern (Appendix G3),

θ_i is the look angle at range pixel coordinate i (Appendix B).

PRI products generated at ESRIN, D-PAF and I-PAF:

product processing date	Cpl	Explanation
ERS-1 PRI product		
1st August 1991 to 31st August 1992	1	No antenna pattern applied.
1st September 1992 to 15th July 1995	g^2Init (θ_i)	Standard antenna pattern applied.
After 16th July 1995	g^2Im (θ_i)	Improved antenna pattern applied.
ERS-2 PRI product		
After 16th October 1995	g^2ERS2 (θ_i)	Antenna pattern applied.
Note: Before 16th October 1995, no ERS-2 SAR PRI products have been distributed to users.		

PRI products generated at UK-PAF:

product processing date	Cpl	Explanation
ERS-1 PRI product		
1st August 1991 to 31st August 1992	1	No antenna pattern applied.
1st September 1992 to 8th April 1993	$E_c(\theta_i)$ x g^2Init (θ_i)	Standard antenna pattern applied incorrectly.
8th April 1993 to 16th July 1995	g^2Init (θ_i)	Standard antenna pattern applied correctly.
After 16th July 1995	g^2Im (θ_i)	Improved antenna pattern applied.
ERS-2 PRI product		
After 16th October 1995	g^2ERS2 (θ_i)	Antenna pattern applied.
Note: Before 16th October 1995, no ERS-2 SAR PRI products have been distributed to users.		

Appendix F1. ERS-1 SAR ADC Power Loss Correction Look-up Table

Intensity/K (dB)	Power Loss (dB)		Intensity/K (dB)	Power Loss (dB)
-30.19	-0.36		-5.66	0.72
-26.32	-0.24		-5.34	0.87
-24.74	-0.19		-5.04	1.04
-23.40	-0.15		-4.74	1.25
-21.22	-0.11		-4.46	1.47
-18.72	-0.07		-4.18	1.71
-13.46	-0.03		-3.91	2.00
-10.20	0.00		-3.65	2.30
-9.67	0.02		-3.40	2.63
-9.18	0.04		-3.04	3.23
-8.71	0.06		-2.69	3.94
-8.26	0.11		-2.24	5.08
-7.84	0.16		-2.13	5.29
-7.44	0.21		-2.03	5.53
-7.05	0.29		-1.92	5.82
-6.68	0.37		-1.82	6.01
-6.33	0.47		-1.72	6.22
-5.98	0.59			

ERS-1 SAR ADC Power Loss Correction

input: $10 \cdot \log_{10}(\text{Intensity/K})$, dB
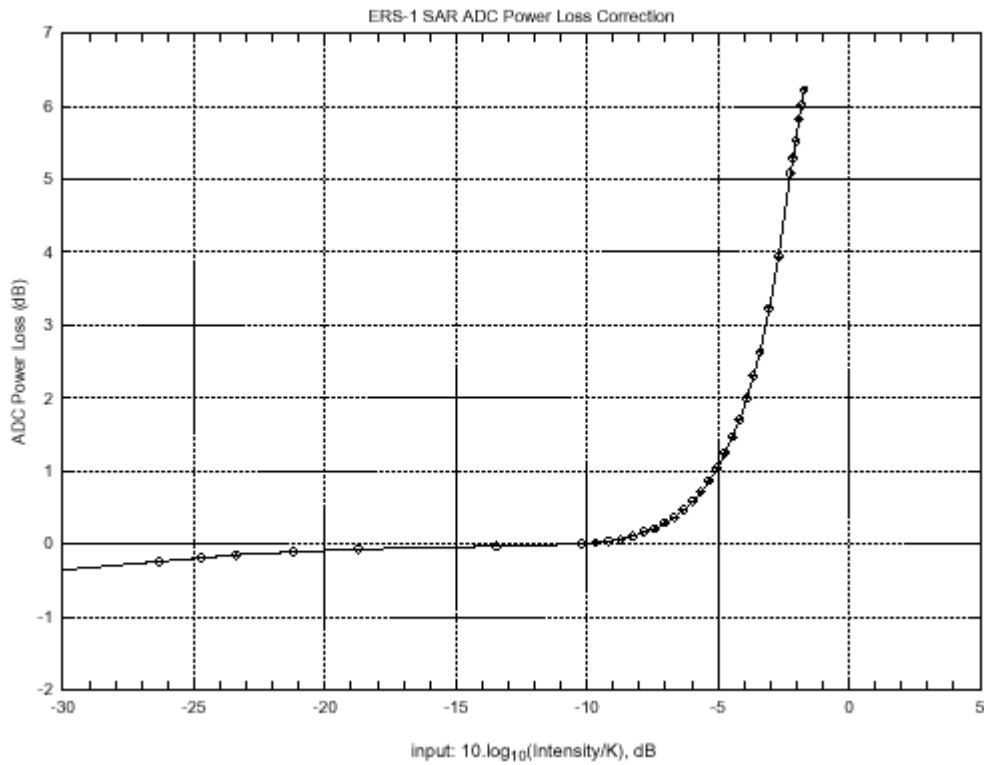
Appendix F2. ERS-2 SAR ADC Power Loss Correction Look-up Table

Intensity/K (dB)	Power Loss (dB)		Intensity/K (dB)	Power Loss (dB)
-29.20	-1.23		-2.62	0.35
-28.75	-1.10		-2.38	0.41
-28.42	-1.00		-2.27	0.45
-27.80	-0.90		-2.05	0.53
-27.27	-0.80		-1.83	0.61
-26.61	-0.71		-1.62	0.70
-25.93	-0.61		-1.41	0.80
-24.19	-0.45		-1.21	0.91
-22.42	-0.36		-0.92	1.09
-20.00	-0.24		-0.72	1.23
-17.08	-0.14		-0.54	1.39
-13.39	-0.07		-0.35	1.53
-10.28	-0.04		-0.18	1.70
-7.74	-0.02		0.00	1.90
-5.51	0.01		0.17	2.10
-4.69	0.05		0.34	2.29
-4.12	0.10		0.51	2.51
-3.77	0.14		0.67	2.73
-3.38	0.19		0.83	3.03
-3.10	0.25		0.98	3.31
-2.85	0.30		1.14	3.63
			1.29	3.97

