UWA processing algorithm specification Version 2.0

Guy Brooker ESTEC/NWP

Prepared by: G. Brooker _____

Authorised by: G. Levrini _____

Change History

Revision	Date	Pages	Change	By
Issue 1.0 Draft(a)	28/06/95	All	Combined version 0.9 with SAR FDP UWA specification ER-TN-ESA-GS-0341 **[R9]**	Guy Brooker
Issue 1.0 Draft (f)	02/10/95	All	Updated document with respect to changes discussed in LRDPF Wave Requirements review 7330-SPT-0013/95 on 07/09/95	Guy Brooker
Issue 1.0 Draft (g)	01/11/95	20	Azimuth Cut-off derivation autocovariance function specification.	Guy Brooker
		22	Modified scaling and location of product SPH annotation. Now uses fileds reserved for image use. Larger fields allow simpler unit scales.	
		24	Removed reference to decoding log scaled fields.	
Issue 1.0 Rev 0	07/11/95	None	Draft status removed. No other changes	Guy Brooker

Change bars between Issue 1.0 Draft (e) and Issue 1.0 Rev 0.

Acronyms and Abbreviations

AMI	Active Microwave Instrument
BUFR	Binary Universal Form for Representation (on GTS)
CFE	Customer Furnished Equipment (and software)
DSR	Data Set Record (of ESA FD product)
ERS	European Remote Sensing Satellite(s)
ERSORB	ERS Orbit propagator CFE software
ESA	European Space Agency
FD	Fast Delivery
FDP	Fast Delivery Processor
FFT	Fast Fourier Transform
F-PAF	French PAF
GTS	Global Telecommunication System (of WMO)
IPR	Impulse Response Function
IQ	In-phase & Quadrature components (complex image)
IWA	Intermediate Wave Product
LRDPF	Low Rate Data Processing Facility
LUT	Look Up Table
MMCC	Mission Management and Control Centre
MPH	Main Product Header (of ESA FD product)
MPI	Max Plank Institute
OBRC	On-Board Range Compression
OGRC	On-Ground Range Compression
PAF	Processing and Archive Facilities
PCD	Product Confidence Data
SAR	Synthetic Aperture Radar
SPH	Specific Product Header (of ESA FD product)
STAVIS	Station Visibility CFE software
STF	Static Transfer Function
UWA	SAR wave fast delivery product. Wave spectra
WMO	World Meteorological Organisation

References

R1   ER-SA-MDA-SY-0001   SAR FDP Architectural Design Document.
MDA. Issue 1.0. Dec 2, 1988.

R2   ER-TN-ESA-GS-0050   Improvements of FD Chains Specification.
J.P Guignard et al. Issue 2.20. Oct. 26, 1990.

R3   ER-RS-MDA-GS-5001   SAR FDP Requirements Specification.
MDA. Issue 4.2. May 2, 1991.

R4   ER-TN-ESA-GS-0071   Wave Mode Spectrum Derivation.
J.P Guignard. Issue 2.0. 22 January, 1992

R5   ER-TN-ESA-JP-0014   UWA processing Software Change Request.
J.P Guignard. Version 1.2 May 7, 1992.

R6   ER-TN-ESA-GS-0250   FD Processing modifications during commissioning phase.
J.P Guignard. Version 2.93. May 20, 1992.

R7   ER-IS-EPO-GS-0204   ERS-1 Ground Station Product Specifications.
Earthnet. Issue 2.4. 22 September 1992.

R8   ER-IS-MDA-GS-0020   Kiruna Station to MMCC Interface Specification.
MDA. Issue 7.1. Dec. 15, 1992.

R9   ER-TN-ESA-GS-0341   UWA processing algorithm description
G. Brooker. Issue 1.1. Jan. 19, 1994

R10   ER-MN-ESA-GS-0373   Minutes of Meeting, ERS-1 SAR Wave Algorithm Improvements
G. Brooker. Feb. 23, 1994

1. Introduction

1.1 Scope

This technical note specifies version 2 of the algorithm to derive a SAR wave spectrum product from ERS AMI wave mode data.

This method, UWA v.2.0, aims to improve on previous versions in terms of product content, quality and more rigorous application of signal processing techniques. The significant improvements over UWA v.1.5/1.6 as implemented in the SAR FDP 4.2 and 5.0 include information at shorter and longer wavelengths, correction for a calibration constant and an impulse response function, and the computation of the azimuthal clutter cut-off.

These improvements have been made under the constraint that there should be no impact on the product size and minimal impact on the internal format.

1.2 ERS SAR Wave mode and processing

The ERS SAR wave mode measures the radar reflectivity of the sea surface influenced by ocean waves. The object of this mode is to produce significant wave heights and directional spectra of the ocean waves from small SAR images (imagettes), at a fixed position within the 100 km SAR swath. In wave mode, an imagette is produced every 200 km (or 300km) along track. ERS-1 imagettes have been acquired at near image swath (19.3° incidence angle) until the launch of ERS-2. Since then, the wave swath has been positioned at the centre of the image swath (23° incidence angle) for both satellites.

SAR data acquired in wave mode are recorded on-board the satellite, and transmitted over X-band links to one of the ESA ground stations. Data may be acquired in one of two modes, on-board (OBRC) or on-ground (OGRC) range compression. This data is processed at the ground station to form imagettes, from which SAR spectra are obtained using the algorithm specified herein.

The size of an imagette in azimuth (along track) is 5.12 km (320 pixels). The size in range (across track) depends on the range compression mode used, in OBRC it is approximately 10 km (600 pixels) and in OGRC mode 6 km (400 pixels). Small additional variations in the size of the imaged area are possible, due to the geometry of the earth and orbit, and most significantly the incidence angle of the wave swath within the full 100 km SAR swath. No impact is made on the IWA product size due to these variations. Pixels containing no image data are set to zero. At an incidence angle of 23° the size of a typical image is 300 pixels in azimuth and 500 pixels in range.

The generation of imagettes (IWA) and spectra (UWA) are performed by the SAR FDP installed at ERS ground stations (future versions may use the LRDPF). IWA products are archived onto Exabyte tape, and are sent to the F-PAF. UWA products are distributed over the ERS data network and are archived at ESRIN, ESOC and ESTEC. Raw SAR wave
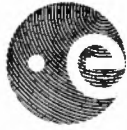
mode data (EWAC) are not archived. A UWA spectrum may be re-generated by re-processing an IWA imagette.

UWA products are distributed to the meteorological community via the GTS. This requires a translation of the ESA UWA product into BUFR format. Software to perform this translation is installed and maintained at ESRIN.

A reference processor developed at ESTEC to test and verify algorithm enhancements is installed at the F-PAF for the reprocessing of IWA products into UWA.

1.3 UWA Algorithm modification history

SAR wave mode processing change history

- *ERS-1 Launch, July 1991. Commissioning Phase* [**R6**]
  UWA v.0.0   SAR FDP version 2.500
  Initial power variance spectrum algorithm [**R1, R4**] installed at ESA ground stations.
  Incorrect due to I and Q swapped on-board. On-board gains set.

- *August 10, 1991*
  UWA v.0.1   SAR FDP version 3.000
  Swap I and Q within the SAR FDP processor when writing raw data into Array Processor cache.

- *August 23, 1991.*
  Wind/Wave OGRC nominal mode.

