# Determination of surface reflectivity using radio signals of opportunity

Alexander G. Voronovich and Valery U. Zavorotny

*Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder CO, U.S.A.*

A. G. Voronovich, 325 Broadway Ave., Boulder CO, 80305; tel. (303) 497-6464; Email address: Alexpander.Voronovich@noaa.gov (corresponding author)

V.U. Zavorotny, 325 Broadway Ave., Boulder CO, 80305; tel. (303) 497-6616; Email address: valery.Zavorotny@noaa.gov

# Determination of surface reflectivity using radio signals of opportunity

Use of a bistatic reflectometry technique which employs signals of the Global Navigation Satellite System (GNSS) scattered off the Earth surface opened new opportunities in the environmental remote sensing. At the same time, similar approach can be implemented with non-GNSS signals. Recently, it was demonstrated that other signals of opportunity can be used, such as produced by communication satellites in K-, X-, S- at VHF bands and even by the Sun. This paper presents a theoretical analysis of a possible use of a noise-like broadband radio signal emitted by a point source for measuring reflectivity properties of Earth's surface. We provide estimates which demonstrate the feasibility of measurements of the mean reflection coefficient for the case of a slightly rough, statistically homogeneous surface using signals of opportunity and receivers mounted on a moving platform. This would provide an opportunity to retrieve not only the parameters of the medium underlying the rough surface, but the RMS elevations of the roughness as well. Using an airborne receiver and a large variety of available sources of opportunity one can perform measurements of the parameters of soil moisture, snow, ice, etc.

Keywords: rough surface scattering; bistatic radar; signals of opportunity; soil moisture

## 1. Introduction

Remote sensing using radio signals of opportunity, called bistatic reflectometry, eliminates a necessity of carrying a transmitter on board of the receiving platform. Remote sensing techniques exploiting reflected GNSS signals has recently become available [1–4]. Soon, it was demonstrated that other signals of opportunity can be used for this purpose also, such as produced by communication satellites in K-, X-, S- at VHF bands [5–8] and even by the sun [9]. Usually, sun glints created by the Earth surface can be a nuisance for microwave radiometers used for soil moisture and ocean salinity measurements (see, e.g., [10–13]). However, someone's noise can be another person's signal. Using the Sun as a source of opportunity suggests an advantage of very broad selection of both carrier frequency and bandwidth, although man-made sources may provide more powerful signals (for instance, spectral density of the power flux of L1 GPS signal within its 2-MHz frequency band is 10 dB higher than the radiation at L-band by the calm Sun and about the same for the active Sun [14]). In this case, one has to take into account Sun's finite angular extent which impose some limitations on this technique.

Generally, a signal of opportunity arrives to a receiver located near the surface in two ways: as a direct signal propagating from the source, and via reflection/scattering off the surface. We will assume here that the signal frequency band is sufficiently large, so the corresponding correlation time is smaller than the time lag between the direct and the reflected signals. This will insure that the correlated parts of those two signals do not overlap in time, so by correlating the received signal with itself (subjected to an appropriate time delay) will provide us with a correlation of the direct signal with a reflected one. In contrast to the well-established GNSS reflectometry technique [15] which is based on the Kirchhoff approximation for a description of the EM rough surface scattering, in this paper we consider the situation of a small Rayleigh parameter. If the signal carrier wavelength is large enough compared with the roughness height, it will cover a large variety of possible environmental scenarios. Here, we will limit ourselves by determining an average reflection coefficient, which is close to a Fresnel reflection coefficient slightly modified by roughness. The dependence of the average reflection coefficient on angle and frequency can be used for inferring parameters of the reflecting/scattering medium such as soil moisture, snow/ice thickness and structure.

