A CONCEPT FOR MEASURING THE SEA SURFACE WIND

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Summary. A conceptual approach for airborne weather radar functionality enhancement enabling its use for measuring the near-surface wind vector over water, in addition to its standard meteorological and navigation applications, has been proposed. The airborne weather radar operates in the ground-mapping mode in the range of high to medium incidence angles as a scatterometer. Using the aircraft rectilinear flight over the water surface, measuring geometry and geophysical model function, it has been shown that the near-surface wind speed and direction can be retrieved from the azimuth normalized radar cross-section data obtained from a scanning sector of up to ±100°. The efficiency and accuracy of the proposed wind vector measurement algorithm have been supported by computer simulation. Some limitations and recommendations to perform the measurements have also been considered.

Keywords: airborne weather radar; sea wind; algorithm

1. INTRODUCTION

Applications of modern radars are highly diverse, including air and terrestrial traffic control, radar astronomy, air-defense systems, antimissile systems, marine radars to locate landmarks and other ships, aircraft anti-collision systems, ocean surveillance systems, outer space surveillance and rendezvous systems, meteorological precipitation monitoring, altimetry and flight control systems, guided missile target locating systems, ground-penetrating radar for geological observations, and range-controlled radar for public health surveillance. High-tech radar systems are associated with digital signal processing, machine learning and are capable of extracting useful information from very high noise levels.

Radar placed on aircraft calls airborne radar. Modern airborne radars are integrated into appropriate avionics systems and provide observation, navigation, and avoidance [1]. Rapid development of radars leads not only to their integration but also to extension of their functionality and applicability [2].

Microwaves are widely used for various remote sensing applications including study and monitoring of the environment. One of such microwave applications is a remote sensing of water surface and wind over it. Near-surface wind measurements over sea are very important for navigation as well as for meteorology and operational oceanography.

On the global scale, the information about sea winds and waves, in general, can be obtained from a satellite using active microwave instruments: Scatterometer, Synthetic Aperture Radar (SAR) and Radar Altimeter. However, for local numerical weather and wave models the local data on wave height, wind speed and direction are required.

Wind and wave measuring by those remote sensing instruments is based on the features of microwave backscattering from the water surface. Scatterometer provides estimates of the near-surface wind vector because the normalized radar cross section (NRCS) of the water surface depends on the wind speeds and directions. The accuracy of the wind direction measurement is ± 20°, and the accuracy of the wind speed measurement is ± 2 m/s in the wind speed range 3 – 24 m/s.

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In order to retrieve the wind vector from NRCS measurements, the relationship between the NRCS and near-surface wind, called the “geophysical model function”, is applied. Scatterometer experiments have shown that the NRCS model function for medium incidence angles at appropriate transmit and received polarization (vertical or horizontal) can be represented by one of the widely used forms as following [3]

$$\sigma^{\circ}(U,\theta,\alpha)=A(U,\theta)+B(U,\theta)\cos\alpha+C(U,\theta)\cos(2\alpha), \tag{1}$$

where $A(U,\theta)$, $B(U,\theta)$ and $C(U,\theta)$ are the Fourier terms that depend on sea surface wind speed and incidence angle, $A(U,\theta)=a_0(\theta)U^{\gamma_0(\theta)}$, $B(U,\theta)=a_1(\theta)U^{\gamma_1(\theta)}$, and $C(U,\theta)=a_2(\theta)U^{\gamma_2(\theta)}$; $a_0(\theta)$, $a_1(\theta)$, $a_2(\theta)$, $\gamma_0(\theta)$, $\gamma_1(\theta)$ and $\gamma_2(\theta)$ are the coefficients dependent on the incidence angle.

The NRCS azimuth curve (1) has two maxima and two minima. Its principal maximum is located in the up-wind direction, the second maximum corresponds to the down-wind direction, and the two minima are in the cross-wind directions displaced slightly to the second maximum direction. With the increase of the incidence angle, the difference between the two maxima and the difference between the maxima and minima becomes so significant (especially at medium incidence angles) that this feature can be used for the retrieval of the wind direction over water [4].

Generally, the problem of estimating the navigational direction of the sea surface wind ψ_w consists in defining the principal maximum of a curve of the reflected signal intensity (azimuth of the principal maximum of the NRCS curve $\psi_{\sigma^{\circ}_{\max}}$)

$$\psi_w=\psi_{\sigma^{\circ}_{\max}}\pm 180^{\circ}, \tag{2}$$

while the problem of deriving the sea surface wind speed consists in determination of a reflected signal intensity value from the up-wind direction or from some or all of the azimuth directions.

