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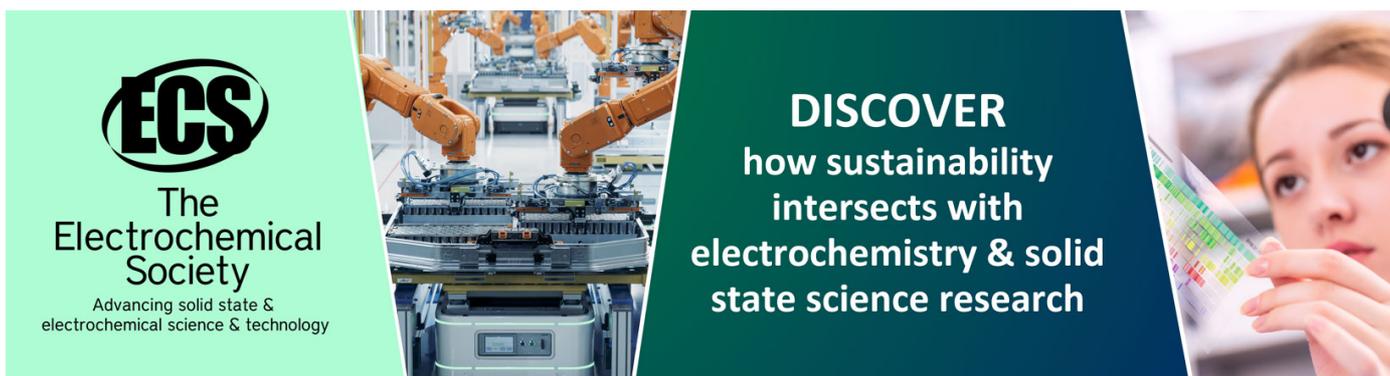
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# Sea wind parameters retrieval using Y-configured Doppler navigation system data. Performance and accuracy

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**Abstract.** The authors report the results of the computer simulations of the performance and accuracy of the sea wind speed and direction retrieval. The analyzed measurements over the sea surface are made by the airborne microwave Doppler navigation system (DNS) with three Y-configured beams operated as a scatterometer enhancing its functionality. Single- and double-stage wind measurement procedures are proposed and recommendations for their implementation are described.

## 1. Introduction

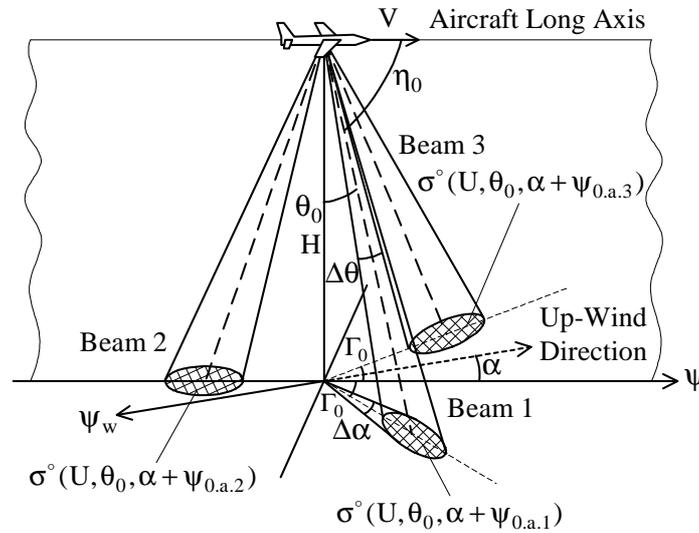
In avionics systems, one of the key problems is measuring a sea surface wind. It is desirable to integrate the remote sensing technique with the typical airborne instruments on board of the aircraft, such as the DNS.

Several design concepts of airborne accelerometers of the sea surface wind based on the physical models of backscattering from the sea surface have been recently suggested and evaluated by the authors in [1–3]. Here let us focus on the Y-beam configuration of the DNS and evaluate the accuracy of procedure for the wind retrieval over the water. The roll-and-pitch-stabilized antenna system provides stability of beams locations, which is significant for airborne scatterometers. At the same time, due to the specificity of the three-beam geometry of DNS, some disadvantages may be revealed at sea wind retrieval. The conceptual approach, measurement principle, recommendations and algorithm considered in this paper could be used for the functionality enhancement of the three-beam DNS.

