Remote Sensing of Soil Moisture Using the Propagation of Loran-C Navigation Signals

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***Abstract*—The fractional water content of soil plays a central role in the complex interactions between the Earth and its hydrological cycle. However, obtaining continuous measurements of wide-area soil moisture is difficult. In this study, a novel way of estimating soil moisture is explored that makes use of the variations in time delay on Loran-C surface waves. An analysis was carried out using such signals recorded over a 3-week period at the University of Bath in the UK from a Loran-C transmitting station in Northern France. Model data from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used for calculation, calibration and inter-comparison. Good agreement between the soil moisture estimated using the Loran-C method and the ECMWF product was found for soil depth of 0 to 28 cm.**

***Index Terms*—Remote sensing, soil moisture, soil properties, surface waves.**

I. Introduction

Information on wide-area soil moisture is essential in many applications including land use planning, agriculture, environmental monitoring, weather pattern prediction and early warning of floods and droughts. At the moment, there exists no pre-established method for continuously measuring near-surface soil moisture on a wide-scale.

In recent years, efforts around the worldwide have focused on the use of satellite-based, microwave-derived methods for the remote sensing of soil moisture. The most recent developments include the Soil Moisture and Ocean Salinity (SMOS) mission and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E).

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The SMOS satellite was developed by the European Space Agency (ESA) as part of its Living Planet Program. It was launched on 2 November 2009 and then entered routine operations in May 2010. Being placed in a sun-synchronous orbit, SMOS passes over a location on earth at 6 A.M. and 6 P.M. local solar time (LST). The payload of SMOS consists of a passive microwave radiometer operating at 1.413 GHz within the protected L- band [1]. Its operational target for soil moisture estimation is to achieve an accuracy of 4% at a spatial resolution of 35-50 km.

On board NASA’s Aqua satellite is the AMSR-E. Unlike its European counterpart, it measures brightness temperature at six different frequencies – 6.9, 10.6, 18.7, 23.8, 36.5 and 89.0 GHz. The crossing time of AMSR-E is 1:30 A.M. and 1:30 P.M. LST, and the spatial resolution is 60 km at 6.9 GHz (C-band).

Microwave soil moisture retrievals are limited to the top few centimeters of soil, and the continuity of measurements is determined by the revisit period of the platforms that carry the microwave sensors . In order to improve temporal sampling, it has been suggested that changes in wide-area soil moisture can be deduced from the finite electrical conductivity of soil [2], which may be inferred from the delay fluctuations in low-frequency radio signals travelling along the ground. In this paper, we wish to validate this using low-frequency Loran-C navigation signals.

II. Background

Loran-C is a hyperbolic navigation system which operates in the 90 to 110 kHz frequency band with a carrier frequency of 100 kHz. Loran-C transmitting stations can be found in Europe and East Asia. They are grouped in chains of 3 to 6 stations each transmitting regularly spaced pulses. A transmission chain consists of a master station and at least 2 secondary stations. Loran-C signals propagate as either a ground wave or sky wave. In this study we are interested in the ground wave component, which takes the form of a surface wave that propagates across the surface of the Earth. The propagation time, or time delay, is usually expressed in terms of the primary factor (PF), the secondary factor (SF) and the additional secondary factor (ASF) [3].

PF is the atmospheric delay, which is governed by the refractive index of the atmosphere. The refractive index, η, can be determined by knowledge of the atmospheric temperature, pressure and water vapor values, which are used to calculate the refractivity, *N*, and hence the refractive index [4]. These are given by the following equations:

$$N = \frac{77.6p}{T} + \frac{e_s \times 3.73 \times 10^5}{T^2} \quad (1)$$

$$N = (\eta - 1) \times 10^6 \quad (2)$$

where p is the barometric pressure (in millibars); T is the absolute temperature (in Kelvin), and e_s is the partial pressure of water vapor (in millibars).

PF takes into the account the fact that the refractive index η in the atmosphere is slightly greater than unity. The United States Coast Guard used a constant value of 1.000338 for η in the Loran-C signal specification [5], which was published in 1994. Mathematically, PF, in seconds, is written as:

$$\text{PF} = \frac{d}{(\frac{c}{\eta})} = \eta\frac{d}{c} \quad (3)$$

where d is the signal propagation distance, and c is the speed of light in free space (299792458 m/s).