Airborne scatterometer wind measurements are typically performed at either the circle track flight for a scatterometer with an inclined one-beam fixed-position antenna or the rectilinear track flight for a scatterometer with a rotating antenna [5-7]. Unfortunately, a microwave narrow-beam antenna has considerable size at Ku-, X- and C-bands that makes its placing on an aircraft difficult. Therefore, use of the modified conventional navigation instruments of aircraft in a scatterometer mode seems to be the best way in that case.

From that point of view, a promising navigation instrument is the airborne weather radar (AWR). In this connection, a conceptual approach for a rectilinear track flight measuring the wind vector over sea by the AWR having a wide-size scanning sector and operating in the ground-mapping mode as a scatterometer, in addition to its standard application, is discussed in this paper.

2. AIRBORNE WEATHER RADAR FUNCTIONALITY

AWR is radar equipment mounted on aircraft for the purposes of weather observation and avoidance, finding the aircraft position relative to landmarks, and drift angle measurement [8]. The AWR is necessary equipment for any civil aircraft. It also must be installed on all airliners. Military transport aircrafts are usually equipped by weather radars too. Due to the specificity of airborne application, designers of avionics systems always try to use the most efficient progressive methods and reliable engineering solutions that provide flight safety and flight regularity in harsh environments [9].

AWR development is mainly associated with growing functionalities in the detection of different dangerous weather phenomena. The radar observations involved in a weather mode are magnitude detection of reflections from clouds and precipitation, and Doppler measurements of the motion of particles within a weather formation. Magnitude detection allows determination of particle type (rain, snow, hail, etc.) and precipitation rate. Doppler measurements can be performed to yield estimates of turbulence intensity and wind speed. Reliable determination of the presence and severity of the phenomena such as wind shear and microburst is an important area of study too [2].

The second assignment of the AWR is providing a pilot with reliable navigation information using surface mapping. In this case a possibility to extract some navigation information that allows determining the aircraft position with respect to a geographic map is very important for air navigation. Landmark's coordinates measured by the AWR relative to aircraft give a possibility to set flight computer for more exact and efficient en-route flight, cargo delivery, and cargo throw down to the given point. Altogether this improves tactical possibilities of transport aircraft, airplanes of search-and-rescue service, and local airways [9]. Other specific function of the AWR is the interaction with ground-based responder beacons. New functions of the AWR include detection and visualization of runways at approach landing as well as visualization of taxiways and obstacles on the taxiway at taxiing.

Certainly, not all of the mentioned functions are implemented in a particular airborne radar system. Nevertheless, the AWR is a multifunctional system that provides earth surface surveillance and weather observation. Usually, weather radar should at least be able to detect clouds and precipitation, select zones of meteorological danger, and show radar image of surface in the ground-mapping mode.

AWRs or multimode radars with a weather mode are usually nose mounted. Most AWRs operate in either X- or C-band [2]. Newer radars operate in the X-band to maximize radar reflectivity of weather formations, which is proportional to λ^{-4} (λ is the radar wavelength). At the same time, the long-range weather mode is provided in the X-band much better than in Ku-band. In the ground-mapping mode, the AWR antenna has a large cosecant-squared elevation beam. A horizontal dimension of the beam is narrow (2° to 6°) while the vertical dimension is relatively wide (10° to 30°). The beam sweeps in an azimuth sector (up to $\pm$ 100°) [2, 8, 9]. The scan plane is horizontal because the antenna is stabilized (roll-and-pitch-stabilized). Those AWR features allow enhancing its functionality to use the radar in the ground-mapping mode as a scatterometer for measuring the water surface backscattering signature and wind vector over the water surface.

3. SEA WIND RETRIEVAL

Depending on the AWR scanning features, three general cases may take place: a narrow scanning sector, a medium scanning sector, and a wide scanning sector (up to $\pm$ 100°). The latter case allows obtaining azimuth NRCS values from a sector of up to 200° width. NRCS values are sampled from significantly different azimuth directions that provide sufficient information for wind vector estimation, and thus such an AWR seems to be the most suitable airborne radar for measuring the wind speed and direction over water during a rectilinear flight.

