# On Measurement of the Sea Surface Wind Vector by the Airborne Weather Radars Having a Various Scanning Sector

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**Abstract:** A method for estimating the near-surface wind vector over water using the airborne weather radar in addition to its standard navigational application is discussed. A case of an airplane rectilinear flight over the water surface is considered. The radar operates in the ground-mapping mode in the range of middle incidence angles as a scatterometer. Wind vector is recovered from the azimuth normalized radar cross section data obtained from a scanning sector. Algorithms for extracting the wind speed and direction are proposed.

**Keywords:** Airborne weather radar, scatterometer, sea wind, algorithm.

## INTRODUCTION

Many researchers solve the problem of remote measuring of the wind vector over sea actively [1-8]. On the global scale, the information about sea waves and wind, in general, could be obtained from a satellite using active microwave instruments: Scatterometer, Synthetic Aperture Radar (SAR) and Radar Altimeter. However, for the local numerical weather and wave models as well as for a pilot on a seaplane having to make a landing decision, the local data about wave height, wind speed and direction are required.

Research on microwave backscatter by the water surface has shown that the use of a scatterometer also allows an estimation of the near-surface wind vector because the normalized radar cross section (NRCS) of the water surface depends on the wind speed and direction. Based on experimental data and scattering theory, a significant number of empirical and theoretical backscatter models and algorithms for estimation of a near-surface wind vector over water from satellite and airplane have been developed [9]. 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.

SAR provides an image of the roughness distribution on the sea surface with large dynamic range, high accuracy, and high resolution. Retrieval of wind information from SAR images provides a useful complement to support traditional wind observations [10]. Wind direction estimation amounts to measuring the orientation of boundary-layer rolls in the SAR image, which are often visible as image streaks. The sea surface wind direction (to within a 180° direction ambiguity) is assumed to lie essentially parallel to the roll or image-streak orientation. Wind speed estimation from SAR images is usually based on a scatterometer wind retrieval models. This approach requires a well-calibrated SAR image. The wind direction estimated from the European remote sensing satellites ERS-1, ERS-2, and ENVISAT SAR images is within a root mean square (RMS) error of about ±20° of in situ observations, which in turn results in an RMS wind speed error of about ±1.2 m/s [11-14].

The radar altimeter also provides the information on the sea wind speed, which can be determined from the intensity of the backscattered return pulse, and on the sea wave height, which can be deduced from the return pulse shape. At moderate winds (3-12 m/s), the wind speed can be measured by the altimeter with an accuracy of about ±2 m/s. The typical accuracy of radar altimeter measurements of the significant wave height is of the order of ±0.5 m (or 10 %, whichever is higher) for wave heights between 1 and 20 m [15]. Unfortunately, altimeter wind measurements yield wind velocity magnitude only, and do not provide information on wind direction.

To extract the wind vector from the 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 $\sigma^\circ(U,\theta,\alpha)$ for middle incidence angles is of the widely used form [16]

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

where $A(U,\theta)$, $B(U,\theta)$ and $C(U,\theta)$ are the Fourier terms that depend on sea 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 $C(U,\theta) = a_2(\theta)^{\gamma_2(\theta)}$; $a_0(\theta)$, $a_1(\theta)$, $a_2(\theta)$, $\gamma_0(\theta)$, $\gamma_1(\theta)$ and $\gamma_2(\theta)$ are the coefficients dependent on the incidence angle; $\alpha$ is the azimuth observation angle relative to the up-wind direction.

As we can see from (1), an NRCS azimuth curve has two maxima and two minima. The main maximum is located in the up-wind direction, the second maximum corresponds to the down-wind direction, and two minima are in cross-wind

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directions displaced slightly to the second maximum. With increase of the incidence angle, the difference between two maxima and the difference between maxima and minima become so significant (especially at middle incidence angles) that this feature can be used for retrieval of the wind direction over water [17].

In the general case, the problem of estimating the sea surface wind navigation direction $\psi_w$ consists in finding the azimuth of the principal maximum of a curve of the backscattered signal intensity (direction of the principal maximum of the NRCS relative to the north $\psi_{\sigma^\circ_{\max}}$)

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

and 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 a circle track flight using fixed fan-beam antenna or a rectilinear track flight using rotating antenna [5, 6, 8, 18]. Unfortunately, a microwave narrow-beam antenna has considerable size at Ku-, X- and C-bands that makes its placing on a flying apparatus difficult. Therefore, a better way needs to be found.

