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

Yi Feng and Ivan Astin

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 our study, a novel method for the remote sensing of 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 three-week period at the University of Bath, Bath, U.K., from a Loran-C transmitting station in Northern France. Model data from the European Centre for Medium-Range Weather Forecasts (ECMWF) were used for calculation, calibration, and intercomparison. Reasonable correspondence between the soil moisture estimated using the Loran-C method and the ECMWF product was found for a soil depth of 0–28 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 preestablished method for continuously measuring near-surface soil moisture on a wide scale.

In recent years, efforts worldwide have focused on the use of satellite-based and 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).

The SMOS satellite was developed by the European Space Agency as part of its Living Planet Program. It was launched on November 2, 2009 and then entered routine operations in May 2010. Being placed in a sun-synchronous orbit, the SMOS satellite passes over a location on Earth at 6 A.M. and 6 P.M. local solar time (LST). The payload of the SMOS satellite 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.

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The authors are with the Department of Electronic and Electrical Engineering, Faculty of Engineering and Design, University of Bath, Bath BA2 7AY, U.K.

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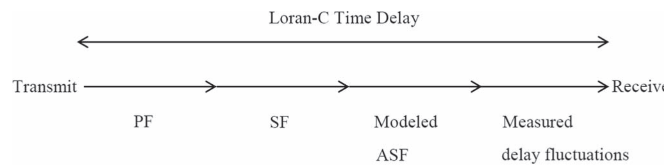

Fig. 1. Factors affecting the time delay of Loran-C signals.

On board the National Aeronautics and Space Administration's Aqua satellite is the AMSR-E. Unlike its European counterpart, it measures the brightness temperature at six different frequencies, i.e., 6.9, 10.6, 18.7, 23.8, 36.5, and 89.0 GHz. The crossing time of the 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 the temporal resolution and subsurface sampling, it has been suggested in [2] that changes in wide-area soil moisture can be deduced from the finite electrical conductivity of soil, which may be inferred from the delay fluctuations in low-frequency radio signals traveling along the ground. In this letter, we wish to validate this using low-frequency Loran-C navigation signals.

II. Background

The method presented in this letter is a variation of that reported by Scheftic *et al.* [2], where the time delay rather than amplitude variations in low-frequency signals is used to infer changes in ground conductivity. This section describes what influences the time delay of Loran-C signals and how the time delay is related to near-surface electrical conductivity and soil moisture (see Fig. 1).

Loran-C is a hyperbolic navigation system that operates in the 90–110-kHz frequency band with a carrier frequency of 100 kHz. Loran-C stations can be found in Europe and East Asia. They are grouped in chains of three to six stations, each transmitting regularly spaced pulses. A transmission chain consists of a master station and at least two secondary stations.

Loran-C signals propagate as either a ground wave or a sky wave. In this letter, 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 SF (ASF) [3].

The PF is the atmospheric delay, which is governed by the refractive index of the atmosphere. The refractive index, i.e.,

η, can be determined by the knowledge of the atmospheric temperature (T in Kelvins), the pressure (p in millibars), and the partial pressure of water vapor (e_s in millibars), which are used to calculate refractivity N and, hence, the refractive index [4]. These are given by the following equations:

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

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

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

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

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

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

When $d \leq 100$ statute miles ($\sim$160 km), we have

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

When $d \geq 100$ statute miles, we have

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

The ASF compensates for the 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, the ASF depends on the 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 the ASF can be found from generalized curves derived numerically (e.g., see [6]).

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 [7]).

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, see [8].

The Loran-C time delay may be also influenced by topography, particularly in mountainous regions, that increases the effective propagation distance. To improve navigation accuracy, modeled ASFs, which are 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 be only represented by real-time measurements of Loran-C delay fluctuations.

Near-surface electrical conductivity variations may be inferred from measured Loran-C delays with the assumption of nominal average conductivity and a linear delay–conductivity relationship. The conductivity is related to soil moisture by the following equation:

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

where σ is the ground conductivity (in siemens per meter), 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 aforementioned 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 with 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

$$\text{EC}_t = \text{EC}_{25}\left[1 + a(t - 25)\right] \quad (7)$$

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 100-kHz Loran-C pulses transmitted from the Lessay Loran-C station and received at Bath between February 1, 2012 and February 21, 2012 were used in the following analysis. The signals were recorded at the University of Bath campus using a low-frequency receiver module described in [10]. Measured delays at around 00:00, 06:00, 12:00, and 18:00 coordinated universal time (UTC) were selected for each day for a direct comparison with six-hourly interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). In Fig. 2, each data sample in the time series represents the deviation in the delay with respect to a reference delay on February 18, 2012.

The modeled soil temperature and soil moisture at 1.5° × 1.5° spatial resolution (and with a temporal resolution of 6 h) were retrieved from the interim reanalysis. For the interim reanalysis (January 1979 onward) and the 40-year reanalysis (from September 1957 to August 2002), the ECMWF adopts the same multilayer model where the soil is discretized into four layers. The first three layers, i.e., 0–7 cm, 7–28 cm, and 28–100 cm, are considered here. For a comprehensive overview of the ECMWF data assimilation system, see [11].

