Sun Glint and Sea Surface Salinity Remote Sensing

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Popular Summary

A new mission in space, called Aquarius/SAC-D, is being built to measure the salinity of the world’s oceans. Salinity is an important parameter for understanding movement of the ocean water. This circulation results in the transportation of heat and is important for understanding climate and climate change. Measuring salinity from space requires precise instruments and a careful accounting for potential sources of error. One of these sources of error is radiation from the sun that is reflected from the ocean surface to the sensor in space. This paper examines this reflected radiation and presents an advanced model for describing this effect that includes the effects of ocean waves on the reflection.
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Sun Glint and Sea Surface Salinity Remote Sensing

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Abstract—The Aquarius/SAC-D mission will employ three L-band (1.41 GHz) radiometers dedicated to remote sensing of Sea Surface Salinity. The mission will be in a dawn/dusk sun-synchronous orbit with the beam oriented toward the night side of the orbit in order to limit interference from the Sun. In this manuscript, the influence of Sun radiation reflected at the Earth surface is examined for its dependence on the surface roughness. It is shown that the reflected Sun radiation can be separated into two components: (a) A quasi-specular component which has a large brightness temperature but is located far from the antenna boresight; and (b) A scattered component, due largely to small-scale roughness, which has relatively small brightness temperature, but can extend into the antenna boresight, where the gain is maximum, during some portion of the orbit at some times of the year. The latter component induces the largest (and the only critical) contamination of the measurements. It is shown that that significant contamination is possible at high latitude close to the summer solstice, when the antenna footprint is not in shadow.

Keywords-component; sea surface salinity, sun glint, L-band, Aquarius

I. INTRODUCTION

The Aquarius/SAC-D mission is dedicated to the remote sensing of Sea Surface Salinity (SSS) and is to be launched in 2009 [1]. An L-band (1.41 GHz) radiometer, with three beams pointing at 25.8°, 33.8° and 40.3° off the nadir (see Figure 1.), is the core instrument for retrieving SSS. The accuracy required on the radiometric measurements for retrieving SSS within the required 0.2 practical salinity unit (psu) is about 0.1 Kelvin (K). An important potential source of noise that could hinder this accuracy is the Sun. The Sun brightness temperature at L-band is three orders of magnitude larger than that of the ocean. It ranges mostly from 100,000 K to 500,000 K depending on the solar activity (see section II.C), whereas the ocean brightness temperature is in the range 70-110 K at the incidence angles of Aquarius. The approach followed to minimize the Sun contamination was to adopt a dusk/dawn (6 PM/AM ascending/descending equatorial crossing) sun-synchronous orbit, and to orient the antenna beams towards the night side of the Earth surface. Doing so, the Sun is in the direction of the antenna back lobes and the specular reflection of the Sun radiation does not come through the main beam. In addition, the Aquarius antennas have been specifically designed to offer a gain as low as possible in the direction of the direct and specularly reflected radiation. However, the ocean surface is rough and during certain seasons the footprint is not in shadow. Hence, the reflection is not truly specular and the possibility that scattered solar radiation can induce a significant signal requires investigation.

First, even in the ideal case where the Sun is oriented at a right angle with the Aquarius orbit plane, and therefore the antennas always point towards the night side, a significant part of earth visible to the antenna is on the day side. That means that Sun radiation scattered towards the antenna side-lobes can come from relatively large area if one accounts for the roughness of the ocean surface.
Yueh et al. made a preliminary study of the potential Sun glint contamination on an Aquarius-like radiometer [2]. Using simplifying hypothesis regarding the antenna gain and the scattering at the surface, they derived an order of magnitude for the maximum contamination of 0.1 K to 10 K, depending on the solar activity. However, these values were derived for a worst case scenario, where the antenna is pointing towards the day-side. It certainly shows that the Sun is a potential issue for L-band radiometry, and that pointing towards the Sun should be avoided. Unfortunately, it does not provide an estimate for the contamination in the realistic case of a night-side pointing mission like Aquarius/SAC-D. Le Vine et al. [3] account for the proper geometry for the mission and find a total contamination (i.e., direct and reflected rays from the Sun) up to 0.1 K. However, they assume specular reflection (smooth surface) and do not account for the presence of land surfaces in the antenna field of view (FOV). They also report the combined influence the direct and reflected ray which makes it hard to identify the sole contribution of the later. Finally, Reul et al. estimate the effect of the Sun on the Soil Moisture and Ocean Salinity (SMOS) mission [4], which is also an L-band radiometer, but with a very different geometry (orbit and antenna pointing direction) and technology. The SMOS instrument is a two dimensional interferometer used to produce images of the surface \( T_s \) of large spatial coverage (of the order of 1000 km), half of the image being over the day-side. The range of incidence angles of the measurements is also different than those of Aquarius. They find contaminations up to 50 K during the winter solstice at high latitudes of the southern hemisphere.

