QUANTITATIVE REMOTE SENSING: HORNS REV WIND FARM CASE STUDY

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ABSTRACT

Wind vector observations from 85 ERS-2 SAR using CMOD4, and daily wind vector maps for five years from the Quikscat scatterometer archive at IFREMER/CERSAT are used to estimate wind patterns near the Horns Rev wind farm located in the North Sea, Denmark. At this site a large offshore wind farm (80 2MW-turbines) is in operation. The study includes spatial analysis of wind climatology maps derived from satellite observations, as well as time series statistics based on offshore meteorological observations collected near the wind farm. Focus of the case study is on the spatial variations in wind fields within the region. The overall aim is to provide quantitative estimates on offshore wind resources, and to demonstrate possibilities and limitations on the use of quantitative remote sensing for wind resource estimation.

1. INTRODUCTION

Possibilities and limitations on mapping the offshore wind climate using images from Earth Observing satellites is the key component of the SAT-WIND project (Winds from satellites for offshore and coastal wind energy mapping and wind-indexing (year 2004-2005)). It is a basic research project in which all available types of satellite-based ocean surface wind maps will be investigated. It will include satellite Synthetic Aperture Radar (SAR), scatterometer, radar altimeter and passive microwave. The current paper only addresses SAR and scatterometer observations.

SAR wind vector maps seem, at first instance, to be the most interesting type as spatial details can be mapped with a very high resolution (~500 m by 500 m). Comparison results between SAR wind maps and high-quality offshore wind observations from the North Sea show good results [1]. A major limitation using satellite SAR for wind climate estimation is the few available images. It is of the order of a few hundred for any local area of interest. This conflicts with the necessary number of observations [2,3] for wind resource assessment within the standards in wind energy application. It means that satellite SAR cannot be used as a stand-alone solution to map the coastal offshore wind resource. SAR-based wind climate maps provide unique information, and therefore may be an attractive supplementary source in combination with other wind observations.

A prototype software to handle satellite SAR images for wind engineers was developed within the EC project WEMSAR (Wind Energy Mapping using SAR, year 2000-2003). The software is currently being refined in the ESA EOMD project EO-windfarm (year 2003-2006) and combined with other satellite based information types (e.g. digital elevation data, land surface roughness, scatterometer winds). Only development work is undertaken within the EO-windfarm project [4].

In contrast, the SAT-WIND project is a basic research project. It focuses on satellite observations for offshore

- spatial regional wind mapping,
- time-series wind mapping (wind-indexing),

and on detailed comparison and validation studies. The Danish seas are the prime area of investigation. The work is carried out jointly (Risoe, Energy- and Environmental Data (EMD) and Elsam Enginering).

2. SATELLITE SOURCES

Common to satellite SAR and scatterometers is the geophysical model function typically applied to the calibrated images in order to estimate the wind vector. For radar altimeter and passive microwave the retrieval techniques are different and only wind speed (not direction) is retrieved.

Satellite SAR images are available since 1991. ERS-1 from the European Space Agency (ESA) was the first research satellite with a SAR onboard. It was a very successful instrument (for sea ice, flood monitoring, vegetation, soil moisture, digital elevation mapping, land slide, etc.), and followed by ERS-2 SAR in 1996, and in 2002 by the Advanced SAR (ASAR) at the Envisat satellite. Radarsat-1 from the Canadian Space Agency launched 1995 was designed to map sea ice and there is a follow-up mission satellite in place, Radarsat-2, to be launch in year 2005.

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Radarsat has C-band HH polarization whereas ERS-1/-2 has C-band VV polarization, and Envisat ASAR has both C-band VV, HH, HV and VH. At the moment ERS-2, Envisat and Radarsat-1 are observing the Earth. None of the SAR sensors are designed specifically for ocean wind mapping but it is nonetheless possible to map wind vectors from all of them.

The 85 SAR images investigated in the present context are from ERS-2 SAR and each image covers an area of 100 km by 100 km. The raw grid cell resolution is 25 m by 25 m but in order to decrease noise inherent in SAR images, averaging (multi-looking) to a 400 m by 400 m grid cell resolution is performed.

