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VIERS-1 Final Report Phase 4

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BELEIDSCOMMISSIE REMOTE SENSING

VIERS-1 Final Report Phase 4

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both to tilting of the small waves by the long ones and to hydrodynamic modulation), slicks on the water surface and atmospheric stability. In the course of the project several different methods to deal with the various aspects of the scattering process were tested in the model. The incorporation of these modules was a relatively simple job because the computer programme embodying the algorithm has a modular structure that allows for easy upgrading of the model.

In the final stages of the project comparisons were made with the results of the CMOD4 algorithm that had been developed at the European Centre for Medium Range Weather Forecasts (ECMWF; Stoffelen and Anderson, 1995). The global wind fields, as analyzed by ECMWF, were used as the yardstick for the qualities of the algorithms. It was with a sense of satisfaction that in the final phase the project team concluded that the VIERS-1 results were in general comparable to and in a number of respects (especially at high wind speeds) closer to the ECMWF wind fields than those of CMOD4. This is a better result than might be thought at first reading: CMOD4 has been tuned in an exquisite way to the ECMWF data and to beat such a model "at its own game" is no mean feat. The power of the VIERS-1 model furthermore is its physical basis, which, together with its modular structure, allow for possibilities for easy further development in the future, whereas CMOD4 in its way is next to perfect and has to be considered as more or less the end of its road. (Another and different question in this respect is whether analyzed wind fields are indeed a correct yardstick: the color pictures toward the end of this report, showing the intercomparison, indicate that meteorological models tend to smooth the actual wind fields).

The VIERS-1 project has been split up in four phases and the project team, in different combinations, has duly reported on each of them (van Halsema et al, 1989, Calkoen et al 1990, Snoeij et al, 1992, Janssen et al 1993 and now Janssen et al, 1995). All of these reports have been issued by one of the few steady elements in this whole shifting field of knowledge and interests: the Netherlands Remote Sensing Board BCRS, which supported the project from its frail beginnings up to the present time. We thank them for their confidence and their financial contributions which were essential to this result.

2 Executive summary

Using scatterometer data from ERS-1 we have shown that realistic wind fields may be obtained with the VIERS scatterometer algorithm.

The VIERS algorithm determines for given parameters such as wind speed and direction, sea state and radar incidence angle, the radar backscatter at the ocean surface. Thus, by inverting the algorithm the wind field over the ocean may be determined from the observed radar backscatter provided the sea state (given by the WAM model) is known. The inversion of the algorithm was achieved by means of minimisation of a cost function that penalises deviations between modelled and observed radar backscatter and deviations between retrieved and atmospheric model wind direction.

The retrieved wind fields are in good agreement with analysed ECMWF winds. After the completion of the VIERS project, H. Roquet of ECMWF found good agreement between retrieved winds from the VIERS algorithm and observed winds from buoys. Compared to the present operational CMOD4 algorithm we found that the VIERS algorithm performs better in extreme conditions; in the high wind speed regime wind waves are in a relatively early stage of development and are therefore so steep that the radar backscatter from the short waves is affected.

From a synoptic study we have concluded that the VIERS winds are of high quality. The VIERS algorithm performs well in cases of frontal systems, for example, and only occasionally problems with the wind direction ("the ambiguity problem") occur.

The end result is that we have developed a scatterometer algorithm based on our present knowledge of the physics of the relevant processes. From the observed radar backscatter this algorithm enables us to obtain reliable wind fields.

3 Introduction

Traditionally, the operational retrieval algorithms for the scatterometer relating the radar backscatter measurements to surface wind vectors have been empirical. The assumption that the backscatter only depends on the local wind field may be questioned however, since the backscatter reflects to some extent the state of the high-frequency wind waves. The spectrum of wind-generated gravity-capillary waves not only depends on the local wind, but is determined by a number of physical processes, namely wind input, nonlinear three and four-wave interactions, viscous dissipation and dissipation due to slicks. Thus, for high winds when the waves are sufficiently steep, nonlinear processes may be dominant so that the state of the short waves is mainly determined by the longer gravity waves. The state of the longer waves depends on factors such as coastal geometry, duration of a storm system, currents and bathymetry and therefore the radar backscatter may depend on these environmental circumstances as well. On the other hand, for low wind speed, viscous dissipation and dissipation due to slicks may be relevant processes in determining the shape of the short wave spectrum, again suggesting that not only the local wind determines the backscatter.

Furthermore, it should be pointed out that the radar backscatter shows an additional dependence on the state of the long gravity waves, because the short waves which provide the backscatter are tilted by the longer gravity waves. This effect is especially relevant for small incidence angles.

The above considerations prompted an extensive investigation into the dependence of the radar backscatter on physical parameters such as wind speed, sea state, the presence of slicks and even parameters such as the air-sea temperature difference. The latter parameter becomes relevant when it is realized that the high-frequency wave spectrum depends on the surface stress and the relation between surface stress and wind speed involves atmospheric stability. The VIERS group emerged and started an experimental study in the laboratory and at sea to address the above mentioned issues. Parallel to the experimental work, the VIERS group started the development of a scatterometer algorithm based on the present understanding of the radar backscatter process and of the relevant processes governing the shape of the gravity-capillary spectrum. The observed results on radar backscatter and the short wave spectrum were used as a guideline to tune a number of unknown parameters in the scatterometer algorithm. As a result, a backscatter algorithm based on physics rather than empirical fitting was obtained (van Halsema, 1989; Calkoen, 1990; Snoeij, 1993; Janssen, 1994).

Confidence in the performance of the VIERS algorithm increased when the simulated backscatter, obtained using the ECMWF wind and WAM wave fields, was compared with the backscatter as observed by the ERS-1 satellite. The air-sea temperature difference was set to zero since neutral stability is the most common situation that occurs over the oceans. The period of interest was the 6th of November 1991 at 12Z. In fig. 1 we compare the simulated backscatter with the observed ones showing an overall good agreement, even for low wind speed. As a benchmark, we have also shown results of the present operational scatterometer algorithm CMOD4.

We conclude from this comparison that the VIERS scatterometer algorithm, based on our present knowledge of air-sea interaction, is performing well, even compared to CMOD4. Despite the good agreement between observed and simulated backscatter it should be pointed out that the rms error, which is of the order of 2-3 dB, is large when compared with the observation error which is about 0.2 dB. This could imply two things. On the one hand, it can be argued that the large rms error is caused by model errors. This possibility seems to be unlikely, however, since it is known that CMOD4, which has the bigger rms error, has a reasonable skill in retrieving wind speed and direction. On the other hand, a source of error could be provided by the analysed wind and wave field used in the generation of the simulated backscatter with the backscatter algorithms. In other words, the observed backscatter might contain relevant information regarding the surface wind field. In view of the large difference between the rms error of fig. 1 and the measurement error, the information contained in the observed backscatter might therefore be quite considerable.

In order to substantiate this claim we need to invert the VIERS algorithm so that a retrieval of wind speed and direction from the observed backscatter returns becomes feasible. The remainder of this report is devoted to this task.

The program of this report is as follows. In chapter 2 a review of the VIERS scatterometer algorithm is given, including a description of the energy balance for the short waves. Once the wave spectrum is known a two-scale model is used to determine the normalized backscatter. The scatterometer algorithm thus obtained gives the radar backscatter as a function of a number of geophysical parameters such as wind speed and direction, the sea state, slicks, air-sea stability, the sea surface temperature and of course geometrical parameters such as the incidence angle.

In this report we restrict our attention only to the usual parameters wind speed and direction and incidence angle and allow as additional parameter the sea state. We disregard effects of air-sea stability because air flow over the oceans is almost always neutrally stable and we take only an averaged effect of slicks into account. Nevertheless, the VIERS algorithm is computationally very expensive and is as such not a feasible option when used in routine applications such as wind retrieval for determining the initial conditions of an atmospheric model.

For practical applications we therefore generated tabulated values of the radar backscatter σ_0 as function of wind speed, wind direction, incidence angle and sea state. Once this table of σ_0 is known we retrieve wind speed and direction from the observed ERS-1 σ_0 triplet by minimizing a measure of distance between observed and modelled backscatter under the side constraint that the retrieved wind direction does not deviate too much from the first-guess wind direction provided by the ECMWF model. This procedure allows for a unique solution of the wind vector and is, in fact, as efficient as present day operational algorithms such as CMOD4. This set-up was used to perform a fine-tuning of the VIERS algorithm where we concentrated on the generation of realistic wind fields from observed radar backscatter from ERS-1 (cf. chapter 3).

Chapter 4 is devoted to a description of the VIERS software. An overview of the program structure is given, while also an example is presented which may be

Figure 1: Simulated σ_0 using CMOD4 (top) and VIERS algorithm (bottom) versus observed σ_0 from ERS-1 on 911106.

used to check the software when installed in a different environment. Also individual subroutines are discussed in some detail.

In chapter 5 we compare retrieved wind vectors by means of the VIERS scatterometer algorithm with the ECMWF analysed wind fields and it is found that the VIERS and ECMWF winds are compatible in a statistical sense. In addition we use as a reference results from CMOD4. A direct comparison between VIERS and CMOD4 reveals a generally good agreement between the two products except that in the high wind speed range VIERS has higher winds than CMOD4 while at low winds VIERS has lower winds. The reason for the difference at low winds is that the CMOD4 algorithm has a cut-off at a speed of 2 m/s. Regarding the difference at high wind speed it should be remarked that compared with the ECMWF wind speed the VIERS winds show a better agreement than the CMOD4 winds. As an atmospheric model usually underpredicts the extreme winds because the finite resolution cannot resolve the pressure low properly, it is concluded that CMOD4 is underpredicting in the high wind speed range while VIERS is performing better. After the statistical comparison we proceed with a synoptic discussion of the differences between retrieved and analysed winds concentrating on a frontal system that occured in the Norwegian sea on November 6th 1991. It is concluded that generally there is better agreement between retrieved winds from VIERS and CMOD4 than with the analysed winds. Also, the ambiguity removal by using meteorological winds as initial guess winds seems to work satisfactory. Furthermore, it appears that the VIERS wind direction has a better spatial consistency than the wind direction from CMOD4 while the VIERS model is capable to predict low wind speeds.

The overall conclusion is that the VIERS algorithm performs in a satisfactory way. The final question therefore is whether it is feasible to use this rather involved algorithm. This question is addressed in chapter 6 on cost-benefit analysis. By using tabulated values of σ_0 we show that even a complicated algorithm based on physics such as VIERS may be used in an operational environment. In fact, the computational cost is as high as for CMOD4. A drawback is, however, that due to the use of a rather coarse-grained table the misfit in σ_0 space between modelled and observed backscatter may be rather high. However, even with this rather coarse-grained table we know from our synoptic discussion (where we compared observed winds with retrieved ones) that we still obtain reasonable results. Nevertheless, it should be pointed out that the misfit in σ_0 space between modelled and observed backscatter is generally larger for VIERS than for CMOD4. This is probably caused by a too simple directional distribution of wind waves in VIERS as compared to CMOD4. In addition, it should be remarked that in CMOD4 an incidence angle dependent bias correction was introduced, which assures a much better fit in σ_0 space. We have not followed this approach thus far because we have the impression that already a good quality wind product is delivered by VIERS. No doubt retrieved winds from VIERS will certainly provide information on the initial condition of a meteorological model. Although we have not been able to show this thus far, we expect that a model based on physics should be preferred in the end because it is capable to model situations such as fronts, low wind speeds,

etc., much better. A convincing proof of this can only be given by a study of those circumstances where both satellite data, in situ observations and analysed model fields are available.

4 Model description

The VIERS model relates radar backscatter to windvector, measurement geometry (=incidence angle), sea state (period of the dominant waves), air-sea temperature and slicks. In the remainder of this report we shall only consider effects of the sea state, although in the synoptic discussion we also study effects of atmospheric stability. In the so-called interpretative mode the windvector $\vec{U}_{10}$, incidence angle θ and wave period P appear at the input level, whereas the normalized cross-section for radar backscatter σ_0 is the output variable. The relationship is established in three consecutive steps. Each is described by its own submodel.

First comes the submodel (wind-stress module) that relates windspeed and wave period to wind stress at the water surface (parameter u_*). In the HEXMAX experiment (Maat et al, 1991; Smith et al, 1992) evidence was found for a sea-state dependent roughness length; the HEXMAX parametrisation has been adopted and implemented into the VIERS model.

The second submodel is the stress-waves module. Here the full (i.e. both gravity and gravity-capillary waves) spectrum of water waves is determined from wind stress and wave period. The gravity part is obtained by invoking a JONSWAP spectrum, the parameters of which follow from growth laws. The JONSWAP function is assumed to describe the wave spectrum up to the frequency f_{join} ($f_{\text{join}} \approx 2 - 5$ Hz). The grav-cap part is separately obtained by solving a simplified energy-balance equation which includes all relevant processes (i.e. wind input, wave breaking, viscous dissipation, nonlinear wave-wave interactions, dissipation by slicks). The resulting grav-cap part of the spectrum is continously joined to the gravity part at f_{join}.

Finally the structure of the water surface, represented by the wave spectrum, has to be related to the radar backscatter (σ_0). This is done in the third submodel, the waves-scatter module. In VIERS a more or less standard two-scale approach was adopted in which the waves are separated into short and long ones. The short waves that obey the Bragg criterion resonantly scatter the radar wave, whereas the long waves act as facets that tilt the short ones.

For practical purposes (wind retrieval from ERS-1 scatterometer measurements) the interpretative model has to be inverted (i.e. in- and output have to be interchanged). In order to produce an optimal windvector the inverted VIERS model requires three σ_0's (normalized radar cross-section of respectively for-, mid- and aftbeam) plus the period of the dominant waves. The inversion procedure is a very simple and straightforward one and will be described in section 2.4.

4.1 Wind-stress module

The stress field at the air-sea interface is determined by the wind speed, the stability of the air colomn (air-sea temperature difference) and the sea state (wave age of the dominant waves). For given wind velocity U_z at height z, period of the dominant waves P and the temperatures of sea and air (T_{sea} and T_{air}) the VIERS module yields the friction velocity u_*, the roughness length z_0 and the Monin-Obukov stability length L.