At least two ways can be proposed. The first way is to apply the airborne scatterometers with wide-beam antennas as it can lead to the reduction in the antenna size. The second way is to use the modified conventional navigation instruments of flying apparatus in a scatterometer mode.

From that point of view, a promising navigation instrument is the airborne weather radar (AWR). In this connection, the possibility of recovering the wind vector over sea by the AWR operating in the ground-mapping mode as a scatterometer, in addition to its standard navigation application, is discussed in this paper.

## MATERIAL AND METHODS

### Airborne Weather Radar

AWR is radar equipment mounted on an aircraft for purposes of weather observation and avoidance, aircraft position finding relative to landmarks, and drift angle measurement [19]. The AWR is necessary equipment for any civil airplane. It must be installed on all civil 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 [20].

The development of the AWR is mainly associated with growing functionalities on 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 made to yield estimates of turbulence intensity and wind speed. Reliable determination of the presence and severity of the phenomenon known as wind shear is an important area of study too [21].

Nevertheless, the second important assignment of the AWR is providing a pilot with navigation information using earth surface mapping. In this case a possibility to extract some navigation information that allows determining aircraft position with respect to a geographic map is very important for air navigation. Landmark's coordinates relative to the airplane that are measured by the airborne weather radar give a possibility to set flight computer for exacter and more efficient fulfillment of en-route flight, cargo delivery, and cargo throw down to the given point. These improve tactical possibilities of transport aircraft, airplanes of search-and-rescue service, and local airways [20].

Other specific function of the AWR is interaction with ground-based responder beacons. New functions of the AWR are 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 always is a multifunctional system that provides earth surface surveillance and weather observation. Usually, weather radar should at least enable to detect clouds and precipitation, select zones of meteorological danger, and show radar image of surface in the map mode.

AWR or multimode radars with a weather mode are usually nose mounted. Most AWR operate in either X- or C-band [21]. The $\lambda^{-4}$ dependence of weather formations on carrier wavelength $\lambda$ favours X-band radar for their detecting. At the same time, the X-band provides the performance of the long-range weather mode better than Ku-band. The AWR antenna, in the ground-mapping mode, has a large cosecant-squared elevation beam where horizontal dimension is narrow (2° to 6°) while the other is relatively broad (10° to 30°), and it sweeps in an azimuth sector (up to ± 100°) [21-23]. The scan plane is horizontal because of the antenna is stabilized (roll-and-pitch-stabilized). Those features allow supposing that the AWR in the ground-mapping mode can be also used as a scatterometer for the wind speed and direction retrieval over water.

### Wind Vector Recovering over Water Surface

#### *Narrow Scanning Sector Case*

At least three or four NRCS values obtained from considerably different azimuth directions may be quite enough to measure the wind vector over water by the scatterometer method [24]. As the AWR azimuth sector of scanning may be narrow, medium, or wide (up to ±100°), this feature should be taken into account under measuring algorithms developing.

Let a flying apparatus equipped with an AWR make a horizontal rectilinear flight with the speed $V$ at some altitude $H$ above the mean sea surface, the AWR operate in the ground-mapping mode as a scatterometer, the radar antenna have 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, 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