- *September 23, 1991*
  UWA v.0.2   SAR FDP version 3.200
  Doppler ambiguity fixed using azimuth angle bias in EXT_SAR LUT.
  Processing range compression gain change to remove saturation.
  New on-board gain settings.

- *November 27, 1991*
  Wind/Wave OBRC nominal mode.

- *December 11, 1991, End of ERS-1 Commissioning Phase.*
  UWA v.0.3   SAR FDP version 3.300
  Slope spectra produced (total energy in each wave cell computed, rather than average).
  Doppler centroid confidence calculation corrected. Chirp extraction corrected.
  On-board gains fixed removing saturation from OBRC products.
  Products are considered to be calibrated.

- *April 10, 1992*
  UWA v.0.4   SAR FDP version 3.400
  Return to variance spectra (average energy in each wave cell computed).
  Error in gain reported in product corrected.

- *June 1992- February 1993*
  UWA v.0.5   SAR FDP version 3.500

- *May 1992*
  UWA v.1.0
  Modifications to the Wave processing algorithm were specified [**R5**] in response to improvements requested by the Max Plank Institute Hamburg (MPI), the University of Hamburg and ESA. MPI supplied an implementation (SARIM) of the proposed algorithm. A reference processor UWA v.1.0 was developed at ESTEC to rigorously verify and test the improvements.

- *June 18, 1992 - February 28, 1993*
  UWA v.1.4
  Deficiencies in SARIM detected during the implementation of the reference processor resulted in a new baseline algorithm for implementation UWA v.1.4.
  IWA products from the June 18, 1992 to February 28, 1993 were reprocessed at ESTEC. Industrial development and testing of the SAR FDP

- *After February 1993*
  UWA v.1.5   SAR FDP version 4.2
  The implementation on the SAR FDP (version 4.2) required a number of minor modifications to the algorithm [**R9**] (a Hamming rather than Hanning window and the indices of area for clutter noise estimation). The update was installed at the ESA ground stations in February 1993.

- *February 1994*
  Additional improvements were proposed [**R10**] by MPI, Ifremer and Meteomer after analysis of the results of the UWA v.1.5 (SAR FDP 4.2).

- *June 1994*
  MPI provided a suggested implementation of some of the new proposals (SAR512). Comments and additional improvements were given by Sintef.

- *March 1995*
  UWA v.1.6
  ESTEC reference processor installed in F-PAF to reprocess IWA imagettes between launch and February 1993. The version number change due to the re-hosting of the software from VMS to Unix. Spectra equivalent to UWA v.1.5.

- *July 1995*
  UWA v.2.0
  Kickoff of contract to transfer SAR wave processing from SAR FDP to LRDPF 2. Assimilation of proposals from interested parties throughout scientific community (MPI, Ifremer, Sintef Meteomer) for algorithm improvements, resulting in the specification documented herein.

2. Wave algorithm description

The production of wave spectra from SAR raw data passes through two steps; the generation of a SAR Imagette or Intermediate Wave product (IWA), followed by the computation of the spectrum of that imagette (UWA).

Steps which are modified from the current practice on the SAR FDP are marked with an **M**, new steps are marked **N**. Unmarked steps remain unchanged from previous versions.

2.1 Intermediate Wave product - IWA

An imagette (IWA) is produced in the same manner as the current implementation of the SAR FDP processor version 4.2 [R1], except for look summation. The steps are summarised below. The typical result can be seen in **Figure 1**.
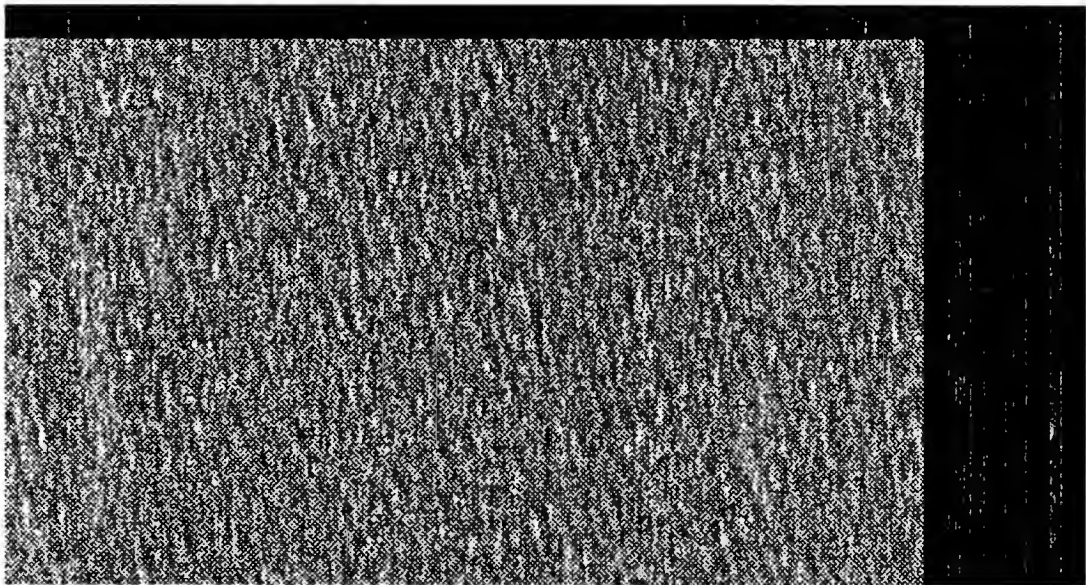

Figure 1. An IWA, OBRC SAR Imagette
ERS-2 29-JUN-95 21:21:55

2.1.1 Range processing

- **Step 2.1.1.1**   *Range-line matched filter generation*
- **Step 2.1.1.2**   *Raw data correction and range compression*
- **Step 2.1.1.3**   *Calibration pulse extraction and statistics calculation*

2.1.2 Azimuth processing

- **Step 2.1.2.1**   *Azimuth FFT*
- **Step 2.1.2.2**   *Doppler centroid estimation*
- **Step 2.1.2.3**   *Range cell migration correction*

- **Step 2.1.2.4 M** *Look compression, detection with summation in power (intensity)*

  Each of the three looks are summed in power, and the square root of the result (amplitude) is output in the product.

- **Step 2.1.2.5** *Slant range to ground range conversion*

- **Step 2.1.2.6 N** *Computation of statistics for annotation*

  The IWA product annotation in the SAR SPH [**R7**] will be computed as in the SAR FDP version 4.2, with the addition of two fields.

  Table 1 describes the format and location of the two additional fields.

  The first (Field 1, bit 12) is an additional PCD flag identifying land within a scene. An internal look-up table on the LRDPF contains a high resolution bit-map of land coverage on a 5' x 5' grid. This will be used to set the Land/Sea flag to 1 if any land is imaged.

  The second field is the incidence angle at the centre of scene. This will be computed at the latitude and longitude of the centre of the imaged area.

