ERS National & Foreign Stations

SAR processor calibration and products validation plan

This document describes the procedure required for the calibration of SAR processor and validation of products from ERS national & foreign Stations.

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Prepared:	Jean-Charles Bigot - RS/EF, ESRIN	....
Reviewed:	V. Beruti - H/RS/EF, ESRIN	....
Approved:	M. Albani - H/RS/E, ESRIN	....

1 - Introduction

1.1. Purpose

The purpose of this document is to outline the work to be carried out for the validation of the ERS-1/2 SAR products generated by the ERS-1/2 National & Foreign Stations spread around the world, for the calibration of their SAR processor, and the line of responsibility for the various activities.

The detailed description of the validation and calibration activities are specified later in this document after a short introduction on the ERS ground segment.

It is proposed that a technical report be produced by the station for the validation results of the Station ERS-1/2 SAR products if not already done.

1.2. Scope

The ERS-1/2 National & Foreign Stations spread around the world have different SAR processor build by different companies. The SAR products generated from these SAR processors are quite different from a station to another so that the user may be confused in the variety of products delivered around the world. Thus ERS SAR users should be fully informed on the products delivered by all ERS National & Foreign Station. The validation exercise contributes to reach this goal.

In general, SAR products delivered by the ERS-1/2 NFS should be validated before being distributed as soon as the processor is considered calibrated and tuned. This validation and calibration exercise is necessary prior to the issuing of the products to the users.

The methodologies of the validation of the SAR products and the method to derive the product calibration constant are addressed in ad-hoc documents which are given in the appendixes.

2 - ERS ground segment

2.1. The overall ground segment

The ERS ground segment consists of:

- The Mission Management and Control Center (MMCC) at ESOC, Darmstadt, Germany;
- The Esrin ERS Central Facility (EECF) at Frascati, Italy;
- The real-time ESA Ground Stations (EGS) at Salmijärvi (Sweden), Fucino (Italy), Maspalomas (Canary Islands- Spain), Gatineau and Prince Albert (Canada);
- The Processing and Archiving Facilities (D-PAF) at Oberpfaffenhofen (Germany), F-PAF at Brest (France), I-PAF at Matera (Italy) and UK-PAF at Farnborough (United Kingdom);
- the National Stations - NS - (in ESA Member States) and the Foreign Stations - FS - (in Non-ESA Member States).

2.2. ERS ground stations

2.2.1. Introduction

The ERS-1 orbit - near-polar and sun-synchronous and the need for direct readout of the SAR telemetry have dictated the geographical locations of the ground stations around the world.

All ERS ground stations receive, from the EECF in Frascati, the input data needed to acquire and distribute the SAR data and they report back to the EECF on their station activities and status. These stations generate and distribute products developed nationally to ESA Principal Investigators, Pilot Projects, Research users and Commercial users.

2.2.2. National and Foreign Stations

In addition to the ESA Ground Stations, some national (belonging to countries participating in the ERS program) and some foreign (non-participating countries) ground stations have been set up or are in the process of being set up around the world in order to acquire ERS-1/2 HR data. These stations operate under the terms and conditions of a standard Memorandum of Understanding (MOU) with ESA. This extends the coverage of the SAR operating in Image Mode outside Europe.

The National and Foreign Stations (NFS) are up until end December 1996:

National Stations (NS):

- Aussaguel, France (TO)
- Cordoba (transportable station located in Argentina), Germany (CA)
- Gatineau, Canada (GH)
- Libreville (Transportable station located in Gabon), Germany (LI)
- Malindi, in Kenya for Italy (MA)
- Neustrelitz, Germany (NE)
- O'Higgins, Antartica for Germany (TF)
- Prince Albert, Canada (PH)
- Tromsø, Norway (TS)
- West-Freugh, Scotland, UK (WF)

Foreign Stations (FS):

- Alice Springs, Australia (AS)
- Bangkok,Thailand (TH)
- Beijing, China (BE)
- Chung-Li, Taiwan (TW)
- Cotopaxi, Ecuador (CO)
- Cuiaba, Brazil (CU)

- Fairbanks, Alaska, USA (AF)
- Hatoyama, Japan (HA)
- Hobart, Tasmania, Australia (HO)
- Hyderabad, India (SE)
- Johannesburg, South-Africa (JO)
- Kumamoto, Japan (KU)
- Mac-Murdo, Antartica for USA (MM)
- Norman, Oklahoma, USA (NO)
- Pare-Pare, Indonesia (IN)
- Riyadh, Saudi-Arabia (SA)
- Singapore, Rep. Of Singapore (SG)
- Syowa, Antartica for Japan (SY)
- Tel-Aviv, Israel (IR)

2.3. SAR commercial distribution agreement

ESA has signed an agreement with the ERSC Consortium for the worldwide promotion, marketing and commercial distribution of data from the ERS satellites. Each ERS Consortium's company serves users from a specific area of the world:

- Users in Europe, N. Africa and the Middle East - Eurimage ERS-1 Order Desk
- Users in Canada - Radarsat International ERS-1 Order Desk
- Users in USA and all other countries - Spot Image ERS-1 Order Desk

The ERS Consortium commercializes all data products generated at the ERS ESA Ground Stations (EGS) and at the ERS Processing and Archiving Facilities (PAF). SAR data and images generated at further National and Foreign Stations (NFS) spread around the world are also commercialized by the ERS Consortium, if the customer is outside the country of the station where these data have been received.

Note: All the Principal Investigators (PIs) whose research projects have been accepted by ESA as significant contributions to ERS data exploitation, will continue to get access, directly from ESA-ESRIN, to the data they require to perform their scientific studies.

3 - SAR product validation and SAR processor calibration

3.1. Introduction

Whenever a Station has been granted access to ERS, the technical facilities (Data Acquisition Facility and Data Processing Facility) have to be validated before actual operations take place. The activities concerning the verification of the station itself is twofold:

- Acquisition & Recording validation: the purpose is then to ensure that the station is capable of properly acquiring, recording and archiving SAR raw data in line with ESA standards such as recorder compatibility. This is not the purpose of this document.

- Products validation and processor calibration: the purpose is to ensure that the station is capable of generating SAR products with a quality endorsed by ESA. This is the purpose of this document.

Validation of the SAR products corresponds to the verification of the quality parameters of the products generated by the station.

Calibration of the SAR processor, related to image product (such as the ESA image precision PRI), corresponds to the calculation of the Calibration constant and the application of the Antenna Pattern Correction for ERS-1 and -2.

3.2. Operational procedure

3.2.1. Objectives and responsibilities

The Agency shall ensure that products generated at the national and/or foreign stations are validated for both ERS-1 and ERS-2 missions and eventually that the SAR processors are properly calibrated (on station's request).

The responsibility of the station's operator is to demonstrate the quality of the SAR products generated by its SAR processor while ESA's responsibility is to endorse SAR products for release. This procedure is composed of different phases:

- Initial statement of SAR product quality. The station should provide the specifications of the SAR products;

- Processing of ESA reference data set and generation of products by the station. ESA provides to ground station raw data on CCT or EXA to check the station SAR processor independently of the HDDT ingestion;

- Validation report which includes assessment of quality parameters by the station;

Calibration of the SAR processor by the station (Calibration constant to be calculated and Antenna Pattern correction to be applied) is an optional exercise. As a matter of fact, ESA should check that the calibration is properly done by the station whenever the station has announced that calibrated data is available.

3.2.2. Deliverables by NFS to ESA

During these phases the station has to provide deliverables to ESA

- Information about the SAR processor,

- Detailed SAR products specifications,
- Detailed validation report,
- Sample products on CCT (or EXA) and on slides (with annotations).

3.2.3. Parameters to be evaluated

The parameters to be evaluated for the quality of SAR image are:

- Spatial resolution (range and azimuth) - Point target;
- Peak Sidelobe ratio (range and azimuth) - Point target;
- Integrated Sidelobe ratio - Point target;
- Ambiguity ratio (azimuth) - Point target;
- Radiometric resolution - Distributed target;
- Absolute Localization accuracy - Ground control point;

The definition of these parameters can be found in the document *SAR data Quality Assessment and Rectification*, done by GEC-Marconi Research Centre under ESA contract no. 6635/86/HGE-I found in appendix.

3.2.4. Deliverables by ESA to NFS

For the purpose of the evaluation to be done by ESA, ESRIN send to all NFS after their request:

- Test raw data ERS-1.SAR (orbit 1273, frame 1053 dated 13 Oct. 91) and ERS-2.SAR (orbit 1508, frame 2547 dated 4 Aug. 95) from our reference scene over Flevoland area (ESA test calibration site located in the Netherlands);
- List of the SAR quality parameters needed for the validation of the products, (cf. Appendix A);
- Methodology to calculate the calibration constant (This last document describes the ESA official method to be applied for the calibration of the SAR processor) - (cf. Appendix B);
- Antenna pattern correction for ERS-1 and ERS-2 to be applied (cf. Appendix C);
- Specification of ESA CEOS format if required by the station;

The test raw data are send together with the state vectors (orbital data and time correlation) on CCT or/and EXA from referenced SAR scenes over Flevoland. These data are:

	Date	Orbit	Frame
ERS-1	13 Oct. 1991	1273	1053
ERS-2	04 Aug. 95	1508	2547

The coordinates, electronic delay and RCS (radar cross section) of the three transponders (active radar calibrators) in Flevoland scene are:

Transponder #	Lat DD:MM:SS.sss	Long DD:MM:SS.sss	Delay microsec	RCS
T#1	52:21:59.205	05:09:07.999	1.536	58.39 dBm2
T#2	52:27:28.481	05:31:39.193	1.552	57.69 dBm2
T#3	52:33:17.846	05:40:08.154	1.545	57.85 dBm2

The RCS value is the average of the different calibrations carried out with the transponders at ESTEC.

SAR products processed from these test raw data over the Flevoland calibration site should then be sent to ESRIN for evaluation and validation together with products description and a validation report as stated before.

3.2.5. ESA evaluation

The evaluation, based on the NFS validation report, done by ESA concerns:

- Visual inspection (to detect artifacts);
- Basic measurements (radiometric resolution, impulse response function, localization accuracy);
- Intermediate measurements (dynamic range, point target linearity, radiometric accuracy and radiometric stability);
- Validation of the product's format.

3.2.6. Calibration of SAR Processor

The calibration constant is calculated following the method included in Appendix B. This document has been updated during the ERS2 SAR Commissioning phase. There is no problem to generalize this method to complex data (e.g. SLC product).

In addition the SAR processors should use the SWST (Sample Window Start Time) bias of 6265 nsec both for ERS1 and ERS2 and the antenna pattern correction. Antenna Pattern correction files for ERS-1 and for ERS-2 can be found in Appendix C.

The first two values are the boresight angle (fixed angle between satellite nadir and SAR instrument viewing direction) and the number of samples.

It is recommended to use a linear interpolation of these files.

The correction is referenced to boresight angle (20.355 degrees --> 0dB att). The samples range from -3.3 to 2.8 degrees around the boresight angle.

3.2.7. Validation Report from NFS

A validation report should describe in detail the analysis done by the station to check and ensure the correctness of quality of the products, by mean of a methods described in this document.

It should includes the two following tables at least:

Table 1 -

	ERS-1 T#1	ERS-1 T#2	ERS-1 T#3	ERS-1 Average
1 - Impulse response function ■ range spatial resolution (m) ■ azimuth spatial resolution (m) ■ range peak sidelobe ratio (dB) ■ azimuth peak sidelobe ratio (dB) ■ Integrated sidelobe ratio (islr) (dB) ■ Ambiguity ratio (dB)				
2 - Absolute localization accuracy ■ latitude (m) ■ Longitude (m)				
3 - Radiometric resolution (db)				

The same table should be done for ERS-2

Table 2 (optional. Only when calibration exercise is completed) -

Calibration constant for ERS-1	
Calibration constant for ERS-2	

3. 3. Requirements for products

It concerns the following products:

- SAR.RAW,
- SAR.SLC (or similar complex product),
- SAR.PRI (or similar image product),

- SAR.GEC (or similar image geocoded product).

Details of the validation work are given below for each the four products.

3.3.1. SAR.RAW

The following activities have to be planned:

(a) Product header examination,

(b) Statistical analysis of raw data,

(c) Replica Pulse examination.

3.3.2. SAR.SLC

The following activities are planned:

(a) Product header examination,

(b) Image quality assessment based on detected data using the ESA transponders,

(c) Interferometry offset test as described in Appendix D,

(d) Calibration constant and product scaling factor derivation.

3.3.3. SAR.PRI

The majority of the validation work is to be performed using this product type. The following activities are planned as outlined in the paragraph 3.2.3. of this document:

(a) Visual inspection of image for any obvious defects or problems,

(b) Product header examination,

(c) Image quality assessment.

Based on transponders (or natural point targets) the following parameters are to be derived:

- Spatial resolution (azimuth and range)

- Peak, integrated and spurious sidelobe ratios,

- Azimuth ambiguity ratio (assuming low water backscatter in the transponder ambiguity regions)

Based on distributed targets, the following parameters are to be derived:

- Radiometric resolution,

- Noise equivalent sigma nought (assuming low backscatter region available).

(d) Image localization (transponders)

(e) Calibration constant.

3.3.4. SAR.GEC

The requirements for Geocoded products are:

- Analysis of the geometric accuracy for flat area (this should be done for ascending and descending geometry). Originally ESRIN is using Flevoland as reference. The requirement was to have residuals lower than 100 m. Tie points should be regularly selected. At least ten points should be used. It would be better around 20.
- Radiometric characteristics of the GEC should remain unchanged with respect to the non geocoded image. This is done by checking that pixel statistics are the same (mean and standard deviation are sufficient). This allows the calibration of the GEC product in the same way as the PRI.
- Product format verification
- Verification of GEC photo products annotations (if the station produces photo products, of course).

Acronyms and abbreviations

AMI	Active Microwave Instrument
D-PAF	The German PAF
EECF	Esrin ERS Central Facility
ERS	European Remote Sensing satellite
ERS-1	European Remote Sensing satellite 1
ERS-2	European Remote Sensing satellite 2
F-PAF	The French PAF
HDDT	High Density Digital Tape
HBR	High Bit Rate
I-PAF	The Italian PAF
IDHT	Instrument Data Handling and Transmission subsystem
LBR	Low Bit Rate
MOU	Memorandum Of Understanding
MMCC	Mission Management and Control Center
NFS	National and Foreign Stations
PAF	Processing and Archiving Facility
SAR	Synthetic Aperture Radar
SWST	Sample Window Start Time
UK-PAF	The United Kingdom PAF

Appendix A - List of parameters for SAR quality image

SAR PERFORMANCE PARAMETERS

3.1. INTRODUCTION

An image product quality measure or performance parameter provides a numerical characterisation of a particular property of a SAR image, e.g. spatial resolution, radiometric resolution etc. In order to perform a comprehensive assessment of image quality, a set of performance parameters characterising all the important properties of an image is required. These parameters are inter-correlated in such a way that an improvement in one parameter will often lead to a degradation in another. For example, an improvement in radiometric resolution can generally be obtained at the expense of spatial resolution.

The development of an SAR system normally starts with a performance criterion, commonly specified in terms of requirements placed on the image product performance parameters. The performance criterion represents a compromise between the often conflicting requirements of all potential users of the SAR data. In order for the quality of an image to be considered acceptable, the image should, strictly speaking, satisfy all the specified performance requirements. However, whether an image is considered acceptable by a particular user depends in practice on the requirements of that user. For example, a person who wishes to use SAR imagery to discriminate between different crop types may consider as perfectly acceptable an image in which the radiometric accuracy and radiometric resolution satisfy the performance requirements but the spatial resolution does not.

In order to ensure that the image product performance parameters satisfy the user requirements, it is necessary to place requirements on the performance of the on-board radar hardware through the specification of a set of instrument performance parameters. These parameters are verified against the user requirements during an on-ground pre-launch characterisation process, using a combination of testing and analysis. Routine post-launch measurements of the instrument performance parameters should also be performed, where possible; this facilitates accurate calibration of the system response and enables any changes in instrument performance, which might result in degraded image quality, to be detected and, if possible, corrected.

The image product quality is also dependent on the performance of the SAR processor. Thus a number of processor performance parameters must be formulated; the performance of the processor can be assessed from analysis of these parameters in processed images produced from simulated raw data sets.

Performance requirements can also be placed on the raw data signal prior to processing. This avoids unnecessary processing of 'bad' data into images, thus saving on processor time. Evaluation of the raw data quality also aids in determining whether any degradation in image quality is attributable to a change in the performance of the radar hardware or to processing errors.

We shall therefore consider SAR performance parameters under the following four headings:

(i) Image Product Quality
(ii) Raw Data Quality
(iii) Instrument Performance
(iv) Processor Performance

Ideally, a list of all relevant image product performance parameters should be provided with each SAR image. However, for most users' requirements, a subset will suffice. In the case of ERS-1, it is intended that estimates of the peak sidelobe ratio, spatial resolution and radiometric resolution performance parameters will be provided [3.1].

3.2. IMAGE PRODUCT QUALITY

In Table 3.1 we present a complete set of SAR image product performance parameters, together with the performance requirements designated for ERS-1 [3.2; pg 101].

TABLE 3.1

SAR Image Product Performance Parameters
& Designated Values for ERS-1

IMAGE PRODUCT PERFORMANCE PARAMETER	ERS-1 REQUIREMENT
(i) IMPULSE RESPONSE FUNCTION	
- RANGE SPATIAL RESOLUTION	< 26.3 m
- AZIMUTH SPATIAL RESOLUTION	< 30 m
- RANGE PEAK SIDELOBE RATIO	< -18 dB
- AZIMUTH PEAK SIDELOBE RATIO	< -20 dB
- INTEGRATED SIDELOBE RATIO	< -8 dB
- RANGE AMBIGUITY RATIO	< -31 dB
- AZIMUTH AMBIGUITY RATIO	< -25 dB
(ii) RADIOMETRIC STABILITY	< 0.95 dB
RADIOMETRIC ACCURACY	--
(iii) RADIOMETRIC RESOLUTION	< 2.5 dB for a target with radar cross-section 10.7 dBm^2 (Noise subtraction performed)
(iv) ABSOLUTE LOCALISATION ACCURACY	
- RANGE	< 0.9 Km
- AZIMUTH	< 1.0 Km

We shall now discuss each of these performance parameters in turn. The parameter definitions are from [3.2; pgs 82-87], with additional points taken from [3.2; pgs 175-210] and [3.3; pgs 30-65].

(i) IMPULSE RESPONSE FUNCTION

The impulse response function (IRF) of a SAR system is defined as the 2-dimensional response to a point target, assuming negligible background reflectivity and thermal noise. This performance parameter encompasses a number of separate measures which characterise various properties of the IRF:

(a) Spatial Resolution

The spatial resolution in azimuth/range is in general defined as the -3 dB width of the IRF in the azimuth/range direction. The -3 dB width is the distance between the points on the mainlobe of the IRF which are 3 dB below the peak intensity value.

The ERS-1 range spatial resolution requirement shown in Table 3.1 applies to ground range, not slant range, resolution. The ground range spatial resolution is dependent on the radar incidence angle and thus varies across the imaged swath and around the orbit. The ERS-1 ground range spatial resolution requirement is specified for the mid-swath position in the so-called 'reference geometry' (see [3.2; pgs 75-77]) and is equivalent to a near-swath (worst case) spatial resolution requirement of $\leq$ 30 m. The slant range spatial resolution is independent of swath and orbit position.

The slant range resolution tests the system performance. If the slant range resolution is known, the ground range resolution can be used to test the slant range to ground range interpolator. However, the performance of the interpolator is assessed during routine processor performance testing (see Section 3.5). Thus, in view of the independence of the slant range spatial resolution of both swath and orbit position, it is preferable that measurements of spatial resolution be performed on slant range images.

The azimuthal spatial resolution depends on the along-track velocity of the beam over the ground and on the fraction of the full (3 dB width) Doppler bandwidth of the return signal that is processed coherently; it changes only slightly ($\leq$ 1%) across the imaged swath and around the orbit.

(b) Peak Sidelobe Ratio

The peak sidelobe ratio (PSLR) is defined as the ratio of the peak intensity of the most intense sidelobe of the IRF to the peak intensity in the mainlobe of the IRF. For ERS-1, the PSLR requirement applies to a rectangular region, centred on an imaged point target, with sides of length 10x in the azimuth direction and 10y in the range direction, where x and y are the achievable azimuth and range spatial resolutions, respectively. In the event that the first sidelobe of the error-free response is masked by the main lobe of the error-included response (i.e. there is no detectable minimum between the centre of the IRF and the first sidelobe position), then the intensity at the position corresponding to the first sidelobe in the error-free case will be used for PSLR determination [3.2].

(c) Integrated Sidelobe Ratio

The integrated sidelobe ratio (ISLR) is a measure of the ratio of the energy in the sidelobes of the IRF to the energy in the mainlobe. For ERS-1, the ISLR is defined as the ratio of the energy within an area bounded by a rectangle, centred on an imaged point target, with sides of length 20x and 20y in the azimuth and range directions, respectively, but outside a rectangle, centred on the point target, with sides of length 2x and 2y in the azimuth and range directions, to the energy within the second rectangle.

(d) Ambiguity Ratio

A SAR system is unable to distinguish between radar echoes from a desired point target at a slant range R and radar echoes from point targets (range ambiguities) lying on the same azimuth line at slant ranges R_{AMB}, where

$$R_{AMB} = R \pm \frac{mc\ PRI}{2} \qquad \ldots.. (3.1)$$

m is an integer,
c is the speed of light
and PRI is the pulse repetition interval

The system is also unable to distinguish between radar echoes from the desired target and radar echoes from targets (azimuth ambiguities) lying at the same slant range at positions where

$$D_{AMB} = D \pm m\ PRF \qquad \ldots.. (3.2)$$

D is the Doppler frequency of the target
D_{AMB} is the Doppler frequency of the ambiguity
and PRF is the pulse repetition frequency

To prevent a SAR system being fully ambiguous, (i.e. receiving ambiguous returns from within the mainlobe of the antenna pattern) it is essential that the round-trip delay between the reception of radar echoes from the near and far edges of the imaged swath be less than the PRI to avoid range ambiguity and that the IRF be greater than the processed Doppler bandwidth to avoid azimuth ambiguity. Additional suppression of ambiguities is dependent on shaping the antenna pattern, to keep the gain through the sidelobes low, and, to a lesser extent, on processing strategy (see e.g.[3.4]).

For ERS-1, the nominal swath width and processed Doppler bandwidth specify the unambiguous zone. The ambiguous zone is outside this area. The range and azimuth ambiguity ratios for a point target are defined as $10 \log_{10} [\ I_A(ra)/I_T\ ]$ and $10 \log_{10} [\ I_A(az)/I_T\ ]$, respectively, where

I_T is the peak intensity of the SAR system response to a point target P, located within the unambiguous zone.