## 2. Theoretical formulation

Consider a monochromatic scalar plane wave of a unit amplitude, frequency $\omega$, and with a horizontal projection $\vec{k}_0$ of wave vector, incident on the plane in average and generally rough steady surface. The amplitude of the total field $\tilde{\Psi}$ measured by a receiver located at a point $(\vec{r},z)$ reads:

$$\tilde{\Psi} = e^{i\vec{k}_0\vec{r}-iq_0 z} + q_0^{1/2}\int q_k^{-1/2} e^{i\vec{k}\vec{r}+iq_k z} S\left(\vec{k},\vec{k}_0\right) d\vec{k}\,, \quad (1)$$

where $S\left(\vec{k},\vec{k}_0\right)$ is a scattering amplitude of the plane wave with horizontal projection $\vec{k}_0$ of the wave vector into a plane wave with horizontal projection of the wave vector equal to $\vec{k}$ [16]. In equation (1), $q_0$ and $q_k$ are the vertical projections of the corresponding wave vector; the *z*-axis is directed upward, so that the incident wave propagates in the negative direction of the *z*-axis. The scalar $\tilde{\Psi}$ may represent an electromagnetic field of certain polarization. Let us assume that the incident plane waves are due to a distant point source, so that they all come from the same direction and have random, statistically stationary spectral amplitude $a(\omega)$:

$$\overline{a(\omega)a^*(\omega')} = I(\omega)\delta(\omega-\omega'). \quad (2)$$

The overbar in equation (2) represents an averaging over a source statistics which is equivalent to integration of the signal over a significantly large time *T*. The assumption of a point source here is an important issue because it warranties a complete spatial coherence of the signal required by the technique discussed below, even though the signal can be incoherent, or partially-incoherent. The assumption of a point source is legitimate for sources of opportunity such as GNSS and communication satellites. However, in the case of the Sun, its significant angular size ($\theta_S \sim 0.5°$) might produce a too small spatial radius of coherence which would render direct and reflected signals temporally incoherent due to their significant transverse separation. Indeed, using the Van Cittert-Zernike theorem one can estimate the spatial radius of coherence of the solar radiation at a specific wavelength $\lambda$ as

$$\rho_{coh} = \lambda / \theta_s.$$

For a platform at height $z$ above the ground, the limitation on the incidence angle $\theta_{\mathrm{inc}}$ would be

$$\sin\theta_{inc} < \rho_{coh} / 2h.$$

Estimates for $\lambda$ = 0.19 m (L1 band) and reasonable incidence angles less than 45° show that the coherence of the solar radiation between direct and reflected signals for reasonable incidence angles can be preserved only for relatively low $h$ < 15 m of the platform height. So, the discussed technique based on Sun reflections can be implemented only from low stationary receivers.

Let us also assume that the receiver passes the signal through a band-pass filter with width $\Omega$ centered at a frequency $\omega_0$ with a flat phase and the following Gaussian-shaped amplitude characteristics:

$$F(\omega) = \exp\left[-(\omega-\omega_0)^2 / 2\Omega^2\right] / \sqrt{I(\omega)}. \quad (3)$$

As a result, an expression for the signal received by an omnidirectional antenna reads:

$$\Psi(t) = \int d\omega F(\omega) a(\omega) e^{-i\omega t}\left[e^{i\vec{k}_0\vec{r}-iq_0 z} + q_0^{1/2}\int q_k^{-1/2} e^{i\vec{k}\vec{r}+iq_k z} S(\vec{k},\vec{k}_0) d\vec{k}\right]. \quad (4)$$

Then, the following expression for the normalized autocorrelation function of the received signal can be obtained:

$$\tilde{C}(\tau,\vec{r}) = \overline{\Psi^*(t-\tau)\Psi(t)} e^{i\omega_0\tau} / \sqrt{\pi}\Omega = \frac{1}{\sqrt{\pi}\Omega}\int d\omega e^{-i(\omega-\omega_0)\tau-(\omega-\omega_0)^2/\Omega^2}$$

$$\times\left[e^{i\vec{k}_0\vec{r}-iq_0 z} + q_0^{1/2}\int q_k^{-1/2} e^{i\vec{k}\vec{r}+iq_k z} S(\vec{k},\vec{k}_0) d\vec{k}\right]^*\left[e^{i\vec{k}_0\vec{r}-iq_0 z} + q_0^{1/2}\int q_k^{-1/2} e^{i\vec{k}\vec{r}+iq_k z} S(\vec{k},\vec{k}_0) d\vec{k}\right]. \quad (5)$$