Let an aircraft equipped with an AWR perform a horizontal rectilinear flight with the speed V at some altitude H above the mean sea surface. Let the AWR operate in the ground-mapping mode as a scatterometer, with the radar antenna having different beamwidth in the vertical $\theta_{a.v}$ and horizontal $\theta_{a.h}$ planes ($\theta_{a.v} > \theta_{a.h}$) as shown in Fig. 1, scan periodically through an azimuth in a sector wider than $\pm$ 90°, and a delay selection be used to provide a necessary resolution in the vertical plane. Then, the beam scanning allows selecting a power backscattered by the underlying surface for given incidence angle θ from various directions in a wide azimuth sector. Angular selection (by a narrow horizontal beamwidth) in the horizontal plane along with the delay selection provide angular resolutions in the azimuthal and vertical planes $\Delta\alpha_b$ and $\Delta\theta$, respectively.

Let the sea surface wind blow in direction ψ_w, and the angle between the up-wind direction and the aircraft course ψ be α. Let the NRCS model function for medium incidence angles be of the form (1). Since the selected cell is narrow enough in the vertical plane, the NRCS model function for medium incidence angles (1) can be used without any correction at wind measuring when the azimuth angular size of a cell is up to 15° – 20° [10].

As AWR beam scans periodically through an azimuth, the current NRCS value is obtained not from the same direction but from a narrow sector having the azimuth width of $\Delta\alpha_S$. NRCS samples obtained from the narrow sector and averaged over all measured values in that sector provide an appropriate NRCS value corresponding to the azimuth angle of the sector. The number of narrow sectors formed in the wide scanning sector equals $N = 180^{\circ} / \Delta\alpha_s + 1$. Thus, N NRCS values can be obtained from significantly different azimuth angles, and a system of N equations of form (1) can be written down.

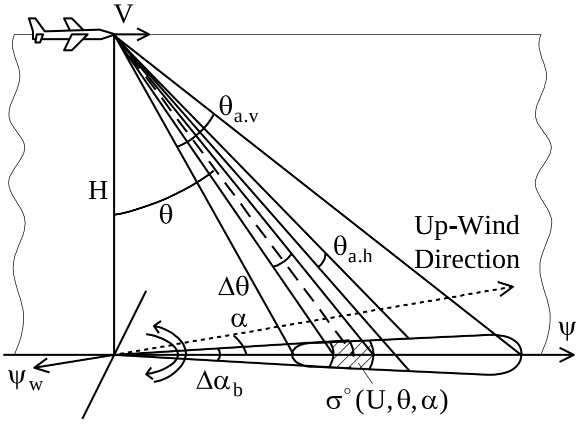

Figure 1 AWR ground looking scanning beam and selected cell geometry: $\sigma^{\circ}(U,\theta,\alpha)$ is the current NRCS value.

Let the width of the narrow sector be 5°. Then, the number of the narrow sectors is 37, and the following system of 37 equations can be written down

$$\begin{cases} \sigma^{\circ}(U,\theta,\alpha-90^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha-90^{\circ}) + C(U,\theta)\cos(2(\alpha-90^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha-85^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha-85^{\circ}) + C(U,\theta)\cos(2(\alpha-85^{\circ})), \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \sigma^{\circ}(U,\theta,\alpha-45^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha-45^{\circ}) + C(U,\theta)\cos(2(\alpha-45^{\circ})), \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \sigma^{\circ}(U,\theta,\alpha) = A(U,\theta) + B(U,\theta)\cos\alpha + C(U,\theta)\cos(2\alpha)), \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \sigma^{\circ}(U,\theta,\alpha+45^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha+45^{\circ}) + C(U,\theta)\cos(2(\alpha+45^{\circ})), \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \sigma^{\circ}(U,\theta,\alpha+85^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha+85^{\circ}) + C(U,\theta)\cos(2(\alpha+85^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha+90^{\circ}) = A(U,\theta) + B(U,\theta)\cos(\alpha+90^{\circ}) + C(U,\theta)\cos(2(\alpha+90^{\circ})), \end{cases} \tag{3}$$

where $\sigma^{\circ}(U,\theta,\alpha-90^{\circ})$, …, $\sigma^{\circ}(U,\theta,\alpha)$, …, and $\sigma^{\circ}(U,\theta,\alpha+90^{\circ})$ are the NRCS values obtained from the directions $\alpha-90^{\circ}$, …, α, …, and $\alpha+90^{\circ}$ respectively.

