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Dielectric Constant Measurements for Remote Sensing of Seawater Salinity

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Abstract

This paper describes a cavity technique to determine the dielectric constant of seawater at a frequency of 1.413 GHz, the center of the protected L-band (i.e. passive use only). The purpose of this study is to provide an accurate model function for NASA satellite missions to retrieve seawater salinity from remote sensing. The measurements are made using standard seawater at salinities of 30, 33, 35 and 38 psu over a range of temperatures from 0° C to 35° C in 5° C intervals. Based on the measurement data, an accurate model function of seawater dielectric constant as a function of salinity and temperature has been developed. The model function will be compared with the model functions of Klein and Swift and Meissner and Wentz.

1. Introduction

To determine the dielectric constant of seawater, a brass microwave cavity that operates at L-band (1.413 GHz) has been employed in the experiments. The measurements have been made in support of the Aquarius space-borne satellite mission with its goal of measuring sea surface salinity. Because of the small variation in sea surface salinity over the open ocean, highly accurate L-band radiometric measurements are required. There are two model functions that are presently being employed in inverting surface brightness temperature into sea surface salinity at 1.413 GHz. These model functions are: the Klein-Swift (KS) model [1] and the Meissner-Wentz (MW) model [2]. Both models are based on the Debye model for the polarization of water molecules and have coefficients that are functions of temperature and salinity. This permits the model functions to cover a large range of frequencies. Remote sensing of salinity from space, however, requires high accuracy and the aim of this work is to provide a model function that is based entirely on accurate laboratory measurements made at 1.413 GHz (Lang et al [3]).

This paper is structured as follows: In Section 2, the dielectric measurements are introduced. Section 3 gives the development of the GW model function. In Section 4, the GW model function is compared with other model functions and the application of the model function in salinity retrieval is shown. Finally, the conclusions are presented in Section 5.

2. Seawater Dielectric Measurements

A brass microwave cavity resonant at 1.413 GHz is used to measure the dielectric constant of seawater. The seawater is introduced into the cavity through a capillary glass tube having an inner diameter of 0.1 mm. After introducing the seawater sample into the cavity, the seawater perturbs the field inside the cavity causing a change in both the resonant frequency and the cavity quality factor, Q. Under the assumption that the amount of seawater introduced into the cavity is small, the complex permittivity of seawater can be retrieved by using the following perturbation relations [4]:

$$\varepsilon' - 1 = 2C\Delta f / f_o \quad , \quad \Delta f = f_o - f \qquad \text{(1a)}$$

$$\varepsilon'' = C\Delta(1/Q) \quad , \quad \Delta(1/Q) = 1/Q - 1/Q_o \qquad \text{(1b)}$$

where ε' and ε'' are the real and imaginary parts of the relative dielectric constant of the seawater sample and C is a calibration constant. The variables f_0, Q_0 and f, Q are the resonant frequency and the quality factor of the cavity before and after the sample solution has been introduced respectively.

In the perturbation formulas, the calibration constant C has been determined by using a reference liquid with a known dielectric constant. In this work the measurements of the dielectric constant for methanol at 20° C, made by Gregory and Clarke [5, 6], are employed as the reference liquid to determine the calibration constant C.

The seawater used in this study is standard IAPSO seawater which is approved by the International Association for Physical Sciences of the Ocean (IAPSO) as the only transfer standard for the Practical Salinity Scale that is recognized by the major oceanographic bodies. [7]. Batches of various IAPSO seawater were purchased from Ocean Scientific International Limited (OSIL) located in Havant, Hampshire in the United Kingdom.

The seawater dielectric measurements were made at salinity values of 30, 33, 35, 38 psu from 0° to 35°C with a 5°C interval between temperatures. At each temperature at least three measurements were made. These measurement data span the observed open ocean values of salinity and temperature.

3. Model Function Development

An accurate expression for the dielectric constant of seawater as a function of temperature and salinity is important for the remote sensing of sea surface salinity from space. This expression is called the model function of the seawater dielectric constant. In this section, the GW model function is developed based on the results obtained from the seawater dielectric measurements.

The GW model function is expressed in terms of a polynomial in salinity, S, and temperature, T, as shown in eq. (2). The unknown complex coefficients, $p_{m,n}$, are determined using the measurement data given in Table 5 of Lang et al [3] by a least squares fitting method. The highest order of S and T is chosen to be 3.

$$\varepsilon_{GW}(S,T) = \sum_{m=0}^{3}\sum_{n=0}^{3} p_{m,n} S^m T^n \tag{2}$$

The coefficients for the model function are obtained by minimizing the normalized square error between the measured dielectric data and the model function. The minimization will be done separately for the real part of the coefficients, $p'_{m,n} = \mathrm{Re}(p_{m,n})$ and for the imaginary part of the coefficients, $p''_{m,n} = \mathrm{Im}(p_{m,n})$. For $p'_{m,n}$, the squared error is,

$$\chi'^2 = \sum_{i=1}^{4}\sum_{j=1}^{8} \frac{\Delta\varepsilon'^2_{i,j}}{\sigma'^2_{i,j}} \tag{3}$$

where $\Delta\varepsilon'_{i,j}$ is the difference between the model function value and the mean value of the measurements at the i-th value of the seawater sample salinities, S_i, and j-th value of the measurement temperature, T_j; $\sigma'_{i,j}$ is the standard deviation of the measured data (given in parentheses in Table 5 of Lang et al [3]) at S_i and T_j. The measurements have been made on 4 types of seawater samples at 8 different temperatures, $i = 1, 2, \ldots, 4$ and $j = 1, 2, \ldots, 8$.