$I_A(ra)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous range.

$I_A(az)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous azimuth.

The range and azimuth ambiguity ratio requirements shown in Table 3.1 are specified for a point target. For a distributed target, the ambiguous energy must be summed over all ambiguous range and azimuth positions, resulting in much higher ambiguity ratios (> -20 dB: see Appendix 1B).

In-flight measurements of each of the IRF performance parameters given above can be performed using artificially-constructed point targets situated on the ground near to the mid-swath position. Since the IRF is not intensity-dependent, the radar cross-sections of such point targets need not be determined accurately. However, in order to minimise distortions of the IRF attributable to system noise and contributions from the local background, a point target must be bright, physically small, isolated and situated on a low-reflectivity, uniform background. The performance parameters can be determined automatically, using a combination of curve characterisation procedures and numerical integration techniques. Interpolation is required to determine the peak intensities of the IRF mainlobe and sidelobes.

Recent work at MRC [3.5], has shown that in order to verify all the IRF requirements specified for ERS-1, the radar cross-section of the point target under consideration must exceed the point target equivalent strength of the background by at least 45 dBm^2. Thus a point target situated on a background of normalised radar cross-section -10 dB must have a radar cross-section of 62 dBm^2 or greater. However, it is possible to obtain an estimate of the spatial resolution alone using point targets with radar cross-sections ~ 20–25 dBm^2 above the background (i.e. ~ 40-50 dBm^2 for backgrounds with normalised radar cross-sections of ~ -10 to 0 dB). Thus it should be possible to use point-like 'targets-of-opportunity' of radar cross-section > 40 dBm^2 to obtain estimates of the spatial resolution in a number of land images. [Unfortunately, very few sea images exhibit any point-like features.] However, the only way of ensuring the presence of point targets suitable for the routine verification of

ALL the IRF requirements is through the use of special artificially-constructed targets e.g. transponders (see also Appendix 4).

In some cases, it may be important to locate point targets-of-opportunity in a SAR image which does not contain any artificially-constructed point targets, in order to estimate the spatial resolution in that image. At present, visual inspection is used routinely to locate possible point targets in SAR images. However, it should be possible to implement an automatic method of locating possible point targets in a SAR image, as follows:-

(a) The image is thresholded, using a threshold pixel intensity I_T, such that any pixel with an intensity $I < I_T$ is set to zero and any pixel with an intensity $I > I_T$ is set to 1.

(b) The image is segmented using standard segmentation techniques and all regions with the desired characteristics (e.g. single pixel regions) are selected for further investigation.

(c) Regions of (say) 7 x 7 pixels in the original image, centred on the pixel positions which have been selected from the thresholded image, are then subjected to a point target validation test (e.g. that outlined in [3.6]) and those (if any) which are accepted by the test are used to estimate the spatial resolution in the image concerned.

Of course, the success of this method in identifying point targets-of-opportunity would have to be investigated thoroughly prior to implementation.

Appendix 6A outlines a possible means of at least partially overcoming the need to locate point targets in SAR images, in order to perform the IRF quality measures, through the use of the coherent correlation function (CCF). The CCF is the autocorrelation function of the complex SAR image and thus can be obtained directly from the complex image of a scene. The determination of the CCF does not require the presence of point-like features in an image and can be achieved using automatic techniques.

It is not possible to recover unambiguously the IRF which gives rise to a particular CCF. Thus it is not sensible to attempt to derive the IRF from the CCF. It is, however, possible to make useful image quality measurements directly on the CCF. In order to do this, it is necessary to determine theoretically the CCF corresponding to the 'ideal' IRF and to determine appropriate performance parameters for the resolution, peak sidelobe level etc. of the CCF. Routine automatic measurements can then be performed on the complex data and the relevant performance parameters

measured. Should these routine measurements reveal a significant change in the CCF, indicating a possible degradation in the IRF, measurements should then be performed on the IRF using images containing artificially constructed point targets or point targets-of-opportunity (see also Appendices 6A and 8).

(ii) <u>RADIOMETRIC ACCURACY</u>

SAR calibration can be defined simply as the transfer function relating the pixel values in the final SAR image to the radar cross-section of the corresponding imaged target. In-flight calibration can be performed using a calibration point target of very stable radar cross-section previously measured accurately under laboratory conditions. A radiometrically accurate SAR system must be well-calibrated, i.e. it must possess only a small absolute calibration (bias) error. In addition, any measurement uncertainties must be small; this necessitates that the system be radiometrically stable with respect to both time and space.

An absolute calibration error occurs due to the uncertainty in the radar cross-section of the calibration target and the instantaneous (random) error in the on-board radar hardware, SAR processor and atmospheric propagation path. This absolute calibration error contributes to the radiometric error in the measured radar cross-sections of all subsequently imaged targets and remains constant until the next calibration. In addition to the absolute calibration error, measurements of the radar cross-sections of arbitrary imaged targets are themselves subject to errors due to short-term and long-term (quasi-static) radiometric instabilities in the on-board radar hardware, SAR processor and atmospheric propagation path. The quasi-static (drift) errors will result in the system becoming increasing inaccurate with time subsequent to calibration: the rate of increase of these quasi-static errors will determine how often the system needs to be calibrated (see Appendix 1B).

Since the propagation path is not strictly part of the SAR system, atmospheric instabilities can be ignored in the specification of a radiometric stability performance parameter for the system. However, any measurement of radiometric stability from SAR imagery must include propagation effects. Radiometric stability is a measure of the amount by which a measurement of radar cross-section is likely to differ from that obtained when the system is in a nominal 'stable' state. Radiometric stability can be determined from in-flight measurements of the standard deviation of the radar echoes from a number of identical point or distributed targets with stable radar cross-sections, of such magnitude that the system is operating within its dynamic range. These targets may be artificially-constructed or targets-of-opportunity. To verify that the SAR system is stable with respect to both time and space, the measurements must be performed on a number of independent occasions at a number of positions along the flight line.

Radiometric stability is dependent on the system noise (thermal and quantisation), the power transfer function or gain characteristic, the antenna gain pattern and processing errors. Radiometric stability is thus a requirement which must be satisfied by the SAR instrument and processor (for ERS-1, the radiometric stability requirement is 0.95 dB). However, the users of the image products are, in fact, interested in the degree of accuracy with which the radar cross-section of an imaged target can be determined. Thus radiometric accuracy is more useful than radiometric stability as an image product performance parameter. The radiometric accuracy of a SAR system at a time t is given by

$$R_a = \langle \sigma_e - \sigma_r \rangle \qquad \ldots\ldots (3.3)$$

where σ_r is the true radar backscatter value for a calibration target,

σ_e is the radar backscatter value obtained using the calibrated SAR system

and the angle brackets $\langle\rangle$ denote an average over a number of calibration targets imaged at time t.

The radiometric accuracy of a SAR system is dependent on factors which are hard to quantify, such as atmospheric effects and the ambiguous energy contribution due to bright extended regions situated near to an imaged target. For this reason, no radiometric accuracy requirement has been specified for ERS-1, although a nominal one standard deviation error of 1.1 dB has been estimated [3.7; pg 111]. Appendix 1B outlines the way in which frequent calibration of ERS-1 during the commissioning phase can be used to estimate the temporal variation of radiometric accuracy due to drift errors. Hence the radiometric accuracy can be predicted at any time between calibration observations during the routine imaging phase of the satellite and the maximum interval allowable between calibration observations can be determined.

(iii) RADIOMETRIC RESOLUTION

Radiometric resolution is a measure of the ability of a SAR system to distinguish between uniform regions with different backscatter levels. The standard definition of radiometric resolution is

$$\gamma = 10 \log_{10} \left(1 + \sigma/\mu \right) \qquad \ldots\ldots (3.4)$$

where μ, σ are, respectively, the sample mean and standard deviation of the signal power in a SAR image of a uniform region.

The value obtained for γ is different in images which include the additive noise signal and images in which the additive noise contribution has been subtracted. Detailed equations are given in Appendix 2B which allow theoretical values of γ to be derived for both noisy and noise-corrected images produced by the incoherent summation of a number of looks of different intensities. However, a measurement of radiometric resolution obtained directly from the final processed imagery is important to verify that the actual value of γ is consistent with the theoretical value. The measurement of γ in processed SAR images involves the determination of μ and σ in verified uniform regions and substitution of the derived values into (3.4). Possible methods for determining γ are discussed in detail in Appendix 2A.

It must be stressed that routine measurement of the radiometric resolution in the processed images must be performed. Deriving a value for γ using the equations given in Appendix 2B is useful if one wishes to verify some aspect of instrument performance (e.g. the level of system noise) but cannot be considered to be a measure of image product quality.

The current method of defining radiometric resolution is not entirely satisfactory as it is difficult for users to relate values of γ to the ability to discriminate between targets with different radar cross-sections (which, after all, is what the users actually wish to know). Recent work at MRC [3.8] has used classical statistical methods to determine the probability of distinguishing between two target regions in an image which are of equal size and have known radar cross-sections. By combining the methods outlined in Appendix 2A and [3.8], it should be possible, if required, to generate for any SAR image a probability curve which gives an estimate of probability of distinguishing between imaged targets as a function of target size and contrast.

(iv) ABSOLUTE LOCALISATION ACCURACY

The absolute localisation accuracy of an image is a measure of the accuracy with which any pixel in the image can be located on the ground. A SAR locates a target in range by the time delay of its radar response and in azimuth by its Doppler history. The SAR processor can use this information, together with orbit and timing data and a suitable earth model, to provide a coarse estimate of the location of an image on the ground. For an airborne SAR, the earth can be assumed flat; for a spaceborne SAR, the curvature of the earth is significant and it is usually assumed to be circular or ellipsoidal. For ERS-1, the Verification Mode Processor will nominally derive the latitude and longitude of the four corners and the centre of each SAR image. The ERS-1 range and azimuth localisation accuracy requirements for this coarse image location are shown in Table 3.1. These requirements can be verified directly by analysis of the radar echoes from a calibration point target and comparison between the location, x_e, of the point target derived by the SAR processor and its location, x_r, as given by 'ground

truth' data. The localisation accuracy, L_a, of the system at a time t is given by:

$$L_a = \langle x_e - x_r \rangle \qquad \text{..... (3.5)}$$

where the angle brackets <> denote an average over a number of calibration targets imaged at time t.

In order to perform a more detailed analysis of localisation accuracy in a SAR image, it is necessary to compare the SAR image with a reference image, which is assumed to be free of errors. This reference is typically a Digital Terrain Model (DTM) or a digitised map. In order to compare the SAR image with such reference images, two transformations must be applied to the SAR data: a conversion to ground range co-ordinates using a suitable earth model, followed by a transformation to a specified map projection, e.g. a Universal Transverse Mercator (UTM) projection. Subsequent to these transformations, the image is known as a GEOCODED image. The production of a geocoded image requires precise orbit data, timing data, earth model data and auxiliary processor data.

Users of geocoded images generally require a much greater localisation accuracy than the coarse specification provided by the SAR processor. However, no localisation accuracy requirements have yet been specified for the geocoded image products (although a nominal localisation accuracy error budget is available [3.9]). This is largely attributable to the fact that there is no simple measure of localisation accuracy, which can vary significantly from one region of an image to another. Thus localisation accuracy cannot be represented by a single performance parameter, but rather requires a number of parameters which characterise both systematic and random location errors.

The localisation accuracy of a geocoded image is generally investigated using selected ground control points (GCPs) distributed throughout the image. The positions of these GCPs can be compared with the ground truth positions obtained using the reference image, thus enabling a set of displacement vectors to be determined. The displacement vectors can be used to generate a set of performance parameters which characterise the localisation accuracy of the geocoded image. For example, a set of such parameters might be:

(a) The displacements of the GCPs in the range/azimuth directions as a function of range/azimuth.

(b) Simple polynomial functions fitted to the displacements in range and azimuth.

(c) The standard deviations of the displacements in range and azimuth.

(d) The residual errors of the displacements in range and azimuth with respect to the fitted polynomials.

(a) and (b) characterise systematic errors in localisation (absolute positional errors), while (c) and (d) characterise random errors (residual distortions).

Errors in localisation will arise due to variations in terrain height. Using terrain information obtained from Digital Elevation Models (DEMs), it should be possible to produce a geocoded terrain-corrected image, the localisation accuracy of which could be examined as outlined above.

At present GCPs are located within an image by eye, with the problems of extended operating time and reduced accuracy which this entails. The ultimate aim is that automatic location of GCPs in a geocoded image be achieved using information derived from cartographic data, with a search in the geocoded image performed using correlation techniques (see e.g. [3.10]).

Appendix B - Methodology to calculate the Calibration Constant

Annex C

Evaluation of the Calibration Constant using Point Targets

1. Introduction

For the absolute calibration of ERS SAR Precision image (PRI[1]) products and ERS SAR Single Look Complex Image (SLC[2]) products, a PRI image and respectivelly an SLC image covering the Flevoland calibration site[3] (the Netherlands), are used. These scenes contain the three transponders deployed by ESA for the calibration and validation of the entire imaging chain. The method adapted here, for the evaluation of the calibration constant, is the so called integration method on pixel values. This method consists in integrating the signal intensity of a transponder in a rectangular area whose size is expressed in resolution cells. This summation however also includes the background signal intensity. By averaging the background intensity in a surrounding area free from point targets (whose size is also expressed in terms of resolution cells), this background contribution can be removed.

2. ESA Procedure for the Evaluation of the Calibration Constant

The calibration of SAR data involves the determination of the constant of proportionality K, which relates the pixel value in the image to the radar cross-section, in this case the backscattering coefficient $\sigma°$ of the corresponding imaged target in the scene.

$$\langle I \rangle = K(\alpha) \cdot \sigma°$$

The constant of proportionality, K, also called calibration constant, varies with the incidence angle α (or the depression angle θ). This dependency arises from the physical projection of the system transfer function upon the surface being imaged. The solution adopted by ESA is to determine K at a reference incidence angle. This reference angle coincides with the mid-range incidence angle i.e. $\alpha_{ref} = 23$ degrees. The value $\boldsymbol{K}$ given in ESA SAR PRI and SLC products is thus:

$$\boldsymbol{K} = K(\alpha_{ref} = 23°)$$

To derive a local estimate of the calibration constant K, users should apply the following equation

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

See Annex A of ref.[1] for the evaluation of the local incidence angle α.

1. A PRI product is a multi-look (speckle reduced), ground range projected and system corrected digital SAR image. The product is corrected for the in-flight SAR antenna pattern and compensated for range-spreading loss.
2. A SLC product is a single-look, slant range projected digital SAR image.
3. Data acquisition time 13/10/91 at 21:40:37 for ERS-1 and 4/8/95 at 10:35:01 for ERS-2.

Calibration using ESA Transponders

The ESA procedure used to calculate an estimate of the calibration constant can be described as follows:

* A tile of image data is extracted around the calibration target i.e. an ESA transponder.

* The peak is located in the image tile. The number of pixels contained in a single resolution cell is calculated using the spatial resolutions and the pixel spacings (sample spacing for SLC products), in respectively range and azimuth i.e. the number of pixel in range (azimuth) per resolution cell is the ratio of the range (azimuth) resolution and the range (azimuth) pixel spacing, both expressed in meters.

Product type	SLC	PRI
Range resolution (m)	9.68	10 (in slant range) $10/sin\alpha$ (in ground range)
Azimuth resolution (m)	5.25	22
Range pixel spacing (m)	7.9	12.5
Azimuth pixel spacing (m)	3.98	12.5
Nb of pixels per resolution cell in range	1.22	$0.8/sin\alpha$ (in ground range)
Nb of pixels per resolution cell in azimuth	1.32	1.76

Table 1: Resolutions and pixel (sample) spacings for PRI (SLC) products.

Multiplying the number of pixels per resolution cell by the number of resolution cells NC_c, NC_Δ and NC_d, and rounding the results, yields the number of pixels (in azimuth and range) required in the computation of I_{int} and C, defined bellow.

* The integrated power I_{int} is computed by summing the pixel intensities over a rectangular area centred around the peak or target (transponder IRF) and NC_c (=10) resolution cells in size, see figure 1.

* The background backscatter C is calculated by summing the pixel intensities over four rectangular areas symmetrically positioned around the target, distant NC_d (=10) resolution cells from it and NC_Δ (=20) resolution cells in size, see figure 1.

Examples:

for a PRI image with a point target at mid-range ($\alpha=\alpha_{ref}$), the size of the central area is 21 pixels in range and 18 pixels in azimuth. The size of a background area is 41 pixels in range and 36 pixels in azimuth, and each background area is separated from the target by 21 pixels in range and 18 pixels in azimuth.

For an SLC image, the size of the central area is 13 pixels in range and 14 pixels in azimuth. The size of a background area is 25 pixels in range and 27 pixels in azimuth and each background area is separated from the target by 13 pixels in range and 14 pixels in azimuth.

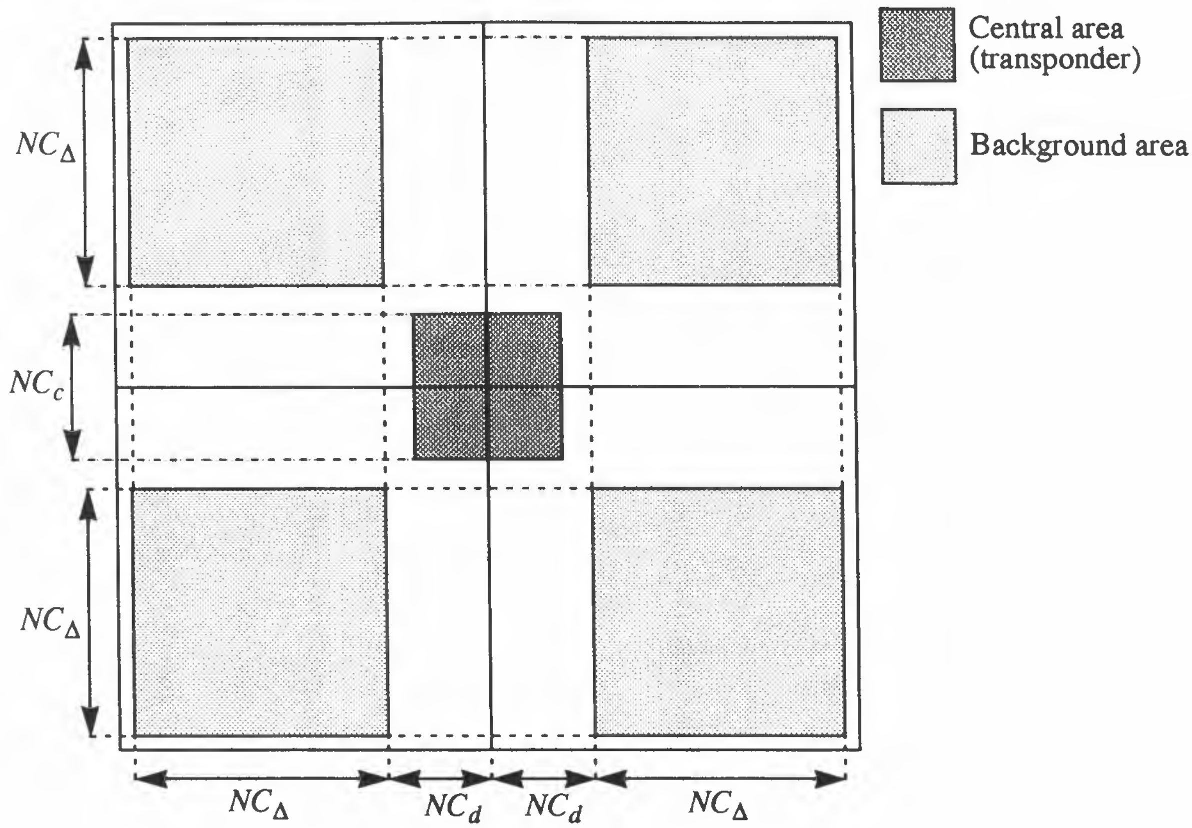

Figure 1. Areas around the target over which the summation of the pixel intensities is required.

The background corrected integrated power is given by:

$$I = I_{int} - \frac{nC}{4m}$$

where n and m denote the total number of pixels in respectively the central area and in one of the background areas. $C/4m$ is the clutter density or average background power (i.e. power per pixel).

* The slant range pixel area, Δa_s, is evaluated:

In the case of a PRI product:

$$\Delta a_s = \Delta x \Delta y \sin\alpha_K$$

where Δx and Δy are the ground range pixel spacings (in metres) in respectivelly range and azimuth, and α_K the incidence angle at the calibration target location.

In the case of an SLC product:

$$\Delta a_s = \Delta x_s \Delta y_s$$

where Δx_s and Δy_s are the slant range pixel spacings (in metres) in respectivelly range and azimuth. The ground range pixel area Δa_{ref} at the reference incidence angle α_{ref} is given by:

$$\Delta a_{ref} = \Delta a_s / \sin\alpha_{ref}$$

* The nominal radar cross section σ of the point target being known a priori, we can determine the calibration constant $\boldsymbol{K}$.

In the case of a PRI product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma}$$

In the case of an SLC product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma} \cdot \left(\frac{r_K}{r_{ref}}\right)^3 \cdot \frac{1}{g^2(\theta_K)}$$

where r_K and r_{ref} are respectivelly the slant range distance at the target's location and the reference slant range distance (i.e. the mid-swath slant range distance $r_{ref} = 847.0km$), $g^2(\theta)$ is the two-way antenna pattern profile and θ_K is the depression angle at the target's location. These corrections are required because SLC-products are not corrected for antenna elevation gain and range spreading loss.

The different NC parameters are chosen such that small variation in these parameters does not affect the calculated calibration constant $\boldsymbol{K}$ (see figure 2).

