WIDE BANDWIDTH RADIOMETER SENSITIVITY FOR REMOTE SENSING OF OCEAN SALINITY

D.M. Le Vine and E. P. Dinnat

Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

Modern microwave radiometers have demonstrated the feasibility of monitoring surface salinity from space and also the need for better accuracy in cold water. Accuracy could be improved by adding measurements at lower frequencies (lower than the measurement at 1.4 GHz currently used) and closer to the peak in sensitivity of brightness temperature to changes in salinity. Proposals to accomplish this have focused on wide bandwidth receivers which include at the low end frequencies close to the peak in sensitivity. This strategy involves trade-offs, some obvious such as radio frequency interference (RFI) when operating outside the protected band at 1.4 GHz and the loss of spatial resolution at lower frequencies. Others stemming from the interdependence of the retrieval of salinity on water temperature and surface roughness are more subtle. The objective of this manuscript is to examine this interdependence and its implications to future wide bandwidth instruments for remote sensing of salinity from space.

***Index Terms*— microwave radiometry, ocean salinity**

1. INTRODUCTION

Radiometers on the Soil Moisture and Ocean Salinity (SMOS) mission [7], on Aquarius [9] and on the Soil Moisture Active Passive (SMAP) mission [5], have demonstrated the feasibility of measuring sea surface salinity (SSS) from space [4], [11]. However, they have also demonstrated the need for better accuracy, especially at high latitude and cold water [4], [6], [14]. These radiometers operate in a narrow, 27 MHz wide, spectral window at 1.413 GHz protected for passive use only. While this is nearly ideal (protected spectrum and near the peak in sensitivity to SSS and a null in sensitivity to SST), the actual peak is closer to 800 MHz and moves to even lower frequency as the water temperature drops [12]. Simply moving to a frequency closer to the sensitivity peak is not feasible because of the lack of spectrum protected from RFI.

Proposals to improve accuracy have largely involved adding lower frequencies by using wide bandwidth radiometers and dividing the signal into several frequency channels [1], [3], [15]. Typical frequency ranges suggested are in the range 0.3 – 3.0 GHz. The lower frequency will result in improved sensitivity to sea surface salinity (SSS) and the higher frequency provides sensitivity to sea surface temperature (SST) and the potential to retrieve, simultaneously, the SST needed in the salinity retrieval algorithm. This is illustrated in Fig 1 which shows the sensitivity of microwave brightness temperature to a change in salinity, dTB/dSSS, as a function of SST and frequency. Current measurements are made at 1.4 GHz because it is the location of 27 MHz of spectrum protected from manmade interference (RFI) which makes possible the sensitive measurements of thermal radiation needed to measure salinity [10]. As can be seen in Fig 1, the peak in sensitivity to salinity moves toward lower frequency as the temperature decreases and in cold water (e.g. SST = 0 C) the sensitivity 1.4 GHz is much reduced.

The concept behind wideband sensors is to include lower frequencies closer to the peak in sensitivity to salinity. By including a range of frequencies (e.g. uniformly spaced between 0.4 – 2.0 GHz), there would always be some close to the peak as it moved from cold to warm water and including the traditional band at 1.4 GHz. An obvious problem is RFI in this portion of the spectrum, which is crowded with manmade radiation. But technology to detect RFI is improving as demonstrated by SMAP [13] and in the open ocean and areas far from civilization RFI tends to be less of a problem. Rather than gamble on the availability of a few select frequencies, the concept is to measure over the full band, filter for RFI, and then use the remaining signal for the retrieval.

A less obvious issue is the interdependence of the salinity retrieval on SST. The peak in sensitivity to changes in SST also moves toward lower frequencies as the temperature decreases (e.g. Fig 7 in [12]). This means that the impact of an error in the ancillary SST needed in the retrieval of salinity also increases at lower frequencies, and could offset the gain in sensitivity to salinity. The purpose of this manuscript to look at this interaction, and the dependence on surface roughness (wind speed, WS) which also depends on frequency, to assess the potential of wideband measurements in the band 0.3 – 3.0 GHz for improving the remote sensing of SSS.

2. APPROACH

The approach is to look at the change in the retrieved value of SSS due to radiometric noise and error in the ancillary values of SST and WS needed in the algorithm. Only random errors are considered and systematic errors such as calibration bias and instrument drift or contamination from land are not addressed. If the noise in TB, SST and WS are zero, then in this approach the retrieved SSS is correct.

2.1. Error model

Salinity will be considered to be a function of TB, SST and WS and that function, SSS(TB, SST, WS), is then expanded in a Taylor series about the correct value. The deviation from the correct value, ΔSSS, is a measure of the error. The expansion can be written in the form:

$$\Delta SSS = dSSS/dTB\ \Delta TB + dSSS/dSST\ \Delta SST + dSSS/dWS\ \Delta WS \tag{1}$$

Then using:

$$dSSS/dSST = (dSSS/dTB)\ dTB/dSST \tag{2}$$

$$dSSS/dWS = (dSSS/dTB)\ dTB/dWS \tag{3}$$

Equation 1 can be rewritten in the form:

$$\Delta SSS = \{ \Delta TB + dTB/dSST\ \Delta SST + dTB/dWS\ \Delta WS \} / (dTB/dSSS) \tag{4}$$

Equation 4 is the deviation in the estimate of salinity from its correct value due to errors in brightness temperature, ΔTB, sea surface temperature, ΔSST, and in wind speed, ΔWS. It is assumed that ΔTB represents radiometric noise and bias and other issues of calibration are not included. Equation 4 does not include many other potential sources of error such antenna pattern issues, radiation from the Sun and galactic background, Faraday rotation or attenuation and emission from the atmosphere which can be important at these frequencies.

