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WIDE-AREA SOIL MOISTURE ESTIMATION USING THE PROPAGATION OF LIGHTNING GENERATED LOW-FREQUENCY ELECTROMAGNETIC SIGNALS

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1. INTRODUCTION

Land surface moisture measurements are central to our understanding of the earth's water system, and are needed to produce accurate model-based weather/climate predictions. For weather forecasting in particular, soil moisture is an essential boundary condition for coupling with atmospheric dynamics. Wide-area soil moisture measurements are also important for land use planning, agriculture and water management. Currently, there exists no in-situ network capable of estimating wide-area soil moisture.

Several methods currently exist that are used for estimating soil moisture. One method is the use of in-situ soil moisture probes that measure the soil at a point location. The benefit of these observations is that they retrieve an accurate measurement at several different depths up to a few meters. However, these measurements are point samples taken on a very sparse spatial network and they are poor at representing wide-area soil moisture in areas dominated largely by convective precipitation. Implementing an effective continental scale network of these soil moisture probes would be prohibitively expensive.

There are also a variety of techniques available for estimating soil moisture on a wide-scale with satellites. Walker and Houser (2004) determined that any remote sensing based measurement system should have a spatial resolution better than the land surface models (LSM) (~ 50 km), a temporal resolution of a few days, and accuracy within 5% of the volumetric fraction to effectively model changes in soil moisture.

The Advanced Microwave Scanning Radiometer for EOS (AMSR-E) is a passive scanner that has the ability to estimate soil moisture down to about 60 km spatial resolution twice a day (Njoku et al. 2003). While, AMSR-E may have adequate spatial resolution, it can only estimate the moisture in the top few centimeters of the soil. Also, due to signal attenuation by vegetation, this technique is optimal only over barren land.

Another method that uses satellites is the Gravity Recovery and Climate Experiment (GRACE). Two satellites are paired together in orbit and the precise change in distance between the two can be processed to yield information about the gravitational field of the column of Earth below the satellites. Changes in the gravitational field can yield information about total column water storage change at a spatial resolution of around 400 km. GRACE fully scans the Earth once every month (GRACE 2004). GRACE is most useful for long-term groundwater storage monitoring, but does not have adequate resolution for near-surface soil moisture monitoring.

While adequate near-surface soil moisture measurements may be obtained through space-based passive microwave radiometers, there is no direct method for estimating the soil moisture below the surface. The soil moisture at depths down to around 1 meter is currently estimated through use of LSMs and significant differences can arise between different models (Schaake et al. 2004).

In this paper, we explore an alternative method of estimating soil moisture through the effect that soil moisture has on finite electrical conductivity of the soil and on the resulting surface propagation of low-frequency (LF) and medium-frequency (MF) electromagnetic waves. The waves in this frequency range are significantly impacted by the conductivity of the soil at depths up to several meters.

Two sources of electromagnetic waves in these frequencies are being explored. The first source is the risetime of lightning generated broadband electromagnetic waves as measured by the U.S. National Lightning Data Network (NLDN) (Cummins et al. 1998). The use of the NLDN sensors can also be extended to include monitoring the signal attenuation and phase changes of anthropogenic radio transmissions such as amplitude modulated (AM) radio signals. It is a goal of this project to use the existing infrastructure of the NLDN and Canadian Lightning Detection Network (CLDN) to detect, locate, and quantify both long-term and short-term changes in soil moisture over North America with a spatial resolution of about 30 km.

2. BACKGROUND

Electromagnetic fields in the Low-Frequency (LF) range (~30 kHz to 300 kHz) and Medium-Frequency (MF) range (~300 kHz to 3 MHz) can propagate as a ground-wave for hundreds of kilometers over finite-conductivity ground with modest but measurable losses. These losses can be described by an attenuation function and phase shift, both of which increase with increasing angular frequency. The specific nature of these losses is well-understood, as described by Wait (1985), and is a function of source height above ground, effective surface conductivity, permittivity, and propagation distance. For frequencies below about 1 MHz and conductivities above 1 mS/m, permittivity has little effect on the attenuation function.

