STF90 A05084 Unrestricted

REPORT

Intercomparisons of Directional Wave Spectra from ASAR, Buoys and the WAM Model: The Co-location Database

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SINTEF ICT Applied Mathematics

June 2005

SINTEF REPORT

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TITLE

INTERCOMPARISONS OF DIRECTIONAL WAVE SPECTRA FROM ASAR, BUOYS AND THE WAM MODEL: THE CO-LOCATION DATABASE

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REPORT NO. STF90 A05084	CLASSIFICATION Unrestricted	CLIENTS REF. Harald Johnsen	
CLASS. THIS PAGE Unrestricted	ISBN 82-14-03801-4	PROJECT NO. 424538	NO. OF PAGES/APPENDICES 56
ELECTRONIC FILE CODE		PROJECT MANAGER (NAME, SIGN.) Harald E. Krogstad Harald E. Krogstad	CHECKED BY (NAME, SIGN.) Karstein Sørli Karstein Sørli
FILE CODE	DATE 2005-06-24	APPROVED BY (NAME, POSITION, SIGN.) Tore Gimse, Research Director on behalf of K. Eidsvik	

ABSTRACT

This report is part of the deliverable to the project *Development and Application of Validated Geophysical Ocean Wave Products from ENVISAT ASAR and RA-2 Instruments (EnviWave)*, contract no. EVG1-CT-2001-00051. It describes the use and some applications of a database of co-located buoy, ASAR, and WAM directional wave spectra, and complex Envisat imagettes. The database is compiled mostly from the ASAR/NDBC buoy co-located database at CERSAT, Brest, but all data have been through additional quality controls. The system is written in Matlab and, apart from the separate collection imagettes, the database itself is less than 10Mb and kept as a binary Matlab MAT-file stored in the form of *cell arrays*.

For all co-located data, the difference in time between the ASAR and the buoy spectra are less than 1 hour and the distance less than 275km. Similarly, for the ASAR and WAM data, the time difference is less than 3 hours and the distance less than 25km. The present database consists of all together 2760 different co-located cases.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Oceanografi	Oceanography
GROUP 2	Bølge	Wave
SELECTED BY AUTHOR	Envisat	Envisat
	ASAR	ASAR
	Bøyer	Bøyer

EnviWave

Development and Application of Validated Geophysical Ocean Wave Products from ENVISAT ASAR and RA-2 Instruments

Contract N^{o} : EVG1-CT-2001-00051

An EESD project supported by the Commission of the European Community

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CONTENTS

1 INTRODUCTION

Early in the EnviWave project it became obvious that the ASAR/NDBC buoy co-located database from Centre ERS d'Archivage et de Traitement (CERSAT) did not fulfil all the needs we foresaw for the analysis. First of all, the WAM data were not integrated in the database, and use of the HDF-EOS format is not very convenient when dealing with Matlab. Moreover, we were primarily interested in directional spectra, and this was available only for a small fraction of the data.

It also soon became clear that meaningless SAR spectra from land areas have been included in the original database, although a hidden “land flag” was provided in the original data. This flag was not included in the standard Cersat data description, but the information has later been obtained directly from Cersat. For this reason, we have preferred to apply the TerrainBase geographical database, which is part of the freely available package **M_MAP**, also used for maps below.

The purpose of the database described below is thus to collect directional wave data which have been measured or computed by different means into a uniform structure that provides easy extraction, analysis and intercomparison of the data. To ease the use, it is also important to keep the size of the storage space needed for the database low. There are two types of measured data in the database; ENVISAT ASAR wave mode data (imagettes and computed spectra), and measured buoy data from NDBC (US) network. There is one source of computed data, the WAM data.

The database is completely written in the Matlab programming environment. Apart from the separate collection of complex imagettes (677Mb), the database itself is less than 10Mb and is kept as a binary MAT file. The content is stored in the flexible *cell array* structure Matlab.

The present database consists of all together 2760 different co-located *cases*. A case consists of co-located ASAR, WAM and Buoy directional spectra. Non-directional buoys are not included. Some of the cases also include complex co-located imagettes. An *event* contains several cases and is typically associated with one satellite pass. There are 304 different events in the database covering a time span from 24 November, 2002 to 27 July, 2004.

Unfortunately, no imagettes have been available to the project after August 27, 2003, and altogether there are 204 imagettes in the database, covering 559 of the 2760 cases and contributing to 59 independent events.

For all co-located data, the difference in time between the ASAR and the buoy spectra are less than 1 hour and the distance less than 275km. Similarly, for the ASAR and WAM data, the time difference is less than 3 hours and the distance less than 25km.

The present report is meant to serve as an introduction to the database, how it is structured and how it may be is used. A study of the data quality has been included as an example on how the database can be used.

An appendix to the report describes how to use the co-location database, and in more details how the database was compiled.

2 OVERVIEW OF THE DATABASE

2.1 Data Structure

The database consists of several tables of information stored in the form of Matlab matrices and cell arrays. The data are separated into four main parts; the ASAR data, the directional buoy data, the WAM data, and the Imagette data. A sketch showing the different input to the database is presented in Fig. 2.1.

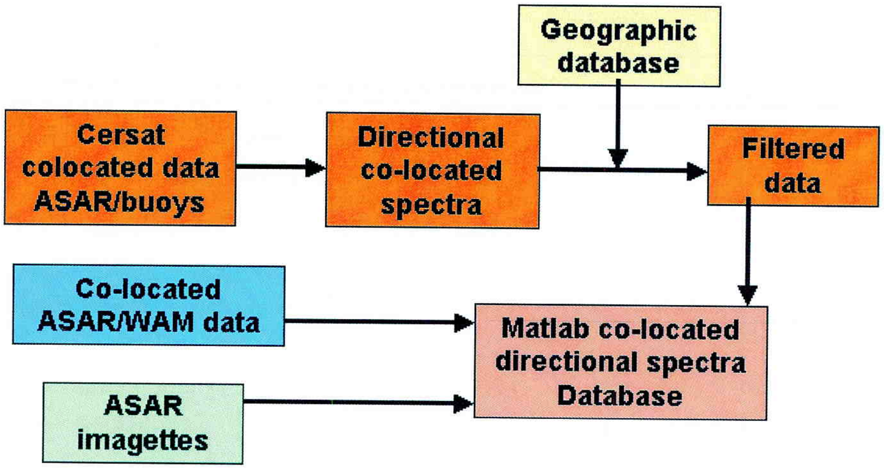

Figure 2.1: The various data sets going into the database.

The whole database is saved in one Matlab file with .mat extension. This file is thus in a proprietary binary format and can only be read by Matlab.

The file is organized through an overall index data matrix containing reference indices to the various co-located data sets. These are in turn stored in four cell arrays. The imagette cell array only contains the parameters for the imagettes, whereas the imagettes themselves, because of their size, are kept in a separate catalogue.

When the database is opened in Matlab, it is structured into 5 tables, as illustrated in Fig. 2.2.

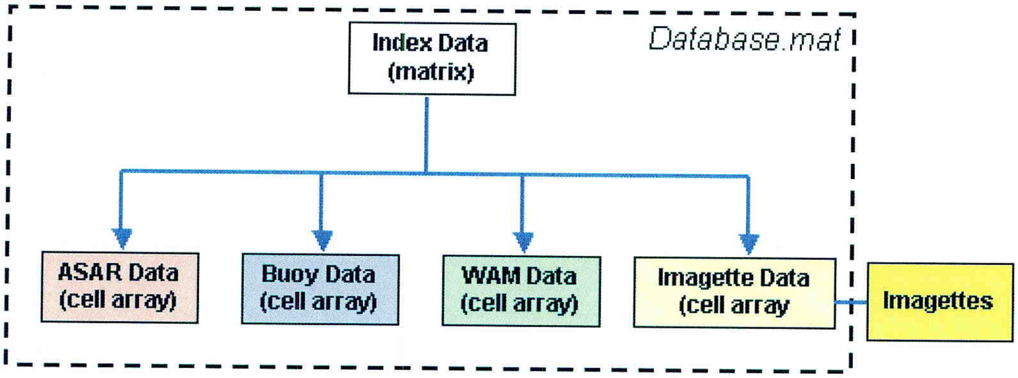

Figure 2.2: Organization of the Matlab .mat-file containing the Index Data matrix and the various cell arrays. The imagettes are stored separately.

The database has been compiled using suitable Matlab software that searches through the Cersat files containing data from ENVISAT ASAR, buoy data from the NDBC (US) network, and WAM data. There are actually two kind of input files. The first one is the HDF-EOS file that contains the ASAR/NDBC buoy co-located data, and the second is an ASCII file containing the ASAR/WAM co-located data.

The aim has been to find measured and computed data for locations that are close enough in space and time to enable a meaningful intercomparison. The record numbers in each data table containing data that are close to each other are stored in the index table. The Index Data matrix, *IndexData,* is an $n\times4$ matrix, where n is the number of co-located points. It is important to note that one Buoy data set can belong to more than one data set. A detailed description of how the database was created is found in an accompanying report.

Tables listing the content of the various cell arrays are described in the Appendix. Note that the contents in and the size of the various cells vary considerably.

2.2 The Data Sets

2.2.1 The ASAR spectra

The ASAR directional wave spectra given in the database are those from the Level 2 product of the Envisat ASAR Wave Mode [1, 2]. They are extracted from the Envisat ASAR/NDBC buoys collocation database set up by Cersat-Ifremer, where they are stored using the Hierarchical Data Format-Earth Observation System (HDF-EOS) format.

Data can be downloaded from the following ftp site:

ftp://ftp.ifremer.fr/pub/ifremer/cersat/products/colocated/envisat-ASA_WVW_2P/BUOY_SWAV/data/EWVWR0/ .

More information about the product may be found in [1].

The ASAR spectra in the database are scaled wavenumber spectra expressed as two-dimensional byte arrays on a log-polar grid in wavenumber (k) and direction (ϕ). The spectral have to be converted to physical values, $\widetilde{S}$, by using the byte value, S, and the values $S_{\max}$ and $S_{\min}$, according to the following formula:

$$\widetilde{S}(n,m)=S(n,m)\frac{S_{\max}-S_{\min}}{255}+S_{\min},$$

where the wavenumber index, n, runs from 0 to N_k-1, and the direction index, m, runs from 0 to $N_\phi-1$.

The size of the wavenumber/direction grid is N_k=24 and N_ϕ=36, respectively and the unit for $\widetilde{S}_{n,m}$ is m^4. The wavenumbers k_n (in rad/m) are given in a logarithmic grid,

$$k_n=\frac{2\pi}{\lambda_0}\left(\frac{\lambda_0}{\lambda_{N_k-1}}\right)^{\frac{n}{N_k-1}},\ n=0,\cdots,N_k-1.$$

The maximum and minimum wavelengths are λ_0 = 800m and λ_{N_k-1} = 30m, respectively.

The directions (in degrees clockwise from North) are given as

$$\phi_m = m\frac{2\pi}{N_\phi - 1}, m = 0, \cdots, N_\phi - 1.$$

In addition to the wave spectra, the following confidence parameters from the Level 2 products are included in the database [1]:

- **Land flag**: Equal to 1 for "above land" spectra, 0 otherwise
- **Normalized image variance**: Intensity variance of the imagette relative to the variance for pure speckle, σ_1.
- **Confidence swell**: equal to 1 if the retrieved wave direction shows an 180° ambiguity.
- **Confidence wind** is equal to 0 if an external wind direction was used during the inversion, 0 otherwise.
- **Attach_flag:** Equal to 1 if the cross-spectrum could not be computed from the imagette.
- **Azimuth cut-off wavelength:** Wavelength characterizing the azimuth cut-off of the SAR spectrum, and hence the azimuth pass band for meaningful spectral information.

2.2.2 The Directional Buoys

All co-locations currently in the database are with respect to NOAA directional buoys that belong to the US network with positions shown in Fig. 2.3.

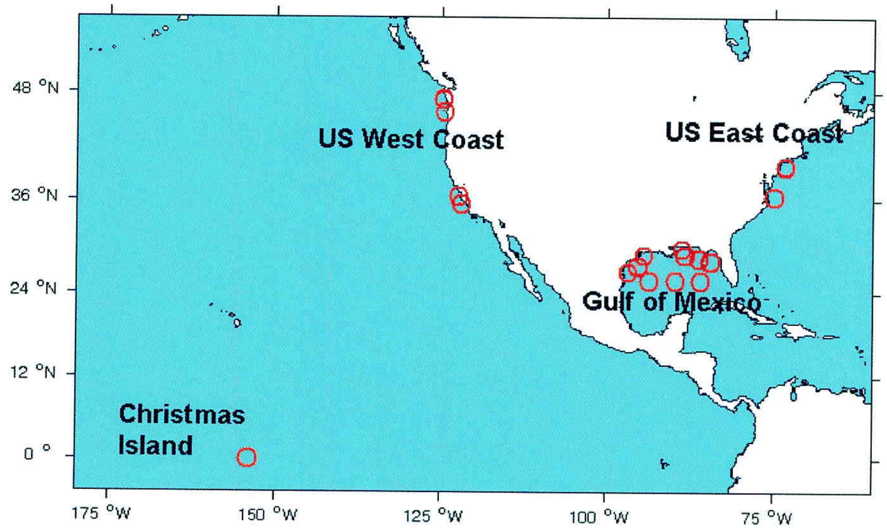

Figure 2.3: Locations of the US buoy network.

All buoys are discus buoys with circular hulls. NDBC's operational discus buoys are designed in three sizes: 12-meters, 10-meters, and 3-meters. According the NDBC website, the steel-hulled, 12-meter discus buoys are more sturdy in rough weather than the smaller, steel-hulled 10-meter discus buoy, but are more costly to maintain. The 10-meter buoy has been known to capsize in certain environmental conditions and the overall motion of the buoy is more vigorous than that of the 12-meter buoy. The Aluminium-hulled, 3-meter discus is very cost-effective but does not offer long-term survivability that the larger discus hulls provide.

The buoys are located in four different major areas. These are conveniently sorted out by checking the buoy longitude, see Table 2.1.

Table 2.1: Longitudes identifying the major regions in the collocation database.

Longitude	Location
140 deg < LongE	Chrismas Island
110deg < LongE < 130deg	US West Coast
80deg < LongE < 100deg	Gulf of Mexico
LongE < 80deg	US East Coast

A survey of all NDBC buoys used in the database and their respective locations are shown in Table 2.2. Pictures of the buoys are shown in Figs. 2.4 and 2.5.

Table 2.2: Survey of the 17 NDBC directional wave buoys that are providing data to the collocation database.

Buoy Name	Site	Latest known location	Type	Water depth	Anem. height
NDBC 46041	CAPE ELIZABETH- 45NM West of Aberdeen, WA	47.34 N 124.75 W	3-meter discus	132 m	5 m
NDBC 46029	COL RIVER BAR - 78NM South Southwest of Aberdeen, WA	46.12 N 124.51 W	3-meter discus	128 m	5 m
NDBC 46042	MONTEREY - 27NM West of Monterey Bay, CA	36.75 N 122.42 W	3-meter discus	1,920 m	5 m
NDBC 46028	CAPE SAN MARTIN - 55NM West Northwest of Morro Bay, CA.	35.74 N 121.89 W	3-meter discus	1,112 m	5 m
NDBC 42001	MID GULF - 180NM South of Southwest Pass, LA.	25.84 N 89.66 W	12-meter discus	3,246 m	10 m
NDBC 42002	W GULF - 240NM South-Southeast of Sabine, TX.	25.17 N 94.42 W	10-meter discus	3,200 m	10 m
NDBC 42019	FREEPORT, TX. - 60NM South of Freeport, TX.	27.91 N 95.36 W	3-meter discus	82 m	5 m
NDBC 42020	CORPUS CHRISTI, TX. - 50NM Southeast of Corpus Christi, TX.	26.95 N 96.70 W	3-meter discus	79 m	5 m
NDBC 42035	GALVESTON - 22NM East of Galveston, TX.	29.25 N 94.41 W	3-meter discus	14 m	5 m
NDBC 42040	MOBILE SOUTH - 64NM South of Dauphin Island, AL	29.18 N 88.21 W	3-meter discus	444 m	5 m
NDBC 42039	PENSACOLA - 115NM East Southeast of Pensacola, FL	28.80 N 86.06 W	3-meter discus	284 m	5 m
NDBC 42007	BILOXI - 22NM South-Southeast of Biloxi, MS.	30.09 N 88.77 W	3-meter discus	13.4 m	5 m
NDBC 42036	W. TAMPA - 106NM West Northwest of Tampa, FL	28.51 N 84.51 W	3-meter discus	53 m	5 m
NDBC 42003	E GULF - 260NM South of Panama City, FL	26.01 N 85.91 W	10-meter discus	3,164 m	10 m
NDBC 44025	LONG ISLAND - 33NM South of Islip, NY	40.25 N 73.17 W	3-meter discus	36 m	5 m
NDBC 44014	VIRGINIA BEACH - 64NM East of Virginia Beach, VA	36.61 N 74.84 W	3-meter discus	48 m	5 m
NDBC 51028	CHRISTMAS ISLAND DWA	0.02 N 153.87 W	3-meter discus	4,755 m	5 m

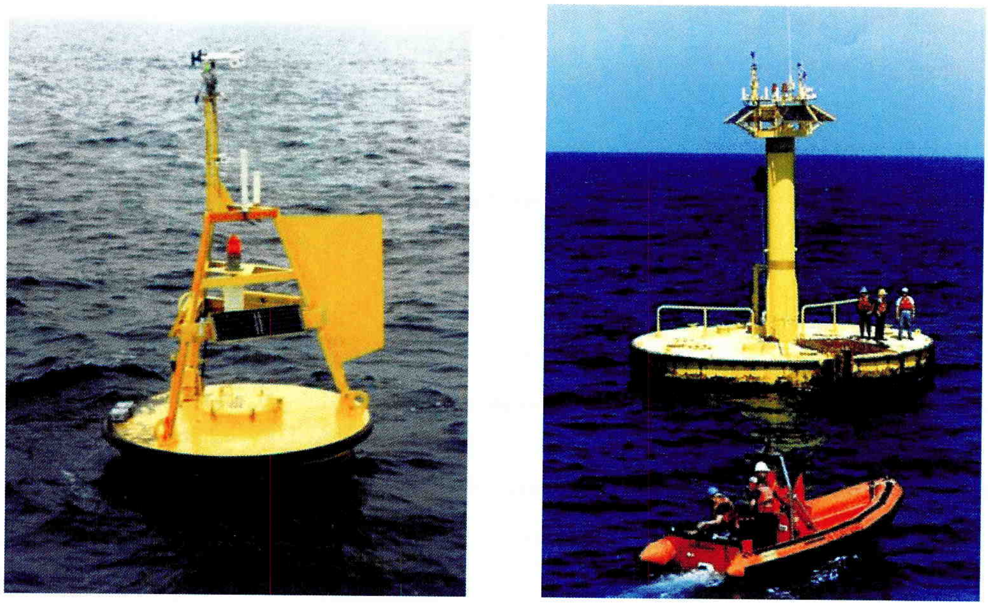

Figure 2.4: The 3 and 10m NOAA discus buoys (Photos copied from the NOAA WEB-pages).

