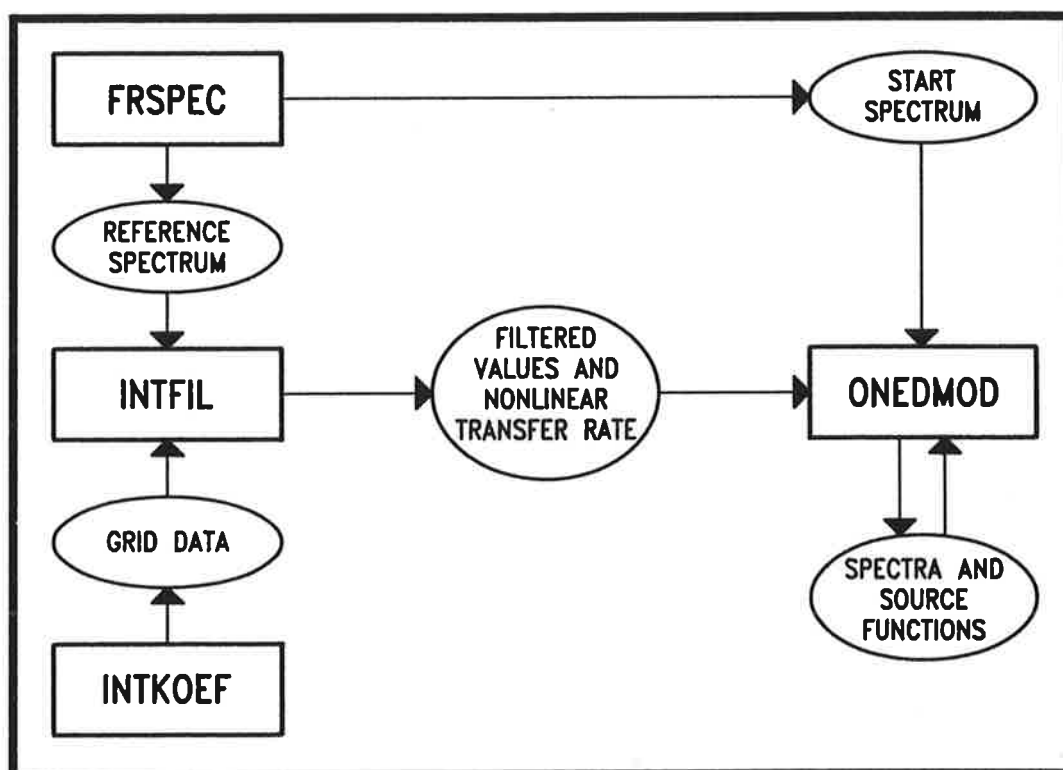




# Max-Planck-Institut für Meteorologie

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### GUIDE FOR THE PROGRAM EXACT-NL

by

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**GUIDE FOR THE PROGRAM EXACT-NL**

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**Abstract**

A detailed description is given of a set of programs called EXACT-NL, which computes fetch- or duration limited wave growth with an explicit expression for the resonant four-wave interactions. This guide is meant as a user's manual. It describes the principles and usage of each program of the EXACT-NL model. We used the EXACT-NL model for the computation of shallow water growth curves (Weber) and for the investigation of the directional response of waves to variations in the wind field (Van Vledder). The modifications necessary for these specific purposes are also described.

## Introduction

EXACT-NL is a set of programs for the computation of fetch- or duration limited wave growth with an explicit expression for the resonant four-wave interactions. These programs were developed by S. and K. Hasselmann from the Max Planck Institut für Meteorologie in Hamburg. EXACT-NL can be classified as a one-dimensional discrete coupled spectral model. The name EXACT-NL refers to the main feature of the programs: the calculation of the exact expression for the nonlinear interactions, as opposed to the parameterizations used in other wave prediction models. An extensive description of the principles on which the algorithm for the calculation of the nonlinear transfer is based is given in Hasselmann and Hasselmann (1981).

This guide is meant as a manual to help future users to get acquainted with the programs. Its content is based on our experience and on helpful discussions with S. Hasselmann and G. Komen (Royal Netherlands Meteorological Institute, de Bilt, The Netherlands).

EXACT-NL was used to make deep water simulation runs (Hasselmann and Hasselmann, 1984; Komen et al., 1984), to investigate the directional response of waves to turning winds (Young et al., 1987; Van Vledder and Holthuijsen, 1988) and for shallow water simulation runs (Weber, 1988).

## Chapter 2

### GENERAL INFORMATION

The evolution of the wave spectrum is given by the so called energy balance equation (flat bottom, no currents, one space dimension):

$$\frac{\partial F}{\partial t} + c_g \frac{\partial F}{\partial x} = S_{tot} \quad (2.1)$$

in which  $F = F(f, \Theta; \mathbf{x}, t)$  is the two-dimensional frequency spectrum,  $f$  the frequency,  $\Theta$  the direction,  $\mathbf{x}$  the space coordinate and  $t$  is time.  $c_g = d\omega/dk$  is the group velocity,  $k$  the wavenumber and  $\omega = 2\pi f = (g \cdot k \cdot \tanh(kd))^{1/2}$  the radian frequency and  $d$  the depth.  $S_{tot} = S_{tot}(f, \Theta; \mathbf{x}, t)$  is the total source function, which consists of the wind input  $S_{in}$ , the dissipation by whitecapping  $S_{Ds}$  and the nonlinear interaction  $S_{nl}$ . Expression (2.1) is solved in program ONEDMOD with either  $\partial/\partial t = 0$  (fetch-limited) or with  $\partial/\partial x = 0$  (duration limited).

