WIND RETRIEVAL CAPABILITY OF A ROTATING, RANGE-GATED, FAN BEAM SCATTEROMETER IN SPACE

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ABSTRACT

The primary aim of a wind scatterometer is to determine wind speed and direction over the ocean. This is achieved by performing a set of radar cross-section measurements at different azimuth view-angles over the resolution cell, and inverting the geophysical model function (GMF) to extract the wind information.

A new concept of a rotating fan beam scatterometer was introduced which operates in C-band. The present paper describes an analysis of the new concept by means of wind retrieval simulations. The simulator used for this analysis permits a wide range of instrument settings and concepts to be tested. This was used to test advanced features such as multi-beam, dual-polarisation and polarimetric capabilities, in improving the wind retrieval accuracy.

End-to-end simulations of the complete system are performed starting from wind fields which are sampled by the scatterometer model. The simulated noisy radar echos are then converted to sets of backscattering coefficients, which in turn are inverted to obtain the wind fields (containing measurement errors and noise). The performance of the selected systems is assessed by analysing the error behavior as function of the instrument concept and characteristics (parameters).

The performance assessment is reduced to a single Figure-of-Merit number (FoM), that measures the information content of the derived winds in relation to the user requirements. For validation, the FoM is also computed for real data of the ERS and SeaWinds scatterometers, and proves indeed useful. The FoM that has been derived is quite general and could be used for any (ambiguous) observation set.

Results for different options, such as adding horizontal polarization measurement capability, polarimetric capability, or the advantage of a rotating fan beam in comparison to a set of fixed antennas will be presented.

1 ROTATING FANBEAM SCATTEROMETER CONCEPT

Windscatterometer data are at the moment in operational use, and are for example assimilated into numerical weather prediction models with a clear positive inpact [1].

Two essential requirements for any scatterometers operating in the future are:

1. High quality (accurate) wind data derived from the system in order to enable further positive impacts on the forecasts of highly sophisticated, steadily improving NWP models
2. Frequent global coverage, requiring a very large instantaneous swath, for covering the needs of very short-range forecasting (up to 24 hrs), in particular for storm-track predictions and off-shore applications

A new scatterometer concept [2] was studied under ESA which attempts to meet the above two requirements, yet simple and robust enough to permit a cost-effective system implementation. To recall the basic idea of the new concept, the working principle of the Rotating Fanbeam SCATterometer (RFSCAT) is illustrated in Fig. 1.

A wide-fanbeam antenna rotates around the vertical axis such that its footprint sweeps a fat donut-shape on the Earth surface. Combined with the spacecraft motion of approx. 7 km/s ground-speed, large overlaps are produced by the successive sweeps. A pixel within the total swath, depending on its across-track position, is intercepted by the antenna footprint at a number of occasions, first in the forward direction and later in the backward direction. The radar operates in a pulsed mode, so that each point of the echo (time) profile can be attributed to a unique pixel position within the antenna footprint along the radial direction (range-gated).

In the above-mentioned study [2], a preliminary optimisation of the instrument parameters was performed based on simple design guidelines, driven mostly by:

- a large, useful swath-width exceeding 1500 km
- the required spatial resolution

