Remote Sensing of Ocean Salinity: Results from the Delaware Coastal Current Experiment

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ABSTRACT

A comparison is presented of remote and shipboard measurements of sea surface salinity made in the vicinity of the Delaware coastal current, a low salinity band with its source in the mouth of Delaware Bay. The remote sensing measurements were made from an aircraft with the Electronically Scanned Thinned Array Radiometer. The shipboard measurements were made with a thermosalinograph on board the R/V Cape Henlopen. On 29–30 April 1993, the R/V Cape Henlopen sailed from the mouth of Delaware Bay south toward Chesapeake Bay in an east–west zig-zag pattern, repeatedly crossing the coastal current. The aircraft, a NASA P-3, flew the same lines on the afternoon of 30 April. Both thermosalinograph- and microwave radiometer-derived salinity maps clearly show the freshwater signature of the coastal current and generally are in agreement to within about 1 psu.

1. Introduction

The possibility of measuring sea surface salinity from a satellite in space has been discussed seriously in the past (Swift and McIntosh 1983). Recent developments have fostered a resurgence of interest in using remote measurements from space to obtain a global map of the salinity field of the world ocean. Among these developments is the availability of satellite-generated maps of sea surface temperature and surface winds that provide the framework into which global maps of the salinity field can be added to improve understanding of ocean circulation, air–sea interaction, and the influence these have on global climate (Lagerloef et al. 1995).

Equally important is the emergence of new microwave radiometer technology (Le Vine et al. 1989; Le Vine et al. 1994) that addresses the problems of putting large antennas in orbit, thus making the measurement of salinity from space more practical (Swift et al. 1993; Lagerloef et al. 1995).

The physics of microwave remote sensing of sea surface salinity is well known. It is well established that the passive microwave signature (emissivity) of water depends on salinity (e.g., Blume et al. 1978; Klein and Swift 1977), and measurements demonstrating the capability of microwave radiometers to remotely monitor salinity have been made from aircraft. The first such measurements were made by Thomann (1976) and somewhat later by Blume and colleagues at the National Aeronautics and Space Administration (NASA) Langley Research Center (Blume et al. 1978; Blume and Kendall 1982), who showed that by using two channels (L and S bands) the effects of sea surface temperature could be eliminated.

Discussion of the possibility of obtaining global maps of salinity remotely from space followed the success of these measurements (e.g., Swift and McIntosh 1983). Recently, it has been proposed that such measurements be made using new passive sensor technology called aperture synthesis (Swift et al. 1993; Lagerloef et al. 1995). This is an interferometric technology similar to what is called earth rotation synthesis in radio astronomy (Napier et al. 1983; Thompson et al. 1986). It is being developed to help overcome the limitation antenna size imposes on microwave remote sensing from space. In particular, the remote sensing of salinity is optimally done at the long wavelength end of the microwave spectrum where the dynamic range (response due to changes in salinity) is strong and the dependence on temperature is weak (Swift and McIntosh 1983; Klein and Swift 1977). However, the long wavelengths mean that large antennas are required in space to obtain adequate resolution at the surface.
To demonstrate that aperture synthesis could be successfully employed for remote sensing of the earth surface, an instrument prototype called the Electronically Scanned Thinned Array Radiometer (ESTAR) was developed at the Goddard Space Flight Center and the University of Massachusetts (Le Vine et al. 1994). The first images were reported in 1990 (Le Vine et al. 1990) and success in the measurement of soil moisture (which is measured in the same portion of the microwave spectrum as salinity) was demonstrated in a series of experiments at the United States Department of Agriculture’s research watersheds in Arizona and Oklahoma (Le Vine et al. 1994; Jackson et al. 1995; Jackson et al. 1993). During this same period experiments were begun to evaluate the potential of applying this new technology to the remote sensing of sea surface salinity (e.g., Lagerloef et al. 1992). The measurements to be presented here were part of that evaluation and are important because they represent successful, nearly simultaneous measurements from a ship and from the airborne ESTAR.