A representative example of the attenuation as a function of frequency is shown in Figure 1, where the propagation distance is 100 km, and the source is on the earth's surface. The red curve shows the attenuation (fraction of the initial signal amplitude) as a function of frequency, and the dashed blue curve shows the phase change (in Radians). Note that significant conductivity-related changes in both attenuation and phase occur in the frequency range of 100 kHz to 1 MHz.

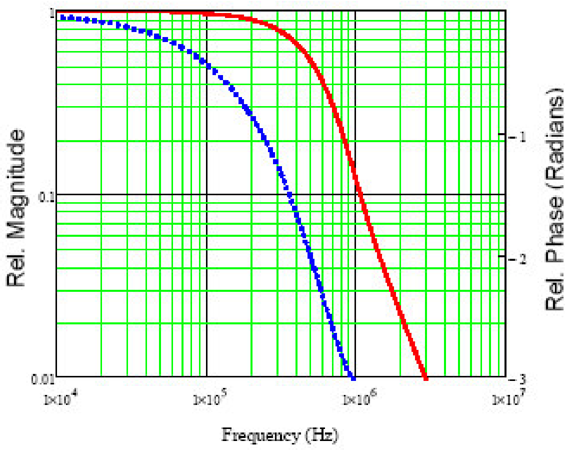

Figure 1. Signal Attenuation (red line) and phase characteristics (blue dotted line) for an EM wave propagating along the earth's surface. Conductivity = 10 mS/m; Propagation distance = 100 km.

Any wide-area time-varying changes in near-surface (a few meters) electrical conductivity of the ground can be monitored using LF/MF "probe" signals. A particularly important example is changes in soil moisture, which has an extremely strong influence on the electrical conductivity of the soil. Our recent work (Sternberg, in preparation) relating changes in soil moisture to changes in electrical conductivity has demonstrated that their relationship is only weakly dependent on soil properties, as exhibited in Figure 2.

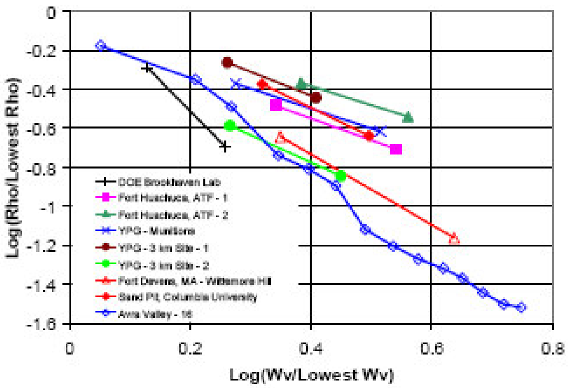

Figure 2. The log of resistivity change vs. the log of water volume change for 9 widely-varying soil samples.

These samples represent a broad variety of soil types, with resistivities ranging from tens of ohm-meters to thousands of ohm-meters. They include very clean sands (Brookhaven, Fort Devins, and Columbia University) with very little clay content, as well as clay-rich soils (Avra, Yuma (YPG), Fort Huachuca). Despite the wide variety of geologic conditions, these samples show a reasonably consistent trend for the dependence of change in resistivity on the change in water content. If we combine these datasets with no correction for soil type, we see that 75% of the variance in these data can be accounted for by a single power-law expression with an exponent of 1.82 (Figure 3).