## 2. Materials and methods

DNS is a self-contained radar system designed to provide the measurement of the aircraft ground speed and drift angle based on the Doppler principle and to perform the dead-reckoning navigation of aircraft. Modern standalone DNSs are the Ku-band radars. Three typical beam geometries can be realized for the DNS three beam antenna. The typical geometry of the DNS with three Y-configured beams is given in Figure 1.





**Figure 1.** The typical geometry of the DNS with three Y-configured beams.

The geometry is such that Beams 1 and 3 are forward-looking and pointed correspondingly to the right and left sides of the aircraft long axis. The mounting angle of the beam axis in horizontal plane  $\Gamma_0$  is typically between  $15^\circ$  and  $45^\circ$ . Beam 2 is after-looking with a  $0^\circ$  mounting angle of a beam axis in the horizontal plane. The beams are identical and the mounting angle for a beam axis in vertical plane  $\theta_0$  (typically between  $15^\circ$  and  $45^\circ$ ) is the same for all the beams. For Beams 1 and 3, the mounting angle of a beam axis in inclined plane  $\eta_0$  (nominal angle between antenna longitudinal axis and central beam direction) is between  $65^\circ$  and  $80^\circ$ . Effective antenna beamwidth  $\theta_a$  is between  $3^\circ$  and  $10^\circ$ . The angular resolutions provided in the azimuthal and vertical planes are  $\Delta\alpha$  and  $\Delta\theta$ , respectively. Thus, operating over the water, DNS can select the power reflected from the sea surface from three different azimuth directions relative to aircraft course  $\psi$  that can be used for sea-surface wind retrieval when DNS is working as a three-beam wind scatterometer.

Geophysical model functions that describe the backscatter from the sea/ocean surface are presented frequently in the following form [4]:

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

where  $\sigma^\circ(U, \theta, \alpha)$  is the normalized radar cross section (NRCS);  $A(U, \theta)$ ,  $B(U, \theta)$  and  $C(U, \theta)$  are the Fourier terms dependent on water-surface wind speed  $U$  and incidence angle  $\theta$ ,  $A(U, \theta) = a_0(\theta)U^{\gamma_0(\theta)}$ ,  $B(U, \theta) = a_1(\theta)U^{\gamma_1(\theta)}$ , 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, radar wave length, and polarization;  $\alpha$  is the azimuth illumination angle relative to the up-wind direction. The key feature of Equation (1) is that, if three or more NRCSs are obtained from different directions with the equal azimuthal angle between the nearest directions (beams), the sum value of  $N$  NRCSs obtained will be equal to the product of  $N$  and  $A(U, \theta)$ , and so the wind speed could be easily found from  $A(U, \theta)$ .

Let the aircraft use DNS with a three-beam antenna that is physically stabilized to the local horizontal so that current beam incidence angle  $\theta$  remains essentially constant and equal to the beam mounting angle in vertical plane  $\theta_0$ . The aircraft performs a horizontal rectilinear flight with speed  $V$  at some altitude  $H$  above the mean sea surface, and aircraft course  $\psi$  is the same as its ground track. In that case,  $\psi_{0.a.1}$ ,  $\psi_{0.a.2}$ , and  $\psi_{0.a.3}$  are the directions of Beams 1, 2, and 3 relative to the aircraft course,  $\psi_{0.a.1} = \Gamma_0$ ,  $\psi_{0.a.2} = 180^\circ$ , and  $\psi_{0.a.3} = 360^\circ - \Gamma_0$ ; and so the NRCSs obtained with Beams 1, 2, and 3 are  $\sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.1})$ ,  $\sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.2})$ , and  $\sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.3})$ , respectively.

Assuming that the wind blows over the sea in direction  $\psi_w$ , the angle between the up-wind direction and aircraft course  $\psi$  is  $\alpha$ , and the geophysical model function used for the wind retrieval is in the form of Equation (1), the wind speed and up-wind direction can be evaluated from the system of three equations:

$$\begin{cases} \sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.1}) = A(U, \theta_0) + B(U, \theta_0)\cos(\alpha + \psi_{0.a.1}) + C(U, \theta_0)\cos(2(\alpha + \psi_{0.a.1})), \\ \sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.2}) = A(U, \theta_0) + B(U, \theta_0)\cos(\alpha + \psi_{0.a.2}) + C(U, \theta_0)\cos(2(\alpha + \psi_{0.a.2})), \\ \sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.3}) = A(U, \theta_0) + B(U, \theta_0)\cos(\alpha + \psi_{0.a.3}) + C(U, \theta_0)\cos(2(\alpha + \psi_{0.a.3})), \end{cases} \quad (2)$$

and then, the navigational direction of the sea wind can be found as:

$$\psi_w = \psi - \alpha \pm 180^\circ. \quad (3)$$

Hence, the problem of the sea-surface wind estimation by the three-beam DNS comes to the problem of the wind measurement by means of a three-beam scatterometer with the implementation of the appropriate scatterometer technology, including an internal calibration realized in scatterometers by coupling a small portion of a signal from the transmitter channel into the receiver channel.