SPH Field	No. of Bytes	Data Type	Description	Units	Current Type	Current Use
1 bit 12	2 (1 bit)	1 Bit	bit 12. Land / Sea Flag 0 = Sea (No land within Imagette) 1 = Land within scene	N/A	Bit	Spare
7	2	I2	Incidence angle at imagette centre	10^{-3} deg	I2	Spare

Table 1. Additional IWA SPH annotation in UWA v.2.0

2.1.3 Clarification of SPH annotation

2.1.3.1 Latitude and Longitude co-ordinates of an imagette.

Fields 17 to 26 of the SAR SPH contain the latitude and longitude of the corners and centre of the image. However, it is not clearly defined which pixels these corners refer to. As the **imaged scene** is generally smaller, in both azimuth and range, than the image product (i.e some pixels are blank at far range, and far azimuth), the corner co-ordinates may refer to the either the corners of the imaged scene, or to the whole product. What is more, the implementation has changed over the history of the SAR FDP. The current status in the SAR FDP is unclear.

Clarification: *The latitude and longitude coordinates of the corners of the image must refer to the co-ordinates of the* **imaged scene** *(normally smaller than the whole imagette). Similarly, the centre co-ordinates must correspond to the centre of the imaged scene.*

2.1.3.2 SAR Image statistics PCD

Field 1 of the SPH contains a number of PCD flags related to product quality. Two flags are related specifically to the image input and output data statistics; bit 7, the IQ statistics flag, and bit 11 the Image statistics flag.

These flags are set if the statistics are not within thresholds supplied in the EXT_SAR LUT. An error in the SAR FDP 4.2 causes the Image and IQ statistics PCD flags to be set if any of the calculated statistics are *less* than thresholds supplied. The specification states that these flags should be raised if any of the values are *greater* than the thresholds.

Clarification: *the I Q statistics flag will be set if the following condition is true;*

```
IF  abs(Sph.MeanI + Sph.BiasI - DNR/2)> (DNR * ExtSar.InputMeanI/100)/2
OR  abs(Sph.MeanQ + Sph.BiasQ - DNR/2)> (DNR * ExtSar.InputMeanQ/100)/2
OR  abs(Sph.SdI) > (DNR * ExtSar.InputSdI/100)
OR  abs(Sph.SdQ) > (DNR * ExtSar.InputSdQ/100)
```

Where   `DNR`   is the Dynamic Range

                             Image OGRC = 31   Image OBRC = 63

                             Wave OGRC = 3   Wave OBRC = 15

             `ExtSar...`   fields within the EXT_SAR LUT

             `Sph...`   fields within the SAR specific product header.

Clarification: *the Image statistics flag will be set if the following condition is true;*

```
IF  Sph.ImageMean  > iDNR * ExtSar.OutputMean / 100
OR  Sph.ImageSd    > iDNR * ExtSar.OutputSd   / 100
```

Where   `iDNR`   is Image Dynamic Range = 65535

2.2 Wave spectrum product - UWA

The following steps are performed to produce a UWA wave spectra version 2.0. The effect on the Imagette in **Figure 1** will be illustrated as it passes through the processing steps.

2.2.1 Derivation of Power Spectrum

• **Step 2.2.1.1**   *Compute the bounds of the image in range B_x and azimuth B_y.*

Due to timing and geometry, the imaged scene is often smaller than the area covered by the IWA product. Consequently not all pixels at far range and azimuth in an IWA contain image data, as seen in **Figure 1**. Empty pixels are set to zero. The bounds are limited by the size of the fft, B_f, such that $B_x \leq B_f$ and $B_y \leq B_f$. B_f is 512 pixels.

• **Step 2.2.1.2 M**   *Calibrated Intensity Image*

Form an intensity (power) image (**Figure 2**) from IWA.

$$I_{(x, y)} = \frac{A^2_{(x, y)}}{K}$$

Where x = range position, $1 \ldots B_x$

            y = azimuth position, $1 \ldots B_y$

            $I_{(x,y)}$ = Intensity sample.

            $A_{(x,y)}$ = Amplitude sample.

            K = calibration constant.

Scaling by a constant, K, passed in the EXT_SAR LUT (see Section 4. on page 24) as a floating point value, allows for the possibility of making an approximate calibration of the imagette to the radar backscatter measurement, σ^0.

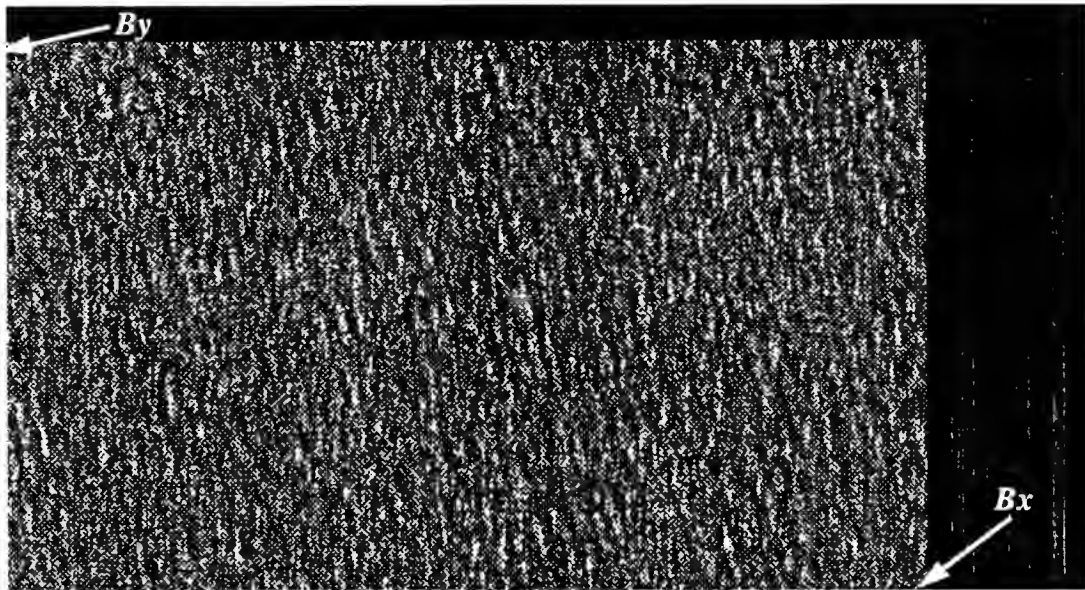Once in intensity, the image pixels must be stored in a floating point data type.

Figure 2. Calibrated imagette in power

• **Step 2.2.1.3 M** *Compute relative modulation image.*

Compute the mean, I_M, of the calibrated intensity imagette.

$$I_M = \frac{\sum I_{(x, y)}}{B_x \cdot B_y}$$

Where B_x = number of samples in range.
        B_y = number of samples in azimuth.
        (x,y) = coordinates, (*[1...Bx], [1...By]*)
        I_M = image mean.

$$M_{(x, y)} = \frac{I_{(x, y)} - I_M}{I_M}$$

Where (x,y) = coordinates, (*[1...Bx], [1...By]*)
        $M_{(x,y)}$ = relative modulation image.

NOTE pixels outside the imaged scene are ignored in this computation, and thus remain at zero.

• **Step 2.2.1.4 N** *Compute image variance.*

Compute the variance of the relative modulation image.

$$M_V = \frac{\sum M^2 (x, y)}{(B_x \cdot B_y) - 1}$$

Where (x,y) = coordinates, $([1...Bx], [1...By])$

NOTE the correct relation for variance requires the image mean. This has been eliminated from the equation above, as it is equal to zero following **Step 2.2.1.3**.