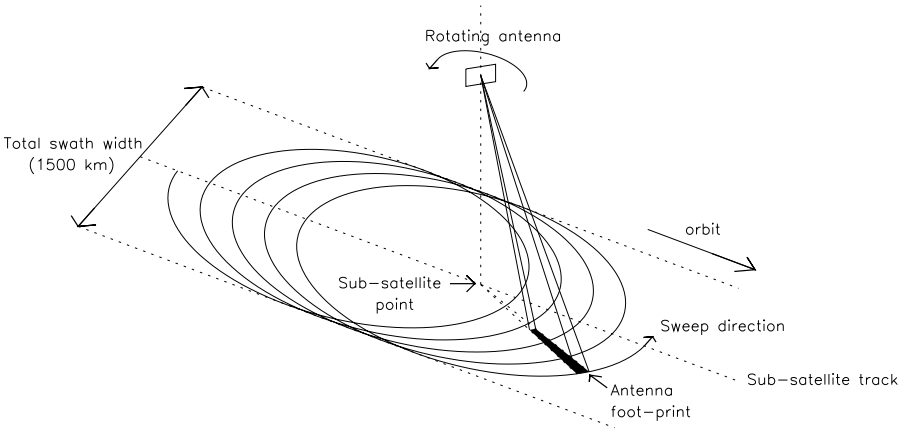

Figure 1: *concept for a rotating fanbeam scatterometer*

- the required radiometric resolution across the swath for a specified minimum wind speed (signal-to-noise ratio of unity for minimising the radar average power at the minimum wind speed)

A simple, C-band, single polarisation (VV) system was presented as a result of a first iteration. It requires only a single passive antenna which size is comparable to the fore- (or aft-) antenna of ASCAT instrument (the latter has 6 antennas). A further step in elaborating the concept for improving the performance is to carry out end-to-end simulations of the complete system, starting with wind fields and attempting to recover the same fields by optimising the system parameters. Further sophistications of the system could be beneficial in improving the overall performance such as:

- use of a dual-beam antenna
- addition of a second (horizontal) polarisation channel
- addition of a second (Ku-band) frequency channel
- a polarimetric measurement scheme

2 MEASUREMENT CHARACTERISTICS

The orbital spacecraft motion, combined with the regular fanbeam rotation, generates an epicycloidal footprint pattern on the Earth surface, depending on the spacecraft (orbit) altitude, the antenna footprint size and position (with respect to the sub-satellite point), and the antenna rotation speed.

The width of the total swath is determined by the farthest point of the antenna footprint. Generally, a largest possible swath is desirable. This can be achieved by two means:

1. increase the orbit altitude for a given incident angle, or
2. increase the incident angle (range) for a given orbit altitude

The optimisation requires that the signal-to-noise ratio be maintained close to unity for the lowest required wind speed. As a consequence, the achievable swath width is constrained by the on-board power resource and the maximum allowable antenna size.

The inversion of the data to extract wind information requires 2 but prefers 4 or more acquisitions at different azimuth view-angles during an over-flight. It is furthermore desirable that those azimuth view-angles are spaced not too close each other in order to limit the number of ambiguous solutions. Provision of a higher number of acquisitions (¿4) per over-flight could reduce the ambiguity problem by rendering the inversion over-deterministic.

In Fig. 2 an example is given for the initially choosen set of system parameters for RFSCAT. These are given in table 1.