The objective of this study is to determine if Sun glint is an issue for remote sensing of SSS with a conventional radiometer and geometry such as will be flown on Aquarius. First the impact of various scales of surface roughness on the Sun radiation scattered toward the satellite is discussed to illustrate the circumstances under which the contamination can be significant. Then we derive estimates for the Sun glint contamination, and emphasize when in a year and where on the Earth surface the Sun is at an optimal position. In all cases, the direct ray from the Sun is very far from the boresight (more than \( 85^\circ \) off it) and it appears in the far sidelobes of the antenna pattern. The issue of the contamination by the direct Sun has already been discussed [3] and remains an antenna design issue that will not be addressed in this paper.

In the calculations reported here, the intersection of the antennas FOV's with the Earth surface (referred hereafter as the visible disk) is computed. The visible disk has a diameter of the order of 5000 km on the Earth surface. The illuminated area on the Earth surface is also computed from the position of the Sun, and the intersection between the visible disk and the illuminated area (referred hereafter as the illuminated FOV) is retained for the computations. The local incidence and azimuth angles for rays from the Sun and to the satellite are then computed for each point over the entire illuminated FOV. This is done at the angular resolution of the antenna pattern (see section I.1D). This provides the bistatic configuration for the incident and scattered radiations needed for computing the scattering intensities.

II. MODELLING INFLUENCE OF THE REFLECTED SUN ON THE MEASUREMENTS

A. Geometry of the Sun contamination

We use simulations of the Aquarius/SAC-D orbit (JPL, personal communication) to locate the satellite in the Earth Centered Inertial (ECI) coordinate system (epoch J2000) during the year 2009 at a time resolution of up to 1 seconds. We also calculate the Sun position in the ECI at the same times. Figure 2. shows the angle between the Sun direction and 1) the antenna boresight for the inner beam (the one pointing the closest to the Sun) and 2) the angular momentum vector of the satellite (\( \alpha \) angle in Figure 1.).
B. Surface reflectivity and antenna temperatures

In all the following, we assume homogeneous sea surface temperature (15°C) and salinity (35 psu). The influence of these parameters on the results is expected to be small because of their relative small influence on the reflection and scattering coefficients. We compute the antenna temperature induced by the Sun radiations after reflection from the Earth surface (referred hereafter as the Sun glint $T_a$) using three different hypotheses: (1) Assuming specular reflection (a smooth surface); (2) Using geometrical optics to compute the scattered radiation from a rough surface; and (3) Using a two-scale model to include the effect of small scale roughness. These various approaches allow us to understand how the various roughness scales influence the final results and their relative importance.

1) The specular model

![Figure 3](image)

Figure 3. geometry for the scattering at the surface. The satellite is at the location $S$ at an altitude $h$, above the Earth surface, the antenna beam points toward the left side at an angle $\alpha_s$ with respect to the nadir direction. Radiation is coming to the antenna from the location $P$ on the surface, after specular reflection (i.e. the local incidence angle $\theta_i$ is the same for the incoming and emerging radiation).

