Radiometry and Remote Sensing of the Environment

Roger H. Lang

The George Washington University, Washington DC 20052 USA , lang@gwu.edu

Abstract

Three new L band passive satellite missions to measure sea surface salinity and soil moisture are reviewed. The first is the ESA Soil Moisture Ocean Salinity (SMOS) satellite. It features the first spaceborne synthetic aperture antenna with enhanced resolution and multiple incident angle looks. The second is the NASA Aquarius mission to sense sea surface salinity with a 0.2 psu accuracy and an on-board radar to correct for surface roughnesss. The last is NASA's Soil Moisture Active Passive (SMAP) mission to measure soil moisture with a 6m mesh antenna for increased resolution and a radar to enhance its performance.

1. Introduction

The sensing of ocean salinity and soil moisture from space by recently launched or soon to be launched passive or passive/active sensors will be reviewed. Understanding the earth's environment becomes an ever more important goal as mankind's population increases. Ocean salinity and soil moisture are two surface environmental variables that have not been measured globally. The knowledge of ocean salinity enhances our understanding of the flow of ocean currents and their long term effect upon heat distribution within the seas. In like manner, soil moisture provides a boundary condition for global circulation models over land. Although both active and passive sensors have been employed over the past 30 years, adequate sensing of these variables has not been attempted. In November, 2009 ESA (European Space Agency) launched SMOS (Soil Moisture Ocean Salinity), an L band passive instrument, to measure these quantities [1]. NASA (National Aeronautics and Space Administration) in June, 2011 will launch Aquarius, an L band passive/active instrument, to sense ocean salinity [2], and in 2014 NASA is expected to launch SMAP, an L band passive/active instrument to measure soil moisture [3]. Our objective here is to understand why an L band passive or passive /active instrument has been employed and how each instrument has been designed to sense these hard to determine environmental variables.

2. Background

In planning to make ocean salinity or soil moisture measurements, the decision must be made about whether active or passive sensing will be used and what frequency of operation will be employed. As part of the design process, the required instrument sensitivity, resolution and satellite revisit time must be considered. Algorithm development must account for the effects of sea surface roughness for ocean sensing and surface roughness and vegetation cover for soil moisture retrieval.

2.1 Passive Versus Active Sensors

Passive sensors respond to the incoherent thermal sources distributed throughout material medium, be it land or sea. Radars or active sensors, on the other hand, require scattering to return incident energy. If a calm sea or a flat ground were being sensed, a radiometer would receive a signal at any pointing angle while a radar would only respond if pointed directly downward. This illustrates why radiometers have been the first choice to measure sea surface salinity and soil moisture. For radars to respond, surface roughness or vegetation would have to be present for the radar to receive a return signal. The radiometers would perceive these, as surface perturbations on the original signal. Radiometers also have the added advantage that they don't suffer from the speckle observed in radar returns since they receive incoherent thermal radiation.

2.2 Frequency of Operation and Resolution

The choice of the instrument frequency of operation will be considered next. In the case of sea surface salinity, the variation in salinity in the open ocean is very slight, although this slight variation has a major effect on ocean circulation. The greatest sensitivity to sea surface salinity occurs somewhat below 1 GHz. The radio astronomy band of 1400 to 1427 MHz provides protection from unwanted radar and communication transmissions (RFI) that

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

would swamp the small thermal signals. It has thus been the natural choice for salinity missions. The low L band frequency has the unfortunate effect of making the instrument resolution large. Typical resolutions of passive instruments in low Earth orbit range from 50 to 100 kilometers for reasonable antenna sizes of 3 to 6 meters. Since open ocean salinity variation has large scales, this low resolution does not present a major problem.

Soil moisture missions face somewhat different considerations. Sensitivity to soil moisture changes are, in general, much larger than open ocean salinity changes. Soil moisture can be easily measured with passive instruments at P, L and C band frequencies. The depth of penetration in the soil becomes deeper as the frequency deceases (1m at P, 5 cm at L and 2 cm at C for moderate moistures). The real problem occurs in the presence of vegetation which attenuates the thermal radiation from the soil and contributes some emission of its own to the observed brightness temperature. At C band, only bare soils and soils under small vegetation can be measured (for example, short grasses). At L band the response to changes in soil moisture is measureable for soils under crops such as corn or small trees. Measurements at P band will respond through most forests and will penetrate down to the root zone. The problem at P band is twofold: antenna size and distortion of the signal by the ionosphere. Once again, L band becomes the natural choice with the protected frequency band of 1400 to 1427 MHz being employed. An added consideration for soil moisture missions is the revisit time. Hydrologists want to measure soil moisture on a two to three day cycle while oceanographers are satisfied with a 7 to 10 day revisit time. Finally, a major consideration for soil moisture measurements is resolution. Although scale length over rangelands is greater than the typical L band resolution size, many agricultural areas have sizes of less than a kilometer. This is not a problem encountered by the sea surface salinity missions. The NASA SMAP mission has used an on-board radar to attempt to overcome this limitation.