In the paragraphs to follow, a comparison will be presented of salinity measurements obtained with the prototype radiometer ESTAR and measurements obtained with a thermostalinograph aboard the R/V Cape Henlopen. The data were collected in April 1993 during observations of the Delaware coastal current, a relatively freshwater outflow with origin in the Delaware Bay (Munchow and Garvine 1993a,b). In section 2, a brief description will be given of the ESTAR instrument. This will be followed by a description of the observations. The paper will conclude with examples of the data from the shipboard theromosalinograph and from the airborne ESTAR plus a comparison of the salinity fields obtained with each instrument. The difference field is, with a few exceptions, on the order of 1 psu.

2. The ESTAR instrument

ESTAR is a prototype for a new technology, aperture synthesis, being developed at the Goddard Space Flight Center and the University of Massachusetts for microwave remote sensing from space (Le Vine et al. 1990; Le Vine et al. 1994). It is an interferometric device intended to reduce the antenna aperture needed in space. Antenna size is an important issue for remote sensing of parameters such as soil moisture over land and salinity over the ocean, which are best measured at the long wavelength end of the microwave spectrum (e.g., Murphy et al. 1987; Swift and McIntosh 1983). Since spatial resolution depends on the ratio of wavelength to antenna aperture (e.g., diameter), the long wavelengths mean large antennas are needed in orbit to obtain adequate spatial resolution at the surface.

Aperture synthesis is similar in principle to earth rotation synthesis developed in radio astronomy (Thompson et al. 1986). In aperture synthesis, one measures the correlation (product) of signals from pairs of antennas at different spacing. Each spacing provides a sample point in the Fourier spectrum of the scene. The scene is obtained by inverting the transform using the sample data (e.g., Le Vine et al. 1994). In principle, one can obtain the resolution of a single large antenna using a relatively small set of judiciously spaced small antennas. ESTAR was developed to demonstrate that the practical issues of implementing such an algorithm for remote sensing could be overcome.

The remote sensing configuration of the ESTAR instrument is illustrated at the top of Fig. 1. ESTAR is a hybrid of a real and a synthetic aperture radiometer. It obtains resolution in the direction of motion using the real antenna aperture. The real antennas consist of five thin “stick” antennas oriented with the long axis in the direction of flight, as indicated in Fig. 1. These antennas produce a narrow “fan” beam with good resolution in the direction of motion but essentially no resolution in the across-track dimension. Resolution across track is
obtained synthetically by measuring the correlation among pairs of the stick antennas with different spacing (Le Vine et al. 1990).

The signal processing involved is illustrated at the bottom of Fig. 1. Each stick antenna is horizontally polarized and comprised of an array of eight dipoles. The five antennas are spaced in multiples of a half-wavelength (about 11.5 cm at 1.4 GHz), and with the configuration employed in ESTAR (Fig. 1, bottom) seven correlations with unique baselines are obtained plus one at zero spacing. The antenna beam, which can be synthesized in the across-track dimension with this configuration, has a width at half-power of about ±3° (Le Vine et al. 1994). This beam is scanned across track in software, covering a swath of about 40° to either side of nadir. Since the processing is done in software after the data have been collected, the across-track scan is essentially instantaneous. An image of the surface is formed by plotting these across-track scans sequentially (one every 0.25 s, which is the ESTAR integration time) as the aircraft drags the fan beam along the scene. Examples of images and additional details including specifics of the image reconstruction algorithm and calibration procedures are given in Le Vine et al. (1990) and Le Vine et al. (1994).