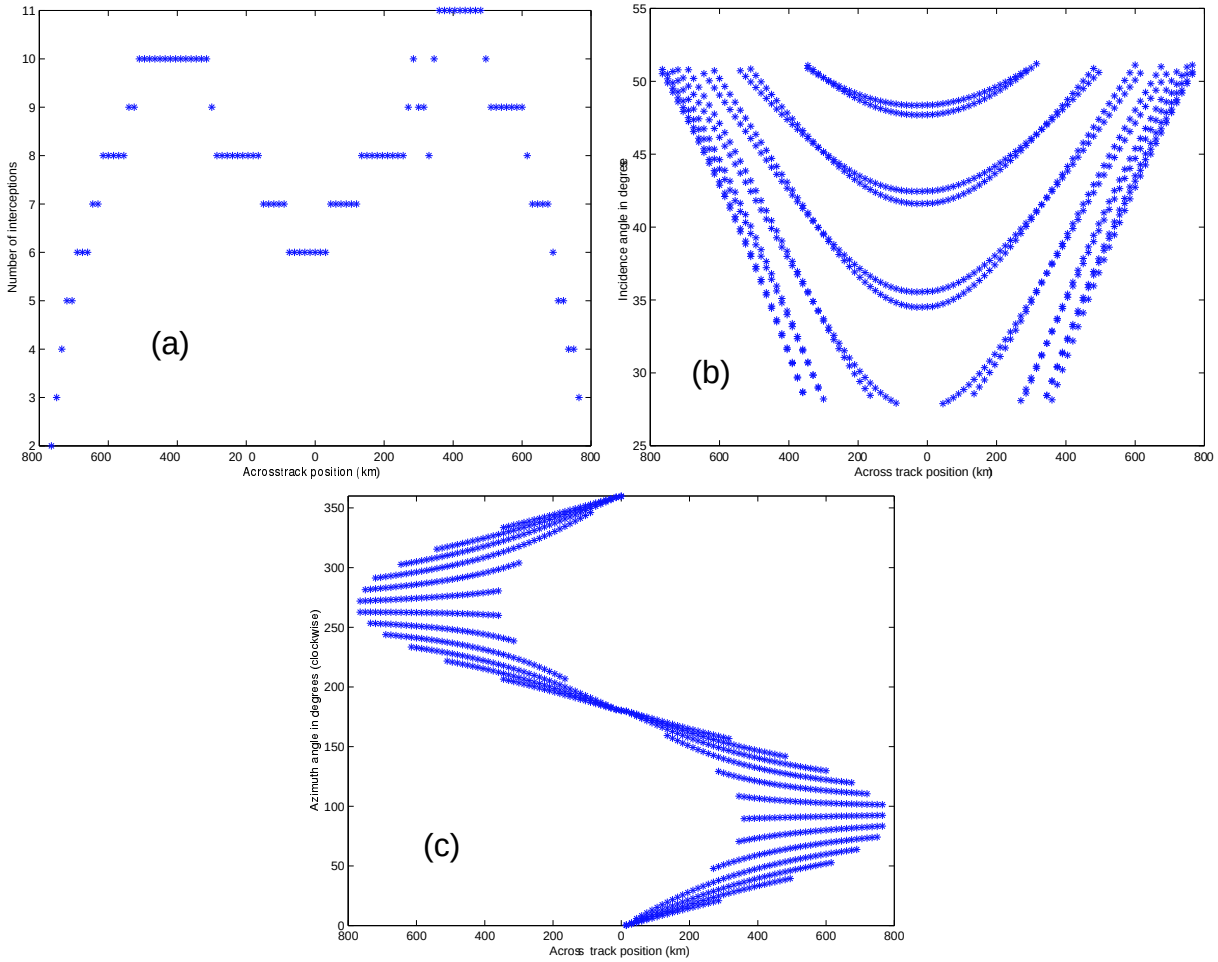

Figure 2: *example of the number of interceptions (a), the local incidence angles (b) and the azimuth view-angles(c) per pixel, as a function of its across-track position.*

3 THE SCATTEROMETER SIMULATOR

The RFSCAT simulator is designed for the end-to-end performance analysis of wind field retrieval with the RFSCAT system. However, its parameters allow it to be adjusted to simulate any type of scatterometer. A schematic overview of the RFSCAT simulator is given in Fig. 3.

The simulation starts with an input wind field and a set of parameters defining the radar system and the applied processing. The output is a set of possible wind solutions for each grid point or so-called Wind Vector Cell (WVC). The difference between input wind field and output wind field are expressed as a Figure-of-Merit (FoM). The FoM is the metric used for the optimisation of the RFSCAT system.

As input to the simulator, a spatially coherent wind field, or a systematic scan of the wind domain using discrete steps in the wind components (this resembles a uniform distribution over all wind vectors up to a certain maximum wind speed, or a set of random wind vectors representing a realistic global wind vector distribution can be selected providing full flexibility. For testing of the RFSCAT concept, we follow the latter approach and create an artificial set of random wind vectors. Each wind component is chosen from a Gaussian distribution

Table 1: initial RFSCAT parameters

Orbit height	725 km (vg = 6.7 km/s)
Total swath width	1500 km
Footprint Length	410 km
Incidence angle	28 - 51 degrees
Antenna scan rate	0.35 rad/s (3.3 rpm)

centred at 0 m/s and with a half width of 5.5 m/s. Since the wind vectors are chosen at random, no spatial relation exists between them. In this way, it can be avoided that for example seasonal or local preferences in wind direction will cause a biased sampling of the wind distribution.