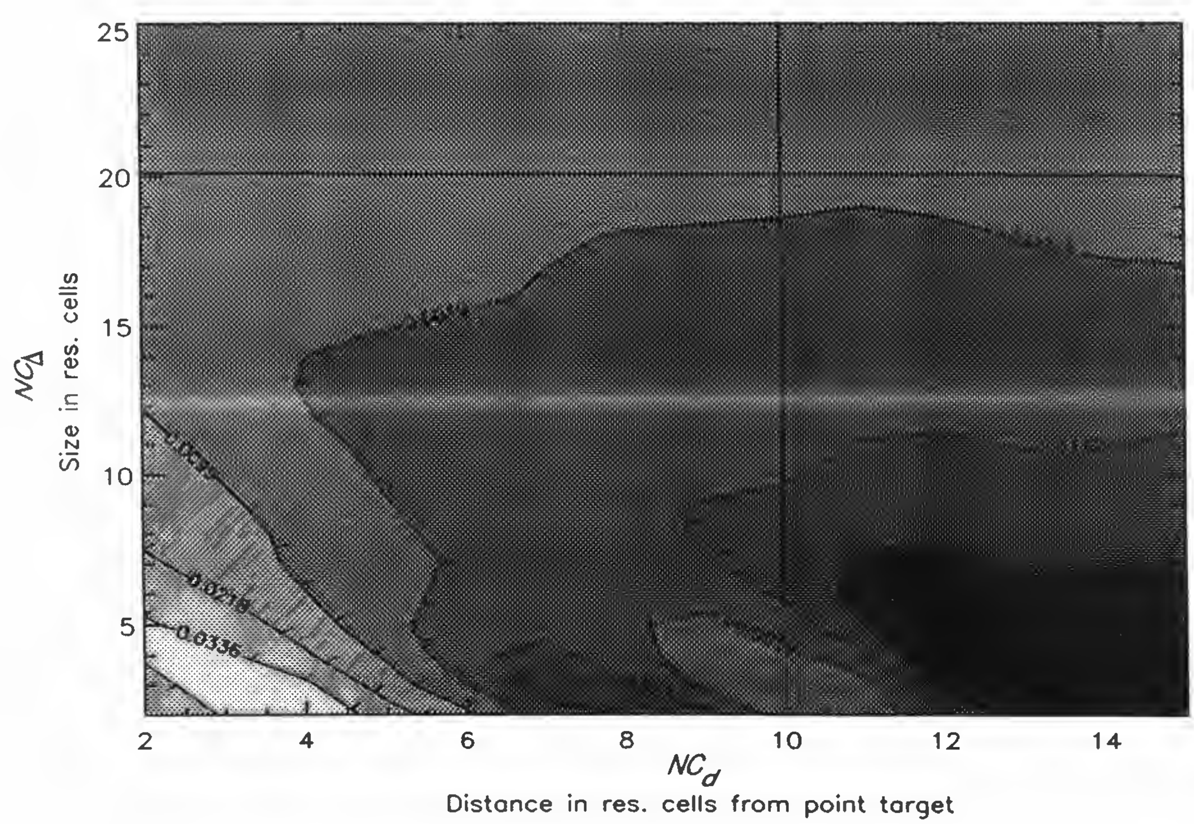

Figure 2. **Calibration constant variations (in decibels) as a function of NC_d and NC_Δ.**

Symbols

$\langle I \rangle$ is the mean pixel intensity,

$\boldsymbol{K}$ is the calibration constants at the mid-range incidence angle,

σ° is the backscattering coeficient and σ the radar cross section,

α is the incidence angle and $\alpha_{ref} = 23°$ is the reference (at mid-range) incidence angle,

Δy and Δx are respectively the azimuth and range pixel spacings in ground range,

Δy_s and Δx_s are respectively the azimuth and range pixel spacings in slant range,

Δa_s, Δa_{ref} are respectively the slant range pixel area and the ground range pixel area at the reference incidence angle α_{ref},

r and $r_{ref} = 847.0km$ are respectivelly the slant range distance and the reference slant range distance,

$g^2(\theta)$ is the two-way antenna pattern profile and θ is the depression angle,

NC_c and NC_{Δ} are the sizes in resolution cells of respectively the central area and of one of the background areas (all four areas have identical dimensions). NC_d is the distance in resolution cells separating the point target from each background area.

n is the number of pixels in the central area and m is the number of pixels in each one of the background areas.

I_{int} and C are the sum of the pixel intesities respectively over the central area and over the background area,

I is the background corrected integrated power.

References

Ref.[1]: ERS-1 SAR Calibration.

Derivation of Backscattering coefficient in ERS-1.SAR.PRI products

Henri Laur. Issue 1, Rev. 0, 17th October 1992

Ref.[2]: SAR Geocoding: Data and Systems

Gunter Schreier (ed.)

Karlsruhe: Wichman, 1993. ISBN 3-87907-247-7

Appendix C - Antenna Pattern correction for ERS-1 and ERS-2

Appendix A: The Improved Antenna Pattern

TABLE 4. Improved Antenna Pattern

Degrees (rel. to Boresight)	Power (dB)
-3.1	-1.420
-3.0	-1.245
-2.9	-1.067
-2.8	-0.901
-2.7	-0.746
-2.6	-0.605
-2.5	-0.478
-2.4	-0.365
-2.3	-0.269
-2.2	-0.186
-2.1	-0.116
-2.0	-0.064
-1.9	-0.022
-1.8	0.012
-1.7	0.036
-1.6	0.053
-1.5	0.066
-1.4	0.071
-1.3	0.071
-1.2	0.067
-1.1	0.060
-1.0	0.053
-0.9	0.045
-0.8	0.035
-0.7	0.023
-0.6	0.011
-0.5	0.001
-0.4	-0.009
-0.3	-0.013
-0.2	-0.013
-0.1	-0.009
0.0	0.000

Degrees (rel. to Boresight)	**Power (dB)**
0.1	0.015
0.2	0.033
0.3	0.056
0.4	0.081
0.5	0.107
0.6	0.133
0.7	0.165
0.8	0.197
0.9	0.231
1.0	0.264
1.1	0.294
1.2	0.317
1.3	0.335
1.4	0.348
1.5	0.356
1.6	0.358
1.7	0.354
1.8	0.343
1.9	0.322
2.0	0.291
2.1	0.249
2.2	0.188
2.3	0.112
2.4	0.023
2.5	-0.085
2.6	-0.209
2.7	-0.334
2.8	-0.485

ERS-2 Antenna Pattern

The first two values are:

- the boresight angle in degrees (angle between satellite nadir & SAR viewing direction)
- the number of samples.

The correction is referenced to boresight angle (20.355 degrees at 0dB attenuation).

The samples which can be used range from -3.3 to 2.8 degrees.

This correction is valid for the whole ERS-2 ground segment and thus can be used in the whole NFS network.

Note : It is recommended to use a linear interpolation of this file

20.355	71
-3.5	0.0000
-3.4	0.0000
-3.3	-2.0168
-3.2	-1.8282
-3.1	-1.5290
-3.0	-1.3058
-2.9	-1.0914
-2.8	-0.9196
-2.7	-0.7612
-2.6	-0.6215
-2.5	-0.5004
-2.4	-0.3915
-2.3	-0.2948
-2.2	-0.2124
-2.1	-0.1423
-2.0	-0.0852
-1.9	-0.0414
-1.8	-0.0098
-1.7	0.0135
-1.6	0.0298
-1.5	0.0403
-1.4	0.0434
-1.3	0.0416
-1.2	0.0365
-1.1	0.0296
-1.0	0.0223
-0.9	0.0124
-0.8	0.0051
-0.7	-0.0007
-0.6	-0.0061
-0.5	-0.0126
-0.4	-0.0105
-0.3	-0.0100
-0.2	-0.0109
-0.1	-0.0088
0.0	0.0000
0.1	0.0128
0.2	0.0307
0.3	0.0529

0.4	0.0770
0.5	0.1033
0.6	0.1296
0.7	0.1588
0.8	0.1876
0.9	0.2166
1.0	0.2434
1.1	0.2655
1.2	0.2880
1.3	0.3091
1.4	0.3219
1.5	0.3271
1.6	0.3264
1.7	0.3099
1.8	0.2810
1.9	0.2449
2.0	0.1968
2.1	0.1368
2.2	0.0676
2.3	-0.0095
2.4	-0.1009
2.5	-0.2120
2.6	-0.3381
2.7	-0.4827
2.8	-0.6359
2.9	0.0000
3.0	0.0000
3.1	0.0000
3.2	0.0000
3.3	0.0000
3.4	0.0000
3.5	0.0000

Appendix D - SAR Single Look Complex Image suitable for Interferometry (Test on processor phase preservation)

Product name | *Product code*

SAR Single Look Complex Image (suitable for interferometry) | **ERS.SAR.SLC-I**

DEFINITION

Single-look, complex, slant-range, full frame digital image generated from raw SAR image mode data with up-to-date (at time of processing) auxiliary parameters. This product is suitable for interferometric applications.

DESCRIPTION

as ERS.SAR.SLC

SPECIFICATIONS

Units: as ERS.SAR.SLC.
Pixel spacing: as ERS.SAR.SLC.
Product size: Full frame, i.e. 4900 samples in range and at least 26000 samples in azimuth.
Data presentation: as ERS.SAR.SLC.
Product localisation: referenced to standard ERS SAR frames.
reported in product annotations: as ERS.SAR.SLC.
Localisation accuracy: as ERS.SAR.SLC.
Spatial resolution: as ERS.SAR.SLC.
Coordinate system: as ERS.SAR.SLC.
Range spectral weighting: as ERS.SAR.SLC.
Number of looks: as ERS.SAR.SLC.
Look bandwidth: as ERS.SAR.SLC.
Look spectral weighting function: as ERS.SAR.SLC.
Azimuth frequencies: not shifted to azimuth baseband, i.e. as ERS.SAR.SLC (the Doppler spectrum is left at the Doppler centroid frequency).
Azimuth reference function: phase of zero at its zero-Doppler point (time origin) and not normalized to the phase at Doppler centroid.
Phase preservation (see annex): the SLC-I product shall be generated with a phase preserving processor. The processor shall verify the phase-preservation tests with the following results:

- the *interferometric offset processing test* with the following results:
  - interferometric phase mean value $\leq$ 0.1 degree,
  - interferometric phase standard deviation (i.e. phase noise) $\leq$ 5 degrees,
  - no obvious phase noise strips shall be observable in the interferogram.
- the *interferometric simulated point target test* with the following results:
  - the phase error at the correlation peaks is $\leq$ 0.1 degree,
  - the phase of the 2-D Fourier transform contains no other terms than linear and constant terms.

Range cell migration artifact: as ERS.SAR.SLC.
Point target geometric mis-registration: as ERS.SAR.SLC.
Processor point target linearity: as ERS.SAR.SLC.

Processor point target linear output dynamic range: as ERS.SAR.SLC.
Processor gain stability: as ERS.SAR.SLC.
Quality parameters: as ERS.SAR.SLC.
Internal calibration: as ERS.SAR.SLC.
Absolute calibration: as ERS.SAR.SLC.

DATA VOLUME

Data set and CEOS superstructure is 531.2 Mbytes.

MEDIUM

Exabyte cassette.

FORMAT

as ERS.SAR.SLC.

NOTES

Notes 1, 4, 5 and 6: as ERS.SAR.SLC

Notes 2 and 3: not applicable for ERS.SAR.SLC-I

ANNEX

Phase preservation processing and testing

[Based on D-PAF DLR Technical Note (R. Bamler & B. Schattler): Phase-Preservation in SAR Processing - Definition, Requirements and Tests, Version 1.0, May 1995.]

1- Phase preservation processing

The processing of SLC-I product shall be phase preserving, which means that the following requirements shall be observed:

1. The azimuth reference function (when represented in the time domain) must have a phase equal to zero at its zero Doppler point (time origin) and must not be normalized to the phase at Doppler centroid.

2. The signal spectrum must not be shifted (i.e. no baseband conversion applied). For the azimuth spectrum, this means that it must be left at the Doppler centroid frequency.

3. The processing parameters varying along the scene must be sufficiently updated to avoid the introduction of focusing errors. All corrections and compensations must be performed with the necessary accuracy to avoid focusing errors (for the Range-Doppler algorithm, this implies a proper FM rate update and a perfect range migration compensation).

4. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) have to be avoided.

5. The Offset Processing Test must be performed with the following results:
   - Mean of the interferometric phase ≤ 0.1 degrees,
   - Standard deviation of the interferometric phase ≤ 5 degrees,
   - No obvious phase noisy strips shall be observable in the interferogram (in particular, this implies that the structure of the processing blocks shall not be distinguished in the phase noise pattern).

6. The Simulated Point Target Test must be performed with the following results:
   - Phase at the correlation peaks ≤ 0.1 degrees,
   - Phase of the 2-D Fourier transform of the focused point target containing only linear terms and a constant.

2- Phase-preservation testing

2.1- Interferometric Offset Processing Test:

<u>Test Principle:</u>

Generate two complex products by processing independently twice the same raw data, but starting at different azimuth and range positions (i.e. the products will be shifted by y lines in azimuth and x samples in range).

Using the same raw data prevents from interferometric phase aberrations (phase bias and standard deviation) due to inherent SAR system effects. The obtained interferometric phase should ideally have a constant phase of zero. Thus, detected phase aberrations will reveal processor induced artifacts.

Practical considerations:

a. Both products must be processed using the same Doppler centroid frequency.

b. The number of offset lines and samples between both products should not be an integer multiple of the processing block dimension (nor in azimuth nor in range). Furthermore if an "overlap & save" technique is used to process the data, the offset value between products should not be either an integer multiple of the number of valid lines (samples in range) of each processed data block.

c. It is recommended that the scene shifts in both directions are chosen in such a way that the relative azimuth and range offset between the products are integer multiples of the azimuth and range sampling intervals respectively. This avoids the coregistration step before interferometry generation, which is critical for the test, since it tends to introduce additional phase noise.

d. A nominal chirp should be used to perform the range compression (an extracted chirp could introduce phase aberrations related to problems inherent to the chirp and/or to the chirp processing inside the processor).

e. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) should be avoided. The interferogram should be generated using non rescaled complex products (i.e. with their floating point representation if available), in order to avoid the quantisation noise associated to the rescaling.

f. The interferometric phase analysed must include areas generated from the same processing block for each generated product as well as areas corresponding to consecutive processing blocks. The statistical values should be independently measured over both areas.

g. As the test is performed with real SAR data, the areas with very low backscattering coefficients (e.g. calm water, shadow effect) should be avoided since the noise level of these areas is already higher in each product of the interferometric pair.

h. The test may also be performed using white circular Gaussian noise as raw data.

2.2- Interferometric Simulated Point Target Test:

Test description.
Simulate a raw data scene with some point targets homogeneously distributed along range and azimuth (locating some of them on processing block boundaries). After processing this scene, analyse the peak phases as well as the 2-D fourier transform of the focused point targets.

Appendix E - State Vectors and Time Correlation for the two ERS-1/2 reference scenes over Flevoland in The Netherlands

ERS-1

PCF Parameters for order number 12344
Input UTC date/time 13-OCT-1991 21:40:37.945

State Vector Type: Restituted
Orbit number: 1273
Orbit Vector Position (metres): 4332915.113000, 68324.403000, 5687762.133000
Orbit Vector Velocity (metres/sec): -5729.388953, -2231.331188, 4380.982972
Orbit Vector UTC: 13-OCT-1991 21:41:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1273
UTC reference: 13-OCT-1991 21:39:27.120
SBT reference: 1971655215
SBT step length (nanoseconds) 3906249

ERS-2

PCF Parameters for order number 44321
Input UTC date/time 04-AUG-1995 10:35:01.383

State Vector Type: Restituted
Orbit number: 1508
Orbit Vector Position (metres): 4323215.082000, 761068.498000, 5652398.402000
Orbit Vector Velocity (metres/sec): 6006.074500, -1104.391748, -4434.628533
Orbit Vector UTC: 04-AUG-1995 10:35:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1508
UTC reference: 04-AUG-1995 10:22:58.542
SBT reference: -1957651866
SBT step length (nanoseconds) 3906249

ERS National & Foreign Stations

SAR processor calibration and products validation plan

This document describes the procedure required for the calibration of SAR processor and validation of products from ERS national & foreign Stations.

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Prepared:	Jean-Charles Bigot - RS/EF, ESRIN	....
Reviewed:	V. Beruti - H/RS/EF, ESRIN	....
Approved:	M. Albani - H/RS/E, ESRIN	....

1 - Introduction

1.1. Purpose

The purpose of this document is to outline the work to be carried out for the validation of the ERS-1/2 SAR products generated by the ERS-1/2 National & Foreign Stations spread around the world, for the calibration of their SAR processor, and the line of responsibility for the various activities.

The detailed description of the validation and calibration activities are specified later in this document after a short introduction on the ERS ground segment.

It is proposed that a technical report be produced by the station for the validation results of the Station ERS-1/2 SAR products if not already done.

1.2. Scope

The ERS-1/2 National & Foreign Stations spread around the world have different SAR processor build by different companies. The SAR products generated from these SAR processors are quite different from a station to another so that the user may be confused in the variety of products delivered around the world. Thus ERS SAR users should be fully informed on the products delivered by all ERS National & Foreign Station. The validation exercise contributes to reach this goal.

In general, SAR products delivered by the ERS-1/2 NFS should be validated before being distributed as soon as the processor is considered calibrated and tuned. This validation and calibration exercise is necessary prior to the issuing of the products to the users.

The methodologies of the validation of the SAR products and the method to derive the product calibration constant are addressed in ad-hoc documents which are given in the appendixes.

2 - ERS ground segment

2.1. The overall ground segment

The ERS ground segment consists of:

- The Mission Management and Control Center (MMCC) at ESOC, Darmstadt, Germany;
- The Esrin ERS Central Facility (EECF) at Frascati, Italy;
- The real-time ESA Ground Stations (EGS) at Salmijärvi (Sweden), Fucino (Italy), Maspalomas (Canary Islands- Spain), Gatineau and Prince Albert (Canada);
- The Processing and Archiving Facilities (D-PAF) at Oberpfaffenhofen (Germany), F-PAF at Brest (France), I-PAF at Matera (Italy) and UK-PAF at Farnborough (United Kingdom);
- the National Stations - NS - (in ESA Member States) and the Foreign Stations - FS - (in Non-ESA Member States).

2.2. ERS ground stations

2.2.1. Introduction

The ERS-1 orbit - near-polar and sun-synchronous and the need for direct readout of the SAR telemetry have dictated the geographical locations of the ground stations around the world.

All ERS ground stations receive, from the EECF in Frascati, the input data needed to acquire and distribute the SAR data and they report back to the EECF on their station activities and status. These stations generate and distribute products developed nationally to ESA Principal Investigators, Pilot Projects, Research users and Commercial users.

2.2.2. National and Foreign Stations

In addition to the ESA Ground Stations, some national (belonging to countries participating in the ERS program) and some foreign (non-participating countries) ground stations have been set up or are in the process of being set up around the world in order to acquire ERS-1/2 HR data. These stations operate under the terms and conditions of a standard Memorandum of Understanding (MOU) with ESA. This extends the coverage of the SAR operating in Image Mode outside Europe.

The National and Foreign Stations (NFS) are up until end December 1996:

National Stations (NS):

- Aussaguel, France (TO)
- Cordoba (transportable station located in Argentina), Germany (CA)
- Gatineau, Canada (GH)
- Libreville (Transportable station located in Gabon), Germany (LI)
- Malindi, in Kenya for Italy (MA)
- Neustrelitz, Germany (NE)
- O'Higgins, Antartica for Germany (TF)
- Prince Albert, Canada (PH)
- Tromsø, Norway (TS)
- West-Freugh, Scotland, UK (WF)

Foreign Stations (FS):

- Alice Springs, Australia (AS)
- Bangkok,Thailand (TH)
- Beijing, China (BE)
- Chung-Li, Taiwan (TW)
- Cotopaxi, Ecuador (CO)
- Cuiaba, Brazil (CU)

- Fairbanks, Alaska, USA (AF)
- Hatoyama, Japan (HA)
- Hobart, Tasmania, Australia (HO)
- Hyderabad, India (SE)
- Johannesburg, South-Africa (JO)
- Kumamoto, Japan (KU)
- Mac-Murdo, Antartica for USA (MM)
- Norman, Oklahoma, USA (NO)
- Pare-Pare, Indonesia (IN)
- Riyadh, Saudi-Arabia (SA)
- Singapore, Rep. Of Singapore (SG)
- Syowa, Antartica for Japan (SY)
- Tel-Aviv, Israel (IR)

2.3. SAR commercial distribution agreement

ESA has signed an agreement with the ERSC Consortium for the worldwide promotion, marketing and commercial distribution of data from the ERS satellites. Each ERS Consortium's company serves users from a specific area of the world:

- Users in Europe, N. Africa and the Middle East - Eurimage ERS-1 Order Desk
- Users in Canada - Radarsat International ERS-1 Order Desk
- Users in USA and all other countries - Spot Image ERS-1 Order Desk

The ERS Consortium commercializes all data products generated at the ERS ESA Ground Stations (EGS) and at the ERS Processing and Archiving Facilities (PAF). SAR data and images generated at further National and Foreign Stations (NFS) spread around the world are also commercialized by the ERS Consortium, if the customer is outside the country of the station where these data have been received.

Note: All the Principal Investigators (PIs) whose research projects have been accepted by ESA as significant contributions to ERS data exploitation, will continue to get access, directly from ESA-ESRIN, to the data they require to perform their scientific studies.

3 - SAR product validation and SAR processor calibration

3.1. Introduction

Whenever a Station has been granted access to ERS, the technical facilities (Data Acquisition Facility and Data Processing Facility) have to be validated before actual operations take place. The activities concerning the verification of the station itself is twofold:

- Acquisition & Recording validation: the purpose is then to ensure that the station is capable of properly acquiring, recording and archiving SAR raw data in line with ESA standards such as recorder compatibility. This is not the purpose of this document.

- Products validation and processor calibration: the purpose is to ensure that the station is capable of generating SAR products with a quality endorsed by ESA. This is the purpose of this document.

Validation of the SAR products corresponds to the verification of the quality parameters of the products generated by the station.

Calibration of the SAR processor, related to image product (such as the ESA image precision PRI), corresponds to the calculation of the Calibration constant and the application of the Antenna Pattern Correction for ERS-1 and -2.

3.2. Operational procedure

3.2.1. Objectives and responsibilities

The Agency shall ensure that products generated at the national and/or foreign stations are validated for both ERS-1 and ERS-2 missions and eventually that the SAR processors are properly calibrated (on station's request).

The responsibility of the station's operator is to demonstrate the quality of the SAR products generated by its SAR processor while ESA's responsibility is to endorse SAR products for release. This procedure is composed of different phases:

- Initial statement of SAR product quality. The station should provide the specifications of the SAR products;

- Processing of ESA reference data set and generation of products by the station. ESA provides to ground station raw data on CCT or EXA to check the station SAR processor independently of the HDDT ingestion;

- Validation report which includes assessment of quality parameters by the station;

Calibration of the SAR processor by the station (Calibration constant to be calculated and Antenna Pattern correction to be applied) is an optional exercise. As a matter of fact, ESA should check that the calibration is properly done by the station whenever the station has announced that calibrated data is available.

3.2.2. Deliverables by NFS to ESA

During these phases the station has to provide deliverables to ESA

- Information about the SAR processor,

- Detailed SAR products specifications,
- Detailed validation report,
- Sample products on CCT (or EXA) and on slides (with annotations).