Scatterometers are designed for ocean wind mapping. So in contract to imaging SAR, there is a nominal product specification on ocean wind retrieval. It is ±2 ms^{-1} and ± 20º. The first was onboard ERS-1, and the second onboard ERS-2. NSCAT (1996), Quikscat (1999) and Midori-2 (2002) all from National Aeronautics and Space Administration (NASA) followed. Quikscat observes the globe twice per day. At high latitudes many samples are collected per day whereas the twice-per-day coverage near the equator is not complete. Wind vector maps are produced near-real time and used extensively (assimilated) in weather forecast modelling, wave forecasting, etc.

The entire Quikscat data-series is available in form of morning and evening passes per day since July 1999. The archive at http://podaac.jpl.nasa.gov/ contains ~3600 global wind vector maps in a grid resolution of 25 km by 25 km. These maps are not kriged (geo-statistically sampled) for filling out spatial gaps. In contrast, this has been done at the IFREMER/ CERSAT archive http://www.ifremer.fr/cersat/. Here Quikscat data are stored as 50 km by 50 km wind vector data as averages per day, per week and per month. The monthly maps are investigated in the current study.

3. STUDY AREA AND OBJECTIVES

The study area is the Danish seas including the North Sea, the Baltic Sea and interior waters. A region in the North Sea near Horns Rev has been studied [1]. It is based on the unique offshore meteorological time-series collected by Elsam Engineering. The data constitutes an excellent in-situ comparison data set. It covers the period from May 1999 to present [5]. Offshore and coastal observations will be used also from other sites, e.g. Høvsøre, Vindeby and Læsø.

3.1 Objectives

The objectives of the present analysis are

- identification of spatial wind patterns at local and regional scale,
- time-series analysis from several years.

For the first objective both satellite SAR and Quikscat observations are used, for the second only Quikscat. In both cases meteorological observations from Horns Rev are used for comparison.

4. RESULTS

4.1 SAR

Satellite SAR wind maps are produced using the Wemsartool [6]. It is software that identifies the wind direction over the ocean from wind streaks in each image from two-dimensional Fast Fourier Transforms[7]. Subsequently the wind direction is input to the CMOD4 algorithm [8]. The resulting wind direction and wind speed maps are then read into software RWT [4] in which a spectral filtering and footprint averaging [1] is applied. The resulting mean wind speed map represents the mean wind speed in each grid point of the domain.

The footprint averaging technique ensures that the number of pixels is always located upwind of the point of interest, and thus truly representative the upwind flux area. The filtering reduces noise due to e.g. speckle and small-scale atmospheric and oceanic effects. The simple footprint method is used [1].

The resulting mean wind speed map based on 85 ERS-2 SAR satellite scenes is used in the subsequent analysis. The mean wind speed map is shown in Fig. 1.

The map shows mean winds speeds around 6 to 7 $m\ s^{-1}$ (green colour) but near the coastline somewhat lower winds (reddish). To the far west high wind (blue/ purple) is found but this is not a mean wind speed as there is only one satellite SAR image from this location included in the present study. This image is a high wind speed case. The flow is from the northwest. The alignment of wind streaks can be seen.

In Fig. 1 it is clear that the region is covered by different satellite track and frame positions (each scene is 100 km by 100 km). Fig. 2 shows the number of images, and the position of ten horizontal (West to East) and three vertical (North to South) transect lines. A total of 85 satellite images are included in the analysis but the maximum shown with the scale in Fig.2 is 67.

This is explained as follows. Nearly all of the 85 scenes (82 to be precise) cover the site of the meteorological mast (red crosshair). However for a number of cases, a polygon has been drawn to deselect the area close to the wind farm area as the wind farm provides an extra backscatter that falsely would give too high wind speeds. The present wind farm at Horns Rev [5] (http://www.hornsrev.dk/) is located to the east and the prospect further west. Both are indicated in Fig. 1. Furthermore the wake area (i.e. the area downwind of the wind farm where the mean wind speed is reduced and the turbulence intensity is increased) is deselected. Thus the mean wind speed map in Fig. 1 is produced as to represent an undisturbed situation.

The satellite SAR wind vector observations are compared to the in-situ wind vector data for all cases (56) collected prior to construction of the wind farm (before November 2001) [1]. For wind speed the bias is found to be –0.3 m s^{-1} and the standard error 1.3 m s^{-1}. For wind direction a bias of 5° and standard error 16° is found. Further analysis has revealed that the negative bias is pronounced for offshore flow whereas for onshore flow this is not the case (Hasager et al. submitted).