SF is the extra delay due to propagation over an all-seawater path rather than through the atmosphere. SF is a function of distance and can be calculate from the following equations [3]:

when d ≤ 100 statute miles (~160 km),

$$\text{SF } (\mu s) = -0.1142 + 0.00176d + \frac{0.510483}{d} \quad (4)$$

when d ≥ 100 statute miles,

$$\text{SF } (\mu s) = -0.40758 + 0.00346776d + \frac{24.0305}{d} \quad (5)$$

ASF compensates for propagation over land rather than seawater. The travel time of Loran-C signals over an all-seawater path (i.e. PF + SF) can be accurately modeled. In contrast, ASF depends on land surface dynamics that influences the conductivity of the ground, and is therefore much more difficult to model. For a homogenous path of constant conductivity, the value of ASF can be found from generalized curves derived numerically (e.g., [7]). In practice, it is unlikely for an entire propagation path to be represented by a single nominal conductivity value.

One of the commonly used techniques for modeling the effects of conductivity inconsistency along a mixed path is Millington's method (also known as the Millington-Pressey method [8]). Millington's method divides the propagation path into a number of homogenous segments. Based on the principle of reciprocity, the total time increment is averaged over the forward and backward directions. For a detailed description of Millington's method, the reader is referred to [6].

Loran-C time delay may also be influenced by topography, particularly in mountainous regions, that increases the effective propagation distance. To improve navigation accuracy, modeled ASFs, based on topography and conductivity information averaged over a certain period of time, are widely used in receivers and navigation charts. However, the ASF variations caused by short-term changes in ground conductivity can only be represented by real-time measurements of Loran-C delay fluctuations.

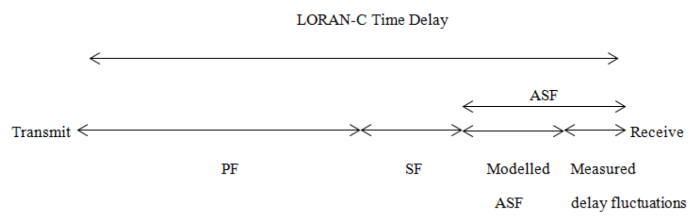


Fig. 1. Factors affecting the time delay of Loran-C signals

The electrical conductivity of the ground is related to soil moisture by the following equation:

$$\sigma = W^{\alpha}\beta \quad (6)$$

where σ is the ground conductivity (in S/m); W is the fractional water content of soil, or soil moisture; α is a constant that lies between 1.5 and 2.2 and β is the conductivity of water in the soil.

The only challenge of directly using the above equation comes from β, because it varies with other properties such as the temperature and salinity of the water in the soil. However, since fresh water contains much less salt than seawater, the effect of salinity may be ignored as compared to the effect of temperature in this case.

It has been suggested that although the relationship between water conductivity and temperature is generally nonlinear, the degree of nonlinearity may be small enough for this relationship to be represented by a linear equation instead [9]. This is expressed as:

$$EC_t = EC_{25}\,[1 + a\,(t - 25)] \quad (7)$$

where EC_t is the conductivity of water at temperature t °C; EC_{25} is the conductivity of water at 25 °C and a is a temperature compensation factor which lies around 0.02 °C^{-1}.

III. Results and discussion

The time delay fluctuations of Loran-C pulses transmitted from the Lessay station and received at Bath, between 1 February 2012 and 21 February 2012, was used in the following analysis. The signals were recorded at the University of Bath campus using the low-frequency receiver module described in [10]. Measured delays at around 00:00, 06:00, 12:00 and 18:00 UTC were selected for each day for a direct comparison with the 6-hourly data from ECMWF. In Figure 2 below, each data sample in the time series is the deviation in delay with respect to a reference delay on 18 February 2012.