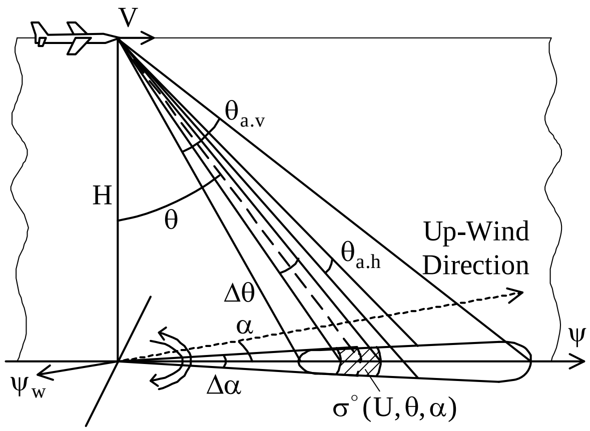


**Fig. (1).** Airborne weather radar beam and selected cell geometry.

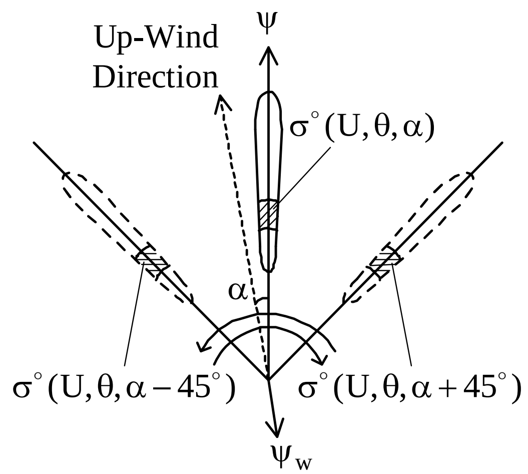


**Fig. (2).** Scanning beam footprints in a narrow sector and selected cells.

the underlying surface for given incidence angle $\theta$ from various directions in an azimuth sector. Angular (narrow horizontal beamwidth) selection in the horizontal plane along with the delay selection provide angular resolutions in the azimuthal and vertical planes, $\Delta\alpha$ and $\Delta\theta$ respectively.

Let the sea surface wind blow in direction $\psi_w$, and the angle between the up-wind direction and the aircraft course $\psi$ is $\alpha$. Let the NRCS model function for middle incident angles be of the form (1). In case of the selected cell is narrow enough in the vertical plane, the NRCS model function for middle incidence angles (1) can be used without any correction for wind measurement while the azimuth angular size of a cell is up to 15°-12° [25].

If the scanning sector is narrow but not narrower than ±45°, the NRCS values may be obtained from 3 directions $\alpha$–45°, $\alpha$, and $\alpha$+45° as shown in Fig. (**2**). The NRCS values are $\sigma°$ ($U$, $\theta$, $\alpha$–45°), $\sigma°$ ($U$, $\theta$, $\alpha$), and $\sigma°$ ($U$, $\theta$, $\alpha$+45°), respectively. Then, the following algorithm to estimate the wind vector over the sea surface can be proposed.

Using the measuring geometry, equation (1), and taking into account that the azimuth angular size of the selected sells are narrow enough, the following system of equations can be written down.

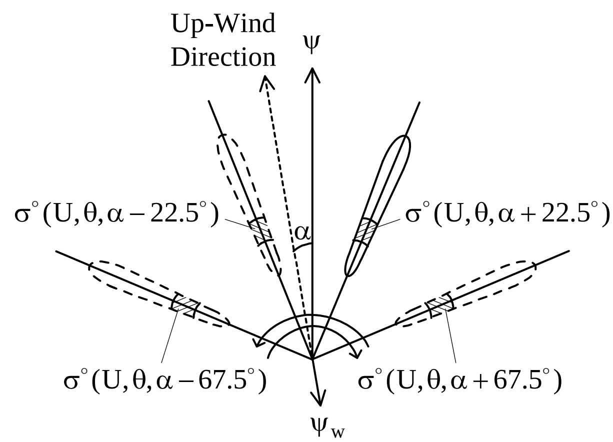


**Fig. (3).** Scanning beam footprints in a medium sector and selected cells.

The wind speed and up-wind direction are found by solving the following system of equations

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

approximately using searching procedure within the ranges of discrete values of possible solutions, or analytically.