Thus, the wind retrieval method considered in the manuscript consists in obtaining the required number of NRCS samples for each azimuthal direction observed by the DNS beams, search for the best coincidence of the integrated NRCS values with the geophysical model function (1) by solving the System of Equation (2) by the method of least squares to obtain the wind speed and up-wind direction, and then its recalculation into navigation wind direction with Equation (3).

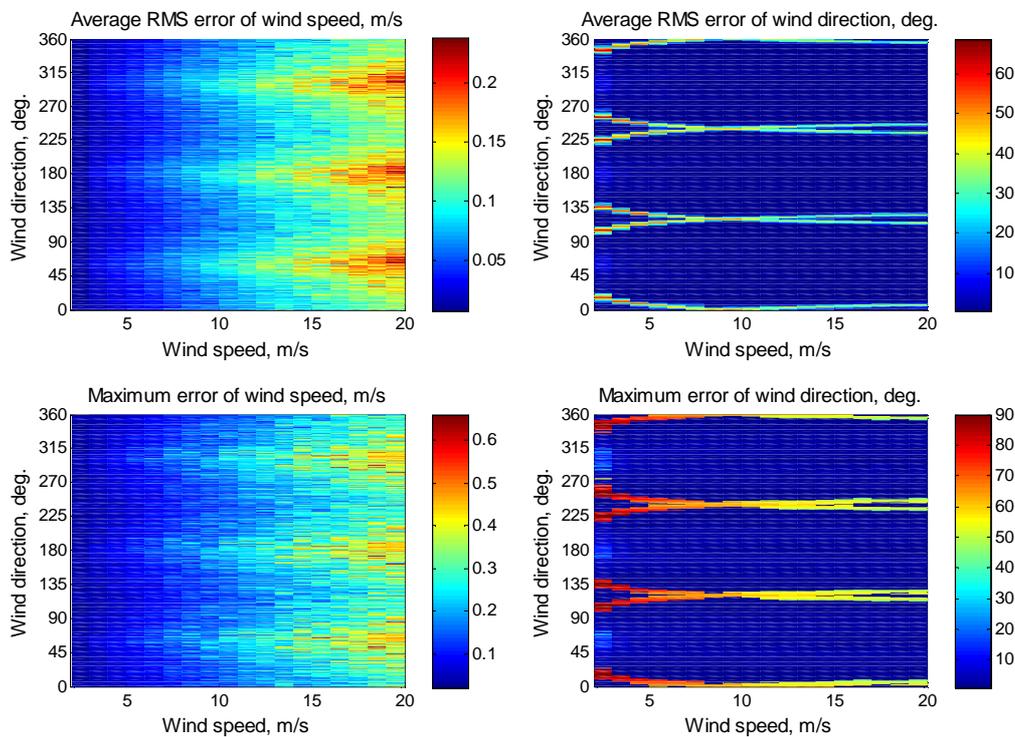
To investigate the sea-wind measurement applicability of the measuring geometry (Figure 1), a simulation for some particular locations of beams needs to be performed. For this purpose, the geophysical model function (1) from [4] for the horizontal transmitted polarization is used to obtain the ideal azimuthal NRCS curve. Then, a Rayleigh Power (Exponential) distribution is used to generate the “measured” azimuth NRCSs. Further, “measured” azimuth NRCSs are integrated and wind retrieval procedure described above is applied with the help of the Monte Carlo simulations with 50 trials at the wind speeds from 2 to 20 m/s. The simulation results are presented in the next section.