The wind profile is assumed to have the following form:

$$U_z = \frac{u_*}{\kappa}(\log(z/z_0) - \Psi_M(z/L)), \tag{1}$$

where κ is the von Karman constant.

The roughness length is parametrized according to Smith et al. (1992).

$$z_0 = 0.48\frac{2\pi u_*^3}{g^2 P}, \tag{2}$$

where g is the gravitational acceleration.

For the stability parameter Ψ_M the Businger-Dyer expression (Businger et al, 1971; Dyer et al, 1970) is adopted.

$$\Psi_M = -4.7z/L \qquad \text{(stable)}$$

$$\Psi_M = 2\log((1+\Phi_M)/2) + \log((1+\Phi_M^2)/2) - 2\tan(\Phi_M) + \pi/2 \qquad \text{(unstable)}$$

with

$$\Phi_M = (1 - 16z/L)^{0.25} \tag{3}$$

The Monin-Obukov length is computed according to Stewart (1985),

$$L = \frac{-U_z u_*}{g\kappa}\frac{T_{air}}{T_{sea} - T_{air}} \tag{4}$$

The equation for the wind profile is solved iteratively in order to obtain a self consistent value for the friction velocity.

4.2 Stress-waves module

In general, the gravity part of the wave spectrum consists of wind sea and swell, which in principle may be provided by an ocean wave prediction model (e.g. the WAM model; Komen et al, (1994)). For simplicity, we only use as measure of the sea state the mean period P_{mean} of the ocean waves, and we only consider wind sea spectra given by the JONSWAP shape. In order to avoid contamination with swell we therefore take as period the smallest of the Pierson-Moskovitch period ($1.2U_{10}2\pi/g$) and the peak period as obtained from the WAM model (where $P = 1.2P_{\text{mean}}$).

From peak period P and friction velocity u_*, the wave age ξ is obtained as

$$\xi = gP/2\pi u_* \tag{5}$$

It is assumed that the 1-D gravity part may be well parametrized by the JONSWAP shape (Hasselmann et al, 1973).

$$E_{\mathrm{JON}}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp[-\frac{5}{4}(\frac{f_p}{f})^4]\gamma^r \tag{6}$$

where

$$r = \exp[-\frac{(f - f_p)^2}{2\sigma^2 f_p^2}]$$

For old windsea the JONSWAP form asymptotes to the Pierson-Moskowitz expression, because the so-called "peak enhancement factor" γ^r approaches 1. For young waves there is a considerable enhancement of the peak ($\gamma \approx 3$).

In the JONSWAP experiment the peak frequency f_p (or friction velocity u_*) and dimensionless fetch were used as independent parameters. In VIERS the shape parameters f_p, (α, γ, σ) depend on the alternative independent parameters peak period and wave age,

$$f_p = P^{-1} \tag{7}$$

$$\alpha = A\xi^{-B} \tag{8}$$

$$\gamma = \max(1, 1 + 3(1 - (0.00608\frac{2\pi}{\xi})^2)) \tag{9}$$

$$\sigma = 0.08 \tag{10}$$

The parametrisation for the Phillips constant α was not obtained from the JONSWAP experiment; in a tuning procedure for the full model it was found that $A = 0.24$ and $B = 1$. This parametrisation of the Phillips constant is in agreement with the reanalysis of JONSWAP data performed by Günther (1981).

The JONSWAP spectrum is strictly speaking only valid for frequencies up to 3 times the peak frequency. Recent observations of Banner (1989) confirm, however, that up to a frequency of 4Hz the wave spectrum indeed follows a f^{-5} law, thus the region of validity of the JONSWAP spectrum may be extended to these high frequencies.

At the frequency f_{join} ($2 < f_{\mathrm{join}} < 5$) a new regime is entered. In this regime it is assumed that the spectral energy is determined by an energy balance that is both stationary and homogeneous and includes the 3-wave interactions. Theoretical details have been given in VIERS-1 report (1993). Here only a brief resumé is given.

In the regime of grav-cap waves the energy balance takes the following form:

$$0 = \frac{\partial F}{\partial t} + \vec{v}_g \cdot \frac{\partial F}{\partial \vec{x}} = S_{in} + S_{nl} + S_{dis} \tag{11}$$

Here, F is the 1-D wavenumber spectrum, normalized as $\int_0^\infty F k dk = E_v$ (E_v=variance wave field), and v_g is the group velocity. The source term consists of a wind input (S_{in}), a nonlinear interactions term (S_{nl}) and a dissipation term (S_{dis}).

For S_{in} Plant's expression (Plant, 1980) is adopted,

$$S_{in} = \beta F \ , \qquad \beta = \delta\omega\frac{u_*^2}{c^2} \ , \tag{12}$$

where ω is the angular frequency and c the phase speed of the wind-generated wave. The dimensionless constant δ is 0.03. The quasi-linear effect can be incorporated by renormalizing δ (cf. Janssen et al, 1989a; VIERS-1 report, 1993)

It is assumed that S_{nl} may be well represented by a local (in k space) expression,

$$S_{nl} = -\frac{1}{k}\frac{\partial}{\partial k}\varepsilon(k). \tag{13}$$

Here, $\varepsilon(k)$ is the energy flux (in k space). Assuming that only three- and four-wave interactions contribute one arrives at the following expression for ε,

$$\varepsilon(k) = \frac{c^4}{v_g}(\alpha_3(k^4F)^2 + \alpha_4(k^4F)^3) \ , \tag{14}$$

where α_3 and α_4 are dimensionless "coupling constants".

There are three dissipative processes that play a role in the grav-cap regime: viscous damping, wave breaking and damping due to slicks.

$$S_{dis} = S_{vis} + S_{br} + S_{sl}. \tag{15}$$

For viscous damping one has the following exact expression (Lamb, 1934),

$$S_{vis} = -4\nu k^2 F \ , \tag{16}$$

where ν is the kinematic viscosity of water.

The damping by slicks is determined by the Marangoni effect (Alpers and Hühnerfuss, 1989), which causes a resonance type of damping in the short gravity regime. Therefore, the water waves experience an additional viscous damping,

$$S_{sl} + S_{vis} = -4\nu_{\text{eff}} k^2 F = -4\nu y(f) k^2 F. \tag{17}$$

Here, $y(f)$ is the relative damping ratio, given by

$$y(f) = \frac{1 + X(\cos\delta - \sin\delta) + XY + Y\sin\delta}{1 + 2X(\cos\delta - \sin\delta) + 2X^2} \ , \tag{18}$$

δ is the phase angle, and,

$$X = \mid \frac{E_s}{\rho_w} \mid \frac{k^2}{\sqrt{2\nu\omega^3}} \ , \tag{19}$$

$$Y = \mid \frac{E_s}{\rho_w} \mid \frac{k}{4\omega\nu}. \tag{20}$$

Finally, E_s is the dilational modulus of the surface film and ρ_w the density of the water.

It is seen that a surface film is determined by two parameters δ and E_s. The phase angle δ is approximately 180° whereas E_s depends strongly on the type of slick. For a natural slick (mostly of biological origin) E_s can be estimated to have the value 0.01 N/m, whereas for chemical slicks the value can vary from 0.01 up to 0.05 N/m.

However, slicks should be washed-down once the wind is strong enough (cf. Alpers and Hühnerfuss). This process has been modelled by letting the dilational modulus go to zero for strong winds: $E_s = 0.005(1 - \tanh(10u_* - 4.33))$. Because it seems very unrealistic that the ocean is covered by a single large slick, a second modification was implemented. Slicks come in patches and this can be modelled by a fractional filling faction F (Lombardini, 1986). For $F < 1$ the damping is modified according to $y_F(f) = 1/(1 - F + F/y_1(f))$, where y_1 is the damping when the coverage is complete. Typical F-values are in the range 0.88 - 0.99 (cf. Lombardini, 1986).

Because of strong nonlinearity it is very difficult to model effects of wave breaking. Nevertheless, for gravity waves Komen et al (1984) suggest the following expression with $n = 2$,

$$S_{\text{dis}} = -a\bar{\omega}(\frac{\omega}{\bar{\omega}})^n(\frac{\hat{\alpha}}{\alpha_{\text{PM}}})^n F(k) \tag{21}$$

where a and α_{PM} are constants and

$$\hat{\alpha} = \frac{E_v\bar{\omega}^4}{g^2} \tag{22}$$

with E_v is the variance and $\bar{\omega}$ the mean angular frequency of the wave field.

For the VIERS application the above expression (with $n = 2$) has been generalized for gravity-capillary waves. It reads:

$$S_{\text{dis}} = -\beta_1\bar{\omega}(\bar{k}^2E_v)^2(k/\bar{k})F(k) \tag{23}$$

The constant β_1 should be of the order of 2 to produce realistic spectral tails.

An alternative expression for wave breaking relies on an analogy with viscous dissipation, however, with a viscosity that depends on the sea state. Thus,

$$S_{\text{dis}} = -\beta_2\bar{\omega}(\bar{k}^2E_v)^2(k/\bar{k})^2F(k)\cdot \tag{24}$$

For high winds ($U_{10} > 20m/s$) the breaking according to this model becomes too violent resulting in unrealistic spectra. We therefore took $\beta_2 = 0$.

If one substitutes the explicit expressions for the source terms, the energy balance (11) becomes

$$\frac{\partial}{\partial k}\varepsilon(k) = \gamma c^2k^2F \tag{25}$$

The coefficient γ is defined as

$$\gamma = \delta\omega\frac{u_*^2}{c^2} - 4\nu yk^2 - \beta_1\bar{\omega}(\bar{k}^2E_v)^2(k/\bar{k}) \ , \tag{26}$$

hence it gives the net effect of wind input and dissipation. The energy flux $\varepsilon(k)$ is given by

$$\varepsilon(k) = c^2v_g(\alpha_1S^2 + \alpha_2S^3) \qquad S = \frac{c}{v_g}k^4F \tag{27}$$

The coupling constants for the three- and four-wave interactions are modelled as

$$\begin{aligned} \alpha_1 &= T_3 \frac{\pi}{16}(\tanh(\Sigma(x-1))+1), \\ \alpha_2 &= T_4. \end{aligned} \tag{28}$$

Here, $x = f/f_{join}$.

In order to obtain a unique solution of the above equation, it has to be supplemented with a boundary condition, viz. the continuity of the spectrum at $k = k_{\text{join}}$.

The solution of the energy balance equation is the 1-D wavenumber spectrum $F(k)$. If one ignores the frequency shifting (=Doppler) effect due to the orbital motion of the long waves, $F(k)$ may be related to the 1-D frequency spectrum $E(f)$ as follows:

$$\frac{2\pi k}{v_g} F(k) = E(f) \tag{29}$$

Having found the 1-D frequency spectrum in the grav-cap range of frequencies ($f > f_{\text{join}}$), one may combine it with the JONSWAP spectrum in the gravity range ($f < f_{\text{join}}$) to obtain the full spectrum.

In order to describe the structure of the water surface a 1-D wavenumber spectrum is not sufficient: the directional distribution of the waves has to be included. In the VIERS model it is assumed that the 2-D wavenumber spectrum is given by

$$W(k,\alpha) = F(k)D(\alpha) \ , \tag{30}$$

where

$$D(\alpha) = \frac{1}{2\pi}(1 + 2a_2 \cos 2(\alpha - \alpha_W)) \ , \tag{31}$$

and α_W is the direction of the wind. The parameter a_2 measures the width of the directional distribution. It is assumed to depend only on stress, not on frequency. In practice it was treated as a tuning parameter.

4.3 Waves-scatter module

Once the 2-D wave spectrum is known, the next step is to determine the normalized backscatter. This task is performed by the waves-scatter module. In VIERS a two-scale model was chosen. According to the 'wave-facet model' (Plant, 1990) the following expression for the normalized radar cross-section applies.

$$\sigma_0 = \sigma_0^{\text{sp}} + \int_{-\infty}^{\infty} d(\tan\psi) \int_{-\infty}^{\infty} d(\tan\delta) P_B(\tan\psi, \tan\delta) \sigma_0^{\text{Br}}(\theta_{\text{loc}}) \cdot \tag{32}$$

Here, P_B is the probability that a (Bragg-)facet is oriented with tilts $\tan\psi$ (parallel) and $\tan\delta$ (right angles to the wind), and, θ_{loc} is the local incidence angle. For an anisotropic Gaussian surface one has:

$$P_B = \frac{1}{2\pi s_{u,b} s_{c,b}} \exp(-\frac{\tan^2\psi}{2s_{u,b}^2} - \frac{\tan^2\delta}{2s_{c,b}^2}) \ , \tag{33}$$

with $s^2_{u,b}$ and $s^2_{c,b}$ the slope variances in the upwind and crosswind direction respectively. The Bragg contribution of a facet is proportional to the 2-D wavenumber spectrum at the resonant wavenumber vector,

$$\sigma_0^{Br} \sim W(\vec{k}_B). \tag{34}$$

The contribution due to specular reflection is given by:

$$\sigma_0^{\mathrm{sp}} = \pi \mid R(0) \mid^2 \sec^4 \theta P(\zeta_x, \zeta_y) \ , \tag{35}$$

where P is the probability that a (specular) facet is oriented with tilts ζ_x (parallel) and ζ_y (right angles to radar look direction). For an anisotropic Gaussian surface one has:

$$P = P(\zeta_x = \tan\theta, \zeta_y = 0) = \frac{1}{2\pi s_{u,s} s_{c,s}} \exp(-\frac{\tan^2\theta}{2s^2_{L,s}}) \tag{36}$$

with $s^2_{u,s}$ and $s^2_{c,s}$ the slope variances in the upwind and crosswind direction respectively, whereas $s^2_{L,s}$ is the variance in the radar look direction. Only those waves that have a wavelength longer than the radar wavelength contribute to the slope variances (Stewart, 1985).