The nonlinear interactions are given by the Boltzmann integral (Hasselmann, 1961):

$$\begin{aligned} S_{nl}(\mathbf{k}_4) = & \int \int \int \omega_4 d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3 \\ & \cdot A(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) \\ & \cdot \left[ N_1 \cdot N_2 (N_3 + N_4) - N_3 \cdot N_4 (N_1 + N_2) \right] \\ & \cdot \delta(\omega_1 + \omega_2 - \omega_3 - \omega_4) \cdot \delta(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4) \end{aligned} \quad (2.2)$$

with  $N_i = N(\mathbf{k}_i) = F(\mathbf{k}_i)/\omega_i$  the number density,  $A$  is the interaction coefficient. The delta functions in (2.2) reflect the resonance conditions:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \quad (2.3)$$

$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 + \mathbf{k}_4$$

A set of four interacting wave components which fulfil the resonance conditions is called a quadruplet. All quadruplets of interacting wave components are called the (discrete) phase space. The calculation of (2.2) is done in three steps:

- (i) the discrete phase space, the interaction coefficients and the transformation Jacobian are computed in INTKOEf and partly in INTFIL.
- (ii) insignificant parts of the phase space are filtered out for a certain reference spectrum in INTFIL. Experience shows that for typically peaked wave spectra only 10% of the phase space contributes more than 95% to the nonlinear transfer. This filtering is performed with two levels of accuracy, which results in a so-called fine filtered phase space and a coarse filtered phase space. To check on the accuracy of the filtering, the nonlinear transfer is computed from both phase spaces separately and the results are compared (this can be done in INTFIL or in ONEDMOD). Normally, the nonlinear transfer is computed from both spaces.
- (iii) the nonlinear transfer can now be computed from the filtered phase space at every integration step in ONEDMOD with the aid of a simple scaling law.

The generation of an input spectrum for ONEDMOD and the reference spectrum for INTFIL, is done by a separate program called FRSPEC. The relation between the various subprograms and the data files is shown in Figure 1. The data files which concern the discrete phase space are very large: they should be stored on temporary disk or on magnetic tape. All other files can be stored on permanent disk.

The wind input source function is based on the expression given by Snyder et al. (1981) and modified by Komen et al. (1984):

$$S_{in}(\mathbf{k}) = \max \left[ 0, 0.25 \frac{\rho_a}{\rho_w} \left[ 28 \frac{u_*}{c} \cos(\Theta) - 1 \right] \omega \right] \cdot F(\mathbf{k}) \quad (2.4)$$

with  $\rho_a$  and  $\rho_w$ , the densities of air and water respectively,  $u_*$  is the friction velocity and  $c = \omega/k$  the phase velocity.



For the dissipation by whitecapping the following generalized expression is used (Komen et al., 1984).

$$S_{ds}(k) = -c \left[ \frac{\omega}{\bar{\omega}} \right]^n \left[ \frac{\alpha}{\alpha_{PM}} \right]^m \frac{1}{\omega} F(k) \quad (2.5)$$

with  $\hat{\alpha}$  the integral wave steepness,  $\hat{\alpha}_{PM} = 4.57 \cdot 10^{-3}$  and  $\bar{\omega}$  is the mean radian frequency.

The computation of the exact nonlinear transfer is primarily not vectorizable because the calculation of the contributions to the nonlinear transfer from the different wave components is done randomly. Vectorization is only achieved by running different cases in one run. The optimal number of cases depends on the type of vector machine used. Although the programs don't have to be run on supercomputers, it is advised to do so, to keep the computing time within acceptable limits (Note that supercomputers are by definition the fastest machines available). Important characteristics of these computers are their ability to perform computations in vector mode, which makes them very fast and the fact that they have a large internal memory. The first feature is used especially in program ONEDMOD, which has the possibility to compute several cases in vector mode. The second feature is used for transfer of large files with buffer in or buffer out statements, which allow the execution sequence to proceed simultaneously with the data transfer.

Some figures for a Cray-XMP machine: Step (iii) of the calculation of the nonlinear transfer takes about 5% of the computing time compared to those of steps (i) and (ii). With the present discretization of the phase space (See Chapter 3, example input on unit 5) this means 10 seconds for step (iii) and 200 seconds for step (i) and (ii). A large simulation run (200-300 integration steps) takes about 30-60 minutes. The data files transferred from INTKOE to INTFIL consist of about 2.5 million 64 bit words, the fine and coarse filtered phase space each consist of about 3 million words.