From the sum of the first and the third equations of (3) we have

$$\cos\alpha = \frac{\sigma^\circ(U,\theta,\alpha-45^\circ) + \sigma^\circ(U,\theta,\alpha+45^\circ) - 2A(U,\theta)}{\sqrt{2}B(U,\theta)}. \tag{4}$$

Using (4) and the expression $\cos(2x) = 2\cos^2 x - 1$, the second equation of (3) can be represented in the following form

$$\sigma^\circ(U,\theta,\alpha) = \left(1-\sqrt{2}\right)A(U,\theta) +$$

$$\frac{1}{\sqrt{2}}\left(\sigma^\circ(U,\theta,\alpha-45^\circ) + \sigma^\circ(U,\theta,\alpha+45^\circ)\right) +$$

$$C(U,\theta)\left[\left(\frac{\sigma^\circ(U,\theta,\alpha-45^\circ) + \sigma^\circ(U,\theta,\alpha+45^\circ) - 2A(U,\theta)}{B(U,\theta)}\right)^2 - 1\right]. \tag{5}$$

The wind speed over water can be calculated from (5). Then, two possible up-wind directions relative the course of the flying apparatus can be found from (4). They are

$$\alpha_{1,2} = \pm\arccos\left(\frac{\sigma^\circ(U,\theta,\alpha-45^\circ) + \sigma^\circ(U,\theta,\alpha+45^\circ) - 2A(U,\theta)}{\sqrt{2}B(U,\theta)}\right). \tag{6}$$

The unique up-wind direction $\alpha$ relative the course can be found by substitution of the values $\alpha_1$ and $\alpha_2$ into the first and the third equation of the system of equations (5). Finally, the wind direction $\psi_w$ can be found

$$\psi_w = \psi - \alpha \pm 180^\circ. \tag{7}$$

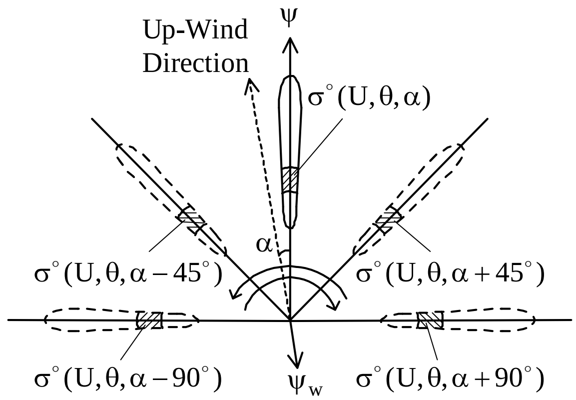


**Fig. (4).** Scanning beam footprints in a wide sector and selected cells.

### *Medium Scanning Sector Case*

When the scanning sector has the medium width that is narrower than ±90° but allowing to obtain the NRCS values from 4 directions, e.g. from α–67.5°, α–22.5°,α+22.5°, and α+67.5°, as shown in Fig. (**3**), which are σ° $(U,\theta,\alpha-67.5°)$, σ°$(U,\theta,\alpha-22.5°)$,σ°$(U,\theta,\alpha+22.5°)$,σ°$(U,\theta,\alpha+67.5°)$ respectively, another system of equations could be written down

$$\begin{cases} \sigma^{\circ}(U,\theta,\alpha-67.5^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha-67.5^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha-67.5^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha-22.5^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha-22.5^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha-22.5^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha-22.5^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha+22.5^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha+22.5^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha-67.5^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha+67.5^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha+67.5^{\circ})). \end{cases} \tag{8}$$

The system of equations (2) could be solved approximately using searching procedure within the ranges of discrete values of possible solutions. Then, the wind direction can be found from (7).

### *Wide Scanning Sector Case*

One more case takes place when the AWR beam scans periodically through an azimuth in a wide sector of ±90° or wider as shown in Fig. (**4**). I this case, the NRCS values could be obtained form 5 directions, namely from $\alpha$–90°, $\alpha$–45°, α, $\alpha$+45°, and $\alpha$+90°. They are σ°$(U,\theta,\alpha-90°)$σ°$(U,\theta,\alpha-45°)$,σ°$(U,\theta,\alpha)$,σ°$(U,\theta,\alpha+45°)$, and σ°$(U,\theta,\alpha+90°)$ respectively. Then, the following algorithm to estimate the wind vector over water can be proposed.