### 3. Results and discussion

First of all, the authors had evaluated Y-configured beams geometry for Beams 1, 2, and 3 with the directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course, respectively. This geometry is very convenient for a simple wind speed retrieval procedure using the following equation:

$$U = \left( \frac{A(U, \theta_0)}{a_0(\theta_0)} \right)^{\frac{1}{\gamma_0(\theta_0)}} = \left( \frac{\sum_{i=1}^N \sigma^\circ(U, \theta_0, \alpha + \psi_{0.a.i})}{Na_0(\theta_0)} \right)^{\frac{1}{\gamma_0(\theta_0)}}, \quad (4)$$

where  $i = \overline{1, N}$ ,  $N$  is the number of NRCS values obtained from different directions with the equal azimuthal angles between the nearest directions (beams),  $N \geq 3$ . In this case,  $N$  equals 3. Simulations had been performed for the incidence angles of  $45^\circ$  (the increased incidence angle providing better usage of the anisotropy of the microwave backscattering from the water surface). 1565 “measured” NRCS samples had been averaged for each azimuthal angle at the  $45^\circ$  incidence angle. The simulation results without instrumental noise and with the assumption of the additive instrumental noise had been obtained. A 0.2 dB instrumental noise had been considered at the incidence angle of  $45^\circ$  to analyses its influence on wind retrieval in spite of the fact that the 0.2 dB instrumental noise could lead to the wind speed retrieval error of 0.5 m/s only at a C band [5]. The results of the authors’ study are summed in Figures 2 and 3 that represent the average root-mean-square (RMS) and maximum errors of wind speed and direction retrieval for the wide ranges of simulated wind speed (from 2 m/s to 20 m/s) and azimuth angles (from  $0^\circ$  to  $359^\circ$ ).



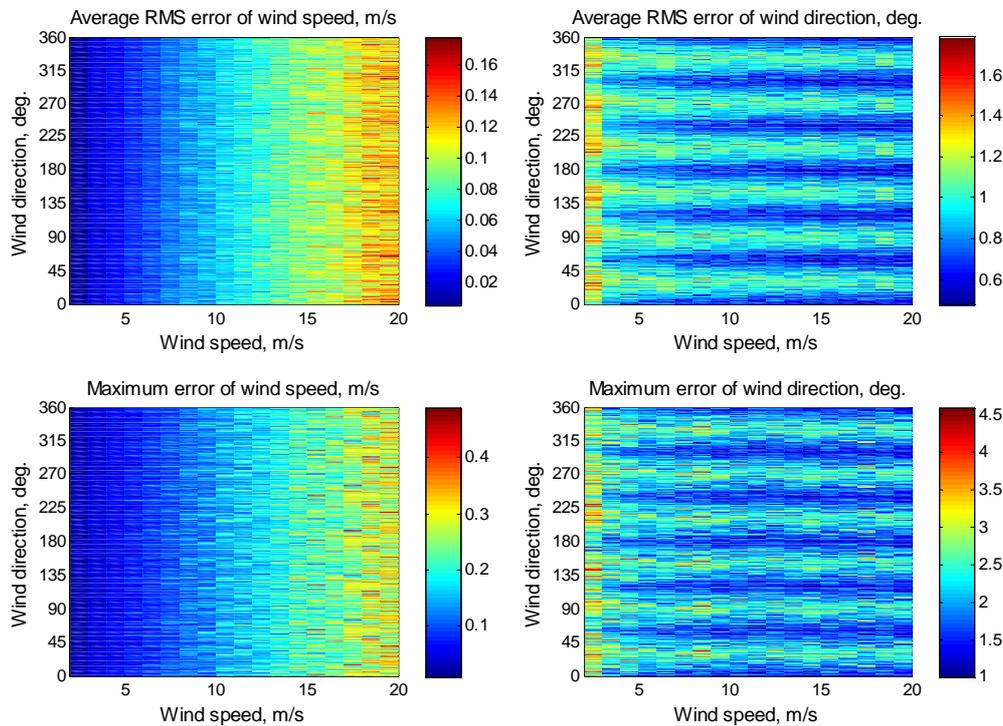
**Figure 2.** Simulation results for the three Y-configured beams geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course at the incidence angle of  $45^\circ$  with the assumption of 0.1 dB at the wind speeds of 2–20 m/s with 1565 averaged NRCS samples for each azimuthal angle.

The simulations for the three Y-configured beams geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course at the incidence angle of  $45^\circ$  had shown that the maximum errors of the wind speed and direction retrieval without instrumental noise are 0.65 m/s and  $90^\circ$ , and with assumption of 0.2 dB instrumental noise, they are 0.66 m/s and  $90^\circ$  (Figure 2).

The wind speed retrieval errors are within the range of typical errors of a scatterometer, and the wind direction retrieval errors exceed the typical errors of scatterometer measurements.