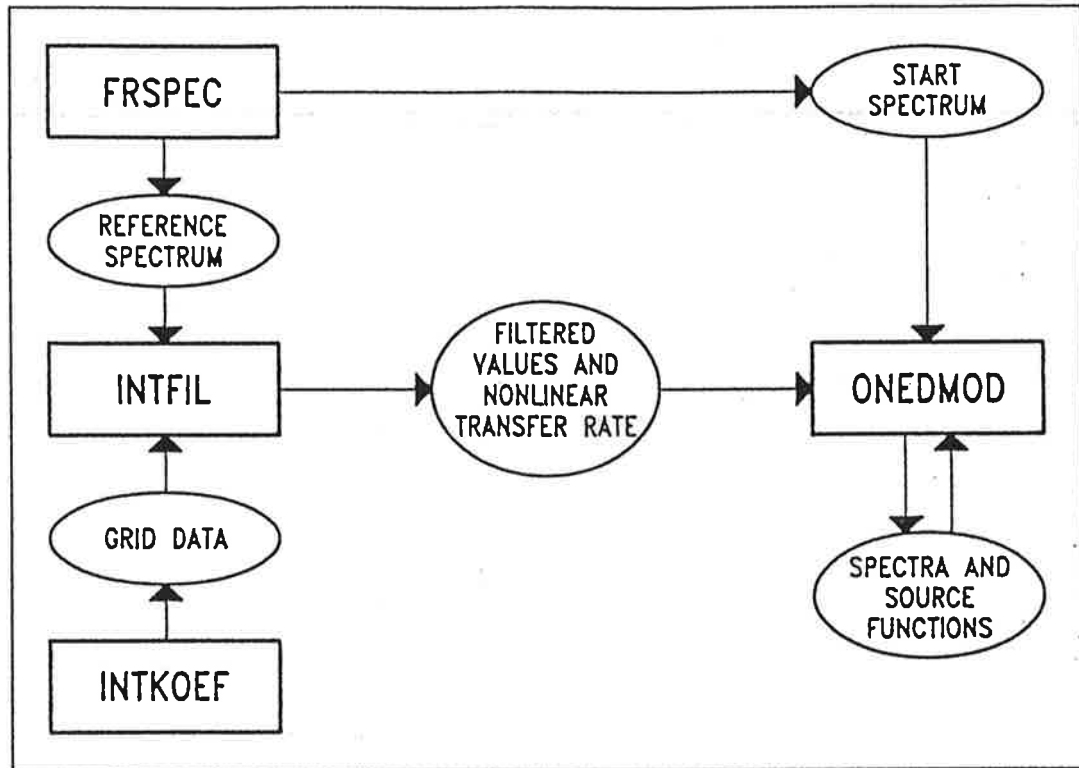


Figure 1: Relations between the programs and data files. The grid data consist of the interaction coefficient and interacting wavenumbers of each quadruplet. The filtered data consist of the frequencies, directions, transformation Jacobian and scattering coefficient of each quadruplet.

## Chapter 3

### DESCRIPTION OF THE SUBPROGRAMS

#### 3.1 FRSPEC

##### 3.1.1 Purpose

FRSPEC is a program to generate an arbitrary spectrum for a given water depth.

##### 3.1.2 General description

The shape of the two-dimensional spectrum is determined by the parameter  $ITYP = 10 \cdot ID1 + ID2$ ;  $ID1$  specifies the type of frequency spectrum (Pierson-Moskowitz, JONSWAP or other) whereas  $ID2$  specifies the type of directional distribution.

#### ID1 TYPE OF FREQUENCY SPECTRUM

---

- ID1 = 1: Frequency spectrum read in
- ID1 = 2: PM-Spectrum, read wind velocity U10
- ID1 = 3: PM-Spectrum, read peak frequency FM
- ID1 = 4: PM-Spectrum with Cartwright distribution
- ID1 = 5: JONSWAP-spectrum, read ALFA, FM, GAMMA, SIGA, SIGB

#### ID2 TYPE OF DIRECTIONAL DISTRIBUTION

---

- ID2 = 1:  $\text{COS}(\text{TETA}/2)^{2S}$ ,  $S = S(\text{FREQ}, \text{FM})$  (cf. Hasselmann et al., 1980)
- ID2 = 2:  $\text{COS}(\text{TETA})^{**2}$
- ID2 = 3:  $\text{COS}(\text{TETA})^{**3}$
- ID2 = 4:  $\text{COS}(\text{TETA})^{**4}$
- ID2 = 5: BOXCAR
- ID2 = 6: ISOTROPIC

Two types of frequency spacings of the spectrum can be generated, an arbitrary and a logarithmic frequency spacing. The first type is determined from a course frequency array together with the number of grid points in each interval. For the second type the frequencies are distributed on a logarithmic scale according to:

$$FR(I) = FR(I - 1) * (1 + CO) \quad \text{for } I = 1, IFN \quad (3.1)$$

in which  $CO > 0$ . The number of frequency points is given implicitly by the value of the parameter  $IFN$ . The logarithmic frequency grid is constructed in a DO-loop, which terminates if the condition  $(I.GT.M)$  is fulfilled. The parameter  $IFN$  is then given the value  $M$ .  $IFN$  can also be computed by changing this to a condition of the form  $IF (FR(I).GT.X)$ .

### 3.1.3 Output

The output consists of the number of frequency grid points, number of directional grid points, angular increment, a frequency array, a frequency increment array, the JONSWAP parameters and the number density in k-space  $N(k)$  (for INTFIL) and the 2-d spectrum in F-TETA-space  $F(f, \Theta)$  (for ONEDMOD).

