FEASIBILITY STUDY OF SEA SURFACE CURRENTS MEASUREMENTS WITH DOPPLER SCATTEROMETERS

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Abstract

We present the activity carried out in the framework of the ESA GSP study called "Feasibility Investigation of Global Ocean Surface Current Mapping using ERS, MetOp and QuikScat Wind Scatterometer" (DOPSCAT). The study was aimed at assessing the potential of scatterometer instruments for sea surface current vector retrieval under the strong requirements of preserving both the swath and the surface wind vector estimation performances offered by the existing scatterometers. The paper describes the main results obtained during the DOPSCAT study and provides some recommendations for this new instrument concept.

1. INTRODUCTION

Satellite altimetry is a very mature technique with an extensive body of literature and an extremely large number of users. Altimeter data have led to breakthroughs in the understanding of the large scale (> 200km) oceanic circulation, leading to unequalled views of the eddy field and its kinetic energy on a global scale, to significantly advance the study of the dynamics of oceanic variability.

Yet, the wide spacing between the satellite ground tracks severely hampers the cross-track resolution to several hundred km. This has for consequences that the resolution of gridded maps of sea surface height (SSH) produced from multiple satellite altimeter data sets is not better than 100 km, and the temporal resolution on the order of 10 days. Accordingly, satellite altimetry data cannot resolve the smaller scales (20-100km) whose signatures are ubiquitous on high resolution optical, infrared and radar images. To address this so-called "altimetry gap" issue, national and international efforts have focused on new technologies to refine the characteristics of future altimetry, namely SWOT and WaveMill concepts, or on virtual constellation possibilities.

Eddies in the North Atlantic have typical radii of 20-30 km, amplitudes of 45 cm, and translational velocities of 2.5 km/day. Ideally, measurements to be made must then be at spatial intervals of 25-30 km on a daily basis. Very short scale dynamical processes are emerging as vital for biogeochemical processes and mixing, and for the transfer of energy between scales. Consequently, observation requirements in terms of spatial resolution will certainly go even beyond the 25 km resolution. For coastal applications, the resolution issue is obviously more stringent. The structure of surface currents in the coastal environment is generally very complex, dominated by the local bathymetry, tidal cycles, and wind and sea state conditions. Imaging instruments are then certainly more ideally suited for coastal observations.

Use of SAR derived Doppler shift to estimate surface current in some selected area of strong persistent currents such a Gulf stream and Agulhas current has emerged recently, even if proper validation is still ongoing, based on the few opportunities offered by Lagrangian surface drifters of the world ocean drifter program. One key element is that Doppler shift is not only sensitive to the underlying ocean surface current but also strongly dependent on short wind sea direction generally aligned with wind direction. Even if promising methodology has been developed, some intrinsic limitations of SAR Doppler shift for surface current mapping remains such as the need to rely on model wind direction to make the necessary corrections of Doppler shift to get surface current. Note that wind direction extraction from SAR boundary layer rolls alignment is not always possible. On top

of that, usual side looking space-borne SARs can only provide one component of the surface velocities in the radar line of sight, not to mention the global ocean coverage that is not realistically achievable, considering the limited operating time per orbit.
Scatterometers, on the other hand, with multiple antenna pointing azimuths, global ocean coverage and simultaneous wind direction estimation (in fact full wind vector) appears, at first glance, to be ideal candidate for ocean surface current mapping using Doppler shift information. A closer look points out a clear limitation in terms of sampling of the Doppler spectra that could be estimated from each antenna echoes. The usual Nyquist–Shannon sampling criteria is not verified between a low PRF (imposed by the need of 2x500km swath) and a high Doppler bandwidth (few kHz on fore and aft ASCAT beams). The question remains whether this apparent limitation can be overcome in some ways and whether a dedicated scatterometer design, in line with the evolving requirements of high resolution scatterometry, could be optimized to remove this limitation.
This question is at the base of the ESA GSP study called "Feasibility Investigation of Global Ocean Surface Current Mapping using ERS, MetOp and QuikScat Wind Scatterometer" (DOPSCAT), which was aimed at investigating the potential of scatterometer instruments for sea surface current vector retrieval under the strong requirements of preserving both the swath and the surface wind vector estimation performances offered by the existing scatterometers.
The DOPSCAT study main goals were:

- Review of user requirements for ocean surface current observation and of existing surface current estimation methods
- Analysis of both real and simulated datasets to assess the possibility of retrieving Doppler information from scatterometer data.
- Elaboration of concept idea for combined wind field and surface current scatterometer

2. USER REQUIREMENTS FOR OCEAN SURFACE CURRENT OBSERVATION

- Ocean circulation is one of the most important parameters regulating and determining the Earth´s climate. Currents are generated from the forces acting upon the water mass including the rotation of the Earth, winds, temperature and salinity differences as well as tidal forces. Additionally, the bathymetry, the shoreline influence the currents' direction and strength.
- Conventional along-track interferometry techniques can provide a measure of the instantaneous sea surface scatterer velocity by measuring the phase difference between two return signals from the same surface patch, separated by a very short time interval.
- Direct instantaneous frequency determination from the phase history analysis of single antenna returns is less conventional, but can also be used to evaluate the mean velocity of scatterers on the ocean surface.
- Both techniques have demonstrated the feasibility to infer current velocities along the radar line-of-sight direction. These techniques have the potential to meet very high spatial resolution requisites of the order of km, but have the disadvantage that only one component of the two-component surface current is mapped. Furthermore the radar line-of-sight velocity is strongly influenced by the wind generated wavelet motion, long wave orbital velocities, wind and residual wave drifts [1][2]. These sources must be correctly removed before the strength of the range directed surface current can be determined.
- Table 1 contains the characteristic velocities of some ocean current regimes along with the typical temporal and spatial scales of the different current structures and clearly reveals the contrast between open ocean current features and common coastal ocean current features (e.g. tidal currents). The total dynamic range of surface currents is rarely exceeding 4-5 m/s. However, the range varies from current regimes to current regimes such as, for instance, associated with exceptionally strong tidal currents versus mesoscale eddy currents. Moreover, the measurement retrieval accuracy is also highly important. Typically this must be less than approximately 0.10 m/s and independent of current regimes.

Considering the values in this table as a general guide to surface current characterization [3][4][5] and observation requirements a number of regions can be specified as suitable for case studies to investigate the satellite retrievals of ocean surface currents using scatterometers:

- The Gulf Stream region
- Agulhas Current
- Regional sea (Western Mediterranean),
- Coastal up-welling region in Spain and Portugal
- Open ocean gyre.

- These regional characteristics are used to define the dynamic range of surface currents spanning from 0.05 m/s to 4 m/s with a retrieval accuracy of ~ 0.10 m/s at a spatial and temporal resolution of approximately 10 km and 12-24 hours.

Phenomenon	Time scale [hr]	Length scale [km]	Velocity scale [cm/s]
Equatorial currents	240	50-100	10-150
Western boundary currents	48	10-100	10-200+
Ocean meso-scale eddies	120	10-20	10-50
Ocean fronts	120	1-5	30
Tidal currents	1	0.1-20	10-200+
Coastal currents	6	0.1-5	5-50

Table 1. Characteristic velocities arranged according to oceanic phenomena

3. SURFACE CURRENT ESTIMATION FROM ERS-2 WIND SCAT DATA

One of the main goals of the DOPSCAT study was to exploit existing Scatterometer data to test the possibility of Doppler shift estimation and ocean surface currents signature retrieval. The main issue related to the usage of real datasets was to find on-ground data still maintaining the Doppler information. Indeed a lot of scatterometers (e.g. ASCAT) perform detection on board (discarding the phase information), in order to reduce data amount to be down-linked. The second requirement was the possibility to access a scientifically relevant dataset, possibly including data acquired over land-masses for Zero Doppler calibration purposes. The only sensor to meet these requirements is the ERS-2 Wind Scatterometer (WS), whose data have been selected for the activity.

The ERS-2 sensor was launched in 1995 and carried on board several sensors, among which the Wind Scatterometer [6][7]. The instrument was made of three antennas pointing at 45 degrees separated directions, allowing the estimation of the speed and the direction of the ocean wind fields. The WS antennas transmitted rectangular pulses with a Pulse Repetition Frequency (PRF) around 100 Hz. This results in an along-track spectrum very flat due to aliasing whereas the across-track spectrum presents a classical sinc shape. Therefore, unlike SAR, Doppler shift estimation from Scatterometer data has to be performed from the across-track spectrum. Two different Doppler estimation techniques were considered:

- a time domain Doppler shift estimation technique, based on the Adjacent Cross-Correlation Coefficient (ACCC) method [8];
- a frequency domain technique, based on the MLS fitting of the received signal spectrum.