• **Step 2.2.1.5 M** *Apply a Hamming window and frequency shift.*

Prepare for the application of a Fast-Fourier Transform (fft) by applying a hamming window to the image. A frequency shift is introduced by multiplying alternate pixels by -1 to centre the spectrum produced the fft at zero wavenumber[1] ($B_f/2 = 256$).

$$G_{(x, y)} = -1^{(1 + x + y)} \cdot H(x, B_x) \cdot H(y, B_y) \cdot M_{(x, y)}$$

Where (x,y) = coordinates, $([1...Bx], [1...By])$
        $G_{(x,y)}$ = Windowed image.
        $H(j,n)$= Hamming function defined as

$$H(j, n) = \alpha + (1 - \alpha) \cos \frac{2\pi (j - n/2)}{n}$$

Where α = weight or window roll-off coefficient = 0.5.
        j = sample position $(1...n)$.
        n = number of samples in window.

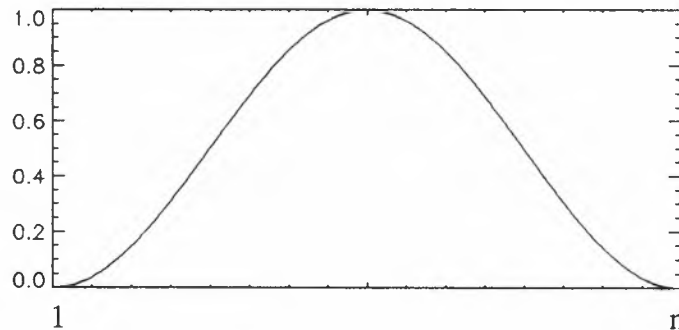The hamming coefficient, α, is fixed to 0.5. **Figure 3** shows the shape of such a window function.

Figure 3. Hamming Window with a weight, α, of 0.5

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1. wavenumber, $k = 2\pi / l$. Units are radians/m. where l = wavelength in meters.

• **Step 2.2.1.6 M** *Prepare for FFT by padding to the size of the fft.*

The windowed image is padded out to the size of the fft, B_f, with pixels set to zero.

$$G_{(x, y)} = 0 \Big|_{x = B_x}^{B_f} \Big|_{y = B_y}^{B_f}$$

Where B_f = size of 2-d FFT = 512.

A square 2-d fft, with the size a power of two, is significantly more efficient in terms of processing time than for any other case. For efficient UWA processing, a square 2-d FFT is used, with a size of 512 by 512 pixels. As an imagette is not square, nor necessarily 512 pixels in range or azimuth, some pixels must be added for padding, and some may be lost.

An imagette has at most 320 pixels in azimuth. In OGRC mode, there are at most 400 pixels in range. In OBRC (the nominal operational mode) there are at most 600 pixels in range. The number of pixels in range is dependent on the viewing geometry, consequently the location of the imagette within the 100 km full SAR swath, and the position within the orbit. The number of pixels in azimuth is primarily dependant on the position within the orbit.

• **Step 2.2.1.7** *Compute complex spectrum.*

A 2-d fft is used to transform the windowed, padded image from the spatial to the frequency domain. Post fft normalisation is performed in **Step 2.2.1.9**.

$$F = fft_{512x512}(G)$$

• **Step 2.2.1.8** *Compute Cartesian spectrum*

The spectrum, F, is converted from complex to real space.

$$T_{(x, y)} = F_{(x, y)} \cdot conj(F_{(x, y)})$$

Where (x,y) = coordinates, $([1...B_f] , [1...B_f])$
$conj()$ = complex conjugate of argument.

• **Step 2.2.1.9 M** *Normalise spectrum.*

Fourier transform theory states that the integral of the image in the frequency domain equals the image variance in the spatial domain. The cartesian spectrum computed in **Step 2.2.1.8** must be normalised to ensure this is the case. This normalisation removes scaling introduced by padding and windowing the image, and the algorithm used for computing the fft.

Compute the sum, T_S, of the cartesian spectrum T.

$$T_S = \sum T_{(x, y)}$$

Where (x,y) = coordinates, $([1...B_f] , [1...B_f])$
T_S = Sum of cartesian spectrum.

The normalised spectrum, S, is computed as follows

$$S_{(x,\,y)} = T_{(x,\,y)} \cdot \frac{M_V}{T_S \cdot \delta kx \cdot \delta ky}$$

Where δkx = spectral sample spacing in range = $2\pi / (\delta x \cdot B_f)$
δky = spectral sample spacing in azimuth = $2\pi / (\delta y \cdot B_f)$
δx = IWA range sample spacing in metres ($\sim$ 20m. SPH field 49).
δy = IWA azimuth sample spacing in metres ($\sim$ 16m. SPH field 50).
$S_{(x,y)}$ = normalised spectrum.

NOTE The above equation is independent on the method used to perform the fourier transform in **Step 2.2.1.7**. Some fft routines perform their own normalisation after the spectrum is computed, some do not. It is recommended that a non-normalising fft is used in the implementation, for speed efficiency.

A complete normalised spectrum can be seen in **Figure 4**. As evident in the figure, the spectrum is symmetrical. Further processing requires only the first half of the spectrum in the range direction, 1...256. The second half of the image in range, pixels 257...512 may be discarded for purposes of efficiency at the implementers discretion.

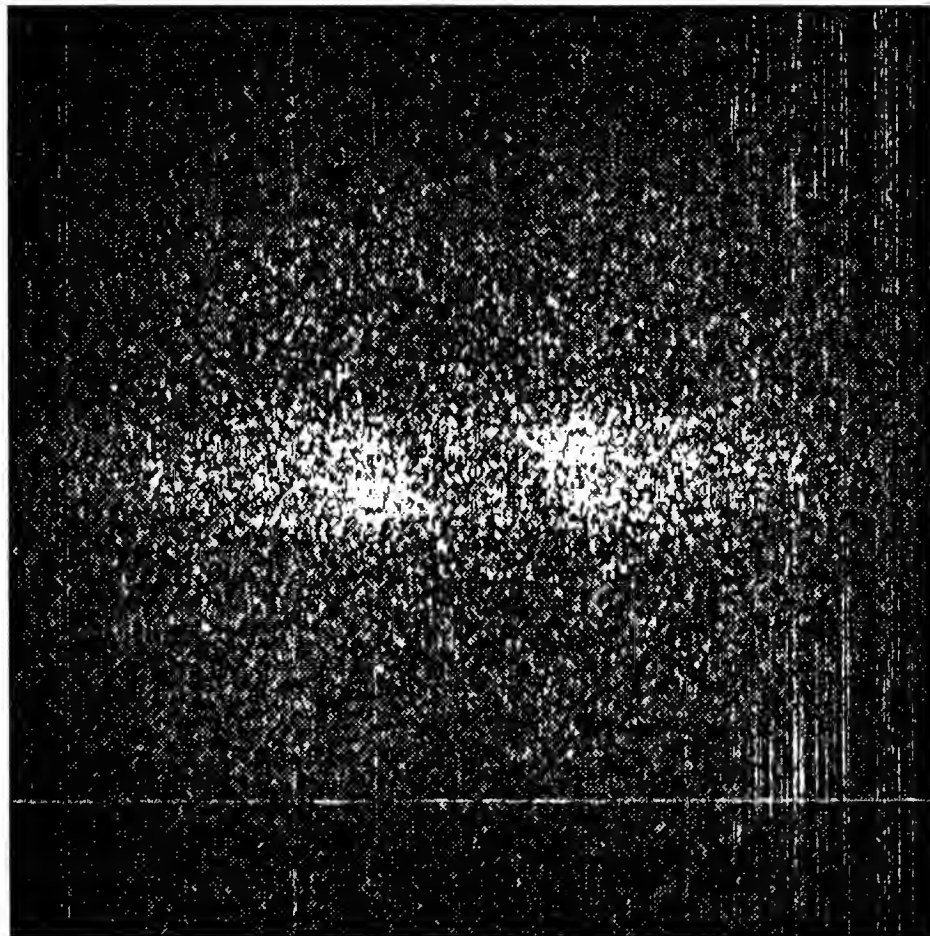In all the following figures, the whole 512 by 512 spectrum is illustrated to aid clarity.