### 3.1.4 Input on unit 5

IFRL	Flag determining frequency distribution (I4)
CO, FR(1)	if $IFRL < 0$ , $DELFR(I) = CO * FR(I)$ FR(1) is the lowest frequency.
	if $IFRL > 0$ , FR and DELFR determined by NF, NFF and FRG. (2F10.5)
BETA	Water depth in meters (F10.5)
NF	Number of coarse frequency points (I4)
NFF(I), I = 1, NF-1	Number of frequency points per coarse interval (5I4)
FRG(I), I = 1, NF	Course frequencies (F10.5)
IAN	Number of directions + 1 (I4)
ITYP	Parameter specifying type of frequency spectrum and directional distribution (I4) $ITYP = 10 * ID1 + ID2$
shape parameters viz. 5 JONSWAP parameters (5F6.2)	
THETA	Mean wave direction in degrees (the wind direction is taken to be zero degrees) (F10.5)

### 3.1.5 Example input for a JONSWAP spectrum

For the generation of a JONSWAP spectrum with the following parameters ALFA = 0.01, FM = 0.3, GAMMA = 3.3, SIGA = 0.07 and SIGB = 0.09, with a water depth of 30 meter, 12 directions (increment of 30 degrees) and a logarithmic frequency spacing with DELFR(I)/FR(I) = 0.1 and FR(1) = 0.07, we have the following input on unit 5:

-1							IFRL < 0 → FR(I) = FR(I-1)*(1 + CO)
0.1	0.07						CO = 0.1 and FR(1)
30.							WATER DEPTH
6							<NOT USED HERE>
1	1	1	1	1			<NOT USED HERE>
0.1	0.2	0.3	0.4	0.5	0.6		<NOT USED HERE>
13							IAN
51							ITYP
0.01	0.3	3.3	0.07	0.09			JONSWAP PARAMETERS (ID1 = 5 !)
0.							MEAN WAVE DIRECTION IN DEGREES

## 3.2 INTKOEUF

### 3.2.1 Purpose

INTKOEUF is a program to calculate the discrete phase space, the interaction coefficients and the transformation Jacobians.

### 3.2.2 General description

INTKOEUF begins the calculation of the discrete phase space of wavenumber quadruplets which fulfil the resonance conditions (2.3). Essentially INTKOEUF consists of four nested loops over K-HAT, W-HAT, ALFA1-SNAKE and ALFA3-SNAKE respectively, in which:

$$K\text{-HAT} = \text{ABS}(K1 + K2)$$

$$W\text{-HAT} = W1 + W2$$

$$\text{ALFA1-SNAKE} = \text{angle of } K1 \text{ relative to } K\text{-HAT}$$

$$\text{ALFA3-SNAKE} = \text{angle of } K3 \text{ relative to } K\text{-HAT}$$

The relations between these parameters are illustrated in Figure 2. The parameters K-HAT, W-HAT, ALFA1-SNAKE and ALFA3-SNAKE, refer to the parameters  $\hat{k}$ ,  $\hat{\omega}$ ,  $\hat{\alpha}_1$  and  $\hat{\alpha}_3$  in Hasselmann and Hasselmann (1981). This loop structure is chosen to account for the symmetric properties of the Boltzmann integral.

For reasons of numerical stability the integration variables  $\hat{\omega}$ ,  $\hat{\alpha}_1$  and  $\hat{\alpha}_3$  are transformed to the variables  $\zeta$ ,  $\eta_1$  and  $\eta_3$ , in order to remove a singularity of the transformation Jacobian at the center of the interaction diagram, where  $k_1 = k_2 = k_3 = k_4$  (see Hasselmann and Hasselmann, 1981). The values of the original variables are given by the user, see example input. The values of the transformed variables are then obtained from the original ones by applying a coordinate stretching transformation near the peak of the spectrum, and the loop is over the transformed variables.