Specular reflection is assumed, obeying Fresnel’s laws in a plane tangent to the surface at the point of reflection. The Earth curvature is taken into account. There is at most one wavelength larger than $4h$ (i.e. 84 cm) and, therefore, a significant portion of the roughness scale is ignored. Contrary to the smooth surface, in this case any point on the illuminated surface can potentially reflect the Sun specularly towards the satellite if the tilt of the local surface due to the waves is in the proper direction. We first compute the tilting angles required to put the satellite and the Sun in a specular configuration for each location in the illuminated FOV. The tilting angles are then converted into so-called wave ‘specular’ slopes in the upwind ($S_u$) and crosswind ($S_c$) direction. The contribution of each location to the $T_a$ will then be weighted by the probability of occurrence of the wave with the specular slopes. To derive this probability, we assume that the probability density function (PDF) of the waves with slopes $S_u$ and $S_c$ is a zero-mean Gaussian function and is given by

$$P(S_u, S_c) = \frac{1}{2\pi \sigma_{S_u} \sigma_{S_c}} \exp \left\{-\frac{1}{2} \left( \frac{S_u}{\sigma_{S_u}} \right)^2 + \left( \frac{S_c}{\sigma_{S_c}} \right)^2 \right\}$$

where $\sigma_{S_u}$ and $\sigma_{S_c}$ are the RMS of the slopes of waves with a wavelength larger than $4\lambda$. The $T_a$ is then derived by integration of the weighted local reflectivity over the entire illuminated area:

$$T_a = \int_{\text{FOV}} G(\theta, \phi) R(\theta_i, \phi_i) T_o \Omega \frac{\sin \theta \sin \phi}{4\pi} d\theta d\phi$$

with the weighted local reflectivity

$$R^*(\theta_i, \phi_i) = R(\theta_i) \Omega C(\theta, \phi) J(\theta, \phi)$$

where $\theta$ and $\phi$ are the spherical coordinates of the specular point in the antenna reference frame, $G$ is the antenna gain in that direction and $R$ is the surface Fresnel reflection coefficient, at the local incidence angle $\theta_i$, $\Omega$, and $T_o$ the Sun solid angle (assumed to be conserved after reflection) and brightness temperature, respectively, and are discussed in section C. The local incidence angle at the surface of a radiation coming from the direction $(\theta, \phi)$ is given by (see Figure 3.)

$$\theta_i = \sin^{-1} \left( -\sin \alpha_s (R_{\theta_i} + h) / R_{\theta_0} \right)$$

with $h$, the altitude of the satellite, $R_{\theta_0}$ the radius of the Earth and the angle $\alpha_s$ between the incoming radiation and the nadir direction given by

$$\alpha_s = \pi - \cos^{-1} \left( \sin \theta \sin \phi \sin \alpha_{\theta_0} + \cos \theta \cos \alpha_{\theta_0} \right).$$

The angle $\alpha_{\theta_0}$ is the boresight elevation.

2) The geometric optics model

In this approach, a geometrical optics (GO) model is used to account for the tilting of the local surface due to the large-scale ocean waves. The model is valid only for waves with wavelength larger than $4h$ (i.e. 84 cm) and, therefore, a significant portion of the roughness scale is ignored. Contrary to the smooth surface, in this case any point on the illuminated surface can potentially reflect the Sun specularly towards the satellite if the tilt of the local surface due to the waves is in the proper direction. We first compute the tilting angles required to put the satellite and the Sun in a specular configuration for each location in the illuminated FOV. The tilting angles are then converted into so-called wave ‘specular’ slopes in the upwind ($S_u$) and crosswind ($S_c$) direction. The contribution of each location to the $T_a$ will then be weighted by the probability of occurrence of the wave with the specular slopes. To derive this probability, we assume that the probability density function (PDF) of the waves with slopes $S_u$ and $S_c$ is a zero-mean Gaussian function and is given by

$$P(S_u, S_c) = \frac{1}{2\pi \sigma_{S_u} \sigma_{S_c}} \exp \left\{-\frac{1}{2} \left( \frac{S_u}{\sigma_{S_u}} \right)^2 + \left( \frac{S_c}{\sigma_{S_c}} \right)^2 \right\}$$

where $\sigma_{S_u}$ and $\sigma_{S_c}$ are the RMS of the slopes of waves with a wavelength larger than $4\lambda$. The $T_a$ is then derived by integration of the weighted local reflectivity over the entire illuminated area:

$$T_a = \int_{\text{FOV}} G(\theta, \phi) R^*(\theta_i, \phi_i) T_o \Omega \frac{\sin \theta \sin \phi}{4\pi} d\theta d\phi$$

with the weighted local reflectivity

$$R^*(\theta_i, \phi_i) = R(\theta_i) \Omega C(\theta, \phi) J(\theta, \phi)$$

where $\theta$ and $\phi$ are the spherical coordinates of the specular point in the antenna reference frame, $G$ is the antenna gain in that direction and $R$ is the surface Fresnel reflection coefficient, at the local incidence angle $\theta_i$, $\Omega$, and $T_o$ the Sun solid angle (assumed to be conserved after reflection) and brightness temperature, respectively, and are discussed in section C. The local incidence angle at the surface of a radiation coming from the direction $(\theta, \phi)$ is given by (see Figure 3.)

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$$\alpha_s = \pi - \cos^{-1} \left( \sin \theta \sin \phi \sin \alpha_{\theta_0} + \cos \theta \cos \alpha_{\theta_0} \right).$$

The angle $\alpha_{\theta_0}$ is the boresight elevation.
where \( \theta_i \) is the local incidence of the satellite and the Sun with respect to the normal of the tilted surface, \( J(\theta, \phi) \) is the Jacobean determinant that converts the differential term \( \sin \theta d\theta d\phi \) into \( dS_x dS_c \) and \( \Omega_{\alpha}(S_x, \theta) = 1 - S_x / \tan(\theta_i) \) is the solid angle from the satellite for the wave of slope \( S_x \) in the satellite direction.

According to (4), the PDF is the largest at the specular point, where the slopes for the specular waves are zero. Therefore the weighting of the local reflection is also the largest at the specular point. The further from the specular point is a location in the illuminated FOV, the lower is the value of PDF at that point, and so is the weight for the reflected radiation. Basically, the glint that was concentrated in the close vicinity of the specular point direction when the surface was assumed to be smooth is now spread over a broader area with size determined by the slopes RMS but with an exponential decrease in intensity from the center to the edge of the Sun image. However, that does not mean that the local contribution to \( T_a \) given by the integrand in (5) necessarily decreases the same way as the PDF does, because the changes in \( \theta_i \) and the antenna gain will also modulate the contribution of the individual integration points.

3) The Two-scale model

To account for all the scales of ocean waves we use a two-scale model (TSM). In this approach [5] the scattering induced by the small scales is computed using the small perturbation method (SPM), and this is modulated by the tilting induced by the large-scales. The two-scale reflection coefficient \( I_{2s} \) to be applied to the Sun \( T_b \) before integrating over the illuminated FOV is then:

\[
T_a = \iint_{\text{FOV}} G(\theta, \phi) I_{2s} T_b \sin \theta d\theta d\phi
\]  

where the two-scale reflectivity is given by

\[
I_{2s} = \left[ \frac{\sigma^0(\theta_i^j, \phi_i^j; \theta_i^t, \phi_i^t)}{\cos \theta_i^t} \right] \Omega_{\alpha}(S_u, S_c, \theta) \frac{\Omega_{\alpha}}{4\pi} dS_u dS_c
\]

and results from the integral over the slopes PDF of the SPM scattering coefficients \( \sigma^0 \) for local incident \( (\theta_i^j, \phi_i^j) \) and scattered \( (\theta_i^t, \phi_i^t) \) directions [6] (here \( \sigma^0 \) is the sum of copol and crosspol term).

An example of scattering coefficients for the GO and TSM (i.e. \( R^2 \) and \( I_{2s} \) both normalized by \( 4\pi \cos \theta_i^t / \Omega_{\alpha} \) ) is reported in Figure 4. for a radiation incident at an angle \(-30^\circ\). Both models are relatively close around the specular reflection direction (i.e. radiation emerging at \(+30^\circ\)). Away from the specular direction, the GO model falls off rapidly whereas the TSM predicts significant scattering at large emerging angles, particularly in v-pol, because of the influence of the small-scale roughness. Scattering in h-pol falls much faster than in v-pol and is less than in v-pol, particularly at angles far from the specular direction.