Figure 2.5: 12m discus buoy (Photo copied from the NOAA WEB-pages).

2.2.3 The WAM Data

The directional wave spectra from the numerical model WAM are extracted from the Envisat ASAR/WAM collocation database, where they are stored as ASCII data. These data can be downloaded from ftp://ftp.ifremer.fr/. The spatial resolution of the grid used to run the WAM model is 0.5 degree, and the spectra are computed every sixth hour.

The spectra are given as a function of the wave frequency f (in Hz) and the wave direction ϕ (in radians). The frequency and direction vectors are provided in the database and the size of the spectral grid is 25 frequencies and 24 directions. The spectra $S(f,\phi)$ given in the database are scaled with respect to their maximum value $S_{\max}$ and have to be computed through

$$\tilde{S}(f,\phi)=S(f,\phi)\frac{S_{\max}}{999}.$$

The unit of $\tilde{S}(f,\phi)$ is $m^2 s \cdot rad$. The ECMWF wind velocities (in m/s) and directions (in degrees, clockwise from north) that were used to compute the WAM spectra are also included in the database.

2.2.4 M_Map

The charts displayed along with the various wave spectra have been plotted using the freely available Matlab package M_Map v1.3g (http://www2.ocgy.ubc.ca/~rich/private/mapug.html).

This has been applied together with the global 5-minute bathymetry/topography database **TerrainBase** available from ftp://ncardata.ucar.edu/datasets/ds759.2/data/tbase.Z . This package makes it convenient to plot charts that include coastlines and bathymetry under the Matlab environment. It also provides functions to compute the distance between to locations given through their longitudes and latitudes.

3 COMPUTATION OF WAVE PARAMETERS

The wave parameters used in the following are all defined in term of the directional wave spectrum, $E(f,\theta)$, written as $E(f,\theta)=S(f)D(\theta,f)$, where S is the *frequency spectrum* and D the frequency dependent *directional distribution* expressed as the Fourier series

$$D(\theta,f)=\frac{1}{2\pi}+\frac{1}{\pi}\sum_{n=1}^{\infty}\{a_n(f)\cos n\theta+b_n(f)\sin n\theta\}\,.$$

Table 3.1 gives the detailed definitions.

Table 3.1: Definitions of wave parameters

Name	Symbol	Definition
Significant wave height	$Hm0$	$Hm0=4\left(\int_{f=f_{low}}^{f_{high}} S(f)df\right)^{1/2}$ 1)
Mean zero-upcrossing period	$Tm02$	$Tm02=\left(\int_{f=f_{low}}^{f_{high}} S(f)df\Big/\int_{f=f_{low}}^{f_{high}} f^2S(f)df\right)^{1/2}$ 1)
Peak period	Tp	$Tp=1/fp,\ \max_f S(f)=S(fp)$
Mean Wave Direction	θ_1	$\theta_1(f)=\mathrm{atan2}\left(b_1(f),a_1(f)\right)$
Directional spread	σ_1	$\sigma_1(f)=\sqrt{2\left(1-\left(a_1^2(f)+b_1^2(f)\right)^{1/2}\right)}$
Main wave direction	$MDIR$	$MDIR=\arg(z),\ z=\dfrac{\int_{f_{low}}^{f_{high}}\left(a_1(f)+ib_1(f)\right)S(f)df}{\int_{f_{low}}^{f_{high}}S(f)df}$ 1)
Unidirectivity index	UI	$UI=\lvert z\rvert$, see definition of $MDIR$
Direction at the spectral peak	$ThTp$	$ThTp=\theta_1(f=1/Tp)$
Spread at the spectral peak	$SprTp$	$SprTp=\sigma_1(f=1/Tp)$
1) f_{low} and f_{high} may be selected according to the application.		

The resolution in frequency and direction varies for the three data sets, but the relatively small amount of data makes it easy to re-compute all wave parameters using one common method. This re-computation is carried out in two steps. In the first step, the data records in the Cell Array are converted to a common form of directional and non-directional spectra by calling suitable Matlab m-functions described in the Appendix. The frequency range for the buoy data vary, and for all data sets, the actual frequencies are part of the information provided with the data set. If necessary, the spectra are extrapolated outside their actual data range, using standard analytical expressions for the spectrum.

In a second step, these data are input to m-functions that re-compute the directional and non-directional parameters as found in Table 3.1.

The following describes the re-computation of the spectra in more details.

3.1 The Frequency Spectrum

All frequency spectra are first interpolated to a fine frequency resolution. Since parameters like significant wave height and the mean periods are dependent of the cut-off frequencies in the spectrum, the algorithm may extrapolate the spectrum by standard power laws outside the cut-off limits,

$$S(f)=\begin{cases}\left(\dfrac{f}{f_L}\right)^{10} S(f_L), f \le f_L, \\ \left(\dfrac{f}{f_H}\right)^{-4.5} S(f_H), f \ge f_H.\end{cases}$$

For the intercomparisons shown later, all spectral moments are computed between 0.01 and 1Hz, unless stated otherwise.

The ASAR spectra are given as wavenumber spectra, and the transformation to frequency uses the depth-dependent k-to-f dispersion relation,

$$(2\pi f)^2 = gk\tanh(kh).$$

The difference between old and recomputed parameters is mostly negligible, apart from the ASAR peak period which changes due to the wavenumber-to-frequency conversion.

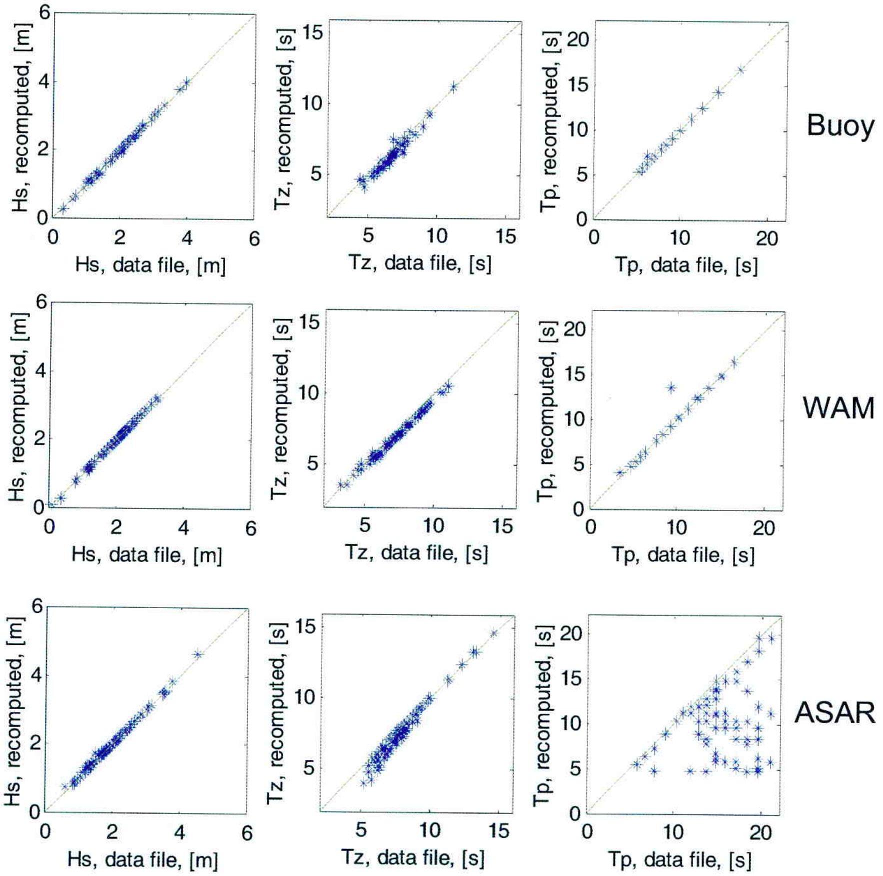

Figure 3.1: Original and recomputed non-directional wave parameters shown for a subset of the data (the first version of the database).

3.2 The Directional Buoy Spectra

The NDBC standard method for reconstructions of directional distributions, and the method also applied for the Cersat collocation data base for computing directional distributions, is just a truncated Fourier series chopped off for negative values. However, the file has sufficient information so as to reconstruct the original Fourier coefficients $\{a_1, b_1, a_2, b_2\}$ as functions of the frequency, since the following four parameters are provided:

$$
\begin{aligned}
r_1 &= \sqrt{a_1^2 + b_1^2}, \\
r_2 &= \sqrt{a_2^2 + b_2^2} \\
\alpha_1 &= \operatorname{atan}_2(b_1, a_1), \\
\alpha_2 &= \frac{\operatorname{atan}_2(b_2, a_2)}{2}(+\pi).
\end{aligned}
$$

From these expressions the first two complex Fourier coefficients

$$
\begin{aligned}
c_1 &= a_1 + ib_1 = r_1 \exp(i\alpha_1), \\
c_2 &= a_2 + ib_2 = r_2 \exp(i\alpha_2).
\end{aligned}
$$

However, in order to really be Fourier coefficients of non-negative distributions with integral equal to 1, the Fourier coefficients have to fulfil certain feasibility conditions, namely,

$$
\begin{aligned}
&|c_1|, |c_2| \le 1, \\
&\left|c_2 - c_1^2\right| \le 1 - |c_1|^2.
\end{aligned}
$$

(Kahma et al. 2005). It has turned out that data from several of the US buoys did not comply with the feasibility conditions, and this points to flaws in the initial data processing of the buoys. This is probably beyond repair, but it is possible to restore the data partly by fitting a simple cosine-2s distribution to the first pair of Fourier coefficients in the non-feasible cases.

The directional estimate $D(\theta)$ used in plots of the directional spectra is the standard Maximum Entropy directional estimate,

$$
\begin{aligned}
D(\theta) &= \frac{1}{2\pi} \frac{\sigma_1^2}{\left|1 - \phi_1 e^{-i\theta} - \phi_2 e^{-2i\theta}\right|^2}, \\
\phi_1 &= \left(c_1 - c_2 \bar{c}_1\right) \Big/ \left(1 - |c_1|^2\right), \\
\phi_2 &= c_2 - \phi_1 c_1, \\
\sigma_1^2 &= 1 - \phi_1 \bar{c}_1 - \phi_2 \bar{c}_2,
\end{aligned}
$$

(Kahma et al. 2005). The estimate works reasonably well most of the times and for most of the buoys, but gives too spiky spectra for some of the data (apparently because of near to non-feasible parameters). An example showing a heavily corrupt buoy directional spectrum from the Gulf of Mexico is shown in Fig. 3.2.

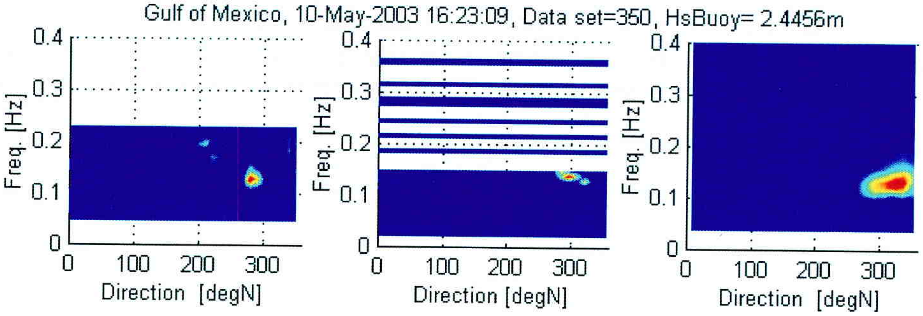

Figure 3.2: Simultaneous directional spectra from the Mexican Gulf. The ASAR spectrum is shown to the left, the buoy spectrum is in the center, whereas the WAM spectrum is shown to the right.

The restored spectra leave the most important directional parameters θ_1 (the mean wave direction) and σ_1 (the directional spread) unchanged,

$$\theta_1 = \mathrm{atan}_2\left(b_1, a_1\right),$$
$$\sigma_1 = \sqrt{2\left(1 - r_1\right)}\,, r_1 = \left(a_1^{\,2} + b_1^{\,2}\right)^{1/2}.$$

Spectrally averaged data, made from restored non-feasible data, include

$$\mathrm{MDIR} = \mathrm{atan}_2\left(\overline{b}_1, \overline{a}_1\right),$$
$$\mathrm{UI} = \sqrt{\overline{a}^2 + \overline{b}^2},$$

where

$$\overline{a} = \frac{\int a(f)S(f)df}{\int S(f)df},$$
$$\overline{b} = \int b(f)S(f)df.$$

In addition, the mean direction and the directional spread values at the spectral peak period are computed, $\theta_1\left(f_p\right), \sigma_1\left(f_p\right)$.

4 CO-LOCATED DATA

4.1 Cases and Events

The present database consists of all together 2760 different co-located *cases*. A case consists of co-located ASAR, WAM and Buoy directional spectra. Non-directional buoys are not included. Some of the cases also include complex co-located imagettes.

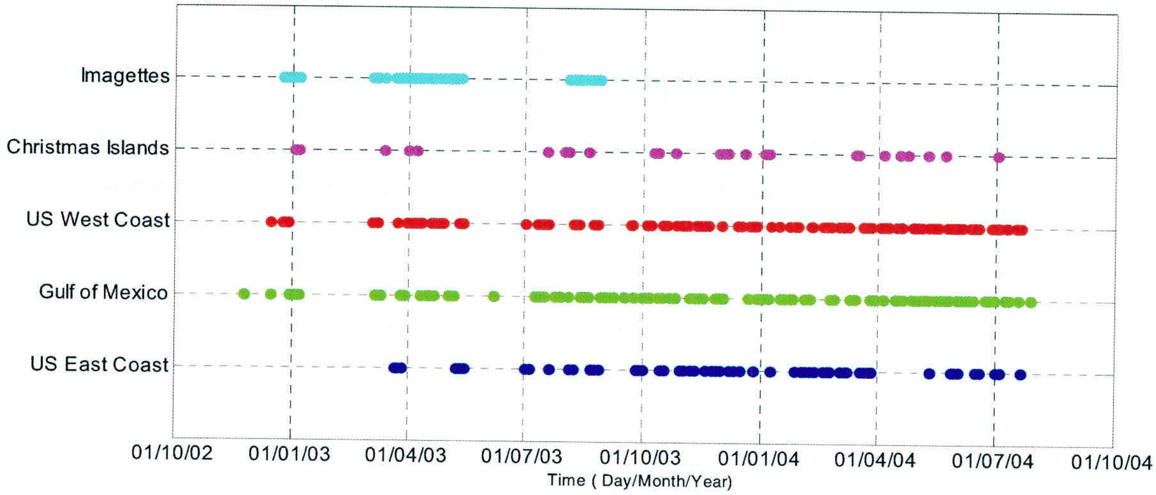

Figure 4.1: All 2760 cases sorted on location and time.

An *event* contains several cases and is typically associated with one satellite pass. One ASAR spectrum/imagette may be combined with several buoy spectra. There is a one-to-one relationship between the ASAR and the WAM spectra; only the closest WAM spectrum in time and space is included in the database. Moreover, more than one imagette may belong to the same event. There are 304 different events in the database covering a time span from 24 November 2002 to 27 July 2004. Unfortunately, no imagettes have been available after August 27, 2003, and altogether there are 204 imagettes in the database, covering 559 of the 2760 cases and contributing to 59 independent events.

Table 4.1: Number of events and events with imagettes.

Location	Number of cases	Number of imagettes	Number of events	Events w/imagettes
Chrismas Island	352	32	56	9
US West Coast	856	19	103	17
Gulf of Mexico	1430	109	119	27
US East Coast	122	44	26	6
SUM	2760	204	304	59

A list of the 59 events also including co-located imagettes is given in Tables. 4.2.

The database does not contain real high sea states and many cases are from near-shore areas where the wave conditions are likely to be rapidly varying in space.

Table 4.2: Survey of all 59 events containing imagette information sorted according to the locations. The case numbers refer to the numbering of the IndexArray database, whereas the imagette number refers to the actual number of the data file. The significant wave height is approximate and will typically vary over the event.