The above general two-scale theory has to be supplemented with a criterion to separate long waves from short ones. The 2-D wavenumber spectrum is separated into a low and high wavenumber part with the help of the splitting parameter k_c,

$$\begin{aligned} W_L(k,\alpha) = F_L(k)D(\alpha) &= W(k,\alpha) & k < k_c \\ &= 0 & k \geq k_c \\ W_H(k,\alpha) = F_H(k)D(\alpha) &= W(k,\alpha) & k \geq k_c \\ &= 0 & k < k_c \end{aligned} \tag{37}$$

Hence the slope variances of the tilting waves are given by:

$$s^2_{u,b} = \frac{1+a_2}{2} \int_0^{k_c} k^3 F(k) dk \tag{38}$$

$$s^2_{c,b} = \frac{1-a_2}{2} \int_0^{k_c} k^3 F(k) dk \tag{39}$$

It is noted that the slope variance of the waves that contribute to specular reflection is given by $s^2_{L,s} = \int_0^{k_c} k^3 F(k) dk$.

The splitting parameter k_c is determined by the condition $\beta = 4k_0^2\sigma_H^2$, where $\sigma_H^2 = \int_{k_c}^{\infty} F(k)dk$. It can be argued that the parameter β should lie in the range 0.1-1 (VIERS-1 report, 1993).

4.4 The inverse model

In order to use the VIERS model for wind retrieval from ERS-1 scatterometer data, it has to be inverted. The following simple but straightforward scheme has been used.

First a table of σ_0's is produced; the interpretative model is run for different incidence angles, wind vectors and wave periods and the resulting sigma's are collected in a table. The windparameters are U, the absolute value, and ϕ, the direction with respect to the lookdirection of the radar. If one accepts an accuracy of 1 m/s in the retrieved wind speed and 15° in the wind direction, one may choose the incidence angle from 18 until 57 in steps of 1, U from 1 until 30 in steps of 1 (m/s) and ϕ from 15 until 360 in steps of 15 (^{o}), for instance.

For a certain cell number i and measured sigma triplet $(\sigma_f, \sigma_m, \sigma_a)$ the wind retrieval procedure is as follows.

1. Determine incidence angles of for-, mid- and aftbeam: $\theta_f(i), \theta_m(i), \theta_a(i)$.

2. Calculate model triplets (for all 30×24 tabulated wind vectors $U = 1, 2..., 30$ and $\phi = 15, 30, ..., 360$) according to:

$$\begin{aligned} \sigma_f^{mod} &= \sigma^{tab}(\theta_f, U, \phi + 45) \\ \sigma_m^{mod} &= \sigma^{tab}(\theta_m, U, \phi) \\ \sigma_a^{mod} &= \sigma^{tab}(\theta_a, U, \phi - 45) \end{aligned} \tag{40}$$

   Hence ϕ is the direction of the wind vector with respect to the midbeam.

3. Determine the normalized quadratic distance between model and measured triplets,

$$Q_{ERS-1} = Q_f + Q_m + Q_a$$

$$Q_{f,m,a} = (\frac{\sigma_{f,m,a} - \sigma_{f,m,a}^{mod}}{k_p \sigma_{f,m,a}})^2.$$

   Here, k_p is the relative accuracy of the measurement (of the order of 5%); $k_p\sigma_0$ is the measurement error in σ_0.

4. Determine the normalized quadratic distance between model and ECMWF wind (magnitude and direction),

$$Q_{GEO} = (\frac{U - U_{GEO}}{\Delta U_{GEO}})^2 + (\frac{\phi + \chi_2 - \phi_{GEO}}{\Delta \phi_{GEO}})^2$$

   where χ_2 is the look direction of the midbeam with respect to north. The errors in the ECMWF wind fields are estimated as $\Delta U_{GEO} = 2$ m/s and $\Delta\phi_{GEO} = 20^o$.

5. Determine the absolute minimum of the cost function D,

$$D = \sqrt{Q_{ERS-1} + Q_{GEO}}.$$

6. The model wind that minimizes D is the 'retrieved wind'. The direction of the wind with respect to north, ϕ_W, is given by $\phi_W = \chi_2 + \phi_{ret}$, where ϕ_{ret} is the retrieved wind direction with respect to the midbeam.

The fourth step is inserted in order to ensure that the retrieved wind vector is close to the ECMWF one, both in magnitude and direction. This is a rather strong requirement that may introduce a spurious interdependence between retrieved and ECMWF winds. An alternative would be not to take Q_{GEO} into account and remove the 180° ambiguity in the retrieved wind by selecting the direction closest to ECMWF's.

5 Model configuration

Initially, we tested the VIERS algorithm in interpretative mode. Thus, the simulated backscatter, obtained using ECMWF winds and WAM model periods, was compared with the backscatter as observed by ERS-1. After some tuning a reasonable agreement between simulated and observed backscatter was obtained. An example is given in fig. 1 where we note that the standard deviation of error is about 2dB. In view of our knowledge of the evolution of short waves and in view of the accuracy of the analysed wind field (which we assume to be 2 m/s) this is already quite an achievement.

In fact, we were quite optimistic that the thus obtained algorithm would be succesfull in retrieving winds from the observed radar backscatter. Unfortunately, this turned out not to be case and some additional tuning was required to obtain reliable winds. The mean reason for the additional tuning is that we needed an accuracy of the model algorithm of at least 0.5dB which cannot be achieved using analysed winds with a relatively large error of 2 m/s.

5.1 Incorporation into the full model; interpretative mode

After the incorporation of the stress-waves module into the full scatterometer algorithm, the model output was critically looked at. The following procedure was adopted.

First the σ_0's in the upwind direction ($\phi = 0$) were monitored as a function of incidence angle at different wind speeds. The sea state parameter (wave age or wave period) was not independent, but coupled to the wind speed (this is a good first approximation). The parameters and parametrisations in the stress-waves module were determined in such a way that the model curves were as close as possible to the CMOD4 model curves. (For a description of the CMOD4 model cf. Stoffelen and Anderson, 1995). Subsequently the VIERS model was fed with ECMWF winds and WAM sea state data (hence in this case the sea state parameter was not directely coupled to the wind). The wind and wave data were collocated with the ERS-1 scatterometer swath at a particular day (911106). The model σ_0's were compared to the σ_0's measured with the ERS-1 forbeam. The same comparison was made with model σ_0's obtained with the operational model CMOD4.

The first attempts revealed some incompatibilities between the model and the measurements: the small model σ_0's were 4 dB too high and the large model σ_0's were 4 dB too low. The first discrepancy could be remedied by the inclusion of a suitable slick, for the second one the model had to be extended. It turned out that the stress-waves module generated slope variances that were quite low. In fact they were too low (at low winds) to produce any significant specular reflection. It was concluded that the slope variance from the stress-waves module were too low and that they had to be augmented before putting them through to the waves-scatter module.

In low wind speed cases, swell is usually present and therefore it was decided to increase the slope variance by a fixed amount, of the order of 0.02. This resolved the problem of underestimation of the backscatter for large values.

The above procedure was succesful in the sense that a good scatter plot for the VIERS model could be obtained, even better than the corresponding CMOD4 plot. The CMOD4 model generates very small σ_0's (much smaller than measured) at low wind speeds, whereas the VIERS model does not suffer from this problem. It turned out that this was a generic picture as the same features were found at other dates and other beams.

It thus seemed that the configuration and tuning of the VIERS model was succesfully completed. However, new problems emerged once the model was inverted.

5.2 Incorporation into the full model; inverse mode

It was expected that the inverted VIERS model fed with ERS-1 σ_0's and WAM wave data would yield wind fields compatible with collocated ECMWF fields. This turned out not to be the case: the model winds differed significantly from the ECMWF winds. Mean model winds were unequal to mean ECMWF winds.

The inversion procedure was not to blame for this as the same inversion applied to the CMOD4 model produced winds compatible with ECMWF. Apparently the tuning procedure in σ_0 space was not sound: the ECMWF winds produce too much scatter thus preventing a meaningful tuning.

A new tuning procedure was started aiming at compatible winds: the model winds should lie as close as possible (in a statistical sense) to the ECMWF winds. Not only should the model winds follow ECMWF in the mean, but also should the variance be minimal. In a later stage another requirement was added: the statistics of the cost function should be optimal (i.e. average costs as low as possible). This latter condition ensures that the modelled backscatter approximates the observed backscatter as good as possible.

The major problem to be overcome was that in the regime of low wind speeds the VIERS winds were too high. It turned out that this problem was connected to the parametrisation of the Phillips constant α_P. Therefore the original JONSWAP parametrisation, $\alpha_P = 0.52\xi^{-1.41}$, was dropped and replaced by $\alpha_P = A\xi^{-B}$ (A and B to be determined). After a tuning exercise the values $A = 0.24$ and $B = 1$ were selected, in agreement with the reanalysis of JONSWAP data by Günther (1981).

A weak point of the VIERS model is that its performance depends critically on the precise parametrisation of f_{join} and a_2 (as a function of u_*), whereas there are no theoretical guidelines what they should be. As far as a_2 is concerned, the CMOD4 model gives some empirical hints, which have been followed.

5.3 Tuning of the model

Several parameters in the wave module are not fixed a priori, the most important being f_{join}, a_2 and α_P. The model output depends critically on the precise choice of f_{join} and a_2 as a function of u_* and of α_P as a function of the wave age. These three variables were the basic tuning parameters.

For the final fine-tuning the following procedure was adopted. About 30.000 σ_0 triplets, measured with the ERS-1 scatterometer at 6th November 1991, together with collocated WAM information on the spectral peak (period of the dominant waves) were fed into the inverted VIERS model. The produced model winds (magnitude and direction) were plotted against collocated winds calculated by the numerical weather prediction model at ECMWF. The tuning parameters f_{join}, a_2 and α_P were chosen in such a way that the average bias and scatterindex (between VIERS and ECMWF winds) were as low as possible and the spectra of the wave module of the best quality. This method ensures that the VIERS and ECMWF winds are compatible in a statistical sense.

The VIERS version 2.0 has been used to produce the plots depicted in figures 2-4. In order to visualize the density of points contour lines of equal density (number of points per square m/s c.q. ^{o}) are drawn. As a reference the same plots are produced with the CMOD4 model (the same inversion technique was used for both models). It can be seen that the VIERS model is well-tuned in the sense as explained above.

6 The VIERS Software

In this section we discuss the software implementation of the VIERS model to compute the radar backscatter for a given wind velocity and direction. We give an overview of the program structure, indicate how the model code may be compiled, installed and used, and give an example application of the model which may be used to check proper operation of the software. We discuss individual routines in more detail, showing the used algorithms and some validation tests.

6.1 Program setup

The VIERS-1 model was programmed in FORTRAN77 as a subroutine, callable from a main program as:

```
call VIERS
```

Note that this subroutine call has no parameters. The VIERS model is controlled by the users in two ways:

1. the data file NVIERS.DAT contains global parameters like: radar wave number, water and air temperature, salinity, and some tuned model parameters.

2. all variables which are likely to change from one location to another, such as wind velocity and direction, radar incidence angle, etcetera, are collected in a common block `user`. On return, this common block also contains the computed backscatter values `sig0hh` and `sig0vv`. To specify the input parameters and to obtain the results, the user should have a line

   ```
   include 'user.cmn'
   ```

   in the calling program (see the example discussed below). Note that global parameters relevant for users, such as radar wave number and temperatures, may be changed in this common block as well.

As an example we show how the program may be used. Consider the following calling program `test.f`:

```
      program test
      include 'user.cmn'
*
      Uz      = 15.
      Hz      = 10.
      period  = 5.
      the_rad = 45.
      fi_rad  = 0.
```

```
      fi_wind = 0.
*
      call VIERS
      write(*,*) '*****************************************************'
      write(*,*)
      write(*,*) ' basic test of VIERS model cycle 2.0'
      write(*,*)
      write(*,*) ' test conditions:'
      write(*,*) '   Uz      = 15. m/s'
      write(*,*) '   Hz      = 10. m'
      write(*,*) '   period  = 5.  s'
      write(*,*) '   the_rad = 45. degrees'
      write(*,*) '   fi_rad  = 0.  degrees'
      write(*,*) '   fi_wind = 0.  degrees'
      write(*,*)
      write(*,*) ' results:'
      write(*,*) '   sig0hh = ', sig0hh, ' dB'
      write(*,*) '   sig0vv = ', sig0vv, ' dB'
      write(*,*)
      write(*,*) '*****************************************************'
      end
```

In this program we tell the VIERS routine that the wind velocity (Uz) is 15 m/s at a height (Hz) of 10 m. The significant wave period (period) is 5 s, the radar incidence angle (the_rad) is 45 degrees, the radar look direction (fi_rad) and the wind direction (fi_wind) are both 0 degrees. All these parameters are stored in the common block /user/.

We have used the following "default" data file NVIERS.DAT:

```
data file for VIERS program

117.      rk:      wave number of the radar (117=C-band)
1         pol:     1 = VV
80.       AirHum   humidity
20.       Tsea:    sea water temperature (degr. C)
20.       Tair:    air temperature (degr. C)
35.0      sal:     salinity
0.65      rzer:    effective reflection coefficient
20        nx:      number of Gauss-Legendre integration points in x-direction
20        ny:      number of Gauss-Legendre integration points in y-direction
0         nout:    output level
1         nunit:   output unit number
0.04      fr1:     lowest frequency in TESTWA
0.066     delf:    fr(n+1)/fr(n)-1
```

All these parameter values will be referred to as the "standard test conditions" in software tests in the remainder of this section.

Running the program `test.f` should yield:

```
*****************************************************

 basic test of VIERS model cycle 2.0

 test conditions:
   Uz      = 15. m/s
   Hz      = 10. m
   period  = 5.  s
   the_rad = 45. degrees
   fi_rad  = 0.  degrees
   fi_wind = 0.  degrees

 results:
   sig0hh =  -12.2694 dB
   sig0vv =  -8.91251 dB

*****************************************************
```

For further reference and to get an impression of the behaviour of the VIERS model we have made test runs under standard test conditions in which we varied:

- the wind speed at a height of 10 m (`U10`)
- the radar incidence angle (`the_rad`)
- the radar look direction (`fi_rad`)

The results of these test runs are given in Appendix 1.