2.2. Statistics

The goal is to compute the mean and standard deviation of the salinity error, ΔSSS. To do so, it will be assumed that ΔTB, ΔSST, ΔWS are zero mean and independent random variables. Then

$$< \Delta SSS> = 0 \tag{5a}$$

$$<\Delta SSS^2> = \{ <\Delta TB^2> + (dTB/dSST)^2 <\Delta SST^2> + (dTB/dWS)^2 <\Delta WS^2> \} / (dTB/dSSS)^2 \tag{5b}$$

and the standard deviation of the error in salinity is:

$$\sigma s = \mathrm{sqrt}\{<\Delta TB^2> + (dTB/dSST)^2 <\Delta SST^2> + (dTB/dWS)^2 <\Delta WS^2> \} / \left| dTB/dSSS \right| \tag{6}$$

In (6), the term sqrt($<\Delta TB^2>$) is the radiometer sensitivity (i.e. NEDT), and sqrt($<\Delta SST^2>$) and sqrt($<\Delta WS^2>$) are the STD of the errors in sea surface temperature and wind speed, respectively used in the retrieval algorithm. The error in salinity, σs, is a function of frequency because the sensitivities, dTB/dSSS, dTB/dSST and dTB/dWS are frequency dependent. However, the random variables, ΔTB, ΔSST and ΔWS are independent of frequency. One could make a case that ΔTB might depend on frequency given the relatively large frequency range to be considered. This is nota limitation on the approach taken here but for simplicity and because it is likely to be a secondary issue, the radiometric error, ΔTB, will be assumed to be independent of frequency.

2.3. Sensitivities

The sensitivities, dTB/dSSS, dTB/dSST are obtained assuming a flat surface (WS = 0) and using the model of Klein and Swift [8] for the dielectric constant of seawater. The dependence of the results on the model function is not likely to be large (e.g. see [12]) but should be checked for cold water. The effect of wind speed is to roughen the surface and increase emission. Roughness will shift these curves but it is assumed that this change is only weakly dependent on SSS and SST and that the sensitivities at WS = 0 can be used. A hybrid approach has been adopted to compute the sensitivity dTB/dWS: The model for the dependence of TB on wind speed developed by Yin et al [16] for 1.4 GHz and validated for Aquarius and SMOS observations is used for the effect of wind speed, and this is extended to other frequencies using a two-scale scattering model [2]. Then the frequency dependence from the two-scale model is normalized to unity at 1.4 GHz and multiplied by the predictions of the Yin et al model [16] for the change in with wind speed. Figure 2 plots the sensitivity dTB/dWS as a function of windspeed at 1.4 GHz (top) and as a function of frequency with WS = 7 m/s (bottom).

3. RETRIEVAL ERROR VS FREQUENCY

Fig 3 shows examples of the salinity error computed from (6) as a function of frequency for the case SSS = 35, WS = 7 m/s and with radiometric noise sqrt($<\Delta TB^2>$ = 0.1 K and errors in the input parameters sqrt($<\Delta SST^2>$) = 0.5 C and sqrt($<\Delta WS^2>$ = 0.5 m/s. At the top SST = 20 C and at the bottom SST = 2 C. The solid curves are for 40 degrees incidence and the dashed curve for nadir. The radiometer sensitivity, 0.1 K, is approximately the value per data sample (1.44 sec) of the Aquarius radiometer (a very good radiometer) and the errors for SST and WS are representative of good ancillary data. The error of 0.2 psu at 1.4 GHz (top) is comparable to that achieved by Aquarius level-2 data.

The shape of the curves in Fig 3 is predominately a reflection of the variation of the sensitivities dTB/dSSS and dTB/dSST with frequency (dTB/dWS is slowly varying with frequency over this frequency range). For frequencies above 1.4 GHz the decrease in sensitivity to SSS results in an increase in error; and for frequencies below 1.4 GHz the sensitivity to SSS increases (Fig 1) but so does the sensitivity to SST (Fig 7 in [12]). Hence, the asymmetric "U" shape with a minimum near 1.4 GHz. But, the shape is strongly dependent on SST. This is illustrated in Fig 3 (bottom) which shows the error under the same conditions in the top panel but for SST = 2 C. As the water temperature decreases, the minimum shifts toward lower frequency from near 1.4 GHz for warm water to below 1.0 GHz for cold water. The error at frequencies above and below the minimum also increases as temperature decreases resulting a more pronounced "U" shape. The reasons for this behavior can be seen in Fig 1. In particular, the peak sensitivity to SSS moves toward lower frequency as SST decreases. This is also true of dTB/dSST although the amplitude at the peak also increases with decreasing temperature. Hence, the curves keep the "U" shape but shift with the sifting sensitivity curves.