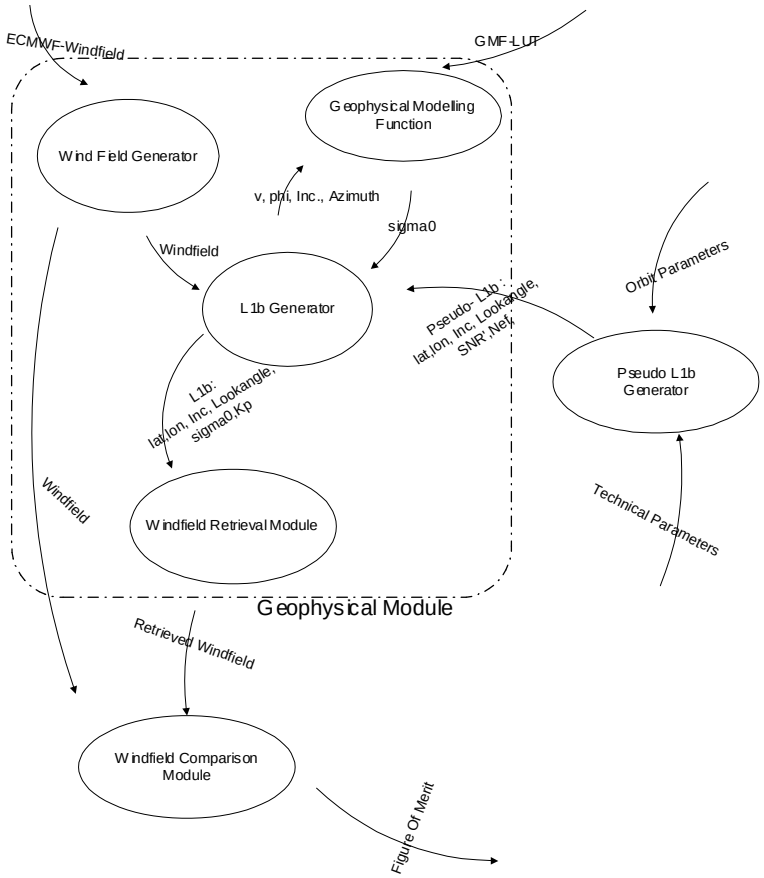

Figure 3: *Schematic overview of the set-up of the RFSCAT simulator*

The GMF, providing the normalised radar backscatter coefficient, depends on the measurement geometry (relative azimuth and incidence angle), sensing parameters (frequency, polarisation) and the wind vector. The GMF is a function devised to fit the available experimental data as good as possible. For the RFSCAT project the CMOD4 function for C-band VV-polarisation (both transmitting and receiving in vertical polarisation) is used [3, 4]. This function has been used for operational wind retrieval for the ERS-2 Scatterometer data. For Ku-band, the NSCAT2 functions are used for VV and HH polarisation [5]. These functions have been used for the final reprocessing of all NSCAT data and are used at KNMI for SeaWinds processing. A GMF function for C-band HH-polarisation is not readily available. Therefore, it was estimated by scaling the CMOD4 function with the HH/VV ratio as defined by the NSCAT2 HH and VV functions. The estimated function is called CMOD4H. GMF functions for polarimetric measurements at C and Ku-band do not yet exist. Therefore, a similar scaling procedure was necessary. The equations necessary to do this are given by Tsai et al. [6]. Furthermore a depolarisation ratio of -15dB, a symmetry factor of 0.5 and a signal attenuation of 1.0 were chosen. Using these formulas and assumptions, a new function called NSCAT2P was derived from the NSCAT2 functions, and a new function called CMOD4HP was derived from the CMOD4 and the CMOD4H functions.