6.2 Program structure

Below we give a simplified reference structure of the VIERS routine:

```
VIERS  INIT   INICON
              INIRD
              INIDER PHYEMC
                     DAMPRAT
                     INISPEC
                     INITW
       WINDPR PROPAR
       SCAT   WTAIL
                     GWAMOD
                     GRACAW AVPAR
                            ESUPP
                            PSINV
                     SPLINE
                     SPLINT
              SEPSC
              VSLOPE
              BRINTA GAULEG
                     BRAGG  SPEC   WTAIL
                     PSLOPE
```

The VIERS routine consists of three sub-blocks:

init Here some physical and mathematical constants are initialized, the input data file NVIERS.DAT is read, and physical parameters such as the electro-magnetic properties of the water are computed for the given salinity and temperatures.

windpr Computes the wind friction velocity from the given wind speed at the given height, taking the air and water temperature into account.

scat This module computes the radar backscatter using a two-scale model and the short wave model.

The communication between various subroutines in the VIERS program proceeds mainly through common blocks and not through parameter lists. We have chosen for this method because it enables us to exchange sub-modules in a simple way. For instance, we have implemented the Holliday backscatter model in a subroutine which can also be called as SCAT. The common blocks contain all parameters used by all implemented scattering models. By linking the Holliday module in stead of the two-scale module we can simply switch the backscatter model without any re-programming.

6.3 VIERS-1 software distribution

The software implementation of the VIERS-1 model is available as a set of FORTRAN source code and common block include files. The distribution should contain the following source code files:

`bragg.f`	*the low level Bragg backscatter routines*
`init.f`	*the initialization routines*
`scat.f`	*the two-scale backscatter routines*
`specwwf.f`	*the wave spectrum routine*
`u_ustar.f`	*the wind profile routines*
`viers.f`	*the main VIERS entry*
`wavetw.f`	*the short wave model*

The common blocks which take care of the communication between the modules are in the files:

`airwater.cmn`	*air-water interface parameters*
`mathcon.cmn`	*mathematical constants*
`output.cmn`	*controls the output for testing purposes*
`physcon.cmn`	*physical constants*
`spectra.cmn`	*spectral wave parameters*
`twosc.cmn`	*two-scale model parameters*
`twpars.cmn`	*internal short wave model parameters*
`user.cmn`	*all parameters that may be changed by users*
`wave.cmn`	*parameters to construct the Bragg wave energy*
`wenie.cmn`	*effective angles in the two-scale model*
`wind.cmn`	*wind profile parameters*

Further included are the data file `NVIERS.DAT` and the test program `test.f`, given in section 4.1.

The above files should compile without problems using a FORTRAN77 compiler, provided that the compiler supports the `include` statement, which is a non-standard but widely supported feature.

6.4 Algorithm and validation details

In this section we discuss individual modules in the VIERS software, comment on the algorithms used to solve model equations, show the validation tests which have been carried out to check that the program really solves the model equations, and archive results of reference runs.

6.4.1 The INIT module

The INIT module is fairly straightforward: reading of input data and some simple computations of physical parameters. All initialized common block parameters are printed in appendix 1. The computed physical parameters have been compared with literature values and have (at least) the expected order of magnitude.

6.4.2 The WINDPR module

In this module the friction velocity `ustar`, the roughness length `hz0` and the stability parameter `spsi_m` are computed from the wind velocity `uz` at height `hz` and the water and air temperature. This is an inversion problem: knowing the friction velocity and the temperatures one can compute the wind profile and therefore the wind velocity at height `hz`. This inversion is carried out iteratively, using a Richardson extrapolation technique to accelerate the convergence.

Reference run results: for a wind velocity of 15 m/s at a height of 10 m, a period of 5 s, and water and air temperatures of 20 degrees Celsius the WINDPR module gives:

```
ustar  =  .7446905
hz0    =  2.59057E-03
spsi_m =  .0
```

6.4.3 The GWAMOD module

GWAMOD computes a JONSWAP spectrum to provide boundary conditions for the short wave model. The results for the standard test run, using $U_{10} = 15$ m/s and a peak wave period of 5 s are given in Appendix 1. This spectrum was computed by independent means. The results agree within a relative error of 2.e-5.

6.4.4 The GRACAW module

This module solves the short wave model equation on a logarithmic equidistant grid. A fourth-order Runge-Kutta method has been used to solve this differential equation. To validate the implementation of this method we have simplified the source term in the action balance equation such that an analytic solution could be found. This analytic solution was compared with the numerical results of the Runge-Kutta method and the relative accuracy turned out to be better than 2.e-5.

GRACAW calls the subroutine AVPAR to compute the mean frequency and the variance of a wave spectrum. For the JONSWAP spectrum computed by GRACAW for the standard test conditions we find the results:

```
fmean    = .219794
variance = .276898
```

Independent computation of the average parameters for the JONSWAP spectrum using a PV-WAVE program agreed with this result.

GRACAW calls the subroutine PSINV, which inverts a model function PSI relating the energy flux through the spectral tail to the energy density. The correctness of the inversion has been checked by first running the function PSI on a given set of energy densities and subsequently inverting these results using PSINV. The inversion turned out to be correct within a relative accuracy of 1.e-5.

6.4.5 The SCAT module

SCAT computes the radar backscatter according to a two-scale model. SCAT first calls the routine SEPSC to compute the wave number which separates the long waves from the short ones. The long waves serve the purpose of generating surface tilts on which the short waves, who take care of the actual scattering of the radar waves, are propagating. The routine VSLOPE computes the parameters of the Gaussian probability function for the 2-dimensional surface tilt from the long-wave part of the spectrum. SCAT integrates over the radar backscatter for a given tilt, as computed by the BRAGG module, times the probability of that tilt occurring. The integration is performed in the BRINTA module using a Gauss-legendre technique.

For the standard test conditions SEPSC finds a separation wave number in m^{-1} of

```
ksep = 50.2548.
```

The routine VSLOPE yields for the standard deviation of the slope in the radar look direction `stdx_r` and in the cross-radar direction `stdy_r` the values

```
stdx_r =  .233098
stdy_r =  .185064
```

The reference output of the BRINTA module is given in Appendix 1. This output may be obtained by putting the output parameter `nout` in the file NVIERS.DAT equal to 8.

7 The VIERS model in operation

In this chapter we would like to present our results for wind retrieval with the VIERS algorithm. As a reference the CMOD4 model is used. We shall compare in great detail our results with analysed windfields from ECMWF and with the CMOD4 algorithm. Two approaches are followed. In section 5.1 we shall use statistical tools to compare results, while in section 5.2 we give a comparison of results with emphasis on synoptic situations. We feel that these two approaches are to some extent complementary and they will highlight the strong and weak points of the VIERS algorithm.

7.1 Statistical comparison

We have applied the wind retrieval with VIERS and CMOD4 to three cases on Nov. 6th, Nov. 7th 1991 and March 10th 1992 all on 12Z. To that end we collocated at ECMWF the σ_0 triplets, as measured by the ERS-1 scatterometer with mean periods of the WAM model and with analysed windfields from the ECMWF atmospheric model. As a first result we compare retrieved wind speed and wind direction from VIERS with the analysed ECMWF winds. The comparison for the three dates is shown in the Fig. 2-4.

Figure 2: Retrieved wind speed using CMOD4 (top) and VIERS algorithm versus analysed ECMWF windspeed on 911106

Figure 3: Same as Fig. 2 but now for date 911107.

Figure 4: Same as Fig. 2 but now for date 920310.

In order to visualize the density of points, contour lines of equal density (number of points per square m/s c.q.^{o}) are shown. As a reference the same plots are produced with CMOD4 using the same inversion technique as VIERS. As already discussed in section 2 we have performed fine tuning on the VIERS algorithm on the case of Nov. 6th, 1991. The results of the two other dates show that the tuning procedure was robust. Although the scatter on these last two dates has increased somewhat it should be noted that for CMOD4 a similar remark applies. The statistics for the three dates are summarized in Table 1.

MODEL	VIERS	CMOD4	VIERS	CMOD4	VIERS	CMOD4
DATE	911106	911106	911107	911107	920310	920310
number	29752	29752	25771	25771	30049	30049
μ_U (m/s)	-0.08	-0.02	+0.02	+0.10	+0.10	+0.07
σ_U (m/s)	2.04	2.04	2.20	2.20	2.35	2.43
$\mu_\phi(^o)$	+1.6	-3.2	-0.5	-4.4	0	-1
$\sigma_\phi(^o)$	28	33	29	31	24	26
D_σ	5.2	3.8	5.9	3.9	5.4	3.7
σ_R (m/s)	0.75	0.47	0.80	0.47	0.69	0.49

Table 1: Statistical comparison of VIERS and CMOD4 winds against ECMWF analysed winds. (Here, μ refers to the bias and σ is the standard deviation). Also, the distance between modelled and observed backscatter is given, as well as the anticipated error in wind speed caused by the misfit in σ-space.

The statistics of VIERS and CMOD4 regarding the wind vector are compatible, with VIERS having slightly better directional properties. However, as may be inferred from the Figs. 2, 3 and 4 CMOD4 does not allow winds below 2 m/s and this may contribute to more favourable statistics. Furthermore, CMOD4 seems to underestimate the wind speed for high winds. To see this point more clearly, we have restricted the determination of the statistical parameters to those cases where the analysed ECMWF wind was higher than 15 m/s. Results are displayed in Table 2. The statistics in Table 2 show that both retrieval algorithms are biased low, but that CMOD4 clearly underestimates the wind speed. We would like to emphasize that an underestimation of wind speed at high winds is an undesirable property of a retrieval algorithm. When used in an atmospheric data assimilation scheme, the retrieved winds could result in a considerable slowing down of the major storm systems. Of course, our conclusion on the weak performance of CMOD4 at high wind speeds depends on the quality of the analysed ECMWF winds. It therefore requires convincing evidence that the quality of the modelled winds is good, which is not an easy task at high winds.

A method to judge the quality of modelled winds is nowadays available, however, since it is known that a wave model is sensitive to errors in the driving wind field (cf. e.g. Janssen et al (1989b)). We therefore investigated the performance of the WAM

MODEL	VIERS	CMOD4	VIERS	CMOD4	VIERS	CMOD4
DATE	911106	911106	911107	911107	920310	920310
number	1324	1324	1124	1124	1237	1237
μ_U (m/s)	-0.89	-2.56	-2.18	-3.04	-0.14	-1.26
σ_U (m/s)	2.02	2.02	2.13	2.51	2.55	2.44
$\mu_\phi(^o)$	-3.2	-4.8	-6.2	-6.8	4.9	4.21
$\sigma_\phi(^o)$	12.3	11.5	14.8	15.4	15.5	15.0
D_σ	5.1	3.6	4.5	3.0	4.7	3.6
σ_R (m/s)	1:14	0.60	0.84	0.52	0.98	0.71

Table 2: Same as Table 1 but now under the restriction that the ECMWF windspeed is bigger than 15 m/s.

model which is running operationally at ECMWF and which is driven by ECMWF wind fields. It is known that the WAM model performs well in extreme conditions when driven by manually analysed winds which are regarded of high quality. An example, namely the SWADE storm of October 27th, 1990, showing an excellent performance of the WAM model in extreme conditions is given in Fig. 4.13 of Komen et al (1994). Therefore, the WAM model may be regarded as a useful tool to judge the performance of an atmospheric model at the ocean surface. In Fig. 5 we show the verification of modelled significant wave height against buoy observations in the open ocean and in the coastal zone around the U.K. We have chosen a one month period from April 19 until May 19, 1994. From Fig. 5 it is concluded that modelled wave heights agree well with observed ones, even for extreme conditions. Thus, the analysed ECMWF winds have a good quality for high winds, although the open ocean data suggest that the ECMWF model underestimates the winds in extreme conditions. However, the resolution of the driving wind field (which was 1.5^o.) might be too coarse to properly resolve the extreme conditions.

It is therefore concluded that for high wind speeds the VIERS algorithm outperforms CMOD4. A similar remark applies to the low wind speed cases. A summary of the difference in wind retrieval of VIERS and CMOD4 is given in Fig. 6 where we compare retrieved winds from VIERS with those of CMOD4. The differences at low and high wind speed confirm the picture we have sketched above. We emphasize that high wind cases usually correspond to young wind sea since the time it takes to obtain a saturated wind sea condition is proportional to wind speed. For example, for a 20 m/s surface wind it takes two days or more to arrive at the old sea state and usually storm systems do not reside for such a long time at one location. Young wind waves are usually steeper than old wind waves and therefore for the same wind speed a larger backscatter should result. However, if one would not take the sea state dependence of radar backscatter into account, by taking for example a fixed wave age $c_p/u_* = 35$, then the short waves would be less steep giving for the same wind a smaller backscatter. As a consequence, with the same observed backscatter one would expect larger winds in a

Figure 5: Verification of modelled WAM wave height against buoy observations for open ocean and buoys around UK.

sea-state independent algorithm than in a sea-state dependent algorithm. This turns out to be the case. We reran the VIERS algorithm in sea-state independent mode by fixing the wave age c_p/u_* to a constant value, $c_p/u_* = 35$. We chose the period of November 6th, 1991 and we restricted the wind retrieval to those cases where the ECMWF wind speed is larger than 15 m/s.

Figure 6: Comparison of VIERS windspeed and CMOD4 windspeed for 911106.

When comparing the retrieved winds with the analysed ECMWF winds we found, as expected a positive bias of 1.64 m/s while the standard deviation of error was 2.74 m/s which is considerable larger than obtained from the sea-state dependent version of VIERS (cf. Table 2). The bias in retrieved wind direction was -4.6^o while the standard deviation of error was 12.0^o, statistics which are similar to Table 2. Furthermore, the misfit in $\sigma_{\text{space}} D_\sigma$ was 4.4 and therefore somewhat smaller than the sea-state dependent version of VIERS. We conclude from this comparison that the sea-state dependence of radar backscatter is quite considerable. It gives rise to a change in wind speed bias of 2.5 m/s. Moreover, in view of the smaller standard deviation of error we conclude that a sea state dependent backscatter algorithm is to be preferred. Another interesting quantity to discuss is the wind speed distribution of the retrieved winds. We present in Fig. 7 the VIERS wind speed distribution for Nov. 6, 1991 and March 10, 1992.

For comparison we also show the ECMWF and the CMOD4 distribution.