We present in Fig. 3 the variation from North to South as an average of the three vertical transects. In Fig. 4 the variation from West to East as an average of ten transects is shown. Mean wind speed, Weibull A and k, and number of samples are shown. Table 1 shows the mean, minimum and maximum for the four parameters for the transects.

Table 1. Wind statistics of mean, minimum and maximum for North to South (NS) and West to East (WE) average transect lines based on satellite SAR wind maps.

		Wind speed (m s^{-1})	**Weibull A (m s^{-1})**	**Weibull k**	**# Obs.**
Mean	NS	6.4	7.2	2.1	49
Min.	NS	6.0	6.7	1.8	28
Max.	NS	6.7	7.6	2.4	58
Mean	WE	6.6	7.4	2.1	37
Min.	WE	3.5	3.9	1.6	8
Max.	WE	7.2	8.1	2.4	46

4.2 Scatterometer

Quikscat monthly mean values from the North Sea are extracted for a five-year period. The spatial variation as an average from all years covering horizontal transects from South to North, and from East to West, are extracted. The location of the study area and positions of transects are plotted in Fig. 5. Fig. 6 and 7 shows the results for the South to North transect and the West to East wind speed transect values, respectively. The minimum value is found to be 8.16 m s^{-1} in the South to North transect, and 8.20 m s^{-1} in the West to East transect.

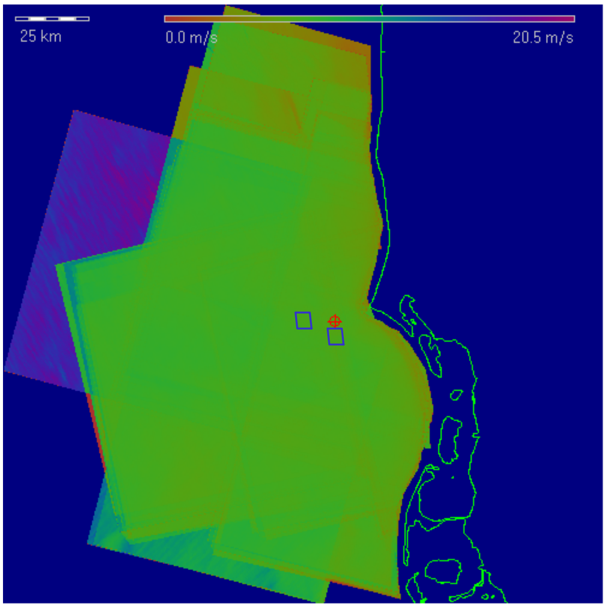

Fig. 1 Mean wind speed from 85 ERS-2 SAR satellite images near Horns Rev in the North Sea. Meteorological mast at red crosshair. Trapezoids with current (eastern) and prospected wind farm (western).

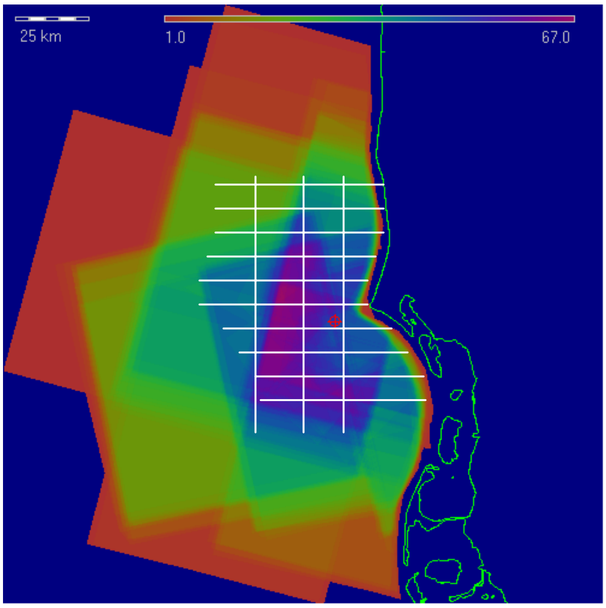

Fig. 2 Number of ERS-2 SAR satellite images. Location of the horizontal and vertical transects are indicated.