Case	Date/time	Location	Imagette	Hs(m)	Wave modulation
192-199	20030321/0828	Chrismas Island	57-60	1.8	Strong
216-221	20030323/2000	Chrismas Island	65-67	2.8	Strong. Mixed seas
234-241	20030326/2005	Chrismas Island	68-71	2	Strong (directions)
454-457	20030508/0820	Chrismas Island	140-141	2.0	Swell
684-691	20030805/0822	Chrismas Island	148-151	1.7	-
712-719	20030808/0828	Chrismas Island	157-160	1,7	Strong
792-797	20030821/0820	Chrismas Island	185-187	2.3	Very weak
814-921	20030824/0825	Chrismas Island	194-197	2.0	Short wave mod.
838-843	20030827/0831	Chrismas Island	202-204	1.8	-
27-36	20021224/1628	Gulf of Mexico	1-4	2	-
37-54	20021225/1556	Gulf of Mexico	5-9	2.5	Weak/strong
55-70	20021228/1602	Gulf of Mexico	10-16	1.2	-
121-134	20030304/1628	Gulf of Mexico	38-41	2	Weak
145-160	20030307/1634	Gulf of Mexico	45-50	1	-
161-163	20030308/1603	Gulf of Mexico	51-52	1.5	Very weak
200-215	20030323/1631	Gulf of Mexico	61-64	0.5	-
246-251	20030330/1611	Gulf of Mexico	74-75	3	No mod. Far from buoy?
264-275	20030403/1544	Gulf of Mexico	76-78	.5	Very weak
276-291	20030405/1622	Gulf of Mexico	79-84	1.3	Weak mod. Fits WAM
292-301	20030406/1550	Gulf of Mexico	85-87	0.5	-
306-319	20030408/1628	Gulf of Mexico	90-93	2.8	-
320-335	20030409/1556	Gulf of Mexico	94-96	1	-
346-353	20030411/1634	Gulf of Mexico	100-101	0.3	-
366-374	20030418/1614	Gulf of Mexico	107-110	0.8	-
374-379	20030419/1542	Gulf of Mexico	111-113	0.5	No mod.
384-395	20030421/1619	Gulf of Mexico	116-120	1.0	-
396-411	20030424/1625	Gulf of Mexico	121-125	1.8	Weak, short waves
412-423	20030427/1631	Gulf of Mexico	126-129	0.8	-
424-433	20030428/1559	Gulf of Mexico	130-132	0.7	Very weak
482-487	20030511/1551	Gulf of Mexico	142-143	1.0	-
692-711	20030807/1625	Gulf of Mexico	152-156	0.8	-
720-739	20030808/1553	Gulf of Mexico	161-166	1.0	-
740-742	20030810/1631	Gulf of Mexico	167	0,8	-
744-761	20030811/1559	Gulf of Mexico	168-173	0.2	-
798-813	20030823/1622	Gulf of Mexico	188-193	0.3	-
822-837	20030826/1628	Gulf of Mexico	198-201	0.3	Large scale m. No waves
81-90	20030102/1501	US East Coast	21-25	3	-
101-114	20030105/1507	US East Coast	29-34	1	Very weak on some
184-191	20030313/1501	US East Coast	53-56	1	Very weak
302-305	20030407/1516	US East Coast	88-89	2,6	SAR partly on shore
676-679	20030803/1507	US East Coast	144-145	1.0	-
782-783	20030819/1504	US East Coast	181	0.5	-
71-80	20021229/1846	US West Coast	17-20	1.6	Medium modulation
91-100	20030102/1823	US West Coast	26-28	2.7	Strong/weak
115-120	20030105/1829	US West Coast	35-37	5	Strong
135-144	20030306/1840	US West Coast	42-44	3	Strong
242-245	20030328/1849	US West Coast	72-73	2.5	Strong
336-345	20030410/1841	US West Coast	97-99	2	Strong
354-359	20030414/1818	US West Coast	102-103	2.5	Moderate/strong
360-365	20030417/1823	US West Coast	104-106	2.0	Strong
380-383	20030420/1829	US West Coast	114-115	2.3	Strong
434-439	20030502/1849	US West Coast	133-135	1.3	North loc. Weak mod.
440-445	20030503/1821	US West Coast	136-137	2.1	Strong/malfunc. buoy
446-453	20030506/1826	US West Coast	138-139	1.9	Strong/mixed
680-683	20030803/1829	US West Coast	146-147	1.3	Strong
762-777	20030812/1843	US West Coast	174-178	1.0	Large scale mod. only
778-779	20030813/1815	US West Coast	179	1.6	-
780-781	20030815/1849	US West Coast	180	1.5	Very weak
784-791	20030819/1826	US West Coast	182-184	2.2	Very weak

4.2 Examples of Data

A complete PDF-file (more that 1000 pages) containing plots of all imagettes, co-located spectra, survey location maps, and tables of the main wave parameters are published electronically along with this report. This book gives a comprehensive overview of the 559 cases where imagettes are also present (at the locations of the ASAR spectrum.

Figure 4.2 shows co-located wavenumber spectra as indicated on the graph. The lower right corner shows the map around the site. Note that this figure is just a low-resolution copy of the original PDF-figure.

Although preferred presentation in the Remote Sensing community, the Ocean Engineering community prefers directional spectra presented in terms of the θ - *f*-variables, as shown in Fig. 4.3.

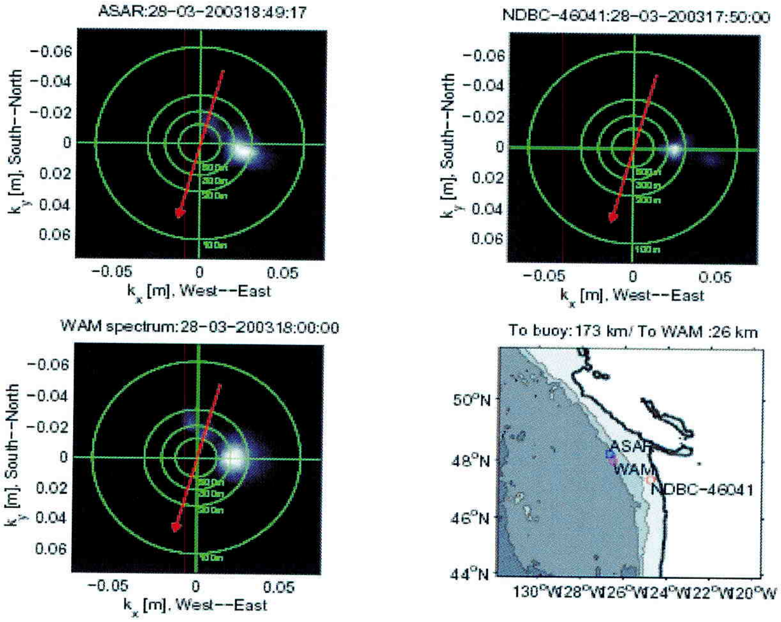

Figure 4.2: Directional wavenumber spectra showing the satellite azimuth heading as a red arrow. The circles are (from outer to inner) 100, 200, 300, 400 m, and the shading is autoscaled according to the maximum. The scale of the map is adjusted according to the distances between the measurements.

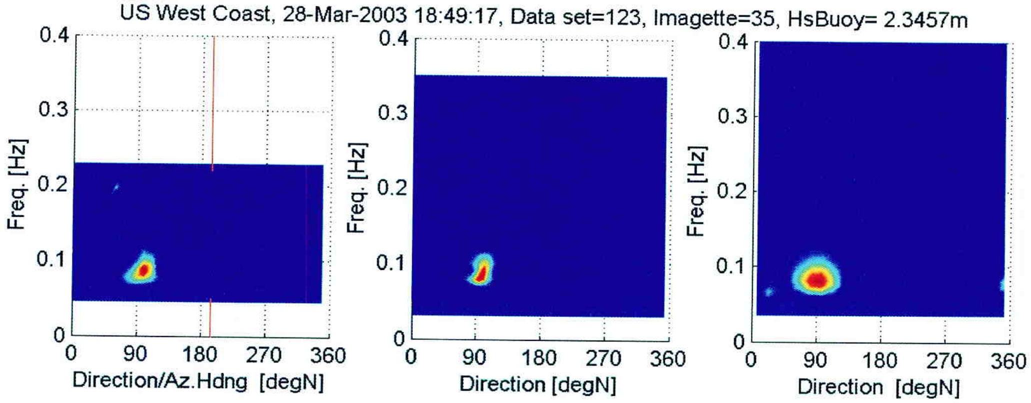

Figure 4.3: Directional spectra shown for ASAR (left) wave buoy (middle), and WAM (right). Same case as shown in Fig. 4.2.

The imagettes data in the database are single look complex imagettes, which for simplicity have been stored as a Matlab structure variable.

The data are given as (int16, int16) complex numbers in azimuth and slant range. However, the imagettes below are shown in *azimuth* and *ground* range implying that the scales in both directions are the same. For noise suppression, the modulus of the complex amplitude has been averaged (in the Fourier domain) with a 2D Gaussian window where

$$\sigma_{Az} = 2.4 \times \Delta_{Az} = 9.7\,\mathrm{m}$$
$$\sigma_{Rg} = 0.6 \times \Delta_{Rg} = 12.1\,\mathrm{m}$$

The grey scale is adjusted so as to extract so as to maximize the contrast without missing too much information.

The imagette corresponding to the case on the previous figures is shown in Fig. 4.4,

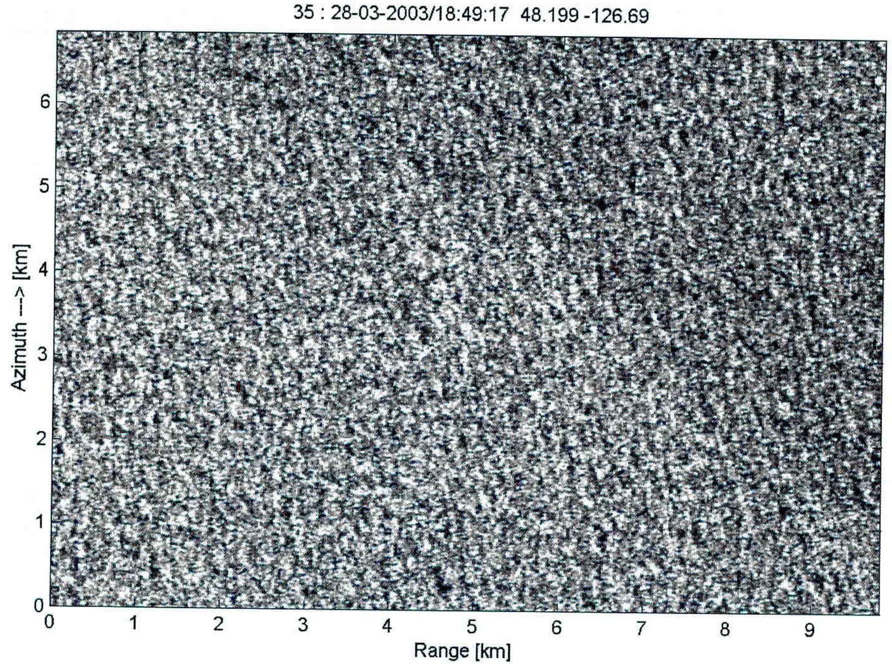

Figure 4.4 Imagette no. 35 shown in the ground range/azimuth coordinates.

Table 4.4: Copy of the tables of wave parameters shown in the PDF compilation

Field name [unit] / Method	WAM	ASAR	Buoy
Wave height [m]	1.79	1.64	1.83
Peak period, T_p [s]	14.86	19.62	7.14
Main wave dir. [^{o}]	102.24	98.50	262.24
Wind speed [m/s]	4.18	0.81	7.20
Wind dir. [^{o}]	284.30	328.68	304.00

Figures 4.5 – 4.6 show additional cases from the database.

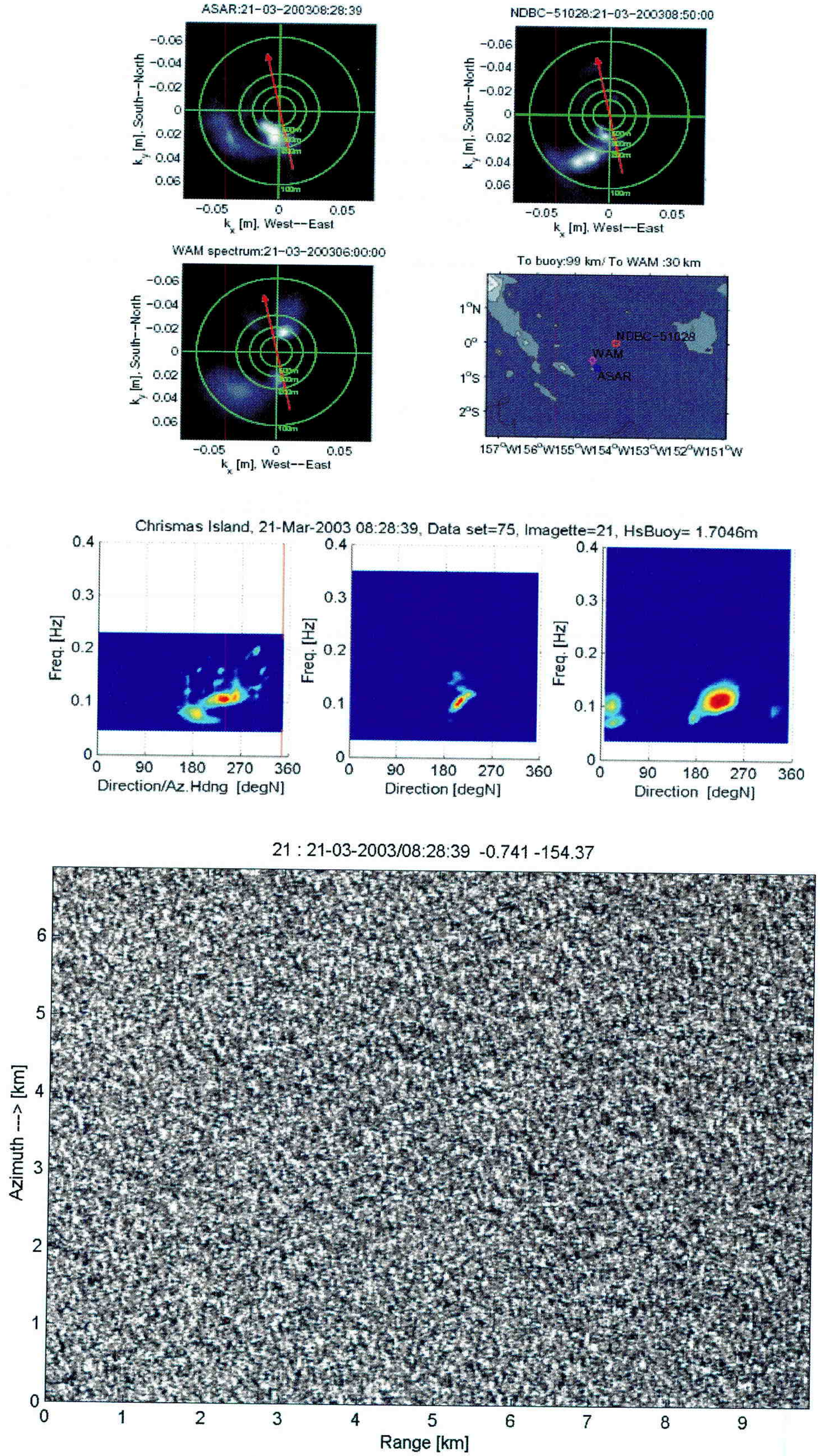

Figure 4.5: Data set from the Christmas Island

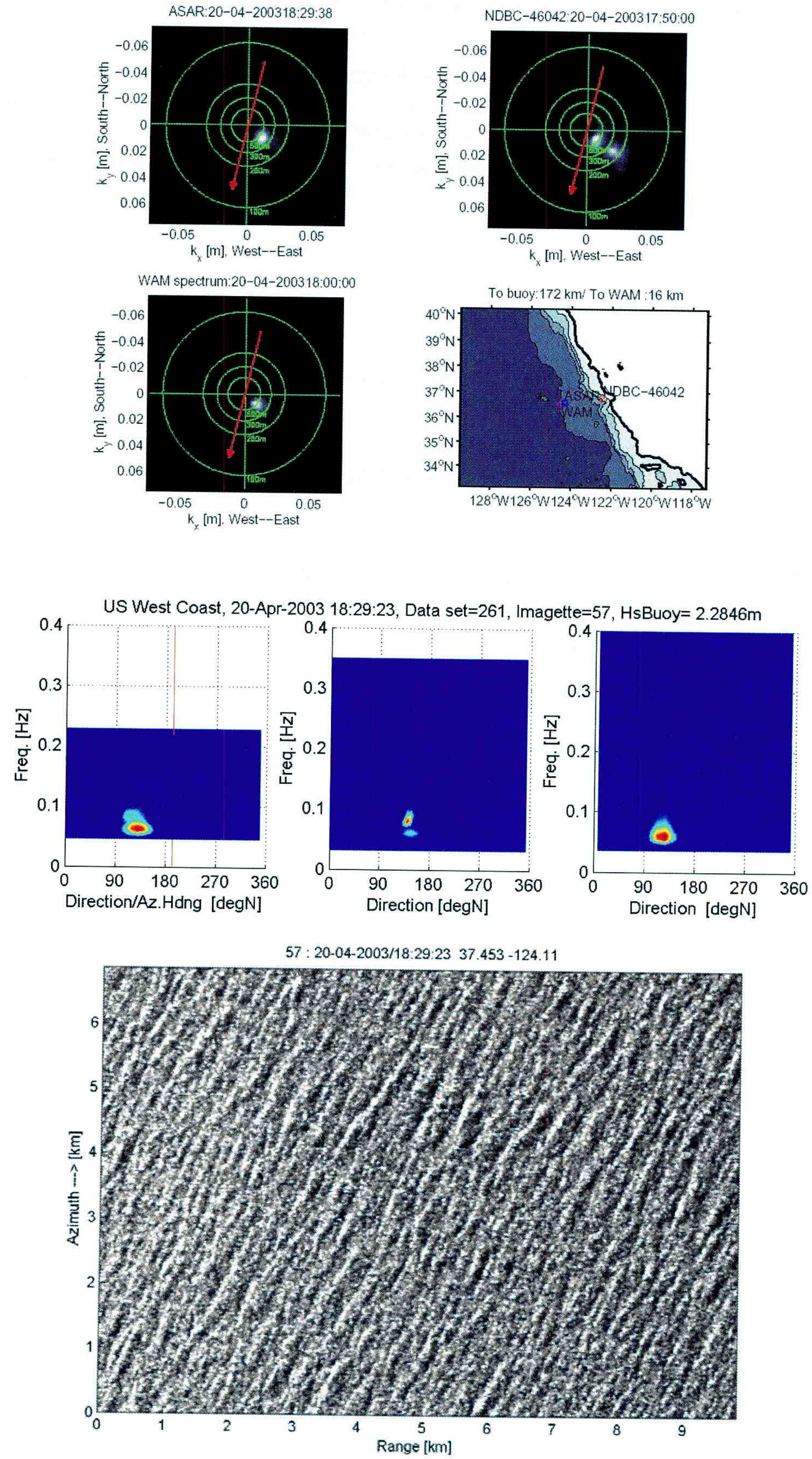

Figure 4.6: Data set from the US West Coast.

5 DATA SURVEY AND QUALITY TESTING

The following section contains an overview of the database and illustrates first of all that simply taking all data together as they are does not make much sense.

Figure 5.1 shows scatter plots of non-directional parameters for all 2760 cases in the database. There is a considerable amount of scatter and many outliers in the ASAR spectra. We shall later trace these to be numerous cases of virtually useless ASAR spectra.

In addition, the scatter between buoys and the WAM model is also surprisingly high, in particular with respect to the peak wave period.

The main directional parameters are shown in Figure 5.2. The scatter is again quite large, both for the dominant wave directions and in particular for the directional spread.

It is obvious that the ASAR spectra cannot be used in any sensible way without further internal and external quality checks.

In the following we show various tests with the data in order to trace the sources of the observed deviations. First of all, a visual scan through all data is carried out by inspecting all cases manually for a graph similar to Fig. 4.3 and categorizing each case into one of four classes, ranging from an almost perfect match to completely meaningless spectra.

Only about 1/3 of the imagettes contain visible wave information, and by limiting the intercomparison to these cases only, the intercomparison improves significantly.