In addition, retrieved from the interim reanalysis were atmospheric data fields, including 2-m temperature, surface pressure, and total column water vapor. Since the PF is not time invariant

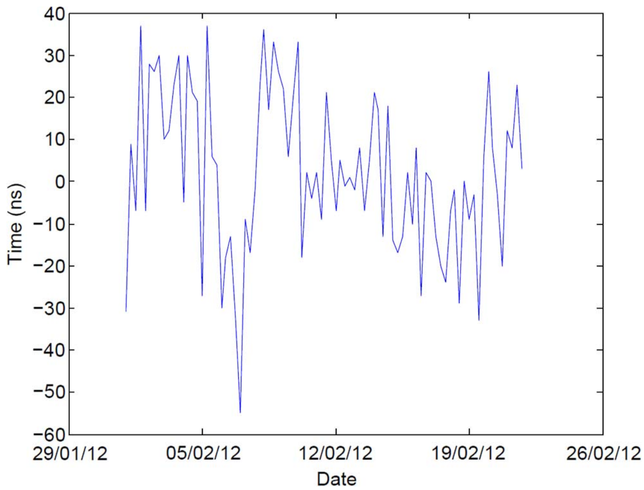

Fig. 2. Measured Loran-C delay fluctuations along the propagation path.

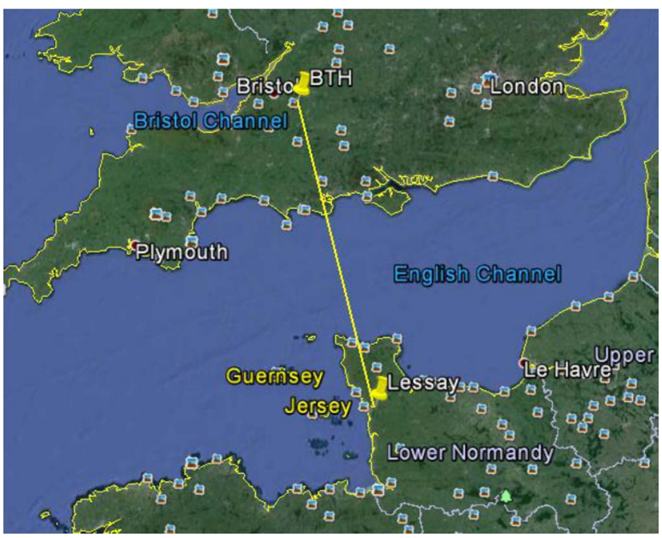

Fig. 3. Map showing the Loran-C propagation path between Bath and Lessay (image from Google Earth).

due to changes in the atmospheric refractive index η, the variations in the PF were computed using the retrieved atmospheric parameters and then removed from the measured delays at the beginning of the analysis.

The direct signal propagation path between Bath and Lessay is approximately 250 km in length (see Fig. 3). It consists of a seawater path and two land paths. The electrical conductivity of the seawater path ($\sim$105 km) is expected to remain relatively constant over the three-week measurement period. During this time period, precipitation occurred along both land paths. For this letter, the location for the retrieval of the ECMWF data is chosen to be between Bath and the south coast of England ($\sim$95 km). Since the ECMWF data set is on a $1.5^\circ \times 1.5^\circ$ Gaussian grid, the retrieved data fields represent the English section of the path.

In the following analysis, it is assumed that the ground conductivity at the time of the reference delay for the chosen location is 0.006 S/m and that an increase of 50 ns in the time delay represents a decrease of 0.001 S/m in the conductivity (the latter is derived from the modeled delays given in [7]). This