Figure 7: Normalised windspeed distribution for ECMWF, CMOD4 and VIERS winds on 911106 (left) and 920310 (right).

Regarding Nov. 6 we observe that all three distributions have a single maximum but that the VIERS's extremum is lower than ECMWF's while CMOD4's extremum is larger. The larger maximum of CMOD4 is probably related to the inability to produce wind speeds below 2 m/s thereby increasing the wind speed distribution between 3 and 5 m/s. The lower maximum of in the VIERS distribution is probably caused by the larger misfit in σ-space as will be discussed below. The wind speed distribition of March 10th 1992 is of some interest because both VIERS and the ECMWF distribution show two extrema while CMOD4 only shows one. We emphasize here that we have obtained the wind speed distribution from a global data set. Therefore, one cannot exclude the possibility of a bimodal distribution. Considering the wind speed range between 5 and 9 m/s which are typical wind speeds for the trade winds it probably means that one trade wind area has stronger winds than another. Anyway, CMOD4 fails to produce a second maximum while VIERS does, although the second maximum is positioned at 9 m/s and not at 8 m/s as in ECMWF. Furthermore, in Fig. 8 we show the directional distribution of the VIERS, CMOD4 and ECMWF winds for Nov 6th 1991. Comparing retrieved wind and analysed wind direction there appears to be a fair agreement although both retrieved products have a maximum at a wind direction

of 120° measured clockwise with respect to true North which is not present in the analysed ECMWF direction.

Figure 8: Normalised wind direction distribution for ECMWF, CMOD4 and VIERS direction on 911106.

In order to conclude our discussion on the performance of the VIERS algorithm we finally concentrate on the properties in the so-called σ-space. The σ-space is the space spanned by the radar backscatter of the fore, mid and aft beam. We have seen in section 2.4 that the VIERS and CMOD4 model is inverted by minimizing a cost function,

$$D = \sqrt{Q_{ERS-1} + Q_{EC}}\ , \tag{1}$$

where Q_{EC} is the normalised quadratic distance between retrieved and ECMWF wind while Q_{ERS-1} is the normalised quadratic distance between modelled and measured backscatter. We recall that

$$Q_{ERS-1} = Q_f + Q_m + Q_a \tag{2}$$

$$Q = (\frac{\sigma_{obs} - \sigma_{mod}}{k_p \sigma_{obs}})^2 \tag{3}$$

where the subscripts f, m and a are an abbreviation for fore, mid and aft beam. The quadratic distance in σ-space has been normalised by the observation error $k_p\sigma_{obs}$ where k_p is of the order of 5%. Let us finally introduce the distance D_σ in σ-space as

$$D_\sigma = \sqrt{Q_{ERS-1}} \ , \tag{4}$$

then, ideally, a perfect model should have a distance which is as small as possible, i.e. $D_\sigma = 0$. There are two reasons why in practice D_σ attains a finite value. The first reason is finite observation errors (of course for this reason we have normalised D_σ with the measurement error). Assuming that there is no bias between model and observation, $< \sigma_{obs} - \sigma_{mod} >= 0$, and assuming that the backscatter model is perfect one obtains

$$< Q_f >=< Q_m >=< Q_a >= 1 \ , \tag{5}$$

and therefore the minimal distance in σ-space becomes

$$D_\sigma = \sqrt{3}. \tag{6}$$

Assuming, in addition, that the variable $\delta = (\sigma_{obs} - \sigma_{mod})/k_p\sigma_{obs}$ is a Gaussian variable, then for a perfect model the distribution of the distance D_σ can be calculated. Thus, the statistics of D_σ is determined by 3 independent Gaussian variables δ_f, δ_m and δ_a with $< \delta >= 0$ and $< \delta^2 >= 1$. An elementary result in statistics then states that the distribution of D_σ^2 is chi-square with 3 degrees of freedom. This result is valid if the assumption of Gaussian variables is justified and if the model at hand is perfect.

In practice, however, the actual distribution may deviate from the theoretical one. The discrepancy is caused by random model errors (where it is assumed that all systematic errors are eliminated) that broaden the distribution of δ. In stead of unit variance one will have $< \delta^2 >= 1 + f^2$ where f^2 is the additional variance due to the random model errors. As a result, in practice the mean distance $< D_\sigma >$ may be larger than $\sqrt{3}$ and the distribution of D_σ^2 may be different from the chi-square distribution.

In Table 1 and 2 we show the mean values of D_σ for VIERS and CMOD4 and evidently the CMOD4 has smaller model error then VIERS, i.e. fits the observed back scatter more closely. This conclusion is supported by Fig. 9 where we have plotted the distribution of D_σ for CMOD4 and the VIERS model. The period was Nov 6th, 1991. The distribution for a perfect model is shown as well. We note from Fig. 9 that CMOD4 has a more narrow distribution than VIERS but both models distributions deviate considerably from the one of a perfect model. Assuming that the model function describes reality in a reasonable manner it is even possible to infer from the misfit in σ-space the rms error of the retrieved wind speed. Of course, a misfit in σ-space will induce an error in both wind speed and direction.

$$x = \frac{1}{2}(\sigma_a + \sigma_f) \tag{7}$$

is to a good approximation independent of the azimuth angle. Assuming Bragg scattering, this readily follows from the directional wave spectrum, given by (Eq. (31),

which involves a $\cos(2\theta)$ where θ is the difference between azimuth angle and wind angle. Since the azimuth angle for the fore and aft beam is 90° apart, it follows at once that the sum of fore and aft beam backscatter is independent of azimuth angle. The error in wind speed then immediately follows from

$$\delta x = \frac{\partial x}{\partial U_{10}} \delta U_{10} \tag{8}$$

where δx is the difference between modelled and observed mean backscatter and the derivative of x with respect to U_{10} can be obtained readily at the minimum of the distance D.

Figure 9: Normalised distance in σ-space distribution for CMOD4 and VIERS. The distribution for a perfect model is shown as well.

By averaging the square of the error δU_{10} over all retrievals one may determine the overall rms error in wind speed σ_R according to

$$\sigma_R = \sqrt{< \delta U_{10}^2 >} \tag{9}$$

Results of this calculation are shown in Table 1 en 2. In a similar manner the wind speed error caused by the observation error may be obtained as $\delta x/_{\text{obs}} = k_p x_{\text{obs}}/\sqrt{2}$

According to this estimate VIERS has an rms error in wind speed of about 0.75 m/s while CMOD4 has an rms of 0.5 m/s. On the other hand, for the high wind speed cases of Table 2 we get 1 m/s and 0.6 m/s respectively.

Thus, one would be inclined to conclude that CMOD4 gives a more accurate wind speed retrieval. It has smaller rms error in wind speed because the misfit in σ-space is smaller than for VIERS. However, inspecting Table 2 for the high wind speed cases it is seen that when compared to the ECMWF winds CMOD4 has a larger rms error than VIERS. The reason for this is that CMOD4 has a considerable negative bias, in other words, the high wind speed cases are underpredicted by CMOD4 in a considerable manner. It follows that the assumption of a fair description of reality by the model function is perhaps not valid because of bias problems. We conclude therefore that, although the misfit in σ-space may provide important information on the quality of the model function, it does not tell the whole story because there may be considerable bias problems. Hence, despite the larger mis fit in σ -space we conclude that the VIERS model is an acceptable model to retrieve the wind vector. In fact, in the low and high wind speed regime it seems to perform better than CMOD4. Furthermore, the overall rms error in wind speed of VIERS, which is 0.75 m/s, is quite small compared to the analysed ECMWF wind speed error of 2 m/s. Finally, VIERS seems to capture features in the global wind fields (cf. the secondary peak on March 10, 1992) which are missed by CMOD4.

Although the VIERS model seems to perform in a reasonable manner it is still of interest to investigate possible reasons for the larger misfit in σ-space. One of the reasons seems to be that VIERS has a considerable bias in σ-space. This is shown in Fig. 10 where we have plotted the average difference between modelled and observed σ as function of incidence angle for the fore, aft and mid beam. Results for CMOD4 are displayed as well. Regarding the fore and aft beam it is seen that VIERS has a large bias at the low incidence angles, while CMOD4's bias is quite low. Fortunately, the biases in fore and aft beam are almost identical so that the wind speed retrieval may not be affected by this bias problem since wind speed is determined by the mean σ of fore and aft beam. The figure for the mid beam also shows a large bias for VIERS, especially for high incidence angles. It could be argued that the misfit in σ-space may be reduced by removing the bias as a function of incidence angle. This turns out to be the case with the result that there is a considerable narrowing of the distribution of the distance in σ-space, D_σ. However, there is hardly no effect on the wind speed statistics nor the anticipated wind speed error σ_R.

Another factor that could be important for the misfit in σ-space is the directional spectrum. In VIERS (see Eq. (31)) we use a rather simple directional distribution with a wind speed dependent width. From observations it is known, however, that the width also depends on the ratio of frequency to peak frequency of the spectrum (Donelan et al 1985). In order to see to what extent the directional distribution of the waves plays a role in the wind retrieval, it was decided to do a retrieval experiment using only two beams, namely the fore and aft beam, since the mean of the fore and aft beam backscatter is approximately independent of the directional distribution. A

much better fit of the VIERS model to the observed backscatter was obtained in this manner. Noting that the mean distance in σ-space for fore and aft beam is usually about 4.2, with two beams this mean distance reduces to about 3, while the wind speed error obtained from the misfit in σ-space becomes about 0.5 m/s. Our results therefore suggest that the directional distribution of waves in the VIERS model is still not optimal.

Figure 10: Bias in fore, aft (top) and mid beam (bottom) for CMOD4 and VIERS.

Nevertheless, the statistical comparisons between the VIERS winds and the analysed ECMWF winds have shown that the VIERS model is an acceptable model for wind retrieval. In circumstances such as extreme low and high winds the VIERS model even seems to perform better than CMOD4. It is now of interest how the VIERS model performs in special situations such as fronts. This point will be adressed in the next Section.

7.2 Synoptic validation using CAL/VAL data

Sofar the VIERS model has been validated in a statistical way by comparing the VIERS generated winds with the winds calculated by meteorological models. This section deals with another approach in validating the model, by comparing the VIERS wind fields in a synoptical way with the wind fields from meteorological models and with wind fields from CMOD4.

Comparing the synoptic wind fields has the following advantages above statistical validation:

1. one can more easily verify the internal consistency of the wind speeds and directions of adjacent scatterometer cells,
2. one can compare the structure of the wind fields of ERS-1 derived wind fields and model derived wind fields,
3. one can easily identify ambiguity errors in the wind direction by comparison with adjacent scatterometer cells,
4. one can identify structural, e.g. incidence angle dependent, problems in the algorithm.

The main disadvantage is that most of the comparisons listed above are qualitative. However it is a valuable addition to the quantitative statistical validation reported in the previous subsection. Thus this validation should be treated as an addition to the statistical validation.

7.2.1 The calibration and validation campaign

When ESA distributed an Announcement of Opportunity for the calibration and validation of the sensors and products of the ERS-1, the VIERS group submitted a proposal for the validation of the wind scatterometer product. This proposal was granted by ESA and access was given to the Calibration and Validation data acquired during the CalVal campaign in the Norwegian part of the North Sea and the Atlantic Ocean between 5° W and 10° E and 60° and 70° N in 1991. ESA was the initiator of this large campaign in which information on the ocean and meteorological conditions were acquired during overpasses of the ERS-1 satellite. The satellite was at that time in a three day repeat orbit which had a scatterometer cross-over point west of Norway.

The data acquired from the in situ sensors and other sensors were used together with those of the Norwegian meteorological model (called METEO from now on) to provide the best possible estimate of the wind field over the scatterometer swath during the passage of the satellite. The results of the ERS-1 scatterometer measurements were combined with the calculations of the METEO model in so-called collocation files. These are files with meteorological and sensor data at the exact location and time of the passage of the scatterometer. This gives an optimal dataset for verification of the ERS-1 scatterometer models which derive wind speed and direction.

Besides the ERS-1 measured triplets of the radar scattering at the ocean surface, the VIERS model also needs to have the peak frequency of the dominant waves as input. These parameters were not included in the collocation files since none of the empirical models do include any dependence on the long wave spectrum. Results from six hourly operational calculations with the WAM model were acquired over the period and collocated with the ERS-1 overpasses. A nearest neighbour approximation was conducted on these data to find the closest wave frequency, in terms of location and time, for each scatterometer cell.

After that an input file for the VIERS model was generated and the VIERS model was run in inverse mode (generating wind speeds and directions) using the collocated wind speeds and directions as initial guess. The latter solves the ambiguity problem in finding the best possible solution to the wind speed and direction.

In order to do a fair comparison with the CMOD4 model, which is currently being used by ESA, the CMOD4 model was inverted similar to the VIERS model using the collocated wind as initial guess. The inversion procedure is described in section 2.4.

After calculation of the VIERS and CMOD4 winds, the wind speeds and wind directions were imaged on a plane tangential to the earth at 65 degrees North and 5 degrees East (see fig. 11). The wind speed is coded by means of a color scale which is shown as well in figures 11 and 21. The scale ranges from 0 till 24 m/s. The latter wind speed was the highest velocity which occurred in the data set.

Wind direction can be plotted using a so-called quiver plot. The arrows in the plot indicate the flow direction of the air and therefore they are 180 degrees out of phase with the wind direction. The length of the arrows are a measure of the wind speed, thus emphasizing the largest wind speeds. Combination of the color coded wind speed and the quiver plot for the wind direction gives a full overview over the wind results (fig. 11a).