The data are also checked with respect to the distance between the ASAR and buoy locations. The distance between the ASAR and the WAM locations are less than 50km in all cases.

Finally, the internal quality parameters provided with the ASAR product are considered.

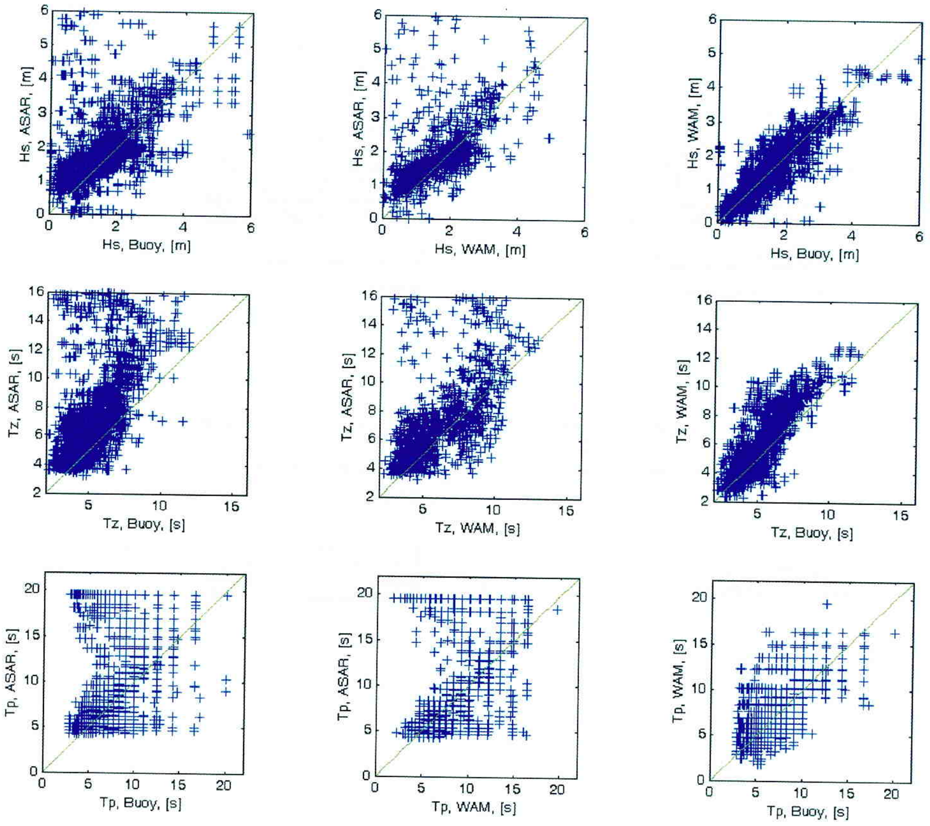

Figure 5.1: Scatter plots of the significant wave height, *Hs*, mean wave period, *Tm02*, and the peak period, *Tp*.

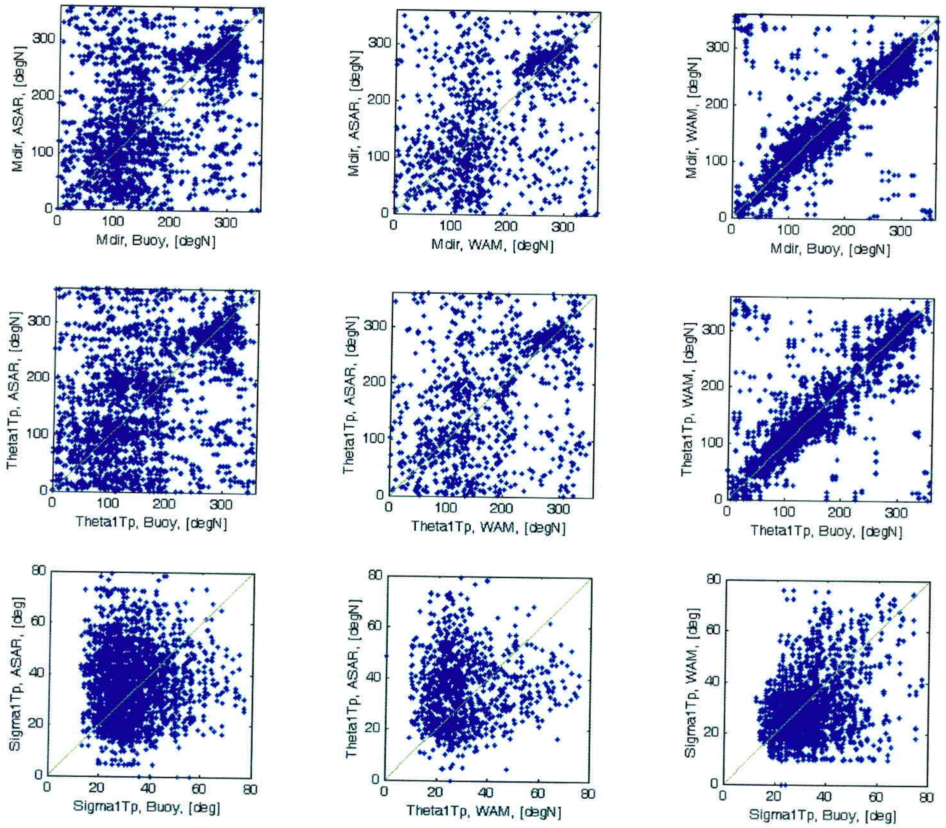

Figure 5.2: Scatter plot of all data for the main directional parameters,

5.1 Manual Quality Checks

5.1.1 Visual Inspection of Spectra

The size of the database makes it possible to carry out a manual quality check of all spectra and assign a quality parameter to each case. The cases have thus been divided into 4 categories ranging from a near perfect match to what looks like completely meaningless spectra. The categories may be described as follows, where the amount in each category has been listed as well.

Category 1: Very Good (18%): *All three spectra are visually similar, apart from minor differences probably caused by in-homogeneities in the wave field and sampling variations.*

Category 2: Good (12%): *Larger deviations, but generally good agreement, at least between the ASAR spectrum and one of the other spectra.*

Category 3: Some correspondence (10%): *Part of the ASAR spectrum show some resemblance to the others, but typically the spectrum contains additional spurious contributions not seen in the buoy and the WAM spectra.*

Category 4: Meaningless (60%): *No apparent similarity between the ASAR spectrum and any of the other spectra.*

The subdivision is subjective and should not be considered absolute.

Examples of spectra from the different categories are shown in Fig. 5.3.

The distributions of the cases into the various categories are highly different for the various locations. This is shown in Fig. 5.4. The US west coast has by far the largest fraction of good cases, in accordance with rather rough wave climate and mostly range travelling waves.

On the other extreme, more than 80 % of all spectra from the Gulf of Mexico appear to be useless. Also the US east coast has a surprisingly high number of meaningless cases.

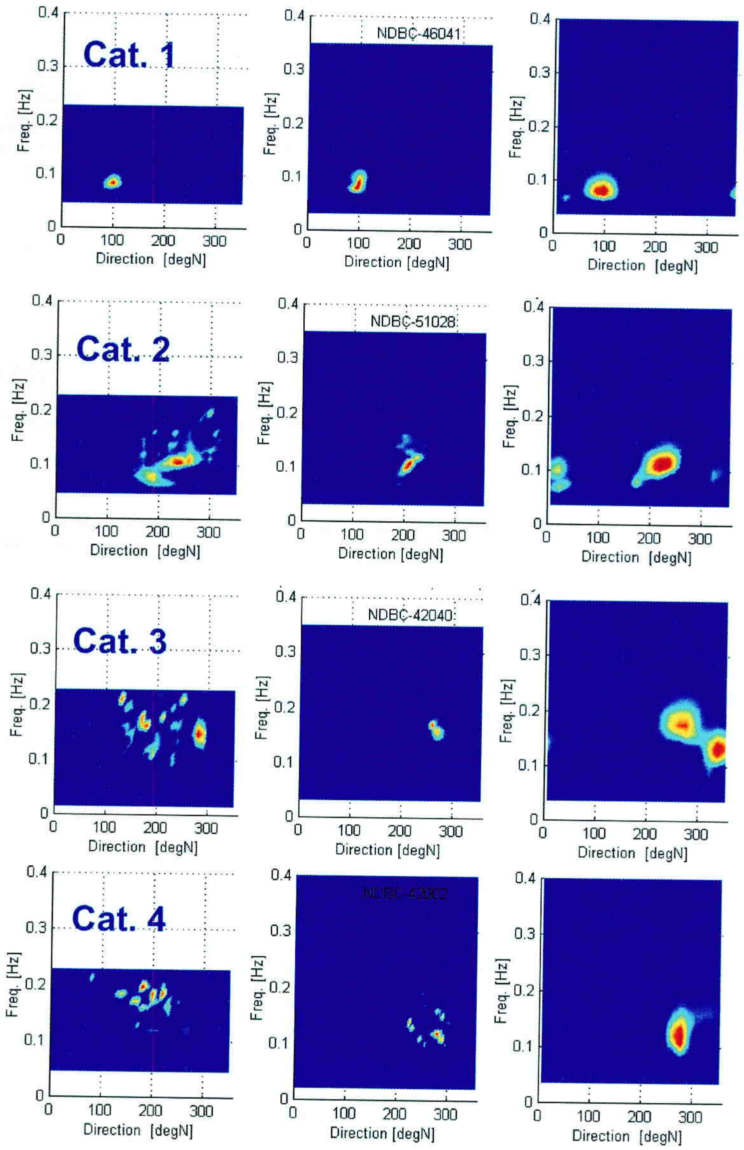

Figure 5.3: Examples of spectra from the various categories.

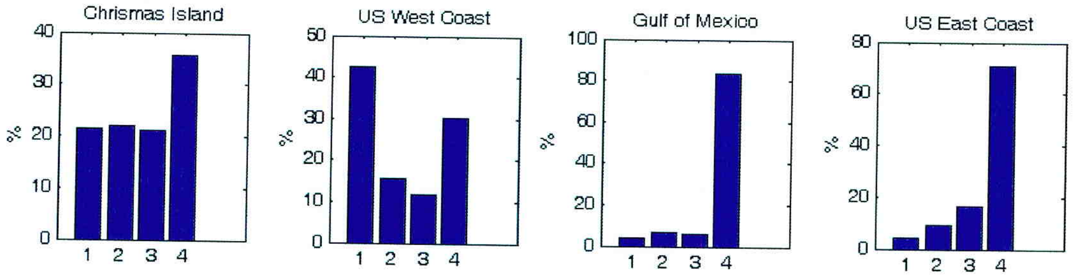

Figure 5.4: Percentage occurrence of cases sorted according to category.

By restricting the scatter plots to Category 1 cases, the quality of the regressions improve considerably and is, in fact, quite comparable to the scatter between the buoys and the WAM data. The non-directional wave parameters are all computed from extrapolated spectra. We observe that outliers for *Hs* seem to be caused by the buoy data. There is also a clear tendency to longer mean wave periods from ASAR compared to the buoy. However, this is somewhat surprising and for an unknown reason, also evident in the WAM/buoy intercomparison. There are some long peak periods caused by spurious low frequency contributions in the ASAR spectrum. This is often seen in the ASAR spectra and is probably caused by large-scale non-wave features in the imagettes.

Peak and mean directions are comparable to the WAM/buoy intercomparison, whereas the directional spread shows virtually no correspondence for any of the data sets.

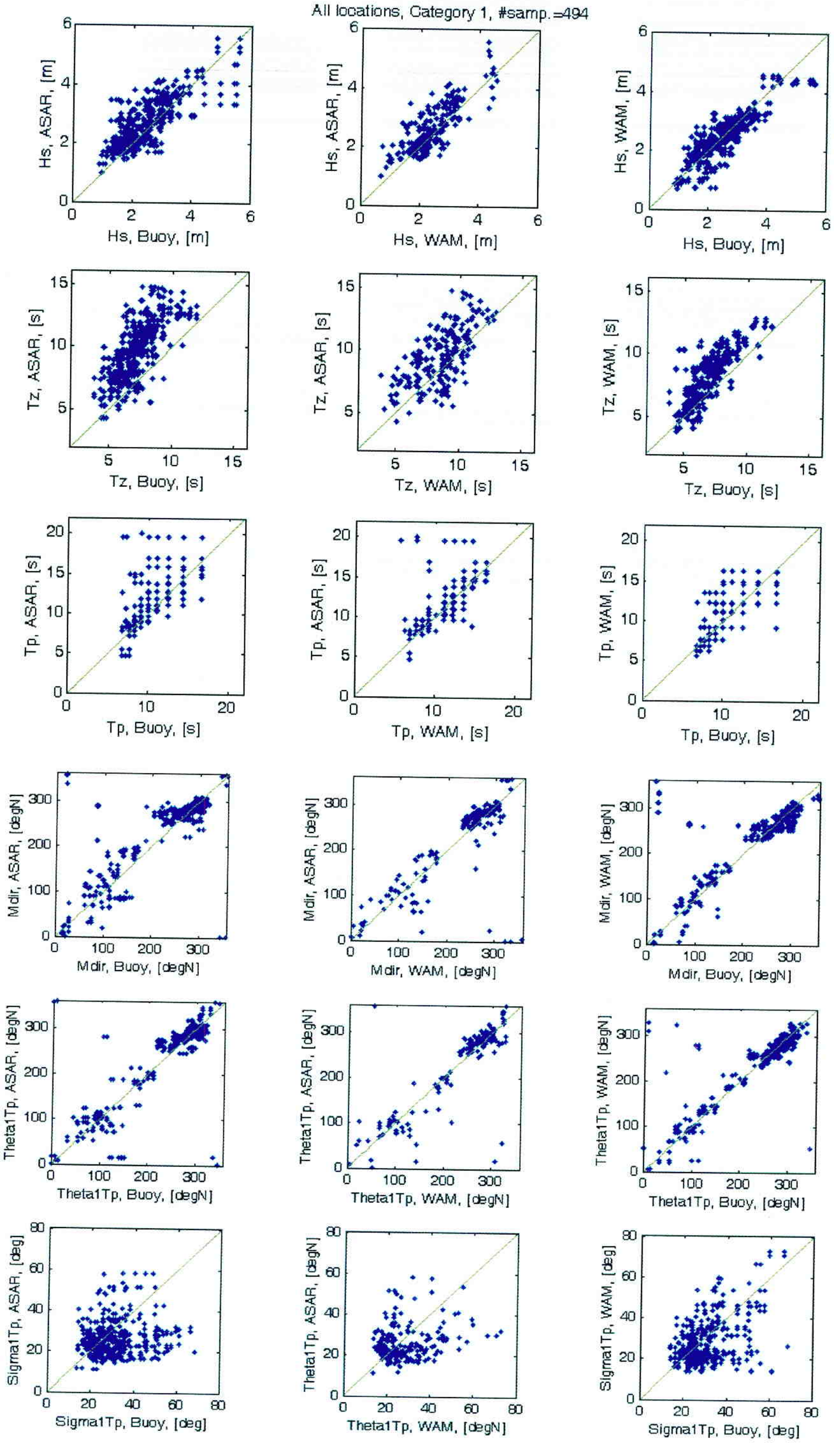

Figure 5.5: Intercomparison of wave data for Category 1 cases. All four locations pooled together.

Restricting the comparisons to the best location, the US West Coast, improves the correspondence even further, as illustrated in Fig. 5.6.

Outliers in the directions are obviously due to the buoys. However, the directional spread still shows very little correspondence.

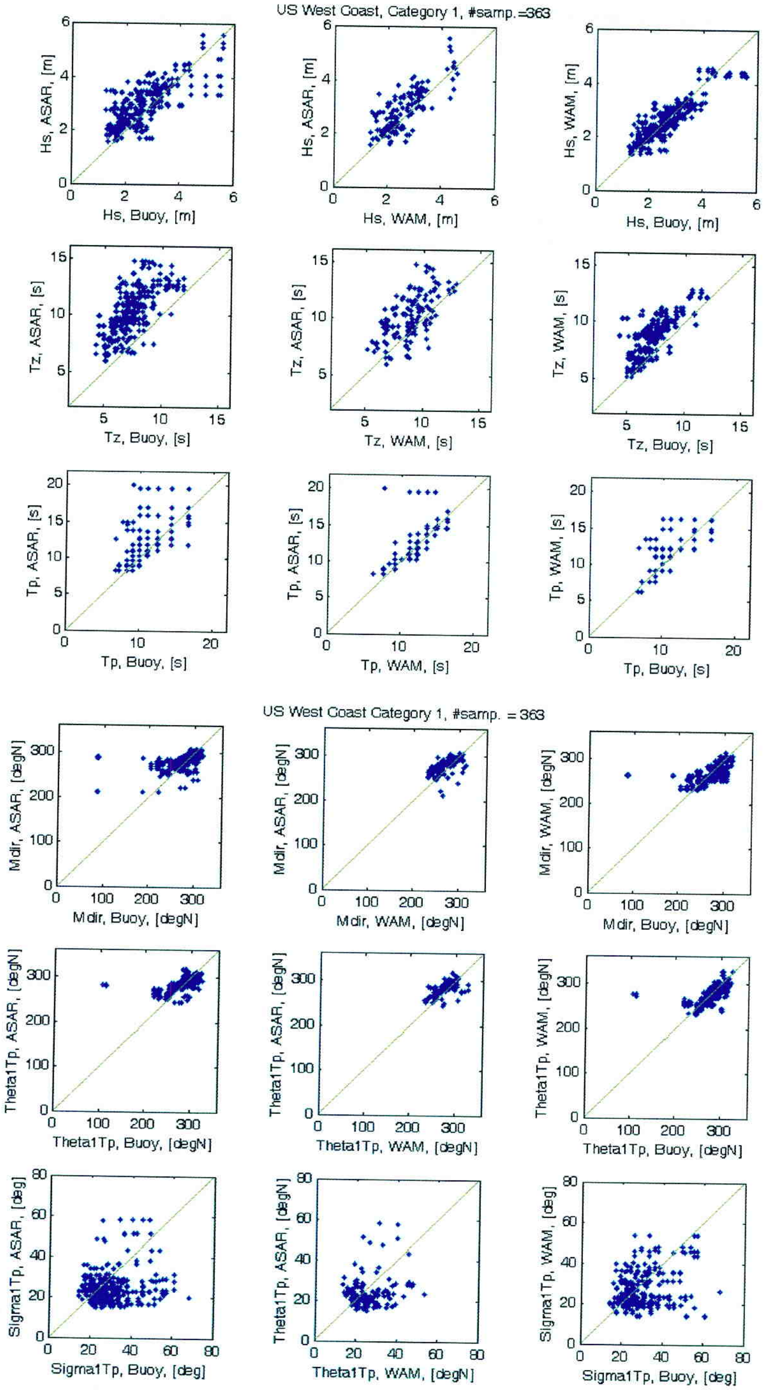

Figure 5.6: Intercomparisons of Category 1 cases for the US West Coast.