ERS-2 SAR ADC Power Loss Correction

input: $10.\log_{10}$(Intensity/K), dB
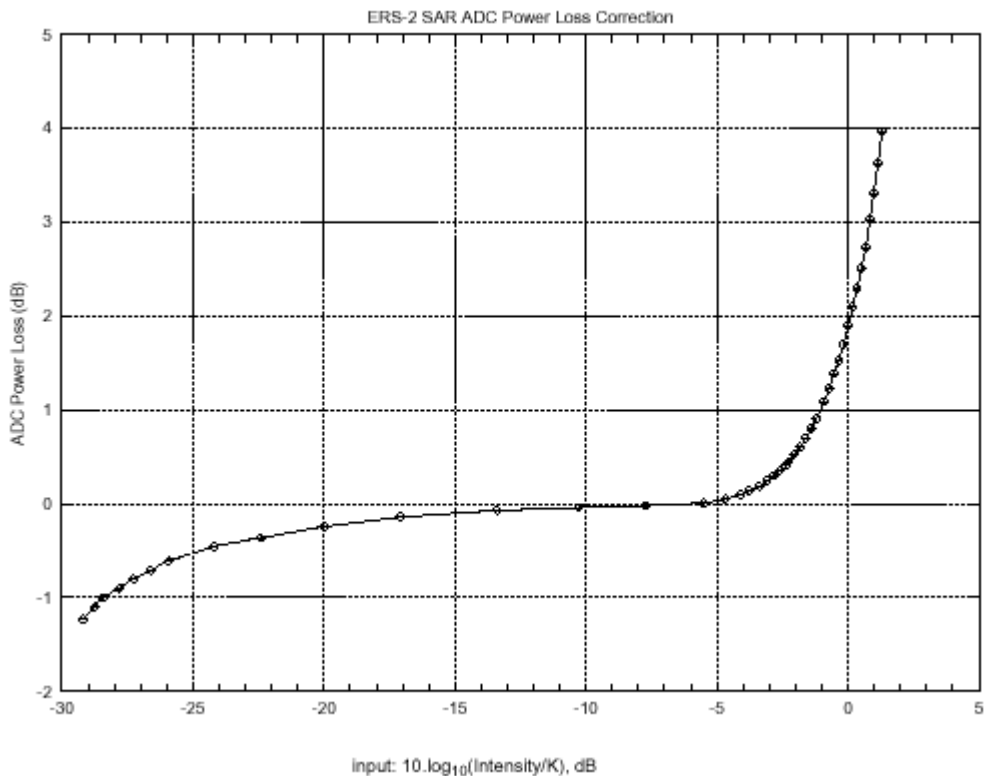
Appendix G1.   Initial ERS-1 SAR Elevation Antenna Pattern (ref. [1])
For products processed before 16th July 1995.

Rel. Look Angle $(\Delta\theta)$ (Degree)	g^2Init $(\Delta\theta)$ (dB)	Rel. Look Angle $(\Delta\theta)$ (Degree)	g^2Init $(\Delta\theta)$ (dB)
-3.5	-2.098	0.1	+0.002
-3.4	-1.892	0.2	+0.007
-3.3	-1.685	0.3	+0.014
-3.2	-1.479	0.4	+0.023
-3.1	-1.272	0.5	+0.034
-3.0	-1.066	0.6	+0.048
-2.9	-0.869	0.7	+0.063
-2.8	-0.696	0.8	+0.080
-2.7	-0.545	0.9	+0.097
-2.6	-0.416	1.0	+0.115
-2.5	-0.305	1.1	+0.132
-2.4	-0.212	1.2	+0.149
-2.3	-0.133	1.3	+0.163
-2.2	-0.068	1.4	+0.175
-2.1	-0.015	1.5	+0.183
-2.0	+0.028	1.6	+0.187
-1.9	+0.060	1.7	+0.184
-1.8	+0.085	1.8	+0.175
-1.7	+0.101	1.9	+0.157
-1.6	+0.112	2.0	+0.129
-1.5	+0.116	2.1	+0.089
-1.4	+0.117	2.2	+0.036
-1.3	+0.113	2.3	-0.033
-1.2	+0.106	2.4	-0.121
-1.1	+0.097	2.5	-0.228
-1.0	+0.086	2.6	-0.360
-0.9	+0.074	2.7	-0.517
-0.8	+0.062	2.8	-0.699
-0.7	+0.049	2.9	-0.883
-0.6	+0.038	3.0	-1.066
-0.5	+0.027	3.1	-1.249
-0.4	+0.018	3.2	-1.433
-0.3	+0.010	3.3	-1.616
-0.2	+0.005	3.4	-1.800
-0.1	+0.001	3.5	-1.983
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{Init}(\theta) = g^2_{Init}(\Delta\theta)$; $\Delta\theta = \theta - 20.355$ (Degree, the boresight angle).

Appendix G2(a). Improved ERS-1 SAR Elevation Antenna Pattern (ref. [10])
For UK-PAF products processed after 16th July 1995 and before 21st January 1997.

Rel. Look Angle ($\Delta\theta$) (Degree)	g^2Im ($\Delta\theta$) (dB)	Rel. Look Angle ($\Delta\theta$) (Degree)	g^2Im ($\Delta\theta$) (dB)
-3.5	-1.986	0.1	+0.015
-3.4	-1.831	0.2	+0.033
-3.3	-1.676	0.3	+0.056
-3.2	-1.521	0.4	+0.081
-3.1	-1.366	0.5	+0.107
-3.0	-1.211	0.6	+0.133
-2.9	-1.056	0.7	+0.165
-2.8	-0.901	0.8	+0.197
-2.7	-0.746	0.9	+0.231
-2.6	-0.605	1.0	+0.264
-2.5	-0.478	1.1	+0.294
-2.4	-0.365	1.2	+0.317
-2.3	-0.269	1.3	+0.335
-2.2	-0.186	1.4	+0.348
-2.1	-0.116	1.5	+0.356
-2.0	-0.064	1.6	+0.358
-1.9	-0.022	1.7	+0.354
-1.8	+0.012	1.8	+0.343
-1.7	+0.036	1.9	+0.322
-1.6	+0.053	2.0	+0.291
-1.5	+0.066	2.1	+0.249
-1.4	+0.071	2.2	+0.188
-1.3	+0.071	2.3	+0.112
-1.2	+0.067	2.4	+0.023
-1.1	+0.060	2.5	-0.085
-1.0	+0.053	2.6	-0.209
-0.9	+0.045	2.7	-0.334
-0.8	+0.035	2.8	-0.485
-0.7	+0.023	2.9	-0.636
-0.6	+0.011	3.0	-0.787
-0.5	+0.001	3.1	-0.938
-0.4	-0.009	3.2	-1.089
-0.3	-0.013	3.3	-1.240
-0.2	-0.013	3.4	-1.391
-0.1	-0.009	3.5	-1.542
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{ERS2}(\theta) = g^2_{ERS2}(\Delta\theta)$; $\Delta\theta = \theta - 20.355°$ (the boresight angle).

Appendix G2(b). Improved ERS-1 SAR Elevation Antenna Pattern (ref. [10])
For VMP products processed after 16th July 1995 and prior to v6.8.