Figure 4. Cartesian SAR Power Spectrum

2.2.2 Correction for the impulse response function

Figure 4 clearly illustrates a significant tail-off in the spectrum at high wavenumbers (or short wavelengths). This effect, which extends over the entire spectrum, is due to the impulse response function (IPR), or sensitivity of the system to a given wavenumber in both azimuth and range. A typical IPR can be seen in **Figure 5**.

It has been shown that the IPR can be fitted by a Gaussian function in the azimuth direction, and a Butterworth function in range. The function will be normalised, such that the maximum, at the centre, equals 1.0. The reciprocal of the IPR, or system transfer function (STF) will be passed to the processor in the SAR_STF LUT.
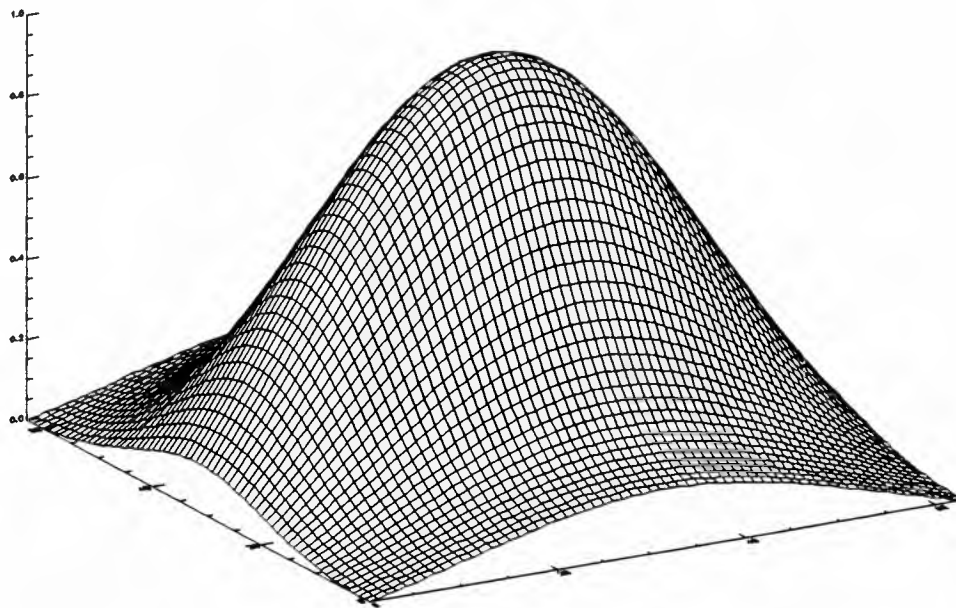
$$STF_{(x, y)} = \frac{1}{IPR_{(x, y)}}$$

Figure 5. Impulse Response Function, IPR

• **Step 2.2.2.1**   *System transfer function correction*

Correct the SAR image spectrum for the system transfer function by multiplying each pixel by the corresponding element of the SAR_STF LUT (Section 4.2 on page 25).

$$Z_{(x, y)} = S_{(x, y)} \cdot STF_{(x, y)}$$

The corrected spectrum can be seen in **Figure 6**.

The contents of the SAR_STF LUT will be published, and made available to the user community. At the discretion of ESA, this table may be updated should improved estimates of the function be derived. Each version of the table has an identifying number, which is given in the product annotation (SPH field 65). Users may thus determine what correction has been performed on a given product, and if required, may remove the effect of that correction, and apply another.
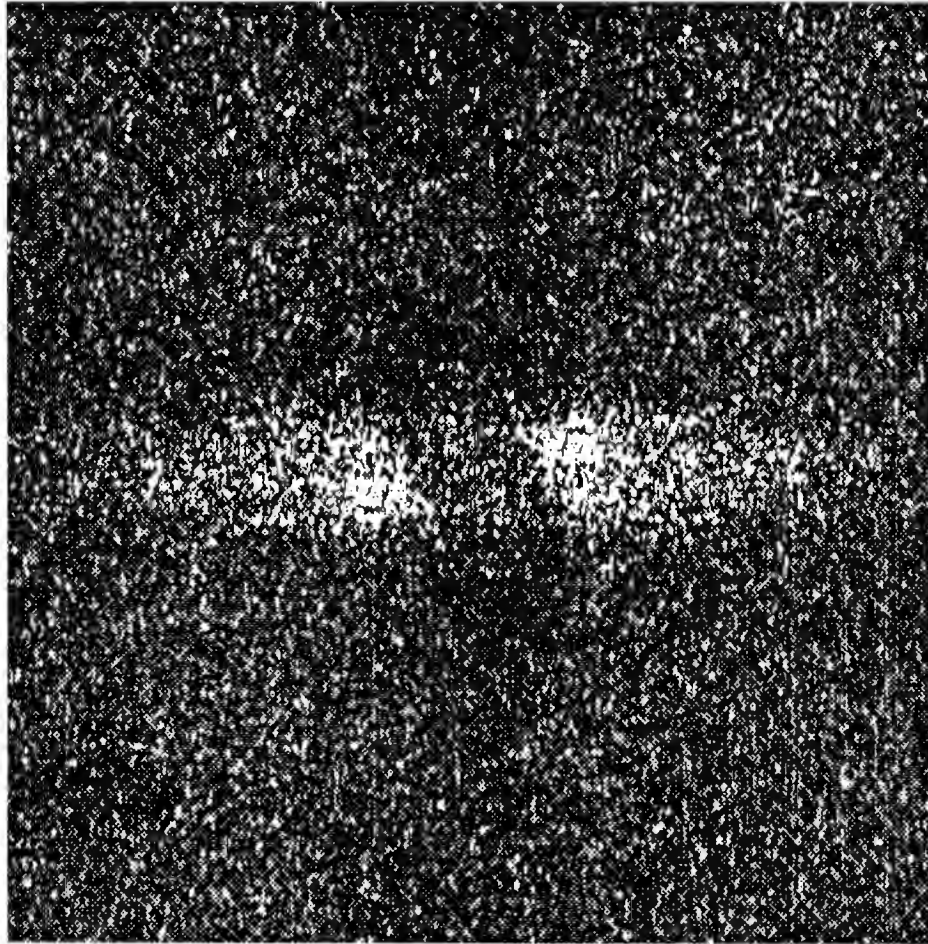

Figure 6. Cartesian SAR Spectrum, corrected for the Impulse Response Function

2.2.3 Transformation to polar coordinates

The ESA UWA product is processed and distributed in near real time onto the international meteorological network, GTS. With an average 2500 products per day per ERS satellite, the size of the product has to be severely restricted to be capable of fitting in to the available bandwidth. The UWA product has two header records, containing processing parameters and statistics, followed by a single data record containing the average spectrum level on a twelve by twelve polar grid, between 60m and 730m in logarithmic steps.