3.2.3. Parameters to be evaluated

The parameters to be evaluated for the quality of SAR image are:

- Spatial resolution (range and azimuth) - Point target;
- Peak Sidelobe ratio (range and azimuth) - Point target;
- Integrated Sidelobe ratio - Point target;
- Ambiguity ratio (azimuth) - Point target;
- Radiometric resolution - Distributed target;
- Absolute Localization accuracy - Ground control point;

The definition of these parameters can be found in the document *SAR data Quality Assessment and Rectification*, done by GEC-Marconi Research Centre under ESA contract no. 6635/86/HGE-I found in appendix.

3.2.4. Deliverables by ESA to NFS

For the purpose of the evaluation to be done by ESA, ESRIN send to all NFS after their request:

- Test raw data ERS-1.SAR (orbit 1273, frame 1053 dated 13 Oct. 91) and ERS-2.SAR (orbit 1508, frame 2547 dated 4 Aug. 95) from our reference scene over Flevoland area (ESA test calibration site located in the Netherlands);
- List of the SAR quality parameters needed for the validation of the products, (cf. Appendix A);
- Methodology to calculate the calibration constant (This last document describes the ESA official method to be applied for the calibration of the SAR processor) - (cf. Appendix B);
- Antenna pattern correction for ERS-1 and ERS-2 to be applied (cf. Appendix C);
- Specification of ESA CEOS format if required by the station;

The test raw data are send together with the state vectors (orbital data and time correlation) on CCT or/and EXA from referenced SAR scenes over Flevoland. These data are:

	Date	Orbit	Frame
ERS-1	13 Oct. 1991	1273	1053
ERS-2	04 Aug. 95	1508	2547

The coordinates, electronic delay and RCS (radar cross section) of the three transponders (active radar calibrators) in Flevoland scene are:

Transponder #	Lat DD:MM:SS.sss	Long DD:MM:SS.sss	Delay microsec	RCS
T#1	52:21:59.205	05:09:07.999	1.536	58.39 dBm2
T#2	52:27:28.481	05:31:39.193	1.552	57.69 dBm2
T#3	52:33:17.846	05:40:08.154	1.545	57.85 dBm2

The RCS value is the average of the different calibrations carried out with the transponders at ESTEC.

SAR products processed from these test raw data over the Flevoland calibration site should then be sent to ESRIN for evaluation and validation together with products description and a validation report as stated before.

3.2.5. ESA evaluation

The evaluation, based on the NFS validation report, done by ESA concerns:

- Visual inspection (to detect artifacts);
- Basic measurements (radiometric resolution, impulse response function, localization accuracy);
- Intermediate measurements (dynamic range, point target linearity, radiometric accuracy and radiometric stability);
- Validation of the product's format.

3.2.6. Calibration of SAR Processor

The calibration constant is calculated following the method included in Appendix B. This document has been updated during the ERS2 SAR Commissioning phase. There is no problem to generalize this method to complex data (e.g. SLC product).

In addition the SAR processors should use the SWST (Sample Window Start Time) bias of 6265 nsec both for ERS1 and ERS2 and the antenna pattern correction. Antenna Pattern correction files for ERS-1 and for ERS-2 can be found in Appendix C.

The first two values are the boresight angle (fixed angle between satellite nadir and SAR instrument viewing direction) and the number of samples.

It is recommended to use a linear interpolation of these files.

The correction is referenced to boresight angle (20.355 degrees –> 0dB att). The samples range from -3.3 to 2.8 degrees around the boresight angle.

3.2.7. Validation Report from NFS

A validation report should describe in detail the analysis done by the station to check and ensure the correctness of quality of the products, by mean of a methods described in this document.

It should includes the two following tables at least:

Table 1 -

	ERS-1 T#1	ERS-1 T#2	ERS-1 T#3	ERS-1 Averag e
1 - Impulse response function ■ range spatial resolution (m) ■ azimuth spatial resolution (m) ■ range peak sidelobe ratio (dB) ■ azimuth peak sidelobe ratio (dB) ■ Integrated sidelobe ratio (islr) (dB) ■ Ambiguity ratio (dB)				
2 - Absolute localization accuracy ■ latitude (m) ■ Longitude (m)				
3 - Radiometric resolution (db)				

The same table should be done for ERS-2

Table 2 (optional. Only when calibration exercise is completed) -

Calibration constant for ERS-1	
Calibration constant for ERS-2	

3. 3. Requirements for products

It concerns the following products:

- SAR.RAW,
- SAR.SLC (or similar complex product),
- SAR.PRI (or similar image product),

- SAR.GEC (or similar image geocoded product).

Details of the validation work are given below for each the four products.

3.3.1. SAR.RAW

The following activities have to be planned:

(a) Product header examination,

(b) Statistical analysis of raw data,

(c) Replica Pulse examination.

3.3.2. SAR.SLC

The following activities are planned:

(a) Product header examination,

(b) Image quality assessment based on detected data using the ESA transponders,

(c) Interferometry offset test as described in Appendix D,

(d) Calibration constant and product scaling factor derivation.

3.3.3. SAR.PRI

The majority of the validation work is to be performed using this product type. The following activities are planned as outlined in the paragraph 3.2.3. of this document:

(a) Visual inspection of image for any obvious defects or problems,

(b) Product header examination,

(c) Image quality assessment.

Based on transponders (or natural point targets) the following parameters are to be derived:

- Spatial resolution (azimuth and range)

- Peak, integrated and spurious sidelobe ratios,

- Azimuth ambiguity ratio (assuming low water backscatter in the transponder ambiguity regions)

Based on distributed targets, the following parameters are to be derived:

- Radiometric resolution,

- Noise equivalent sigma nought (assuming low backscatter region available).

(d) Image localization (transponders)

(e) Calibration constant.

3.3.4. SAR.GEC

The requirements for Geocoded products are:

- Analysis of the geometric accuracy for flat area (this should be done for ascending and descending geometry). Originally ESRIN is using Flevoland as reference. The requirement was to have residuals lower than 100 m. Tie points should be regularly selected. At least ten points should be used. It would be better around 20.
- Radiometric characteristics of the GEC should remain unchanged with respect to the non geocoded image. This is done by checking that pixel statistics are the same (mean and standard deviation are sufficient). This allows the calibration of the GEC product in the same way as the PRI.
- Product format verification
- Verification of GEC photo products annotations (if the station produces photo products, of course).

Acronyms and abbreviations

AMI	Active Microwave Instrument
D-PAF	The German PAF
EECF	Esrin ERS Central Facility
ERS	European Remote Sensing satellite
ERS-1	European Remote Sensing satellite 1
ERS-2	European Remote Sensing satellite 2
F-PAF	The French PAF
HDDT	High Density Digital Tape
HBR	High Bit Rate
I-PAF	The Italian PAF
IDHT	Instrument Data Handling and Transmission subsystem
LBR	Low Bit Rate
MOU	Memorandum Of Understanding
MMCC	Mission Management and Control Center
NFS	National and Foreign Stations
PAF	Processing and Archiving Facility
SAR	Synthetic Aperture Radar
SWST	Sample Window Start Time
UK-PAF	The United Kingdom PAF

Appendix A - List of parameters for SAR quality image

SAR PERFORMANCE PARAMETERS

3.1. INTRODUCTION

An image product quality measure or performance parameter provides a numerical characterisation of a particular property of a SAR image, e.g. spatial resolution, radiometric resolution etc. In order to perform a comprehensive assessment of image quality, a set of performance parameters characterising all the important properties of an image is required. These parameters are inter-correlated in such a way that an improvement in one parameter will often lead to a degradation in another. For example, an improvement in radiometric resolution can generally be obtained at the expense of spatial resolution.

The development of an SAR system normally starts with a performance criterion, commonly specified in terms of requirements placed on the image product performance parameters. The performance criterion represents a compromise between the often conflicting requirements of all potential users of the SAR data. In order for the quality of an image to be considered acceptable, the image should, strictly speaking, satisfy all the specified performance requirements. However, whether an image is considered acceptable by a particular user depends in practice on the requirements of that user. For example, a person who wishes to use SAR imagery to discriminate between different crop types may consider as perfectly acceptable an image in which the radiometric accuracy and radiometric resolution satisfy the performance requirements but the spatial resolution does not.

In order to ensure that the image product performance parameters satisfy the user requirements, it is necessary to place requirements on the performance of the on-board radar hardware through the specification of a set of instrument performance parameters. These parameters are verified against the user requirements during an on-ground pre-launch characterisation process, using a combination of testing and analysis. Routine post-launch measurements of the instrument performance parameters should also be performed, where possible; this facilitates accurate calibration of the system response and enables any changes in instrument performance, which might result in degraded image quality, to be detected and, if possible, corrected.

The image product quality is also dependent on the performance of the SAR processor. Thus a number of processor performance parameters must be formulated; the performance of the processor can be assessed from analysis of these parameters in processed images produced from simulated raw data sets.

Performance requirements can also be placed on the raw data signal prior to processing. This avoids unnecessary processing of 'bad' data into images, thus saving on processor time. Evaluation of the raw data quality also aids in determining whether any degradation in image quality is attributable to a change in the performance of the radar hardware or to processing errors.

We shall therefore consider SAR performance parameters under the following four headings:

(i) Image Product Quality
(ii) Raw Data Quality
(iii) Instrument Performance
(iv) Processor Performance

Ideally, a list of all relevant image product performance parameters should be provided with each SAR image. However, for most users' requirements, a subset will suffice. In the case of ERS-1, it is intended that estimates of the peak sidelobe ratio, spatial resolution and radiometric resolution performance parameters will be provided [3.1].

3.2. IMAGE PRODUCT QUALITY

In Table 3.1 we present a complete set of SAR image product performance parameters, together with the performance requirements designated for ERS-1 [3.2; pg 101].

TABLE 3.1

SAR Image Product Performance Parameters
& Designated Values for ERS-1

IMAGE PRODUCT PERFORMANCE PARAMETER	ERS-1 REQUIREMENT
(i) IMPULSE RESPONSE FUNCTION	
- RANGE SPATIAL RESOLUTION	< 26.3 m
- AZIMUTH SPATIAL RESOLUTION	< 30 m
- RANGE PEAK SIDELOBE RATIO	< -18 dB
- AZIMUTH PEAK SIDELOBE RATIO	< -20 dB
- INTEGRATED SIDELOBE RATIO	< -8 dB
- RANGE AMBIGUITY RATIO	< -31 dB
- AZIMUTH AMBIGUITY RATIO	< -25 dB
(ii) RADIOMETRIC STABILITY	< 0.95 dB
RADIOMETRIC ACCURACY	---
(iii) RADIOMETRIC RESOLUTION	< 2.5 dB for a target with radar cross-section 10.7 dBm^2 (Noise subtraction performed)
(iv) ABSOLUTE LOCALISATION ACCURACY	
- RANGE	< 0.9 Km
- AZIMUTH	< 1.0 Km

We shall now discuss each of these performance parameters in turn. The parameter definitions are from [3.2; pgs 82-87], with additional points taken from [3.2; pgs 175-210] and [3.3; pgs 30-65].

(i) IMPULSE RESPONSE FUNCTION

The impulse response function (IRF) of a SAR system is defined as the 2-dimensional response to a point target, assuming negligible background reflectivity and thermal noise. This performance parameter encompasses a number of separate measures which characterise various properties of the IRF:

(a) Spatial Resolution

The spatial resolution in azimuth/range is in general defined as the -3 dB width of the IRF in the azimuth/range direction. The -3 dB width is the distance between the points on the mainlobe of the IRF which are 3 dB below the peak intensity value.

The ERS-1 range spatial resolution requirement shown in Table 3.1 applies to ground range, not slant range, resolution. The ground range spatial resolution is dependent on the radar incidence angle and thus varies across the imaged swath and around the orbit. The ERS-1 ground range spatial resolution requirement is specified for the mid-swath position in the so-called 'reference geometry' (see [3.2; pgs 75-77]) and is equivalent to a near-swath (worst case) spatial resolution requirement of $\leq$ 30 m. The slant range spatial resolution is independent of swath and orbit position.

The slant range resolution tests the system performance. If the slant range resolution is known, the ground range resolution can be used to test the slant range to ground range interpolator. However, the performance of the interpolator is assessed during routine processor performance testing (see Section 3.5). Thus, in view of the independence of the slant range spatial resolution of both swath and orbit position, it is preferable that measurements of spatial resolution be performed on slant range images.

The azimuthal spatial resolution depends on the along-track velocity of the beam over the ground and on the fraction of the full (3 dB width) Doppler bandwidth of the return signal that is processed coherently; it changes only slightly ($\leq$ 1%) across the imaged swath and around the orbit.

(b) Peak Sidelobe Ratio

The peak sidelobe ratio (PSLR) is defined as the ratio of the peak intensity of the most intense sidelobe of the IRF to the peak intensity in the mainlobe of the IRF. For ERS-1, the PSLR requirement applies to a rectangular region, centred on an imaged point target, with sides of length 10x in the azimuth direction and 10y in the range direction, where x and y are the achievable azimuth and range spatial resolutions, respectively. In the event that the first sidelobe of the error-free response is masked by the main lobe of the error-included response (i.e. there is no detectable minimum between the centre of the IRF and the first sidelobe position), then the intensity at the position corresponding to the first sidelobe in the error-free case will be used for PSLR determination [3.2].

(c) Integrated Sidelobe Ratio

The integrated sidelobe ratio (ISLR) is a measure of the ratio of the energy in the sidelobes of the IRF to the energy in the mainlobe. For ERS-1, the ISLR is defined as the ratio of the energy within an area bounded by a rectangle, centred on an imaged point target, with sides of length 20x and 20y in the azimuth and range directions, respectively, but outside a rectangle, centred on the point target, with sides of length 2x and 2y in the azimuth and range directions, to the energy within the second rectangle.

(d) Ambiguity Ratio

A SAR system is unable to distinguish between radar echoes from a desired point target at a slant range R and radar echoes from point targets (range ambiguities) lying on the same azimuth line at slant ranges R_{AMB}, where

$$R_{AMB} = R \pm \frac{mc\ PRI}{2} \qquad \text{..... (3.1)}$$

m is an integer,
c is the speed of light
and PRI is the pulse repetition interval

The system is also unable to distinguish between radar echoes from the desired target and radar echoes from targets (azimuth ambiguities) lying at the same slant range at positions where

$$D_{AMB} = D \pm m\ PRF \qquad \text{..... (3.2)}$$

D is the Doppler frequency of the target
D_{AMB} is the Doppler frequency of the ambiguity
and PRF is the pulse repetition frequency

To prevent a SAR system being fully ambiguous, (i.e. receiving ambiguous returns from within the mainlobe of the antenna pattern) it is essential that the round-trip delay between the reception of radar echoes from the near and far edges of the imaged swath be less than the PRI to avoid range ambiguity and that the IRF be greater than the processed Doppler bandwidth to avoid azimuth ambiguity. Additional suppression of ambiguities is dependent on shaping the antenna pattern, to keep the gain through the sidelobes low, and, to a lesser extent, on processing strategy (see e.g.[3.4]).

For ERS-1, the nominal swath width and processed Doppler bandwidth specify the unambiguous zone. The ambiguous zone is outside this area. The range and azimuth ambiguity ratios for a point target are defined as $10 \log_{10} [I_A(ra)/I_T]$ and $10 \log_{10} [I_A(az)/I_T]$, respectively, where

I_T is the peak intensity of the SAR system response to a point target P, located within the unambiguous zone.

$I_A(ra)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous range.

$I_A(az)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous azimuth.

The range and azimuth ambiguity ratio requirements shown in Table 3.1 are specified for a point target. For a distributed target, the ambiguous energy must be summed over all ambiguous range and azimuth positions, resulting in much higher ambiguity ratios (> -20 dB: see Appendix 1B).

In-flight measurements of each of the IRF performance parameters given above can be performed using artificially-constructed point targets situated on the ground near to the mid-swath position. Since the IRF is not intensity-dependent, the radar cross-sections of such point targets need not be determined accurately. However, in order to minimise distortions of the IRF attributable to system noise and contributions from the local background, a point target must be bright, physically small, isolated and situated on a low-reflectivity, uniform background. The performance parameters can be determined automatically, using a combination of curve characterisation procedures and numerical integration techniques. Interpolation is required to determine the peak intensities of the IRF mainlobe and sidelobes.

Recent work at MRC [3.5], has shown that in order to verify all the IRF requirements specified for ERS-1, the radar cross-section of the point target under consideration must exceed the point target equivalent strength of the background by at least 45 dBm^2. Thus a point target situated on a background of normalised radar cross-section -10 dB must have a radar cross-section of 62 dBm^2 or greater. However, it is possible to obtain an estimate of the spatial resolution alone using point targets with radar cross-sections ~ 20-25 dBm^2 above the background (i.e. ~ 40-50 dBm^2 for backgrounds with normalised radar cross-sections of ~ -10 to 0 dB). Thus it should be possible to use point-like 'targets-of-opportunity' of radar cross-section > 40 dBm^2 to obtain estimates of the spatial resolution in a number of land images. [Unfortunately, very few sea images exhibit any point-like features.] However, the only way of ensuring the presence of point targets suitable for the routine verification of

ALL the IRF requirements is through the use of special artificially-constructed targets e.g. transponders (see also Appendix 4).

In some cases, it may be important to locate point targets-of-opportunity in a SAR image which does not contain any artificially-constructed point targets, in order to estimate the spatial resolution in that image. At present, visual inspection is used routinely to locate possible point targets in SAR images. However, it should be possible to implement an automatic method of locating possible point targets in a SAR image, as follows:-

(a) The image is thresholded, using a threshold pixel intensity I_T, such that any pixel with an intensity $I < I_T$ is set to zero and any pixel with an intensity $I > I_T$ is set to 1.

(b) The image is segmented using standard segmentation techniques and all regions with the desired characteristics (e.g. single pixel regions) are selected for further investigation.

(c) Regions of (say) 7 x 7 pixels in the original image, centred on the pixel positions which have been selected from the thresholded image, are then subjected to a point target validation test (e.g. that outlined in [3.6]) and those (if any) which are accepted by the test are used to estimate the spatial resolution in the image concerned.

Of course, the success of this method in identifying point targets-of-opportunity would have to be investigated thoroughly prior to implementation.

Appendix 6A outlines a possible means of at least partially overcoming the need to locate point targets in SAR images, in order to perform the IRF quality measures, through the use of the coherent correlation function (CCF). The CCF is the autocorrelation function of the complex SAR image and thus can be obtained directly from the complex image of a scene. The determination of the CCF does not require the presence of point-like features in an image and can be achieved using automatic techniques.

It is not possible to recover unambiguously the IRF which gives rise to a particular CCF. Thus it is not sensible to attempt to derive the IRF from the CCF. It is, however, possible to make useful image quality measurements directly on the CCF. In order to do this, it is necessary to determine theoretically the CCF corresponding to the 'ideal' IRF and to determine appropriate performance parameters for the resolution, peak sidelobe level etc. of the CCF. Routine automatic measurements can then be performed on the complex data and the relevant performance parameters

measured. Should these routine measurements reveal a significant change in the CCF, indicating a possible degradation in the IRF, measurements should then be performed on the IRF using images containing artificially constructed point targets or point targets-of-opportunity (see also Appendices 6A and 8).

(ii) RADIOMETRIC ACCURACY

SAR calibration can be defined simply as the transfer function relating the pixel values in the final SAR image to the radar cross-section of the corresponding imaged target. In-flight calibration can be performed using a calibration point target of very stable radar cross-section previously measured accurately under laboratory conditions. A radiometrically accurate SAR system must be well-calibrated, i.e. it must possess only a small absolute calibration (bias) error. In addition, any measurement uncertainties must be small; this necessitates that the system be radiometrically stable with respect to both time and space.

An absolute calibration error occurs due to the uncertainty in the radar cross-section of the calibration target and the instantaneous (random) error in the on-board radar hardware, SAR processor and atmospheric propagation path. This absolute calibration error contributes to the radiometric error in the measured radar cross-sections of all subsequently imaged targets and remains constant until the next calibration. In addition to the absolute calibration error, measurements of the radar cross-sections of arbitrary imaged targets are themselves subject to errors due to short-term and long-term (quasi-static) radiometric instabilities in the on-board radar hardware, SAR processor and atmospheric propagation path. The quasi-static (drift) errors will result in the system becoming increasing inaccurate with time subsequent to calibration: the rate of increase of these quasi-static errors will determine how often the system needs to be calibrated (see Appendix 1B).

Since the propagation path is not strictly part of the SAR system, atmospheric instabilities can be ignored in the specification of a radiometric stability performance parameter for the system. However, any measurement of radiometric stability from SAR imagery must include propagation effects. Radiometric stability is a measure of the amount by which a measurement of radar cross-section is likely to differ from that obtained when the system is in a nominal 'stable' state. Radiometric stability can be determined from in-flight measurements of the standard deviation of the radar echoes from a number of identical point or distributed targets with stable radar cross-sections, of such magnitude that the system is operating within its dynamic range. These targets may be artificially-constructed or targets-of-opportunity. To verify that the SAR system is stable with respect to both time and space, the measurements must be performed on a number of independent occasions at a number of positions along the flight line.

Radiometric stability is dependent on the system noise (thermal and quantisation), the power transfer function or gain characteristic, the antenna gain pattern and processing errors. Radiometric stability is thus a requirement which must be satisfied by the SAR instrument and processor (for ERS-1, the radiometric stability requirement is 0.95 dB). However, the users of the image products are, in fact, interested in the degree of accuracy with which the radar cross-section of an imaged target can be determined. Thus radiometric accuracy is more useful than radiometric stability as an image product performance parameter. The radiometric accuracy of a SAR system at a time t is given by

$$R_a = \langle \sigma_e - \sigma_r \rangle \qquad \text{..... (3.3)}$$

where σ_r is the true radar backscatter value for a calibration target,

σ_e is the radar backscatter value obtained using the calibrated SAR system

and the angle brackets <> denote an average over a number of calibration targets imaged at time t.

The radiometric accuracy of a SAR system is dependent on factors which are hard to quantify, such as atmospheric effects and the ambiguous energy contribution due to bright extended regions situated near to an imaged target. For this reason, no radiometric accuracy requirement has been specified for ERS-1, although a nominal one standard deviation error of 1.1 dB has been estimated [3.7; pg 111]. Appendix 1B outlines the way in which frequent calibration of ERS-1 during the commissioning phase can be used to estimate the temporal variation of radiometric accuracy due to drift errors. Hence the radiometric accuracy can be predicted at any time between calibration observations during the routine imaging phase of the satellite and the maximum interval allowable between calibration observations can be determined.

(iii) RADIOMETRIC RESOLUTION

Radiometric resolution is a measure of the ability of a SAR system to distinguish between uniform regions with different backscatter levels. The standard definition of radiometric resolution is

$$\gamma = 10 \log_{10} \left(1 + \sigma/\mu \right) \qquad \text{..... (3.4)}$$

where μ, σ are, respectively, the sample mean and standard deviation of the signal power in a SAR image of a uniform region.