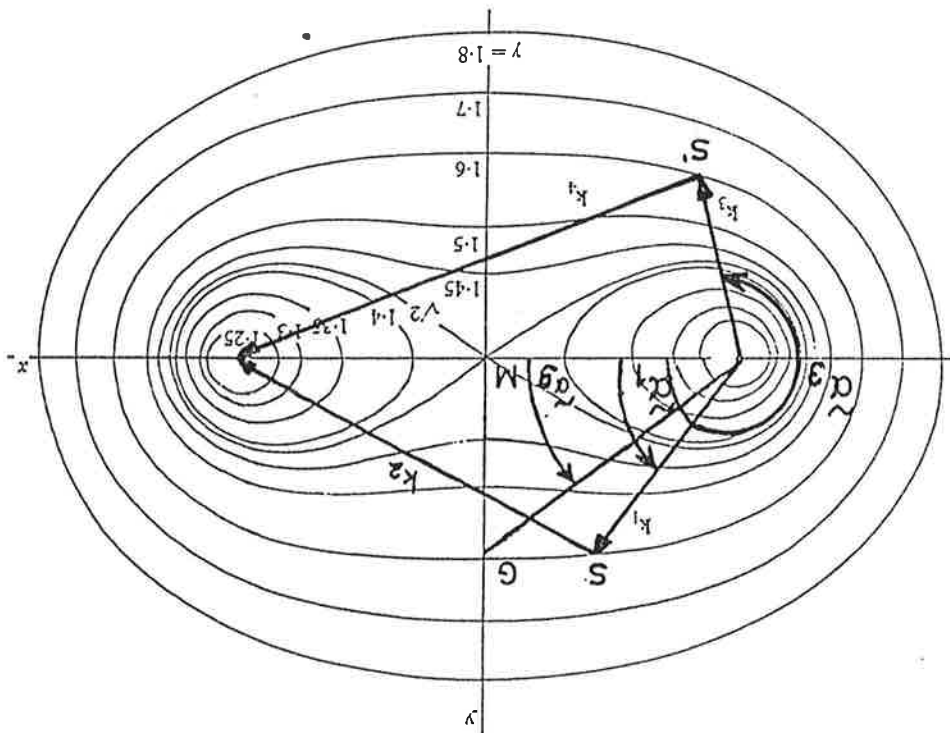


Figure 2: Interaction diagram for third order resonant wave-wave interactions for deep water (Hasselmann and Hasselmann 1981). The diagram applies for given  $\hat{k}$ , with each curve corresponding to fixed  $\hat{\omega}$ . The parameter  $\gamma$  is defined as  $\hat{\omega} = \gamma(g\hat{k})^{1/2}$ .

Each combination of K-HAT, W-HAT, ALFA1-SNAKE and ALFA3-SNAKE gives the frequencies and angles relative to K-HAT of four interacting wavenumber components (a quadruplet); all those quadruplets together form a grid for the nonlinear transfer. As the nonlinear transfer depends on the input spectrum, it is evident that our choice of a K-HAT and a W-HAT- grid should be related to the (frequency grid of the) input spectrum for INTFIL. It must be ensured that the W-HAT array generates frequencies within the energy containing part of the spectrum. The finer mesh must be located around the peak of the spectrum. Some considerations for the choice of a W-HAT grid are as follows (INTKOE creates a coarse K-HAT-grid from the coarse W-HAT grid by the expression  $K\text{-HAT} = 2 * K((W\text{-HAT})/2)$ ):

- (i) If the energy-containing range of our input spectrum lies between a lower frequency limit FLOW and an upper frequency limit FUPP, choose  $2 * \pi * FLOW$  as lowest value for W-HAT and  $2 * \pi * FUPP$  as highest value.
- (ii) Choose a fine resolution for W-HAT around  $2 * \pi * FPEAK$ .

It is important to choose FLOW small enough and FUPP large enough in order not to neglect parts of the integral.

An optimal grid can only be found by trial and error. The given W-HAT grid has been used for a JONSWAP-spectrum with peak frequency  $FM = 0.3$ , it can always be scaled to other values of FM by multiplication with  $FM/0.3$ .

Quadruplets which contain two very small (less than  $2 * \pi * FLOW$ ) and two large interacting frequencies will have a very small or zero contribution to the Boltzmann integral. This means that they will be filtered out in the program INTFIL, so we can save computing time and memory space by stating that those quadruplets will not be taken into account. This is the function of the lower cut-off for the radian frequency FVGL. For a JONSWAP spectrum with peak frequency FM, we can take for FLOW approximately  $0.5 * FM$ , so that a safe value for FVGL seems to be:

$$FVGL = 0.5 * FM * 2 * \pi = 3 * FM \quad (3.2)$$

A too large value for FVGL will lead to inaccuracies, as we will leave out quadruplets which do contribute significantly to the nonlinear transfer, but a

too small value will lead to an enormous output file, causing INTFIL to spend too much time in the high frequency part of the spectrum at the expense of the computation of the interactions near the peak of the spectrum.

### 3.2.3 Output

The output file on unit 2 consists of the following quantities:

- (i) the indices of the K-HAT array, OMEGA-HAT, ALFA1-SNAKE and ALFA3-SNAKE,
- (ii) frequencies of four interacting wave components,
- (iii) the interaction coefficient and the transformation Jacobian and
- (iv) angles relative to K-HAT of the four wave components.

The first of these quantities is not used in program INTFIL and could be dropped.

### 3.2.4 Input on unit 5

ICASE	Case number, for administration purposes (10I4)
BETA, FVGL	BETA, Water depth in meters FVGL, lower cutoff for W-HAT (radians) (2E12.6)
N1,N2,NSS	N1, Number of intervals in coarse K-HAT grid N2, Number of intervals in coarse W-HAT grid NSS, Number of intervals in angular grid (10I4)
OMDG(I), I = 1,N2 + 1	Course W-HAT array (10E12.6)
KFD(J), J = 1,N1	Number of subintervals per interval in coarse K-HAT array (10I4)
MFD(J), J = 1,N	Number of subintervals per interval in coarse W-HAT array (10I4)



### 3.2.5 Example input

```

1
0 .30E + 02      0.9E + 00
  5   5   3
0.214000E + 010. 270000E + 010.43000E + 010.6000000E + 010. 900000E + 010. 120000E + 02
 15  45  16   8   3
 15  45  16   8   3

```

## 3.3 INTFIL

### 3.3.1 Purpose

INTFIL is a program which completes the calculation of the discrete phase space. Insignificant parts of the phase space are filtered out for a certain reference spectrum.

### 3.3.2 General description

INTFIL loops over the angle ALFA-HAT (direction of K-HAT) and its symmetric counterpart. Insignificant parts of the phase-space are filtered out. This filtering is controlled by the values of ABF1, ABF2 and SFAC. SFAC makes it possible to relate the filtering to the scaling of the nonlinear transfer which is performed in ONEDMOD. The value of SFAC is related to the spectral shape. For a mean JONSWAP spectrum a value of SFAC = 1 is recommended.