Rel. Look Angle $(\Delta\theta)$ (Degree)	g^2Im $(\Delta\theta)$ (dB)	Rel. Look Angle $(\Delta\theta)$ (Degree)	g^2Im $(\Delta\theta)$ (dB)
-3.5	0.0	0.1	+0.015
-3.4	0.0	0.2	+0.033
-3.3	0.0	0.3	+0.056
-3.2	0.0	0.4	+0.081
-3.1	-1.366	0.5	+0.107
-3.0	-1.211	0.6	+0.133
-2.9	-1.056	0.7	+0.165
-2.8	-0.901	0.8	+0.197
-2.7	-0.746	0.9	+0.231
-2.6	-0.605	1.0	+0.264
-2.5	-0.478	1.1	+0.294
-2.4	-0.365	1.2	+0.317
-2.3	-0.269	1.3	+0.335
-2.2	-0.186	1.4	+0.348
-2.1	-0.116	1.5	+0.356
-2.0	-0.064	1.6	+0.358
-1.9	-0.022	1.7	+0.354
-1.8	+0.012	1.8	+0.343
-1.7	+0.036	1.9	+0.322
-1.6	+0.053	2.0	+0.291
-1.5	+0.066	2.1	+0.249
-1.4	+0.071	2.2	+0.188
-1.3	+0.071	2.3	+0.112
-1.2	+0.067	2.4	+0.023
-1.1	+0.060	2.5	-0.085
-1.0	+0.053	2.6	-0.209
-0.9	+0.045	2.7	-0.334
-0.8	+0.035	2.8	-0.485
-0.7	+0.023	2.9	0.0
-0.6	+0.011	3.0	0.0
-0.5	+0.001	3.1	0.0
-0.4	-0.009	3.2	0.0
-0.3	-0.013	3.3	0.0
-0.2	-0.013	3.4	0.0
-0.1	-0.009	3.5	0.0
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{ERS2} (\theta) = g^2_{ERS2} (\Delta\theta)$; $\Delta\theta = \theta - 20.355°$ (the boresight angle). For the processor name version number see *processing system identifier* and *processing version identifier*.

ERS SAR Calibration:
Derivation of σ°
in ESA ERS SAR PRI products

ES-TN-RS-PM-HL09

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Appendix G2(c).Improved ERS-1 SAR Elevation Antenna Pattern (ref. [10])
For VMP products processed with v6.8 or later

Rel. Look Angle ($\Delta\theta$) (Degree)	g^2Im ($\Delta\theta$) (dB)	Rel. Look Angle ($\Delta\theta$) (Degree)	g^2Im ($\Delta\theta$) (dB)
-3.5	-2.120	0.1	+0.015
-3.4	-1.945	0.2	+0.033
-3.3	-1.770	0.3	+0.056
-3.2	-1.595	0.4	+0.081
-3.1	-1.420	0.5	+0.107
-3.0	-1.245	0.6	+0.133
-2.9	-1.067	0.7	+0.165
-2.8	-0.901	0.8	+0.197
-2.7	-0.746	0.9	+0.231
-2.6	-0.605	1.0	+0.264
-2.5	-0.478	1.1	+0.294
-2.4	-0.365	1.2	+0.317
-2.3	-0.269	1.3	+0.335
-2.2	-0.186	1.4	+0.348
-2.1	-0.116	1.5	+0.356
-2.0	-0.064	1.6	+0.358
-1.9	-0.022	1.7	+0.354
-1.8	+0.012	1.8	+0.343
-1.7	+0.036	1.9	+0.322
-1.6	+0.053	2.0	+0.291
-1.5	+0.066	2.1	+0.249
-1.4	+0.071	2.2	+0.188
-1.3	+0.071	2.3	+0.112
-1.2	+0.067	2.4	+0.023
-1.1	+0.060	2.5	-0.085
-1.0	+0.053	2.6	-0.209
-0.9	+0.045	2.7	-0.334
-0.8	+0.035	2.8	-0.485
-0.7	+0.023	2.9	-0.636
-0.6	+0.011	3.0	-0.787
-0.5	+0.001	3.1	-0.938
-0.4	-0.009	3.2	-1.089
-0.3	-0.013	3.3	-1.240
-0.2	-0.013	3.4	-1.391
-0.1	-0.009	3.5	-1.542
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{ERS2}(\theta) = g^2_{ERS2}(\Delta\theta)$; $\Delta\theta = \theta - 20.355°$ (the boresight angle). For the processor name version number see *processing system identifier* and *processing version identifier*.

Appendix G3(a). The ERS-2 SAR Elevation Antenna Pattern
For UK-PAF products processed before 21st January 1997

Rel. Look Angle ($\Delta\theta$) (Degree)	g^2ERS2 ($\Delta\theta$) (dB)	Rel. Look Angle ($\Delta\theta$) (Degree)	g^2ERS2 ($\Delta\theta$) (dB)
-3.5	-2.395	0.1	+0.013
-3.4	-2.206	0.2	+0.031
-3.3	-2.017	0.3	+0.053
-3.2	-1.828	0.4	+0.077
-3.1	-1.529	0.5	+0.103
-3.0	-1.306	0.6	+0.130
-2.9	-1.091	0.7	+0.159
-2.8	-0.920	0.8	+0.187
-2.7	-0.761	0.9	+0.217
-2.6	-0.622	1.0	+0.243
-2.5	-0.500	1.1	+0.266
-2.4	-0.392	1.2	+0.288
-2.3	-0.295	1.3	+0.309
-2.2	-0.212	1.4	+0.322
-2.1	-0.142	1.5	+0.327
-2.0	-0.085	1.6	+0.326
-1.9	-0.041	1.7	+0.310
-1.8	-0.010	1.8	+0.281
-1.7	+0.014	1.9	+0.245
-1.6	+0.030	2.0	+0.197
-1.5	+0.040	2.1	+0.137
-1.4	+0.043	2.2	+0.068
-1.3	+0.042	2.3	-0.010
-1.2	+0.037	2.4	-0.101
-1.1	+0.030	2.5	-0.212
-1.0	+0.022	2.6	-0.338
-0.9	+0.012	2.7	-0.483
-0.8	+0.005	2.8	-0.636
-0.7	-0.001	2.9	-0.789
-0.6	-0.006	3.0	-0.942
-0.5	-0.013	3.1	-1.096
-0.4	-0.011	3.2	-1.249
-0.3	-0.010	3.3	-1.402
-0.2	-0.011	3.4	-1.555
-0.1	-0.009	3.5	-1.708
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{ERS2} (\theta) = g^2_{ERS2} (\Delta\theta)$; $\Delta\theta = \theta - 20.355°$ (the boresight angle).

Appendix G3(b). The ERS-2 SAR Elevation Antenna Pattern
For VMP products processed prior to v6.8

Rel. Look Angle ($\Delta\theta$) (Degree)	g^2ERS2 ($\Delta\theta$) (dB)	Rel. Look Angle ($\Delta\theta$) (Degree)	g^2ERS2 ($\Delta\theta$) (dB)
-3.5	0.0	0.1	+0.013
-3.4	0.0	0.2	+0.031
-3.3	-2.017	0.3	+0.053
-3.2	-1.828	0.4	+0.077
-3.1	-1.529	0.5	+0.103
-3.0	-1.306	0.6	+0.130
-2.9	-1.091	0.7	+0.159
-2.8	-0.920	0.8	+0.187
-2.7	-0.761	0.9	+0.217
-2.6	-0.622	1.0	+0.243
-2.5	-0.500	1.1	+0.266
-2.4	-0.392	1.2	+0.288
-2.3	-0.295	1.3	+0.309
-2.2	-0.212	1.4	+0.322
-2.1	-0.142	1.5	+0.327
-2.0	-0.085	1.6	+0.326
-1.9	-0.041	1.7	+0.310
-1.8	-0.010	1.8	+0.281
-1.7	+0.014	1.9	+0.245
-1.6	+0.030	2.0	+0.197
-1.5	+0.040	2.1	+0.137
-1.4	+0.043	2.2	+0.068
-1.3	+0.042	2.3	-0.010
-1.2	+0.037	2.4	-0.101
-1.1	+0.030	2.5	-0.212
-1.0	+0.022	2.6	-0.338
-0.9	+0.012	2.7	-0.483
-0.8	+0.005	2.8	-0.636
-0.7	-0.001	2.9	0.0
-0.6	-0.006	3.0	0.0
-0.5	-0.013	3.1	0.0
-0.4	-0.011	3.2	0.0
-0.3	-0.010	3.3	0.0
-0.2	-0.011	3.4	0.0
-0.1	-0.009	3.5	0.0
0.0	+0.000		