Suppose the signal is acquired by a receiver installed on the platform moving along the $x$-axis; we will choose the coordinate system such that a cross-track coordinate of the receiver equals to zero: $y=0$. The correlation function $\tilde{C}(\tau,\vec{r})$ is a random function of the coordinates due to a spatial variability of the roughness. To partially suppress such variations of $\tilde{C}(\tau,\vec{r})$ during measurements, it should be integrated over some along-track distance *L* being larger than the characteristic spatial scale of $\tilde{C}(\tau,\vec{r})$:

$$C(\tau)=\frac{1}{L}\int_{-L/2}^{L/2}\widehat{C}(\tau,x,y=0)\,dx. \tag{6}$$

The value of $C(\tau)$ can be measured experimentally. However, it still experiences residual variations due to a finite value of *L*. Let us average $C(\tau)$ with respect to spatial realizations of the rough surface and also calculate a variance of this estimate. When averaging in (5), one takes into account that due to assumed statistical homogeneity of roughness in the horizontal plane the following relations hold:

$$\left\langle S\left(\vec{k},\vec{k}_0\right)\right\rangle=\bar{V}_{\vec{k}_0}\delta\left(\vec{k}-\vec{k}_0\right), \tag{7}$$

$$\left\langle \Delta S^*\left(\vec{k},\vec{k}_0\right)\Delta S\left(\vec{k}',\vec{k}_0\right)\right\rangle=\sigma\left(\vec{k},\vec{k}_0\right)\delta\left(\vec{k}-\vec{k}'\right), \tag{8}$$

where

$$\Delta S\left(\vec{k},\vec{k}_0\right)=S\left(\vec{k},\vec{k}_0\right)-\left\langle S\left(\vec{k},\vec{k}_0\right)\right\rangle. \tag{9}$$

The brackets stand for averaging over the ensemble of realizations of the rough surface; $\bar{V}_{\vec{k}_0}$ is the mean reflection coefficient, and $\sigma\left(\vec{k},\vec{k}_0\right)$ is a scattering cross section of the rough surface. As a result of averaging over the surface statistics in equation (5) one finds:

$$\left\langle \tilde{C}(\tau,x)\right\rangle=\frac{1}{\sqrt{\pi}\Omega}\int d\omega e^{-i(\omega-\omega_0)\tau-(\omega-\omega_0)^2/\Omega^2}$$

$$\times\left[1+\left|\bar{V}_{\vec{k}_0}\right|^2+2\,\mathrm{Re}\left(e^{2iq_0z}\bar{V}_{\vec{k}_0}\right)+q_0\int\sigma\left(\vec{k},\vec{k}_0\right)\frac{d\vec{k}}{q_k}\right]. \tag{10}$$

The RHS of this equation does not depend on *x*, and averaging with respect to *x* according to (6) does not change the result: $\left\langle C(\tau)\right\rangle = \left\langle \tilde{C}(\tau,x)\right\rangle$.

Let us now perform integration in (10) over $\omega$. Note that the dependences on $\omega$ in $\left|\overline{V}_{\vec{k}_0}\right|^2$ and $\sigma\left(\vec{k},\vec{k}_0\right)$ are rather slow (do not include fast-oscillating terms). On the other hand, term $2\,\mathrm{Re}\left(e^{2iq_0 z}\overline{V}_{\vec{k}_0}\right)$ does include a fast-oscillating function. Assuming that bandwidth $\Omega \ll \omega_0$ is small enough, and using a linear approximation for $q_0$:

$$q_0 = \frac{\omega}{c}\cos\theta_0, \tag{11}$$

where $\theta_0$ is an incidence angle, one can calculate corresponding Gaussian integrals in (10) . As a result we arrive to:

$$\left\langle C(\tau)\right\rangle = \left[1 + \left|\overline{V}_{\vec{k}_0}\right|^2 + q_0 \int \sigma\left(\vec{k},\vec{k}_0\right)\frac{d\vec{k}}{q_k}\right]\exp\left(-\frac{\Omega^2\tau^2}{4}\right)$$

$$+\overline{V}_{\vec{k}_0} e^{2i\cos\theta_0\omega_0 z/c}\exp\left[-\frac{\Omega^2}{4}\left(\tau - 2\frac{z}{c}\cos\theta_0\right)^2\right] + \overline{V}^*_{\vec{k}_0} e^{-2i\cos\theta_0\omega_0 z/c}\exp\left[-\frac{\Omega^2}{4}\left(\tau + 2\frac{z}{c}\cos\theta_0\right)^2\right]. \tag{12}$$

If the receiver is located sufficiently far away from the surface, so that the following condition holds,

$$\Omega^2\left(\frac{z}{c}\cos\theta_0\right)^2 \gg 1, \tag{13}$$

the three terms in equation (12) do not overlap in time with a very high accuracy, and the function $\left\langle C\left(\pm 2\cos\theta_0 z/c\right)\right\rangle$ provides the value of the average reflection coefficient, $\overline{V}_{\vec{k}_0}$ . Assuming for an estimate that $\Omega = \left(\pi/\sqrt{2}\right)\cdot 10^6$ rad/s, one finds that the receiver height above the surface

$$z \gg \frac{c}{\sqrt{2}\Omega}\frac{1}{\cos\theta_0} \sim \frac{50\mathrm{m}}{\cos\theta_0} \tag{14}$$

would suffice to insure non-overlapping of the correlated parts of the direct and reflected signals. The physical meaning of equation (13) is a requirement that the receiver height $z$ should be large enough so that a portion of the direct signal with effective length $c/\Delta\omega$ does not overlap with the corresponding portion of the signal reflected from the surface.

### 3. Evaluation of signal-to-noise ratio

Let us now evaluate the variance of the estimate in equation (6) associated with finite values of the averaging distance *L* and the finite integration time *T*. As it is well known, signal-to-noise ratio, *SNR* due to the finite integration time is proportional to $\sqrt{\Omega T}$. Assuming for an estimate that $T = 1$ s and $\Omega = \left(\pi/\sqrt{2}\right)\cdot 10^6$ rad/s, one finds that in this case *SNR* is about 30 dB. Let us now evaluate the variance due to the finite averaging length *L*. Since the Rayleigh parameter is assumed to be small, we will neglect higher powers of $\Delta S$ in what follows. Then, one finds that

$$\Delta\tilde{C}(\tau,x,y=0) = \frac{q_0^{1/2}}{\pi^{1/2}\Omega}\int d\omega e^{-i(\omega-\omega_0)\tau-(\omega-\omega_0)^2/\Omega^2}$$

$$\times\left[\int q_k^{-1/2} e^{i\left(k_x-k_{0,x}\right)x+i(q_0+q_k)z}\Delta S\left(\vec{k},\vec{k}_0\right)d\vec{k}+c.c.\right]. \tag{15}$$

Integration over *x* gives:

$$\frac{1}{L}\int_{-L/2}^{L/2}\Delta\tilde{C}(\tau,x,0)dx = \frac{q_0^{1/2}}{\pi^{1/2}\Omega}\int d\omega e^{-i(\omega-\omega_0)\tau-(\omega-\omega_0)^2/\Omega^2}$$

$$\times\int q_k^{-1/2}\frac{\sin\left[\left(k_x-k_{0,x}\right)L/2\right]}{\left(k_x-k_{0,x}\right)L/2}\left[e^{i(q_0+q_k)z}\Delta S\left(\vec{k},\vec{k}_0\right)+c.c.\right]d\vec{k}. \tag{16}$$