Then, to retrieve the wind speed and up-wind direction from the azimuth NRCS data set obtained the system of equations (3) should be solved approximately using searching procedure within the ranges of discrete values of possible solutions. Finally, the navigation wind direction can be found as following

$$\psi_w = \psi - \alpha \pm 180^{\circ}. \tag{4}$$

Wind measurement is started when a stable horizontal rectilinear flight at given altitude and speed of flight has been established. The measurement is finished when the required number of NRCS samples for each narrow azimuth sector observed is obtained. To obtain a greater number of NRCS samples for each direction observed several consecutive beam sweeps should be used.

To investigate capability of the proposed wind algorithm, a computer simulation of the wind vector retrieval has been performed. As coefficients for the X-band geophysical model function of the form (1) for the horizontal transmit and receive polarization were unavailable, the coefficients suggested in [11] for the neighboring Ku-band have been used. This substitution is supported by the review of NRCS values [5] indicting only modest differences between the X- and Ku-band backscatters. The incidence angle of 45° was considered at the simulation. The “measured” azimuth NRCS values were generated using the Rayleigh Power (Exponential) distribution.

Fig. 2 shows the azimuth NRCS curve by model (1) at the given incidence angle, “true” wind speed of 10 m/s and “true” up-wind direction of 0° (solid trace) used for generation of the “measured” NRCSs. Dot trace in this figure presents “measured” NRCS after averaging of 315 NRSC samples in a five-degree azimuth sector. Using system of equations (3), the “measured” wind speed is 9.9557 m/s for the “true” wind speed of 10 m/s, and the “measured” up-wind direction is 357.1° for the “true” up-wind direction of 0° have been calculated from the azimuth sector of [0°, 180°]. Dash trace in Fig. 2 demonstrates retrieved azimuth NRCS curve corresponding to “measured” wind speed and up-wind direction in this case.

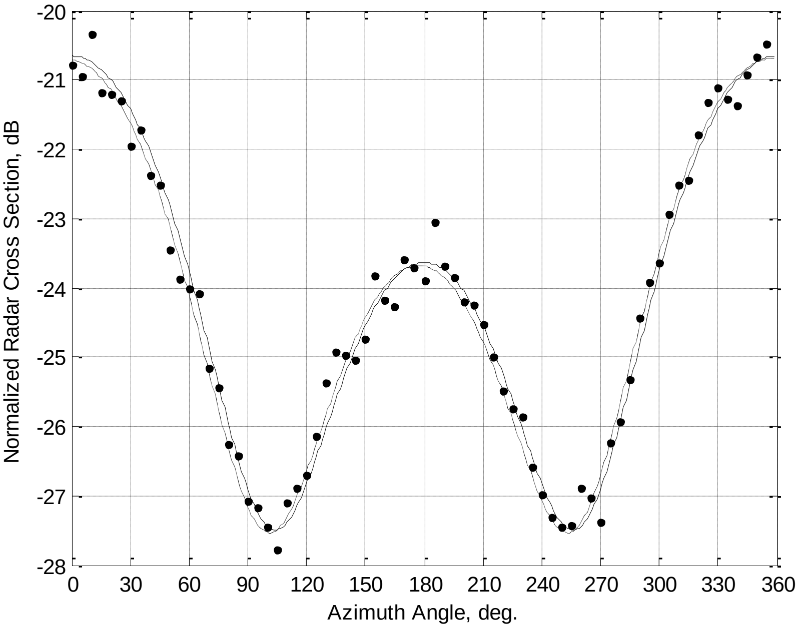

Figure 2 Azimuth NRCS curve by model (1) at “true” wind speed of 10 m/s and “true” up-wind direction of 0° (solid trace), “measured” NRCSs after averaging of 315 samples in a five-degree azimuth sector (dot trace), and retrieved azimuth NRCS curve by model (1) corresponding to the “measured” wind speed of 9.9557 m/s and up-wind direction of 357.1°, retrieved from the azimuth sector of [0°, 180°] (dash trace).

Thus, this example shows us clearly the feasibility of the algorithm proposed. Other simulation results, not presented here, have shown the wind speed deviation of ± 0.2 m/s and the direction deviation of ± 5° for the wind speed range from 3 to 20 m/s, which are within the typical accuracy of the scatterometer.