The scientific validation of ESTAR in previous work has been done in the context of the measurement of soil moisture (Le Vine et al. 1994; Jackson et al. 1993; Jackson et al. 1995). Whereas the measurement of soil moisture and sea surface salinity is both done at the same frequency (L band, 1.4 GHz), the accuracy required for a successful measurement of salinity is much more demanding. For example, a change in 1 psu at 15°C corresponds to a radiometric change of about 0.5 K (Klein and Swift 1977). In contrast, a change in volumetric moisture of 1% corresponds to a change in radiometric response of about 4 K. Furthermore, requirements by the science community for soil moisture are for resolution to within a few percent, whereas 1 psu is at the minimal end of requirements for oceanographic applications. Thus, the demands on the radiometer (noise level, stability, and absolute calibration) are much greater for the successful measurement of sea surface salinity.

ESTAR was designed to be an engineering model to develop the concept of aperture synthesis and to demonstrate its application in the context of the measurement of soil moisture. The radiometric noise in ESTAR is about 0.5 K, and additional noise is added by the aircraft platform and image processing. To measure sea surface salinity, averaging is necessary to reduce sensor noise. Even with engineering consideration given to reducing sensor noise, a similar averaging is likely to be necessary for a sensor in space (Lagerloef et al. 1995).

3. Delaware Coastal Current Experiment

The Delaware coastal current (DCC) is a relatively low saline outflow originating in Delaware Bay (Munchow and Garvine 1993a, b). The data to be presented here were collected in April 1993 as part of a series of observations to study this outflow. During this experiment, the R/V Cape Henlopen sailed from Delaware Bay south toward Chesapeake Bay in a series of zigzag tracks that crossed the coastal current into shelf water. Figure 2 (top panel) shows the ship track sailed on 29–30 April. The irregularities on several of the tracks show detours the ship made to recover drifting buoys. The ship track shown took approximately two days to complete.

Surface (0.5-m depth) salinity and temperature were obtained along the track from the shipboard thermosalinograph. The insert at the bottom of Fig. 2 shows an example of the salinity measurements. In this figure,
salinity (psu) is plotted as a function of longitude along segment D–E, the fourth segment from the top (north) in Fig. 2. The salinity signature of the DCC is clearly evident. In particular, to the east (point D) the salinity is representative of shelf water in this region (31 psu). It then decreases suddenly as the ship (moving westward toward point E) crosses the freshwater outflow from the Delaware Bay. On 29–30 April, evidence for the DCC in the salinity signature extended south to near the Maryland–Virginia border (37.8° latitude). The surface temperature changed very little, even in the region of the coastal current. (The surface temperature was about 9.0°–8.5°C along the track.)

4. Aircraft remote sensing

On 30 April, the P-3 aircraft carrying ESTAR flew over the same track followed by the ship during the previous day. The plane left NASA's Wallops Flight Facility in the late afternoon and, beginning at the southernmost point, flew over the ship track from south to north at an altitude of about 300 m. The P-3 passed over the R/V Cape Henlopen near the eastern end of the third segment from the bottom of Fig. 2 (indicated with a circle) as the ship was still making its way south. Upon reaching Delaware Bay, the P-3 returned by flying south along the middle of the domain. The surface track of the aircraft is shown in Fig. 3 (left panel). The entire flight took less than 2 h.

Data were not collected at all points along the aircraft flight lines—only when the wings were level because the microwave data depends on the angle of incidence. Thus, all data from turns were eliminated. Also, data from the end of the center track were eliminated because there were indications that the wings were not level. Data were also lost on one segment due to a computer malfunction. The remaining data were processed to yield estimates of salinity. Then, the salinity estimates were examined for indications of spurious behavior (extremely large or small signals). This resulted in some minor editing (at the beginning and end of the segments near the turns) and one data leg was dropped entirely. The portions of the aircraft track that passed this scrutiny are shown in Fig. 3 (right panel). Salinity estimates generated along this track were compared with the thermostsalinograph measurements.

Converting brightness temperature into salinity requires knowledge of the surface temperature (e.g., Klein and Swift 1977; Lagerloef et al. 1995). During the flight, temperature measurements were obtained with a thermal infrared radiometer (PRT-5) that was on board the aircraft. These were compared to the temperature measurements from the shipboard thermostsalinograph. After a correction for a bias (about 3°) the measurements were in good agreement. The PRT-5 data corrected for this bias were then used to convert brightness temperature to salinity.