5.1.2 Visual Inspection of Imagettes

Only 61 of the 204 imagettes contain visible wave information, and by restricting the intercomparisons to the corresponding 157 cases, the intercomparison improves considerably from the all-inclusive case, but is still far from being perfect. The result is shown in Fig. 5.7. For some reason, the scatter between the WAM data and ASAR appears to be smaller than the corresponding scatter between ASAR and the buoys. In particular, the direction at the spectral peak is now reasonably good.

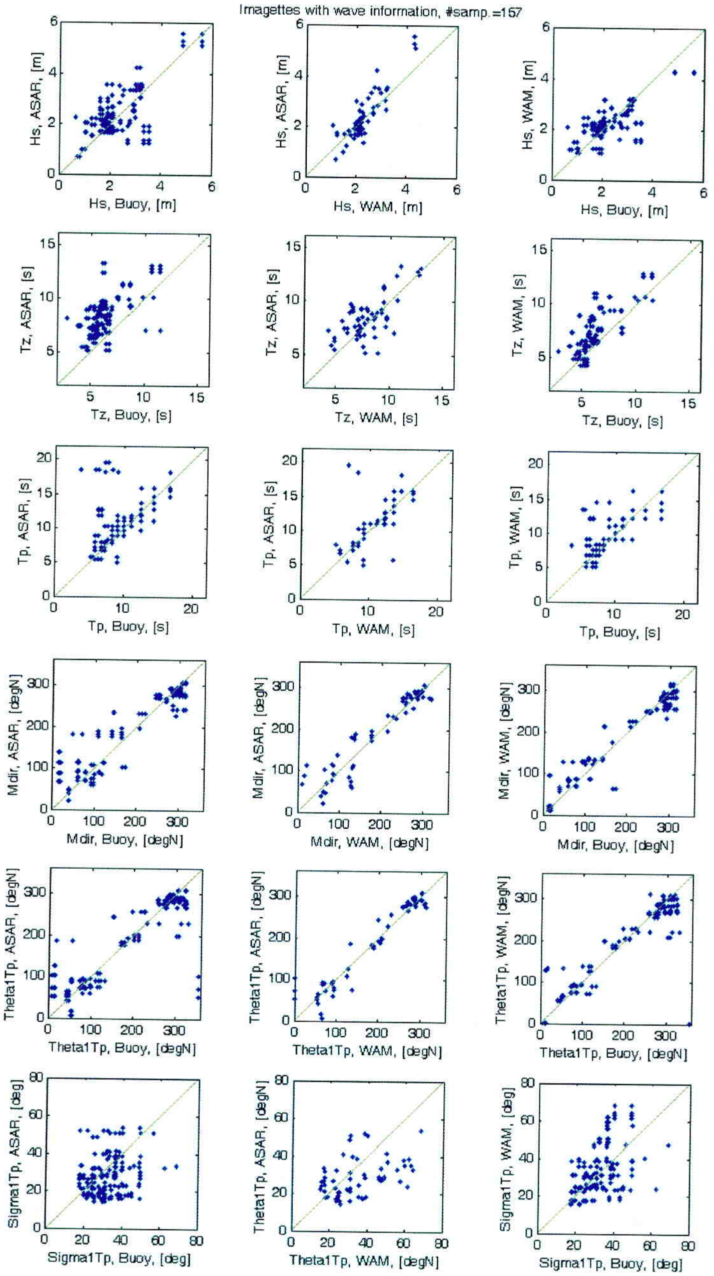

Figure 5.7: Intercomparison of wave parameters for cases where the corresponding imagettes show visible wave modulation.

5.2 Distance Dependence

Since the maximum distance between the ASAR/imagette and the nearest WAM point is less or equal to 25km, we do not expect any distance dependence in the WAM-ASAR intercomparison. The time difference may, however, may be up to three hours, but this has not been looked at more closely.

On the contrary, the distance between the buoy and ASAR location may reach 275km, whereas the time difference is less than one hour.

Figures 5.8a–c show the main wave parameters and how they change with the distance between the Buoys and the ASAR. A very slight improvement of the correlation may be observed when distance diminishes.

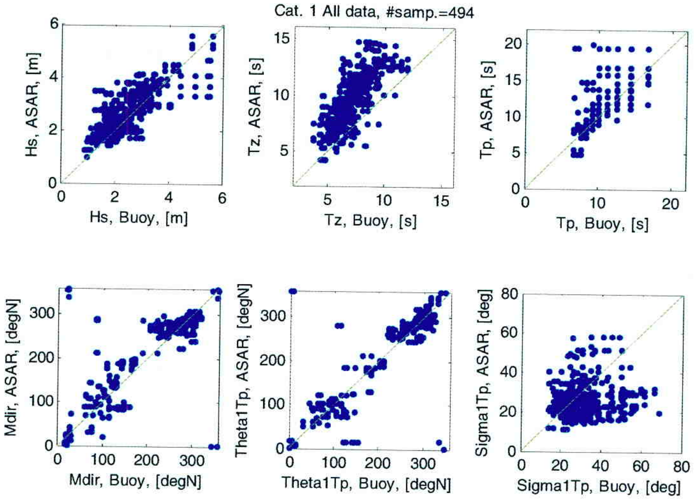

Figure 5.8a: Scatter plots for buoy and ASAR wave parameters including all data in the database.

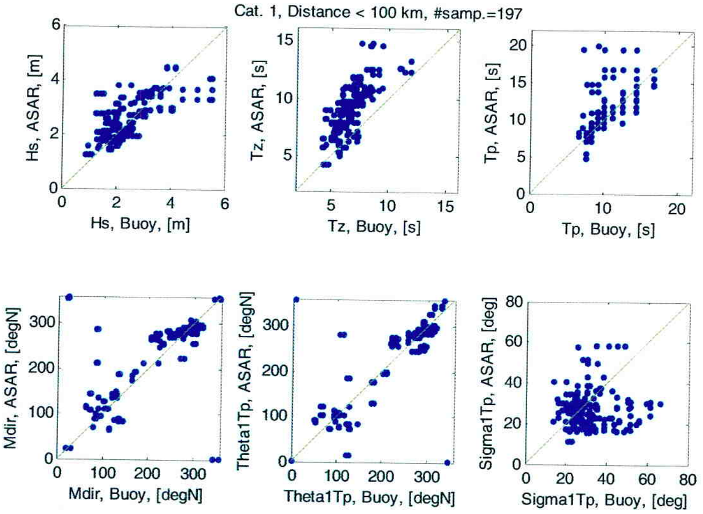

Figure 5.8b: Scatter plots for buoy and ASAR wave parameters including all data where the ASAR – buoy distance is less than 100km.

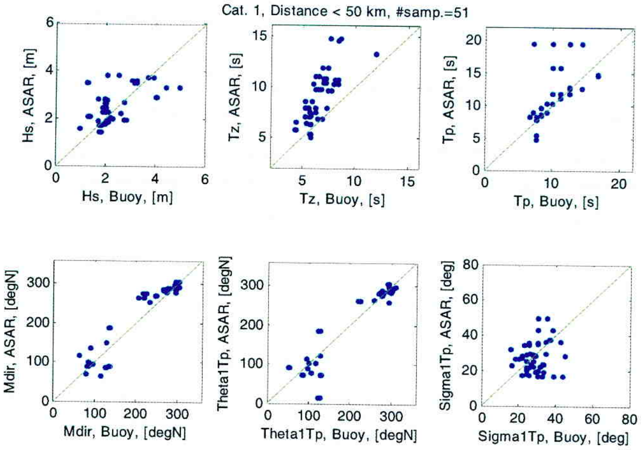

Figure 5.8c: Scatter plots for buoy and ASAR wave parameters including all data where the ASAR – buoy distance is less than 50km.

5.3 Testing of the Internal Quality Parameters

The ASAR spectra are distributed with a set of automatically generated quality parameters. The parameters were already listed in Section 2.2.1, and consist of 4 binary flags (default 0):

Land Flag: 1 for "above land" spectra.

Confidence swell: 1 if the retrieved wave direction shows an 180° ambiguity.

Confidence wind: 1 if an external wind direction was used during the inversion.

Attach_flag: 1 if the cross-spectrum could not be computed from the imagette.

In addition, the following parameters are included:

Normalized Image Variance, σ_1: The image variance scaled with the variance for pure speckle noise. The values range from 1 and upwards.

Azimuth cut-off wavelength, λ_c: The azimuth cut-off of the SAR spectrum defines the azimuth pass band for meaningful spectral information.

Further descriptions of the parameters are found in [1].

A scan through the database shows that the *Confidence wind* flag is set for all cases, and this is therefore not considered further. Moreover, none of the cases have *Attach flag* equal to zero.

The Land flag is up for 61 of the cases. Most of these were given visual quality factor equal to 3 and 4, but there are actually 2 spectra that have visual quality factor equal to 1, and this is apparently caused by an erroneous land mask. The M_Map terrain database showed these ASAR spectra in fact were from the open ocean, as is also obvious from a visual inspection of the ASAR spectrum.

The only remaining flag is the *confidence swell* flag, set for 59 cases. All the cases have quality 3 and 4 apart from one case, where the swell direction is perfect, although shows a 180 degree ambiguity.

A histogram of the Normalized Image Variance, σ_1 is shown in Fig. 5.9. As discussed in [1], the good cases are usually found for σ_1 around 1.2.

A similar figure for the azimuth cut-off wavelength λ_c is given in Fig. 5.10. This cut-off wavelength should not be used directly for the ASAR spectrum, but be corrected according to the formula

$$\lambda^*_{cut} = \frac{\lambda_c}{2} + 90\text{m},$$

following the information in [1].

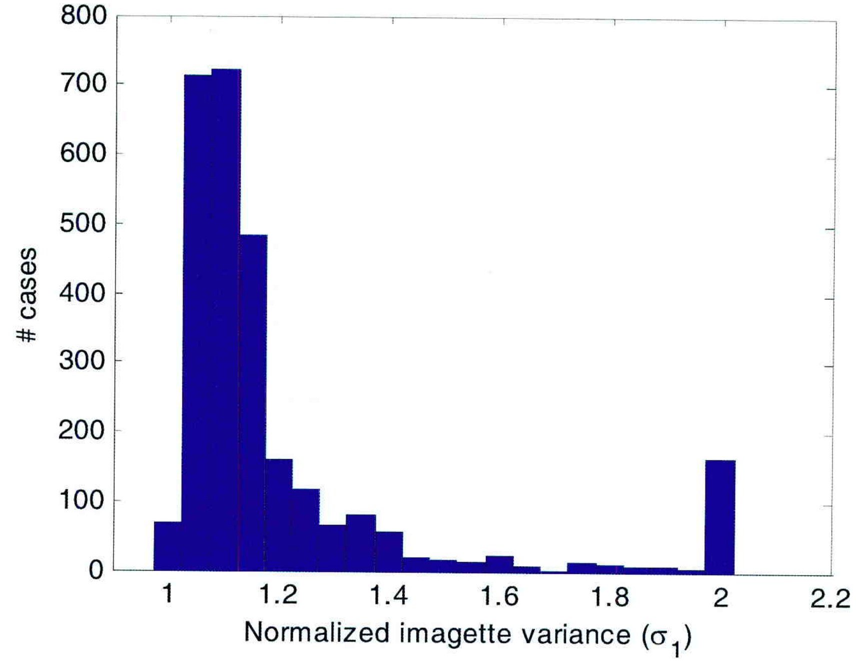

Figure 5.9: Histogram of the normalized image variance for all cases on the database. All values above 2 are pooled into the last bin.

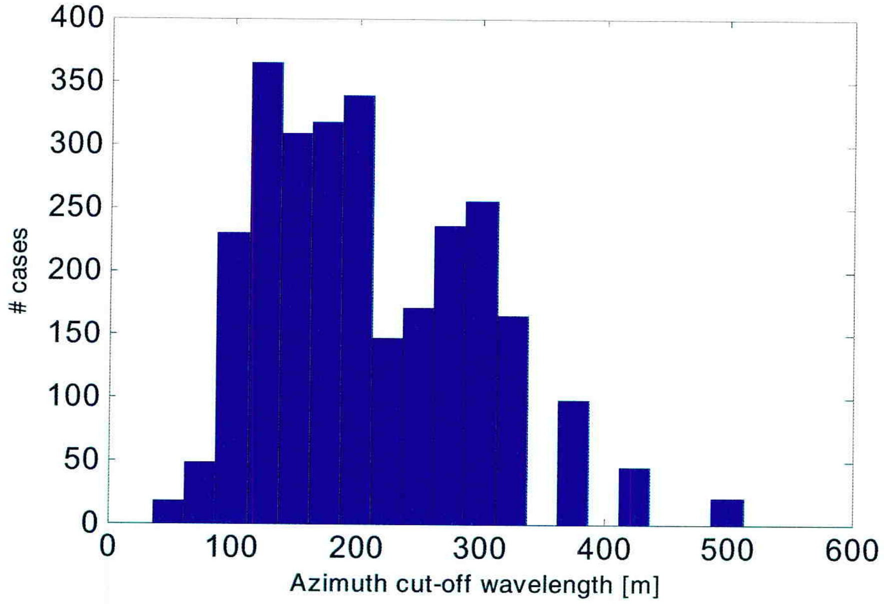

Figure 5.10: Histogram of the azimuth cutoff wavelength.

5.3.1 The Normalized Image Variance

If we create histograms of the normalized image variance according to the Visual quality parameters (Fig. 5.11), the difference between the best and the worst quality is quite obvious. However, since a major part of quality 3 and 4 also has $\sigma_1 \approx 1.2$, it is not easy to use this parameter as a test of the quality.

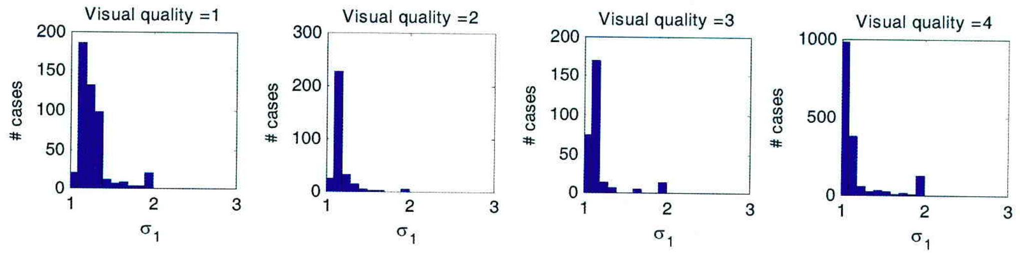

Figure 5.11: Histograms of the normalized image variance sorted according to quality from 1 (best) to 4 (meaningless).

Nevertheless, Figure 5.12 shows the correlation for the significant wave height, using an extrapolated spectrum outside the interval [0.06Hz, 0.13Hz]. By limiting the image variance σ_1 to the neighbourhood of 1.2, the significant wave height does now give a correlation that is comparable to the WAM/Buoy intercomparison.

Two imagettes are shown on the following page; one with normalized image variance equal 3.84 and clearly inhomogeneous, and the other with normalized image variance 1.13. Even the last one is clearly in-homogeneous.

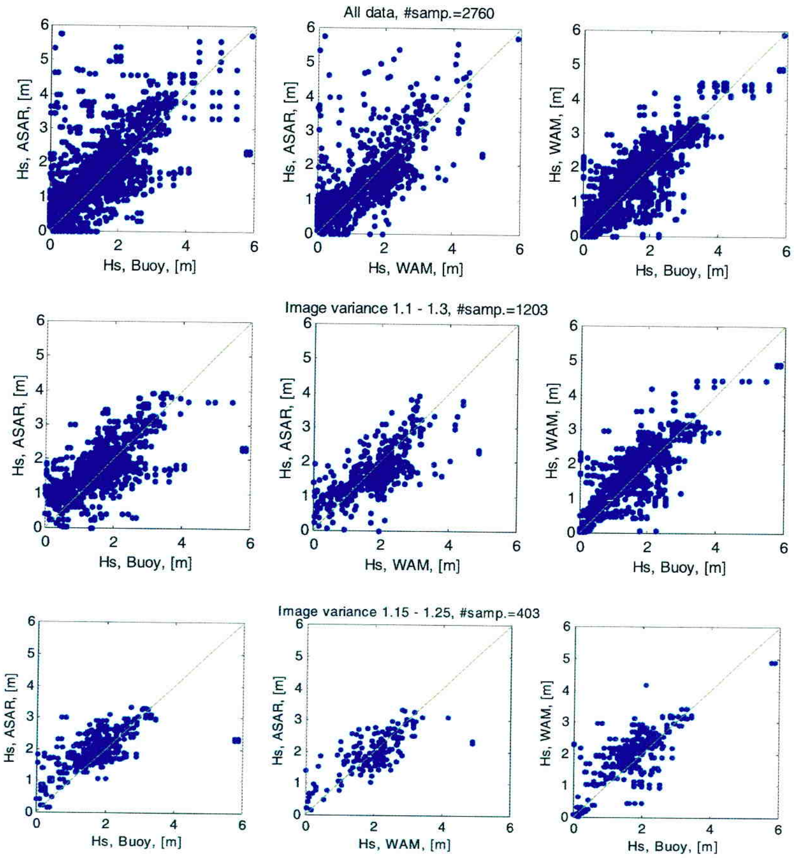

Figure 5.12: The correlation for the significant wave height for various ranges of the normalized image variance.