Geophysical noise is the effect of local variations of the wind inside the WVC. It has been experimentally found that this can be treated as an extra source of noise, on top of the noise produced by the instrument. The variabilities of the two types of noise should then be combined to obtain the total noise (Kp) in the system. It was found [7] that the geophysical noise is a quadratic function of wind speed, increasing dramatically towards low wind speeds, and decreasing to practically zero (i.e. negligible compared to instrument noise) above 16 m/s.

The RFSCAT processing design is - similar to ERS and ASCAT- ”WVC” oriented. The purpose of WVCs is to average many measurements by spatial filtering to one quantity with a low variance. The WVCs are on a (nearly) equidistant two-dimensional grid along the sub-satellite track and the plane perpendicular to the local ground track velocity. For a given set of input parameters the pseudo level 1b generator computes the location of the WVCs, the number of views on each WVC and all quantities (measurement geometry, noise estimate) needed to compute the backscatter for a given wind vector.

The Level 1b (L1b) Generator is the part of the Geophysical module that calculates the simulated measurements and adds the noise to the measurements. In order to do this, it needs the wind vector provided by the wind field generator and the geometry calculated by the Pseudo L1b generator. The resulting simulated measurements are passed on to the wind field retrieval module. The L1b generator actually consists of the main loop of the Geophysical module. It loops over the WVC provided by the Pseudo L1b generator. Kp values are retrieved from the Pseudo L1b file, and the geophysical noise is calculated. Then Gaussian distributed noise is added to the simulated measurement (using the combined geophysical and instrumental noise). Finally the wind retrieval is carried out and the resulting wind vector ambiguities are stored.

The wind retrieval or inversion of the scatterometer data is done by the well-known algorithm that is used for the current as well as past scatterometer instruments (for example for ERS, NSCAT and SeaWinds on QuikScat). A maximum likelihood estimator (MLE) is calculated for a given geometry and simulated measurement using:

$$MLE = \Sigma \frac{(\sigma^0_{measured} - \sigma^0_{tried})^2}{(K_p \sigma^0_{measured})^2}$$

with $\sigma^0_{measured}$ the measured backscatter coefficient of a view, σ^0_{tried} the GMF value for the geometry of the current measurement, and for trial wind speed and direction, $(K_p \sigma^0_{measured})^2$ a normalisation factor [4]. The two-dimensional wind domain (speed and direction) is scanned to find the local minima that are present in this plane. These give the set of wind vectors that give simulated values that best coincide with the measured ones. The number of minima varies, and in special cases there may be just one, but usually 2 to 4 are found. The ambiguous solutions are sorted by MLE value, since the lowest MLE values correspond to a set of simulated NRCS that best fit the measurements.

4 FIGURE OF MERIT FUNCTION

For real scatterometer winds, heuristic methods exist to determine their quality [8]. These methods are based on experience and not fully objective. The problem of determining quality is caused by the ambiguous nature of the winds: multiple solutions exist with varying probability. Ranking scores and closest solution to reference wind vector RMS differences are used for validation, but these need to be combined in a FoM in order to provide a reasonable quality indication. To design future instruments, it may be appropriate to employ more fundamental ways of exploring wind quality and as such a new Figure-of-Merit (FoM) is derived. It is an objective score based on probabilistic arguments. An objective quality measure is dictated by a specification. This specification is driven by the fact that the wind is largely a known quantity. The total dynamic range of wind components is governed by a standard deviation of about 6 m/s, whereas the required accuracy is about 1.5 m/s [9].