The gain at look angle θ is calculated using $g^2_{ERS2}(\theta) = g^2_{ERS2}(\Delta\theta)$; $\Delta\theta = \theta - 20.355°$ (the boresight angle). For the processor name version number see *processing system identifier* and *processing version identifier*.

Appendix G3(c). The ERS-2 SAR Elevation Antenna Pattern
For VMP products processed with v6.8 or later

Rel. Look Angle ($\Delta\theta$) (Degree)	g^2_{ERS2} ($\Delta\theta$) (dB)	Rel. Look Angle ($\Delta\theta$) (Degree)	g^2_{ERS2} ($\Delta\theta$) (dB)
-3.5	-2.726	0.1	+0.013
-3.4	-2.427	0.2	+0.031
-3.3	-2.127	0.3	+0.053
-3.2	-1.828	0.4	+0.077
-3.1	-1.529	0.5	+0.103
-3.0	-1.306	0.6	+0.130
-2.9	-1.091	0.7	+0.159
-2.8	-0.920	0.8	+0.187
-2.7	-0.761	0.9	+0.217
-2.6	-0.622	1.0	+0.243
-2.5	-0.500	1.1	+0.266
-2.4	-0.392	1.2	+0.288
-2.3	-0.295	1.3	+0.309
-2.2	-0.212	1.4	+0.322
-2.1	-0.142	1.5	+0.327
-2.0	-0.085	1.6	+0.326
-1.9	-0.041	1.7	+0.310
-1.8	-0.010	1.8	+0.281
-1.7	+0.014	1.9	+0.245
-1.6	+0.030	2.0	+0.197
-1.5	+0.040	2.1	+0.137
-1.4	+0.043	2.2	+0.068
-1.3	+0.042	2.3	-0.010
-1.2	+0.037	2.4	-0.101
-1.1	+0.030	2.5	-0.212
-1.0	+0.022	2.6	-0.338
-0.9	+0.012	2.7	-0.483
-0.8	+0.005	2.8	-0.636
-0.7	-0.001	2.9	-0.789
-0.6	-0.006	3.0	-0.942
-0.5	-0.013	3.1	-1.096
-0.4	-0.011	3.2	-1.249
-0.3	-0.010	3.3	-1.402
-0.2	-0.011	3.4	-1.555
-0.1	-0.009	3.5	-1.708
0.0	+0.000		

The gain at look angle θ is calculated using g^2_{ERS2} (θ) = g^2_{ERS2} ($\Delta\theta$) ; $\Delta\theta = \theta - 20.355°$ (the boresight angle). For the processor name version number see *processing system identifier* and *processing version identifier*.

Appendix H.   UK-PAF Elevation Antenna Pattern Correction
For ERS-1 products processed at UK-PAF between 1st September 1992 and 8th April 1993

This appendix describes how the UK-PAF elevation antenna pattern correction, Ec(θ), can be calculated. This correction is required for UK-PAF products with *product processing dates* between 1st September 1992 and 8th April 1993 and is a function of image latitude (ref. [7]).

Firstly, the look angle for a given range pixel position needs to be calculated. This is achieved using Appendix B. Secondly, the orbit repeat period of the image is determined from the product acquisition date. This is best determined from the date of the *first orbit state vector*. If the acquisition date is up to 1st April 1992 then the repeat period is 3 days while if the acquisition date is between 14th April 1992 and 8th April 1993 then the repeat period is 35 days. Thirdly, the image latitude is given by *processed scene centre latitude*.

Given the look angle, repeat period and image latitude, the correction is deduced, via interpolating, from the corrections in either Table H1 (3 day repeat period) or Table H2 (35 day repeat period). The look angle is derived from the relative look angle + 20.355 (Degree, the boresight angle).

Table H1: UK-PAF Elevation Antenna Pattern Corrections (dB) for the 3 Day Repeat Period:

Lat (Deg)	Rel. Look Angle (Deg)														
	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
45.0	-0.40	-0.40	-0.23	-0.09	-0.01	0.02	0.02	0.00	-0.02	-0.03	-0.02	0.05	0.19	0.36	0.36
47.5	-0.21	-0.21	-0.11	-0.04	0.00	0.01	0.01	0.00	-0.00	-0.02	-0.01	0.03	0.11	0.19	0.19
50.0	-0.01	-0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
52.5	0.18	0.17	0.08	0.03	0.00	-0.01	-0.01	0.00	0.01	0.02	0.00	-0.03	-0.11	-0.16	-0.16
55.0	0.37	0.33	0.16	0.05	0.00	-0.02	-0.02	0.01	0.03	0.03	0.00	-0.08	-0.26	-0.33	-0.33
57.5	0.56	0.48	0.22	0.07	-0.01	-0.03	-0.02	0.01	0.04	0.04	-0.01	-0.14	-0.42	-0.50	-0.50
60.0	0.74	0.60	0.27	0.08	-0.02	-0.04	-0.02	0.02	0.06	0.05	-0.02	-0.21	-0.58	-0.66	-0.66
62.5	0.91	0.70	0.31	0.09	-0.02	-0.05	-0.03	0.03	0.07	0.06	-0.04	-0.29	-0.73	-0.81	-0.81
65.0	1.07	0.78	0.34	0.09	-0.03	-0.06	-0.03	0.04	0.08	0.07	-0.06	-0.38	-0.87	-0.95	-0.95
67.5	1.22	0.85	0.36	0.09	-0.04	-0.07	-0.02	0.05	0.10	0.07	-0.09	-0.48	-1.01	-1.09	-1.09
70.0	1.33	0.90	0.38	0.09	-0.05	-0.07	-0.02	0.06	0.11	0.07	-0.13	-0.58	-1.13	-1.21	-1.21
72.5	1.43	0.95	0.39	0.08	-0.06	-0.08	-0.02	0.07	0.12	0.07	-0.16	-0.68	-1.24	-1.32	-1.32
75.0	1.52	0.98	0.40	0.08	-0.06	-0.08	-0.02	0.08	0.13	0.06	-0.20	-0.78	-1.34	-1.42	-1.42
77.5	1.58	1.01	0.41	0.08	-0.07	-0.08	-0.01	0.08	0.13	0.06	-0.24	-0.87	-1.43	-1.51	-1.51
80.0	1.63	1.03	0.41	0.07	-0.07	-0.08	-0.01	0.09	0.14	0.05	-0.27	-0.94	-1.50	-1.58	-1.58
82.5	1.67	1.05	0.42	0.07	-0.08	-0.08	0.00	0.09	0.14	0.04	-0.30	-0.99	-1.55	-1.63	-1.63

Appendix H.   UK-PAF Elevation Antenna Pattern Correction (contin.)