• **Step 2.2.3.1 M** *Transform from cartesian to polar coordinates.*

The cartesian spectrum is divided into 12 by 12 bins on a polar grid. The bins range in direction from 0° to 180° in 15° steps, and in wavelength from 59.3m to 730.5m in logarithmic steps of $10^{1/11}$. **Figure 7** shows a spectrum overlaid with the borders of

each of the bins. The angle at the boundaries of the direction sectors are indicated, as are the nominal wavelengths at the centre of each bin.
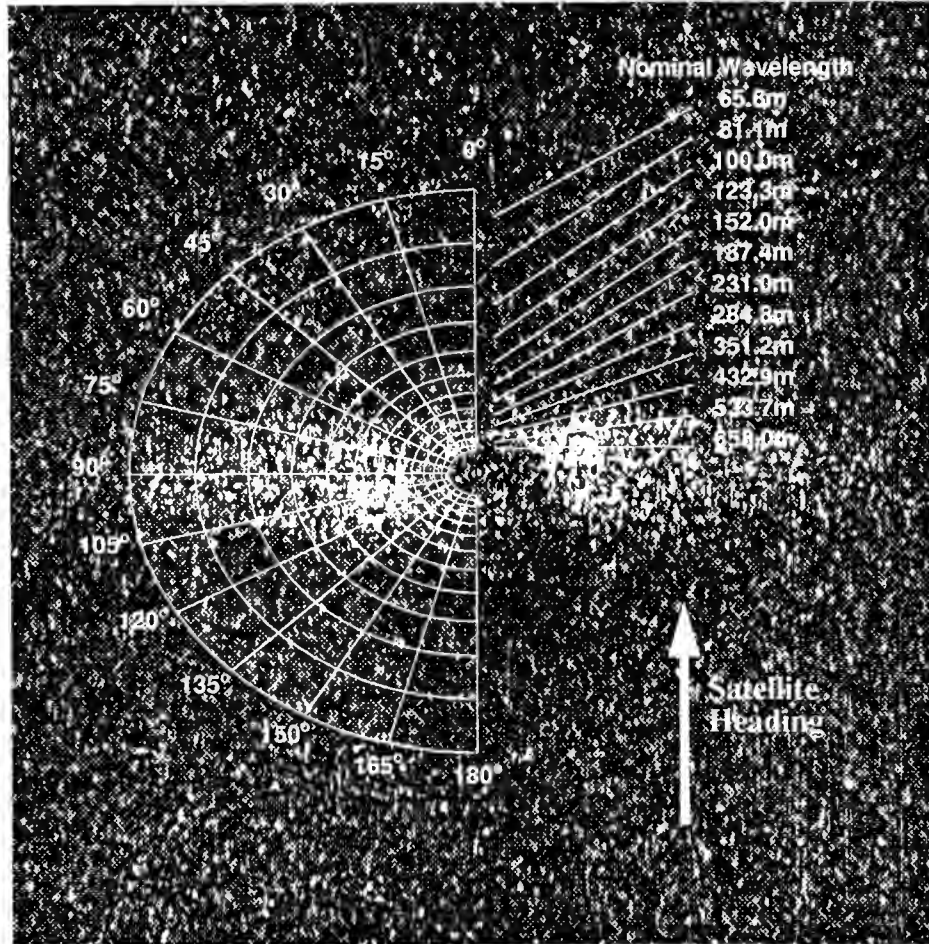

Figure 7. Encoding the spectrum into bins

Compute the average value of all the pixels of the cartesian spectrum that lie within each polar bin.

$$P_{(k, d)} = \frac{\sum Z_{(f(k, d))} + \frac{1}{2} \cdot \sum Z_{(h(k, d))}}{N_{(k, d)}}$$

Where k,d = wave length and direction bin numbers 1…12.
$f(k,d)$ = coordinates for whole samples within bin k, d.
$h(k,d)$ = coordinates for half samples within bin k, d.
$N_{(k, d)}$ = number of samples in each bin (half samples counting for 0.5)
$P_{(k, d)}$ = spectrum bins.

The wave length and direction bins for each pixel is computed, as a real number. Adding or subtracting a small real number (the 'Boundary Width', 10^{-5} is sufficient) to/ from the direction, may result in a different whole directional bin number. In this case the pixel is said to lie on the boundary between two sectors.

The energy of these pixels is split evenly between the two bins on either side of the boundary. Also, half of the energy of pixels lying exactly on the 0° boundary is added both to the corresponding bins at 0°-15° and to 165°-180°. Similarly for pixels lying on the 180° boundary.

NOTE When half the energy of a pixel is added to a given bin, the number of samples in that bin (used to find the average energy) increases by 0.5 not by 1.

The nominal wavelength l_n of a bin, n, may be found by the following relation;

$$l_n = 10^2 \cdot 10^{\frac{n-3}{(m-1)}}$$

Where m = Number of bins = 12

n = bin in range $1...m$

The wavelength of the boundary of a cell may be found using the same relation, adding or subtracting 0.5 from n. For example, the wavelength of inner boundary of bin twelve, 730.5m, is calculated thus $10^2 * 10^{9.5/11}$.

The cartesian coordinates, (x, y), of a given wavelength, l, and direction, θ, are derived

$$x = (1 + B_f/2) - \frac{\delta x \cdot B_f}{l} \cdot \sin\theta$$

$$y = (1 + B_f/2) + \frac{\delta y \cdot B_f}{l} \cdot \cos\theta$$

The wavelength , l, and direction, θ, of cartesian coordinates (x, y), are derived by

$$l = \sqrt{(\delta ky \cdot (y - (1 + B_f/2)))^2 + (\delta kx \cdot (x - (1 + B_f/2)))^2}$$

$$\theta = \operatorname{atan} \frac{\delta kx \cdot (x - (1 + B_f/2))}{\delta ky \cdot (y - (1 + B_f/2))}$$