The ACCC technique looks for the peak of the signal spectrum in an indirect way, exploiting the properties of the power spectral density of the received signal. It uses the Fourier relationship between the power spectrum $S(f)$ and the auto-correlation function $s(\tau)$ of the data. In particular, the phase gradient of the auto-correlation around zero lag results to be proportional to the frequency location of the maximum of the spectral density function (i.e. the searched Doppler shift). This gradient may be estimated by calculating the phases of the autocorrelation samples. As the value of the first sample has the highest signal-to-noise ratio, it's the best option for the algorithm. The returned Doppler shift value is ambiguous, i.e. it is wrapped between $-fs/2$ and $fs/2$. This is usually a problem for SAR data but not for the considered WS data, since the across-track sampling frequency (30 kHz) is sufficient to avoid spectral alias assuming that the geometric DC is compensated on the fore and aft beams.

The Minimum Least Squares (MLS) estimation technique tries to minimize the square error between the calculated and the modelled across-track spectrum. The method requires as input, along with the raw data, additional information (sensor orbit, attitude information ...) in order to improve the model of

the received signal spectrum.
Both these techniques did not allow to obtain accurate enough results, due in particular to the nature of the data itself, which are very low-sampled both in along and across track directions. An accuracy around 50 Hz (1σ) was obtained for the ACCC technique whereas a slightly better accuracy (around 40 Hz) was obtained with the MLS technique. Being the accuracy difference quite reduced the ACCC method was considered for the activity prosecution, thanks to its simplicity.
The ACCC estimator was applied to 3 full cycles of WS data (about 100 days of acquisitions), in order to perform a valid feasibility assessment of the global ocean surface current mapping using scatterometer data. Furthermore ECMWF ERA40 surface winds data have been extracted from the ECMWF archives and collocated in time and location with the ERS data, to correct for wind induced Doppler shift. Fig. 1 shows the wind compensated Doppler shifts of the 3 EWIC cycles, re-gridded over a regular 1 degree by 1 degree latitude/longitude grid.

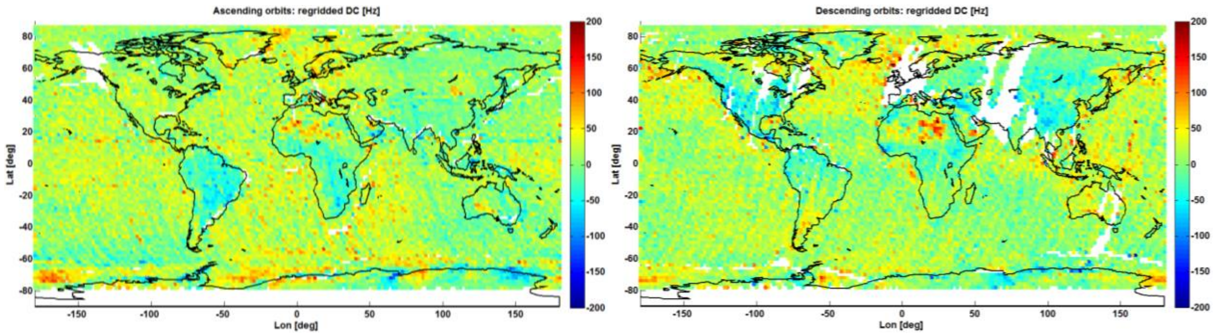

Figure 1. CDOP compensated Doppler shifts re-gridded over a regular 1 by 1 degree latitude/longitude grid. The top image is for ascending orbits while the bottom image is for descending orbits.

As already anticipated the obtained accuracy was around 50 Hz and no particular correlation between the obtained Doppler shifts and the principal ocean currents can be observed. Nevertheless a few very homogeneous regions (e.g. over South America and Equatorial Africa) can be observed.