The value obtained for γ is different in images which include the additive noise signal and images in which the additive noise contribution has been subtracted. Detailed equations are given in Appendix 2B which allow theoretical values of γ to be derived for both noisy and noise-corrected images produced by the incoherent summation of a number of looks of different intensities. However, a measurement of radiometric resolution obtained directly from the final processed imagery is important to verify that the actual value of γ is consistent with the theoretical value. The measurement of γ in processed SAR images involves the determination of μ and σ in verified uniform regions and substitution of the derived values into (3.4). Possible methods for determining γ are discussed in detail in Appendix 2A.

It must be stressed that routine measurement of the radiometric resolution in the processed images must be performed. Deriving a value for γ using the equations given in Appendix 2B is useful if one wishes to verify some aspect of instrument performance (e.g. the level of system noise) but cannot be considered to be a measure of image product quality.

The current method of defining radiometric resolution is not entirely satisfactory as it is difficult for users to relate values of γ to the ability to discriminate between targets with different radar cross-sections (which, after all, is what the users actually wish to know). Recent work at MRC [3.8] has used classical statistical methods to determine the probability of distinguishing between two target regions in an image which are of equal size and have known radar cross-sections. By combining the methods outlined in Appendix 2A and [3.8], it should be possible, if required, to generate for any SAR image a probability curve which gives an estimate of probability of distinguishing between imaged targets as a function of target size and contrast.

(iv) ABSOLUTE LOCALISATION ACCURACY

The absolute localisation accuracy of an image is a measure of the accuracy with which any pixel in the image can be located on the ground. A SAR locates a target in range by the time delay of its radar response and in azimuth by its Doppler history. The SAR processor can use this information, together with orbit and timing data and a suitable earth model, to provide a coarse estimate of the location of an image on the ground. For an airborne SAR, the earth can be assumed flat; for a spaceborne SAR, the curvature of the earth is significant and it is usually assumed to be circular or ellipsoidal. For ERS-1, the Verification Mode Processor will nominally derive the latitude and longitude of the four corners and the centre of each SAR image. The ERS-1 range and azimuth localisation accuracy requirements for this coarse image location are shown in Table 3.1. These requirements can be verified directly by analysis of the radar echoes from a calibration point target and comparison between the location, x_e, of the point target derived by the SAR processor and its location, x_r, as given by 'ground

truth' data. The localisation accuracy, L_a, of the system at a time t is given by:

$$L_a = \langle x_e - x_r \rangle \qquad \ldots\ldots (3.5)$$

where the angle brackets <> denote an average over a number of calibration targets imaged at time t.

In order to perform a more detailed analysis of localisation accuracy in a SAR image, it is necessary to compare the SAR image with a reference image, which is assumed to be free of errors. This reference is typically a Digital Terrain Model (DTM) or a digitised map. In order to compare the SAR image with such reference images, two transformations must be applied to the SAR data: a conversion to ground range co-ordinates using a suitable earth model, followed by a transformation to a specified map projection, e.g. a Universal Transverse Mercator (UTM) projection. Subsequent to these transformations, the image is known as a GEOCODED image. The production of a geocoded image requires precise orbit data, timing data, earth model data and auxiliary processor data.

Users of geocoded images generally require a much greater localisation accuracy than the coarse specification provided by the SAR processor. However, no localisation accuracy requirements have yet been specified for the geocoded image products (although a nominal localisation accuracy error budget is available [3.9]). This is largely attributable to the fact that there is no simple measure of localisation accuracy, which can vary significantly from one region of an image to another. Thus localisation accuracy cannot be represented by a single performance parameter, but rather requires a number of parameters which characterise both systematic and random location errors.

The localisation accuracy of a geocoded image is generally investigated using selected ground control points (GCPs) distributed throughout the image. The positions of these GCPs can be compared with the ground truth positions obtained using the reference image, thus enabling a set of displacement vectors to be determined. The displacement vectors can be used to generate a set of performance parameters which characterise the localisation accuracy of the geocoded image. For example, a set of such parameters might be:

(a) The displacements of the GCPs in the range/azimuth directions as a function of range/azimuth.

(b) Simple polynomial functions fitted to the displacements in range and azimuth.

(c) The standard deviations of the displacements in range and azimuth.

(d) The residual errors of the displacements in range and azimuth with respect to the fitted polynomials.

(a) and (b) characterise systematic errors in localisation (absolute positional errors), while (c) and (d) characterise random errors (residual distortions).

Errors in localisation will arise due to variations in terrain height. Using terrain information obtained from Digital Elevation Models (DEMs), it should be possible to produce a geocoded terrain-corrected image, the localisation accuracy of which could be examined as outlined above.

At present GCPs are located within an image by eye, with the problems of extended operating time and reduced accuracy which this entails. The ultimate aim is that automatic location of GCPs in a geocoded image be achieved using information derived from cartographic data, with a search in the geocoded image performed using correlation techniques (see e.g. [3.10]).

Appendix B - Methodology to calculate the Calibration Constant

Annex C

Evaluation of the Calibration Constant using Point Targets

1. Introduction

For the absolute calibration of ERS SAR Precision image (PRI[1]) products and ERS SAR Single Look Complex Image (SLC[2]) products, a PRI image and respectivelly an SLC image covering the Flevoland calibration site[3] (the Netherlands), are used. These scenes contain the three transponders deployed by ESA for the calibration and validation of the entire imaging chain. The method adapted here, for the evaluation of the calibration constant, is the so called integration method on pixel values. This method consists in integrating the signal intensity of a transponder in a rectangular area whose size is expressed in resolution cells. This summation however also includes the background signal intensity. By averaging the background intensity in a surrounding area free from point targets (whose size is also expressed in terms of resolution cells), this background contribution can be removed.

2. ESA Procedure for the Evaluation of the Calibration Constant

The calibration of SAR data involves the determination of the constant of proportionality K, which relates the pixel value in the image to the radar cross-section, in this case the backscattering coefficient σ^o of the corresponding imaged target in the scene.

$$\langle I \rangle = K(\alpha) \cdot \sigma^o$$

The constant of proportionality, K, also called calibration constant, varies with the incidence angle α (or the depression angle θ). This dependency arises from the physical projection of the system transfer function upon the surface being imaged. The solution adopted by ESA is to determine K at a reference incidence angle. This reference angle coincides with the mid-range incidence angle i.e. $\alpha_{ref} = 23$ degrees. The value $\boldsymbol{K}$ given in ESA SAR PRI and SLC products is thus:

$$\boldsymbol{K} = K(\alpha_{ref} = 23°)$$

To derive a local estimate of the calibration constant K, users should apply the following equation

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

See Annex A of ref.[1] for the evaluation of the local incidence angle α.

1. A PRI product is a multi-look (speckle reduced), ground range projected and system corrected digital SAR image. The product is corrected for the in-flight SAR antenna pattern and compensated for range-spreading loss.
2. A SLC product is a single-look, slant range projected digital SAR image.
3. Data acquisition time 13/10/91 at 21:40:37 for ERS-1 and 4/8/95 at 10:35:01 for ERS-2.

Calibration using ESA Transponders

The ESA procedure used to calculate an estimate of the calibration constant can be described as follows:

* A tile of image data is extracted around the calibration target i.e. an ESA transponder.

* The peak is located in the image tile. The number of pixels contained in a single resolution cell is calculated using the spatial resolutions and the pixel spacings (sample spacing for SLC products), in respectively range and azimuth i.e. the number of pixel in range (azimuth) per resolution cell is the ratio of the range (azimuth) resolution and the range (azimuth) pixel spacing, both expressed in meters.

Product type	SLC	PRI
Range resolution (m)	9.68	10 (in slant range) $10/sin\alpha$ (in ground range)
Azimuth resolution (m)	5.25	22
Range pixel spacing (m)	7.9	12.5
Azimuth pixel spacing (m)	3.98	12.5
Nb of pixels per resolution cell in range	1.22	$0.8/sin\alpha$ (in ground range)
Nb of pixels per resolution cell in azimuth	1.32	1.76

Table 1: Resolutions and pixel (sample) spacings for PRI (SLC) products.

Multiplying the number of pixels per resolution cell by the number of resolution cells NC_c, NC_Δ and NC_d, and rounding the results, yields the number of pixels (in azimuth and range) required in the computation of I_{int} and C, defined bellow.

* The integrated power I_{int} is computed by summing the pixel intensities over a rectangular area centred around the peak or target (transponder IRF) and NC_c (=10) resolution cells in size, see figure 1.

* The background backscatter C is calculated by summing the pixel intensities over four rectangular areas symmetrically positioned around the target, distant NC_d (=10) resolution cells from it and NC_Δ (=20) resolution cells in size, see figure 1.

Examples:

for a PRI image with a point target at mid-range ($\alpha=\alpha_{ref}$), the size of the central area is 21 pixels in range and 18 pixels in azimuth. The size of a background area is 41 pixels in range and 36 pixels in azimuth, and each background area is separated from the target by 21 pixels in range and 18 pixels in azimuth.

For an SLC image, the size of the central area is 13 pixels in range and 14 pixels in azimuth. The size of a background area is 25 pixels in range and 27 pixels in azimuth and each background area is separated from the target by 13 pixels in range and 14 pixels in azimuth.

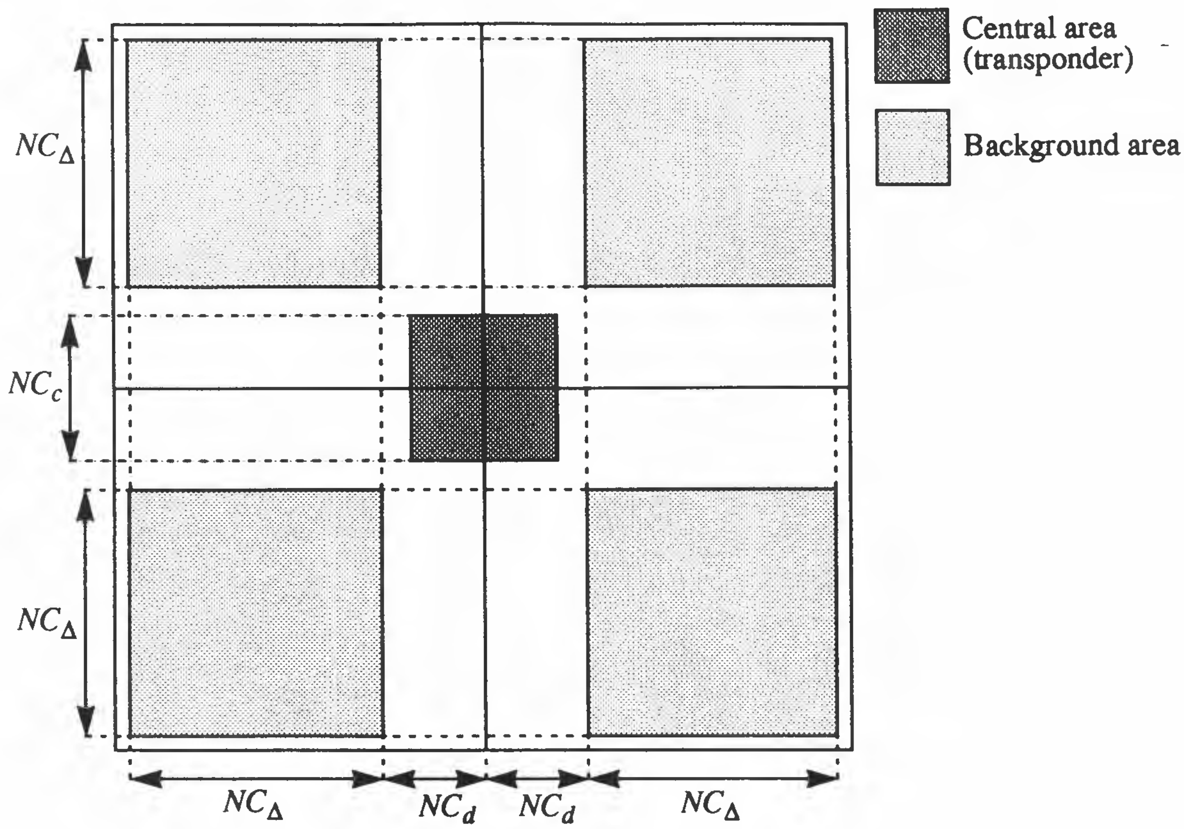

Figure 1. Areas around the target over which the summation of the pixel intensities is required.

The background corrected integrated power is given by:

$$I = I_{int} - \frac{nC}{4m}$$

where n and m denote the total number of pixels in respectively the central area and in one of the background areas. $C/4m$ is the clutter density or average background power (i.e. power per pixel).

* The slant range pixel area, Δa_s, is evaluated:

In the case of a PRI product:

$$\Delta a_s = \Delta x \Delta y \sin \alpha_K$$

where Δx and Δy are the ground range pixel spacings (in metres) in respectivelly range and azimuth, and α_K the incidence angle at the calibration target location.

In the case of an SLC product:

$$\Delta a_s = \Delta x_s \Delta y_s$$

where Δx_s and Δy_s are the slant range pixel spacings (in metres) in respectivelly range and azimuth. The ground range pixel area Δa_{ref} at the reference incidence angle α_{ref} is given by:

$$\Delta a_{ref} = \Delta a_s / \sin \alpha_{ref}$$

* The nominal radar cross section σ of the point target being known a priori, we can determine the calibration constant ***K***.

In the case of a PRI product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma}$$

In the case of an SLC product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma} \cdot \left(\frac{r_K}{r_{ref}}\right)^3 \cdot \frac{1}{g^2(\theta_K)}$$

where r_K and r_{ref} are respectivelly the slant range distance at the target's location and the reference slant range distance (i.e. the mid-swath slant range distance $r_{ref} = 847.0km$), $g^2(\theta)$ is the two-way antenna pattern profile and θ_K is the depression angle at the target's location. These corrections are required because SLC-products are not corrected for antenna elevation gain and range spreading loss.

The different *NC* parameters are chosen such that small variation in these parameters does not affect the calculated calibration constant ***K*** (see figure 2).

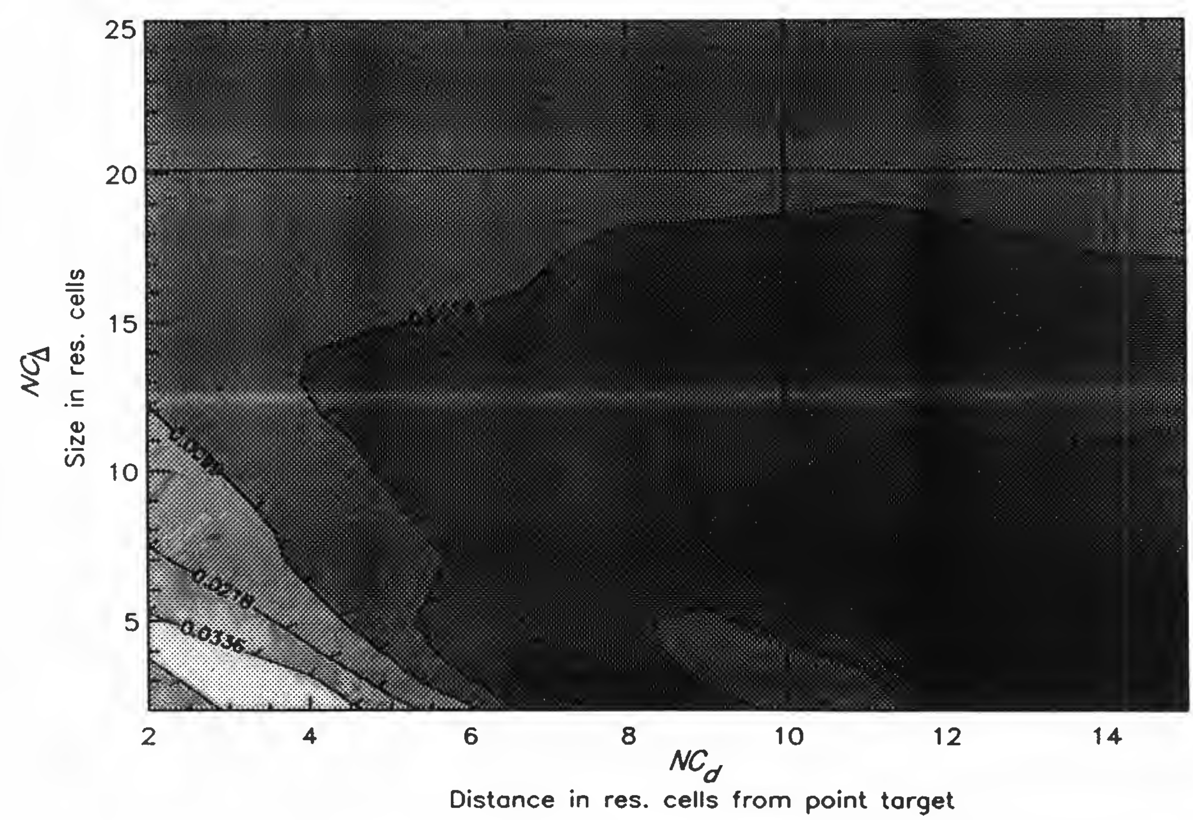

Figure 2. Calibration constant variations (in decibels) as a function of NC_d and NC_Δ.

Symbols

$\langle I \rangle$ is the mean pixel intensity,

K is the calibration constants at the mid-range incidence angle,

σ° is the backscattering coeficient and σ the radar cross section,

α is the incidence angle and $\alpha_{ref} = 23°$ is the reference (at mid-range) incidence angle,

Δy and Δx are respectively the azimuth and range pixel spacings in ground range,

Δy_s and Δx_s are respectively the azimuth and range pixel spacings in slant range,

Δa_s, Δa_{ref} are respectively the slant range pixel area and the ground range pixel area at the reference incidence angle α_{ref},

r and $r_{ref} = 847.0km$ are respectivelly the slant range distance and the reference slant range distance,

$g^2(\theta)$ is the two-way antenna pattern profile and θ is the depression angle,

NC_c and NC_Δ are the sizes in resolution cells of respectively the central area and of one of the background areas (all four areas have identical dimensions). NC_d is the distance in resolution cells separating the point target from each background area.

n is the number of pixels in the central area and m is the number of pixels in each one of the background areas.

I_{int} and C are the sum of the pixel intesities respectively over the central area and over the background area,

I is the background corrected integrated power.

References

Ref.[1]: ERS-1 SAR Calibration.

Derivation of Backscattering coefficient in ERS-1.SAR.PRI products

Henri Laur. Issue 1, Rev. 0, 17th October 1992

Ref.[2]: SAR Geocoding: Data and Systems

Gunter Schreier (ed.)

Karlsruhe: Wichman, 1993. ISBN 3-87907-247-7

Appendix C - Antenna Pattern correction for ERS-1 and ERS-2

Appendix A: The Improved Antenna Pattern

TABLE 4. Improved Antenna Pattern

Degrees (rel. to Boresight)	Power (dB)
-3.1	-1.420
-3.0	-1.245
-2.9	-1.067
-2.8	-0.901
-2.7	-0.746
-2.6	-0.605
-2.5	-0.478
-2.4	-0.365
-2.3	-0.269
-2.2	-0.186
-2.1	-0.116
-2.0	-0.064
-1.9	-0.022
-1.8	0.012
-1.7	0.036
-1.6	0.053
-1.5	0.066
-1.4	0.071
-1.3	0.071
-1.2	0.067
-1.1	0.060
-1.0	0.053
-0.9	0.045
-0.8	0.035
-0.7	0.023
-0.6	0.011
-0.5	0.001
-0.4	-0.009
-0.3	-0.013
-0.2	-0.013
-0.1	-0.009
0.0	0.000

Degrees (rel. to Boresight)	Power (dB)
0.1	0.015
0.2	0.033
0.3	0.056
0.4	0.081
0.5	0.107
0.6	0.133
0.7	0.165
0.8	0.197
0.9	0.231
1.0	0.264
1.1	0.294
1.2	0.317
1.3	0.335
1.4	0.348
1.5	0.356
1.6	0.358
1.7	0.354
1.8	0.343
1.9	0.322
2.0	0.291
2.1	0.249
2.2	0.188
2.3	0.112
2.4	0.023
2.5	-0.085
2.6	-0.209
2.7	-0.334
2.8	-0.485

ERS-2 Antenna Pattern

The first two values are:

- the boresight angle in degrees (angle between satellite nadir & SAR viewing direction)
- the number of samples.

The correction is referenced to boresight angle (20.355 degrees at 0dB attenuation).

The samples which can be used range from -3.3 to 2.8 degrees.

This correction is valid for the whole ERS-2 ground segment and thus can be used in the whole NFS network.

Note : It is recommended to use a linear interpolation of this file

20.355	71
-3.5	0.0000
-3.4	0.0000
-3.3	-2.0168
-3.2	-1.8282
-3.1	-1.5290
-3.0	-1.3058
-2.9	-1.0914
-2.8	-0.9196
-2.7	-0.7612
-2.6	-0.6215
-2.5	-0.5004
-2.4	-0.3915
-2.3	-0.2948
-2.2	-0.2124
-2.1	-0.1423
-2.0	-0.0852
-1.9	-0.0414
-1.8	-0.0098
-1.7	0.0135
-1.6	0.0298
-1.5	0.0403
-1.4	0.0434
-1.3	0.0416
-1.2	0.0365
-1.1	0.0296
-1.0	0.0223
-0.9	0.0124
-0.8	0.0051
-0.7	-0.0007
-0.6	-0.0061
-0.5	-0.0126
-0.4	-0.0105
-0.3	-0.0100
-0.2	-0.0109
-0.1	-0.0088
0.0	0.0000
0.1	0.0128
0.2	0.0307
0.3	0.0529

0.4	0.0770
0.5	0.1033
0.6	0.1296
0.7	0.1588
0.8	0.1876
0.9	0.2166
1.0	0.2434
1.1	0.2655
1.2	0.2880
1.3	0.3091
1.4	0.3219
1.5	0.3271
1.6	0.3264
1.7	0.3099
1.8	0.2810
1.9	0.2449
2.0	0.1968
2.1	0.1368
2.2	0.0676
2.3	-0.0095
2.4	-0.1009
2.5	-0.2120
2.6	-0.3381
2.7	-0.4827
2.8	-0.6359
2.9	0.0000
3.0	0.0000
3.1	0.0000
3.2	0.0000
3.3	0.0000
3.4	0.0000
3.5	0.0000

Appendix D - SAR Single Look Complex Image suitable for Interferometry (Test on processor phase preservation)

Product name	*Product code*
SAR Single Look Complex Image (suitable for interferometry)	**ERS.SAR.SLC-I**

DEFINITION
Single-look, complex, slant-range, full frame digital image generated from raw SAR image mode data with up-to-date (at time of processing) auxiliary parameters. This product is suitable for interferometric applications.