Table 3 presents an overview over the data used. It lists the mean wind speeds, the differences between model and the ERS-1 derived wind speeds as well as the differences between VIERS and CMOD4. The average difference between the neutral condition VIERS winds and the METEO winds is +0.8 m/s and between CMOD4 and METEO +0.3 m/s. The standard deviation of the difference is 2.3 for the difference between VIERS and METEO and 2.0 for CMOD4 and METEO. If unstable conditions are assumed, which is the usual situation for this part of the ocean in the autumn, then the comparison between the VIERS and the METEO winds is even better: +0.1 m/s (std. 2.4 m/s). The differences between VIERS and CMOD4 are in both cases much smaller than between each of them with the METEO winds. This will be illustrated in the next section.

date	METEO	VIERS neutral	CMOD4	VIERS-METEO avg.	VIERS-METEO std	CMOD4-METEO avg.	CMOD4-METEO std	VIERS-CMOD4 avg.	VIERS-CMOD4 std
910919a	11.6	10.1	10.1	-1.5	1.4	-1.4	1.2	-0.1	0.6
910922a	14.1	9.3	8.6	-4.8	2.4	-5.5	2.5	0.8	0.7
910928a	5.9	6.0	6.2	0.1	2.0	0.3	1.9	-0.2	0.6
911007a	10.9	11.1	10.8	0.2	3.3	-0.0	3.1	0.3	0.6
911010a	7.4	7.3	7.5	-0.2	1.6	0.0	1.5	-0.2	0.5
911019a	9.9	13.6	12.9	3.7	1.5	3.1	0.9	0.6	0.8
911022a	9.9	11.5	11.8	1.5	1.6	1.9	1.2	-0.4	0.7
911028a	5.4	4.9	5.0	-0.5	1.4	-0.4	1.2	-0.1	0.5
911103a	6.4	7.8	7.8	1.4	3.0	1.4	2.3	0.0	1.1
911106a	3.1	3.4	4.1	0.3	1.8	0.9	1.7	-0.6	0.7
911112a	6.5	7.8	8.1	1.3	1.9	1.6	1.8	-0.3	0.6
911115a	2.0	4.3	4.7	2.3	2.1	2.7	1.7	-0.4	0.8
911121a	13.2	17.1	15.6	3.8	3.1	2.4	3.0	1.4	1.1
911124a	11.4	14.6	14.1	3.2	4.3	2.7	4.3	0.5	1.0
911130a	14.4	14.4	13.6	0.0	2.8	-0.8	2.2	0.8	0.8
911203a	11.2	13.5	13.2	2.3	1.1	2.0	1.1	0.3	0.6
911209a	8.9	9.9	10.2	1.0	2.4	1.3	2.1	-0.3	0.7
910918b	13.2	10.7	10.0	-2.5	3.5	-3.2	3.4	0.7	1.1
910924b	10.2	10.2	9.1	-0.1	4.0	-1.1	3.8	1.1	1.0
910927b	5.8	5.9	6.1	0.1	2.8	0.3	2.4	-0.2	1.0
911003b	11.6	10.5	9.8	-1.1	2.2	-1.8	2.1	0.7	1.4
911006b	7.7	8.2	7.9	0.5	1.6	0.2	1.1	0.3	1.2
911012b	4.1	5.5	5.5	1.5	3.0	1.4	2.4	0.0	1.2
911015b	2.8	2.8	3.7	0.0	1.7	0.9	1.2	-0.9	1.1
911021b	6.9	9.7	9.5	2.8	1.9	2.6	1.6	0.2	0.9
911024b	7.3	7.2	7.4	-0.0	1.9	0.1	1.6	-0.2	0.9
911030b	12.0	6.7	6.6	-5.3	3.3	-5.4	2.7	0.1	1.1
911102b	8.9	9.1	8.2	0.2	2.0	-0.7	1.5	0.8	1.0
911108b	8.4	9.3	9.4	1.0	2.2	1.0	1.6	-0.0	1.3
911111b	11.2	13.4	12.1	2.2	1.9	0.8	1.6	1.4	1.1
911117b	4.7	7.3	7.1	2.6	2.9	2.5	2.3	0.2	1.2
911126b	12.0	13.9	12.4	1.8	2.5	0.4	2.0	1.5	1.4
911202b	12.3	14.9	13.2	2.6	2.0	0.9	1.6	1.7	1.2
911205b	7.2	7.9	7.9	0.7	1.6	0.7	1.3	0.1	1.0
910919c	12.5	16.5	14.0	4.0	1.1	1.5	1.3	2.5	1.2
910922c	5.2	5.7	6.2	0.5	3.9	1.0	3.5	-0.5	1.2
910928c	5.2	6.1	6.0	0.9	2.2	0.8	1.4	0.1	1.2
911001c	10.9	12.4	11.4	1.5	1.9	0.5	1.6	1.0	1.2
911007c	11.2	11.3	10.1	0.1	2.4	-1.1	1.7	1.1	1.3
911010c	10.1	10.0	9.2	-0.0	1.5	-0.9	1.1	0.9	1.1
911016c	12.6	13.6	13.3	1.0	2.3	0.7	1.9	0.3	1.1
911019c	6.8	7.7	7.4	0.9	2.2	0.6	2.0	0.4	1.2
911025c	8.0	8.3	7.8	0.3	1.5	-0.2	1.0	0.5	1.2
911028c	8.8	8.3	7.4	-0.4	2.0	-1.4	1.1	0.9	1.3
911103c	13.0	15.1	13.9	2.1	2.5	0.9	2.1	1.2	1.3
911106c	10.0	12.5	12.0	2.5	3.6	2.0	3.8	0.4	1.1
911112c	9.5	10.1	9.3	0.5	2.1	-0.2	1.6	0.8	1.4
911115c	9.5	11.5	10.2	2.0	2.9	0.7	2.9	1.2	1.3
911121c	8.5	8.8	8.2	0.3	1.9	-0.3	1.7	0.6	1.1
911124c	10.4	11.2	10.0	0.8	2.8	-0.4	2.2	1.2	1.2
911130c	9.0	11.5	10.3	2.5	2.1	1.2	1.9	1.3	1.3
911203c	8.4	8.2	7.6	-0.2	2.2	-0.8	1.8	0.6	1.1
statistics									
neutral				0.8	2.3	0.3	2.0	0.5	1.0
unstable				0.1	2.4	0.3	2.0	-0.2	1.1

Table 3: Comparison of VIERS and CMOD4 retrieved winds with Analysed Meteo winds during CALVAL campaign.

Qualitative analysis A qualitative analysis was performed on all data which were made available by ESA in the collocation file together with the VIERS and CMOD4 wind speeds and wind directions. This analysis led to a number of conclusions which will be illustrated by four case studies.

Case 1: Detection and localization of frontal areas

This is a very interesting case in which a large front is visible in the ERS-1 data. On the south western part of the front, the wind direction is south westerly, on the other side of the front the wind blows in north-easterly directions. Figure 11 shows the VIERS wind speed and direction on November 6, 1991 in large and the collocated wind speed (hereafter referred to as METEO winds) and CMOD4 wind speed in the sub-images. When comparing the three images one sees a striking correspondence between on one side the VIERS result and the CMOD4 result and a discrepancy between the METEO winds and the ERS-1 derived winds. In the METEO winds the front is not as pronounced as in the ERS-1 derived winds and the position is approximately 200 km North of the front observed by ERS-1. This leads to the conclusions:

Conclusion 1a: *The ERS-1 derived wind fields show more structure than the meteorological model.*

Conclusion 1b: *The difference between VIERS wind fields and CMOD4 wind fields is generally smaller than between ERS-1 derived winds (VIERS and CMOD4) and winds from the meteorological model.*

One of the questions one can have about the inversion procedure used is: How large is the influence of the initial wind speed and wind direction on the ERS-1 derived winds and the meteorological model.

Case 2: Sensitivity to initial wind vectors

The purpose of the use of the METEO wind as first guess wind is primarily to solve the ambiguity of the wind direction. However, if too much emphasis is put on these initial values, then the outcome of the inversion procedure will follow the initial wind field and reduce the influence of the independent information from the satellite. In our approach, as described in section 2.2, we carefully balanced this inversion process. That this approach was succesful can be illustrated again with fig. 11. The initial wind field is represented in fig. 11b and as one can see the ERS-1 derived wind fields are quite different. The ERS-1 measures a sharply defined front which was observed in the wind speed as well as the wind direction. This front is not very well visible in the initial wind field. It shows that the inversion procedure can circumvent initial wind vectors if they are in contradiction with the observations of the satellite. Furthermore the front shown in the CMOD4 results and in the VIERS has a similar shape. This gives confidence that the observed front is indeed a real phenomenon and not introduced by one of the models (VIERS or CMOD4).

Conclusion 2: *Ambiguity removal by using meteorological winds as initial guess winds was implemented succesfully. The approach provides enough freedom to allow large deviations between first guess wind and the final solution.*

Figure 11: Color image of retrieved wind fields from VIERS (left), METEO (top right) and CMOD4 on 911106.

Case 3: Errors caused by erroneous initial values

When the first guess wind deviates to a large extent from the actual situation, then in some cases the ambiguity problem arises again. This can be illustrated with the quiver plots in fig. 12-14 In the area around 68° N and 7° E on November 17th, 1991, the initial wind field differs significantly from the observations of the ERS-1 satellite. The Meteo model fig. 13, shows a low pressure system at 69N 10E which does not show up in the VIERS and CMOD4 wind fields. Since the wind direction around the low pressure system varies rapidly with the location, the initial guess values for the wind retrieval algorithms vary rapidly as well. Especially when the initial guess wind is at approximately right angles with the expected real wind direction, the inversion procedure is not capable of finding the right wind vector. The errors are very similar for CMOD4 and VIERS.

Conclusion 3: *Erroneous first guess winds sometimes lead to ambiguity errors in the ERS-1 derived wind vectors.*

Case 4: Small incidence angles:

Another example of some errors which sometimes occur in the scatterometer derived wind vectors is presented in figure 15-17. Here again large differences occur between the METEO model and the scatterometer derived wind vectors. However in general the inversion algorithm can circumvent the erroneous initial winds and find a consistent wind field for most of the area. At small incidence angles (right most data points) the inversion procedure fails to give wind directions in agreement with the close by second smallest incidence angle. This was observed more often and it is a known problem inherent to the scatterometer. At very small incidence angle the dependence of the backscatter on the wind direction is small. Consequently the system becomes sensitive to erroneous first guesses and is less well capable of producing correct wind vectors. Fortunately, we have observed this phenomena only at the smallest incidence angle and only a few times at the second smallest incidence angle. The above mentioned problem can perhaps be solved by using the direction of the second scatterometer cell as a bounding condition in the inversion procedure for the first cell.

Conclusion 4: *The wind directions in the scatterometer cells with the smallest incidence angle are less reliable than the other wind directions.*

Case 5: Wind directions

Figure 18 shows VIERS calculations of the wind field on October 10th, 1991. It shows a very homogeneous wind field with south westerly winds. Figure 19 shows the METEO wind field and figure 20 the CMOD4 wind field. When comparing these three wind fields it is obvious that the VIERS wind directions follows the METEO more accurately and are internally more consistent than the CMOD4 wind directions. This was observed more often and leads to the following conclusion:

Conclusion 5: *VIERS wind directions have a better internal consistency than CMOD4 wind directions.*

Figure 12: Retrieved wind fields from VIERS on 911117.

Figure 13: Retrieved wind fields from METEO on 911117.

Figure 14: Retrieved wind fields from CMOD4 on 911117.

Figure 15: Retrieved wind fields from VIERS on 911021.

Figure 16: Retrieved wind fields from METEO on 911021.

Figure 17: Retrieved wind fields from CMOD4 on 911021.

Figure 18: Retrieved wind fields from VIERS on 911010.

Figure 19: Retrieved wind fields from METEO on 911010.

Figure 20: Retrieved wind fields from CMOD4 on 911010.

Figure 21: Same as fig. 11 but now for areas with low windspeeds on 911019.

Case 6: Low wind speed areas

Figure 21 shows an interesting case with an area of low wind speeds. As can be seen, the VIERS results give slightly lower wind speeds than CMOD4. It is well known, that CMOD4 experiences some difficulty at low wind speeds and that those wind speeds are generally overestimated. The VIERS model does not have this problem since it incorporates the effect of surface slicks on the ocean surface at low wind speeds. One can also see in figure 21 that around 0° E and $66 - 67^o$ N the inversion procedure has some problems in finding a consistent wind direction. This is again caused by the large difference between the first guess wind (fig. 21b) and the ERS-1 measured backscatter values. CMOD4 wind directions (not shown) experience similar difficulties.

Conclusion 6: *The VIERS model is capable of predicting very low wind speeds.*

Comparison with in situ measurements. During the cal/val campaign in situ measurements were performed by the Naval postgraduate school in Monteray, USA from the Norwegian research vessel Haakon Mosby. The measurements were part of the NORwegian Continental Shelf EXperiment (NORCSEX) and was not as much aimed at verification of the scatterometer as well as at the high resolution wind field estimation from SAR measurements. Nevertheless in a number of occasions coinciding measurements of the scatterometer and the ship borne wind measurements were performed.

In total 7 cases of coinciding measurements were recorded. As criteria for coincidence a distance less than 40 km was taken as well as a time difference smaller than 1 hour.

Table 4 gives an overview over the in situ measurements, the METEO model wind and the VIERS and CMOD4 values for the wind speed. In this table three values for the VIERS wind are presented. These are based on different air-sea temperature differences. The unstable values were calculated with an air-sea temperature difference of -5 degrees, the stable values with +5 degrees and the neutral values with identical air and sea temperatures. The VIERS value matching the environmental conditions best is underlined.

date	Ta-Ts	in situ	meteo	viers-U	viers-N	viers-S	cmod4
911108	-3.5	3.78	2.8	1	1	3	4
911111	-4.3	11.74	7.5	9	9	11	7
911115a	-4.0	1.32	2.2	1	1	4	2
911115b	-5.5	8.68	9.5	9	9	10	8
911121a	-4.6	22.88	18.5	20	20	20	18
911121b	-0.7	19.58	15.8	15	16	17	14
911126	2.5	10.9	7.9	1	1	7	3

Table 4: Comparison of in-situ, meteo VIERS and CMOD4 winds.

Of the 7 cases presented the VIERS wind speed is 5 times closest to the in situ

measurements, CMOD4 and METEO both once. Of course this comparison is very limited in terms of validation of model algorithms since one compares area extended measurements (VIERS, CMOD4) with time dependent point measurements (in situ). Still a few remarks can be made. On November 21st, 1991 strong winds occurred in the experiment area. METEO, VIERS as well as CMOD4 provide smaller wind speeds than measured in situ, but of these three VIERS is closest to the in situ measurements. A second observation concerns the measurement on November 26th, 1991. On this day the air was warmer than the sea water (stable conditions). Since the VIERS model is dependent on this air-water temperature difference one can easily quantify the effect. In this case the effect is quite large: 1 m/s at neutral and 7 m/s at stable conditions.