4. DUAL-CHIRP SCATTEROMETER CONCEPT

4.1. DOPPLER ESTIMATION FROM LFM PULSES

Modern Scatterometers transmit LFM pulses in order to reduce the emitted peak power and increase across-track resolution. This results in a very flat-spectrum even in the across-track direction. The Doppler estimation techniques described in the previous section are consequently not applicable to modern Scatterometer data. In general, the Doppler shift estimation over LFM data is complicated because the Doppler shift is very small w.r.t. the system bandwidth and the pulse spectrum is very flat. Furthermore LFM pulses are affected by the so called range-Doppler coupling effect: after pulse compression a Doppler shift f results in a signal delay τ:

$$\tau = \frac{f}{K_p} \tag{1}$$

where K_p is the chirp rate of the LFM pulse. The effects of Doppler shifts and time delays cannot be distinguished, making the Doppler shift estimation over standard scatterometer data more complicated.
Fortunately the range-Doppler coupling effect can be used for Doppler estimation [9], by exploiting the fact that its effects are opposite for chirps with opposite rates. For this reason we propose a system transmitting dual-chirps (i.e. two chirps with opposite rate). The Doppler estimation will be performed by measuring the relative shift between the two obtained range compressed images, through a standard cross-correlation shift estimator. The processing scheme for the received raw data is illustrated in Fig. 2.
The following processing steps are performed:

- On-board demodulation: this step is required, to cope with the huge range dependent Doppler shift affecting the Scatterometer squinted beams which, if not compensated, would translate the received data outside the receiving filters bandwidth. Note that this step is very critical: an error in the on-board demodulation directly results in an error in the estimated Doppler shift (see Section 4.4).
- Range compression: the received raw data are range-compressed with both the up and down

chirps and two different range compressed images are obtained.

- Relative shift estimation: the principle of the proposed Doppler estimation method is to measure the relative delay between the obtained up and down signals and readily convert this delay into a Doppler shift value. This operation is performed according to the well-known cross correlation technique which is used, for instance, for the coregistration of interferometric SAR images. The two signals obtained with the range compression operation are detected and the cross-correlation is computed via FFT and Inverse FFT. The relative shift is given by the location of the maximum of the cross-correlation function. To increase the accuracy of the estimation process an oversampling in the frequency domain can be performed.
- Shifts to Doppler conversion: the obtained delay values are converted into Doppler shifts according to:

$$f = \frac{\Delta\tau}{2} K_p \quad (2)$$

directly derived from Eq. (1), where $\Delta\tau$ is the relative shift estimated at the previous step.
The whole acquired image can be divided into blocks in order to obtain along and across track variant Doppler shift estimates with the desired resolution and accuracy.

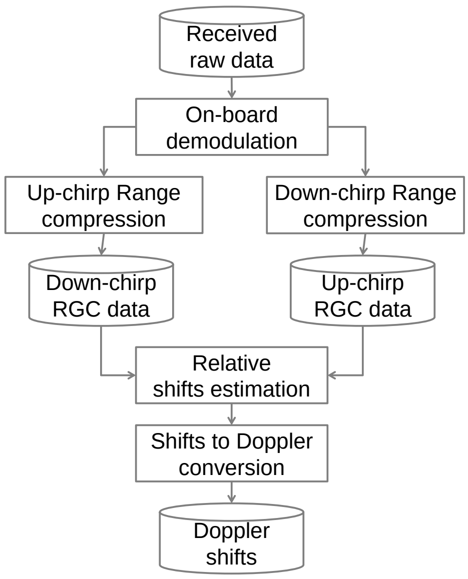

Figure 2. Processing flow-chart for dual-chirp DOPSCAT data

4.2. DOPSCAT SIMULATOR CONCEPT

At the moment no existing scatterometers transmitting LFM pulses provide complex data on ground. For this reason, in the framework of the DOPSCAT study, a raw data simulator has been developed [10] in IDL. In particular the simulator implements the proposed dual-chirp Scatterometer concept. The simulator was exploited to generate a number of datasets with known characteristics in order to test the Doppler shift estimation capability for the proposed dual-chirp Scatterometer concept. The main features of the developed simulator are:

- Includes a mini orbit propagator
- Simulates 3 of 6 beams of an ASCAT-like scatterometer (right looking)
- C band, VV polar only (CMOD, CDOP)
- Most system aspects are user-selectable (PRF, antenna sizes and pointing, orbit, attitude, chirp rate, sampling frequency, demodulation error rate …)
- Geophysical scenario is user selectable (average wind and current velocity vectors)
- Geometric range dependent Doppler shift computed from the orbital position, LoS, rotation rate of an ellipsoid Earth WGS84
- Current Doppler shift obtained by computation of the relative velocity vector along the LoS
- Wind Doppler shift computed from the CDOP GMF
- Azimuth Bandwidth computed & Azimuth Spectrum aliased according to the low PRF
- NRCS calibrated with the GMF output for the steady wind condition + NRCS variability model

The following picture shows some simulator internal parameters for the geophysical scenario and a sensor at ANX on an ascending pass (right looking).

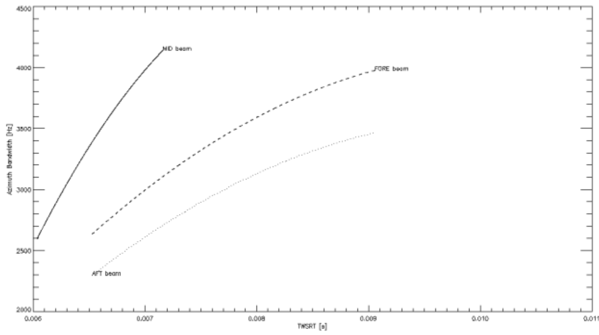

Figure 3. Example of azimuth bandwidth computed by the simulator for the 3beams.

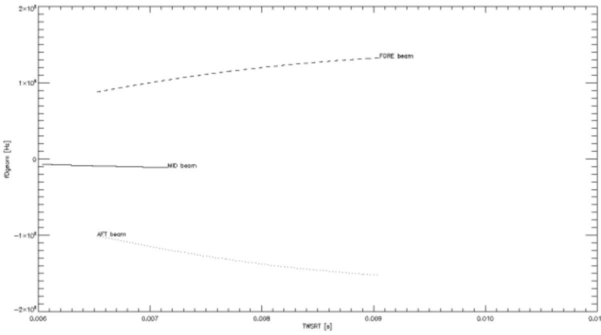

Figure 4. Example of geometric Doppler shift computed by the simulator for the 3beams.

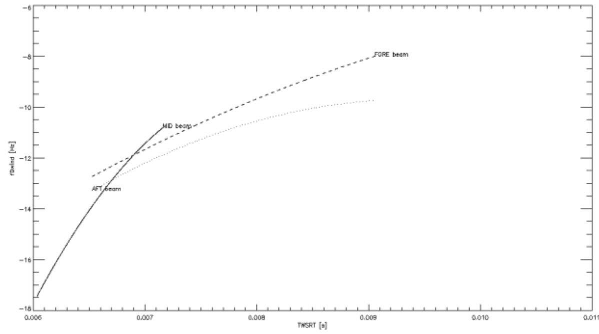

Figure 5. Example of wind Doppler centroid computed by the simulator for the 3beams.

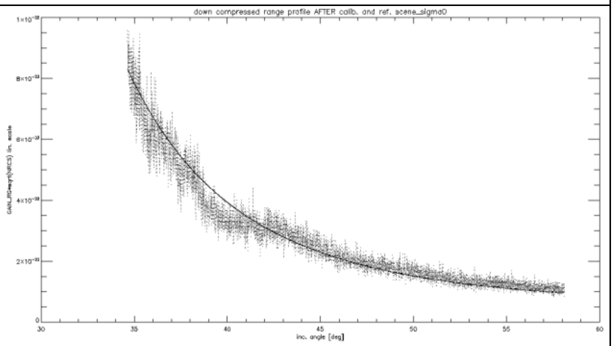

Figure 6. Example of amplitude of down compressed signal for the aft beam versus the scene transfer gain.