DESCRIPTION
as ERS.SAR.SLC

SPECIFICATIONS
Units: as ERS.SAR.SLC.
Pixel spacing: as ERS.SAR.SLC.
Product size: Full frame, i.e. 4900 samples in range and at least 26000 samples in azimuth.
Data presentation: as ERS.SAR.SLC.
Product localisation: referenced to standard ERS SAR frames.
reported in product annotations: as ERS.SAR.SLC.
Localisation accuracy: as ERS.SAR.SLC.
Spatial resolution: as ERS.SAR.SLC.
Coordinate system: as ERS.SAR.SLC.
Range spectral weighting: as ERS.SAR.SLC.
Number of looks: as ERS.SAR.SLC.
Look bandwidth: as ERS.SAR.SLC.
Look spectral weighting function: as ERS.SAR.SLC.
Azimuth frequencies: not shifted to azimuth baseband, i.e. as ERS.SAR.SLC (the Doppler spectrum is left at the Doppler centroid frequency).
Azimuth reference function: phase of zero at its zero-Doppler point (time origin) and not normalized to the phase at Doppler centroid.
Phase preservation (see annex): the SLC-I product shall be generated with a phase preserving processor. The processor shall verify the phase-preservation tests with the following results:

- the *interferometric offset processing test* with the following results:
  - interferometric phase mean value $\leq$ 0.1 degree,
  - interferometric phase standard deviation (i.e. phase noise) $\leq$ 5 degrees,
  - no obvious phase noise strips shall be observable in the interferogram.
- the *interferometric simulated point target test* with the following results:
  - the phase error at the correlation peaks is $\leq$ 0.1 degree,
  - the phase of the 2-D Fourier transform contains no other terms than linear and constant terms.

Range cell migration artifact: as ERS.SAR.SLC.
Point target geometric mis-registration: as ERS.SAR.SLC.
Processor point target linearity: as ERS.SAR.SLC.

Processor point target linear output dynamic range: as ERS.SAR.SLC.
Processor gain stability: as ERS.SAR.SLC.
Quality parameters: as ERS.SAR.SLC.
Internal calibration: as ERS.SAR.SLC.
Absolute calibration: as ERS.SAR.SLC.

DATA VOLUME

Data set and CEOS superstructure is 531.2 Mbytes.

MEDIUM

Exabyte cassette.

FORMAT

as ERS.SAR.SLC.

NOTES

Notes 1, 4, 5 and 6: as ERS.SAR.SLC

Notes 2 and 3: not applicable for ERS.SAR.SLC-I

ANNEX

Phase preservation processing and testing

[Based on D-PAF DLR Technical Note (R. Bamler & B. Schattler): Phase-Preservation in SAR Processing - Definition, Requirements and Tests, Version 1.0, May 1995.]

1- Phase preservation processing

The processing of SLC-I product shall be phase preserving, which means that the following requirements shall be observed:

1. The azimuth reference function (when represented in the time domain) must have a phase equal to zero at its zero Doppler point (time origin) and must not be normalized to the phase at Doppler centroid.

2. The signal spectrum must not be shifted (i.e. no baseband conversion applied). For the azimuth spectrum, this means that it must be left at the Doppler centroid frequency.

3. The processing parameters varying along the scene must be sufficiently updated to avoid the introduction of focusing errors. All corrections and compensations must be performed with the necessary accuracy to avoid focusing errors (for the Range-Doppler algorithm, this implies a proper FM rate update and a perfect range migration compensation).

4. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) have to be avoided.

5. The Offset Processing Test must be performed with the following results:
   - Mean of the interferometric phase ≤ 0.1 degrees,
   - Standard deviation of the interferometric phase ≤ 5 degrees,
   - No obvious phase noisy strips shall be observable in the interferogram (in particular, this implies that the structure of the processing blocks shall not be distinguished in the phase noise pattern).

6. The Simulated Point Target Test must be performed with the following results:
   - Phase at the correlation peaks ≤ 0.1 degrees,
   - Phase of the 2-D Fourier transform of the focused point target containing only linear terms and a constant.

2- Phase-preservation testing

2.1- Interferometric Offset Processing Test:

<u>Test Principle:</u>

Generate two complex products by processing independently twice the same raw data, but starting at different azimuth and range positions (i.e. the products will be shifted by y lines in azimuth and x samples in range).

Using the same raw data prevents from interferometric phase aberrations (phase bias and standard deviation) due to inherent SAR system effects. The obtained interferometric phase should ideally have a constant phase of zero. Thus, detected phase aberrations will reveal processor induced artifacts.

Practical considerations:

a. Both products must be processed using the same Doppler centroid frequency.

b. The number of offset lines and samples between both products should not be an integer multiple of the processing block dimension (nor in azimuth nor in range). Furthermore if an "overlap & save" technique is used to process the data, the offset value between products should not be either an integer multiple of the number of valid lines (samples in range) of each processed data block.

c. It is recommended that the scene shifts in both directions are chosen in such a way that the relative azimuth and range offset between the products are integer multiples of the azimuth and range sampling intervals respectively. This avoids the coregistration step before interferometry generation, which is critical for the test, since it tends to introduce additional phase noise.

d. A nominal chirp should be used to perform the range compression (an extracted chirp could introduce phase aberrations related to problems inherent to the chirp and/or to the chirp processing inside the processor).

e. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) should be avoided. The interferogram should be generated using non rescaled complex products (i.e. with their floating point representation if available), in order to avoid the quantisation noise associated to the rescaling.

f. The interferometric phase analysed must include areas generated from the same processing block for each generated product as well as areas corresponding to consecutive processing blocks. The statistical values should be independently measured over both areas.

g. As the test is performed with real SAR data, the areas with very low backscattering coefficients (e.g. calm water, shadow effect) should be avoided since the noise level of these areas is already higher in each product of the interferometric pair.

h. The test may also be performed using white circular Gaussian noise as raw data.

2.2- Interferometric Simulated Point Target Test:

Test description.
Simulate a raw data scene with some point targets homogeneously distributed along range and azimuth (locating some of them on processing block boundaries). After processing this scene, analyse the peak phases as well as the 2-D fourier transform of the focused point targets.

Appendix E - State Vectors and Time Correlation for the two ERS-1/2 reference scenes over Flevoland in The Netherlands

ERS-1

PCF Parameters for order number 12344
Input UTC date/time 13-OCT-1991 21:40:37.945

State Vector Type: Restituted
Orbit number: 1273
Orbit Vector Position (metres): 4332915.113000, 68324.403000, 5687762.133000
Orbit Vector Velocity (metres/sec): -5729.388953, -2231.331188, 4380.982972
Orbit Vector UTC: 13-OCT-1991 21:41:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1273
UTC reference: 13-OCT-1991 21:39:27.120
SBT reference: 1971655215
SBT step length (nanoseconds) 3906249

ERS-2

PCF Parameters for order number 44321
Input UTC date/time 04-AUG-1995 10:35:01.383

State Vector Type: Restituted
Orbit number: 1508
Orbit Vector Position (metres): 4323215.082000, 761068.498000, 5652398.402000
Orbit Vector Velocity (metres/sec): 6006.074500, -1104.391748, -4434.628533
Orbit Vector UTC: 04-AUG-1995 10:35:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1508
UTC reference: 04-AUG-1995 10:22:58.542
SBT reference: -1957651866
SBT step length (nanoseconds) 3906249

ERS National & Foreign Stations

SAR processor calibration and products validation plan

This document describes the procedure required for the calibration of SAR processor and validation of products from ERS national & foreign Stations.

Document:	RS/EF97/005/JCB	
Issue:	1.0	
Date:	24-Feb-97	
Prepared:	Jean-Charles Bigot - RS/EF, ESRIN	....
Reviewed:	V. Beruti - H/RS/EF, ESRIN	....
Approved:	M. Albani - H/RS/E, ESRIN	....

1 - Introduction

1.1. Purpose

The purpose of this document is to outline the work to be carried out for the validation of the ERS-1/2 SAR products generated by the ERS-1/2 National & Foreign Stations spread around the world, for the calibration of their SAR processor, and the line of responsibility for the various activities.

The detailed description of the validation and calibration activities are specified later in this document after a short introduction on the ERS ground segment.

It is proposed that a technical report be produced by the station for the validation results of the Station ERS-1/2 SAR products if not already done.

1.2. Scope

The ERS-1/2 National & Foreign Stations spread around the world have different SAR processor build by different companies. The SAR products generated from these SAR processors are quite different from a station to another so that the user may be confused in the variety of products delivered around the world. Thus ERS SAR users should be fully informed on the products delivered by all ERS National & Foreign Station. The validation exercise contributes to reach this goal.

In general, SAR products delivered by the ERS-1/2 NFS should be validated before being distributed as soon as the processor is considered calibrated and tuned. This validation and calibration exercise is necessary prior to the issuing of the products to the users.

The methodologies of the validation of the SAR products and the method to derive the product calibration constant are addressed in ad-hoc documents which are given in the appendixes.

2 - ERS ground segment

2.1. The overall ground segment

The ERS ground segment consists of:

- The Mission Management and Control Center (MMCC) at ESOC, Darmstadt, Germany;
- The Esrin ERS Central Facility (EECF) at Frascati, Italy;
- The real-time ESA Ground Stations (EGS) at Salmijärvi (Sweden), Fucino (Italy), Maspalomas (Canary Islands- Spain), Gatineau and Prince Albert (Canada);
- The Processing and Archiving Facilities (D-PAF) at Oberpfaffenhofen (Germany), F-PAF at Brest (France), I-PAF at Matera (Italy) and UK-PAF at Farnborough (United Kingdom);
- the National Stations - NS - (in ESA Member States) and the Foreign Stations - FS - (in Non-ESA Member States).

2.2. ERS ground stations

2.2.1. Introduction

The ERS-1 orbit - near-polar and sun-synchronous and the need for direct readout of the SAR telemetry have dictated the geographical locations of the ground stations around the world.

All ERS ground stations receive, from the EECF in Frascati, the input data needed to acquire and distribute the SAR data and they report back to the EECF on their station activities and status. These stations generate and distribute products developed nationally to ESA Principal Investigators, Pilot Projects, Research users and Commercial users.

2.2.2. National and Foreign Stations

In addition to the ESA Ground Stations, some national (belonging to countries participating in the ERS program) and some foreign (non-participating countries) ground stations have been set up or are in the process of being set up around the world in order to acquire ERS-1/2 HR data. These stations operate under the terms and conditions of a standard Memorandum of Understanding (MOU) with ESA. This extends the coverage of the SAR operating in Image Mode outside Europe.

The National and Foreign Stations (NFS) are up until end December 1996:

National Stations (NS):

- Aussaguel, France (TO)
- Cordoba (transportable station located in Argentina), Germany (CA)
- Gatineau, Canada (GH)
- Libreville (Transportable station located in Gabon), Germany (LI)
- Malindi, in Kenya for Italy (MA)
- Neustrelitz, Germany (NE)
- O'Higgins, Antartica for Germany (TF)
- Prince Albert, Canada (PH)
- Tromsø, Norway (TS)
- West-Freugh, Scotland, UK (WF)

Foreign Stations (FS):

- Alice Springs, Australia (AS)
- Bangkok,Thailand (TH)
- Beijing, China (BE)
- Chung-Li, Taiwan (TW)
- Cotopaxi, Ecuador (CO)
- Cuiaba, Brazil (CU)

- Fairbanks, Alaska, USA (AF)
- Hatoyama, Japan (HA)
- Hobart, Tasmania, Australia (HO)
- Hyderabad, India (SE)
- Johannesburg, South-Africa (JO)
- Kumamoto, Japan (KU)
- Mac-Murdo, Antartica for USA (MM)
- Norman, Oklahoma, USA (NO)
- Pare-Pare, Indonesia (IN)
- Riyadh, Saudi-Arabia (SA)
- Singapore, Rep. Of Singapore (SG)
- Syowa, Antartica for Japan (SY)
- Tel-Aviv, Israel (IR)

2.3. SAR commercial distribution agreement

ESA has signed an agreement with the ERSC Consortium for the worldwide promotion, marketing and commercial distribution of data from the ERS satellites. Each ERS Consortium's company serves users from a specific area of the world:

- Users in Europe, N. Africa and the Middle East - Eurimage ERS-1 Order Desk
- Users in Canada - Radarsat International ERS-1 Order Desk
- Users in USA and all other countries - Spot Image ERS-1 Order Desk

The ERS Consortium commercializes all data products generated at the ERS ESA Ground Stations (EGS) and at the ERS Processing and Archiving Facilities (PAF). SAR data and images generated at further National and Foreign Stations (NFS) spread around the world are also commercialized by the ERS Consortium, if the customer is outside the country of the station where these data have been received.

Note: All the Principal Investigators (PIs) whose research projects have been accepted by ESA as significant contributions to ERS data exploitation, will continue to get access, directly from ESA-ESRIN, to the data they require to perform their scientific studies.

3 - SAR product validation and SAR processor calibration

3.1. Introduction

Whenever a Station has been granted access to ERS, the technical facilities (Data Acquisition Facility and Data Processing Facility) have to be validated before actual operations take place. The activities concerning the verification of the station itself is twofold:

- Acquisition & Recording validation: the purpose is then to ensure that the station is capable of properly acquiring, recording and archiving SAR raw data in line with ESA standards such as recorder compatibility. This is not the purpose of this document.

- Products validation and processor calibration: the purpose is to ensure that the station is capable of generating SAR products with a quality endorsed by ESA. This is the purpose of this document.

Validation of the SAR products corresponds to the verification of the quality parameters of the products generated by the station.

Calibration of the SAR processor, related to image product (such as the ESA image precision PRI), corresponds to the calculation of the Calibration constant and the application of the Antenna Pattern Correction for ERS-1 and -2.

3.2. Operational procedure

3.2.1. Objectives and responsibilities

The Agency shall ensure that products generated at the national and/or foreign stations are validated for both ERS-1 and ERS-2 missions and eventually that the SAR processors are properly calibrated (on station's request).

The responsibility of the station's operator is to demonstrate the quality of the SAR products generated by its SAR processor while ESA's responsibility is to endorse SAR products for release. This procedure is composed of different phases:

- Initial statement of SAR product quality. The station should provide the specifications of the SAR products;

- Processing of ESA reference data set and generation of products by the station. ESA provides to ground station raw data on CCT or EXA to check the station SAR processor independently of the HDDT ingestion;

- Validation report which includes assessment of quality parameters by the station;

Calibration of the SAR processor by the station (Calibration constant to be calculated and Antenna Pattern correction to be applied) is an optional exercise. As a matter of fact, ESA should check that the calibration is properly done by the station whenever the station has announced that calibrated data is available.

3.2.2. Deliverables by NFS to ESA

During these phases the station has to provide deliverables to ESA

- Information about the SAR processor,

- Detailed SAR products specifications,
- Detailed validation report,
- Sample products on CCT (or EXA) and on slides (with annotations).

3.2.3. Parameters to be evaluated

The parameters to be evaluated for the quality of SAR image are:

- Spatial resolution (range and azimuth) - Point target;
- Peak Sidelobe ratio (range and azimuth) - Point target;
- Integrated Sidelobe ratio - Point target;
- Ambiguity ratio (azimuth) - Point target;
- Radiometric resolution - Distributed target;
- Absolute Localization accuracy - Ground control point;

The definition of these parameters can be found in the document *SAR data Quality Assessment and Rectification*, done by GEC-Marconi Research Centre under ESA contract no. 6635/86/HGE-I found in appendix.

3.2.4. Deliverables by ESA to NFS

For the purpose of the evaluation to be done by ESA, ESRIN send to all NFS after their request:

- Test raw data ERS-1.SAR (orbit 1273, frame 1053 dated 13 Oct. 91) and ERS-2.SAR (orbit 1508, frame 2547 dated 4 Aug. 95) from our reference scene over Flevoland area (ESA test calibration site located in the Netherlands);
- List of the SAR quality parameters needed for the validation of the products, (cf. Appendix A);
- Methodology to calculate the calibration constant (This last document describes the ESA official method to be applied for the calibration of the SAR processor) - (cf. Appendix B);
- Antenna pattern correction for ERS-1 and ERS-2 to be applied (cf. Appendix C);
- Specification of ESA CEOS format if required by the station;

The test raw data are send together with the state vectors (orbital data and time correlation) on CCT or/and EXA from referenced SAR scenes over Flevoland. These data are:

	Date	Orbit	Frame
ERS-1	13 Oct. 1991	1273	1053
ERS-2	04 Aug. 95	1508	2547

The coordinates, electronic delay and RCS (radar cross section) of the three transponders (active radar calibrators) in Flevoland scene are:

Transponder #	Lat DD:MM:SS.sss	Long DD:MM:SS.sss	Delay microsec	RCS
T#1	52:21:59.205	05:09:07.999	1.536	58.39 dBm2
T#2	52:27:28.481	05:31:39.193	1.552	57.69 dBm2
T#3	52:33:17.846	05:40:08.154	1.545	57.85 dBm2

The RCS value is the average of the different calibrations carried out with the transponders at ESTEC.

SAR products processed from these test raw data over the Flevoland calibration site should then be sent to ESRIN for evaluation and validation together with products description and a validation report as stated before.

3.2.5. ESA evaluation

The evaluation, based on the NFS validation report, done by ESA concerns:

- Visual inspection (to detect artifacts);
- Basic measurements (radiometric resolution, impulse response function, localization accuracy);
- Intermediate measurements (dynamic range, point target linearity, radiometric accuracy and radiometric stability);
- Validation of the product's format.

3.2.6. Calibration of SAR Processor

The calibration constant is calculated following the method included in Appendix B. This document has been updated during the ERS2 SAR Commissioning phase. There is no problem to generalize this method to complex data (e.g. SLC product).

In addition the SAR processors should use the SWST (Sample Window Start Time) bias of 6265 nsec both for ERS1 and ERS2 and the antenna pattern correction. Antenna Pattern correction files for ERS-1 and for ERS-2 can be found in Appendix C.

The first two values are the boresight angle (fixed angle between satellite nadir and SAR instrument viewing direction) and the number of samples.

It is recommended to use a linear interpolation of these files.

The correction is referenced to boresight angle (20.355 degrees --> 0dB att). The samples range from -3.3 to 2.8 degrees around the boresight angle.

3.2.7. Validation Report from NFS

A validation report should describe in detail the analysis done by the station to check and ensure the correctness of quality of the products, by mean of a methods described in this document.

It should includes the two following tables at least:

Table 1 -

	ERS-1 T#1	ERS-1 T#2	ERS-1 T#3	ERS-1 Averag e
1 - Impulse response function ■ range spatial resolution (m) ■ azimuth spatial resolution (m) ■ range peak sidelobe ratio (dB) ■ azimuth peak sidelobe ratio (dB) ■ Integrated sidelobe ratio (islr) (dB) ■ Ambiguity ratio (dB)				
2 - Absolute localization accuracy ■ latitude (m) ■ Longitude (m)				
3 - Radiometric resolution (db)				

The same table should be done for ERS-2

Table 2 (optional. Only when calibration exercise is completed) -

Calibration constant for ERS-1	
Calibration constant for ERS-2	

3. 3. Requirements for products

It concerns the following products:

- SAR.RAW,
- SAR.SLC (or similar complex product),
- SAR.PRI (or similar image product),

- SAR.GEC (or similar image geocoded product).

Details of the validation work are given below for each the four products.

3.3.1. SAR.RAW

The following activities have to be planned:

(a) Product header examination,

(b) Statistical analysis of raw data,

(c) Replica Pulse examination.

3.3.2. SAR.SLC

The following activities are planned:

(a) Product header examination,

(b) Image quality assessment based on detected data using the ESA transponders,

(c) Interferometry offset test as described in Appendix D,

(d) Calibration constant and product scaling factor derivation.

3.3.3. SAR.PRI

The majority of the validation work is to be performed using this product type. The following activities are planned as outlined in the paragraph 3.2.3. of this document:

(a) Visual inspection of image for any obvious defects or problems,

(b) Product header examination,

(c) Image quality assessment.

Based on transponders (or natural point targets) the following parameters are to be derived:

- Spatial resolution (azimuth and range)

- Peak, integrated and spurious sidelobe ratios,

- Azimuth ambiguity ratio (assuming low water backscatter in the transponder ambiguity regions)

Based on distributed targets, the following parameters are to be derived:

- Radiometric resolution,

- Noise equivalent sigma nought (assuming low backscatter region available).

(d) Image localization (transponders)

(e) Calibration constant.

3.3.4. SAR.GEC

The requirements for Geocoded products are:

- Analysis of the geometric accuracy for flat area (this should be done for ascending and descending geometry). Originally ESRIN is using Flevoland as reference. The requirement was to have residuals lower than 100 m. Tie points should be regularly selected. At least ten points should be used. It would be better around 20.

- Radiometric characteristics of the GEC should remain unchanged with respect to the non geocoded image. This is done by checking that pixel statistics are the same (mean and standard deviation are sufficient). This allows the calibration of the GEC product in the same way as the PRI.

- Product format verification

- Verification of GEC photo products annotations (if the station produces photo products, of course).

Acronyms and abbreviations

AMI	Active Microwave Instrument
D-PAF	The German PAF
EECF	Esrin ERS Central Facility
ERS	European Remote Sensing satellite
ERS-1	European Remote Sensing satellite 1
ERS-2	European Remote Sensing satellite 2
F-PAF	The French PAF
HDDT	High Density Digital Tape
HBR	High Bit Rate
I-PAF	The Italian PAF
IDHT	Instrument Data Handling and Transmission subsystem
LBR	Low Bit Rate
MOU	Memorandum Of Understanding
MMCC	Mission Management and Control Center
NFS	National and Foreign Stations
PAF	Processing and Archiving Facility
SAR	Synthetic Aperture Radar
SWST	Sample Window Start Time
UK-PAF	The United Kingdom PAF

Appendix A - List of parameters for SAR quality image

SAR PERFORMANCE PARAMETERS

3.1. INTRODUCTION

An image product quality measure or performance parameter provides a numerical characterisation of a particular property of a SAR image, e.g. spatial resolution, radiometric resolution etc. In order to perform a comprehensive assessment of image quality, a set of performance parameters characterising all the important properties of an image is required. These parameters are inter-correlated in such a way that an improvement in one parameter will often lead to a degradation in another. For example, an improvement in radiometric resolution can generally be obtained at the expense of spatial resolution.

The development of an SAR system normally starts with a performance criterion, commonly specified in terms of requirements placed on the image product performance parameters. The performance criterion represents a compromise between the often conflicting requirements of all potential users of the SAR data. In order for the quality of an image to be considered acceptable, the image should, strictly speaking, satisfy all the specified performance requirements. However, whether an image is considered acceptable by a particular user depends in practice on the requirements of that user. For example, a person who wishes to use SAR imagery to discriminate between different crop types may consider as perfectly acceptable an image in which the radiometric accuracy and radiometric resolution satisfy the performance requirements but the spatial resolution does not.