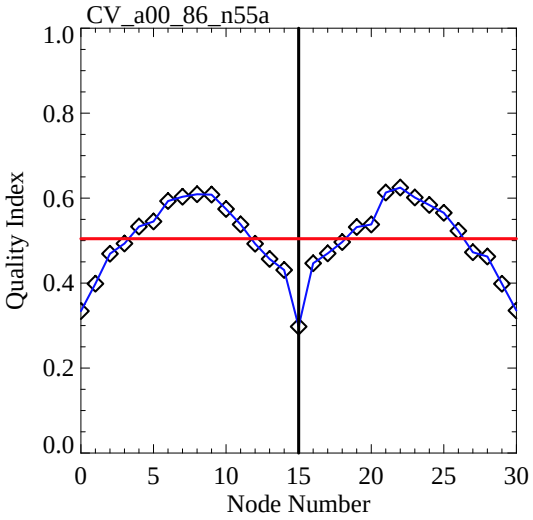

Figure 4: *Example of a FoM curve across the RFSCAT swath, in case of a single beam, C-band VV instrument.*

This is a complication for designing an objective quality measure, i.e., ambiguities much outside the specification range are not bad, since these can be removed by using prior knowledge. However, those inside the specification range are clearly detrimental, as these can in real-life not be distinguished from each other and may cause detrimental impacts. A FoM is developed based on the product of a Probability-Density Function (PDF) encapsulating the prior knowledge and a PDF following from the ambiguous solutions. The FoM takes into account both uniqueness and accuracy properties of the retrieved winds.

5 SIMULATION RESULTS

The wind retrieval performance for different options of RFSCAT instruments depends on the employed radar frequency and polarizations, and thus on the respective GMF as well as on the measurement geometry. The latter varies considerably across the swath of the instrument. For each node across the swath, the quality of the wind retrieval was estimated as described in Section 4, resulting in a curve for the FoM as a function of node number. An example is depicted in Fig. 4.

The FoM is nearly symmetric around the center of the swath which is marked by the vertical line in the plot. The slight asymmetry is caused by different sampling on the right and left side of the swath due to different

projected ground speeds of the footprint. The FoM for an entire simulation is defined as the mean value of the quality index across the entire instrument swath. This mean value is indicated by the horizontal line.

For validating the simulator software, the SeaWinds instrument aboard QuikScat has been simulated and the results were compared to measured data provided by the instrument. QuikScat measurements have been collected globally over a three day period and were processed to 100 km spatial resolution. The outer cells of the swath, which are known to provide winds of poor quality, were not available in the testfile provided to us. The simulation was done at 25 km spatial resolution for the entire 1800 km swath and is based on the technical parameters of the SeaWinds instrument. The result of the simulation together with the measured data is shown in Fig. 5. Except for nodes 59 and 63, there is very good agreement between measurement and simulation.

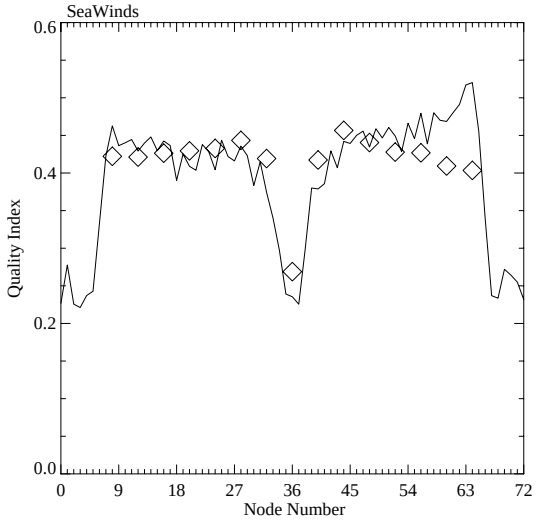

Figure 5: *validation of the simulator, using results from Seawinds (diamonds depict the measured data, line depicts the simulation)*

The wind retrieval performance depends on the signal-to-noise ratio (SNR) for the backscatter estimates. In the course of designing an instrument, an optimum SNR across the entire swath and for the wide range of wind speeds and directions has to be found. Furthermore, ambiguities in the wind retrieval due to the shape of the GMF will limit additionally the wind retrieval performance. Instead of varying the entire set of instrument parameters affecting the SNR of the instrument, e. g., antenna peak gain, bandwidths, pulse peak power, only the transmitted peak power has been varied as a representative measure of the SNR while all others were kept constant. This may lead to unreasonable high power values for pulse peak power, but considering the potential in other design parameters these powers do not indicate an unrealistic instrument design.