4.3. ESTIMATION RESULTS OVER SIMULATED DATA

This section presents the main results obtained applying the proposed Doppler estimation technique on Wind Scatterometer simulated datasets. Each dataset consisted in 3 right-looking beams of an ASCAT-like scatterometer. 64 datasets have been produced for the Doppler estimation technique validation. The reference scenario was always the same with different conditions of SNR and on-board Doppler demodulation errors (different colours in the figure). Fig. 4 shows two scatter plots representing the Doppler estimates bias and accuracy dependency on SNR. As expected, there is a clear correlation between the SNR and the Doppler estimation accuracy. For high SNR an estimation accuracy slightly below 40 Hz is obtained. The on-board Doppler demodulation error also has a direct impact on the quality of the Doppler shifts estimates. When it increases a bias in the estimates is introduced (light blue stars). For sure the obtained accuracy is strongly dependent on the resolution: by averaging (either in time or space) the accuracy improves at the cost of a reduced resolution.

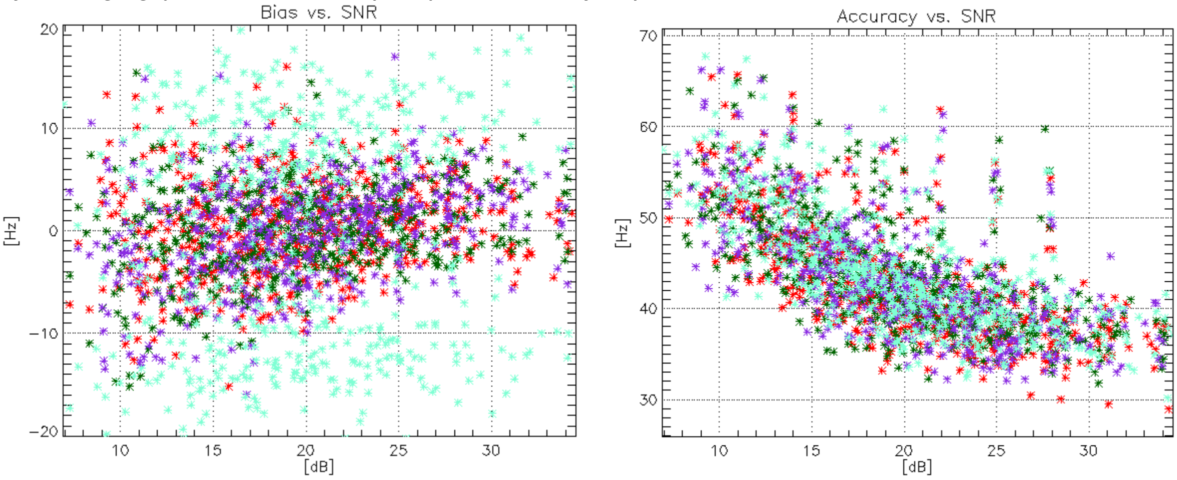

Figure 7. Scatter plots of Doppler estimates bias and accuracy w.r.t. the SNR. The different colours represent different on-board Doppler demodulation errors.

4.4. DUAL-CHIRP CONCEPT TRADE-OFFS

Two implementations of the dual-chirp system are possible:

- Transmission of the sum of the two opposite chirps
- Transmission of two chirps juxtaposed in time

The first solution is optimal from an ocean scene correlation point of view on both compressed signals but foresees the transmission of a non-constant amplitude pulse which may be an issue from technological point of view.
The second solution is optimal from a transmission point of view but the very quick de-correlation time of sea surface shall be considered during system design. Indeed the main issue related to the second approach would be that the two chirps would see two slightly different ground scenes, reducing the performances of the cross-correlation technique. This would not be a problem at all for scenes with coherence times much higher than the pulse length (e.g. land scenes), but for ocean scenes the impacts on the Doppler estimation accuracy should be assessed. A possible solution would be to reduce as much as possible the pulse duration and, at the same time, increase the chirp rate to maintain the system bandwidth fixed.
This solution would have of course an impact on the estimation accuracy. Indeed from Eq. (1) to increase estimation accuracy we would like to maximize the effects of the Doppler shifts in terms of delay. This is possible only by reducing the chirp rate which is at the denominator of the equation. This means that the system parameters shall be selected very carefully in order to make the proposed Doppler estimation technique effective.