Table H2: UK-PAF Elevation Antenna Pattern Corrections (dB) for the 35 Day Repeat Period:

Lat	Rel. Look Angle (Deg)														
(Deg)	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5
45.0	1.66	1.04	0.41	0.07	-0.08	-0.08	-0.01	0.09	0.14	0.05	-0.29	-0.98	-1.54	-1.61	-1.61
47.5	1.76	1.08	0.42	0.06	-0.09	-0.09	0.00	0.11	0.15	0.02	-0.38	-1.14	-1.70	-1.78	-1.78
50.0	1.85	1.11	0.42	0.05	-0.09	-0.08	0.02	0.12	0.15	-0.01	-0.49	-1.30	-1.86	-1.94	-1.94
52.5	1.92	1.14	0.42	0.04	-0.10	-0.08	0.03	0.14	0.15	-0.05	-0.61	-1.46	-2.02	-2.10	-2.10
55.0	1.99	1.16	0.42	0.03	-0.11	-0.08	0.04	0.15	0.15	-0.10	-0.76	-1.62	-2.18	-2.26	-2.26
57.5	2.04	1.17	0.41	0.02	-0.11	-0.07	0.06	0.16	0.14	-0.16	-0.91	-1.78	-2.34	-2.42	-2.42
60.0	2.08	1.18	0.40	0.01	-0.11	-0.06	0.07	0.17	0.12	-0.23	-1.06	-1.93	-2.48	-2.56	-2.56
62.5	2.12	1.18	0.39	0.00	-0.12	-0.05	0.08	0.18	0.10	-0.32	-1.21	-2.07	-2.63	-2.71	-2.71
65.0	2.14	1.18	0.39	-0.01	-0.11	-0.04	0.10	0.18	0.07	-0.41	-1.34	-2.20	-2.76	-2.84	-2.84
67.5	2.16	1.18	0.38	-0.01	-0.11	-0.04	0.11	0.19	0.04	-0.51	-1.47	-2.33	-2.89	-2.97	-2.97
70.0	2.18	1.18	0.37	-0.02	-0.11	-0.03	0.12	0.18	0.01	-0.60	-1.58	-2.45	-3.01	-3.09	-3.09
72.5	2.19	1.18	0.36	-0.02	-0.11	-0.02	0.13	0.18	-0.03	-0.70	-1.69	-2.55	-3.11	-3.19	-3.19
75.0	2.20	1.17	0.36	-0.02	-0.10	-0.01	0.13	0.18	-0.06	-0.80	-1.78	-2.65	-3.21	-3.28	-3.28
77.5	2.20	1.17	0.35	-0.02	-0.10	0.00	0.14	0.17	-0.10	-0.88	-1.86	-2.73	-3.28	-3.36	-3.36
80.0	2.21	1.17	0.35	-0.03	-0.10	0.01	0.14	0.16	-0.13	-0.94	-1.93	-2.79	-3.35	-3.43	-3.43
82.5	2.21	1.16	0.34	-0.03	-0.09	0.01	0.15	0.16	-0.15	-1.00	-1.98	-2.84	-3.40	-3.48	-3.48

Appendix I.

Impact of N on the radiometric resolution errors
of the backscatter measurements using equation (2b)

In this appendix a definition of radiometric resolution is proposed which is further discussed in (ref. [8]). In an analysis of speckle based on the Gamma probability density function, radiometric resolution is defined in terms of the radiometric confidence intervals. Radiometric resolution is determined as a function of the data product's characteristics and of the conditions of application of intensity averaging.

I-1) Glossary and definitions used in Appendix I:

Sigma-nought: backscattering coefficient of a distributed target.

area of interest (AOI): a group of pixels in the radar image.

homogeneous target: target with spatially constant Sigma-nought.

equivalent Number of Looks (ENL): in this document ENL is defined as the inverse of the normalized variance of the signal intensity in the image of a homogeneous target.

radiometric confidence intervals: SAR radiometric resolution bounds for a given confidence level; the confidence level is the probability that the intensity in the radar image lies within these bounds.

A measurement of image radiometric resolution is given by γ (in dB) defined as follows:

$$qr = \sigma \ / \ \mu \ , \ (I\text{-}1)$$

$$\gamma = 10 \ . \ \log_{10} (\ 1 + qr) \ , \ (I\text{-}2)$$

μ and σ are the mean and standard deviation of the signal intensity in the image of a homogeneous target. qr is the normalized standard deviation. The equivalent Number of Looks (ENL) is defined by the normalized standard deviation in a SAR image of a homogeneous target:

$$ENL = 1 \ / \ qr^2 \qquad\qquad\qquad , \ (I\text{-}3)$$

In the case of images displaying high signal to noise ratios (SNR), ENL is substantially the same as the number of independent 'uncorrelated' looks or 'number of multiple looks' used in common SAR terminology.

Appendix I. (contin.)

Radiometric confidence intervals: another measurement of radiometric resolution is given by the confidence intervals using the probability that the image intensity of an homogeneous target lies between error bounds. Confidence intervals are defined by the error bounds that correspond to a confidence level.

For all pixels in the image of an homogeneous target and for a given level of confidence 'P(%)':

If Probability (' $\sigma_{0\ recorded}$ +/− Error_dB $< \sigma_{0\ expected}$, dB ')

is greater or equal to P(%) then

the confidence interval bounds are equal to +/- Error_dB.

The bounds of the P(%) confidence interval are calculated by integrating the normalized Gamma probability density function over the range of intensity values that provide P(%) confidence. +/- Error_dB are the P(%) radiometric resolution error bounds.

The normalized Gamma probability density function is a one parameter function. The parameter is the equivalent Number of Looks of the intensity image.

The confidence level, P(%), is derived by integrating the normalized Gamma probability density function over an interval Δ of intensity values corresponding to +/− Error_dB, the radiometric resolution errors in dB units:

$$\Delta = [10^{-\text{Error\_dB}/10} ; 10^{+\text{Error\_dB}/10}],$$

$$\int_{\Delta} Gamma(I)dI = P \qquad (I-4)$$

The P(%) radiometric confidence interval bounds are +/- Error_-dB.

I-2) The radiometric confidence intervals as a function of ENL:

The confidence level is an increasing function of the width of interval Δ.

The more reduced the error bounds, the lower the related confidence level. In addition, for a given confidence level, the higher the ENL, the smaller the error bounds.

Table I-1 and Figure I-A) illustrate the confidence levels as a function of the equivalent NL.

Appendix I. (contin.)