Fig. 6 shows a typical example of the dependence of the FoM on the SNR represented by the transmitted pulse peak power. The quality of the retrieval increases significantly with SNR until a certain value of pulse peak power and then stays constant. From this point on the FoM is entirely controlled by the wind retrieval, which includes the corresponding geophysical model function (GMF) as well as the employed retrieval technique. From the technical and instrumental point of view, one would not want to operate the instrument in the region of the steep increase in FoM, but there is also no point in further improving the scatterometer beyond the point at which the FoM curves becomes flat.

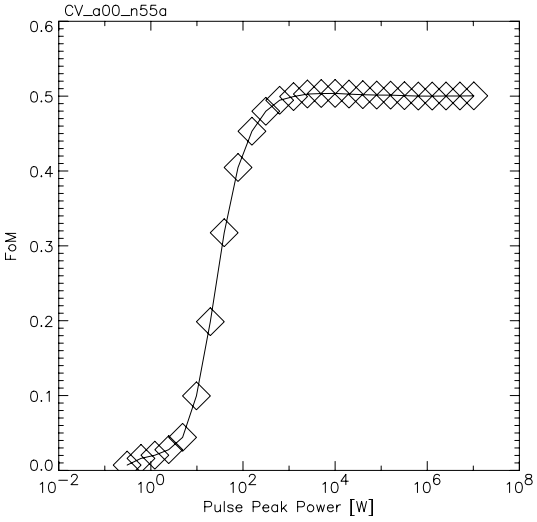

Figure 6: *FoM as a function of pulse peak power*

Within this study, various systems have been analysed. On the radar side, simulations were done for C and Ku-band for vertical (VV) and horizontal (HH) polarizations as well as for polarimetric cases. The measurement geometry includes low (725 km) and high (1075) orbits, narrow (1500 km) and wide (1800 km) swath width as well as low (50 km) and high (25 km) spatial resolution. Special emphasis was put on the analysis combinations of polarizations for the wind retrieval. To enable comparisons also the ERS and ASCAT instruments have been simulated.

In general, a considerable improvement in wind retrieval can be achieved by combining channels. Especially, the polarimetric mode has a strong positive impact herein due to its capability of resolving wind direction ambiguities at the cost of high transmitter power.

In order to compare the different simulated systems from each other, a reference performance point (RPP) is being computed on the respective FoM versus pulse peak power curve for each system. This point has

the co-ordinates of a FoM being 10% below the saturation level of the curve and the corresponding pulse peak power. This reference point allows to relate the optimised scatterometer payload power to the achieved performance in wind retrieval. A summary of RPP for system-options simulated is shown in Fig. 7.

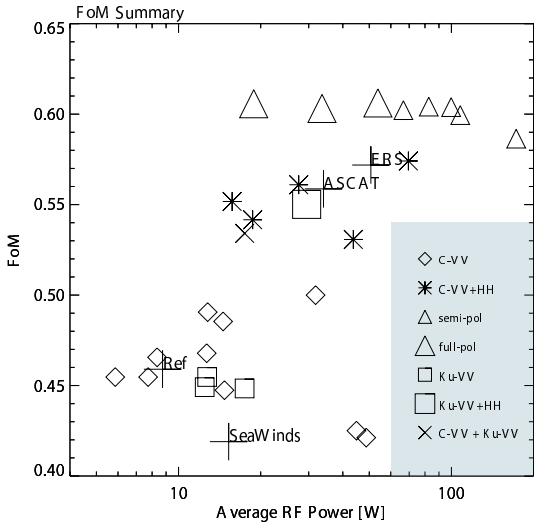

Figure 7: *Summary of reference performance points for various simulated systems.*

The result demonstrates that in general a two-channel system, i.e. 2-polarisation system (C-VV + C-HH) or 2-frequency system (C-VV + Ku-VV), performs better than a single-channel one (C-VV or C-HH). A polarimetric system performs best, but requires considerably more power. The figure demonstrates that a better wind retrieval performance comes at the expense of a higher instrument complexity.