The process of minimizing χ'^2 can be simplified by putting eq. (3) in a matrix form. The solution can then be found by employing the Singular Value Decomposition (SVD) technique. The goodness of fit of the resulting model function is measured by the reduced chi-square statistic χ'^2_ν, which is given as,

$$\chi'^2_\nu = \frac{\chi'^2}{\nu} \tag{4}$$

where ν is the degrees of freedom that equals the number of the equations minus the number of the coefficients to be determined in the model function. For a good fit, the reduced chi-square should be one or less. The reason for choosing 3 as the highest order of S and T is simply because the reduced chi-square of the model function for this case is the smallest.

4. Comparisons between Different Model Functions

The Klein-Swift (KS) and Meissner-Wentz (MW) model functions are used by the SMOS, Aquarius and SMAP satellites to retrieve seawater salinities from remote sensing data. In this section, the GW model function is compared with KS and MW model functions.

Graphical differences between all the three model functions for the real and imaginary parts of the 35 psu seawater are shown in Figures 1-2. It can be seen that the real part of GW model is higher than KS model at low temperatures and lower than KS model at high temperatures. Compared with MW model, the real part of GW model decreases more slowly as temperature gets higher. For the imaginary part, it is difficult to see the differences between curves in the figures because of the poor resolution (i.e. large dynamic range on the vertical axis relative to the differences). The differences between the measurement data, KS model and MW model are documented in Table 8 of Lang et al [3].

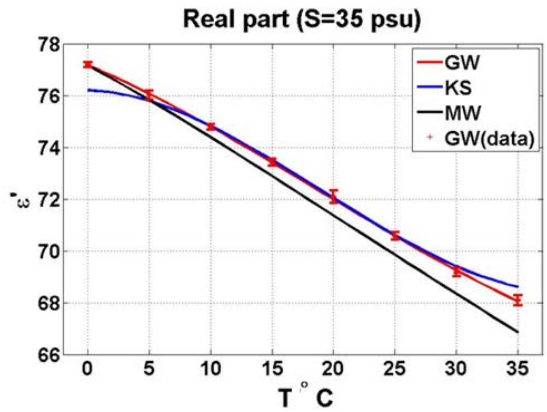

Figure 1. Comparisons of model functions at S=35 psu (real part)

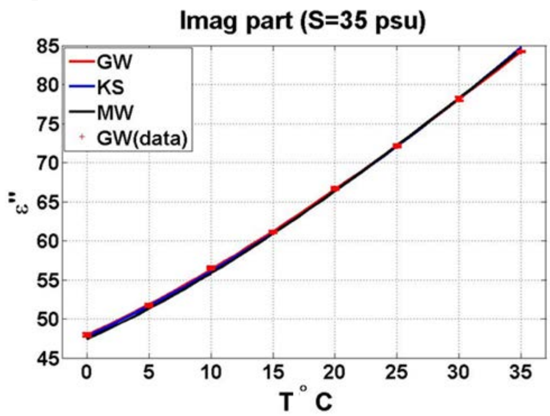

Figure 2. Comparisons of model functions at S=35 psu (Imag part)

In the Aquarius satellite mission, the salinity is obtained by using the model function in the retrieval algorithm to invert the observed brightness temperature data. The comparisons are made between the retrieved salinities from different functions and the in-situ salinity data observed by the Argo buoys. Initial results show GW model function has the best agreement to the Argo buoys' data in the temperature range from 1° to 15°C plus from 25° to 30°C. Cold water is of special concern since this is the region where the sensitivity to changes in salinity is weakest (e.g. Le Vine et al [8]). In the meeting, more details of the application of GW model function will be presented.

5. Conclusion

In summary, this article presents the development of the seawater dielectric model function based on the accurate measurements made by using a cavity technique at the GW microwave lab. The GW model function is then compared with other model functions. GW model function has the best agreement to the in-situ data at most temperatures.

6. References

1. Klein L. and C. Swift (1977), An improved model for the dielectric constant of seawater at microwave frequencies, *IEEE TAP* **25,** 104-111

2. Meissner T. and F. Wentz (2012), The emissivity of the ocean surface between 6 and 90 GHz over a large range of wind speeds and earth incident angles, *IEEE Trans. Geosci. Remote Sens.* **50**, No. 8, 3004-3026

3. Lang, R., Y. Zhou, C. Utku, and D. Le Vine (2016), Accurate measurements of the dielectric constant of seawater at L band, *Radio Sci.*, **51**, 2-24, doi:10.1002/2015RS005776

4. Chen, L.F., C.K. Ong, V.V. Varadan and V.D. Varadan (2004), *Microwave Electronics,*chap. 6, Wiley

5. Gregory A. P. and R. N. Clarke (2009), Traceable measurement of dielectric reference liquids over the temperature interval 10-50° C using coaxial-line method *Meas. Sci. Technol*. **20** 075106

6. Gregory A. P. and R. N. Clarke (2012), Tables of the complex permittivity of dielectric reference liquids at frequencies up to 5 GHz *NPL Report MAT 23* ISSN 1754-2979

7. Bacon S, F. Culkin, N. Higgs and P. Ridout (2007), IAPSO standard seawater: Definition of the uncertainty in the calibration procedure, and stability of recent batches *J. Atmos. Oceanic Technol.* **24** 1785–1799

8. Le Vine D. M., G. Lagerloef and S.E. Torrusio (2010), "Aquarius and Remote Sensing of Sea Surface Salinity from Space", *Proc. IEEE* **98**, 688-703