For that purpose the following system of equations should be solved [26]

$$\begin{cases} \sigma^{\circ}(U,\theta,\alpha-90^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha-90^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha-90^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha-45^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha-45^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha-45^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha) = A(U,\theta) + B(U,\theta)\cos\alpha + \\ \qquad C(U,\theta)\cos(2\alpha)), \\ \sigma^{\circ}(U,\theta,\alpha+45^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha+45^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha+45^{\circ})), \\ \sigma^{\circ}(U,\theta,\alpha+90^{\circ}) = A(U,\theta) + \\ \qquad B(U,\theta)\cos(\alpha+90^{\circ}) + \\ \qquad C(U,\theta)\cos(2(\alpha+90^{\circ})). \end{cases} \tag{9}$$

From the sum of the first and the fifth equations of (9) we have

$$\cos 2\alpha = \frac{\sigma^{\circ}(U,\theta,\alpha-90^{\circ}) + \sigma^{\circ}(U,\theta,\alpha+90^{\circ}) - 2A(U,\theta)}{2C(U,\theta)} \tag{10}$$

From the sum of the second and the fourth equations of (9) we obtain (4). Substitution of cos2α from (10) and cosα from (4) into the third equation of system (9) gives the following equation

$$A(U,\theta) = -\frac{1}{\sqrt{2}}\sigma^{\circ}(U,\theta,\alpha) +$$

$$\frac{1}{2}\left(\sigma^{\circ}(U,\theta,\alpha-45^{\circ}) + \sigma^{\circ}(U,\theta,\alpha+45^{\circ})\right) +$$

$$\frac{1}{2\sqrt{2}}\left(\sigma^{\circ}(U,\theta,\alpha-90^{\circ}) + \sigma^{\circ}(U,\theta,\alpha+90^{\circ})\right). \tag{11}$$

The wind speed over water can be calculated from (11). Then, two possible up-wind directions relative the course of the flying vehicle $\alpha_1$ and $\alpha_2$ can be found from (6). The unique up-wind direction α relative to the course can be found by substitution of the values $\alpha_1$ and $\alpha_2$ into the first and the fifth equations of the system of equations (9). Finally, the wind direction $\psi_w$ can be found form (7).

## RESULTS AND DISCUSSION

The analysis of the AWR, the backscatter model function and the geometry for wind vector estimation have shown that the wind vector over the sea can be measured by the AWR employed in the ground-mapping mode as a scatterometer scanning periodically through an azimuth in a sector in addition to its typical meteorological and navigation application.

Three main cases may take place depending on the AWR scanning features, namely a narrow scanning sector case (not narrower than ±45°), a medium scanning sector case (narrower than ±90° but wider than ±45°), and a wide scanning sector case (±90° or wider).

Depending on the scanning sector width the appropriate measuring geometry and algorithm should be used to obtain the NRCS data from all the possible width of a scanning sector. As an NRCS azimuth curve has two maxima and two minima, and at that the main maximum is in the up-wind direction, the second maximum is in the opposite (down-wind) direction, and both minima are in the cross-wind directions displaced slightly to the second maximum [17], the wide scanning sector of ±90° or wider is much preferable in comparison with medium and, especially, narrow one, as it allows to obtain more NRCS values from significantly different azimuth directions covering a half or more than a half the NRCS azimuth curve that provides better wind vector estimation.

AWR in the mode of the wind vector measurement should use the horizontal transmit and receive polarization as the difference in the up-wind and down-wind NRCS values at that polarization is greater than at the vertical transmit and receive polarization [1, 5, 17]. It also should provide the incidence angle of the selected sells $\theta \to 45^{\circ}$ that is explained by better usage of the anisotropic properties of the water surface scattering at middle incidence angles [17] as well as by power reasons. For the water surface, the NRCS falls radically as the incidence angle increases and assumes 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 [21]. Or, at least, the incidence angle of the selected sells should be in the range of validity for the NRCS model function, and should be out of the "shadow" region of the water backscatter.

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

## CONCLUSION

Thus, the AWR operating in the ground-mapping mode as a scatterometer scanning periodically through an azimuth in a sector is suitable for measuring the near-surface wind speed and direction over water in addition to its typical meteorological and navigation application.

The principle considered and algorithms proposed in the paper can be used for the AWR enhancement, for designing an airborne radar system for operational measurement of the sea roughness characteristics and for estimation of the wind speed and direction over water. They are also may be used for ensuring safe landing of seaplanes on the water surface under search and rescue missions or fire fighting in the coastal areas and fire risk regions.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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