C. The Sun Emission

![Sun effective brightness temperature derived from the flux measurements by the U.S. Air Force at noon time. Measurements were performed at various sites (reported by different line styles). The projected Aquarius/SAC-D operation time (May 2010-2013) is reported by the greyed area.](image)
Figure 6. Sun brightness temperature map (K) at 20 cm wavelength measured from the Very Large Array (S. White, personal communication) during a period of low solar activity (July 6th, 1996).

Emission from the Sun at L-band is complex, but reasonably well modeled as a thermal source [3][4]. Figure 5 shows the effective brightness temperature and its variation with the solar cycle derived from the solar flux measured at the U.S. Air Force Radio Solar Telescope Network (RSTN)[7][8]. Although the brightness temperature is not constant over the solar disc (Figure 6.), the solid angle subtended by the sun where $\alpha_0 = 0.3^\circ$ at L-band is small compared to the resolution of the Aquarius antenna. The Sun will be considered as an homogeneous source of solid angle $\Omega_0$.

The Sun effective $T_b$ exhibits large variations (Figure 5.) but is mostly between 100,000K and 500,000K. The variations follow a cycle of approximately 11 years and it is projected that Aquarius will operate near a period of maximum solar activity. Since we want to determine if the Sun glint is a potential issue, we choose $T_b = 5 \times 10^5$ K in order to provide a reasonable upper bound for the contamination.

D. The antenna gain patterns

We use patterns measured at approximately ten times the mission operating frequency using a scale model of the Aquarius/SAC-D satellite (JPL, personal communication). Given the polarimetric nature of the radiometers, there are 12 gain patterns. They consist of 4 complex parameters (amplitude and phase) for each of the three beams, namely the copol and crosspol for the v- and h-pol. They are sampled at 0.5° resolution in spherical coordinates $(\theta, \phi)$ (see also [9]).

Figure 7. shows the total gain (i.e. sum of the copol and crosspol gains) of the inner beam. It also illustrates the domain in which the Sun will be moving during one year of orbiting and shows that the Sun is located in relatively low gain areas, far from the boresight.

The scale model patterns are the latest and best estimates available of what will be those for the Aquarius antenna. They differ slightly from those obtained from simulations ignoring the platform that are reported in [9]. This is mentioned to emphasize that our results are necessarily sensitive to the accuracy of the patterns, and this issue will be discussed briefly in section III.B.

E. Surface spectrum

We use here the Durden and Vesecky [5] spectrum model, multiplied by a factor of two. The model was developed on a semi-empirical approach, using the theoretical form of Pierson and Moskowitz [10] for the large scales and a form compatible with the Philips [11] equilibrium spectrum and that allows deviation from it for the small scales. It was then adjusted, through parameters, to fit scatterometer data at 13.9 GHz, and to be compatible in order of magnitude with the slope variances estimated from visible measurement by Cox and Munk [12]. Yueh [6] suggested multiplying the spectrum by a factor of two to be in better agreement with SSMI measurement and a few studies suggested that the Cox and Munk slope variances may be underestimated due to the fact that their measurements did not account for all the roughness scales. This is the reason why Etcheto et al [13] include a version of this spectrum with the factor of two (in addition to the original one) when comparing radiometric measurements at L-band with $T_b$ simulation. They find no definitive conclusion on the spectrum models validity, due to the dispersion in the data, but they illustrate that the original model leads to noticeable underestimation of the signal, while including the factor of two leads to a reasonable agreement between the model and the data. As we want to derive an upper bound for the glint contamination, we choose to multiply the spectrum by a factor of two. But it should be noted that it could result in some overestimation of the Sun $T_a$.  

\[ \Omega_0 = 2\pi [1 - \cos \alpha_0] \]  

where $\alpha_0 = 0.3^\circ$ at L-band is small compared to the resolution of the Aquarius antenna. The Sun will be considered as an homogeneous source of solid angle $\Omega_0$. 

\[ \Omega_0 = 2\pi [1 - \cos \alpha_0] \]  