The simulations demonstrated that three beams are not enough for unambiguous retrieval of the wind direction in case of such scatterometer operated at the rectilinear flight during the single-stage measurement, and so a number of the observed directions (number of beams) need to be increased. One way is to use a four-beam scatterometer (DNS) [3]. Another way can be the application for a double-stage wind measurement procedure when NRCSs are obtained from the three azimuthal directions at the first stage and then from the three additional NRCSs for the other three azimuthal directions at the second stage, after the aircraft turn to an appropriate azimuthal angle. Thus, this two-stage measuring procedure allows obtaining NRCSs from six different azimuthal directions. In this case, the wind retrieval procedure is based on the system of equations similar to the System of Equations (2) but with six NRSC equations corresponding to six azimuthal directions observed. This double-stage wind retrieval procedure was also analyzed with the help of the simulations.

The simulations at a double-stage flight measurement for the three Y-configured beams geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course at the incidence angle of  $45^\circ$  with a  $60^\circ$  aircraft turn, the simulations had shown that the maximum errors of the wind speed and direction retrieval without instrumental noise are 0.48 m/s and  $4.4^\circ$ , and with assumption of 0.2 dB



**Figure 3.** Simulation results at a double-stage flight measurement for the three Y-configured beams geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course at the incidence angle of  $45^\circ$  with a  $60^\circ$  aircraft turn under the assumption of 0.1 dB at the wind speeds of 2–20 m/s with 1565 averaged NRCS samples for each azimuthal angle.

instrumental noise, they are 0.49 m/s and  $4.6^\circ$  (Figure 3). The errors are within the range of typical errors for the wind retrieval by a scatterometer.

These simulation results show clearly that airborne scatterometers having Y-configured beams geometries performing a double-stage flight wind measurement are feasible for estimation of the wind speed and direction, and so the DNS operating as a scatterometer with three Y-configured beams is also quite suitable for wind estimation over the sea.

Thus, a single-stage measurement results obtained at the sea-surface wind measurement by the airborne three-beam scatterometer (or DNS in a scatterometer mode), which have the three Y-configured beams geometry, can be refined with the help of the second stage of measurement when joint results from the first and the second stages are used for retrieval of the wind speed and direction.

In fact, the double-stage measurement with the three-beam scatterometer is equivalent to the single-stage measurement with a six-beam scatterometer that allows eliminating ambiguity in the wind direction recovery.

The sea wind measurement by the DNS should be completed in accordance with the following recommendations. The single-stage measurement begins after establishing the stable horizontal rectilinear flight at a given altitude and speed of flight. The measurement finishes after obtaining the required number of NRCS samples for each beam. If necessary, the measurement at the second stage is performed after an aircraft turned at an appropriate azimuthal angle and established again the stable horizontal rectilinear flight at a given altitude and speed of flight.

#### 4. Conclusion

The obtained results show clearly that airborne scatterometers with three Y-configured beams geometries are feasible to perform the sea-wind speed measurements at the rectilinear flight. The best

from the beams geometries considered is the geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course, which has the same azimuthal angle between the nearest beams. This configuration of beams provides the lowest maximum error of the wind speed retrieval. Also, the study has demonstrated that three beams may be not quite enough for the unambiguous retrieval of the wind direction in case of such airborne multibeam scatterometer during a single-stage measurement at the rectilinear flight.

In this connection, a double-stage wind measurement procedure when NRCSs is obtained from the three azimuthal directions at the first stage, and then, other three additional NRCSs are obtained from other three azimuthal directions at the second stage after aircraft turn at an appropriate azimuthal angle. All this can be efficient to decrease both wind direction and wind speed retrieval errors as a double-stage measuring procedure, which, in fact, allows obtaining NRCSs from six different azimuthal directions. In that case, the best from the geometries considered again is the geometry with the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course and a  $60^\circ$  angle of turn between the first and the second stage of measurement.

Regarding the three-beam DNS enhancement to perform the sea-wind measurements, a DNS with the stabilized three Y-configured beams antenna should also have the beam directions of  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  relative to the aircraft course, or to be close to that values. The horizontal transmitter and receiver polarization, providing the greater difference between the up-wind and down-wind NRCS values than the vertical transmitter and receiver polarization, and the internal calibration should be applied in the DNS to provide precise wind measurements in a scatterometer mode.

## 5. Acknowledgments

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