Table I-1: Confidence levels versus equivalent Number of Looks:

dB 0.5	dB 1.0	dB 1.5	dB 2.0	dB 2.5	dB 3.0	dB 3.5	dB 4.0	dB 4.5	dB 5.0	dB 5.5	dB 6.0	Error-dB
Confidence level, %												equivalent NL:
8	16	24	32	40	47	53	59	64	68	72	75	1
12	24	35	46	56	64	71	77	81	85	88	90	2
15	30	43	55	66	74	81	86	89	92	94	95	3
17	34	49	62	73	81	87	91	93	95	97	98	4
19	38	54	68	78	86	90	94	96	97	98	98	5
26	50	69	82	90	95	97	98	99	99	99	99	9
28	53	71	84	92	96	98	99	99	99	99	99	10
34	62	81	92	97	99	99	99	99	99	99	99	15
39	69	87	96	99	99	99	99	99	99	99	99	20
59	89	98	99	99	99	99	99	99	99	99	99	50
75	97	99	99	99	99	99	99	99	99	99	99	100
84	99	99	99	99	99	99	99	99	99	99	99	150
89	99	99	99	99	99	99	99	99	99	99	99	200
93	99	99	99	99	99	99	99	99	99	99	99	250

Figure I-A). The confidence level versus product's ENL as ENL is ranging from 20 to 300.
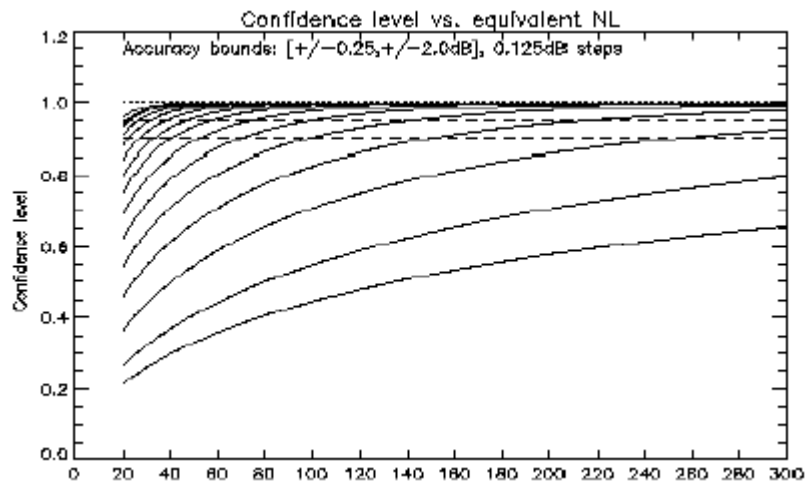
Each curve corresponds to fixed values of Error_$_{dB}$ ranging from 0.25 dB to 2.0 dB with steps of 0.125 dB. The two horizontal dashed lines represent the 90% and 95% confidence levels.

Appendix I. (contin.)

In the case of PRI data products (3 looks) the 90% radiometric confidence interval bounds are +/- 4.5dB (ref. [8]) i.e. the probability that the measured intensity lies between resolution error bounds of +/- 4.5dB is 90% whereas radiometric accuracy and stability errors are less than a fraction of a dB (ref [2]). The confidence level for ±0.5dB radiometric resolution errors is only 15%.

To calculate the backscattering coefficient of a distributed target that corresponds to a certain Area Of Interest (AOI of extent N in pixels) i.e. a group of pixels in the radar image, the expression required is equation (2b):

$$\sigma^o = \frac{1}{N} \Sigma A_{ij}^2 \quad \text{for all pixels within the AOI} \qquad \text{Equation (2b)}$$

Intensity averaging reduces radiometric resolution errors i.e. speckle. In the case of a homogeneous distributed target, the intensity is Gamma distributed (ref. [8]) with an ENL parameter that is the equivalent Number of Looks of the data product, say $ENL_{original}$, and $ENL_{original} \sim 3$ in the case of the ERS SAR PRI data product. The average intensity σ^o is Gamma distributed with an ENL parameter that is the equivalent NL, say ENL_{output}, of the image produced if a block filter (block averaging of the intensity image) of extent N pixels was applied to the pixels within the AOI in the ERS SAR PRI data product. ENL_{output} is a function of, firstly, the value of $ENL_{original}$, and, secondly, the value of N in equation (2b). Figure I-C) shows radiometric confidence intervals as a function of ENL as ENL is ranging from 3 to 370:
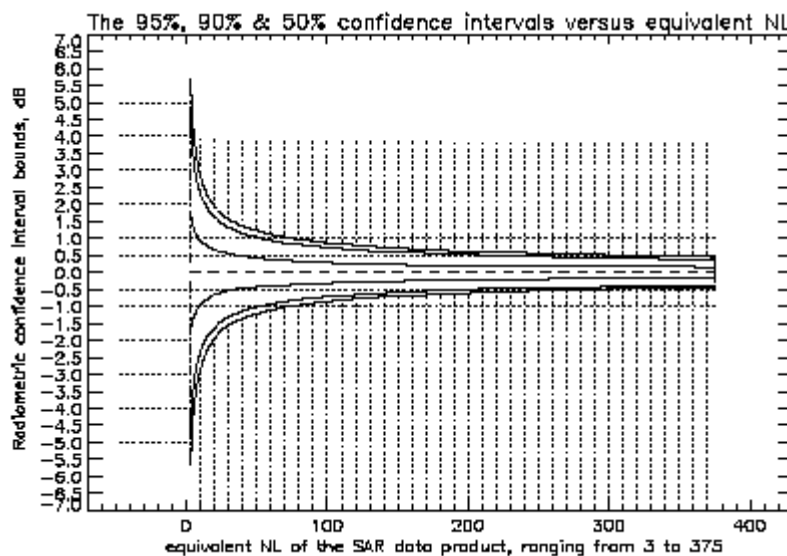

Figure I-B) SAR radiometric resolution: confidence interval bounds (+/- Error_dB, on Y-axis) versus product's equivalent NL (on X-axis) for confidence levels set to 95%, 90% and 50% resulting in 3 curves.

Appendix I. (contin.)

The ENL of the generated image (ENL_{output}) **can be approximated by** the product's equivalent NL ($\text{ENL}_{original}$) times the number N' of independent pixels in the AOI.

The relationship is given by:

$$\text{ENL}_{output} \sim \text{ENL}_{original} \times N / R \qquad , \quad \text{(I-5)}$$

where R = N / N' is the number of pixels per independent pixel in the data product.

I-3) Approximation of the relationship between radiometric confidence intervals and AOI extent N in pixels:

To determine quantitatively speckle reduction applying intensity averaging it is needed to establish a relationship between ENL and the window extent in pixels N i.e. to determine R as used in (I-5). Assuming that the number of independent pixels in the AOI equals the number of resolution cells, R is the number of pixels per resolution cell in the radar image.