Figure 7. shows the total gain of the inner antenna (in dB) with superimposed, the limits of the Earth FOV (black circle), and the limits of the domains inside which the Sun and the specular point travel during one year (yellow and red ellipsoids respectively). The antenna boresight is the dark red area at the center of the figure.
A. Position and extent of the Sun image

Figure 8. illustrates the variability of the position of Sun image and its location with respect to the antenna boresight. The Sun image position is defined here as the position of the specular point (which in the case of the rough surface corresponds to the location of the image of the center of the Sun). One sees a seasonal cycle corresponding to the change in position of the Sun itself, with a large variability at the solstices and a small one at the equinoxes. The Sun image gets relatively closer to the boresight in the middle of summer, but overall, the position of the Sun image is reasonably far from the main beam (more than 71° off the boresight). However, contrary to the Sun itself, which has a small angular extend, its image can spread over large areas on the Earth surface when one takes into account surface roughness. This spreading can potentially bring some parts of the Sun image significantly closer to the main beam than the center of the image.

Figure 9. shows the equivalent brightness temperature at the surface of the Earth surface due to the Sun glint for one of the extreme configurations, a Sun elevation of 30°. The GO model (top) results in a large Sun image that fills a significant portion of the FOV. However, despite the fact that the edge of the Sun image gets relatively close to the antenna boresight (indicated by the red arrow), the main beam is over an area where the brightness temperature of the scattered radiation is less than 0.01 K. The areas of largest brightness temperatures (larger than 100 K) are located near the specular point and are in an area of very low antenna gain. The TSM results are significantly different. In this case, the largest Tb’s are still in the vicinity of the specular point, so still far from the main beam, where the antenna gain is low. But now, scatter from the surface under the boresight has a Tb close to 0.1 K, an order of magnitude larger.

B. Dependence on Wind Speed and Sun Elevation

Figure 10. and Figure 11. report the antenna temperature due to reflected (scattered) radiation from the Sun as a function of the Sun elevation (α in Figure 1.). Results are shown for each of the models assuming a homogeneous wind speed of 8 m/s at 10 m height (azimuthal variation is neglected). The results were obtained using the Aquarius orbit and running the computations for one year in order to include all sun angles. The surface was assumed to be all ocean (effect of land which modifies some cases is discussed in section III.C). Three very different situations can be identified. When the Sun elevation is
low (domain III on the figures), all models predict a very small Sun contribution (less than 0.02 K for all beams, both polarizations). When the Sun is high above the horizon, the glint contamination generally becomes much larger, and some large differences between the various models arise.

The results obtained using the GO and TSM exhibit a trend in elevation whereas the specular point model appears randomly variable. The GO and TSM treat the Sun image as an extended source, and thus they average the bumps and valleys of the antenna gain occurring with high spatial frequency in the sidelobes. Consequently, the contribution from the Sun image follows the large trends in the antenna gain: it increases when part of the Sun image is getting close to the main beam, and remains small otherwise. In contrast, the specular point model treats the Sun as a point source. The specular point never gets close to the main beam, but it moves significantly over bumps and valleys of the antenna back lobes (Figure 7.). Therefore, the contribution derived from this later model is very variable and not noticeably dependent on the Sun elevation, but is more directly related to what particular bump or valley in the gain faces the specular point.

The TSM predicts the largest \( T_a \) of the three models at both polarizations. With this model, scattering of the Sun radiation occurs at any location on the illuminated FOV, towards all directions. So when the Sun elevation is large enough (around 3.5° for the inner beam, of the order of 6° for the outmost beam, see Figure 13.), the illuminated area drifts towards the antenna boresight and some Sun radiation is scattered backward into the main beam. Even if a very small fraction of radiation is scattered (of the order of -20 dB), \( T_a \) and the antenna gain prove to be large enough to induce a significant contamination in v-pol. It is larger than the Aquarius goal of 0.05K contamination by the sun, during 8% of the time. The results for the v-pol (Figure 10.) are different from those of the h-pol (Figure 11.). As illustrated in Figure 4., when the emerging angle is far from the specular reflection angle, the scattering coefficients at h-pol are much less than those in v-pol. Consequently, the results in h-pol are more similar between all models than in v-pol which is dominated by the small-scale contribution. Note however that the TSM has been found to underestimate backscattering measurements in h-pol [14][15].