In all cases listed above the collocation occured at the cell with the smallest or one but smallest incidence angle. As reported above these cells have a smaller accuracy than the other cells. Nevertheless the results are satisfactory, especially for the VIERS derived wind speeds.

Table 5 gives a similar overview as table 4 for the wind directions:

	in situ	METEO	VIERS	CMOD4
911108	34	36	33	33
911111	181	175	182	182
911115a	303	313	339	264
911115b	220	235	231	246
911121a	153	170	174	189
911121b	256	278	276	276
911126	163	188	181	181

Table 5: Comparison of in-situ, meteo, VIERS and CMOD4 wind direction.

The accuracy for the wind direction retrieval was 15 degrees. VIERS and CMOD4 most of the time agree within this margin except for one case at November 21st, there VIERS is closer to the in situ observation than CMOD4. Differences between the in situ observations and the ERS-1 derived wind directions are in the order of 10-15 degrees and show a systematic clockwise shift for the ERS-1 derived directions versus the in situ directions. Differences between the METEO model and the in situ data are similar to differences between ERS-1 derived and in situ.

7.2.2 General conclusion with respect to validation

In this section some results were shown of the VIERS inferred wind speeds and directions as well as those of CMOD4 and the METEO model. A general conclusion is, that the structure of the VIERS wind fields and the CMOD4 wind fields is very similar indeed. The comparison between the METEO wind field and the ERS-1 inferred wind fields (VIERS+CMOD4) is generally less favourable. This has to do with the fact that the METEO model shows much less structure than both VIERS and CMOD4.

Another observation is, that sometimes some displacement of structures is visible (see e.g. fig 11) between ERS-1 and METEO wind fields.

These structure differences between on the one hand the METEO model and on the other hand the ERS-1 wind fields are also visible in the statistical analysis of the differences between the wind fields. Especially the standard deviation of the difference in wind speed is much less when comparing VIERS and CMOD4 (1.1 m/s) than when comparing VIERS and METEO (2.3 m/s) or CMOD4 and METEO (2.0 m/s). A significant portion of the deviation between METEO and ERS-1 winds will be caused by these structure differences. In this context one may ask the question whether the adjustment of model parameters, which is currently based on comparison of ERS-1 derived winds and ECMWF winds, is acceptable.

If the structure differences between METEO and ERS-1 have a random nature, then the adjustment of model parameters will nevertheless result in the optimal parameter set. The error function will be less steep and thus a larger data set is needed in order to come to reliable and stable model parameters. There are no good reasons why the structure differences should not be random. Also the fact that the two completely different parameter estimation processes for VIERS and CMOD4 result in models which give comparable results is an indication for this.

Nevertheless, the partial truth of the METEO wind fields show the limitations of this way of parameter estimation. However, there are at present not many alternatives. Taking into account that one needs approximately 30.000 data points for VIERS and 1.000.000 for CMOD4 in order to perform a parameter estimation, it is clear that such large datasets can not be obtained by conventional means without huge efforts.

Another approach in the parameter estimation proces could be the avoidence of areas with large inhomogenities in the wind field. Tuning on such a sub set will probably result in better defined error functions and thus in more accurate parameter estimation. As far as we know such an analysis has not been carried out sofar.

The best approach would be to avoid the need for parameter tuning at all. For empirical models this is impossible since they are conceptually bound to tuning with reference wind fields. The VIERS model however does have potential in this direction. At present the knowledge on the physics involved in the radar backscattering from the ocean surface did not allow us to construct a model in which all parameters were known. But the dedicated research towards determination of the physical processes involved has already resulted in a model (VIERS) in which most parameters are known within acceptable limits. Further research is needed to limit the ranges of the parameters which are yet unsufficiently known. The major parameters to be estimated are: 1) the frequency where the long wave model and the short wave model should be coupled and 2) the parameter describing the angular distribution of the short waves. Another important parameter of which the boundaries are insufficiently known is the Phillips constant α_P.

The modular design of the VIERS software allows for implementation of future results of research without the need to make a new architectural design. It is hoped that this will lead to a new generation of wind retrieval models which are less dependent

on parameter estimation and more dependent on accurate physical description of the processing contributing to the interactions between atmosphere, ocean surface and the radar backscattering from these surfaces.

8 Cost-Benefit analysis

The main purpose of the development of a scatterometer algorithm is to use the retrieved winds in an atmospheric data assimilation system in order to be able to specify the initial conditions over the oceans in regions where there are hardly any conventional data. Traditional data assimilation schemes, such as Optimum Interpolation, have considerable problems with surface observations, because it is not clear how to transfer the observed information from the surface to the upper layers of the atmosphere. To be sure, if only the winds in the surface layer would be corrected by using observed winds, the atmospheric model would almost immediately reject the observed surface information since the state of the atmosphere is determined to a considerable extent by the pressure distribution at say 5 km height. In the traditional Optimum Interpolation schemes one tries to avoid this rejection of surface data by making use of the geostrophic relation between wind vector and surface pressure gradient (this relation is approximately valid over the oceans). The resulting information in the "observed" surface pressure is then spread towards the layers above the surface by means of so-called vertical structure functions which decay with increasing height. In practice therefore the impact of observed surface winds is only confined to a relatively thin layer of the atmosphere, hence the impact of observed surface winds on the weather analysis is relatively small.

A more promising approach is the so-called 4D VAR assimilation method which uses the atmospheric model to spread the information in observed surface winds towards the upper layers of the atmosphere. In this connection it should be realised that the vertical structure functions of the Optimum Interpolation scheme only describe an average impact of surface wind speed information on the atmospheric state because these structure function are obtained using statistical fitting. In particular situations the impact of surface winds on the atmospheric state may differ from the averaged one to a considerable extent. The actual impact of observed surface winds can only be calculated using the full atmospheric model, therefore one needs variational data assimilation (4D VAR). This follows from the recent results of Thepaut et al (1993) who used a 4D VAR assimilation scheme to show that surface wind data may even give beneficial impact on the atmospheric state throughout the troposphere. Clearly only in the framework of 4D VAR one may expect to have optimal benefits of the wealth of surface data from the scatterometer. It is to be hoped that this 4D VAR assimilation scheme will be implemented at ECMWF in the near future.

Having described the context in which scatterometer data will be used at weather centres such as ECMWF we would like to summarize now the benefits of the VIERS model. In addition, we discuss how expensive the use of such a model is in terms

of memory requirements and computing costs in order to be able to assess whether a model based on physics can really compete with e.g. the present operational wind retrieval algorithm CMOD4 which is based on statistical fitting.

Let us first address the issue of the computing costs. Evidently, a scatterometer algorithm such as VIERS, which is based on the combination of a two-scale model for the scattering process at the ocean surface and a model of the short wave spectrum, is very time consuming when compared to an empirical model such as CMOD4. We solved the problem of excessive computing times by using in the retrieval algorithm not the VIERS model itself but a table which relates the backscatter σ_0 to relevant parameters such as wind speed, wind direction ϕ, incidence angle θ and wave period P. Although the creation of such a table may be time consuming (it took about 900 s on ECMWF's C90 for the resolution in wind speed etc. given in Section 3.4) it only has to be done once. The actual retrieval of winds for a certain date took only about 70 s, which is comparable to the retrieval with CMOD4 which took about 65 s. The reason for the somewhat higher computing cost of VIERS compared to CMOD4 is related to the much larger (8 times in our application) table for VIERS than CMOD4 because the VIERS model uses an additional parameter namely the wave period. On modern vector machines, such as the CRAY C90, a much larger table does not present any special problems because those machines have a fast access to the internal memory. We conclude therefore that there is no impedement for the operational use of a scatterometer algorithm such as VIERS.

Secondly, let us address now the (potential) benefits of the VIERS algorithm. From the statistical comparison presented in chapter 5 we conclude that the VIERS algorithm is performing well when compared to the analysed ECMWF wind fields and the retrieved winds from CMOD4. In fact, there seems to be more agreement between the retrieved winds from VIERS and CMOD4 than between any of the retrieved winds and the analysed ECMWF winds. Nevertheless, there are some important differences between the VIERS and CMOD4 winds to be noted, especially at the extremes of the wind speed range. The CMOD4 algorithm seems to perform less satisfactory for low wind speeds (no winds are generated in the range below 2 m/s) and the high wind speed range, at least compared with the ECMWF winds. The VIERS algorithm is performing better for extreme winds and is for this reason already a better algorithm for wind retrieval than CMOD4. In this context it should be realised that the cases of most interest are storm systems in the extra tropics which involve wind speeds at both extremes, namely in the low pressure area, low speed while outside the low, large speeds. The retrieved winds from CMOD4 would therefore give rise to a considerable less deepening of such a storm system. The synoptic discussion of chapter 5 seems to confirm this picture.

The additional advantage of our approach which was based on the physical modelling of the backscattering and the short wave spectrum is that additional dependencies of the backscatter on e.g. sea state, air-sea temperature of differences, slicks, etc. may be automatically included in the backscatter algorithm. By way of example, we have included the sea state dependence of backscatter in our algorithm and there were no

principal problems in doing so. From our statistical analysis of high wind speed cases we concluded that a sea-state dependent algorithm results in a better wind retrieval. However, more definite information is clearly desirable. This requires the lucky coincidence of having simultaneous observations of wind speed, backscatter, and sea state in the rapidly varying circumstances near a front. Davidson et al (1993), found that during the NORCSEX-88 campaign the radar backscatter indeed was dependent on the wave age. It is clear, however, that more systematic evidence on the sea-state dependence of the backscatter would be most welcome.

We emphasize that the framework of physical modelling as given by VIERS offers great potential for the future. Although CMOD4 at the moment shows a closer fit between modelled and observed backscatter, new insights into the directional distribution of the short waves will most certainly improve the performance of VIERS in this respect as well. Because of our framework this is a relatively easy step to take. Finally, we emphasize that CMOD4 is certainly a valuable model for backscatter. Since it is, however, based on statistical fitting, it will not always provide the most optimal wind retrieval. An example is the case of high wind speed, or the wind field near a front. In those cases, which only occur 10% of the time but which are of great importance, a physical model such as VIERS seems to perform in a more reliable way.

1 Conclusion

This is the last report in a series of investigations into the dependence of the radar backscatter on geophysical parameters such as wind speed, sea state, slicks and the air-sea temperature difference. The initial investigations were concerned with experimental studies in the laboratory and at sea. Basically, in these studies it was attempted to measure simultaneously all the parameters which were thought to be important in the radar backscatter process. For example, the Delft experiment resulted in a unique data set containing backscatter, wind, surface stress, the one dimensional wave spectrum, the two dimensional slope spectrum, etc.

The VIERS group also started the development of a scatterometer algorithm based on the present understanding of the radar backscatter process and of the relevant processes governing the short wave spectrum. The final aim of this part of this study was to be able to obtain wind fields from the backscatter as observed by the scatterometer on board of satellites such as ERS-1.

Using the observed wave spectra and the observed backscatter in the laboratory it was readily recognized that a simple two-scale model for the scattering process performed relatively well compared to other, more complicated models. In addition, it turned out that the VIERS wave model was compatible with the wave measurements, in the sense that spectra sufficiently close to the measured ones could be generated by tuning parameters not fixed a priori. In the final stage of the VIERS project the two-scale model was combined with the wave model into the VIERS scatterometer algorithm. After a fine tuning excercise the algorithm evolved into the form described in this report.

The present VIERS model has been shown to retrieve winds in a satisfactory manner; this followed both from the statistical comparison with ECMWF and CMOD4 wind fields and from the synoptic discussions. Furthermore, we have developed during our project a method which enables us to retrieve in a cost-effective way winds from a rather complicated and expensive algorithm such as VIERS is. In fact, it has been shown that in an operational environment retrieval of VIERS winds may be done as efficient as with the present operational CMOD4 algorithm.

Although the retrieved winds from VIERS and CMOD4 are of a comparable quality in a statistical sense, we found that compared to the ECMWF wind fields the CMOD4 winds are biased low in the high wind speed range. The VIERS bias was much less in this range. It should be noted that a reliable retrieval of winds in the high wind speed range is important. A negative bias in the wind retrieval would result in a considerable less deep analysed storm system since over the oceans the wind vector is related in a good approximation to the pressure gradient (geostrophic balance).

A weak point of the VIERS algorithm is the too simple directional distribution of the waves. This is probably the major cause of the larger misfit in σ-space (when compared to CMOD4). The strong point of the VIERS algorithm, on the other hand, is that we have followed an approach based on physics. For example, as soon as new insights emerge regarding the shape of the directional distribution of waves, they can

be readily implemented in the VIERS program.

We finally comment on the usefulness of scatterometer data for providing information on the initial condition of the weather over the oceans. We have indirect evidence that scatterometer data indeed have relevant information on the weather over the oceans. This follows from Fig. 1 of the introduction where we plotted the simulated VIERS backscatter (obtained using analysed ECMWF winds) against the observed backscatter from ERS-1. The standard deviation of the difference was of the order of 2-3 dB corresponding to a mean distance in σ-space of about 17, which is much larger than the mean distance obtained during the retrieval of winds when we found a mean distance of about 5-6, corresponding to a standard deviation of error of about 0.5 dB. In view of the large rms error for the simulated backscatter one expects that the observed backscatter contains relevant information on the weather. Another piece of evidence that scatterometer data contain relevant information on the weather follows from our finding that the VIERS and CMOD4 winds are closer to each other than to the analyzed ECMWF winds. When comparing VIERS and CMOD4 winds we typically found a standard deviation of error of about 1 m/s, while comparing retrieved winds with analysed winds we found a standard deviation of more than 2 m/s. This again suggests that the observed backscatter contains relevant information.

Whether the retrieved winds from the scatterometer will have impact on the weather forecast depends to a large extent, as was discussed in Chapter 6, on the method of data assimilation. Traditional techniques such as Optimum Interpolation have a tendency to reduce the impact of scatterometer data. New techniques, such as the variational approach (Thepaut et al, 1993) are much more promising in this respect.