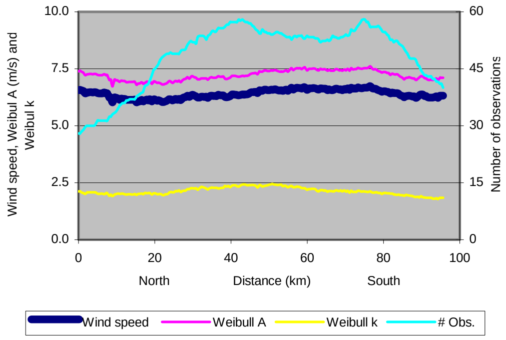

Fig. 3 Vertical transect of mean wind speed from North to South based on 85 ERS-2 SAR images.

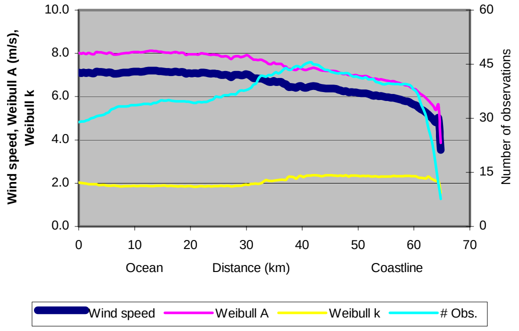

Fig. 4 Horizontal transect of mean wind speed from the ocean to the coastline based on 85 ERS-2 SAR images.

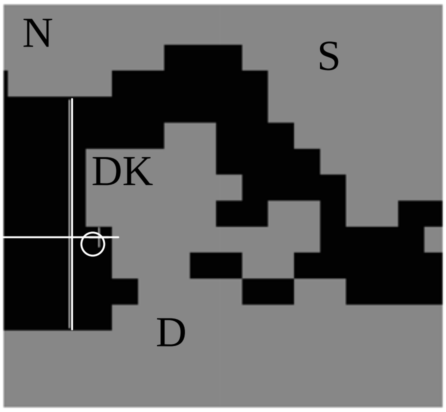

Fig. 5 Map of the eastern part of the North Sea with indication of the horizontal and vertical transects. Circle indicates the Horns Rev wind farm and meteorological mast. Country codes are included for Denmark, Sweden, Norway and Germany. Each grid cell is 50 km by 50 km.

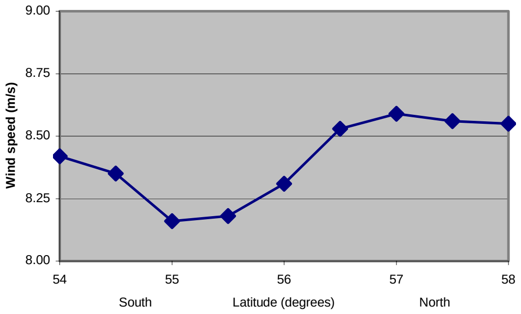

Fig. 6 Vertical transect of mean wind speed from South to North along longitude 7.5º East based on 5 years of gridded monthly Quikscat data from IFREMER/CERSAT.

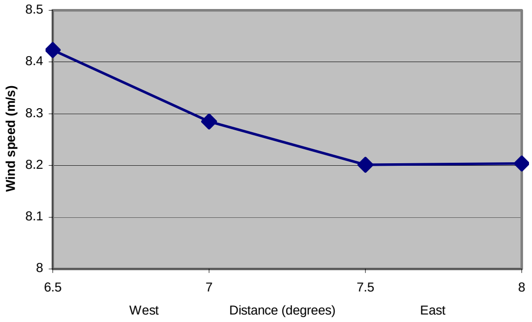

Fig. 7 Vertical transect of mean wind speed from West to East along latitude 55.5º North. Data source as above.

An example of seasonal and inter-annual wind speed variations over the ocean observed from Quikscat is given in Fig. 8. The data are from a grid cell near the wind farm. The distance to the wind farm is around 100 km but not very accurate as the grid cell is representative for a 50 km by 50 km area.