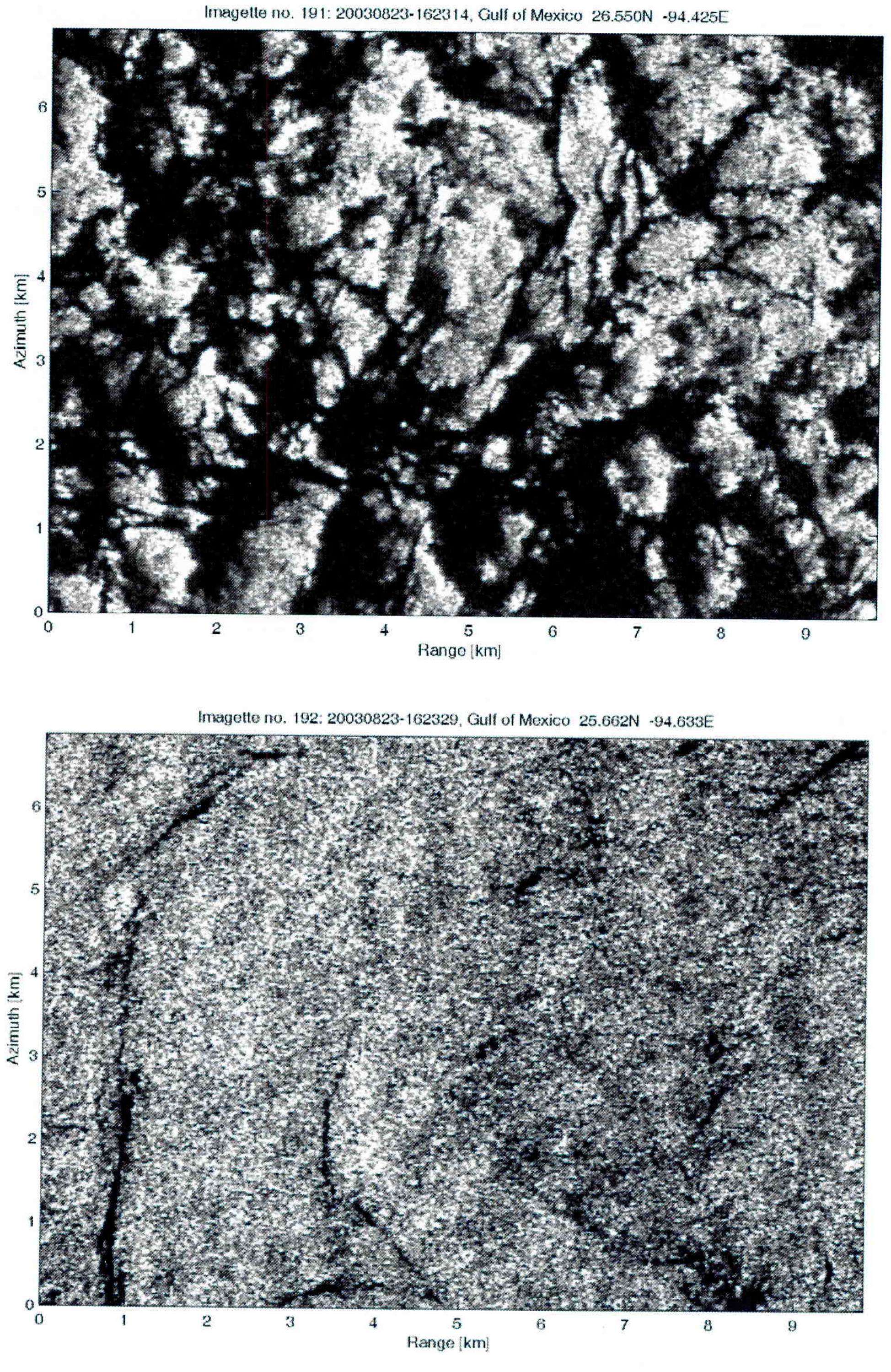

Figure 5.13: Examples of inhomogeneous imagettes. The upper one has normalized image variance equal to 3.84, whereas the lower one has variance 1.13, which is considered quite reasonable.

5.3.2 The Azimuth Cut-off Wavelength

The azimuth cut-off wavelength λ_{cut}^{*} is the final of the internal quality parameters. It defines an azimuth pass band filter parallel to the range axis, which in essence limits the meaningful information to a region

$$\Omega = \left\{ \mathbf{k} = k_{Az}\mathbf{i}_{Az} + k_{Rg}\mathbf{i}_{Rg} \; ; \; k_{\min} \le |\mathbf{k}| \le k_{\max} \, , |k_{Az}| \le \frac{2\pi}{\lambda_{cut}^{*}} \right\},$$

where λ_{cut}^{*} is the *modified* cut-off wavelength. The mask in the frequency/direction domain will have an appearance as indicated in Fig. 5.14. Roughly speaking, the ASAR directional spectrum is only meant to be reasonable within the white region.

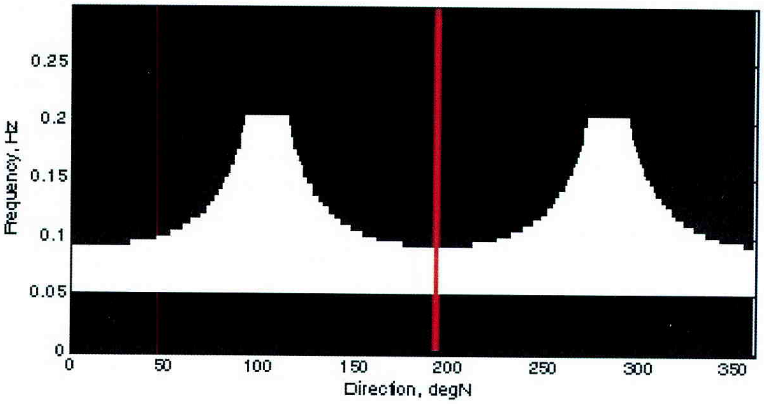

Figure 5.14: ASAR spectrum mask in the Frequency/Direction domain. Frequency band 0.05 – 0.2 Hz, azimuth heading 193 degrees, and λ_{cut}^{*} leading to a frequency cut-off in the azimuth direction at 0.09Hz.

This has been checked out for the database as follows. The parameters determining the mask are the cut-off, λ_{cut}^{*}, the azimuth heading, θ_{Az}, and the reasonable frequency band, say $[f_{\min}, f_{\max}]$. It order to compare the different spectra, this mask has therefore to be applied *for all spectra*, and the only meaningful parameter is the corresponding significant wave height,

$$Hs_{Mask} = 4\left(\int_{Mask} S(f,\theta)\, df d\theta \right)^{1/2} .$$

The result is shown in Fig. 5.15. Note that the directional spectra have somewhat different resolution, but all masks have been based on the ASAR parameters only, and $f_{\min}$=0.05Hz, $f_{\max}$=0.22 Hz. The scatter has diminished somewhat from Fig. 5.1, but taking into account that a meaningless spectrum is still meaningless after being masked, the result is as expected.

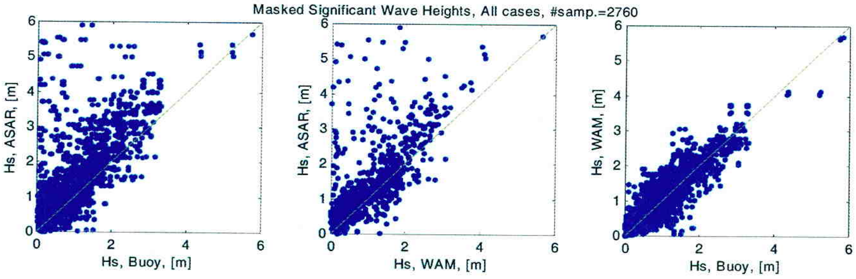

Figure 5.15: Masked significant wave heights, all cases.

Considering only cases of the best quality, Fig. 5.16, the scatter is quite small. However, the ASAR data are slightly biased high, both with respect to the buoy and the WAM data. This seems to indicate that even for the region of the wavenumber (or frequency/direction) plane where the ASAR spectrum is supposed to be reasonable, is seems that the spectral values are slightly high. The same tendency is also evident in the unmasked data shown in Fig. 5.5.

A similar plot for all data from the US West Coast shows the same tendency, although the scatter is still rather high.

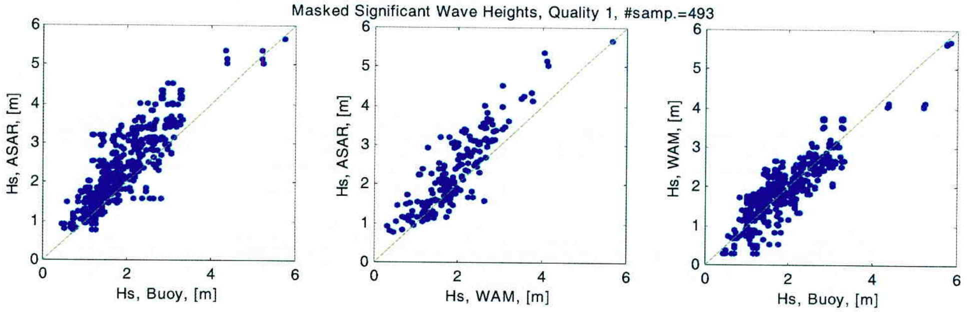

Figure 5.16: Masked significant wave heights for quality 1 data. All locations.

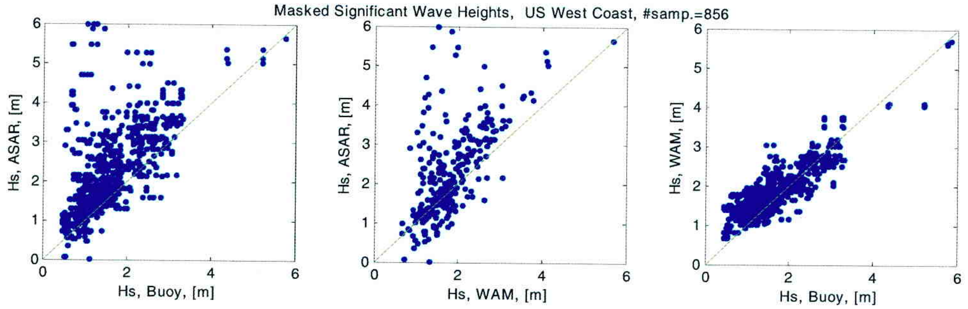

Figure 5.17: Masked significant wave heights for all data from the US West Coast.

6 CONCLUSIONS

The database described in this report describes a simple and effective way of comparing and doing computations with directional wave data from various sources. Apart from the complex imagettes, it is simple to keep all information in all the 2760 cases in the computer memory simultaneously. The cell array data structure of Matlab along with a master Index array makes it simple to extract special subset of the data for further analysis.

A quality assessment of the current ASAR directional spectra has been carried out using the new version of the database with all 2760 data sets from 304 different events. The quality of the ASAR spectra in the data is somewhat lower than expected. However, the locations of the buoys, which for the most part are close to the coast and in rather shielded seas like the Mexican Gulf, are not ideal for such comparisons.

A visual inspection of all cases gives the somewhat negative conclusion that more than half of the co-located ASAR spectra must be characterized as meaningless, as they bear no apparent correspondence to the WAM or the buoy spectra. There are several obvious reasons for this:

- No wave-related wave modulation in the image; which is the case for the majority of the Gulf of Mexico data.
- Large-scale modulations in the image not related to waves and which contaminates the spectrum, in particular for low frequencies.
- Most of the data are from coastal areas with potentially strong in-homogeneities.
- The US buoy directional data are far from perfect where some of the buoys appear to produce directional data which in essence are non-feasible.

The ASAR data contain some internal quality parameters and it has turned out that these may to some extent be used to eliminate meaningless cases. However, the present parameters appear to be insufficient.

7 REFERENCES

[1] Johnsen, H. : *Envisat ASAR Wave Mode Level 2 Product – description and reconstruction procedure*, Note, NORUT IT, May 2004, v.1.1.

[2] Johnsen, H., G. Engen and B. Chapron: *Envisat ASAR Wind&Wave Measurements from Level 1 Product*, Doc. No. IT650/2 – 01- ESA ESTEC Contract NO. 12909/98/NL/PR, 2001.

[3] Hauser, D., K. Kahma, H.E. Krogstad, S. Lehner, J.A.J. Monbaliu, L.R. Wyatt (ed.): *Measuring and Analysing the Directional Spectra of Ocean Waves*, COST Action 714, EUR 21367, 2005.

8 APPENDIX: USE AND PREPARATION OF THE DATABASE

8.1 Documentation of the Tables in the Database

The following tables describe the content of the Index Matrix and the Cell arrays in the database. Note that the variables in the Cell array can be strings, scalars and matrices.

Table A.1.1: The $n \times 4$ IndexData matrix

Column no	Description
1	Row index in the "*ASAR Data*" array
2	Row index in the "*Buoy Data*" array
3	Row index in the "*WAM Data*" array
4	Row index in the "*Imagette Data*" set

Table A.1.2: The ASAR data array

Column Index	Field Name	Column Index	Field Name
1	CERSAT file name	14	Wind direction
2	Date	15	Zero crossing wave period
3	Time	16	Wave peak period
4	Latitude	17	Significant wave slope
5	Longitude	18	Mean wave direction
6	Water depth	19	Main Peak direction
7	Envisat Heading	20	Corresponding imagette number
8	Sign. Waveheight	21	Image normalized variance
9	Directional spectrum	22	Confidence swell
10	Smin	23	Land flag
11	Smax	24	Attach flag
12	Wind confidence	25	Azimuth cut-off wavelength
13	Wind velocity		

Table A.1.3: The Buoy data array

Column Index	Field Name	Column Index	Field Name
1	Buoy name	11	[r1,r2]
2	Date	12	[α1, α2]
3	Time	13	Wind velocity
4	Latitude	14	Wind direction
5	Longitude	15	Zero crossing wave period
6	Water depth	16	Wave peak period
7	-	17	Significant wave slope
8	Sign. wave height	18	Mean wave direction
9	Frequency spectrum	19	Main Peak direction
10	Frequencies		

Table A.1.4: The WAM data array

Column Index	Field Name	Column Index	Field Name
1	WAM data file name	11	Frequencies
2	Date	12	Directions
3	Time	13	Wind velocity
4	Latitude	14	Wind direction
5	Longitude	15	Zero crossing wave period
6	Water depth	16	Wave peak period
7	-	17	Significant wave slope
8	Significant wave height	18	Mean wave direction
9	Scaled dir. spectrum	19	Main Peak direction
10	Spectrum maximum		

Table A.1.6: The Imagette data array.

Column Index	Field Name	Column Index	Field Name
1	CERSAT file name	10	No. of pixels in azimuth
2	Date	11	No. of pixels in range
3	Time (UTC)		
4	Latitude		
5	Longitude		
6	Imagette no. CERSAT file		
7	Corr. ASAR spectrum		
8	Range resolution (m)		
9	-		

The imagettes are stored as Matlab structure arrays, in the form of (int16, int16) complex numbers. The resolution and (ground) range is stated in Table A.1.7.

Table A.1.7: Resolution and size of the complex imagettes.

	Resolution	Number of pixels	Extension
Azimuth	4.05 m	1698 (slightly varying)	~ 6.9 km
Ground Range	20.10 m	489	~ 9.8 km

8.2 User's Guide

The database is loaded into Matlab by the command

```
load -MAT Database
```

or, equivalently,

```
load('Database.MAT')
```

where **`Database.mat`** is the name of the file.

After this is entered, the following parameters reside in the memory:

```
IndexData       (Number of ASAR data x 4 )  int16 array
BuoyData        (Number of ASAR data x 19 ) cell  array
WAMData         (Number of ASAR data x 19 ) cell  array
ASARData        (Number of ASAR data x 24 ) cell  array
ImagetteData    (Number of ASAR data x 14 ) cell  array
```

The following example illustrates how some data can be extracted

```
load -MAT Database;
ncase = 276;
idataA          = IndexData(ncase,1);    % Location in the ASAR array
idataB          = IndexData(ncase,2);    % Location in the Buoy array
idataW          = IndexData(ncase,3);    % Location in the WAM  array
ImagetteNo      = ASARData{idataA,20};   % 0 = no imagette
LatitudeASAR    = ASARData{idataA,4}
LongitureASAR   = ASARData{idataA,5}
```

Note the use of "{ }" instead of "()" for cell arrays.

The imagettes are stored in a separate catalogue, one file for each image. Compilation of the filename, typically including a number corresponding to the location in the ImagetteData cell array, has to be adapted to the user's environment. A typical example could be as follows:

```
IN     = 12;
INtext = num2str(IN);
ImagetteFileName = strcat('Imagettes/Im', INtext,'.DAT');
```

The imagette itself is then loaded by writing

```
Str=load('-MAT',ImagetteFileName);
```

This is a Matlab structure file containing the only field Str.cimag, consisting of the imagette stored as an (int16, int16) complex array, of dimension

```
Str.cimag(1:Nrange,1:Nazimuth)
```

8.2.1 Conversions to Directional Spectra

The following Matlab m-files computes ASAR, Buoy and WAM directional spectra on a common form. No interpolation and extrapolation is applied.