In order to ensure that the image product performance parameters satisfy the user requirements, it is necessary to place requirements on the performance of the on-board radar hardware through the specification of a set of instrument performance parameters. These parameters are verified against the user requirements during an on-ground pre-launch characterisation process, using a combination of testing and analysis. Routine post-launch measurements of the instrument performance parameters should also be performed, where possible; this facilitates accurate calibration of the system response and enables any changes in instrument performance, which might result in degraded image quality, to be detected and, if possible, corrected.

The image product quality is also dependent on the performance of the SAR processor. Thus a number of processor performance parameters must be formulated; the performance of the processor can be assessed from analysis of these parameters in processed images produced from simulated raw data sets.

Performance requirements can also be placed on the raw data signal prior to processing. This avoids unnecessary processing of 'bad' data into images, thus saving on processor time. Evaluation of the raw data quality also aids in determining whether any degradation in image quality is attributable to a change in the performance of the radar hardware or to processing errors.

We shall therefore consider SAR performance parameters under the following four headings:

(i) Image Product Quality
(ii) Raw Data Quality
(iii) Instrument Performance
(iv) Processor Performance

Ideally, a list of all relevant image product performance parameters should be provided with each SAR image. However, for most users' requirements, a subset will suffice. In the case of ERS-1, it is intended that estimates of the peak sidelobe ratio, spatial resolution and radiometric resolution performance parameters will be provided [3.1].

3.2. IMAGE PRODUCT QUALITY

In Table 3.1 we present a complete set of SAR image product performance parameters, together with the performance requirements designated for ERS-1 [3.2; pg 101].

TABLE 3.1

SAR Image Product Performance Parameters & Designated Values for ERS-1

IMAGE PRODUCT PERFORMANCE PARAMETER	ERS-1 REQUIREMENT
(i) IMPULSE RESPONSE FUNCTION	
- RANGE SPATIAL RESOLUTION	$\leqslant$ 26.3 m
- AZIMUTH SPATIAL RESOLUTION	$\leqslant$ 30 m
- RANGE PEAK SIDELOBE RATIO	$\leqslant$ -18 dB
- AZIMUTH PEAK SIDELOBE RATIO	$\leqslant$ -20 dB
- INTEGRATED SIDELOBE RATIO	$\leqslant$ -8 dB
- RANGE AMBIGUITY RATIO	$\leqslant$ -31 dB
- AZIMUTH AMBIGUITY RATIO	$\leqslant$ -25 dB
(ii) RADIOMETRIC STABILITY	$\leqslant$ 0.95 dB
RADIOMETRIC ACCURACY	--
(iii) RADIOMETRIC RESOLUTION	$\leqslant$ 2.5 dB for a target with radar cross-section 10.7 dBm^2 (Noise subtraction performed)
(iv) ABSOLUTE LOCALISATION ACCURACY	
- RANGE	$\leqslant$ 0.9 Km
- AZIMUTH	$\leqslant$ 1.0 Km

We shall now discuss each of these performance parameters in turn. The parameter definitions are from [3.2; pgs 82-87], with additional points taken from [3.2; pgs 175-210] and [3.3; pgs 30-65].

(i) IMPULSE RESPONSE FUNCTION

The impulse response function (IRF) of a SAR system is defined as the 2-dimensional response to a point target, assuming negligible background reflectivity and thermal noise. This performance parameter encompasses a number of separate measures which characterise various properties of the IRF:

(a) Spatial Resolution

The spatial resolution in azimuth/range is in general defined as the -3 dB width of the IRF in the azimuth/range direction. The -3 dB width is the distance between the points on the mainlobe of the IRF which are 3 dB below the peak intensity value.

The ERS-1 range spatial resolution requirement shown in Table 3.1 applies to ground range, not slant range, resolution. The ground range spatial resolution is dependent on the radar incidence angle and thus varies across the imaged swath and around the orbit. The ERS-1 ground range spatial resolution requirement is specified for the mid-swath position in the so-called 'reference geometry' (see [3.2; pgs 75-77]) and is equivalent to a near-swath (worst case) spatial resolution requirement of $\leq$ 30 m. The slant range spatial resolution is independent of swath and orbit position.

The slant range resolution tests the system performance. If the slant range resolution is known, the ground range resolution can be used to test the slant range to ground range interpolator. However, the performance of the interpolator is assessed during routine processor performance testing (see Section 3.5). Thus, in view of the independence of the slant range spatial resolution of both swath and orbit position, it is preferable that measurements of spatial resolution be performed on slant range images.

The azimuthal spatial resolution depends on the along-track velocity of the beam over the ground and on the fraction of the full (3 dB width) Doppler bandwidth of the return signal that is processed coherently; it changes only slightly ($\leq$ 1%) across the imaged swath and around the orbit.

(b) Peak Sidelobe Ratio

The peak sidelobe ratio (PSLR) is defined as the ratio of the peak intensity of the most intense sidelobe of the IRF to the peak intensity in the mainlobe of the IRF. For ERS-1, the PSLR requirement applies to a rectangular region, centred on an imaged point target, with sides of length 10x in the azimuth direction and 10y in the range direction, where x and y are the achievable azimuth and range spatial resolutions, respectively. In the event that the first sidelobe of the error-free response is masked by the main lobe of the error-included response (i.e. there is no detectable minimum between the centre of the IRF and the first sidelobe position), then the intensity at the position corresponding to the first sidelobe in the error-free case will be used for PSLR determination [3.2].

(c) Integrated Sidelobe Ratio

The integrated sidelobe ratio (ISLR) is a measure of the ratio of the energy in the sidelobes of the IRF to the energy in the mainlobe. For ERS-1, the ISLR is defined as the ratio of the energy within an area bounded by a rectangle, centred on an imaged point target, with sides of length 20x and 20y in the azimuth and range directions, respectively, but outside a rectangle, centred on the point target, with sides of length 2x and 2y in the azimuth and range directions, to the energy within the second rectangle.

(d) Ambiguity Ratio

A SAR system is unable to distinguish between radar echoes from a desired point target at a slant range R and radar echoes from point targets (range ambiguities) lying on the same azimuth line at slant ranges R_{AMB}, where

$$R_{AMB} = R \pm \frac{mc\ PRI}{2} \qquad \text{..... (3.1)}$$

m is an integer,
c is the speed of light
and PRI is the pulse repetition interval

The system is also unable to distinguish between radar echoes from the desired target and radar echoes from targets (azimuth ambiguities) lying at the same slant range at positions where

$$D_{AMB} = D \pm m\ PRF \qquad \text{..... (3.2)}$$

D is the Doppler frequency of the target
D_{AMB} is the Doppler frequency of the ambiguity
and PRF is the pulse repetition frequency

To prevent a SAR system being fully ambiguous, (i.e. receiving ambiguous returns from within the mainlobe of the antenna pattern) it is essential that the round-trip delay between the reception of radar echoes from the near and far edges of the imaged swath be less than the PRI to avoid range ambiguity and that the IRF be greater than the processed Doppler bandwidth to avoid azimuth ambiguity. Additional suppression of ambiguities is dependent on shaping the antenna pattern, to keep the gain through the sidelobes low, and, to a lesser extent, on processing strategy (see e.g.[3.4]).

For ERS-1, the nominal swath width and processed Doppler bandwidth specify the unambiguous zone. The ambiguous zone is outside this area. The range and azimuth ambiguity ratios for a point target are defined as $10 \log_{10} [\ I_A(ra)/I_T\ ]$ and $10 \log_{10} [\ I_A(az)/I_T\ ]$, respectively, where

I_T is the peak intensity of the SAR system response to a point target P, located within the unambiguous zone.

$I_A(ra)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous range.

$I_A(az)$ is the peak intensity of the SAR system response to a point target of the same radar cross-section as P, located at an ambiguous azimuth.

The range and azimuth ambiguity ratio requirements shown in Table 3.1 are specified for a point target. For a distributed target, the ambiguous energy must be summed over all ambiguous range and azimuth positions, resulting in much higher ambiguity ratios (> -20 dB: see Appendix 1B).

In-flight measurements of each of the IRF performance parameters given above can be performed using artificially-constructed point targets situated on the ground near to the mid-swath position. Since the IRF is not intensity-dependent, the radar cross-sections of such point targets need not be determined accurately. However, in order to minimise distortions of the IRF attributable to system noise and contributions from the local background, a point target must be bright, physically small, isolated and situated on a low-reflectivity, uniform background. The performance parameters can be determined automatically, using a combination of curve characterisation procedures and numerical integration techniques. Interpolation is required to determine the peak intensities of the IRF mainlobe and sidelobes.

Recent work at MRC [3.5], has shown that in order to verify all the IRF requirements specified for ERS-1, the radar cross-section of the point target under consideration must exceed the point target equivalent strength of the background by at least 45 dBm^2. Thus a point target situated on a background of normalised radar cross-section -10 dB must have a radar cross-section of 62 dBm^2 or greater. However, it is possible to obtain an estimate of the spatial resolution alone using point targets with radar cross-sections ~ 20-25 dBm^2 above the background (i.e. ~ 40-50 dBm^2 for backgrounds with normalised radar cross-sections of ~ -10 to 0 dB). Thus it should be possible to use point-like 'targets-of-opportunity' of radar cross-section > 40 dBm^2 to obtain estimates of the spatial resolution in a number of land images. [Unfortunately, very few sea images exhibit any point-like features.] However, the only way of ensuring the presence of point targets suitable for the routine verification of

ALL the IRF requirements is through the use of special artificially-constructed targets e.g. transponders (see also Appendix 4).

In some cases, it may be important to locate point targets-of-opportunity in a SAR image which does not contain any artificially-constructed point targets, in order to estimate the spatial resolution in that image. At present, visual inspection is used routinely to locate possible point targets in SAR images. However, it should be possible to implement an automatic method of locating possible point targets in a SAR image, as follows:-

(a) The image is thresholded, using a threshold pixel intensity I_T, such that any pixel with an intensity $I < I_T$ is set to zero and any pixel with an intensity $I > I_T$ is set to 1.

(b) The image is segmented using standard segmentation techniques and all regions with the desired characteristics (e.g. single pixel regions) are selected for further investigation.

(c) Regions of (say) 7 x 7 pixels in the original image, centred on the pixel positions which have been selected from the thresholded image, are then subjected to a point target validation test (e.g. that outlined in [3.6]) and those (if any) which are accepted by the test are used to estimate the spatial resolution in the image concerned.

Of course, the success of this method in identifying point targets-of-opportunity would have to be investigated thoroughly prior to implementation.

Appendix 6A outlines a possible means of at least partially overcoming the need to locate point targets in SAR images, in order to perform the IRF quality measures, through the use of the coherent correlation function (CCF). The CCF is the autocorrelation function of the complex SAR image and thus can be obtained directly from the complex image of a scene. The determination of the CCF does not require the presence of point-like features in an image and can be achieved using automatic techniques.

It is not possible to recover unambiguously the IRF which gives rise to a particular CCF. Thus it is not sensible to attempt to derive the IRF from the CCF. It is, however, possible to make useful image quality measurements directly on the CCF. In order to do this, it is necessary to determine theoretically the CCF corresponding to the 'ideal' IRF and to determine appropriate performance parameters for the resolution, peak sidelobe level etc. of the CCF. Routine automatic measurements can then be performed on the complex data and the relevant performance parameters

measured. Should these routine measurements reveal a significant change in the CCF, indicating a possible degradation in the IRF, measurements should then be performed on the IRF using images containing artificially constructed point targets or point targets-of-opportunity (see also Appendices 6A and 8).

(ii) RADIOMETRIC ACCURACY

SAR calibration can be defined simply as the transfer function relating the pixel values in the final SAR image to the radar cross-section of the corresponding imaged target. In-flight calibration can be performed using a calibration point target of very stable radar cross-section previously measured accurately under laboratory conditions. A radiometrically accurate SAR system must be well-calibrated, i.e. it must possess only a small absolute calibration (bias) error. In addition, any measurement uncertainties must be small; this necessitates that the system be radiometrically stable with respect to both time and space.

An absolute calibration error occurs due to the uncertainty in the radar cross-section of the calibration target and the instantaneous (random) error in the on-board radar hardware, SAR processor and atmospheric propagation path. This absolute calibration error contributes to the radiometric error in the measured radar cross-sections of all subsequently imaged targets and remains constant until the next calibration. In addition to the absolute calibration error, measurements of the radar cross-sections of arbitrary imaged targets are themselves subject to errors due to short-term and long-term (quasi-static) radiometric instabilities in the on-board radar hardware, SAR processor and atmospheric propagation path. The quasi-static (drift) errors will result in the system becoming increasing inaccurate with time subsequent to calibration: the rate of increase of these quasi-static errors will determine how often the system needs to be calibrated (see Appendix 1B).

Since the propagation path is not strictly part of the SAR system, atmospheric instabilities can be ignored in the specification of a radiometric stability performance parameter for the system. However, any measurement of radiometric stability from SAR imagery must include propagation effects. Radiometric stability is a measure of the amount by which a measurement of radar cross-section is likely to differ from that obtained when the system is in a nominal 'stable' state. Radiometric stability can be determined from in-flight measurements of the standard deviation of the radar echoes from a number of identical point or distributed targets with stable radar cross-sections, of such magnitude that the system is operating within its dynamic range. These targets may be artificially-constructed or targets-of-opportunity. To verify that the SAR system is stable with respect to both time and space, the measurements must be performed on a number of independent occasions at a number of positions along the flight line.

Radiometric stability is dependent on the system noise (thermal and quantisation), the power transfer function or gain characteristic, the antenna gain pattern and processing errors. Radiometric stability is thus a requirement which must be satisfied by the SAR instrument and processor (for ERS-1, the radiometric stability requirement is 0.95 dB). However, the users of the image products are, in fact, interested in the degree of accuracy with which the radar cross-section of an imaged target can be determined. Thus radiometric accuracy is more useful than radiometric stability as an image product performance parameter. The radiometric accuracy of a SAR system at a time t is given by

$$R_a = \langle \sigma_e - \sigma_r \rangle \qquad \text{..... (3.3)}$$

where σ_r is the true radar backscatter value for a calibration target,

σ_e is the radar backscatter value obtained using the calibrated SAR system

and the angle brackets $\langle\rangle$ denote an average over a number of calibration targets imaged at time t.

The radiometric accuracy of a SAR system is dependent on factors which are hard to quantify, such as atmospheric effects and the ambiguous energy contribution due to bright extended regions situated near to an imaged target. For this reason, no radiometric accuracy requirement has been specified for ERS-1, although a nominal one standard deviation error of 1.1 dB has been estimated [3.7; pg 111]. Appendix 1B outlines the way in which frequent calibration of ERS-1 during the commissioning phase can be used to estimate the temporal variation of radiometric accuracy due to drift errors. Hence the radiometric accuracy can be predicted at any time between calibration observations during the routine imaging phase of the satellite and the maximum interval allowable between calibration observations can be determined.

(iii) RADIOMETRIC RESOLUTION

Radiometric resolution is a measure of the ability of a SAR system to distinguish between uniform regions with different backscatter levels. The standard definition of radiometric resolution is

$$\gamma = 10 \log_{10} \left(1 + \sigma/\mu \right) \qquad \text{..... (3.4)}$$

where μ, σ are, respectively, the sample mean and standard deviation of the signal power in a SAR image of a uniform region.

The value obtained for γ is different in images which include the additive noise signal and images in which the additive noise contribution has been subtracted. Detailed equations are given in Appendix 2B which allow theoretical values of γ to be derived for both noisy and noise-corrected images produced by the incoherent summation of a number of looks of different intensities. However, a measurement of radiometric resolution obtained directly from the final processed imagery is important to verify that the actual value of γ is consistent with the theoretical value. The measurement of γ in processed SAR images involves the determination of μ and σ in verified uniform regions and substitution of the derived values into (3.4). Possible methods for determining γ are discussed in detail in Appendix 2A.

It must be stressed that routine measurement of the radiometric resolution in the processed images must be performed. Deriving a value for γ using the equations given in Appendix 2B is useful if one wishes to verify some aspect of instrument performance (e.g. the level of system noise) but cannot be considered to be a measure of image product quality.

The current method of defining radiometric resolution is not entirely satisfactory as it is difficult for users to relate values of γ to the ability to discriminate between targets with different radar cross-sections (which, after all, is what the users actually wish to know). Recent work at MRC [3.8] has used classical statistical methods to determine the probability of distinguishing between two target regions in an image which are of equal size and have known radar cross-sections. By combining the methods outlined in Appendix 2A and [3.8], it should be possible, if required, to generate for any SAR image a probability curve which gives an estimate of probability of distinguishing between imaged targets as a function of target size and contrast.

(iv) ABSOLUTE LOCALISATION ACCURACY

The absolute localisation accuracy of an image is a measure of the accuracy with which any pixel in the image can be located on the ground. A SAR locates a target in range by the time delay of its radar response and in azimuth by its Doppler history. The SAR processor can use this information, together with orbit and timing data and a suitable earth model, to provide a coarse estimate of the location of an image on the ground. For an airborne SAR, the earth can be assumed flat; for a spaceborne SAR, the curvature of the earth is significant and it is usually assumed to be circular or ellipsoidal. For ERS-1, the Verification Mode Processor will nominally derive the latitude and longitude of the four corners and the centre of each SAR image. The ERS-1 range and azimuth localisation accuracy requirements for this coarse image location are shown in Table 3.1. These requirements can be verified directly by analysis of the radar echoes from a calibration point target and comparison between the location, x_e, of the point target derived by the SAR processor and its location, x_r, as given by 'ground

truth' data. The localisation accuracy, L_a, of the system at a time t is given by:

$$L_a = \langle x_e - x_r \rangle \qquad \text{..... (3.5)}$$

where the angle brackets <> denote an average over a number of calibration targets imaged at time t.

In order to perform a more detailed analysis of localisation accuracy in a SAR image, it is necessary to compare the SAR image with a reference image, which is assumed to be free of errors. This reference is typically a Digital Terrain Model (DTM) or a digitised map. In order to compare the SAR image with such reference images, two transformations must be applied to the SAR data: a conversion to ground range co-ordinates using a suitable earth model, followed by a transformation to a specified map projection, e.g. a Universal Transverse Mercator (UTM) projection. Subsequent to these transformations, the image is known as a GEOCODED image. The production of a geocoded image requires precise orbit data, timing data, earth model data and auxiliary processor data.

Users of geocoded images generally require a much greater localisation accuracy than the coarse specification provided by the SAR processor. However, no localisation accuracy requirements have yet been specified for the geocoded image products (although a nominal localisation accuracy error budget is available [3.9]). This is largely attributable to the fact that there is no simple measure of localisation accuracy, which can vary significantly from one region of an image to another. Thus localisation accuracy cannot be represented by a single performance parameter, but rather requires a number of parameters which characterise both systematic and random location errors.

The localisation accuracy of a geocoded image is generally investigated using selected ground control points (GCPs) distributed throughout the image. The positions of these GCPs can be compared with the ground truth positions obtained using the reference image, thus enabling a set of displacement vectors to be determined. The displacement vectors can be used to generate a set of performance parameters which characterise the localisation accuracy of the geocoded image. For example, a set of such parameters might be:

(a) The displacements of the GCPs in the range/azimuth directions as a function of range/azimuth.

(b) Simple polynomial functions fitted to the displacements in range and azimuth.

(c) The standard deviations of the displacements in range and azimuth.

(d) The residual errors of the displacements in range and azimuth with respect to the fitted polynomials.

(a) and (b) characterise systematic errors in localisation (absolute positional errors), while (c) and (d) characterise random errors (residual distortions).

Errors in localisation will arise due to variations in terrain height. Using terrain information obtained from Digital Elevation Models (DEMs), it should be possible to produce a geocoded terrain-corrected image, the localisation accuracy of which could be examined as outlined above.

At present GCPs are located within an image by eye, with the problems of extended operating time and reduced accuracy which this entails. The ultimate aim is that automatic location of GCPs in a geocoded image be achieved using information derived from cartographic data, with a search in the geocoded image performed using correlation techniques (see e.g. [3.10]).

Appendix B - Methodology to calculate the Calibration Constant

Annex C

Evaluation of the Calibration Constant using Point Targets

1. Introduction

For the absolute calibration of ERS SAR Precision image (PRI[1]) products and ERS SAR Single Look Complex Image (SLC[2]) products, a PRI image and respectivelly an SLC image covering the Flevoland calibration site[3] (the Netherlands), are used. These scenes contain the three transponders deployed by ESA for the calibration and validation of the entire imaging chain. The method adapted here, for the evaluation of the calibration constant, is the so called integration method on pixel values. This method consists in integrating the signal intensity of a transponder in a rectangular area whose size is expressed in resolution cells. This summation however also includes the background signal intensity. By averaging the background intensity in a surrounding area free from point targets (whose size is also expressed in terms of resolution cells), this background contribution can be removed.

2. ESA Procedure for the Evaluation of the Calibration Constant

The calibration of SAR data involves the determination of the constant of proportionality K, which relates the pixel value in the image to the radar cross-section, in this case the backscattering coefficient σ° of the corresponding imaged target in the scene.

$$\langle I \rangle = K(\alpha) \cdot \sigma^\circ$$

The constant of proportionality, K, also called calibration constant, varies with the incidence angle α (or the depression angle θ). This dependency arises from the physical projection of the system transfer function upon the surface being imaged. The solution adopted by ESA is to determine K at a reference incidence angle. This reference angle coincides with the mid-range incidence angle i.e. $\alpha_{ref} = 23$ degrees. The value $\boldsymbol{K}$ given in ESA SAR PRI and SLC products is thus:

$$\boldsymbol{K} = K(\alpha_{ref} = 23°)$$

To derive a local estimate of the calibration constant K, users should apply the following equation

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

See Annex A of ref.[1] for the evaluation of the local incidence angle α.

1. A PRI product is a multi-look (speckle reduced), ground range projected and system corrected digital SAR image. The product is corrected for the in-flight SAR antenna pattern and compensated for range-spreading loss.
2. A SLC product is a single-look, slant range projected digital SAR image.
3. Data acquisition time 13/10/91 at 21:40:37 for ERS-1 and 4/8/95 at 10:35:01 for ERS-2.

Calibration using ESA Transponders

The ESA procedure used to calculate an estimate of the calibration constant can be described as follows:

* A tile of image data is extracted around the calibration target i.e. an ESA transponder.

* The peak is located in the image tile. The number of pixels contained in a single resolution cell is calculated using the spatial resolutions and the pixel spacings (sample spacing for SLC products), in respectively range and azimuth i.e. the number of pixel in range (azimuth) per resolution cell is the ratio of the range (azimuth) resolution and the range (azimuth) pixel spacing, both expressed in meters.