Now we square and average the expression in equation (16) with respect to the realizations of the roughness, neglecting the dependence on frequency in all terms in the second integrand with the exception of $\exp\left[i\left(q_0+q_k\right)z\right]$. When averaging, we use a relationship:

$$\frac{1}{\pi L}\frac{\sin^2 L\xi}{\xi^2}\to\delta\left(\xi\right),\ L\to\infty. \tag{17}$$

As a result one finds:

$$\left\langle\left|\frac{1}{L}\int_{-L/2}^{L/2}\Delta\tilde{C}\left(\tau,x,0\right)dx\right|^2\right\rangle=\frac{2q_0}{L\Omega^2}\int\frac{d\vec{k}}{q_k}\sigma\left(\vec{k},\vec{k}_0\right)\delta\left(k_x-k_{0,x}\right)$$

$$\times\left|\int d\omega e^{-i(\omega-\omega_0)\tau-(\omega-\omega_0)^2/\Omega^2+i(q_0+q_k)z}\right|^2. \tag{18}$$

Thus, integration with respect to $x$ results in a suppression of all scattered signals except for those coming from a cross-range direction. We can integrate in equation (18) over $\omega$, taking into account that at fixed $\vec{k}$ for a sufficiently narrow bandwidth one can set

$$q_0+q_k\approx\frac{\omega_0}{c^2}\left(\frac{1}{q_0}+\frac{1}{q_k}\right)\left(\omega-\omega_0\right). \tag{19}$$

Integrating also over $k_x$, one obtains:

$$\left\langle\left|\frac{1}{L}\int_{-L/2}^{L/2}\Delta\tilde{C}\left(\tau,x,0\right)dx\right|^2\right\rangle$$

$$\approx\frac{2\pi q_0}{L}\int\frac{dk_y}{q_k}\sigma\left(k_{0,x},k_y,k_{0,x},k_{0,y}\right)\exp\left\{-\frac{\Omega^2}{2}\left[\tau-\left(\frac{1}{q_0}+\frac{1}{q_k}\right)\frac{\omega_0 z}{c^2}\right]^2\right\}. \tag{20}$$

A presence of the exponent in the integrand effectively limits the integration over $k_y$ by directions from which the incoming scattered signal has the delay time not exceeding $1/\Omega$. From equations (12) and (20) one finds the following expression for the inverse signal-to-noise ratio:

$$SNR^{-1} = \frac{1}{\left|\left\langle C(\tau)\right\rangle\right|}\left\langle\left|\frac{1}{L}\int_{-L/2}^{L/2}\Delta\tilde{C}(\tau,x,0)\,dx\right|^2\right\rangle^{1/2}\Bigg|_{\tau=2\frac{z}{c}\cos\theta_0}$$

$$= \frac{1}{\left|\overline{V}_{\vec{k}_0}\right|}\left\{\frac{2\pi q_0}{L}\int\frac{dk_y}{q_k}\sigma\left(k_{0,x},k_y,k_{0,x},0\right)\exp\left[-\frac{1}{2}\left(\frac{z\Omega}{c}\right)^2\left(\frac{\omega_0}{cq_k}-2\sin\theta_0\right)^2\right]\right\}^{1/2}. \qquad (21)$$

In the case of a small Rayleigh parameter one has:

$$\sigma\left(\vec{k},\vec{k}_0\right) = 4q_kq_0\left|B\left(\vec{k},\vec{k}_0\right)\right|^2 W\left(\vec{k}-\vec{k}_0\right), \qquad (22)$$

where $W$ is a spectrum of roughness with normalization

$$\int W\left(\vec{k}\right)d\vec{k} = \left\langle h^2\right\rangle,$$

where $\left\langle h^2\right\rangle$ is a variance of surface elevations. $B\left(\vec{k},\vec{k}_0\right)$ in equation (22) is a dimensionless coefficient which depends on boundary conditions and for electromagnetic waves, on polarization; for explicit expressions for $B\left(\vec{k},\vec{k}_0\right)$ see, e.g., [17]. For rough estimate one can replace $B\left(\vec{k},\vec{k}_0\right)$ in equation (22) by $B\left(\vec{k}_0,\vec{k}_0\right) = V_F\left(\vec{k}_0\right)$, where $V_F$ is a Fresnel reflection coefficient, and neglect the exponent in the integrand which leads to some underestimation of *SNR*. Now, equation (20) becomes:

$$\left(\frac{S}{N}\right)^{-1} \sim \frac{\omega_0}{c}\cos\theta_0\left|\frac{V_F\left(\vec{k}_0\right)}{\overline{V}\left(\vec{k}_0\right)}\right|\left(\frac{8\pi}{L}\right)^{1/2}\left(\int W\left(\vec{k}-\vec{k}_0\right)\Big|_{k_x=k_x^0}dk_y\right)^{1/2}. \qquad (23)$$

Consider the case of isotropic power spectrum of roughness:

$$W\left(\vec{k}\right) = \frac{n-2}{2\pi}\left\langle h^2\right\rangle\kappa_0^{-2}\begin{cases}\left(k/\kappa_0\right)^{-n}, & k>\kappa_0,\\ 0, & k<\kappa_0,\end{cases}$$

where $n > 2$ and $\kappa_0$ is an inverse correlation radius. One finds

$$\int W\left(\vec{k}-\vec{k}_0\right)\Big|_{k_x=k_x^0}dk_y = \frac{1}{\pi}\frac{n-2}{n-1}\left\langle h^2\right\rangle\kappa_0^{-1},$$

and equation (23) becomes:

$$\left(\frac{S}{N}\right)^{-1} \sim \left(8\frac{n-2}{n-1}\right)^{1/2} \left|\frac{V_F\left(\vec{k}_0\right)}{\overline{V}\left(\vec{k}_0\right)}\right| \frac{\frac{\omega_0}{c}\left\langle h^2\right\rangle^{1/2}\cos\theta_0}{\left(\kappa_0 L\right)^{1/2}}. \tag{24}$$

The nominator $R = \left(\omega_0/c\right)\left\langle h^2\right\rangle^{1/2}\cos\theta_0$ in equation (24) is the Rayleigh parameter and $\kappa_0 L$ in the denominator by the order of magnitude is, as expected, a total number of different realizations of the roughness within integration distance $L$. One can see that for sufficiently large $L$, the *SNR* can be made rather large, so the value of $\left|\overline{V}\left(\vec{k}_0\right)\right|$ can be measured with a high precision. With an increase of the Rayleigh parameter, $\overline{V}\left(\vec{k}_0\right)$ decreases; for rough estimate one can assume

$$\left|\frac{V_F\left(\vec{k}_0\right)}{\overline{V}\left(\vec{k}_0\right)}\right| \sim e^{2R^2}. \tag{25}$$

One can see that to have a sufficiently large *SNR*, the Rayleigh parameter $R$, in fact, is not required to be small; rather it should not be large, and the $R$ values of the order of one can also be allowed if the integration distance $L$ can be made large enough. So, these would increase a range of roughness heights available for this technique.

## 4. Conclusions

We have provided here some estimates which demonstrate the feasibility of measurements of the mean reflection coefficient $\overline{V}$ for the case of a slightly rough, statistically homogeneous medium using a noise-like signals of opportunity and receivers mounted on a moving platform. Measurements of $\overline{V}$ at a set of carrier frequencies $\omega_0$ provides an opportunity to retrieve not only the parameters of the medium underlying the rough surface, but the RMS elevations of the roughness as well. Flying an airborne receiver with a sufficiently wide band, in principle, one can perform measurements of the parameters of soil moisture, snow, ice, etc. in a fully passive regime using a large variety of available sources of opportunity.

## References


[1] Gleason, S., Lowe, S. and Zavorotny, V. 2009, *Remote Sensing with Bistatic GNSS Reflections*, In *GNSS Applications and Methods*, Gleason, S. and Gebre-Egziabher, D., Eds. (Artech House), 399–436.