In the case of the wind measurement over water, the range of incidence angles observed by the AWR in the ground-mapping mode should be widen from high to medium incidence angles for the better use of anisotropic properties of scattering from the water surface at medium incidence angles [4] as well as for power reasons [8]. For the water surface, the NRCS falls radically as the incidence angle increases, assuming different values for different conditions of sea state or water roughness, while for most other types of terrain, the NRCS decreases slowly with increase of the beam incidence angle [2]. Otherwise, the incidence angle of selected sells should be in the range of validity of the NRCS model function (1), and should be out of the “shadow” region of water backscatter.

Assuming wind and wave conditions as identical in different parts of the observational area, the measurement swath width and length of the area observed should not exceed 15 – 20 km. Such a limitation of the observational area along with the AWR measurement geometry leads to the altitude limitations for the method’s applicability. The maximum altitude for a rectilinear flight will be about 10 km at the incidence angle of 45° and 5 km at the incidence angle of 60°, respectively.

5. CONCLUSION

AWR operating in a wide-size scanning sector and employed in the ground-mapping mode as a scatterometer can be used for remotely measuring the near-surface wind vector over water by the analysis of the azimuth NRCS data, in addition to its typical meteorological and navigation application.

The AWR wide scanning sector concept is more preferable in comparison with the medium sector or especially narrow sector, as it allows obtaining NRCS values from significantly different azimuth directions that provides more accurate wind vector estimation. Despite the fact that the AWR during rectilinear flight measurement dose not allows to obtain an entire 360° azimuth NRSC data set, like it is possible during a classical circular flight or during a two-stage rectilinear flight [12], it is much faster and convenient for a pilot at operational measurements or other special missions.

The proposed concept and principles considered in this paper could be used for the enhancement of the AWR, as well as for the development of an airborne radar system for operational measurement of the sea roughness characteristics and winds over water. They can be used not only for operational research but can also be applied for ensuring safe landing of seaplane or amphibious aircraft on water surface, especially during search-and-rescue missions or fire fighting in the coastal areas and fire risk regions complementing terrain avoidance system.

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References

[1] Collinson, R.P.G. *Introduction to avionics systems*. Dordrecht: Springer. 2006. 492 p.

[2] Kayton, M. - Fried, W.R. *Avionics navigation systems*. New York: John Wiley & Sons, USA. 1997. 773 p.

[3] Spencer, M.W. - Graf, J.E. The NASA scatterometer (NSCAT) mission. *Backscatter*. 1997. Vol. 8. No. 4. P. 18-24.

[4] Ulaby, F.T. - Moore, R.K. - Fung, A.K. *Microwave Remote Sensing: Active and Pasive*, Volume 2: *Radar Remote Sensing and Surface Scattering and Emission Theory*. London: Addison-Wesley, UK. 1982. 1064 p.

[5] Masuko, H. - Okamoto, K. - Shimada, M. - Niwa, S. Measurement of microwave backscattering signatures of the ocean surface using X band and Ka band airborne scatterometers. *Journal of Geophysical Research*. 1986. Vol. 91. No. C11. P. 13065-13083.

[6] Carswell, J.R. et al. Airborne scatterometers: Investigating ocean backscatter under low- and high-wind conditions. *Proceedings of the IEEE*. 1994. Vol. 82. No. 12. P. 1835-1860.

[7] Hildebrand, P.H. Estimation of sea-surface wind using backscatter cross-section measurements from airborne research weather radar. *IEEE Transactions on Geoscience and Remote Sensing*. 1994. Vol. 32. No. 1. P. 110-117.

[8] Sosnovsky, A.A. - Khaymovich, I.A. - Lutin, E.A. - Maximov I.B. *Aviation Radio Navigation*: *Handbook*. Moscow: Transport, USSR. 1990. 264 p., in Russian.

[9] Yanovsky, F.J. Evolution and prospects of airborne weather radar functionality and technology. In: Proceedings of ICECom 2005. Dubrovnik, Croatia, 2005. P. 349-352.

[10] Nekrassov, A. On airborne measurement of the sea surface wind vector by a scatterometer (altimeter) with a nadir-looking wide-beam antenna. *IEEE Transactions on Geoscience and Remote Sensing.* 2002. Vol. 40. No. 10. P. 2111-2116.

[11] Moore, R.K. - Fung, A.K. Radar determination of winds at sea. *Proceedings of the IEEE*. 1979. Vol. 67. No. 11. P. 1504-1521.

[12] Nekrasov, A. - Popov, D. A concept for measuring the water-surface backscattering signature by airborne weather radar. In: Proceedings of the 16th International Radar Symposium IRS 2015. Dresden, Germany, 2015. Vol. 2, P. 1112-1116.