In the case of AOIs containing more than 4 pixels in both azimuth and range i.e. with N greater than 4 x 4, R **can be approximated by** the ratio between the resolution cell size area and the pixel size area:

An approximation of R is given by:

$$R = (\rho_{azimuth} / \Delta\_spa) \times (\rho_{ground-range} / \Delta\_spa) \qquad\qquad , \quad \text{(I-6)}$$

- $\rho_{azimuth}$ is the azimuth spatial resolution and its value is about 22.0 m.
- $\rho_{ground-range}$ is the ground range spatial resolution. Its value is derived from the slant range spatial resolution : $\rho_{ground-range} = \rho_{slant-range} / \sin\alpha$, where $\rho_{slant-range} \sim 9.8$ m and α is the local incidence angle.
- Δ_spa is the azimuth and ground range pixel spacing (i.e. 12.5 m for PRI).

The value of R is dependent on the range location of the AOI in the image.

At near range ($\alpha_{near\ range} \sim 19.4$ deg) : $R_{near\ range} \sim (22.0 / 12.5) \times (29.4 / 12.5) \sim 4.1$

$$\text{leading to ENL} = 0.72 \times N \qquad\qquad , \quad \text{(I-7a)}$$

Appendix I. (contin.)

At mid-swath ($\alpha_{mid\ swath} \sim 23.0$ deg) : $R_{mid\ swath} \sim (22.0 / 12.5) \times (25.0 / 12.5) \sim 3.5$

$$\text{leading to : ENL} = 0.85 \times N \qquad\qquad , \qquad \text{(I-7b)}$$

At far range ($\alpha_{far\ range} \sim 26.6$ deg) : $R_{far\ range} \sim (22.0 / 12.5) \times (21.8 / 12.5) \sim 3.1$

$$\text{leading to : ENL} = 0.98 \times N \qquad\qquad , \qquad \text{(I-7c)}$$

From the value of ENL the backscattering coefficient measurement accuracy can be inferred using (I-4) and/or Table I-1.

As an example, reaching 240 as equivalent NL can be achieved by applying intensity averaging to an Area Of Interest corresponding to 80 resolution cells i.e. ~240 pixels. The 90% confidence interval bounds are +/-0.5dB (third curve from the bottom in Figure I-A).

Radiometric confidence intervals as a function of the spatial scale of observation: when intensity averaging is applied, a 'spatial scale of observation' (Ls) can defined which is given by the area size (in meters) of the surface corresponding to the AOI of N pixels over which the intensity is averaged.

If the window of averaging is square, Ls is the spatial resolution of the generated image.

S_{pixel} is the pixel size in square meters ; Δ_spa is the pixel spacing ;

$S_{pixel} = \Delta\_spa \times \Delta\_spa$

$S_{pixel} \times N$ is the area size of the surface corresponding to the AOI,

thus:

$$Ls = \Delta\_spa \times sqrt(N) , \qquad\qquad\qquad , \qquad \text{(I-8)}$$

Ls can be derived from the equivalent NL using (I-5) and (I-6):

$$Ls = [(\rho_{azimuth} \times \rho_{ground\text{-}range} \times \text{equivalent NL}) / ENL_{original}]^{1/2} , \qquad \text{(I-9)}$$

For a given spatial scale of observation, the equivalent NL is as a function of the product's original equivalent NL and spatial resolution.

Table I-2) shows the confidence levels at mid-swath as a function of Ls, N and the equivalent NL for radiometric resolution bounds ranging from ±0.5 dB to ±5.0 dB in the case of the ERS SAR PRI products (equivalent NL~3). For extrapolation, Ls values are given for near and far range.

Appendix I. (contin.)

<u>Table I-2)</u>: Case of the ERS SAR PRI product: confidence levels <u>at mid-swath</u> versus AOI size i.e. [N] and Ls (meters) for radiometric resolution bounds ranging from +/-0.5 dB to +/-5.0 dB.

Confidence level in % for radiometric resolution bounds ranging from +/- 0.5 to +/- 5.0 dB										[number of pixels] Ls in meters (equivalent NL)		
dB 0.5	dB 1.0	dB 1.5	dB 2.0	dB 2.5	dB 3.0	dB 3.5	dB 4.0	dB 4.5	dB 5.0	near range	mid swath	far range
15	30	43	55	66	74	81	86	89	92	[1] 12.5	[1] 12.5 (3)	[1] 12.5
30	57	76	88	94	97	98	99	99	99	[17] 51.0	[14] 46.9 (12)	[12] 43.8
34	62	81	91	96	98	99	99	99	99	[21] 57.0	[18] 52.4 (15)	[15] 48.9
37	67	85	94	98	99	99	99	99	99	[25] 52.5	[21] 57.5 (18)	[18] 53.6
40	70	88	96	98	99	99	99	99	99	[29] 67.5	[25] 62.1 (21)	[21] 57.9
58	89	98	99	99	99	99	99	99	99	[67] 102	[56.5] 93.9 (48)	[49] 87.5
68	95	99	99	99	99	99	99	99	99	[104] 127	[88] 117 (75)	[77] 109
75	97	99	99	99	99	99	99	99	99	[139] 147	[118] 136 (100)	[102] 126
80	98	99	99	99	99	99	99	99	99	[174] 165	[147] 152 (125)	[128] 141
84	99	99	99	99	99	99	99	99	99	[208] 180	[176] 166 (150)	[153] 155
87	99	99	99	99	99	99	99	99	99	[243] 195	[206] 179 (175)	[179] 167
89	99	99	99	99	99	99	99	99	99	[278] 208	[235] 192 (200)	[204] 178
91	99	99	99	99	99	99	99	99	99	[312] 221	[265] 203 (225)	[230] 189
93	99	99	99	99	99	99	99	99	99	[347] 233	[294] 214 (250)	[255] 200
94	99	99	99	99	99	99	99	99	99	[382] 244	[323] 225 (275)	[281] 209
95	99	99	99	99	99	99	99	99	99	[417] 255	[353] 235 (300)	[306] 219
96	99	99	99	99	99	99	99	99	99	[451] 266	[382] 244 (325)	[332] 228
96	99	99	99	99	99	99	99	99	99	[486] 276	[412] 254 (350)	[357] 236
97	99	99	99	99	99	99	99	99	99	[521] 285	[441] 262 (375)	[383] 244

Note: on going experiments based on the analysis of ERS-1 and ERS-2 SAR PRI images of homogeneous targets indicate that the value of R as approximated using equation (I-6) is underestimated by around 20%. As a consequence, the estimation of the gain in ENL using intensity averaging as given by equations (I-7a), (I-7b) and (I-7c) is an optimistic evaluation.

Appendix J. Calibration of ERS.SAR.SLC/SLCI Products

This appendix describes how complex data products can be calibrated.

Before the backscattering coefficient of a distributed target (σ^0) can be calculated, the complex data has to be detected. The detection operation is $\sqrt{I^2 + Q^2}$ where I and Q are the real and imaginary complex samples. To preserve all the statistical properties of the data, detection should be carried out in a manner which will ensure that the detected image is adequately sampled (i.e. twice per resolution cell). If the complex data is sampled at once per resolution cell, as is the case for ESA ERS SAR complex data, then detection requires the complex data to be resampled by a factor of two prior to detection. Also it is necessary to ensure that the power spectra is completely within the sampling window. If the power spectrum is 'folded over' from one end of the sampling window to the other, then a spectrum shift is required. In the case where only the mean intensity of a distributed target is required (such as for calculation of the backscattering coefficient σ^0) then it is possible to detect the complex data without resampling or ensuring the power spectra is within the sampling window. For practical reasons, this latter approach is given here.