5. COMBINED BACKSCATTER AND DOPPLER WIND RETRIEVALS

To further study the concept of a scatterometer that combines back-scatter and Doppler information, a separate tool was exploited to perform Monte Carlo simulations of wind retrievals. The tool scans input winds, adds scatterometer geometries and noise properties, simulates backscatter and Doppler signals and performs wind retrievals. Based on its results several Figure-of-Merit (FoM) numbers are calculated for wind vector, wind speed, wind components and wind direction differences, and a special FoM sensitive to ambiguity of results in the retrieval problem. Finally scanned wind results are combined using climatological weights for the occurrence of wind speeds.
Results are given in Figures 6 and 7. The left plot (6) scans the weight between back-scatter and Doppler signals. The right plot (7) compares QuikScat, ASCAT and several Doppler enabled ASCAT like instrument configurations.
From the Monte-Carlo simulation results the following conclusions and recommendations can be noted:

- Assuming a value for the relative noise (Kp) it is possible to calculate Figure-of-Merit numbers that allow comparing overall performance for different scatterometer instruments;
- From comparing different Doppler capable systems, adding Doppler capability to the fore and aft beam, and thus sampling two perpendicular Doppler components, gives the best performance results;
- No configuration was found in which extending the wind MLE with Doppler information improves upon the ASCAT instrument performance. This may be caused by the MLE definition used in the simulation, or the CDOP GMF, both of which may be improved.

6. CONCLUSION

It was shown that the technical implementation of Doppler shift anomaly retrievals from scatterometry is feasible even though it was not possible to retrieve accurate enough result from ERS-2 WS data. For this reason a simulator has been developed and a novel scatterometer concept has been proposed. The dual-chirp scatterometer transmits two chirps with opposite rates and exploit the range coupling effect to perform Doppler shift estimation. Some preliminary results on the achievable Doppler estimation accuracy with this new concept have been shown.
Furthermore a set of Monte Carlo simulations over several possible scatterometer concepts combining back-scatter and Doppler information have been performed, trying to calculate several Figure-of-Merit (FoM) numbers for wind vector, wind speed, wind components and wind direction differences, and a special FoM sensitive to ambiguity of results in the retrieval problem.
It is recommended that this study could be extended with further investigation and analyses, including further testing of the proposed dual-chirp concept over simulated or real scatterometer data.

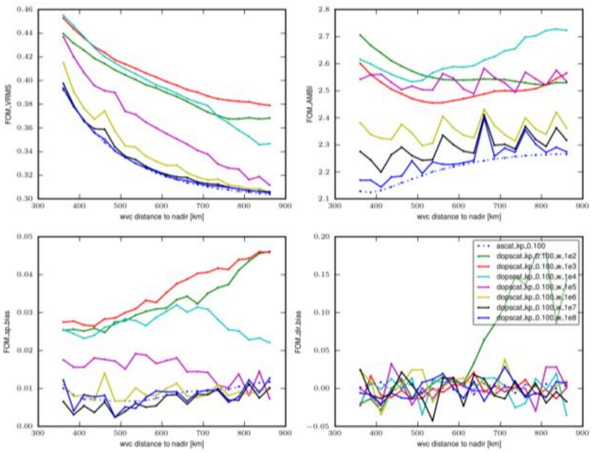

Figure 8. FOM results for a DOPSCAT simulation based on adding Doppler capability to the ASCAT fore and aft beam for Kp=10% and a range of weight values. For reference the ASCAT result for Kp=10% has been added (blue dotted line).

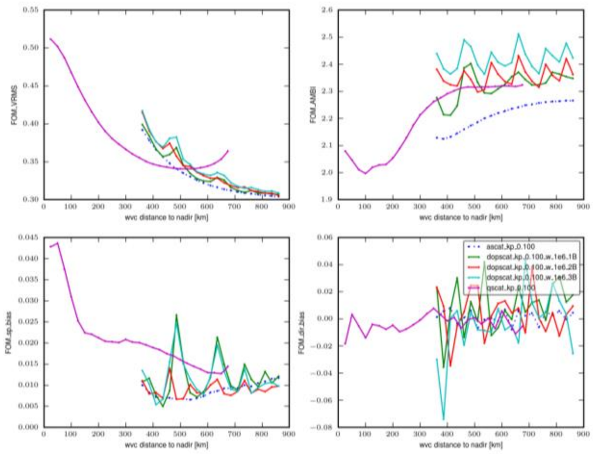

Figure 9. FOM results for different instrument configurations all using Kp=10%. For all DOPSCAT cases a weight of 10^-6 was used.

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