[2] Larson, K. M., Small, E.E., Braun, J. J. and Zavorotny, V. U., 2014, Environmental sensing: A revolution in GNSS applications, *Inside GNSS*, **9**(4), 36–46.

[3] Zavorotny, V., Gleason, S., Cardellach, E. and Camps, A., 2014, Tutorial on remote sensing using GNSS bistatic radar of opportunity, *IEEE Geoscience and Remote Sensing Magazine*, **2**(4), 8–45.

[4] Ulaby, F. T. and Long, D. G., 2014, *Microwave Radar and Radiometric Remote Sensing,* (The University of Michigan Press), 664–669.

[5] Shah, R., Garrison, J. L. and Grant, M. S., 2012, Demonstration of bistatic radar for ocean remote sensing using communication satellite signals, *IEEE Geoscience and Remote Sensing Letters*, **9**(4), 619–623.

[6] Shah, R. and Garrison, J. L., 2014, Application of the ICF coherence time method for ocean remote sensing using digital communication satellite signals, *IEEE Journal of Selected. Topics in Applied Earth Observations and Remote Sensing*, **7**(5), 1584–1591.

[7] Garrison, J. L., 2014, Signals of opportunity airborne demonstrator (SoOp-AD), *Earth Science Technology Forum,* Leesburg, VA.

[8] Ribó, S., Arco, J. C., Oliveras, S., Cardellach, E., Rius, A. and Buck, C., 2014, Experimental results of an X-Band PARIS receiver using digital satellite TV opportunity signals scattered on the sea surface, *IEEE Transactions on Geoscience and Remote Sensing*, **52(**9), 5704–5711.

[9] Cardellach, E., Fabra, F., Rius, A., Pettinato, S., Macelloni, G. and D'Addio, S., 2012, Monitoring snow layers of the Antarctic ice-sheet using reflected signals: GNSS and the Sun as sources of opportunity, *Earth Observation and Cryosphere Science Conference*, Frascati, Italy.

[10] Yueh, S. H., West, R., Wilson, W. J. , Li, F. K., Njoku, E. G. and Samii, Y. R., 2001, Error sources and feasibility for microwave remote sensing of ocean surface salinity," *IEEE Transactions in Geoscience and Remote Sensing*, **39**(5), 1049–1060.
[11] Camps, A., Vall-llossera, M., Duffo, N. Zapata, M., Corbella, I., Torres, F. and Barrena, V., 2004, Sun effects in 2-D aperture synthesis radiometry imaging and their cancelation, *IEEE Transactions in Geoscience and Remote Sensing*, **42**(6), 1161–1167.
[12] Reul, N., Tenerelli, J., Chapron, B. and Waldteufel, P, 2007, Modeling Sun glitter at L-band for sea surface salinity remote sensing with SMOS," *IEEE Transactions in Geoscience and Remote Sensing*, **45**(7), 2073–2087.
[13] Dinnat, E. P. and Le Vine, D. M., 2008, Impact of sun glint on salinity remote sensing: An example with the Aquarius radiometer, *IEEE Transactions in Geoscience and Remote Sensing*, **45**(10), 3137–3150.
[14] *Handbook of Geophysics and the Space Environment*, 1985, 4th edn., Ed. Jursa, A. S. (Springfield, VA: Air Force Geophysics Laboratory, U.S. Air Force).
[15] Zavorotny, V. U. and Voronovich, A. G., 2000, Scattering of GPS signals from the ocean with wind remote sensing application, *IEEE Transactions in Geoscience and Remote Sensing*, **38**(2), 951–964.
[16] Voronovich, A. G., 1999, *Wave Scattering from Rough Surfaces,* 2nd edn., (Berlin: Springer).
[17] Voronovich, A. G. and Zavorotny, V. U., 2001, Theoretical model for scattering of radar signals in Ku- and C-bands from a rough sea surface with breaking waves," *Waves in Random Media*, **11**, 247 –269.