To find the nonlinear transfer for a given input spectrum the frequencies and angles of the interacting wave components are interpolated from the given frequency and angular array. Therefore two extension points are added to the frequency array. The lowest frequency becomes 0 Hz, the highest frequency becomes FRLI Hz. Based on the resonance conditions (2.3) it is found that a safe choice for FRLI is:

$$FRLI = (W - HAT(max) - FVGL) / (2 * PI) \quad (3.4)$$

The highest interacting frequency encountered in the input file is given by the variable OMM, so that we can check on the value of FRLI (FRLI should be greater than OMM). The same parameter FRLI is used in ONEDMOD.

### 3.3.3 Parameters

In the program the following parameters are used:

FRLI	upper extension point for frequency array
ABF1	cut-off level for fine filtering
ABF2	cut-off level for coarse filtering
SFAC	factor in cut-off levels

Example:     FRLI = 2.  
               SFAC = 1.  
               ABF1 = 0.50E-12 \* SFAC  
               ABF2 = 0.50E-11 \* SFAC

These values are given by an assignment statement in the main program. However, it is recommended to read the values of FRLI and SFAC from unit 5. In a later version of the EXACT-NL model the values of these parameters are to be read from unit 5.

### 3.3.4 Input files

The reference spectrum  $N(\mathbf{k})$  is obtained from program FRSPEC. The interacting frequencies and their angles relative to K-HAT, the transformation Jacobian and the interaction coefficient are obtained from program INTKOEf.

### 3.3.5 Output files

The output of the filtered values are written to the units 8 and 9. These data consist of the following quantities:

- (i) frequencies of four interacting wave components,
- (ii) the interaction coefficient and the transformation Jacobian,
- (iii) absolute angles of the four wave components,
- (iv) angular increment.

As (ii) and (iv) are not used separately in program ONEDMOD, they can be stored as one quantity: the output file then consists of a multiple of 9 instead of 11 quantities. There are two output files: one with fine filtered values (unit 8) and

one with coarse filtered values (unit 9). If the nonlinear transfer computed from the coarse filtered values and the one computed from the fine filtered values differ too much, then the values for the cut-off levels are chosen too large. The results of the INTFIL program are not very sensitive to the choice of the input ALFA-HAT array.

### 3.3.6 Input on unit 5

IRUN                    Run number, for administration only (I4)  
 N11,N1,N22,N2        N1    Number of elements in coarse ALFA-HAT array (4I7)  
                          N11     $2\pi/N11$  = increment of coarse ALFA-HAT array  
                          N2    Number of elements in fine ALFA-HAT array  
                          N22     $2\pi/N22$  = increment of fine ALFA-HAT array  
                          between -60, + 60 degrees.

### 3.3.7 Example input

```

1
36 37 90 55

```

This results in the following values for the ALFA-HAT array:

```

0,4,8,...,56,60,70,80,.....,290,300,304,308,.....,356,360
<- fine -><----- coarse --><--- fine ----->

```

## 3.4 ONEDMOD

### 3.4.1 Purpose

ONEDMOD is a program to integrate the one-dimensional energy transport equation with respect to time or fetch for NC cases simultaneously. (The present maximum number of cases is 10). A case is determined by the coefficients and exponents of the dissipation source function and/or by the wind input vector. ONEDMOD has the possibility to stop the computation after a certain number of steps and to resume the computation later with the last computed spectrum as input spectrum.

### 3.4.2 General description

In ONEDMOD the energy balance equation (2.1) is written as:

$$\frac{\partial SPTI}{\partial t}(F, TETA) + CGX(F, TETA) \cdot \frac{\partial SPTI}{\partial x}(F, TETA) = SCFT(F, TETA) \quad (3.5)$$

In which SPTI is the energy density, CGX the group velocity in X-direction and SCFT the total source function. In the present version of ONEDMOD the parameter ICASE determines the type of growth:

ICASE = 1 Duration limited growth, the wave transport equation reduces to:

$$\frac{\partial SPTI}{\partial t} = SCFT \quad (3.6)$$

ICASE = 2 Fetch limited growth, the wave transport equation now reduces to:

$$CGX \cdot \frac{\partial SPTI}{\partial x} = SCFT \quad (3.7)$$

For ICASE = 1 we have a duration limited growth in which the coefficients and exponents of the dissipation function are kept the same for all possible cases. So cases are distinguished by having different wind vectors. When we have more than one case (NC > 1) the model initially computes the growth curve for the first case until the peak frequency FM drops below a specified frequency (FRTURN). When this occurs the wind direction turns for the cases 2,...,NC. The spectrum of case 1 is copied to the spectra of the other cases and the computation continues, but now for NC cases. The wind direction WDIR for each case can be determined by:

$$WDIR = (K - 1) * DELTW \quad (3.8)$$

in which K the case number and DELTW is the directional increment of the wind vector.

For ICASE = 2 we have a fetch-limited growth curve. The present version of ONEDMOD makes it possible to compute NC cases simultaneously with different values for the variables in the dissipation function. The wind velocity and wind

direction are the same and constant for all possible cases. For this case it is assumed that waves which don't have a component in the direction of the wind have zero energy. This is expressed by the directional indices IA1 and IA2.

For both cases it is possible to make slight adjustments of ONEDMOD in order to use different values of the coefficients in the dissipation source function and the wind vector simultaneously. It is even possible to make the wind vector dependent on time.

### Numerical solution

The simplified energy balance equation is solved with an explicit first order difference scheme with a dynamically adjustable time or fetch step.

