Effects of the Antenna Aperture on Remote Sensing of Sea Surface Salinity at L-Band

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***Abstract*—Remote sensing of sea surface salinity can be performed by means of microwave radiometry at L-band, but it requires high radiometric accuracy (e.g., on the order of 0.1 K). Since the variability of salinity in the open ocean exhibits large spatial scales and long temporal scales, it is possible to use antennas with large footprints and averaging to meet this goal. However, antennas with large footprints introduce other problems such as variations of the incidence angle and direction of the polarization vectors over the footprint. Examples of these effects are computed here using antennas that are representative of those that will be flown on the Aquarius/SAC-D mission being developed for remote sensing of salinity from space. It is shown that the antenna temperature (i.e., integrated over the antenna pattern) is biased relative to the value at boresight. In part, this is due to change in incidence angles across the field of view. Polarization mixing, because of the variations of the local plane of incidence across the footprint, also induces bias (peculiarly for the third Stokes parameter). Finally, large antenna footprints limit how close to land measurements can be made.**

***Index Terms*—Antenna radiation patterns, microwave radiometry, remote sensing, sea surface.**

I. Introduction

In 2009, NASA will launch the Aquarius/SAC-D satellite mission to measure the global sea surface salinity (SSS) field [1]. The primary instrument to measure salinity is an L-band (1413 MHz) radiometer, and the goal is to map the global SSS field monthly with an accuracy of 0.2 psu at 150-km spatial resolution. This is a challenging task as it corresponds to an accuracy on the order of 0.1 K on the retrieved brightness temperature and consequently puts very stringent requirements on instrument characteristics, including the antenna gain pattern.

Aquarius will look at the surface, with three beams pointing approximately perpendicular to the satellite track. Basic beam characteristics are reported in Table I. The footprint (corresponding to the half power beam width) is on the order of 100 km, but the portion of the Earth's surface contributing to the signal (i.e., seen by the antenna) has a diameter on the order of 5000 km. Most of this surface is in the antenna sidelobes, but the stringent measurement accuracy requires that such effects be included in the analysis.

TABLE I
Antenna Characteristics for the Three Beams. Beam-Pointing Angles α Are With Respect to the Satellite Nadir

beam:	inner	middle	outer
pointing angle, α (°)	25.8	33.8	40.3
local incidence angle θ_l (°)	28.7	37.9	45.5
gain at boresight (dB)	29.8	29.5	29.2
Half Power Beam Width (°)	6.1	6.2	6.4

For each of the three beams, we use realistic patterns for the Aquarius antenna system to calculate.

1) Variations over the footprint: The situation is illustrated in Fig. 1, which shows the antenna geometry. The local incidence angles (θ_l and θ_l') at points P and P' on the surface, respectively, differ in the two cases, as do vertical and horizontal polarizations (which are defined with respect to the direction of propagation and the local normals to surface $\overrightarrow{N_l}$ and $\overrightarrow{N_l'}$). Of course, polarization at the antenna is fixed by the mechanical orientation of the antenna (e.g., $\overrightarrow{X}$ and $\overrightarrow{Y}$). The variation of polarization and the fact that the emitted signal (brightness temperature) varies with the incidence angle can cause differences between the observed antenna temperature and that which would be observed with an ideal antenna (narrow beam at boresight). The consequences are discussed in Section IV-A; their sensitivity to the beam-pointing error is reported in Section IV-B.
2) Contamination by land: Broad antenna patterns and the need for high radiometric accuracy mean that any contamination by land, even in the antenna sidelobes, can be important. In Section V, calculations are made of the impact of land using the Aquarius antenna patterns and orbit as an example. Statistics are presented, indicating how close to the coast one is likely to be able to retrieve salinity with the desired accuracy.

Effects due to variations in SSS, sea surface temperature (SST), and other parameters for ocean, land, and atmosphere are not considered here (they are assumed homogeneous). A general introduction to the problem of antenna temperature biases can been found in [2], although quantitative results were reported only at 13 GHz for simplified patterns and a flat Earth surface. Land contamination was not assessed. A similar study for an L-band 2-D interferometer has been done by [3]; however, the

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instrumental techniques are very different from the one used on Aquarius.

II. Definition of the Antenna Temperature

The antenna temperature T_a is a measure of the power received by the antenna. It is the integral of power incident on the antenna weighted by the antenna gain pattern. The sources considered here are the ocean and land surfaces, the atmosphere, and the sky background (i.e., the cosmic background and galactic radiation).

The antenna temperature measured at the beam-pointing direction $(\theta_b = \pi - \alpha, \phi_b)$ is computed as

$$\overrightarrow{T_a}(\theta_b, \phi_b) = \frac{\int_\Omega \mathcal{M}_{\mathrm{ap}\to a} \cdot \overrightarrow{T_{\mathrm{ap}}} d\Omega}{\int_\Omega \mathcal{M}_{\mathrm{ap}\to a} d\Omega} \tag{1}$$

where Ω is the whole space around the antenna, $d\Omega = \sin\theta d\theta d\phi$, and explicit dependence on directions (θ, ϕ) for all the terms is omitted (see Fig. 1). $\mathcal{M}_{\mathrm{ap}\to a}$ accounts for the antenna gains and is given by (12) in the Appendix. Examples of the gain patterns are illustrated in Fig. 2. These are simulated patterns for the middle beam of the Aquarius offset feed parabolas. They were provided by the Aquarius antenna engineering team (J. Vacchione, personal communication) using modern numerical tools and the current Aquarius antenna design [1]. The apparent temperature T_{ap} is the power impinging on the antenna (i.e., before weighting by the antenna pattern), and is given by

$$\overrightarrow{T_{\mathrm{ap}}}(\theta, \phi) = \mathcal{M}_{b\to\mathrm{ap}} \cdot \left[T^{\uparrow}_{\mathrm{atm}} + \left(T^{\downarrow}_{\mathrm{atm}}\overrightarrow{R} + \overrightarrow{T_b}\right) e^{-\tau}\right]. \tag{2}$$