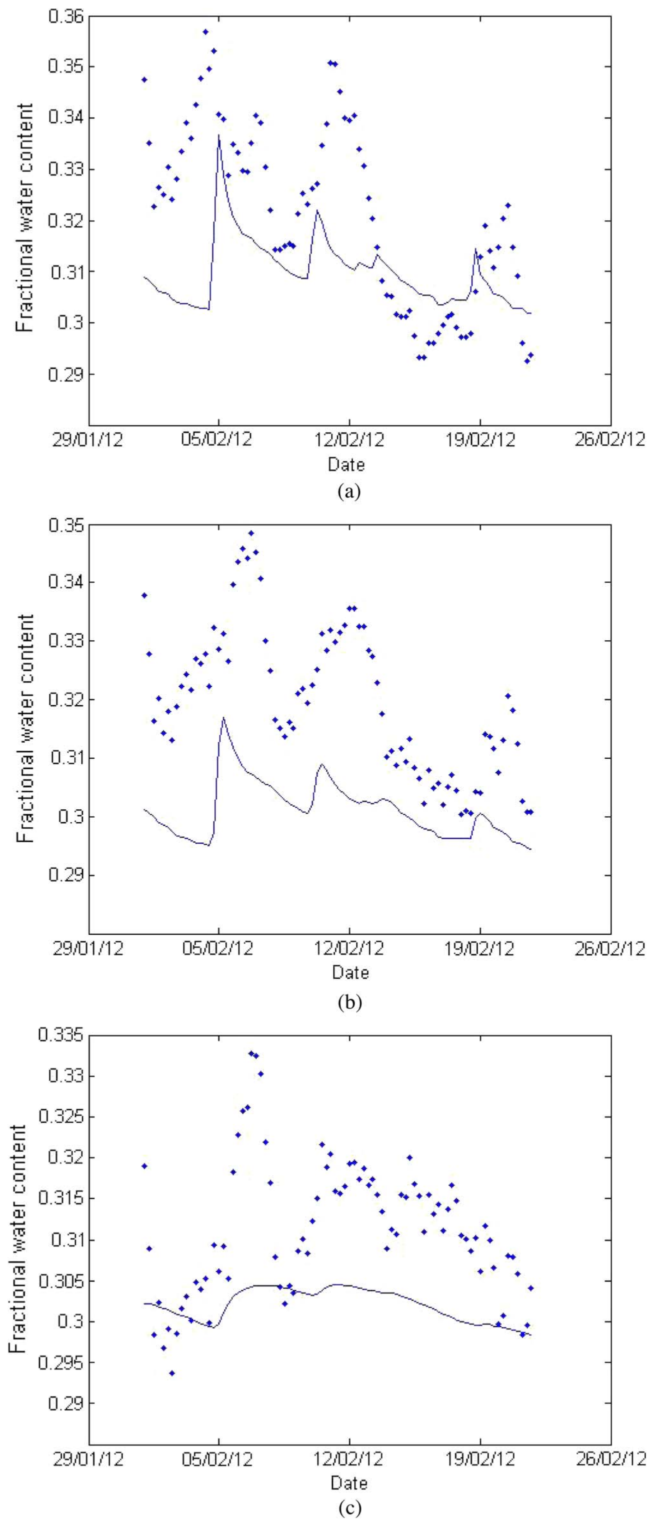

Fig. 4. Comparison between the Loran-C estimated soil moisture (dashed line) and the ECMWF soil moisture product (solid line). (a) 0–7-cm layer. (b) 7–28-cm layer. (c) 28–100-cm layer.

allows the conductivity variations during the three-week period to be revealed, which in turn leads to the determination of soil moisture using (6) and (7), where α and a are taken as 2 and $0.02\ {}^\circ\mathrm{C}^{-1}$, respectively.

The time series comparison of the estimated soil moisture and the modeled soil moisture for the 0–7-cm layer

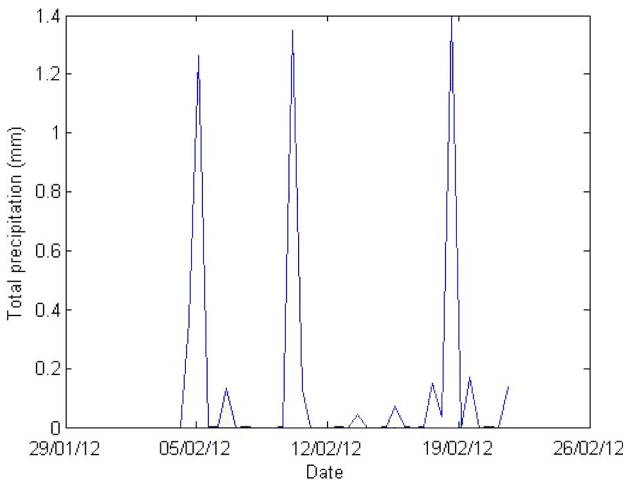

Fig. 5. Precipitation over the measured domain along the English section of the Loran-C propagation path.

[see Fig. 4(a)] shows relatively good agreement between the two data sets, with linear correlation coefficient $\rho = 0.4$ $(p = 0.0002)$. For the 7–28-cm layer [see Fig. 4(b)], 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 Fig. 4(a), 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 root zone, the 28–100-cm layer is insensitive to precipitation, as shown in Fig. 4(c). 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 it was computed using the ECMWF soil temperature data at the corresponding depth. The precipitation pattern during the three-week period (see Fig. 5) shows a clear correlation between precipitation and soil moisture, where the peaks are echoed by distinct transient increases in soil moisture. Overall, the Loran-C method has slightly overestimated the soil moisture in southern England since precipitation events in northern France may have also contributed to the measured delays.

IV. Conclusion

This letter has presented a qualitative validation of the method described in [2] for the continuous monitoring of wide-area soil moisture. It was discovered that there are properly timed variations in near-surface electrical conductivity associated with precipitation events, and these conductivity variations show a time evolution that best matches soil moisture changes with a depth of less than 28 cm in the ECMWF land surface model. This represents an improvement over current spaceborne 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. Validation results suggest that the chosen reference conductivity may need to be lowered for the 7–28-cm layer because of drier soil conditions.

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