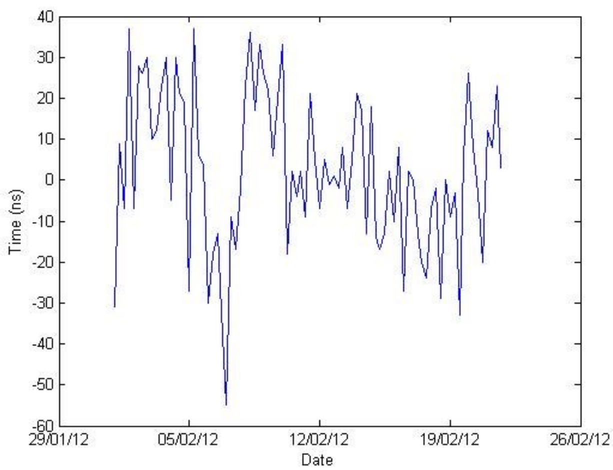


Fig. 2. Measured Loran-C delay fluctuations along the signal propagation path

Modeled soil temperature and soil moisture data at 1.5° × 1.5° spatial resolution (and with a temporal resolution of 6 hours) was retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis data set for the same period. For the Interim Reanalysis (January 1979 onwards) and the 40 Years Reanalysis (September 1957 to August 2002), ECMWF adopts the same multilayer model where the soil is discretized into four layers [11]. The first three layers, 0-7 cm, 7-28 cm and 28-100 cm, are considered here.

Also retrieved from the Interim Reanalysis were atmospheric data fields, which included 2 m temperature, surface pressure and total column water vapor. Since PF is not time invariant due to changes in the atmospheric refractive index η, the variations in PF were calculated using the retrieved atmospheric data and then removed from the measured delays at the beginning of the analysis.

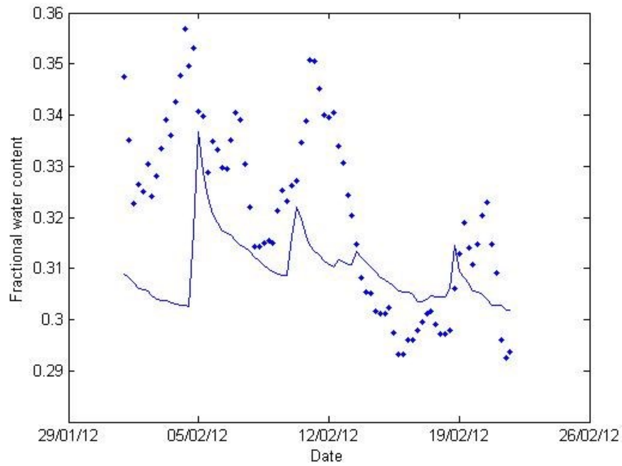
The direct signal propagation path between Lessay and Bath shown in Figure 3 is approximately 250 km in length, and it consists of both land and seawater. The electrical conductivity of the seawater path (~105 km) is expected to remain relatively constant over the 3-week measurement period. According to Interim Reanalysis data, the soil moisture for the land path in England (~95 km) is significantly higher than the land path on the French side of the channel (~50 km), which clearly suggests that its conductivity variations will contribute more to the overall delay fluctuations. Over the time period, the mean surface layer (0-7 cm) soil moisture along the French section of the propagation path is less than 10% compared to over 30% on the other side of the English Channel.

Fig. 3. Map showing the Loran-C propagation path between Bath and Lessay (Image from Google TM Earth).

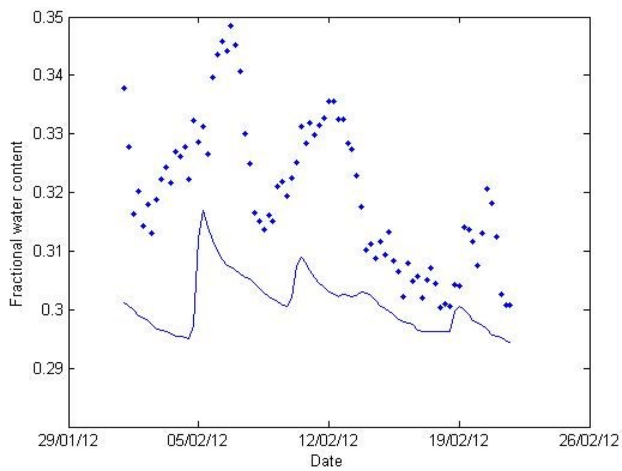
The location for the retrieval of ECMWF data is chosen to be between the South Coast of England and Bath. Since the ECMWF data set is on a 1.5° × 1.5° latitude-longitude grid, the retrieved data fields represent the English section of the propagation path. In the following analysis, it is assumed that the ground conductivity at the time of the reference delay for this location is 0.006 S/m, and that an increase in time delay of 50 ns represents a decrease in conductivity of 0.001 S/m. This allows the conductivity variations during the 3-week period to be revealed, which in turn lead to the determination of soil moisture using equations 6 and 7 where α and a are chosen as 2 and 0.02 ℃$^{-1}$ respectively.