8.2.1.1 The ASAR Spectrum

```
function [Fspec,DirSpec,Freqs,Direcs] = ASARSpectrum(ASARData,p)
%
%------------------------------------------------
%ASAR spectral grid definition
NphiA        =  36;  % Number of directional sectors in the ASAR spectra
NkA          =  24;  % Number of different wavenumbers in ASAR spectra
lambda_minA =  30;  % Found in the corresponding PDS file (*.N1)
lambda_maxA = 800;  % idem
nlam        =  0 : (NkA-1);
alphaASAR =  (lambda_maxA/lambda_minA)^(1/(NkA-1));
lambdaA     =  lambda_maxA*alphaASAR.^(-nlam);    %Log scale
kaA         =  2*pi./lambdaA;
Direcs      =  0:10:350;
dirA        =  Direcs*pi/180;
% Spectrum
Smin   = ASARData{p,10}; Smax=ASARData{p,11};
kspec = Smin+double(ASARData{p,9})*(Smax-Smin)/256;
%
% Transformation to the directional spectrum
depth =  abs(ASARData{p,6});
g   = 9.81;
kh = depth*kaA;
if kh > 5
   Freqs = sqrt(g*kaA)/(2*pi);
   dkdf = 8*pi^2*Freqs/g;
else
   Freqs = sqrt(g*kaA.*tanh(kh))/(2*pi);
   dkdf = 8*pi^2*Freqs./( g*(tanh(kh)+kh./(cosh(kh)).^2) );
end
DirSpec = diag(kaA.*dkdf)*kspec;
Fspec = sum(DirSpec')*pi/18;
```

8.2.1.2 The Buoy Spectrum

```
function [Fspec,DirSpec,Freqs,Direcs] = BuoyMEM2Spectrum(BuoyData,p)
% Computes the MEM-based directional spectrum from the BuoyData cell array
% BuoyData: Cell array
% p:         Number of data set
% Dirs:      User specified directions (DegN)
%
% Fspec:     Frequency spectrum, Fspec(1:Freqs)
% DirSpec:  Directional spectrum, DirSpec(1:Nfreqs,1:Ndirs)
% Freqs:     Array of frequencies (from file)
%
% Non-feasible directional data:
% Replaced by cos-2s distribution based on c1!
%---------------------------------------------------------------------
% (Fixed directional resolution)
Direcs = 0:5:355;
%
r      = BuoyData{p,11};
r1     = r(:,1); r2     = r(:,2);    % r1 and r2
%
alpha = BuoyData{p,12};
alpha1= alpha(:,1); alpha2= alpha(:,2); % directions
```

```
%
Fspec = BuoyData{p,9};                  % Non-directional spectrum
Freqs = BuoyData{p,10} ;                % Frequencies
dirB  = Direcs*pi/180;
dirB  = mod(dirB + pi,2*pi) ;           % Turn 180degs for comparisons
%
NFB=length(Fspec);
Nphi=length(dirB);
%
I=sqrt(-1);
c1=r1.*exp(I*alpha1);                   % Coefficients for MEM
c2=r2.*exp(2*I*alpha2);
%
%  Test on feasability
%  Use "mask = ones(size(c1))./(1 - (abs(c2-c1.*c1) >= 1-abs(c1).^2));"
%  for a NaN-mask.
mask = 1 - (abs(c2-c1.*c1) >= 1-abs(c1).^2);  % For  0-mask
%
phi1=(c1-c2.*conj(c1))./(1-abs(c1).^2);
phi2=c2-c1.*phi1;
sige=mask.*real(1-phi1.*conj(c1)-phi2.*conj(c2));
%
DirSpec=zeros(NFB,Nphi);
for i=1:NFB
    if mask(i) == 0
       sval = r1(i)/( 1-r1(i) );
       ttemp = 0 : pi/180 : 2*pi;
       Dtemp = ( (cos( (ttemp - alpha1(i) )/2 )).^2 ).^sval;
       Dtemp = Dtemp/ ((sum(Dtemp)-Dtemp(1))*pi/180);
       Dmem  = interp1(ttemp,Dtemp,dirB);
    else
       Dmem = sige(i)./abs(1-phi1(i)*exp(-I*dirB)...
              -phi2(i)*exp(-2*I*dirB)).^2/2/pi;
    end
    DirSpec(i,1:Nphi) = Fspec(i)*Dmem;
end
```

Note: The following version of the m-file sets the non-feasible parts of the spectrum to 0:

```
function [Fspec,DirSpec,Freqs,Direcs] = BuoyMEMSpectrum(BuoyData,p)
```

8.2.1.3 The WAM Spectrum

```
function [Fspec,DirSpec,Freqs,Direcs] = WAMSpectrum(WAMData,p)
% WAMData    : WAM data sets,
% p          : Number of data set
%
% Fspec      : Frequency spectrum
% DirSpec    : Directional spectrum, DirSpec(1:Nfreqs,1:Ndirs)
% Freqs      : Frequencies (Hz)
% Direcs     : Directions (degN)
Freqs    = WAMData{p,11};
DeltaTheta = 2* WAMData{p,12}(1);
Direcs   = 360*WAMData{p,12}/(2*pi);
DirSpec = (double(WAMData{p,9})/999.00 )*WAMData{p,10};
Fspec    = sum(DirSpec')*DeltaTheta;
```

8.2.2 Computations of Wave Parameters

8.2.2.1 Non-Directional Parameters

```
function [Hs,Tz,Tp]=SpecPar(Fspec,Freqs,Fmin,Fmax,Extrapol)
% Computes Hs,Tz and Tp from the spectrum.
% May extrapolated spectrum below Fmin and above Fmax
% (Extrapol = 1. Default)
%
% Extrapolates from the end points of Freqs
% if Fmin and Fmax are outside Freqs.
%
% Default: Computation from f = 0,...,1 (Extrapol 1 or not given)
% Extrapol =  0 : No extrapolation outside  Fmin and Fmax.
% Extrapol ~= 0 : Default
%-----------------------------------------
NFr = max(size(Freqs));
FreqR = reshape(Freqs,1,NFr);
FspeR = reshape(Fspec,1,NFr);
Fex   = [0 FreqR 1.0];
Sex   = [0 FspeR 0];
maxSpecin = max(Sex);
%
if maxSpecin == 0
  % Input less or equal to 0
  Hs = NaN;
  Tz = NaN;
  Tp = NaN;
else
  Dfine = 0.001; Nfine = 1000;
  Ffine = Dfine*(1:Nfine);
  Sfine = interp1(Fex,Sex,Ffine);
  % Extrapolation
  fmin  = max(Fmin,Freqs(1));
  fmax  = min(Fmax,Freqs(NFr));
  idxmin = floor(fmin/Dfine);
  idxmax = ceil(fmax/Dfine);
  ff = (1:idxmin)/(idxmin+1)  ;
  Sfine(1:idxmin) = Sfine(idxmin+1)*ff.^10;
  ff = ( (idxmax+1) : Nfine )/idxmax;
  Sfine(idxmax+1 : Nfine) = Sfine(idxmax)*ff.^(-4.5);
  % Compute wave parameters
  if nargin == 5 & Extrapol == 0
     Ffine = Ffine(idxmin:idxmax);
     Sfine = Sfine(idxmin:idxmax);
  end
  m0 = sum(Sfine)*Dfine;
  m1 = sum(Ffine.*Sfine)*Dfine;
  m2 = sum((Ffine.^2).*Sfine)*Dfine;
  Hs = 4*sqrt(m0);
  Tz = sqrt(m0/m2);
  [Smax,Imax]=max(Sfine);
  Tp = 1.0/(Dfine*Imax(1));
end
```

8.2.2.2 Directional Parameters

```
function [Theta1,Sigma1,ThetaTp,Sigma1Tp,Mdir,UI] =
DirPar(Dirspec,Freqs,Direcs)
% Computes frequency dependent and independent
% directional parameters
% Direcs should be given in DegN (0=from N, 90 from E, ... )
% Theta1,Sigma1 are vectors, whereas the rest are scalars
% All are vectors corresponding to the frequencies in Freqs
%-----------------------------------------------------------
DirRads = Direcs*pi/180;
[Nfreqs,Ndirs] = size(Dirspec);
%
sumD = sum(Dirspec');
a1 = ( sum( diag(cos(  DirRads))*Dirspec' )./(sumD+1.e-40) )';
b1 = ( sum( diag(sin(  DirRads))*Dirspec' )./(sumD+1.e-40) )';
theta1 =  atan2(b1,a1) + 5*pi ;
Theta1 = mod( theta1*180/pi,360 );
r1     = sqrt(a1.^2 + b1.^2);
Sigma1 = sqrt(2*(1-r1))*180/pi;
%
% Spectrally weighted direction, MDIR and UI
% NB! Mean only over good spectral values
theta0 = replaceNaN(theta1,0.0);
aMDIR = sum( cos(theta0).*sumD' )./ sum(sumD');
bMDIR = sum( sin(theta0).*sumD' )./ sum(sumD');
Mdir  = atan2(bMDIR,aMDIR) + 2*pi;
Mdir  = mod( Mdir*180/pi ,360 );
UI    = sqrt(aMDIR^2+bMDIR^2);
[smax,imax] = max(sumD);
ThetaTp = Theta1(imax);
Sigma1Tp= Sigma1(imax);
%
% Second order parameters (Currently not used)
%a2 = ( sum( diag(cos(2*DirRads))*Dirspec' )./sumD )';
%b2 = ( sum( diag(sin(2*DirRads))*Dirspec' )./sumD )';
%theta2 =  atan2(b2,a2)/2;
%if cos(theta1-theta2) < 0
%   theta2 = theta2+5*pi;
%end
%r2     = sqrt(a2.^2 + b2.^2);
%theta2 = mod( theta2*180/pi,360 );
%sigma2 = sqrt((1-r2)/2)*180/pi;
```

8.2.3 Sample Matlab Programs

8.2.3.1 Make Scatter-plots

```
load  Database090305_IM -MAT
n = 0;
for norg = 1:2760
   idataA     = IndexData(norg,1);
   idataB     = IndexData(norg,2);
   idataW     = IndexData(norg,3);
   LongW      = -ASARData{idataA,5};
   ImagetteNo= ASARData{idataA,20};
   ImageVariance = ASARData{idataA,21};
   % Elimiate the normalized image variance outside the range 1.1 and 1.3
   if abs(ImageVariance -1.2) < 0.1
      str = 'Image variance 1.1 - 1.3';
      n= n+1;
      [FspecA,DirSpecA,FreqsA,DirecsA] = ASARSpectrum(ASARData,idataA);
      [FspecB,DirSpecB,FreqsB,DirecsB] = BuoyMEM2Spectrum(BuoyData,idataB);
      [FspecW,DirSpecW,FreqsW,DirecsW] = WAMSpectrum(WAMData,idataW);
      Fmin = .06; Fmax = .13;
      [HsA(n),TzA(n),TpA(n)]=SpecPar(FspecA,FreqsA,Fmin,Fmax);
      [HsB(n),TzB(n),TpB(n)]=SpecPar(FspecB,FreqsB,Fmin,Fmax);
      [HsW(n),TzW(n),TpW(n)]=SpecPar(FspecW,FreqsW,Fmin,Fmax);
   end;
end
text = [str ', #samp.=',num2str(n)]
line = 0:1:30;
subplot(1,3,1)
plot(HsB,HsA,'.',line,line); axis([0 6 0 6]); axis('square')
xlabel('Hs, Buoy, [m]');
ylabel('Hs, ASAR, [m]');
subplot(1,3,2)
plot(HsW,HsA,'.',line,line); axis([0 6 0 6]); axis('square')
xlabel('Hs, WAM, [m]');
ylabel('Hs, ASAR, [m]');
title(text)
subplot(1,3,3)
plot(HsB,HsW,'.',line,line); axis([0 6 0 6]); axis('square')
xlabel('Hs, Buoy, [m]');
ylabel('Hs, WAM, [m]');
```

8.2.3.2 Plot Directional Spectra

```
load Database090305_IM -MAT
ncases = max(size(IndexData));
for n = 100:200
   idataA     = IndexData(norg,1);
   idataB     = IndexData(norg,2);
   idataW     = IndexData(norg,3);
   idataI     = IndexData(norg,4);
   %
   LongE = -ASARData{idataA,5};
   if   LongE > 140.0
      str = 'Chrismas Island'  ;
   elseif  abs(LongE-120) < 10.0
      str = 'US West Coast'  ;
   elseif  abs(LongE-90)  < 10.0
      str = 'Gulf of Mexico'  ;
   else LongE < 80.0
      str = 'US East Coast'   ;
   end
   YYMMDD          = ASARData{idataA,2}; HHMMSS = ASARData{idataA,3};
   HsB             = BuoyData{idataB,8};
   AzimuthHeading = ASARData{idataA,7}
   ndate  = leite( str2num(YYMMDD), str2num(HHMMSS)  );
   dstr   = datestr(ndate,0);
   str = [str ', ' dstr ', Data set=' num2str(norg),...
       ', Imagette=', num2str(double(idataI)),',HsBuoy= ', num2str(HsB),'m' ];
   [FspecA,DirSpecA,FreqsA,DirecsA] = ASARSpectrum(ASARData,idataA);
   [FspecB,DirSpecB,FreqsB,DirecsB] = BuoyMEM2Spectrum(BuoyData,idataB);
   [FspecW,DirSpecW,FreqsW,DirecsW] = WAMSpectrum(WAMData,idataW);
   %
   subplot(2,3,1)
   DirSpecA = DirSpecA + .001;
   surf(DirecsA,FreqsA,DirSpecA); view(2); shading interp;
   hold on;
   AZH = AzimuthHeading*[1 1 NaN 1 1];
   AZF = [0 .05 NaN 0.22 0.4 ];
   plot(AZH,AZF, 'r');
   hold off;
   colormap('jet');
   xlabel('Direction/Az.Hdng  [degN]'); ylabel('Freq. [Hz]');
   axis([0 360 0 .4])
   set(gca,'Xtick',[0 90 180 270 360])
   %
   subplot(2,3,2)
   surf(DirecsB,FreqsB,DirSpecB+1e-15); view(2); shading interp;
   axis([0 360 0 .4])
   set(gca,'Xtick',[0 90 180 270 360])
   xlabel('Direction [degN]'); ylabel('Freq. [Hz]');
   title(str);
   %
   subplot(2,3,3)
   surf(DirecsW,FreqsW,DirSpecW); view(2); shading interp;
   axis([0 360 0 .4])
   set(gca,'Xtick',[0 90 180 270 360])
   xlabel('Direction  [degN]'); ylabel('Freq. [Hz]');
   pause
end;
```

8.2.4 General m-files

This section contains two utility functions that may be useful when working with the data.

8.2.4.1 Time/datenumber Conversion

```
function dn = Leite(yyyymmdd,hhmmss)
% Leite returns the scalar Matlab "datenum" variable.
% year,month,day,hour,minute,second can be recovered from
% the output using the standard Matlab
% functions DATESTR or DATEVEC
% The function works even for yyyymmdd given in the form 030315
% (if this means 2003/03/15).
%-----------------------------------------------------------
Y    = floor( yyyymmdd/10000);
M    = floor((yyyymmdd - Y*10000)/100 );
D    = yyyymmdd - Y*10000 -100*M;
if   hhmmss < 10000
     hhmmss = hhmmss*100;
end
H    = floor(hhmmss/10000);
MI   = floor( (hhmmss - H*10000)/100 );
S    = hhmmss - H*10000 -100*MI;
if   Y < 1000
     if Y < 50
         Y = Y + 2000;
     else
         Y = Y + 1900;
     end
end
dn   = datenum(Y,M,D,H,MI,S);
```

8.2.4.2 Distance Between Points on the Earth

```
function dist = LatLongDistance(long,lat)
% Adapted from the freely available M-map package.
% Spherical earth distance between points in long/lat coordinates.
% RANGE= LatLongDistance(LONG,LAT) gives the distance in meters between
% successive points in the vectors LONG and LAT, computed
% using the Haversine formula on a spherical earth of radius
% 6378.137km. Distances are good to better than 1% of the
% "true" distance on the ellipsoidal earth
% Rich Pawlowicz (rich@ocgy.ubc.ca) 6/Nov/00
pi180=pi/180;
earth_radius=6378.137e3;
long1=long(1:end-1)*pi180;
long2=long(2:end)*pi180;
lat1=lat(1:end-1)*pi180;
lat2=lat(2:end)*pi180;
dlon = long2 - long1;
dlat = lat2 - lat1;
a = (sin(dlat/2)).^2 + cos(lat1) .* cos(lat2) .* (sin(dlon/2)).^2;
c = 2 * atan2( sqrt(a), sqrt(1-a) );
dist = earth_radius * c;
```

8.3 Preparation of the Co-location Database

The co-location database is based on the Cersat/Ifremer system for co-locating ENVISAT ASAR Wave mode data and buoy data from the NDBC (USA) and MEDS (Canada) networks. These data include wave parameters for both non-directional and directional wave spectra.

In order to be defined as *co-located*, the ASAR and the buoy spectra have to be separated by less than 200km geographically and 1 hour temporally. A description of the Cersat co-located products can be found at:

ftp://ftp.ifremer.fr/pub/ifremer/cersat/documentation/colocated/satellite-buoy/envisat-ASAR/

It should be noted that some of the co-located wave products given by Cersat correspond to situations when ENVISAT is above land. Although a land flag is included in the database, it appears that in some cases, this flag is in error. Thus, it has been necessary to carry out a re-filtering of the data using an improved geographical database. In addition to buoy data, co-located WAM/Envisat-ASAR products are also available at Cersat.

The present appendix describes briefly how to read the Cersat co-located data using the Matlab program.

8.3.1 The Co-located Buoy/Envisat-ASAR data

Cersat data are stored using the Hierarchical Data Format-Earth Observing System (HDF-EOS) format. The names of the co-located data files are derived from the names of the Level 1 products. For example, the Cersat file corresponding to the Level 1 file

ASA_WVI_1PNPDK20030410_183300_000020842015_00242_05807_0363.N1

is

ASA_WVW_2PNPDK20030410_183300_000020842015_00242_05807_0363R0.EWVW.

8.3.1.1 The HDF data format

A HDF file is composed of *points*. Each point contains various *levels*. Each level contains a given number of records for various fields. A more detailed description of the format can be found by visiting the home page of the *The National Center for Supercomputing Applications* (NCSA) at the WEB-sites

http://hdf.ncsa.uiuc.edu

http://hdf.ncsa.uiuc.edu/hdfeos.html

The HDF files from Cersat contain only one point each.

This point consist of four levels, numbered from 0 to 3:

- **Level 0** (or *Cell data*-level) contains information related to the ASAR wave spectra. Each ASAR spectrum is labelled by the field *ID_cell_data.*
- **Level 1** (or *Cell_data_mpa* level) contains information about Wave Mode Processing Parameters. Actually, this level is just an extension of level 0, since the HDF-EOS format does not support more than 256 fields per level.
- **Level 2** (or *loc_station* level) contains information about the buoys. Each buoy is labelled by the field *ID_loc_station* as well as by the field *ID_cell_data* in order to connect it to a corresponding ASAR spectrum from level 0. The name of the buoy is found in the field *Station_Reference.*

- **Level 3** (or *swav data* level) contains the buoy wave spectra. They are labelled by the field *ID_loc_station* to connect them with levels 2 and 0, as well as by the field *Time*. This means that several buoy spectra at this level can refer to the same buoy at Level 2, the time being the only varying parameter (see the example below).

As already stated, each level is made of fields and records. For example, Level 0 contains the fields *ID_cell_data*, *Latitude*, *Longitude, Time*, ... The fields available at each level can be found either in Cersat's documentation, or by using Matlab. The number of records for each field in this level will be equal to the number of available ASAR spectra. The records are numbered from 0 to (*number of records* -1).

It is important to be aware of that the number of records varies from one field to another.

8.3.1.2 Example

Level 0 (4 records):

ID_cell_data 0 1 2 3

Level 2 (6 records):

ID_cel_data		0	0	1	1	2	3
ID_loc_station		0	1	2	3	4	5
Station_Reference	X	Y	X	Y	Y	Y	

Level 3 (8 records):

ID_loc_station		0	0	1	1	2	3	4	5
Time	t_1	t_2	t_1	t_2	t_2	t_2	t_2	t_2	

Thus, to the first ASAR spectrum at level 0, labeled *ID_cell_data*=0, there are four buoy spectra at Level 3, namely *ID_loc_station*=1 (buoy "X") and *ID_loc_station*=2 (buoy "Y"), for the times t_1 and t_2. Furthermore, there is only one buoy spectrum corresponding to the ASAR spectrum *ID_cell_data* = 2, i.e. *ID_loc_station* = 4 (buoy "Y"), time t_2. We notice that this buoy spectrum appears four times at level 3, illustrating the fact that the information storage is not optimal for the buoy spectra. In our example we have twice as many stored buoy spectra as is really needed.