![Figure 10.](image1.png)  
Figure 10. inner beam Sun glint antenna temperature in vertical polarization versus the Sun elevation angle \( \alpha \). The vertical dashed line illustrates the different regimes (see text) related to the position of the illuminated area with respect to the main beam. The upper x-axis reports the cumulative percentage of Sun occurrence at a given elevation angle (eg. the Sun is 21.9% of the time at elevation larger than 10°). The wind speed is 8 m/s at 10 m height.

![Figure 11.](image2.png)  
Figure 11. same as Figure 10. for the horizontal polarization.

The GO and specular models predict similar order of magnitude, although the GO model estimate is usually less than that of the specular model, especially at very low elevations, when part of the Sun image created by the roughness is outside of the antenna FOV. The GO model is relatively accurate for predicting the Sun contribution when the latter is dominated by the area near the specular point, namely for low Sun elevation. However, when the illuminated area reaches high-gain regions (when antennas point to the illuminated side), this model dramatically underestimates the glint because of the absence of small-scale scattering.

Figure 12. compares the contribution to \( T_a \) from the main beam only and the entire FOV in the case of large elevation angles (where the contamination is largest) using the TSM. For
this purpose, the main beam is defined to be the part of the antenna pattern where the gain is not less than 30 dB of its value at boresight. In the case of the Aquarius antennas that corresponds to an aperture of +/- 10°, and accounts for more than 95% of the total power. As illustrated in Figure 12, at high elevation angles, most of the contamination of $T_a$ comes from to the main beam. The main beam corresponds to an area on the Earth surface with a diameter of the order of 600 km and an accurate correction for the contamination will require information about the surface conditions over this area centered in the direction of the boresight.

The dependence of the Sun glint $T_a$ on the azimuth angle depends on the model. The specular point model is as critically sensitive to the azimuth angle as it is to elevation angle (for the same reasons). The GO model is also sensitive to the azimuth, and the curves reported Figure 10 and Figure 11 would vary by up to ~ 0.01K when the Sun azimuth varies. However, this model always predicts a contamination largely less than 0.05 K, for any Sun azimuth angle. The TSM, which we consider to be the most realistic model, is insensitive to the Sun azimuth angle. First the extended image of the Sun tends to damp most of the azimuthal variations induced by the backlobes. Second, most of the signal actually comes from the main beam that is very azimuthally isotropic.

Figure 12. inner beam Sun glint antenna temperature in v-pol for a wind speed of 8 m/s at 10 m height. The $T_a$ is computed accounting for the whole antenna FOV (plain line) or the main beam only (dashed line)

Figure 13. Sun glint antenna temperature for the inner (plain line), middle (dashed line) and outer (dashed-dotted line) beams. Wind speed is 8 m/s at 10 m height. Black curves are for v-pol, grey ones are for h-pol.

Figure 14. inner beam Sun glint $T_a$ for the following wind speeds (at 10 m height), bottom to top: 0.7, 1, 3, 5, 7, 8, 10, 12 and 15 m/s. Black curves are for v-pol, grey ones are for h-pol.

Figure 14. illustrates the dependence of Sun contamination on wind speed. It shows that the three regime behavior is present at almost all wind speeds. Significant contamination (i.e. larger than 0.05 K) occurs at wind speeds as small as 5 m/s and contamination larger than 0.1 K occur for wind speeds that are not uncommon.

C. Global Results

The highest contamination occurs at high latitudes of the northern hemisphere during seasons when the sun angle is high. In such locations, it is very likely that significant portion of the antenna FOV will be over land/ice with much different scattering properties than ocean. In this section we account for the presence of land surface in the antenna FOV when computing the Sun glint $T_a$. 
In order to bound the problem, we assume that no reflection occurs on land surfaces and set the surface brightness temperature to zero for every pixel where land surface is present. For the reflectivity at the ocean pixels, we use the TSM and assume a homogeneous wind speed of 8 m/s. To locate the land surfaces, we use a landsea mask at 15 arcmin resolution (derived from the GTOPO 30 data). We focus here in the area and time where the contamination is considered significant enough to potentially hinder SSS retrieval. We set the threshold for this to be $T_{ss, max} = 0.05 K$, a value that translates roughly into 1 psu uncertainty. Figure 10. shows that $T_{ss, max}$ is reached or exceeded in v-pol at $U_{10} = 8$ m/s when the Sun elevation is larger than $-20^\circ$ and this happens only between April, 21 and August, 21 (Figure 2.) and only when the satellite is at the high latitudes of the northern hemisphere (not shown).