2.3 Algorithms and Corrections

The basic algorithm used to detect sea surface salinity is to employ a model function that relates sea surface salinity and sea surface temperature to the dielectric constant of sea water. For a flat sea, the dielectric constant is directly related to the brightness temperature measured by the satellite via the Fresnel reflection coefficient of the surface. Given the brightness temperature and the sea surface temperature, the surface salinity can be uniquely found. Oceanographers have determined that they need to know the salinity to within 0.2 psu (physical salinity units). Note that typical variation of the open ocean surface salinity is between 34 and 38 psu. A 0.2 psu determination of salinity means the radiometer must measure correctly to 0.1^0 K. This implies that corrections will have to be made for various deviations from the algorithm. The most important of these is the surface roughness. Its effect increases with wind speed. Geophysical data from weather models can be used to estimate wind speed and direction. This can, in turn, be used in rough surface backscattering models to estimate changes in brightness temperature as a function of wind speed. Alternatively, an on-board radar can be used to estimate wind speed [4]. Some of the other errors that must be taken into account are: corrections to the universally used model function by Kline and Swift [5], atmospheric upwelling radiation, ionospheric Faraday rotation, galactic radiation and down welling atmospheric radiation reflected from the water surface.

The zeroth order soil moisture algorithm for a flat soil surface with no vegetation cover is similar to the salinity algorithm. The brightness temperature is related to the dielectric constant of the ground through the Fresnel reflection coefficient. The dielectric constant of the ground is a function of the soil moisture and a weak function of the soil type. The difference in the case of soil moisture from the sea surface salinity measurement is that the variation of brightness temperature from a wet to a dry soil is much greater than the variation from low open ocean salinity to high open ocean salinity. When small to moderate vegetation is present (vegetation water content up to 5 gm/m^2), ancillary data can be used to estimate the vegetation water content; the water content then is used to compute vegetation absorption. This, together with an empirically determined albedo, is used in a zero order transport theory (tau omega model) to determine the brightness resulting from the presence of the vegetation. Since the vegetation scale is much smaller than the resolution of the radiometer, the vegetation water content is determined on a finer grid and averaged nonlinearly over the resolution cell. NASA has employed an auxiliary radar on-board its SMAP satellite to attempt to measure parameters needed by the radiometer algorithm on a finer scale to increase the accuracy of the algorithm and produce a retrieved soil moisture product that is intermediate in resolution (~9 km) between the radar and radiometer [3].

3. Satellite Missions

3.1 Soil Moisture Ocean Salinity (SMOS)

The SMOS L band radiometer (MIRAS) is based on 2-D aperture synthesis [6] that takes advantage of the incoherence of the signal radiated by the surface. It employing an array of 69 antennas distributed over three arms of a Y shaped structure. The concept was demonstrated by Le Vine et al [7] who developed a one dimensional array radiometer called ESTAR. After processing, a resolution of 50 km is obtained with a processing dependent swath width of 640 km or 1050 km [8]. The lower swath width is used for salinity sensing since the radiometer is more sensitive in this mode. An accuracy of 1.2 psu is expected with a revisit time of 7 days. When the signal is processed for the larger swath, soil moisture measurements are made that require less sensitivity than salinity measurements but have a smaller revisit time. In this mode a 4% soil moisture accuracy is expected with a 3 day revisit time. The antenna system has horizontal and vertical channels and it can produce results over a range of incident angles simultaneously.

Sea surface salinity is retrieved by using brightness temperatures from multiple incident angles. The over determined system is used to reduce noise. Rough surface effects and other corrections are taken into account using ancillary data obtained from the European Centre for Medium Range Weather Forecast (ECMWR). Soil moisture is determined using a multiple incident angle algorithm [9] so the soil moisture and vegetation water content are both determined. As mentioned previously, SMOS was launched in November, 2009 and has undergone a successful commissioning phase. Presently, both global sea surface salinity and soil moisture are being retrieved. Results look as if they are within expected ranges and, in many cases, they are better. They have reported many areas of RFI around the globe. Their mission has been a major technological and remote sensing achievement.

3.2 Aquarius

Aquarius is a joint mission between NASA and the Argentinean space agency CONAE. NASA will build the major instrument, Aquarius, to measure sea surface salinity and CONAE will contribute a suite of smaller instruments that includes a 23.8 and 37 GHz Microwave Radiometer, infrared and visible cameras and several other instruments. The CONAE Microwave Radiometer will measure rain, wind speed, wind direction and sea ice. The Aquarius instrument consists of three polarimetric 1.4 GHz radiometers and a dual polarized 1.26 GHz radar. The antenna is a 2.5 m offset parabolic reflector with three feed horns. The three beams are in a push broom configuration and jointly have a swath of 390 km. Both the radiometer and the radar shared the same antenna.