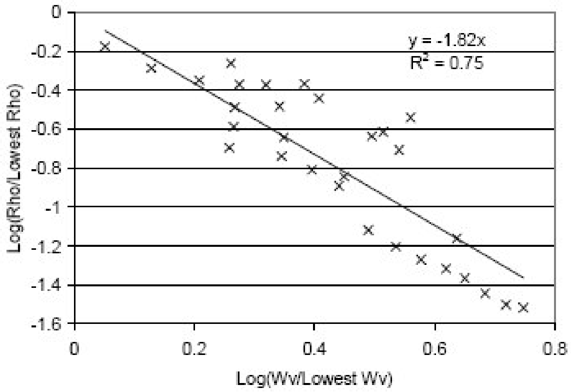

Figure 3. The log of resistivity change vs. the log of water volume aggregated over all soil samples.

3. LIGHTNING METHOD

3.1 Lightning background

The signal transfer behavior shown in Figure 1 produces measurable changes in the initial risetime of fast-rising time-domain waveforms, such as those produced by cloud-to-ground (CG) lightning strokes. This effect has been demonstrated by Bardo et al. (2004) and Cummins et al. (2005) who used CG lightning data derived from the NLDN data archive.

A hypothetical example of how the risetime is affected by the conductivity of the soil is given in figure 4. The input wave (blue) was propagated over a distance 150 km at three surface conductivity values: 15 mS/m (magenta), 5 mS/m (cyan), 3 mS/m (maroon). The graph visually illustrates both a phase delay and a risetime variation of the wave. If the risetime is measured from 10% of the peak amplitude to the peak, the risetimes for 15 mS/m, 5 mS/m, and 3 mS/m are 4.2 µs, 4.6 µs, and 4.9 µs respectively.

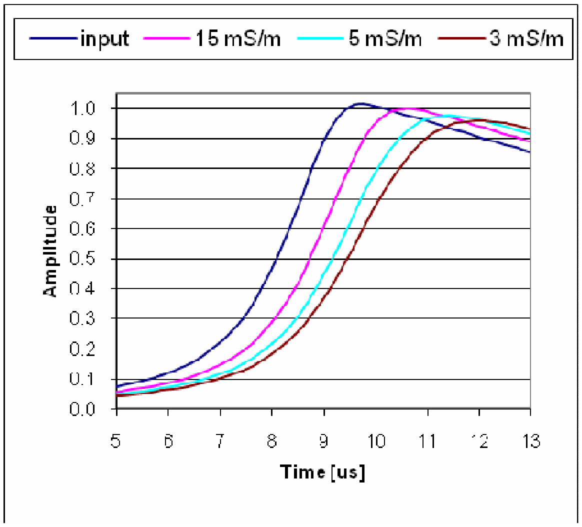

Figure 4. Propagation of a lightning-like input signal (blue) over a distance of 150 km at conductivities of 15 mS/m (magenta), 5 mS/m (cyan), and 3 mS/m (maroon).

Figure 5 shows a national-scale thematic map of the average field risetime of negative first-strokes of CG lightning over the U.S. for a two year period. The "cooler" colors (blue to green) correspond to the short (fast) risetimes (1 to 5 µs), and the "warmer" colors (yellow to red) correspond to longer (slower) risetimes (6 to 12 µs). A "hot pink" color is reserved for risetimes greater than 12 µs (the lowest conductivity). The most prominent features in this figure are the high risetime areas (>12 µs) that coincide with the eastern portion of the Canadian Rockies. These "hot spots" are surrounded by areas that have risetimes in the range of 6 to 12 µs, which generally reflect the low conductivity (1-2 mS/m) of the horse-shoe shaped Canadian Shield and the Canadian Rockies.

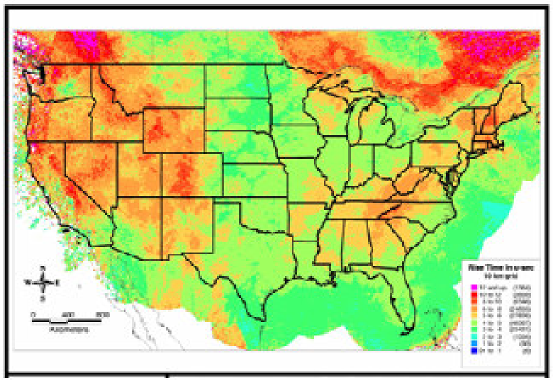

Figure 5. Thematic map showing the average risetime of negative first stroke cloud-to-ground lightning (10x10 km^2).