The time series comparison of estimated and modeled soil moisture for the 0-7 cm layer (Figure 4a) shows good agreement between the two data sets, with linear correlation coefficient $\rho = 0.4$ ($p = 0.0002$). For the 7-28 cm layer (Figure 4b), the two also reveal similar features. However, the Loran-C estimated soil moisture appears to be overestimated for this layer. This is as expected because in Figure 4a, the assumed reference conductivity of 0.006 S/m was chosen for this layer to bring the two sets of values into alignment. The 7-28 cm layer is less affected by precipitation than the surface layer and is therefore predictably drier overall. By slightly adjusting the reference conductivity, the Loran-C estimated soil moisture also displayed good correspondence with the ECMWF product. Deeper into the unsaturated zone, the 28-100 cm layer is insensitive to precipitation as can be seen in Figure 4c. The Loran-C method is unable to produce an accurate estimation of soil moisture for this layer. The Loran-C estimated soil moisture is different in each figure as they were calculated using ECMWF soil temperature data at the corresponding depth. The precipitations pattern during the 3-week period (Figure 5) shows a strong correlation between precipitation and soil moisture, where the peaks are echoed by distinct transient increases in soil moisture.

a)



b)



c)

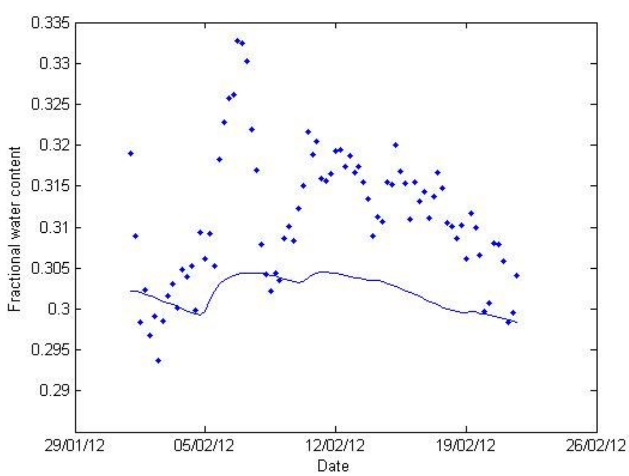


Fig. 4. Comparison between Loran-C estimated soil moisture (dashed line) and the ECMWF soil moisture product (solid line); a) 0-7 cm, b) 7-28 cm and c) 28-100 cm.

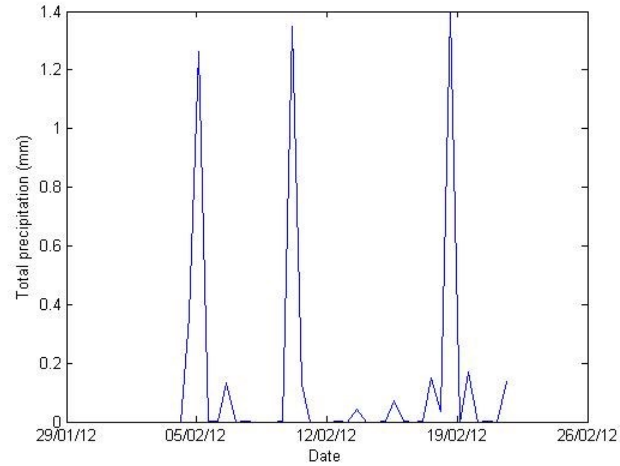


Fig. 5. Precipitation over the measured domain

IV. Conclusions

This paper presents a novel method for the continuous monitoring of wide-area soil moisture. The estimated soil moisture using the Loran-C method demonstrates clear correspondence with validation data at soil depth of 0 to 28 cm. This represents an improvement over current space-borne measurements in terms of not only the temporal resolution, but also the retrieval depth. The Loran-C derived soil moisture requires an assumption of soil conductivity at a reference time and location. Hence an external source of soil moisture data is required to initialize the Loran-C soil moisture retrievals.

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