The wavelength and directional bin indices, (k,d), are derived by

$$k = (m - 1) \cdot (\log l - 2)$$

$$d = 1 + (m - 1)\frac{\theta}{\pi}$$

The results of this transformation can be seen overlaid on the original spectrum in **Figure 8**. For convenience the wave bins are annotated and the direction of motion of the satellite is given.
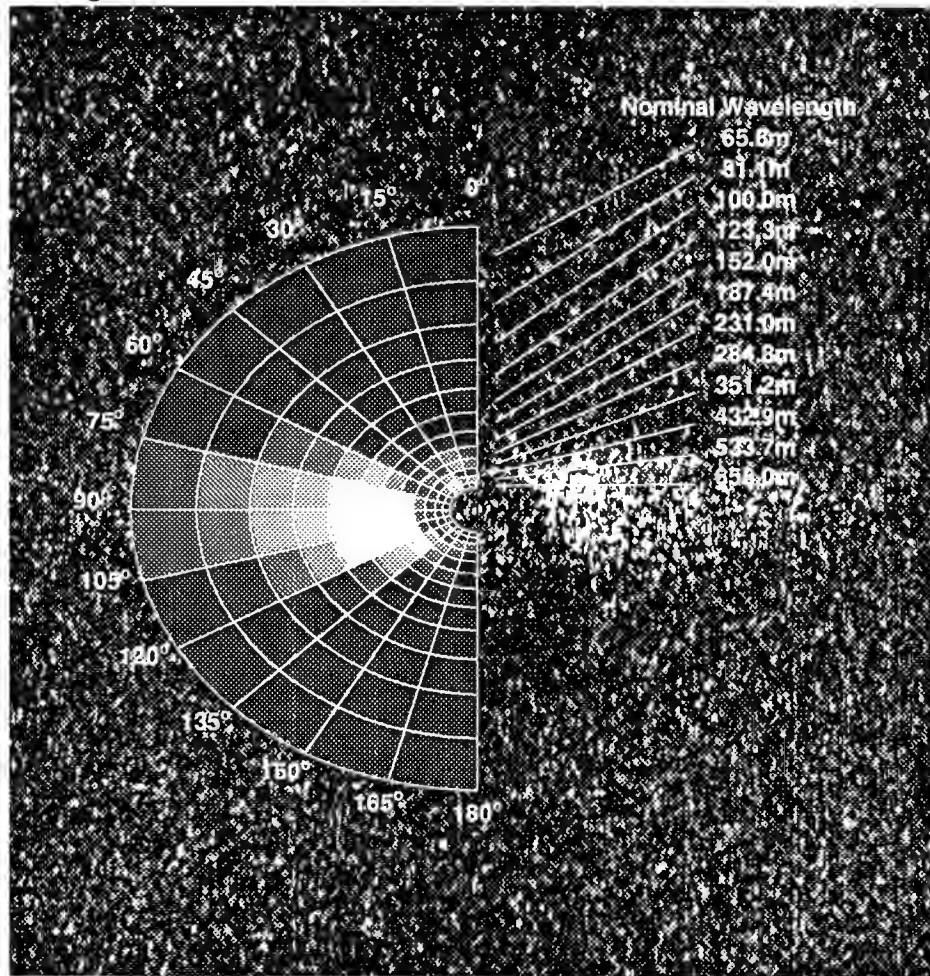

Figure 8. Polar averaged SAR spectrum

2.2.4 Computation of additional statistics

• **Step 2.2.4.1 N** *Azimuthal Clutter Cut-off*

The clutter cutoff wavelength in azimuth has significant interest for SAR wave spectra inversion schemes. It has also been shown to have a significant correlation with wind speed over the ocean surface. It will be computed using an algorithm proposed by Ifremer.

The algorithm derives the azimuthal cutoff from the fourier transform of the spectrum averaged in range, by performing a gaussian fit.

Average the uncorrected spectrum in range

$$A_y = \frac{\sum_{x=1}^{B_f} S_{(x,y)}}{B_f}$$

Perform a hilbert transform

$$D_y = 0 \Big|_{y=1}^{\frac{B_f}{2}-1} \qquad D_{B_f/2} = A_{B_f/2} \qquad D_y = 2A_y \Big|_{y=\frac{B_f}{2}+1}^{B_f}$$

Compute inverse 1-d fourier transform, to derive autocovariance function

$$Q = fft_{512}(D)$$

Determine 3db bandwidth

$$bw = \frac{\left(\frac{1}{50} \sum_{i=-51}^{-100} \left|Q_{(B_f-i)}\right|\right) + \left|Q_{(B_f-3)}\right|}{2}$$

Compute Azimuthal clutter cut-off

$$C_A = 50(i-4) \leftarrow \qquad \left|Q_{(B_f-i)}\right| < bw \Big|_{i=4}^{50}$$

• **Step 2.2.4.2 M** *Clutter noise estimation*

The clutter noise is the average energy of the corrected cartesian spectrum at high wavenumbers. The parameter is computed by finding the average of a fifty by fifty pixel region in the impulse response corrected spectrum, below 40m wavelength in the range direction.

$$C_N = \frac{\sum Z_{(x,y)}}{r^2} \Bigg|_{x=25,\,y=256-r/2}^{r+25,\,256+r/2-1}$$

Where C_N = Clutter noise estimate

r = Clutter sample area width = 50

• **Step 2.2.4.3 N** *Find peak and spread of energy at low wavenumbers*

Statistics are computed describing the distribution of energy at the centre of the spectrum, at wavelengths greater than highest spectral bin (>731m), i.e at the centre of the spectrum. The mean wavelength and direction are determined, and also the spread in direction and wavelength.

These statistics are calculated from the following parameters computed for pixels where the coordinates *(x, y)* are within the low wavenumber region, and after having removed the clutter noise estimate.

$$E_T = \sum W_{(x, y)}$$

$$E_a = \sum (W_{(x, y)} \cdot \cos \theta_{(x, y)}) \qquad E_r = \sum (W_{(x, y)} \cdot \sin \theta_{(x, y)})$$

$$E_1 = \sum (W_{(x, y)} \cdot k_{(x, y)}) \qquad E_2 = \sum \left(W_{(x, y)} \cdot k^2_{(x, y)} \right)$$

$$E_3 = \sum \left(\frac{W_{(x, y)}}{k_{(x, y)}} \right) \qquad E_4 = \sqrt{1 - \left(\frac{E_r^2 + E_a^2}{E_T^2} \right)}$$

Where *(x,y)* = coordinates in low wave number region, $l > l_{12}$
$W_{x,y}$ = $Z_{x,y} - C_N$, spectrum pixel less the clutter noise
E_T = Total Energy in region
E_a = Energy in Azimuth direction
E_r = Energy in Range direction
k = wavenumber
θ = direction

The mean wavelength, w_m, and mean direction, d_m, is then given by

$$w_m = \frac{2\pi}{E_T} \cdot E_3 \qquad\qquad d_m = \text{atan} \frac{E_r}{E_a}$$

The wavelength spread, w_s, and directional spread, d_s, is given by

$$w_s = \sqrt{\frac{1}{E_T} \left(\frac{E_T^3}{E_3^2} - 2 \frac{E_T}{E_3} \cdot E_1 + E_2 \right)} \qquad d_s = \text{asin} E_s \cdot \left(1 + 0.1547 E_4^3 \right)$$

• **Step 2.2.4.4** *Compute the maximum value, of the polar spectrum.*

The maximum value, P_H, of the polar spectrum *P*.

2.3 UWA Wave product format

Having computed the spectrum, and additional statistics, the values are scaled and packed into the standard UWA product. This is to ensure that the station to central facility interfaces, bandwidth and archive estimates will remain unchanged.

A UWA product consists of three records the main product header (MPH), specific product header (SPH) and data set record. This section details the differences of a UWA v.2.0 product from previous versions [R7].

2.3.1 MPH

A standard ESA MPH is produced. The MPH for corresponding IWA and UWA products are identical, other than the product identifier.

Users will be able to distinguish UWA v.2.0 products from previous formats by checking the processor ID and software version number fields.

2.3.2 SPH

Annotation is added to existing spare fields available in the SAR SPH. The scaling for the clutter noise and maximum slope spectrum is modified with respect to pre-UWA v.2.0 products. The SPH for corresponding IWA and UWA products are identical.