When we write SPTI and SPT1 for the spectral density at the beginning and end of a fetch or time integration step respectively, we get

$$SPTI = SPTI + SH \quad (3.9)$$

in which SH is the increment of spectral energy per spectral component, it is computed by:

$$SH = SCFT * DELX / VPH \quad (3.10)$$

in which:

$$\begin{aligned} \text{ICASE} = 1: & \quad \text{DELX} = \text{DELX} \\ & \quad \text{VPH} = 1. \\ \text{ICASE} = 2: & \quad \text{DELX} = \text{DELX} \\ & \quad \text{VPH} = \text{CGX}(F) * \text{COS}(\text{TETA}) \end{aligned}$$

The numerical scheme is applied to the frequency range 0 - 2.5\*FM. The frequency index of the upper limit is indicated by the parameter ICUT, determining the first frequency point beyond 2.5\*FM. Two cut-off levels are used to limit the growth in a spectral bin.

$$FLL = 0.1 * 0.054 * G ** 2 / (2. PI) ** 4 * F ** (-5) \quad (3.11)$$

$$FR25 = 0.3 * ALFA * G ** 2 / (2. PI) ** 4 * F ** (-5)$$

(The values 0.1, 0.3 and 0.054 are based on experience). The step size DELX is divided by two when the following criterion holds:

$$ABS(SH) > SPTI/3 \text{ "AND" } (ABS(SH) > FR25 \text{ "OR" } (SH + SPTI) < 0) \quad (3.12)$$

or in words: when there is too much growth or when the new energy becomes lower than zero. When the following criterion holds we assume that the energy in a bin does not increase:

$$SPTI < FLL \text{ "AND" } SCFT \leq 0 \quad (3.13)$$

To further illustrate the above described algorithm to determine the step size DELX, a FORTRAN-V listing of that part of the program is given:

```

1000  CONTINUE
      FMT = 2.5 * FM
      ICUT = ALOG10(FMT/FR(1)) * 24.16 + 2
1050  CONTINUE
      DO 1100 I = 1, ICUT
      FLL = 0.1 * 0.054 * G**2 / (2. * PI)**4 * FR(I)**(-5)
      FR25 = 0.3 * ALFA * G**2 / (2. * PI)**4 * FR(I)**(-5)
      IF(SPTI.LE.FLL.AND.SCFT.LT.0) THEN
      SCFT = 0.
      SH = 0.
      ELSE
IF(ABS(SH).GT.SPTI/3.AND.(ABS(SH).GT.FR25.OR(SH + SPTI).LT.0) THEN
      DELX = DELX/2
      GOTO 1050
      END IF
      END IF
      SPT1 = SPTI + SH
1100  CONTINUE

```

For ICASE = 2 (Fetch-limited case) it is assumed that wave components which don't have a component in the direction of the wind have zero energy all the time.

## Scaling

To compute the nonlinear transfer for an arbitrary spectrum, this spectrum is scaled to the reference spectrum. Parameter in the scaling is the peak frequency  $FM$ , which is obtained by making a JONSWAP fit to the spectrum. This scaling consists of a transformation of the frequency axis such that the peak frequency of the arbitrary spectrum becomes equal to the peak frequency of the reference spectrum. The nonlinear transfer of the transformed spectrum is computed with the filtered parts of the phase space. Finally the nonlinear transfer is rescaled to the peak frequency of the arbitrary spectrum. We assume thereby that spectra with approximately the same shape (which makes a JONSWAP fit possible), have approximately the same filtered phase space.

In some versions of the ONEDMOD program the feature of the logarithmic frequency spacing is used in the scaling of the spectrum and the nonlinear transfer. A shift of frequency indices then corresponds automatically to a linear scaling of the frequency axis.

In the course of a duration or fetch limited run it could be necessary to rerun the INTFIL program in order to update the filtered phase space. Therefore, one should be careful whether or not the spectral shape of the actual spectrum does not differ too much from the spectral shape of the reference spectrum or by comparison of the nonlinear transfer as computed from the course or fine filtered phase spaces.

### Remark

The parameter  $FRLI$  should have the same value as in INTFIL.

### 3.4.3 Initial conditions

The initial conditions for the model are normally a JONSWAP spectrum (with a given set of parameters  $ALFA$ ,  $FM$ ,  $GAMMA$ ,  $SIGA$  and  $SIGB$ ) an initial time  $T$  or fetch  $X$ , and a wind velocity  $U10$  (given in subroutine SOURCE). The values of the JONSWAP parameters  $ALFA$  and  $FM$  evolve with time or fetch, for which approximate empirical relations are known. One such relation is given by the two parameter model of Hasselmann et al. (1976). For the case of a duration

limited growth under a constant and homogeneous wind field, the parameter model gives:

$$V = 16.8 (G * T / U_{10})^{**(-3/7)} \quad (3.14)$$

$$ALFA = 0.033 * V^{**(2/3)} \quad (3.15)$$

$$E' = 5.28 E - 06 * V^{**(-10/3)} \quad (3.16)$$

in which  $V$  the dimensionless peak frequency defined by  $V = FM * U_{10} / G$  and  $E'$  the dimensionless energy defined by  $E' * G^{**2} / U_{10}^{**4}$ . In order to compute the initial condition we first choose the peak frequency  $FM$  and the wind velocity  $U_{10}$ . The precise shape of the initial spectrum is not critical since the spectrum adjusts rather quickly to the wind field.