The expression required to calculate the backscattering coefficient of a distributed target from ERS-1 detected complex image data is given by:-

$$\sigma^0 = \frac{<DN^2>}{K} \frac{Sin\alpha_D}{Sin\alpha_{ref}} \frac{1}{G(\theta_D)^2} \frac{R^3}{R_{ref}^3} \frac{Image\,Re\,plicaPower}{Re\,ference\,Re\,plicaPower} PowerLoss$$

where

σ^0 = distributed target radar cross-section

$<DN^2>$ = average pixel intensity of distributed target

DN = pixel digital number

K = calibration constant (Appendix D)

α_D = distributed target incidence angle

α_{ref} = reference incidence angle (23°)

$G(\theta_D)^2$ = elevation antenna pattern gain (Appendix G2 or G3)

θ_D = distributed target look angle

R = distributed target slant range

R_{ref} = reference slant range (847.0 km)

Image Replica Power = power of the replica pulse used in the processing (ERS-1 only)

Reference Replica Power = replica pulse power of reference (Appendix D)

Power Loss = analogue to digital convertor (ADC) power loss.

As the detected complex values are in amplitude (DN) we need to determine a calibrated image with pixel values also in amplitude (DNc). This is achieved via the following expression:-

$$DNc_{ij}^2 = DN_{ij}^2 \frac{Sin\alpha_i}{Sin\alpha_{ref}} \frac{1}{G(\theta_i)^2} \frac{R_i^3}{R_{ref}^3} \frac{Image\,ReplicaPower}{Reference\,ReplicaPower} PowerLoss_{ij}$$

$$(i = 1\ to\ n\ and\ j = 1\ to\ m)$$

where i and j are the slant range and azimuth pixel coordinates for a product of size n in slant range and m in azimuth and α_i, θ_i and R_i are the incidence angle, look angle and slant range of a pixel at range coordinate i respectively. The product size can be found in the CEOS header (Appendix A) while the α_i, θ_i and R_i parameters are calculated from geometrical considerations (Appendix B). The image replica power correction in the above two equations is only required for ERS-1.

The Power Loss parameter is required to compensate for the non-linearity of the ERS-1 and ERS-2 SAR on-board ADCs. There are several steps to calculate the power loss. Firstly, the detected complex data <u>must</u> be root mean square (rms) block averaged using a block size of b by b pixels. The block size, b, <u>must</u> be at least 8 by 8 pixels (i.e. using a block size of approximately 32m in azimuth and 63m in slant range or more). A block size of b = 100 is recommended. This is followed by the application of the replica pulse power correction (for both ERS-1 and ERS-2) and then followed by smoothing. Using the resultant smoothed rms block averaged data, the power loss is determined for each block averaged pixel via a look-up table.

The step following rms block averaging can be combined to calculate a power loss amplitude, $DNpl_{uv}$:

$$DNpl_{uv}^2 = DN_{uv}^2 \frac{ImageReplicaPower}{RefernceReplicaPower}$$

$$(u = 1\ to\ n/b\ and\ v = 1\ to\ m/b)$$

where DN_{uv} is the rms block averaged pixel amplitude and, u and v are the rms block averaged slant range and azimuth pixel coordinates for an image of size n/b in slant range and m/b in azimuth. Note that the replica pulse power correction is required for both ERS-1 and ERS-2 in the above equation.

Smoothing using a window of size 5km in slant range and 5km in azimuth is then used on the power loss amplitude image DNpl. For the 7.9m range pixel size, the slant range window size corresponds to approximately 630 pixels while for the 3.9m azimuth pixel size, the azimuth window size corresponds to approximately 1280 pixels. A smoothing operation for a pixel at range coordinate u and azimuth coordinate v for an image of size n/b in range and m/b in azimuth is:-

$$DNpls_{uv} = \frac{b^2}{630*1280} \sum_{k=(u-315/b+1)}^{u+315/b} \sum_{l=(v-640/b+1)}^{v+640/b} DNpl_{kl}$$

$$(u = 315/b \text{ to } (n-315)/b \text{ and } v = 640/b \text{ to } (m-640)/b)$$

Note that this approach will reduce the size of the image DNpls compared to DNpl (by 315/b pixels at near and far range and 640/b pixels at early and late azimuth positions).

Each pixel in the resultant smoothed power loss amplitude image, DNpls, is converted to intensity/K (i.e. $DNpls^2/K$) where K is the calibration constant. The corresponding power loss values can be determined via the look-up tables in Appendix F1 (for ERS-1) and F2 (for ERS-2).

Finally, all the contributing parts of the calibrated image amplitude DNc are then combined to form the calibrated image. With this, the backscattering coefficient of a distributed target can be calculated by simply using the mean calibrated intensity value for the distributed target and the calibration constant, K, thus:-

$$\sigma^0 = \frac{<DNc^2>}{K} = \frac{1}{K}\frac{1}{N}\sum_{1}^{N} DNc^2$$

where N is the number of pixels within the distributed target.

If an SLC/SLCI product has been processed with a nominal replica pulse instead of the usual extracted replica pulse (Appendix A), then both the I and Q channel values need to be corrected. The correction factor is $\sqrt{PRI_{correction}/2}$ where $PRI_{correction}$ is the correction value given in

Appendix K for PRI products. For example, the ERS-1 SLC/SLCI I and Q values need to be divided by $\sqrt{291.5/2}$ or 12.07.

Appendix K. Calibration of Products Generated using a Nominal Replica

This appendix describes how Verification Mode Processor (VMP) products can be calibrated if they have been generated using a nominal replica pulse instead of the usual extracted replica pulse. It is estimated that less than 1% of all VMP products are generated using a nominal replica pulse. The *Processor range compression designator* parameter is used to determine if a product has been generated using a nominal replica pulse or not. Products generated with a nominal replica pulse have significantly higher pixel values than products generated using an extracted replica.

The correction is required because the power of the nominal replica is very different from the extracted replicas for both the ERS-1 and ERS-2 SARs. The correction is applied slightly different for ERS-1 and ERS-2 SAR products.

(a) ERS-1 SAR Products. As the nominal replica has a total power of 704 and the reference replica power for ERS-1 is 205229, the image pixel intensity values are too large by a factor of 291.5. The correction factor applies to all ERS-1 SAR imagery and note that the replica pulse power correction is equal to one when estimating the ADC power loss and deriving the backscattering coefficient σ^o.

(b) ERS-2 SAR Products. Here the correction depends on the ERS-2 extracted replica pulse power at the time of data acquisition. This can be estimated from imagery acquired at almost the same time as imagery processed with the nominal replica. The correction factor for three month periods is provided on line at: http://earth.esa.int/pcs/ers/sar/calibration/replica_pwr/. The correction factor values need to be applied such that the image pixel intensity values are reduced (i.e. by dividing the pixel intensity by the table values). Note that the product replica power used for the ADC power loss calculation is equal to the values given in the table multiplied by 704.0.

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