4. DISCUSSION

Equation 6 as illustrated in Fig 3 is the error at a given frequency. In a wide bandwidth system, measurements are made over a range of frequencies (e.g. a set of uniformly spaced frequencies), and (6) provides insight in how to use these measurements to retrieve salinity. In particular, there does not appear to be an advantage to force the lower bound on the frequency to low values. Even in cold water, measurements below about 0.8 GHz exhibit rapid increase in noise. This is good news because including low frequencies to enhance accuracy also means larger antennas and lower spatial resolution. On the other hand, the error also increases with frequency above the minimum and even in warm water increases rapidly above about 1.5 GHz. The advantage of a wide bandwidth system is that the frequencies actually used in the retrieval can be tuned to fit the conditions of the scene, for example, using a lower set for cold water and a higher set for warm water. Of course, RFI likely will limit the available frequencies.

V. Summary and Conclusion

Wide bandwidth remote sensing has been suggested as a way to improve the accuracy of remote sensing of sea surface salinity especially in cold water. But, moving to lower frequencies to take advantage of the peak in sensitivity to SSS also involves changes in the sensitivity to errors in the SST needed in the retrieval. Both change in similar ways with temperature and tend to compete with each other. The analysis presented here addressed the effect of radiometric noise and errors in the ancillary parameters SST and WS needed in the retrieval. Errors associated with calibration and systematic errors in the retrieval algorithm were not included. The analysis showed that there is a minimum in retrieval error in the range of about 0.9 – 1.4 GHz depending on SST. Tuning the retrieval algorithm to fit the SST by using frequencies close to the minimum might be feasible. This also suggests that there is a limit on using lower frequencies to improve accuracy.

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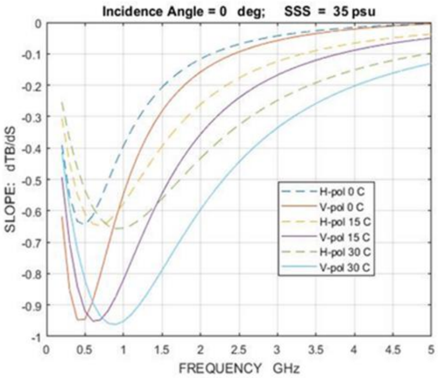

Fig 1. Sensitivity of brightness temperature to changes in salinity, dTB/dSSS, as function of frequency and water temperature, SST.

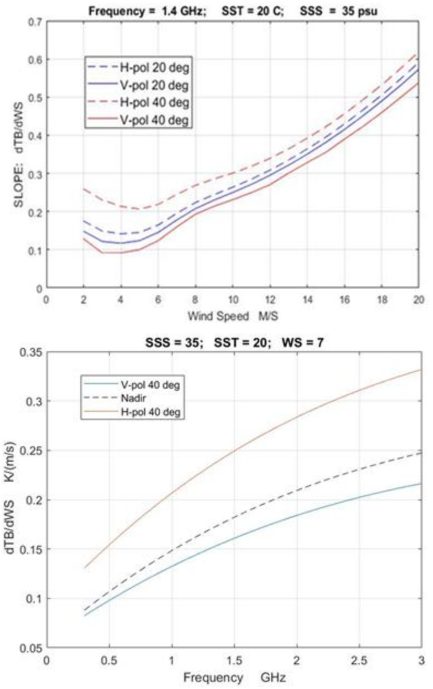

Fig 2. Sensitivity to WS at 1.4 GHz as a function of WS (top) and at WS = 7 m/s as a function of frequency (bottom).

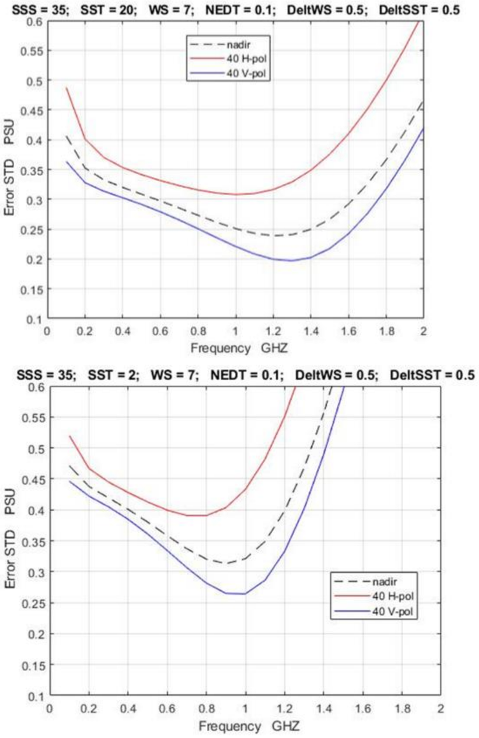

Fig 3. STD of Error in salinity as a function of frequency for (top) SSS = 20 C and (bottom) SSS = 2 C.