The final result is that ERS and ASCAT are amongst the best performing systems, and can only be improved upon, by using a polarimetric measurement technique.

6 CONCLUSION

The next generation of windscatterometer will have to provide data of much improved quality and frequent global coverage in order to meet the ever increasing requirements of NWP and very short-range forecasting. The RFSCAT concept presented herein could meet such requirements in a cost-effective manner. The present study addressed the development of a versatile end-to-end system simulator and a parametric analysis of various instrument configuration-options. The simulator is a flexible modelling tool which can accommodate a wide range of instrument configurations, choices of input wind field and various output options relating to the quality of the retrieved wind. It takes into account the inherent geophysical noise in wind field as well as internally generated system noise (thermal noise and speckle noise).

The results of a parametric analysis show that RFSCAT can provide better performance in comparison to the existing or soon-to-be-flown scatterometers both in terms of product quality and coverage performance (swath width). The system performance improves with increasing instrument complexity: a two-channel system (dual-polarisation or dual-frequency) performs better than a single-channel system; the polarimetric system performs best due to its capability to resolve wind-directional ambiguities, but is penalised by a very high power requirement. With regard to increasing the swath-width, an extension of the incidence range to a higher angle appears more beneficial than an increase of the satellite altitude. This is due to a better behaviour of the GMF at higher incidence angles.

For systems that perform a better wind retrieval than required, also the possibility exists to go to higher spatial resolution, at the cost of a lower wind retrieval quality.

It must be remarked however that the validity of the results rely solely on the quality of the GMFs used in the simulations. Efforts are required to establish accurate model-functions for C-band HH, C-band polarimetric and Ku-band polarimetric cases.

References

[1] Isaksen, L. and Stoffelen, A., “ERS Scatterometer Wind Data Impact on ECMWF’s Tropical Cyclone Forecasts”, IEEE Trans. Geoscience and Remote Sensing, **38**, pp. 1885-1892, 2000.

[2] Lin, C. C., Rommen, B., Wilson, J. J. W., Impagnatiello, F., and Park, P. S., “An Analysis of a Rotating, Range-Gated, Fanbeam Spaceborne Scatterometer Concept”, IEEE Trans. Geoscience and Remote Sensing, **38**, pp. 2114-2121, 2000.

[3] Stoffelen, A., and Andersen, D., “Scatterometer Data Interpretation: Transfer Function Estimation and Validation”, Journal of Geophysical Research, **102(C3)**, pp. 5767-5780, 1997b.

[4] Stoffelen, A. C. M., “Scatterometry”, Ph.D. Thesis, University of Utrecht, ISBN 90-393-1708-9, 1998, http://www.library.uu.nl/digiarchief/dip/diss/01840669/inhoud.htm

[5] Wentz, F. J., and Smith, D. K., “A model function for the ocean normalized cross section at 14 GHz derived from NSCAT observations”, Journal of Geophysical Research, **104(C5)**, pp. 11499-11507, 1999.

[6] Tsai et al., “Polarimetric Scatterometry: A promising technique for improving ocean surface wind measurements from space,” IEEE Transactions on Geoscience and Remote Sensing, **38**, pp. 1903-1921, 2000.

[7] Stoffelen, A., “Simulation of the Wind Performance of ASCAT,” OSI SAF Technical Note, KNMI, De Bilt, 1998.

[8] Stoffelen, A., Vries, J. de, Voorrips, A., “Towards the real-time use of QuikScat winds”, Beleidscommissie Remote Sensing, Report No. USP-2/00-26.

[9] World Meteorological Organisation, SatRep-26, Geneva, 2002, http://www.wmo.ch.