### Example 1

$$FM = 0.4 \text{ Hz}, \quad U_{10} = 10 \text{ m/s:}$$

$$T = (U_{10} / G)^{**(-4/3)} * (FM / 16.8)^{**(-7/3)} = 6000 \text{ s}$$

$$ALFA = 0.033 * (FM * U_{10} / G)^{**(2/3)} = 0.018$$

For the other JONSWAP parameters we take the mean JONSWAP values,  $GAMMA = 3.3$ ,  $SIGA = 0.07$  and  $SIGB = 0.09$ .

For the case of a fetch limited growth under a constant and homogeneous wind field the parameter model gives:

$$V = 2.84 * (G * X / U_{10}^{**2})^{**(-3/10)}$$

$$ALFA = 0.033 * V^{**(2/3)}$$

in which  $X$  is the fetch in meters.



**Example 2**

FM = 0.4 Hz, U10 = 10 m/s:

$$X = U10 * (U10/G)^{(-7/3)} * (FM/2.84)^{(-10/3)} = 6900 \text{ M}$$

$$ALFA = 0.033 * (FM * U10/G)^{(2/3)} = 0.018$$

**3.4.4 Input files**

The input consists of two large files with the fine and coarse filtered phase space (from INTFIL) on units 2 and 9 respectively, the input spectrum in  $f$ - $\Theta$ -space and the peak frequency FMH of the reference spectrum (from FRSPEC).

**3.4.5 Output**

The output consists of the spectra, source functions and spectral parameters every IZDW steps. The precise output can be specified by the user.

**3.4.6 Input on unit 5**

KLL, IZDXE, ICASE, IREAD, IZDW (10I4)

KLL	maximum number of cases in parallel
IZDXE	maximum number of steps
ICASE	see above for explanation
IREAD	if IREAD.EQ.1 computation starts if IREAD.GT.1 computation continues and the last IREAD spectra are read
IZDW	output every IZDW steps

THTURN, XI, FRTURN, FM (8E9.3)

THTURN	Time or fetch indicating turning point of wind (not used in present versions)
XI	Initial fetch or time, see below
FRTURN	Frequency point for turning of wind
FM	Initial peak frequency (not used)

MA(I), I = 1,KLL exponents in ALFA-term in dissipation function (10I4)  
 NA(I), I = 1,KLL exponents in OMEGA-term in dissipation function (10I4)  
 CA(I), I = 1,KLL coefficients in dissipation function (8E9.3)

### 3.4.7 Example input

```

6 100 1 0 5
0.0E + 00 0.60E + 03 0.26E + 00 0.30E + 01
2 2 2 2 2 2
2 2 2 2 2 2
0.333E - 04 0.333E - 04 0.333E - 04 0.333E - 04 0.333E - 04

```

## Chapter 4

### Modifications for specific purposes

#### 4. Introduction

For two specific purposes modified versions of the EXACT-NL model have been made. These are for shallow water runs and for the computation of the response of the spectrum after a sudden wind shift. The changes to the model necessary for these purposes are described below (Weber, 1988; van Vledder and Holthuijsen, 1988).

#### 4.1 Shallow water

The programs FRSPEC, INTKOEf and INTFIL can be used for arbitrary waterdepth  $d$ , on the condition that the full dispersion relation  $\omega^2 = g.k.\tanh(kd)$  is used (check INTFIL-6: integration checks). ONEDMOD has been modified for shallow water simulation runs as follows:

- (i) the group velocity in ONEDMOD-3.5 (computation of spectrum for  $N + 1$ ) is derived from the full dispersion relation.
- (ii) for shallow water there is an additional factor in the scaling law for the nonlinear transfer, which is a complicated function of frequency, direction and water depth. Therefore, in the present modification, scaling is only used for deep water whereas for shallow water the filtered phase space is updated (in INTFIL) when the current spectrum differs too much from the reference spectrum. The product of the peak wavenumber (the wavenumber which corresponds to the peak frequency) and the water depth  $k_p \cdot d$  is used as a flag which determines whether the water is "deep" or "shallow". For  $k_p \cdot d > 1.83$  the water is considered as deep. The phase space is updated when the peak frequency shifts one frequency grid point. To check on this scheme the nonlinear transfers computed from both phase spaces are intercompared. The nonlinear transfer varies smoothly in this updating scheme. Updating had to be performed at the most four times for one simulation run.
- (iii) various concepts which were expressed in frequency space for deep water (the dissipation by whitecapping, the high frequency parameterization, etc.) are rewritten in wavenumber space for shallow water.

- (iv) a bottom dissipation source function is added to the total source function.

#### **4.2 Turning winds**

For the computation of a duration limited run, in which the mean wave directions of the computed spectrum and the reference spectrum differ, an additional transformation is used. This transformation consists of two rotations. In the first rotation the computed spectrum is rotated such that its mean wave direction is as close as possible to the mean wave direction of the reference spectrum. The rotation angle should be a multiple of the directional increment of the model, otherwise the spectrum is smoothed, thereby increasing the direction width. After the nonlinear transfer of this 'rotated' spectrum has been computed, the results are rotated back to the original direction. These rotations are allowed when the shape of the arbitrary and reference spectrum are almost equal, except for their mean wave directions.

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