The majority of the SAR SPH fields are computed during the IWA processing. The UWA processing adds its statistics and parameters to the following fields (additional fields added in new IWA processing are also included see **2.1.2.6** on page 9).

SPH Field	No. of Bytes	Data Type	Description	Units	Current Type	Current Use
1 bit 12	2 (1 bit)	1 Bit	bit 12. Land / Sea Flag 0 = Sea (No land within Imagette) 1 = Land within scene	N/A	Bit	Spare
7	2	I2	Incidence angle at imagette centre	10^{-3} deg	I2	Spare
42	4	I4	B_x, number of samples in range. B_y, number of samples in azimuth.	$B_x + B_y * 2^{16}$	I4	UI8
43	4	I4	E_T, Total Energy > 731m	10^{-3}	I4	UI8
44	4	I4	C_A, Azimuth Clutter cut-off	10^{-3}	I4	UI8
47	4	I4	C_N, Clutter noise estimate	10	I4	UWA
48	4	I4	P_H, Max Spectrum	10^{-3}	I4	UWA
58	4	I4	w_m, Mean wavelength (m) > 731m	10^{-3} m	I4	UI16
59	4	I4	w_s, Wavelength spread (m) > 731m	10^{-3} m	I4	UI16
60	4	I4	d_m, Mean direction (deg) > 731m	10^{-3} deg	I4	UI16
61	4	I4	d_s, Directional spread (deg) > 731m	10^{-3} deg	I4	UI16
62	4	I4	K, Calibration constant.	10^{-3}	I4	UI16

To encode parameters with a log scale, take the $\log_{10}$, subtract the shift value and multiply by the scale. 0.5 is always added when storing a floating point value into an integer.

For example the clutter noise parameter is scaled as follows;

$$\overline{N} = (\log N - L_N) \cdot U_N + 0.5$$

Where
N = Clutter noise.
L_N = Log shift = 3.
U_N = Scale factor = 100.

2.3.3 DSR

The 144 elements of the polar spectrum, P, are stored in the DSR

DSR Field	No. of Bytes	Data Type	Description	Units
1	4	I4	Data record number (always 1)	
2...13	12	I1	Log scaled spectrum intensity Nominal heading 7.5°	log normalised
. 2	1	I1	Nominal wavelength 65.8m	
. 3	1	I1	Nominal wavelength 81.1m	
. ...				
. 13	1	I1	Nominal wavelength 658.0m	
14...25	12	I1	Log scaled spectrum intensity Nominal heading 22.5°	log normalised
26...37	12	I1	Log scaled spectrum intensity Nominal heading 37.5°	log normalised
38...49	12	I1	Log scaled spectrum intensity Nominal heading 52.5°	log normalised
50...61	12	I1	Log scaled spectrum intensity Nominal heading 67.5°	log normalised
62...73	12	I1	Log scaled spectrum intensity Nominal heading 82.5°	log normalised
74...85	12	I1	Log scaled spectrum intensity Nominal heading 97.5°	log normalised
86...97	12	I1	Log scaled spectrum intensity Nominal heading 112.5°	log normalised
98...109	12	I1	Log scaled spectrum intensity Nominal heading 127.5°	log normalised

DSR Field	No. of Bytes	Data Type	Description	Units
110...121	12	I1	Log scaled spectrum intensity Nominal heading 142.5°	log normalised
122...133	12	I1	Log scaled spectrum intensity Nominal heading 157.5°	log normalised
134...145	12	I1	Log scaled spectrum intensity Nominal heading 172.5°	log normalised

Each spectrum bin is normalised to an 8 bit integer on a logarithmic scale as follows.

$$\overline{P_{(k,d)}} = \left(\log\left(\frac{P_{(k,d)}}{P_H} \right) + L_P \right) \cdot \frac{254}{L_P} + 0.5$$

Where L_P = log shift = 3

NOTE the bins are scaled to values between 0 and 254, i.e. 255 is not used. This is to ensure compatibility with BUFR format, for the distribution of the product to meteorological centres over GTS.

3. Decoding UWA product

The polar spectrum bins are decoded as follows

$$P_{(k,d)} = 10^{L_P \cdot \frac{P_{(k,d)}}{254} - L_P} \cdot P_H$$

4. Processing Parameter tables

The generation of IWA and UWA products requires three externally supplied look-up tables (LUTs), EXT_SAR, SAR_STF and LRDPF.5. The first two were used on the SAR FDP v.4.2. The third table is built in to the LRDPF.

4.1 External SAR table, EXT_SAR

Table Type 2.
Size 106 bytes

The format of this table remains as defined in **R8** with the additional use of the one spare field for the calibration constant.

        EXT_SAR.CAL_COEFF.SPARE_1   I4   Mantissa and Exponent K

The ERS float transport format is used to store this parameter; two byte integer mantissa and two byte integer exponent.

4.2 Static Transfer Function table, SAR_STF

Table type 3.
Size 512 kilobytes

Contains 256 (in range) by 512 (in azimuth) floating point values, stored in the ERS float transport format; two byte integer mantissa and two byte integer exponent.

4.3 Land / Sea database, LRDPF.5

Table Type 5.

The format of this table is specified.

5. Changes with respect to pre-UWA v.2.0

The UWA v.2.0 algorithm differs from UWA v.1.5 / SAR FDP 4.2 in a number of respects. Some steps are slightly modified, and some steps have been added.

5.1 Modified Steps

- **Step 2.1.2.4**
  The Imagette looks are summed in power rather than amplitude.

- **Section 2.1.3.1**
  Clarification of geographic co-ordinate annotation

- **Section 2.1.3.2**
  Clarification of PCD computation

- **Step 2.2.1.2**
  Correcting for a calibration constant passed in a look-up table.

- **Step 2.2.1.3**
  Compute relative modulation image, by dividing by mean, rather than subtracting.

- **Step 2.2.1.5**
  Apply hamming window only to image area, not to padding

- **Step 2.2.1.6**
  Pad data with zeros after hamming, rather than before hamming

- **Step 2.2.1.9**
  Scale the spectrum such that the variance is preserved after windowing, padding and computing the fft, rather than just by a fixed scale.

- **Step 2.2.3.1**
  Two wavelength bins are added at 65.8m and 81.1m, and the bins at 811m and 1000m are removed (wave energy above 731m is characterised by parameters in the SPH).

- **Step 2.2.4.2**
  Extended area for clutter noise estimate from 25 by 25 pixels to a 50 by 50 pixels.

5.2 New steps

- **Step 2.1.2.6**
  Computation of incidence angle at centre of scene, and flag land/sea within imaged area

- **Step 2.2.1.4**
  Compute image variance for the correction of the spectrum in **Step 2.2.1.9**

- **Step 2.2.4.1**
  Computation of the Azimuthal clutter cut-off.

- **Step 2.2.4.3**
  Computation of peak and spread of wave energy above highest wavelength bin

- **Section 2.3**
  Store the spectrum and parameters on a logarithmic scale, and add new parameters.

5.3 Removed steps

- Previously, the mean of the imagette, after applying the hamming window, was computed and subtracted. This is no longer performed as the correct normalisation is performed after the fft, in **Step 2.2.1.9**.