Figure 15. shows a 25 minute portion of an orbit over the northern hemisphere during one such period. The Sun glint $T_{s}$ for the three Aquarius beams are reported in Figure 16. as a function of distance along the track. The Sun glint $T_{s}$ is small when the FOV is dominated by land and varies a little bit over the ocean as the latitude changes. The transitions between land and ocean signal are very abrupt as they occur over very short distances. This is due to the fact that most of the signal comes from a limited area around the boresight (Figure 12.). That means that the modulation of the Sun glint $T_{s}$ by land will be small, and that the signal will be mostly driven by the Sun elevation and its brightness temperature. Notice two relatively large changes in the signal that occur at the locations identified by the diamond and circle in both Figure 15. and Figure 16. In these cases, the boresight does not encounter a transition land/ocean. The change in $T_{s}$ is due to the presence of a land/sea transition in the vicinity of the boresight, and is limited to a change of the order of 0.02 K.

Figure 15. tracks on the Earth surface of the inner (plain line), middle (dashed line) and outer (dashed-dotted line) beams on the 06/04/2009 between 01:46:50 and 02:12:20. The filled diamond and circle report the same two locations of interest as in Figure 16. that are discussed in the text.

Figure 16. Sun glint contamination for the inner (plain line), middle (dashed line) and outer (dashed-dotted line) in v-pol versus the distance along track. The tracks on Earth for the three beams are reported in Figure 15. The crosses X report the location where a transition between land and sea occurs. The filled diamond and circle report the same locations as on Figure 15. and are discussed in the text.

The Figure 17. reports the Sun glint $T_{s}$ averaged over one month for the mid- and high-latitudes of the northern hemisphere. The data includes all the three beams. The figures shows that no particularly large influence of land can be noticed at large distance from the coast. Some linear features in the map are due to the different sensitivity of the different beams to the Sun glint. Such stripping could also be present in the retrieved SSS. Finally, as expected from the Sun elevations reported in Figure 2., the month of June exhibits generally larger contamination than the month of May. Note that the month of July and August (not shown) exhibit patterns very similar as June and May respectively.
Figure 17. monthly average maps of the Sun glint in v-pol for (top) May and (bottom) June.

IV. CONCLUSIONS AND PERSPECTIVE

We show that the scattering of Sun radiation from the Earth surface has to be considered in order to account properly for the Sun contamination of the Aquarius measurements. The Sun contamination after reflection on the Earth surface is small, but not always negligible if one considers the demanding accuracy needed for salinity retrieval (e.g. 0.1 K). We find also that it is important to account for the small scale roughness which can significantly increase the potential for contamination. Contamination can noticeably exceed the budgeted value of 0.05 K when the bistatic scattering allowed by the rough nature of the ocean surface is included in the analysis. We show that most of the contamination is due to the scattering that reach antennas through the main beam when the footprint of the antennas is illuminated by the sun. Despite the fact that we have used hypotheses for a worst case scenario, and that large contamination may be rare, it will be necessary to correct for this effect at some times, at least partially. Since the surface roughness and the antenna gain will have to be very well known in the main beam direction independently of the Sun contamination issue, the constraint for an accurate Sun glint correction will be on the accuracy on the Sun brightness temperature. In the near future, the model presented here is to be included in the complete mission simulator that includes complex and realistic scenes for the Earth surface. We will also take into account the Sun brightness temperature variability. Future advanced simulations, including retrieval exercises, will allow us to develop mitigation or correction strategies. Similar techniques will be employed for addressing other potential source of contamination, like the Moon or the galaxy.

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