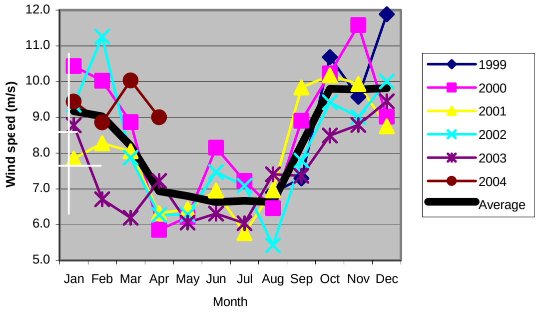

Fig. 8 Wind speed variation in the North Sea near Horns Rev for a five-year period observed as monthly

averages by Quikscat. Data from CERSAT/IFREMER.

5. DISCUSSION

Spatial gradients in the mean wind speed offshore is identified both a local scale from the satellite SAR images and at regional scale from Quikscat scatterometer data. It is well-known that the wind speed increases offshore. However offshore measurements from masts are sparse and the satellite-based wind maps provide new insight to the actual variations.

The SAR mean wind map shows lower values than the Quikscat wind observations. The maximum in SAR is found to be 7.2 m s^{-1} to the far west. The number of satellite images is around 30. It is possible to extend the horizontal transect further West however with increased uncertainty. There is not a physical overlap between the SAR wind map (Fig. 1 and 4) and the Quikscat data (Fig. 7). The vertical transects (North to South) are also placed far apart with the SAR-based wind data (Fig. 3) around 100 km to the East of Fig. 6. The vertical transect in Fig. 3 covers approximately two grid cells in Fig. 6. It is expected that the coastal mean wind speed mapped from satellite SAR is lower than the ocean wind mapped by scatterometer.

The number of satellite SAR images and the derived mean value of wind speed, Weibull A and k parameters can be seen to change simultaneously. It simply means that a few random satellite images and the derived wind statistics are closely connected. The Weibull A and k at Horns Rev at 10 m above sea level is 7.34 m s^{-1} and 2.3 measured from high quality in-situ observations [5]. This compares reasonably to the values in Fig. 3 and 4, and table 1.

The number of satellite SAR (here 85) and scatterometer (here 3500) is lower than a typical meteorological time-series (e.g. one year of hourly observations is 8760).

The low number of observations is the major limitation of satellite SAR. It means that temporal wind variation at seasonal or annual time-scales cannot be mapped, and the uncertainty estimates on Weibull A and k parameters are relatively high [3,4] .

An advantage of satellite SAR is the possibility to produce detailed coastal wind resource maps covering the exact area of interest for offshore wind farms, i.e. the zone between 2 and 30 km offshore in most cases. An example study based on ERS SAR including Horns Rev wind farm in Denmark and the prospected farm at Butendiek in Germany is made [9].

For scatterometer winds, the major limitation is lack of data in the zone of high interest for wind farms. This however, can be overcome using e.g. WASP to identify the change in wind climate as a function of the coastal form (orography and roughness) and distance between the scatterometer observations and the local area of interest. In other words, wind modelling is necessary.

An advantage of scatterometer wind observations is that some of these are collected every 12 hours globally during several years. From Quikscat there is an archive of 3600 wind maps freely available for further investigation. It means that seasonal and inter-annual variations can be identified. Comparison results between the Quikscat observations and data from the meteorological mast at monthly time-scale is promising [10].

The multi-temporal aspect is relevant for two reasons

- to identify if a certain one-year time-series is representative for a longer time period,
- to survey wind climate and power production in combination (wind-indexing).

The first issue is mainly of interest in the planning phase where the offshore wind resource has to be identified. Wind-indexing on the other hand, is of interest during operation of the wind farm.

6. OUTLOOK

Installed offshore wind power in Europe is ~600 MW of which ~400 MW are Danish wind farms. This makes the Danish seas an ideal study site. The satellite analysis will be broadened to the Danish Seas and will include also radar altimeter and passive microwave ocean winds observations. Furthermore the analysis will go into detail in both space and time investigating e.g. the effect of satellite sampling times (around 11.30 and 21.30 local time) for a series of offshore and coastal areas in Denmark.

Methods on kriging wind speed in the Quikscat morning and evening pass images will be pursued prior to advanced Weibull fitting methods [2] is applied to the constrained data set. Constrains are that there are no values below 2 ms^{-1} and above certain thresholds (dependent upon the specific sensor and wind retrieval algorithm).