Two examples of the salinity estimates obtained with ESTAR are shown in Fig. 4. Data are shown for segments C–D and E–F where the DCC had a strong salinity signature. The solid line in each figure is the salinity measured by the thermostsalinograph, and the dotted line is that measured by ESTAR. For these examples (and those to be presented below) each ESTAR estimate was
obtained by first generating an image and then averaging this image across track using a swath of about $\pm 10^8$ and then integrating along track for about 20 s. This is equivalent to averaging pixels in a box about 2 km long and 0.1 km wide.

Segments C–D and E–F were chosen for display because they show evidence of the salinity gradient associated with the DCC. Results for more southerly segments have weaker gradients. Thermosalinograph- and ESTAR-derived values of salinity are in reasonable agreement. Both have about the same level and show the dramatic decrease on the shoreward side in the coastal current. But there are also some significant differences. In particular, ESTAR data show structure not evident in the thermosalinograph measurements. Notice, for example, the oscillatory behavior of the ESTAR estimates for line EF. The origin of these oscillations is not clear. They could be evidence of instrument noise. Also, notice the apparent eastward (right) shift of the DCC from the ESTAR data compared to the shipboard measurements. Since these shipboard measurements were made one day earlier, it is possible that this difference is real and reflects an eastward movement of the DCC.

5. Salinity field

Figure 5 shows the surface salinity fields derived from both the thermosalinograph and ESTAR. Figure 5 was produced using a natural neighbor interpolation routine (Watson 1992) on the thermosalinograph and ESTAR data. The interpolation was done over a square grid with grid node spacing approximately one-half the maximum distance between data points in the alongshelf direction, which tends to minimize interpolation errors. To maintain a conservative solution, neither thermosalinograph nor ESTAR data were extrapolated to produce grid node solutions outside the data’s domain. The salinity levels and general features of the two maps are consistent, including evidence of the coastal current. However, also notice that the coastal current appears to have widened to the east in the field derived from the ESTAR data. There even appears to be somewhat of a southerly migration. Indeed, this trend continued over several days. A subsequent map of the surface salinity field obtained a few days later (1–2 May) by the ship showed a still wider area of low salinity water. This widening coincided with an upwelling (northward) wind event that would be expected to deflect surface DCC water farther offshore. The ESTAR maps appear to have captured the beginning of that widening.

The salinity difference field between the two maps is shown in Fig. 6. For the most part the two maps agree to within 1 psu. The larger differences tend to be in the north where the time difference was greatest. This level of agreement is consistent with the earlier measurements using a state-of-the-art conventional radiometer (Blume et al. 1978; Blume and Kendall 1982; Kendall and Blanton 1981). Also, Kendall and Blanton (1981) report salinity maps in the vicinity of the Savannah River outflow that are similar to those in Fig. 5 and have estimated accuracy of 1 psu.

6. Summary

A comparison has been presented of sea surface salinity data obtained with shipboard thermosalinograph and remotely with an L-band microwave radiometer. The microwave instrument is a synthetic aperture radiometer, a new technology being developed for remote sensing from space. The microwave instrument was designed to measure soil moisture, a measurement requiring much less accuracy than the measurement of sea surface salinity. Even so, reasonable agreement was obtained between the two sets of measurements—generally within about 1 psu. The ESTAR instrument represents technology to make the deployment in space of radiometers at long microwave wavelengths feasible. In contrast to the nadir-pointing radiometers developed in the 1970s (Blume et al. 1978), ESTAR scans across track and is designed for efficient packaging and deployment in space. The development of ESTAR and new conventional radiometers (Miller et al. 1996) suggests...
FIG. 5. Salinity field as obtained from (a) the thermosalinograph data and (b) from ESTAR.

a role for microwave remote sensing of salinity in the future.

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REFERENCES