Matrix $\mathcal{M}_{b\to ap}$ [(13) in the Appendix] accounts for the change of polarization directions over the field of view (FOV) due to the variations of the local incidence plane. $\overrightarrow{T_b}$ is the surface brightness temperature (land or oceans), $T^{\uparrow}_{\mathrm{atm}}$ and $T^{\downarrow}_{\mathrm{atm}}$ are the upward and downward atmospheric brightness temperatures, respectively (see Section III-B), $\overrightarrow{R}$ is the surface reflectivity, and τ is the atmosphere optical thickness. The terms are computed at the local incidence angles θ'_l accounting for the change of incidence angle due to the surface curvature, i.e.,

$$\theta'_l = \sin^{-1}\left(-\sin\alpha'(R_{\mathrm{Earth}} + h_{\mathrm{sat}})/R_{\mathrm{Earth}}\right) \tag{3}$$

where α' is the angle from the satellite nadir and is given by

$$\alpha' = \pi - \mathrm{acos}(\sin\theta\sin\phi\sin\alpha + \cos\theta\cos\alpha). \tag{4}$$

The Earth radius is $R_{\mathrm{Earth}} = 6370$ km, and the satellite altitude is $h_{\mathrm{sat}} = 657$ km [1]. A spherical Earth is assumed, and the T_bs, R, and τ depend only on θ'_l.

The temperatures are 4-D modified Stokes vectors given by

$$\overrightarrow{T_a} = \begin{bmatrix} T_{a,X} \\ T_{a,Y} \\ T_{a,3} \\ T_{a,4} \end{bmatrix} \quad \overrightarrow{T_{\mathrm{ap}}} = \begin{bmatrix} T_{\mathrm{ap},\varepsilon_1} \\ T_{\mathrm{ap},\varepsilon_2} \\ T_{\mathrm{ap},3} \\ T_{\mathrm{ap},4} \end{bmatrix} \quad \overrightarrow{T_b} = \begin{bmatrix} T_{b,v} \\ T_{b,h} \\ T_{b,3} \\ T_{b,4} \end{bmatrix}.$$

The subscripts X and Y for the T_as refer to the antenna linear ports, with $\overrightarrow{Y}$ being in the incidence plane (i.e., aligned with ocean v-pol at boresight) and $\overrightarrow{X}$ being perpendicular to the incidence plane (i.e., aligned with h-pol). The subscripts ε_1 and ε_2 for the T_{ap}s refer to the co-pol and cross-pol vectors for the X- and Y- ports, according to the third definition of Ludwig [4] [see (5)–(7)]. Finally, v and h refer to vertical and horizontal polarizations, which are defined conventionally with respect to the local incidence plane and radiation propagation vector $\overrightarrow{k}$ according to

$$\overrightarrow{h} = \overrightarrow{k} \times \overrightarrow{N_l}$$
$$\overrightarrow{v} = \overrightarrow{h} \times \overrightarrow{k}$$

where $\overrightarrow{N_l}$ is the local Earth's surface normal.

The co-pol and cross-pol vectors for the X- and Y-ports are given by

$$\begin{aligned} X_{\parallel} &= \overrightarrow{\varepsilon_1} \\ X_{\times} &= \overrightarrow{\varepsilon_2} \\ Y_{\parallel} &= \overrightarrow{\varepsilon_2} \\ Y_{\times} &= \overrightarrow{\varepsilon_1} \end{aligned} \tag{5}$$

with

$$\begin{aligned} \overrightarrow{\varepsilon_1}(\theta, \phi) = &\left(1 + (\cos\theta - 1)\cos^2\phi\right)\overrightarrow{X} \\ &+ (\cos\theta - 1)\sin\phi\cos\phi\overrightarrow{Y} \\ &- \sin\theta\cos\phi\overrightarrow{Z} \end{aligned} \tag{6}$$

$$\begin{aligned} \overrightarrow{\varepsilon_2}(\theta, \phi) = &(\cos\theta - 1)\sin\phi\cos\phi\overrightarrow{X} \\ &+ \left(1 + (\cos\theta - 1)\sin^2\phi\right)\overrightarrow{Y} \\ &- \sin\theta\sin\phi\overrightarrow{Z} \end{aligned} \tag{7}$$

where $\overrightarrow{Z}$ is the direction of the antenna boresight.

VI. Conclusion

It has been shown that it is possible to have large biases in the measured antenna temperature compared to the value at the antenna boresight. A simple correction for the component of the antenna pattern off the Earth surface reduces this bias. However, a significant residual remains, which is due to variations over the antenna field of view of the incidence angle and plane of incidence relative to boresight. An exception is the third Stokes parameter, which has a bias that depends entirely on variations of the direction of polarization over the FOV of the antenna and on the cross-pol gain, and is largely unaffected by the renormalization to limit the integration to the Earth-filled FOV. Contamination of the ocean measurements by land surfaces is significant and can be as much as 0.5 K even at a distance of 450 km from the coast, although the mean value is less than 0.1 K at this distance. To get closer will require modeling of the land emissivity and knowledge of geophysical conditions (e.g., moisture content and temperature). Finally, it is noted that measurements over some very important areas, such as the Mediterranean Sea and the North Atlantic, are significantly contaminated by land.