The three radiometers (one for each antenna) are of the Dicke type and use noise injection for calibration. The radiometers are thermally controlled to better than 0.1^0 K over a 7 day period. The instrument is designed to have an accuracy of 0.1^0 K which implies a salinity measurement accuracy of 0.2 psu. The purpose of the scatterometer is to adjust the radiometer signal for the effects of surface roughness. This important addition allows Aquarius to compensate for surface roughness using real time data rather the data obtained from weather services. The radiometers measure a third Stokes parameter that will be used to estimate Faraday rotation through the ionosphere. Numerous other corrections will also be made. The instruments have been built and are in the process of final tests. The launch is schedule for June, 2011 [2].

3.3 Soil Moisture Active Passive (SMAP)

The SMAP instrument uses a single 6 m diameter mesh reflector antenna feed by a single horn feed assembly that operates at 1.413 GHz (radiometer) and 1.26 GHz (radar). The radiometer is fully polarimetric while the radar has three channels (HH, VV and HV). The antenna rotates about the nadir axis and has a surface incidence angle of approximately 40^0. The mission is intended to measure soil moisture and the freeze-thaw state of soils. The SMAP radiometer has a resolution of approximately 40 km. Because of the angular rotation of the antenna, synthetic aperture techniques can be used to generate radar data over 70% of its rotation circle with a resolution of 1-3 km. A standard passive algorithm will be used to generate soil moisture over flat surfaces with no vegetation. When vegetation is present, the tau omega transport model will be employed. Opacity (absorption) and albedo values will be obtained on a finer grid using like and cross polarized radar returns, optical and infrared data or other ancillary data. In addition to the standard soil moisture product, a high resolution (9 km) soil moisture product will be generated by using the less accurate high resolution radar data in conjunction with the accurate low resolution (40 km) radiometer data. Finally, freeze-thaw transitions are identified by large changes in the dielectric constant of the landscape that result in large changes in the temporal radar measurements. The SMAP instrument is expected to be launched in the 2014 time frame [3].

4. Conclusions

The first passive L band instruments since the NASA Skylab mission in 1978 have been or are about to be launched. They have/will measure sea surface salinity and soil moisture – difficult variables to measure at higher frequencies. The first of these satellites, SMOS has been successfully launched and placed into operation with the first spaceborne synthetic aperture antenna. The NASA Aquarius mission will be launched in June, 2011 and promises to make very accurate measurements of seas surface salinity. The NASA SMAP satellite is to be launched in 2014 time frame; it will made high resolution (9km) measurements of soil moisture.

5. References

1. Y. Kerr, et al, "The SMOS Mission: New Tool for Monitoring Key Elements of the Global Water Cycle," *Proc. IEEE*, **98**, May, 2010, pp. 666-687.

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

3. D. Entekhabi, et al, "The Soil moisture Active Passive (SMAP) Mission," *Proc. IEEE*, **98,** May, 2010, pp. 704-716.

4. S. Yueh, S. Dinardo, A. Fore and F. K. Li, "Passive and Active L-Band Microwave Observations and Modeling of Ocean Surface Winds," *IEEE Trans of Geosci. Remote Sens*., **48**, Aug., 2010, pp.3087-3181.

5. L. A. Kline and C.. T. Swift, "An Improved Model for the Dielectric Constant of Sea Water at Microwave Frequencies," *IEEE Trans. Antennas and Propag.* , **AP-25**, 1981, pp. 104-111.

6. A. Camps, J. Bara, I. Corbella and F. Torres, "The Processing of Hexagonally Sampled Signals with Standard Techniques: Application of 2-D Large Aperture Synthesis Interferometric Radiometers*," IEEE Trans. Geosci. Remote Sens.*, **35**, 1997, pp.183-190.

7. D. M. Le Vine, A. J. Griffis, C. T. Swift and T.J. Jackson, "ESTAR:A Synthetic Aperture Microwave Radiometer for Remote Sensing Applications,", *Proc. IEEE*, **82**, 1994, pp.1787-1801.

8. H. Barre, B. Duesmann and Y. Kerr, " SMOS: The Mission and the System," *IEEE Trans of Geosci. Remote Sens*., **46**, March, 2008, pp. 587-593.

9 .J.P. Wigneron, et.al., "L- band Microwave Emission of the Biosphere (L-MEB) Model: Description and Calibration against Experimental Data Sets over Crop Fields," *Remote Sensing of Environment* **107**, 2007, pp. 639-655.