Quikscat wind products may become available also as 12.5 km by 12.5 km grid (pers. comm. Dr. Paul

Chang). This seems especially attractive for near-coastal investigation.

Finally wind retrieval from wide-swath products from Envisat ASAR [11] and possibly Radarsat [12] will be investigated. It is anticipated that the wind grid cell resolution is around 2.4 km by 2.4 km in Envisat. This compares to the multi-looking necessary in ERS-2 SAR to obtain near noise-free average wind speeds [1]. The advantages of ASAR wide-swath images are the following

- each image covers a 405 km broad swath,
- the images are more frequently recorded than e.g. ERS SAR.

The spatial resolution and coverage of Envisat wide-swath images is intermediate between Quikscat and ERS wind data. It is of major interest to search for an effective way of bridging the current gap. This hopefully will facilitate improved practical use of the large archives of ERS, Envisat, Quikscat, NSCAT and MIDORI data in wind energy studies in the future.

7. CONCLUSION

The study is preliminary. The important finding is the large spatial and temporal variations in the offshore wind climate in the North Sea. Verification to high-quality meteorological observations is crucial for further advances in understanding the satellite-based wind observations, and for turning the immense image data set into applied use in relation to wind power meteorology.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Hasager, C. B.; Dellwik, E.; Nielsen, M.; Furevik, B. Validation of ERS-2 SAR Offshore Wind-Speed Maps in the North Sea. International Journal of Remote Sens*ing* **2004,** *25,* 3817-3841.

2. Pryor, S. C.; Nielsen, M.; Barthelmie, R. J.; Mann, J. Can Satellite Sampling of Offshore Wind Speeds Realistically Represent Wind Speed Distributions? Part II Quantifying Uncertainties Associated With Sampling Strategy and Distribution Fitting Methods. *Journal of Applied Meteorology* **2004,** *43,* 739-750.

3. Barthelmie, R. J.; Pryor, S. C. Can Satellite Sampling of Offshore Wind Speeds Realistically Represent Wind Speed Distributions. *Journal of Applied Meteorology* **2003,** *42,* 83-94.

4. Hasager, C. B.; Nielsen, M.; Christiansen, M. B. RWT tool: offshore wind energy mapping from SAR. 2004. Proceedings from Envisat **2004** Symposium, Salzburg, 6-10 September 2004 (same issue).

5. Sommer, A. Offshore measurements of wind and waves at Horns Rev and Laesoe, Denmark. 65-79. **2003**. Athena. OWEMES 10-12 April 2003, Naples, Italy.

6. Furevik, B.; Espedal, H. Wind Energy Mapping Using SAR, Special Issue: Woman Sensing the World (WSW). *Canadian Journal of Remote Sensing* **2002,** *28,* 196-204.

7. Gerling, T. W. Structure of the Surface Wind Field From the SEASAT SAR. *Journal of Geophysical Research* **1986,** *91,* 2308-2320.

8. Stoffelen, A.; Anderson, D. L. T. Scatterometer Data Interpretation: Estimation and Validation of the Transfer Fuction CMOD4. *Journal of Geophysical Research* **1997,** *102,* 5767-5780.

9. Schneiderhan, T.; Schulz-Stellenfleth, J.; Horstmann, J.; Lehner, S. Intercomparison of two offshore windfarm sites using SAR data. 6. 2003. *Geophysical Research Abstracts.* EGU (European Geophysical Sciences General Assembly, Nice (FR), April-2003.

10. Hasager, C. B.; Barthelmie, R. J.; Christiansen, M. B.; Nielsen, M.; Pryor, S. C. Quantifying offshore wind resources from satellite wind maps: study area the North Sea. 2004. European Wind Energy Exhibition and Conference (EWEC) 2004, London (UK). Proceedings paper (accepted)

11. Kim, D.; Moon, W. M.; Nam, S. H. Evaluation of ENVISAT ASAR data for measurement of surface wind field over the Korean East coast. 2003. IEEE IGARSS. Proceedings paper.

12. Choisnard, J.; Bernier, M.; Lafrance, G. RADARSAT-1 SAR scenes for wind power mapping in coastal area: Gulf of St. Lawrence case. 2003. IEEE-IGARSS. Proceedings paper.