Finally, it should be emphasized that the operational implementation of the VIERS scatterometer algorithm at, e.g. ECMWF, will to a large extent depend on the impact of the scatterometer observations on the atmospheric forecast. We have shown that it is certainly possible to use an algorithm based on physics in an operational context. However, tests to show positive impact of the VIERS algorithm on the weather forecast still have to be performed.

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A Software documentation and reference runs

A.1 Wind speed dependence reference run

VIERS-1 reference run: radar wind speed dependence

Conditions: standard test conditions, but variable wind speed U10

results:

U10 [m/s]	sig0hh [dB]	sig0vv [dB]
4	-27.3821	-21.9054
5	-26.2856	-20.6261
6	-24.1579	-18.5532
7	-22.2265	-16.7609
8	-20.8662	-15.5938
9	-19.2744	-14.2534
10	-18.0556	-13.2909
11	-16.6078	-12.1189
12	-15.5678	-11.3817
13	-14.3053	-10.4321
14	-13.3676	-9.77306
15	-12.2694	-8.91251
16	-11.2865	-8.11757
17	-10.5148	-7.53267
18	-9.73803	-6.85801
19	-9.07705	-6.26162
20	-8.46724	-5.77521

A.2 Radar incidence angle dependence reference run

VIERS-1 reference run: incidence angle dependence

Conditions: standard test conditions, but variable incidence angle `the_rad`

results:

the_rad	sig0hh [dB]	sig0vv [dB]
20.0	1.16480	1.45599
22.0	0.444872	0.790577
24.0	-0.359053	0.055536
26.0	-1.24929	-0.746826
28.0	-2.22617	-1.61086
30.0	-3.28673	-2.52627
32.0	-4.42332	-3.47701
34.0	-5.62224	-4.44108
36.0	-6.85975	-5.38938
38.0	-8.11148	-6.29607
40.0	-9.34945	-7.13845
42.0	-10.55156	-7.90438
44.0	-11.7078	-8.59388
46.0	-12.8215	-9.21562
48.0	-13.9035	-9.78080
50.0	-14.9629	-10.2981
52.0	-16.0079	-10.7745
54.0	-17.0171	-11.2086
56.0	-18.0007	-11.6090
58.0	-18.9555	-11.9809
60.0	-19.8824	-12.3288

A.3 Radar look direction dependence reference run

VIERS-1 reference run: radar look angle dependence

Conditions: standard test conditions, but variable radar look angle `fi_rad`

results:

fi_rad	sig0hh [dB]	sig0vv [dB]
0	-12.2694	-8.91251
5	-12.3184	-8.94963
10	-12.4635	-9.05964
15	-12.6992	-9.23851
20	-13.0164	-9.47985
25	-13.4030	-9.77541
30	-13.8443	-10.1155
35	-14.3237	-10.4898
40	-14.8237	-10.8874
45	-15.3268	-11.2976
50	-15.8166	-11.7096
55	-16.2782	-11.1129
60	-16.6992	-12.4963
65	-17.0693	-12.8489
70	-17.3808	-13.1591
75	-17.6279	-13.4155
80	-17.8068	-13.6076
85	-17.9150	-13.7268
90	-17.9512	-13.7671

A.4 Common block parameters after initialization

Reference run: the contents of common blocks after initialisation

conditions: standard test conditions

results:

```
*** common block /mathcon/ ***
pi     =  3.14159
twopi  =  6.28319
raddeg =  .0174533

*** common block /physcon/ ***
grav   =  9.806
vkappa =  .41

*** common block /user/ ***
Tair   =  20.0
Tsea   =  20.0
sal    =  35.0
AirHum =  80.0
rk     =  117.0
npol   =  1
Hz     =  10.
Uz     =  15.
period =  5.
the_rad=  45.
fi_rad =  0.
fi_wind=  0.

*** common block /airwater/ ***
yeps   =  (66.23496,34.98405)
rmu    =  1.0
RhoAir =  1.1957
RhoWat =  1024.762
SurTen =  7.17468E-05
vKin   =  1.05484E-06
rzer   =  .65

*** common block /twosc/ ***
nx     =  20
ny     =  20
beta_co=  .17
```

```
*** common block /output/ ***
nout   =  8
nunit  =  1

*** common block /twpars/ ***
winp   =  .031831
qlfac  =  4180.67
t3     =  3.0
t4     =  .25
width  =  2.0

*** common block /spectra/ ***
fr1    =  .04
fdel   =  .066
```

bin (i)	frequency fr(i)	wave number xxk(i)	phase vel. vph(i)	group vel. vgr(i)
1	.0400000	.0064415	39.01683	18.88518
2	.0426400	.0073199	36.60115	18.30068
3	.0454542	.0083179	34.33509	17.16765
4	.0484542	.0094522	32.20928	16.10464
5	.0516522	.0107410	30.21508	15.10753
6	.0550612	.0122056	28.34436	14.17217
7	.0586953	.0138699	26.58945	13.29472
8	.0625692	.0157612	24.94320	12.47160
9	.0666987	.0179103	23.39888	11.69944
10	.0711008	.0203525	21.95017	10.97508
11	.0757935	.0231276	20.59115	10.29558
12	.0807959	.0262812	19.31628	9.65814
13	.0861284	.0298648	18.12033	9.06016
14	.0918129	.0339371	16.99844	8.49922
15	.0978725	.0385646	15.94600	7.97300
16	.1043321	.0438231	14.95872	7.47937
17	.1112180	.0497986	14.03257	7.01629
18	.1185584	.0565890	13.16377	6.58188
19	.1263832	.0643052	12.34875	6.17438
20	.1347245	.0730736	11.58419	5.79210
21	.1436163	.0830377	10.86697	5.43349
22	.1530950	.0943604	10.19416	5.09708
23	.1631993	.1072269	9.56301	4.78150
24	.1739704	.1218479	8.97092	4.48546
25	.1854525	.1384626	8.41550	4.20775
26	.1976923	.1573428	7.89447	3.94723

27	.2107400	.1787975	7.40569	3.70285
28	.2246489	.2031775	6.94718	3.47360
29	.2394757	.2308820	6.51705	3.25853
30	.2552811	.2623641	6.11356	3.05678
31	.2721297	.2981390	5.73505	2.86753
32	.2900902	.3387920	5.37997	2.68999
33	.3092362	.3849882	5.04688	2.52345
34	.3296458	.4374835	4.73441	2.36721
35	.3514024	.4971368	4.44129	2.22065
36	.3745949	.5649241	4.16631	2.08317
37	.3993182	.6419544	3.90836	1.95419
38	.4256732	.7294881	3.66638	1.83321
39	.4537676	.8289572	3.43939	1.71971
40	.4837163	.9419892	3.22645	1.61325
41	.5156416	1.07043	3.02669	1.51337
42	.5496739	1.21639	2.83931	1.41968
43	.5859524	1.38225	2.66352	1.33180
44	.6246253	1.57072	2.49862	1.24936
45	.6658505	1.78489	2.34394	1.17202
46	.7097967	2.02825	2.19883	1.09948
47	.7566432	2.30480	2.06271	1.03144
48	.8065817	2.61904	1.93502	.9676097
49	.8598161	2.97612	1.81524	.9077412
50	.9165639	3.38187	1.70289	.8515884
51	.9770572	3.84291	1.59750	.7989230
52	1.04154	4.36678	1.49864	.7495304
53	1.11028	4.96201	1.40591	.7032107
54	1.18356	5.63832	1.31893	.6597765
55	1.26168	6.40670	1.23735	.6190538
56	1.34495	7.27966	1.16085	.5808794
57	1.43372	8.27135	1.08910	.5451016
58	1.52834	9.39783	1.02182	.5115776
59	1.62921	10.67727	.9587318	.4801765
60	1.73674	12.13024	.8995912	.4507765
61	1.85136	13.77997	.8441576	.4232660
62	1.97355	15.65265	.7922116	.3975437
63	2.10381	17.77775	.7435486	.3735138
64	2.24266	20.18837	.6979787	.3510931
65	2.39068	22.92147	.6553270	.3302077
66	2.54846	26.01822	.6154323	.3107910
67	2.71666	29.52410	.5781471	.2927872
68	2.89596	33.48905	.5433370	.2761496
69	3.08709	37.96733	.5108805	.2608422
70	3.29084	43.01703	.4806691	.2468377
71	3.50804	48.69944	.4526054	.2341184
72	3.73957	55.07771	.4266042	.2226758

73	3.98638	62.21509	.4025895	.2125086
74	4.24948	70.17253	.3804944	.2036214
75	4.52994	79.00576	.3602582	.1960212
76	4.82892	88.76209	.3418237	.1897142
77	5.14763	99.47727	.3251345	.1847016
78	5.48737	111.1729	.3101310	.1809750
79	5.84954	123.8549	.2967481	.1785128
80	6.23561	137.5138	.2849128	.1772775
81	6.64716	152.1264	.2745435	.1772137
82	7.08587	167.6589	.2655499	.1782503
83	7.55354	184.0717	.2578357	.1803032
84	8.05207	201.3230	.2513007	.1832788
85	8.58350	219.3737	.2458441	.1870793
86	9.15002	238.1898	.2413673	.1916068
87	9.75392	257.7446	.2377767	.1967676
88	10.39767	278.0201	.2349849	.2024735
89	11.08392	299.0070	.2329120	.2086463
90	11.81546	320.7044	.2314864	.2152166
91	12.59528	343.1195	.2306441	.2221230
92	13.42656	366.2662	.2303287	.2293149
93	14.31272	390.1650	.2304909	.2367498
94	15.25736	414.8418	.2310876	.2443919
95	16.26434	440.3275	.2320816	.2522130
96	17.33779	466.6568	.2334404	.2601901
97	18.48208	493.8688	.2351361	.2683053
98	19.70190	522.0056	.2371444	.2765451
99	21.00223	551.1126	.2394445	.2848985
100	22.38838	581.2383	.2420183	.2891028

A.5 TESTWA spectral parameters reference run

TESTWA reference run

conditions: standard test conditions

results: on the TESTWA spectral grid above the two-scale separation the following quantities were printed: the bin frequency fr, the energy flux eps, an internal computational parameter s, the resulting spectral energy density et, and for comparison the JONSWAP spectral density as computed by GWAMOD.

bin (i)	frequency fr(i)	energy flux eps(i)	s(i)	energy TESTWA et(i)	energy JONSWAP
72	3.73957	1.23103E-05	.0219196	1.93223E-06	1.93223E-06
73	3.98638	1.35118E-05	.0234832	1.52190E-06	1.40370E-06
74	4.24948	1.45756E-05	.0249996	1.19471E-06	1.01974E-06
75	4.52994	1.55162E-05	.0265066	9.37441E-07	7.40804E-07
76	4.82892	1.63469E-05	.0280264	7.36653E-07	5.38168E-07
77	5.14763	1.70800E-05	.0295643	5.80381E-07	3.90960E-07
78	5.48737	1.77268E-05	.0311076	4.58674E-07	2.84019E-07
79	5.84954	1.82977E-05	.0326290	3.63627E-07	2.06329E-07
80	6.23561	1.88020E-05	.0340908	2.89112E-07	1.49891E-07
81	6.64716	1.92484E-05	.0354519	2.30459E-07	1.08890E-07
82	7.08587	1.96447E-05	.0366733	1.84121E-07	7.91049E-08
83	7.55354	1.99978E-05	.0377240	1.47399E-07	5.74669E-08
84	8.05207	2.03139E-05	.0385834	1.18224E-07	4.17476E-08
85	8.58350	2.05985E-05	.0392422	9.49992E-08	3.03281E-08
86	9.15002	2.08563E-05	.0397012	7.64779E-08	2.20323E-08
87	9.75392	2.10913E-05	.0399695	6.16837E-08	1.60057E-08
88	10.39767	2.13070E-05	.0400618	4.98473E-08	1.16275E-08
89	11.08392	2.15064E-05	.0399961	4.03609E-08	8.44699E-09
90	11.81546	2.16917E-05	.0397917	3.27440E-08	6.13643E-09
91	12.59528	2.18652E-05	.0394682	2.66163E-08	4.45790E-09
92	13.42656	2.20286E-05	.0390437	2.16766E-08	3.23850E-09
93	14.31272	2.21832E-05	.0385350	1.76863E-08	2.35265E-09
94	15.25736	2.23302E-05	.0379572	1.44561E-08	1.70912E-09
95	16.26434	2.24708E-05	.0373234	1.18357E-08	1.24161E-09
96	17.33779	2.26056E-05	.0366449	9.70564E-09	9.01986E-10
97	18.48208	2.27353E-05	.0359316	7.97081E-09	6.55260E-10
98	19.70190	2.28605E-05	.0351918	6.55515E-09	4.76023E-10
99	21.00223	2.29819E-05	.0344328	5.39791E-09	3.45813E-10
100	22.38838	2.30979E-05	.0339050	4.48263E-09	2.51221E-10

A.6 Bragg integration reference run

If the output parameter in NVIERS.DAT is set to nout = 8 the standard VIERS-1 test program prints the following extra information:

```
BRINTA:
PMINX =  -.696278
PMAXX =  .932392
PMINY =  -.740257
PMAXY =  .740257
PS    =  .191170
SHH =  1.07071E-02
SVV =  2.39336E-02

BRINTA:
PMINX =  -.932392
PMAXX =  -1.30372
PMINY =  -.740257
PMAXY =  .740257
PS    =  .0
SHH =  .0
SVV =  .0

BRINTA:
PMINX =  -1.30372
PMAXX =  -.696278
PMINY =  -.740257
PMAXY =  -.303722
PS    =  2.39528E-05
SHH =  5.42737E-06
SVV =  3.85719E-06

BRINTA:
PMINX =  -1.30372
PMAXX =  -.696278
PMINY =  .303722
PMAXY =  .740257
PS    =  2.39528E-05
SHH =  5.42737E-06
SVV =  3.85719E-06
```

The National Remote Sensing Programme 1990-2000, (NRSP-2) is implemented under the responsibility of the Netherlands Remote Sensing Board (BCRS) and coordinated by the Ministry of Transport and Public Works.

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