All the operations related to HDF files are carried out with function **hdfpt** in Matlab.

8.3.1.3 Opening and closing a HDF file

The variable `filename` contains the name of the file to open, including the correct path. The first call is to obtain the point ID:

```
fileid=hdfpt('open',filename,'DFACC_READ');     % Open the hdf-eos
file
[numpt,ptnames] = hdfpt('inqpoint',filename); % Query the point
name
pointid=hdfpt('attach',fileid,ptnames);          % Attach the point
```

Recall that the HDF files from Cersat always have only one point. The variable `pointid` will be the identification to use whenever operating with this file.

Closing a file is carried out by the following statements

```
status=hdfpt('detach',pointid); % Detach the point
status=hdfpt('close',fileid);   % Close the file
```

8.3.1.4 Extracting fields from a HDF file

For a given level, information about the different fields, and especially about the names of the existing fields, can be found through:

```
[numfield,fieldlist,fieldtype,fieldorder]= ...
hdfpt('levelinfo',pointid,i),
```

where `i` is the level number.

Let us suppose that we want to read the time, the latitude and the longitude of all the ASAR wave spectra (Level 0) in a given file. First, we have to know how many records are available at this level. This is done by the statements:

```
nb_rec0=hdfpt('nrecs',pointid,0); %Nb of records at level 0=nb
records_to_read0=0:nb_rec0-1;      %Begin at 0 !
```

Here `records_to_read0` is a vector containing the records to be read at level 0.
To read the chosen fields we use:

```
fields_to_read='Time,Latitude,Longitude';
ASARdata,status]= ...
hdfpt('readlevel',pointid,0,fields_to_read,records_to_read0);
```

The variable `ASARdata` is a 3×1 Matlab cell array. The first array element, `ASARdata{1}`, is a vector containing the time parameter of the various ASAR spectra. The elements `ASARdata{2}` and `ASARdata{3}` will be vectors with the same length, containing the latitude and the longitude, respectively. Note that the time is written using the so-called TAI93 format, i.e. the number of seconds elapsed since January 1st 1993 at 00:00. To convert this number to a more readable format use for example the Matlab function `datestr`,

```
datestr((ASARdata{1}/3600/24+datenum('01-Jan-93')),15).
```

8.3.2 Description of Spectra

8.3.2.1 ASAR spectra

The directional spectra from ASAR are given as functions of the direction □, clockwise from north, and the wavenumber *k*. A complete description of the data can be found in the note "*Envisat ASAR Wave Mode Level 2 Product - description and reconstruction procedure*", by Harald Johnsen, Norut IT.

The following is an example of Matlab routine that retrieves ASAR directional spectral information:

```
fields_to_read='MDS.ocean_spectra,MDS.min_spectrum,MDS.max_spectr
um';
[ASARdata,status]= ...
hdfpt('readlevel',pointid,0,fields_to_read,records_to_read0);
ASp=ASARdata{1};
```

```
Smin=double(ASARdata{2});
Smax=double(ASARdata{3});
%
%ASAR Level 2 spectrum grid parameters
Nk=24;              %Number of wave number bins
Nphi=36;            %Number of directional bins
lambda_min=30;      %Can be found in the corresponding PDS file
(*.N1)
lambda_max=800;     %Idem
nlam=0:(Nk-1);
alpha=(lambda_max/lambda_min)^(1/(Nk-1));
lambdaA=lambda_max*alpha.^(-nlam);      %Log scale (H.Johnsen) !
kaA=2*pi./lambdaA;
dirA=0:10:350;
%
%Build the matrix spectrum from the data vector
SpectA=zeros(Nk,Nphi);
for i=1:Nphi
  SpectA(:,i)=double(ASp(1+(i-1)*Nk:i*Nk,Spect_nb));
end
SpectA=Smin(Spect_nb)+SpectA*(Smax(Spect_nb)-Smin(Spect_nb))/256;
```

The variable `Spect_nb` corresponds to the spectrum number, i.e. (`ID_cell_data`+1). As a result, `SpectA` is a 24x36 matrix (24 wave numbers and 36 directions) that contains the ASAR wave spectrum. The variable `kaA` contains 24 wavenumbers (logarithmic scale), and `dirA` 36 directions, in degrees clockwise from North.

The significant wave height is computed from this spectrum by the following Matlab statements

```
A=pi/36*(alpha-1/alpha)*kaAi.^2;     % k-bin width
HsA=4*sqrt(sum(sum(A.*SpectA)));     % significant wave height
```

8.3.2.2 Buoy spectra

In general, the directional spectrum may be written as

$$E_B(f,\theta)=S_B(f)D_B(f,\theta)$$

where $S_B(f)$ is the non-directional spectrum, and $D_B(f,\theta)$ the directional spreading function,

$$D_B(\theta,f)=\frac{1}{2\pi}+\frac{1}{\pi}\sum_{n=1}^{\infty}r_n(f)\cos\left(\theta-\alpha_n(f)\right)$$

In the files, the buoy directional spectra may be given in two different forms:

1. The non-directional spectra $S_B(f)$ and $\alpha_1(f)$, $\alpha_2(f)$, $r_1(f)$, and $r_2(f)$.
2. Directional wave spectra computed from the data in the first point, following the NDBC recom-mendations.

The NDBC recommendations can be found at

http://www.ndbc.noaa.gov/wavemeas.pdf

or

http://seaboard.ndbc.noaa.gov/wavemeas.pdf.

The directional distribution is estimated through a simple truncated Fourier series, viz.

$$D_{B,NDBC}(\theta,f)=\frac{1}{2\pi}+\frac{1}{\pi}\left(r_1(f)\cos\left(\theta-\alpha_1(f)\right)+r_2(f)\cos\left(\theta-\alpha_2(f)\right)\right),$$

where the negative parts are just cut off.

In this case, the distribution tends to be quite broad, and some energy is lost when the negative values are replaced by zero. A Maximum Entropy Method (MEM) expression for the directional distribution might therefore have been preferred, see Section 3.2. However, also as noted in Section 3.2, it has been found that for some of the buoys, not only are $\alpha_1(f)$, $\alpha_2(f)$, $r_1(f)$, and $r_2(f)$ occasionally outside the feasible region for non-negative distributions, but also quite frequently close to the border of the feasible region. This generates too spiky distributions, but the exact reason for this behaviour is not known.

The following is a Matlab script that reads a buoy spectrum at level 3. The variable `Buoy_nb` is the buoy spectrum number, from 1 to `nb_rec3` (number of records at level 3).

```
nb_rec3=hdfpt('nrecs',pointid,3); %Nb of records at level 3 =nb of buoy
spectra
records_to_read3=0:nb_rec3-1;      %Begin at 0 !
fields_to_read= ...
'Time,Frequency,ID_loc_station,Alpha1,Alpha2,R1,R2,Density_Energy';
[Buoydata,status]= ...
hdfpt('readlevel',pointid,3,fields_to_read,records_to_read3);
TB0=Buoydata{1}; FreqB0=Buoydata{2};
alpha10=Buoydata{4}; alpha20=Buoydata{5}; r10=Buoydata{6};
r20=Buoydata{7}; DE0=Buoydata{8};
TB=TB0(Buoy_nb);
NFB=max(find(DE0(:,Buoy_nb)<60000));           %find nb of frequency bins
FreqB=1e-3*double(FreqB0(1:NFB,Buoy_nb));      %define the frequency vector
dfB=FreqB(2)-FreqB(1);                         %frequency step
%
%Fourier coefficients for directional spread
alpha1=double(alpha10(1:NFB,Buoy_nb))/180*pi;  %Mean wave dir. [rad]
alpha2=double(alpha20(1:NFB,Buoy_nb))/180*pi;  %Principal wave dir. [rad]
r1=double(r10(1:NFB,Buoy_nb))/100;             %1st Fourier exp. coef
r2=double(r20(1:NFB,Buoy_nb))/100;             %2nd Fourier exp. coef
DE=double(DE0(1:NFB,Buoy_nb))/100;             %Non-directional spectrum
c1=r1.*exp(I*alpha1);                          %Coefficients for MEM
c2=r2.*exp(2*I*alpha2);
phi1=(c1-c2.*conj(c1))./(1-abs(c1).^2);
phi2=c2-c1.*phi1;
sige=real(1-phi1.*conj(c1)-phi2.*conj(c2));
SpectBfmem=zeros(NFB,Nphi);
dirB=(0:10:350)*pi/180;
%
for i=1:NFB
  Dmem=sige(i)./abs(1-phi1(i)*exp(-I*dirB)-phi2(i)*exp(-2*I*dirB)).^2/2/pi;
  SpectBfmem(i,1:Nphi)=DE(i)*Dmem;
end
```

The array `SpectBfmem` is a NFB×36 matrix containing directional spectral information. NFB is the number of frequencies available for this buoy. The vector `FreqB` contains the (linearly spaced) frequencies and `dirB` the 36 directions, in degrees clockwise from North.

8.3.2.3 Colocated WAM/Envisat-ASAR Data

Co-located Envisat-ASAR/WAM data can be downloaded from ftp.ifremer.fr as ASCII files. This section describes the content of these files and provides an example of Matlab function which extracts WAM directional spectra.

Below follows first a copy of the **`read.me`** file distributed along with the co-located WAM data.

I. File Name:

File name is same as the WVS product used for the co-location with WVS part of the name replaced by WAM (or WAB for the collocations with the buoys).

Example:

ASA_WAM_1PXPDE20020503_124242_000021562005_00301_00909_0049.N1

contains the WAM spectra collocated with product:

ASA_WVS_1PXPDE20020503_124242_000021562005_00301_00909_0049.N1

The WAB file that contains the collocations with the buoys (if it exists), would be:

ASA_WAB_1PXPDE20020503_124242_000021562005_00301_00909_0049.N1

II. File Contents & Format:

The file is in ASCII format (UNIX type). Each spectrum is given on four records (in case of buoy co-location files, WAB, it is 5 records as explained above).

First record gives the dates, location, wind information, and spectrum configuration. The spectrum itself spans over the following three records (300 spectral values on the first two records and the remaining 120 on the third of them).

The data is organized as follows:

RECORD 1:

1. Date/time group of the SAR spectrum in the format: `yyyymmddhhnnss` (14 characters).
2. Longitude of the SAR spectrum (F8.2). Latitude of the SAR spectrum (F8.2).
3. Date/time group of the WAM spectrum in the format: `yyyymmddhhnn` (12 characters). Note that WAM spectra are archived at 6-hour interval (at 00, 06, 12, and 18 UTC). Therefore, the time of the ASAR spectrum must be matched with that of WAM within 3 hours.
4. Longitude of the WAM spectrum (F8.2).
5. Latitude of the WAM spectrum (F8.2). Note that the location of the ASAR spectrum is matched with the nearest WAM model grid point. According to the current operational resolution, the grid spacing is 0.5° deg.
6. ECMWF model wind speed in m/s at the WAM spectrum location (F6.2).

7. ECMWF model wind direction in degrees clockwise from North at the spectrum location (F7.1).
8. Number of frequency bins of the spectrum (I3).
9. Frequency of the first bin in Hz (F11.8).
10. Logarithmic increment c_0 in the frequency dimension (F7.4). Note that you can construct the frequency grid using the following formula $f_i = c_0^{i-1} f_1$, where f_i is the frequency of bin number *i*, f_1 is the frequency of the first bin (item 10 above), c_0 is the logarithmic increment (item 11 above).
11. Number of direction bins of the spectrum (I3).
12. The angle of the first directional bin in degrees clockwise with respect to north (F7.3). Note that the directional grid is equally spaced.
13. Maximum energy value in the spectrum in m2s/rad (E15.7).

Spectral values are on RECORDS 2, 3 and 4 as follows:

> The WAM 2-D spectrum normalised so that the maximum value equals 999. The size of the 2-D frequency-direction grid in the current operational WAM model is 720 (30 frequency bins by 24 directional bins). Since it is not possible to fit all 720 values on a single record, the values span over 3 records with a format (10X, 300I3). This implies that the first two records with spectral values have 300 values while the last (third) record has only 120 values.

Note that earlier collocation files with the simulated sample data provided by ESA before the launch of ENVISAT are dated earlier than the current operational ECMWF spectral resolution implemented since 21 November 200. Therefore, the 300 spectral values (25 frequencies by 12 directions) in those files reside on the same record with other information on record 1. The format for those files is (300I3).

Note also that for all data files, the values of the normalised spectral energies are given as a sequence of 3-digit INTEGERS not separated from each other. To construct the original spectral values, it is necessary to use:

`actual_value = normalised_value * spectral_maximum / 999,`

where the `spectral_maximum` is given in item 14 above.

8.3.2.4 Example of Matlab Code for Reading the WAM Data

The present function aims at retrieving the WAM directional spectrum co-located with a given Envisat ASAR complex imagette (Level 1 product). The code can easily be modified to take the name of the level 2 product as an input instead. The function inputs are

- `WVIFile` is the name of the Level 1 ASA-WVI file one wants to find co-located WAM data from.
- `ImNum` contains the imagette number.
- `WAMdir` contains the path to the WAM data directory. The data must be sorted and named on a daily basis, as in the IFREMER FTP site. The directory WAMdir should therefore contain folders named 20021201, 20021202, 20021203 for example.

The output is a matlab structure WAM that contains the WAM data if any have been found. The boolean field WAM.found is set to 1 if co-located WAM data were found. If not, it is set to zero.

```
function WAM=ReadWAMfromWVI(WVIFile,ImNum,WAMdir)
WAM=";
%Look for WAM file
iDateWVI=strfind(WVIFile,'WVI');
WAMdir2=char(strcat(WAMdir,cellstr(WVIFile(iDateWVI+10:iDateWVI+17)),'\'));
WAMFileName="; if exist(WAMdir2)
listWAMfile=dir(WAMdir2);
for j=3:length(listWAMfile)
   WAMname=listWAMfile(j).name;
   if strfind(WVIFile,WAMname(9:59))
      WAMFileName=WAMname;
   end
end
if ~isempty(WAMFileName)
   WAMpathfile=char(strcat(WAMdir2,WAMFileName));
   DD=textread(WVIFile,'%s',150+7*ImNum,'delimiter','\r');  %Look for imagette
   IndADS=strmatch('DS_NAME="PROCESSING PARAMS ADS',DD);
   a=DD{IndADS+3};
   ADSStart0=eval(a(11:31));
   a=DD{IndADS+6};
   ADSSize=eval(a(10:20));
   ADSStart=ADSStart0+ADSSize*(ImNum-1);
   fid=fopen(WVIFile,'r','b');
   fseek(fid,ADSStart,'bof');
   Tid0=fread(fid,3,'int32');   %Read Time
   TidStr=datestr(datenum('1-Jan-2000')+Tid0(1)+Tid0(2)/3600/24,0);
   TidStr=strcat(TidStr,'.',num2str(Tid0(3),'%0.6d'));
   fclose(fid);
   %
   WAMTid1=strrep(datestr(TidStr,30),'T',");
   WAMTid2=strrep(datestr(datenum(TidStr)-1/24/3600,30),'T',");
   WAMdata0=textread(WAMpathfile,'%s','delimiter','%r');
   NSW=length(WAMdata0)/4;        %Number of spectra in the WAM file
   WAM.found=0;
   i=1;
   while (i<=NSW)&~WAM.found  %Check if the desired spectrum is in the file
      dat0=WAMdata0{(i-1)*4+1}; %Read Record 1
      SatDat=cellstr(dat0(1:14));
      if strcmp(SatDat,WAMTid1)|strcmp(SatDat,WAMTid2)
         WAM.found=1;      %WAM spectrum found!!!
         WAMSnb=i;
      end
      i=i+1;
   end
   if WAM.found
      %Read Record 1
      dat0=WAMdata0{(WAMSnb-1)*4+1};
      descW=eval(strcat('[',dat0,']'));
      WAMDateTime=dat0(32:43);
      WAM.Date=WAMDateTime(1:8);
                                                    %Store WAM spectrum date
      WAM.Time=char(strcat(cellstr(WAMDateTime(9:12)),'00'));   %Store WAM
                                                                %spectrum time
      WAM.Lat=descW(6);
      if descW(5)>180                           %Store WAM spectrum latitude
         WAM.Long=descW(5)-360;
      else                                     %Store WAM spectrum longitude
         WAM.Long=descW(5);
      end
      %
      %Read Record 2
      SpectL=zeros(1,720);   %Blank linear spectrum
      dat0=WAMdata0{(WAMSnb-1)*4+2};
```

```
      iadd=900-length(dat0);
      SpectL(1)=eval(dat0(1:3-iadd));
      for j=2:300
         SpectL(j)=eval(dat0(1+3*(j-1)-iadd:3*j-iadd));
      end
      %Read Record 3
      dat0=WAMdata0{(WAMSnb-1)*4+3};
      iadd=900-length(dat0);
      SpectL(301)=eval(dat0(1:3-iadd));
      for j=302:600
         SpectL(j)=eval(dat0(1+3*(j-300-1)-iadd:3*(j-300)-iadd));
      end
      %Read Record 4
      dat0=WAMdata0{(WAMSnb-1)*4+4};
      iadd=360-length(dat0);
      SpectL(601)=eval(dat0(1:3-iadd));
      for j=602:720
         SpectL(j)=eval(dat0(1+3*(j-600-1)-iadd:3*(j-600)-iadd));
      end
      %Set the spectrum into a Frequency*Direction matrix
      NFW=descW(9);
      NDW=descW(12);
      SpectWAM=zeros(NFW,NDW);
      for i=1:NFW
         SpectWAM(i,:)=SpectL((i-1)*NDW+1:i*NDW);
      end
      WAM.SpecFD=SpectWAM/999*descW(14);
      %Frequency and direction vectors
      WAM.F=descW(10)*descW(11).^(0:NFW-1);
      WAM.Dir=(descW(13):360/NDW:descW(13)+360*(NDW-1)/NDW)/180*pi;
      WAM.dF=descW(10)/2*(descW(11)^2-1)*descW(11).^(-1:NFW-2);
      %Compute significant wave height
      SpectFWAM=sum(SpectWAM')*2*pi/NDW/999*descW(14);
      m0fWAM=SpectFWAM*(WAM.dF'.*WAM.F'.^0);
      WAM.Hs=4*sqrt(m0fWAM);
      %ECMWF wind velocity and direction
      WAM.WindVel=descW(7);
      WAM.WindDir=descW(8);
   end
end
```