Product type	SLC	PRI
Range resolution (m)	9.68	10 (in slant range) $10/\sin\alpha$ (in ground range)
Azimuth resolution (m)	5.25	22
Range pixel spacing (m)	7.9	12.5
Azimuth pixel spacing (m)	3.98	12.5
Nb of pixels per resolution cell in range	1.22	$0.8/\sin\alpha$ (in ground range)
Nb of pixels per resolution cell in azimuth	1.32	1.76

Table 1: Resolutions and pixel (sample) spacings for PRI (SLC) products.

Multiplying the number of pixels per resolution cell by the number of resolution cells NC_c , NC_Δ and NC_d, and rounding the results, yields the number of pixels (in azimuth and range) required in the computation of I_{int} and C, defined bellow.

* The integrated power I_{int} is computed by summing the pixel intensities over a rectangular area centred around the peak or target (transponder IRF) and NC_c (=10) resolution cells in size, see figure 1.

* The background backscatter C is calculated by summing the pixel intensities over four rectangular areas symmetrically positioned around the target, distant NC_d (=10) resolution cells from it and NC_Δ (=20) resolution cells in size, see figure 1.

Examples:

for a PRI image with a point target at mid-range (α=α_{ref}), the size of the central area is 21 pixels in range and 18 pixels in azimuth. The size of a background area is 41 pixels in range and 36 pixels in azimuth, and each background area is separated from the target by 21 pixels in range and 18 pixels in azimuth.

For an SLC image, the size of the central area is 13 pixels in range and 14 pixels in azimuth. The size of a background area is 25 pixels in range and 27 pixels in azimuth and each background area is separated from the target by 13 pixels in range and 14 pixels in azimuth.

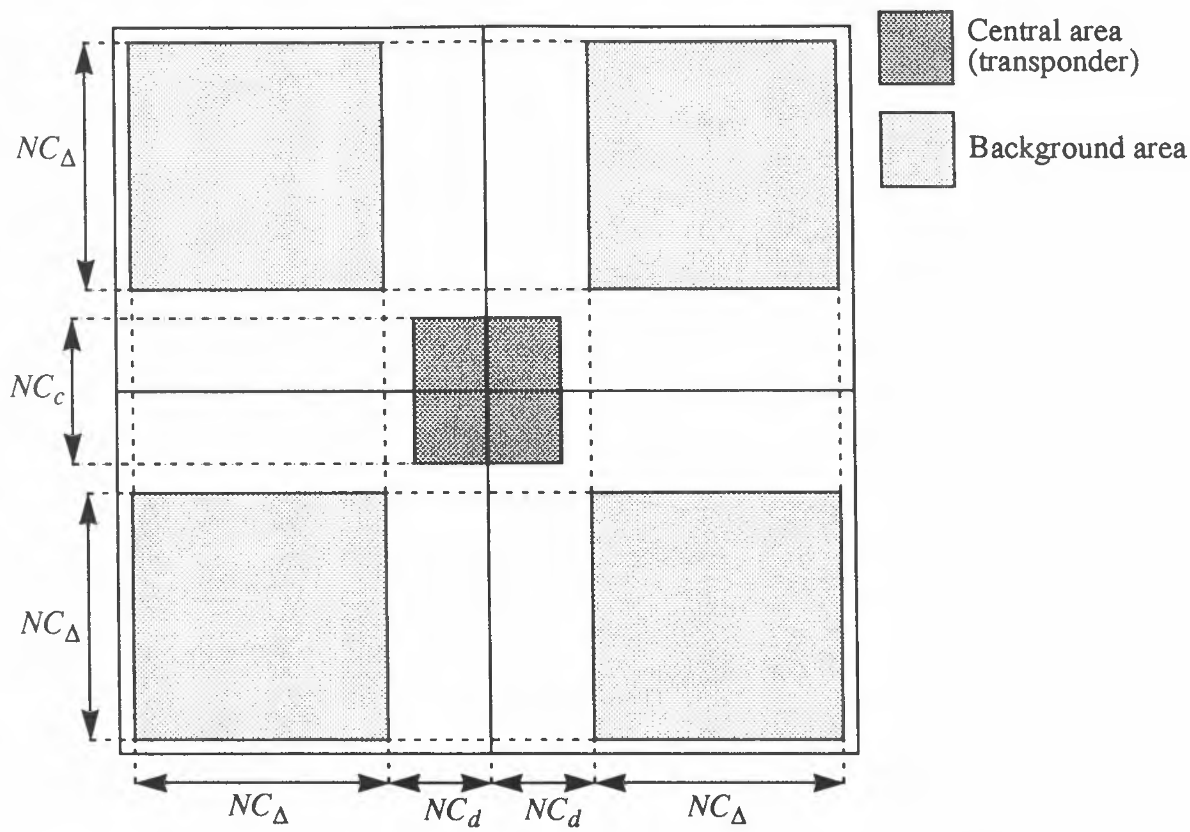

Figure 1. Areas around the target over which the summation of the pixel intensities is required.

The background corrected integrated power is given by:

$$I = I_{int} - \frac{nC}{4m}$$

where n and m denote the total number of pixels in respectively the central area and in one of the background areas. $C/4m$ is the clutter density or average background power (i.e. power per pixel).

* The slant range pixel area, Δa_s, is evaluated:

In the case of a PRI product:

$$\Delta a_s = \Delta x \Delta y \sin\alpha_K$$

where Δx and Δy are the ground range pixel spacings (in metres) in respectivelly range and azimuth, and α_K the incidence angle at the calibration target location.

In the case of an SLC product:

$$\Delta a_s = \Delta x_s \Delta y_s$$

where Δx_s and Δy_s are the slant range pixel spacings (in metres) in respectivelly range and azimuth. The ground range pixel area Δa_{ref} at the reference incidence angle α_{ref} is given by:

$$\Delta a_{ref} = \Delta a_s / \sin\alpha_{ref}$$

* The nominal radar cross section σ of the point target being known a priori, we can determine the calibration constant $\boldsymbol{K}$.

In the case of a PRI product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma}$$

In the case of an SLC product:

$$\boldsymbol{K} = I \cdot \Delta a_{ref} \cdot \frac{1}{\sigma} \cdot \left(\frac{r_K}{r_{ref}}\right)^3 \cdot \frac{1}{g^2(\theta_K)}$$

where r_K and r_{ref} are respectivelly the slant range distance at the target's location and the reference slant range distance (i.e. the mid-swath slant range distance $r_{ref} = 847.0km$), $g^2(\theta)$ is the two-way antenna pattern profile and θ_K is the depression angle at the target's location. These corrections are required because SLC-products are not corrected for antenna elevation gain and range spreading loss.

The different *NC* parameters are chosen such that small variation in these parameters does not affect the calculated calibration constant $\boldsymbol{K}$ (see figure 2).

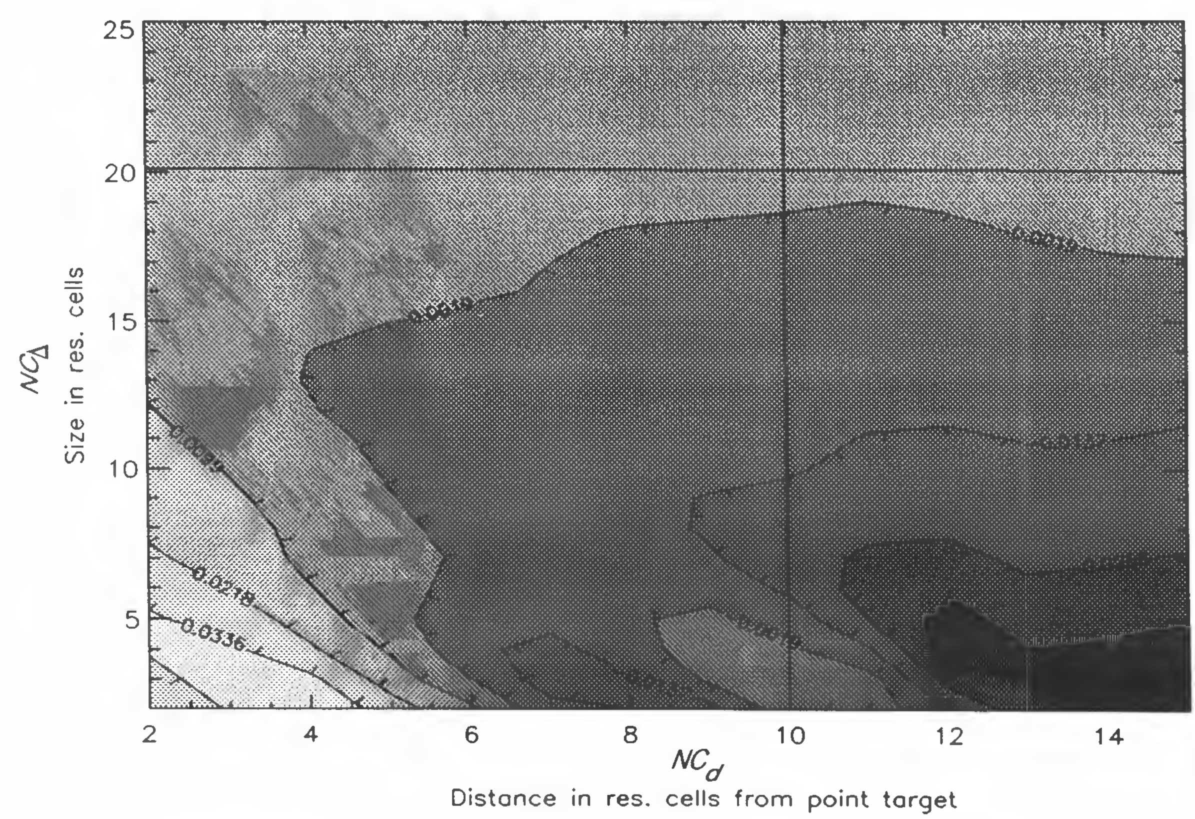

Figure 2. Calibration constant variations (in decibels) as a function of NC_d and NC_Δ.

Symbols

$\langle I \rangle$ is the mean pixel intensity,

K is the calibration constants at the mid-range incidence angle,

σ° is the backscattering coeficient and σ the radar cross section,

α is the incidence angle and $\alpha_{ref} = 23°$ is the reference (at mid-range) incidence angle,

Δy and Δx are respectively the azimuth and range pixel spacings in ground range,

Δy_s and Δx_s are respectively the azimuth and range pixel spacings in slant range,

Δa_s, Δa_{ref} are respectively the slant range pixel area and the ground range pixel area at the reference incidence angle α_{ref},

r and $r_{ref} = 847.0km$ are respectivelly the slant range distance and the reference slant range distance,

$g^2(\theta)$ is the two-way antenna pattern profile and θ is the depression angle,

NC_c and NC_Δ are the sizes in resolution cells of respectively the central area and of one of the background areas (all four areas have identical dimensions). NC_d is the distance in resolution cells separating the point target from each background area.

n is the number of pixels in the central area and m is the number of pixels in each one of the background areas.

I_{int} and C are the sum of the pixel intesities respectively over the central area and over the background area,

I is the background corrected integrated power.

References

Ref.[1]: ERS-1 SAR Calibration.

Derivation of Backscattering coefficient in ERS-1.SAR.PRI products

Henri Laur. Issue 1, Rev. 0, 17th October 1992

Ref.[2]: SAR Geocoding: Data and Systems

Gunter Schreier (ed.)

Karlsruhe: Wichman, 1993. ISBN 3-87907-247-7

Appendix C - Antenna Pattern correction for ERS-1 and ERS-2

Appendix A: The Improved Antenna Pattern

TABLE 4. Improved Antenna Pattern

Degrees (rel. to Boresight)	Power (dB)
-3.1	-1.420
-3.0	-1.245
-2.9	-1.067
-2.8	-0.901
-2.7	-0.746
-2.6	-0.605
-2.5	-0.478
-2.4	-0.365
-2.3	-0.269
-2.2	-0.186
-2.1	-0.116
-2.0	-0.064
-1.9	-0.022
-1.8	0.012
-1.7	0.036
-1.6	0.053
-1.5	0.066
-1.4	0.071
-1.3	0.071
-1.2	0.067
-1.1	0.060
-1.0	0.053
-0.9	0.045
-0.8	0.035
-0.7	0.023
-0.6	0.011
-0.5	0.001
-0.4	-0.009
-0.3	-0.013
-0.2	-0.013
-0.1	-0.009
0.0	0.000

Degrees (rel. to Boresight)	Power (dB)
0.1	0.015
0.2	0.033
0.3	0.056
0.4	0.081
0.5	0.107
0.6	0.133
0.7	0.165
0.8	0.197
0.9	0.231
1.0	0.264
1.1	0.294
1.2	0.317
1.3	0.335
1.4	0.348
1.5	0.356
1.6	0.358
1.7	0.354
1.8	0.343
1.9	0.322
2.0	0.291
2.1	0.249
2.2	0.188
2.3	0.112
2.4	0.023
2.5	-0.085
2.6	-0.209
2.7	-0.334
2.8	-0.485

ERS-2 Antenna Pattern

The first two values are:

- the boresight angle in degrees (angle between satellite nadir & SAR viewing direction)
- the number of samples.

The correction is referenced to boresight angle (20.355 degrees at 0dB attenuation).

The samples which can be used range from -3.3 to 2.8 degrees.

This correction is valid for the whole ERS-2 ground segment and thus can be used in the whole NFS network.

Note : It is recommended to use a linear interpolation of this file

20.355	71
-3.5	0.0000
-3.4	0.0000
-3.3	-2.0168
-3.2	-1.8282
-3.1	-1.5290
-3.0	-1.3058
-2.9	-1.0914
-2.8	-0.9196
-2.7	-0.7612
-2.6	-0.6215
-2.5	-0.5004
-2.4	-0.3915
-2.3	-0.2948
-2.2	-0.2124
-2.1	-0.1423
-2.0	-0.0852
-1.9	-0.0414
-1.8	-0.0098
-1.7	0.0135
-1.6	0.0298
-1.5	0.0403
-1.4	0.0434
-1.3	0.0416
-1.2	0.0365
-1.1	0.0296
-1.0	0.0223
-0.9	0.0124
-0.8	0.0051
-0.7	-0.0007
-0.6	-0.0061
-0.5	-0.0126
-0.4	-0.0105
-0.3	-0.0100
-0.2	-0.0109
-0.1	-0.0088
0.0	0.0000
0.1	0.0128
0.2	0.0307
0.3	0.0529

0.4	0.0770
0.5	0.1033
0.6	0.1296
0.7	0.1588
0.8	0.1876
0.9	0.2166
1.0	0.2434
1.1	0.2655
1.2	0.2880
1.3	0.3091
1.4	0.3219
1.5	0.3271
1.6	0.3264
1.7	0.3099
1.8	0.2810
1.9	0.2449
2.0	0.1968
2.1	0.1368
2.2	0.0676
2.3	-0.0095
2.4	-0.1009
2.5	-0.2120
2.6	-0.3381
2.7	-0.4827
2.8	-0.6359
2.9	0.0000
3.0	0.0000
3.1	0.0000
3.2	0.0000
3.3	0.0000
3.4	0.0000
3.5	0.0000

Appendix D - SAR Single Look Complex Image suitable for Interferometry (Test on processor phase preservation)

Product name *Product code*

SAR Single Look Complex Image (suitable for interferometry) **ERS.SAR.SLC-I**

DEFINITION

Single-look, complex, slant-range, full frame digital image generated from raw SAR image mode data with up-to-date (at time of processing) auxiliary parameters. This product is suitable for interferometric applications.

DESCRIPTION

as ERS.SAR.SLC

SPECIFICATIONS

Units: as ERS.SAR.SLC.
Pixel spacing: as ERS.SAR.SLC.
Product size: Full frame, i.e. 4900 samples in range and at least 26000 samples in azimuth.
Data presentation: as ERS.SAR.SLC.
Product localisation: referenced to standard ERS SAR frames.
reported in product annotations: as ERS.SAR.SLC.
Localisation accuracy: as ERS.SAR.SLC.
Spatial resolution: as ERS.SAR.SLC.
Coordinate system: as ERS.SAR.SLC.
Range spectral weighting: as ERS.SAR.SLC.
Number of looks: as ERS.SAR.SLC.
Look bandwidth: as ERS.SAR.SLC.
Look spectral weighting function: as ERS.SAR.SLC.
Azimuth frequencies: not shifted to azimuth baseband, i.e. as ERS.SAR.SLC (the Doppler spectrum is left at the Doppler centroid frequency).
Azimuth reference function: phase of zero at its zero-Doppler point (time origin) and not normalized to the phase at Doppler centroid.
Phase preservation (see annex): the SLC-I product shall be generated with a phase preserving processor. The processor shall verify the phase-preservation tests with the following results:

- the *interferometric offset processing test* with the following results:
  - interferometric phase mean value $\leq$ 0.1 degree,
  - interferometric phase standard deviation (i.e. phase noise) $\leq$ 5 degrees,
  - no obvious phase noise strips shall be observable in the interferogram.
- the *interferometric simulated point target test* with the following results:
  - the phase error at the correlation peaks is $\leq$ 0.1 degree,
  - the phase of the 2-D Fourier transform contains no other terms than linear and constant terms.

Range cell migration artifact: as ERS.SAR.SLC.
Point target geometric mis-registration: as ERS.SAR.SLC.
Processor point target linearity: as ERS.SAR.SLC.

Processor point target linear output dynamic range: as ERS.SAR.SLC.
Processor gain stability: as ERS.SAR.SLC.
Quality parameters: as ERS.SAR.SLC.
Internal calibration: as ERS.SAR.SLC.
Absolute calibration: as ERS.SAR.SLC.

DATA VOLUME

Data set and CEOS superstructure is 531.2 Mbytes.

MEDIUM

Exabyte cassette.

FORMAT

as ERS.SAR.SLC.

NOTES

Notes 1, 4, 5 and 6: as ERS.SAR.SLC

Notes 2 and 3: not applicable for ERS.SAR.SLC-I

ANNEX

Phase preservation processing and testing

[Based on D-PAF DLR Technical Note (R. Bamler & B. Schattler): Phase-Preservation in SAR Processing - Definition, Requirements and Tests, Version 1.0, May 1995.]

1- Phase preservation processing

The processing of SLC-I product shall be phase preserving, which means that the following requirements shall be observed:

1. The azimuth reference function (when represented in the time domain) must have a phase equal to zero at its zero Doppler point (time origin) and must not be normalized to the phase at Doppler centroid.

2. The signal spectrum must not be shifted (i.e. no baseband conversion applied). For the azimuth spectrum, this means that it must be left at the Doppler centroid frequency.

3. The processing parameters varying along the scene must be sufficiently updated to avoid the introduction of focusing errors. All corrections and compensations must be performed with the necessary accuracy to avoid focusing errors (for the Range-Doppler algorithm, this implies a proper FM rate update and a perfect range migration compensation).

4. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) have to be avoided.

5. The Offset Processing Test must be performed with the following results:
   - Mean of the interferometric phase ≤ 0.1 degrees,
   - Standard deviation of the interferometric phase ≤ 5 degrees,
   - No obvious phase noisy strips shall be observable in the interferogram (in particular, this implies that the structure of the processing blocks shall not be distinguished in the phase noise pattern).

6. The Simulated Point Target Test must be performed with the following results:
   - Phase at the correlation peaks ≤ 0.1 degrees,
   - Phase of the 2-D Fourier transform of the focused point target containing only linear terms and a constant.

2- Phase-preservation testing

2.1- Interferometric Offset Processing Test:

<u>Test Principle:</u>

Generate two complex products by processing independently twice the same raw data, but starting at different azimuth and range positions (i.e. the products will be shifted by y lines in azimuth and x samples in range).

Using the same raw data prevents from interferometric phase aberrations (phase bias and standard deviation) due to inherent SAR system effects. The obtained interferometric phase should ideally have a constant phase of zero. Thus, detected phase aberrations will reveal processor induced artifacts.

Practical considerations:

a. Both products must be processed using the same Doppler centroid frequency.

b. The number of offset lines and samples between both products should not be an integer multiple of the processing block dimension (nor in azimuth nor in range). Furthermore if an "overlap & save" technique is used to process the data, the offset value between products should not be either an integer multiple of the number of valid lines (samples in range) of each processed data block.

c. It is recommended that the scene shifts in both directions are chosen in such a way that the relative azimuth and range offset between the products are integer multiples of the azimuth and range sampling intervals respectively. This avoids the coregistration step before interferometry generation, which is critical for the test, since it tends to introduce additional phase noise.

d. A nominal chirp should be used to perform the range compression (an extracted chirp could introduce phase aberrations related to problems inherent to the chirp and/or to the chirp processing inside the processor).

e. Data manipulations which lead to phase corruption (in particular data rescaling and data resampling by short interpolation kernels) should be avoided. The interferogram should be generated using non rescaled complex products (i.e. with their floating point representation if available), in order to avoid the quantisation noise associated to the rescaling.

f. The interferometric phase analysed must include areas generated from the same processing block for each generated product as well as areas corresponding to consecutive processing blocks. The statistical values should be independently measured over both areas.

g. As the test is performed with real SAR data, the areas with very low backscattering coefficients (e.g. calm water, shadow effect) should be avoided since the noise level of these areas is already higher in each product of the interferometric pair.

h. The test may also be performed using white circular Gaussian noise as raw data.

2.2- Interferometric Simulated Point Target Test:

Test description.

Simulate a raw data scene with some point targets homogeneously distributed along range and azimuth (locating some of them on processing block boundaries). After processing this scene, analyse the peak phases as well as the 2-D fourier transform of the focused point targets.

Appendix E - State Vectors and Time Correlation for the two ERS-1/2 reference scenes over Flevoland in The Netherlands

ERS-1

PCF Parameters for order number 12344
Input UTC date/time 13-OCT-1991 21:40:37.945

State Vector Type: Restituted
Orbit number: 1273
Orbit Vector Position (metres): 4332915.113000, 68324.403000, 5687762.133000
Orbit Vector Velocity (metres/sec): -5729.388953, -2231.331188, 4380.982972
Orbit Vector UTC: 13-OCT-1991 21:41:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1273
UTC reference: 13-OCT-1991 21:39:27.120
SBT reference: 1971655215
SBT step length (nanoseconds) 3906249

ERS-2

PCF Parameters for order number 44321
Input UTC date/time 04-AUG-1995 10:35:01.383

State Vector Type: Restituted
Orbit number: 1508
Orbit Vector Position (metres): 4323215.082000, 761068.498000, 5652398.402000
Orbit Vector Velocity (metres/sec): 6006.074500, -1104.391748, -4434.628533
Orbit Vector UTC: 04-AUG-1995 10:35:00.000

Time Correlation Parameters:
Orbit number of available time correlation data: 1508
UTC reference: 04-AUG-1995 10:22:58.542
SBT reference: -1957651866
SBT step length (nanoseconds) 3906249