Monitoring the changes in the risetime of CG lightning will enable us to estimate changes in electrical conductivity. Over non-frozen ground, the most pronounced changes in conductivity are due to changes in soil moisture. So, even though the absolute risetime information in figure 5 is not enough to estimate soil moisture, the changes in risetime from the mean value allows us to estimate changes in soil moisture.

3.2 Validation source

In order to test the efficacy of using changes in the lightning risetimes as a proxy for soil moisture there needs to be a method for estimating the wide-area soil moisture for validation purposes. Unfortunately, there is no perfect method for estimating soil moisture available today. It would be preferable to have a wide area network of soil moisture probes such as the time-domain reflectometer (TDR) probes used by the USDA-ARS in the San Pedro river basin in southeastern Arizona. Such networks are rare and do not cover much of the continental U.S,, therefore an LSM such as the NOAH LSM used in the North American Region Reanalysis (NARR) (Mesinger et al. 2005) has been used in this study to estimate soil moisture. NARR uses a wide variety of observations (gauge derived precipitation, temperature, pressure, wind, and humidity) in combination with a full atmospheric model and the NOAH LSM to provide an analysis of the conditions of the atmosphere as well as the soil moisture and temperature at 4 depths down to 2 meters.

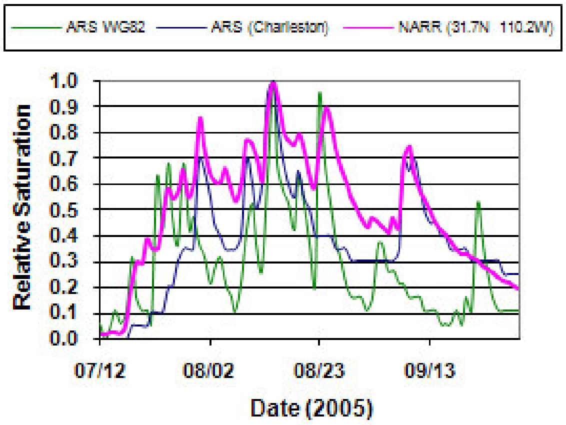

Figure 6. Scaled (relative saturation) daily volumetric soil moisture from NARR (0-10 cm) (magenta), Charleston, AZ (5 cm) (blue), and Walnut Gulch (Green) for the summer of 2005.

Figure 6 shows how grid-volume soil moisture for the top 10 cm in NARR compares to ARS in-situ measurements at 5 cm. The in-situ measurements come from Charleston, AZ and Walnut Gulch (WG gauge 82) which are separated by 15 km and are both in the grid-box of the NARR estimates. This figure shows strong similarities in the shapes and modulation between NARR and the ARS measurements, but there are still significant differences between the sets of data. Due to the sparse nature of convective precipitation during the summer monsoon in southeastern Arizona, a precipitation event that was modeled in NARR to have produced precipitation over the grid-box may not have actually had precipitation at the precise location of the soil moisture probes in Charleston, AZ or Walnut Gulch. NARR has also been shown to miss precipitation events, likely because no precipitation fell at any of the gauges that are assimilated into NARR. Other limitations include shortcomings associated with the NOAH LSM representation of changes in soil moisture at the 4 model depths.

3.3 Validation results

Figure 7 shows an illustrative example of how soil moisture evolved in the southwestern U.S. throughout the 2005 summer monsoon season, together with the risetime of NLDN lightning waveforms recorded by a sensor in Lordsburg, NM. Figure 7a shows three successive periods in July and August of 2005. The first period (7-Jul to 22-Jul) is during the monsoon onset and shows relatively long risetimes corresponding to low soil moisture; as the monsoon progresses, risetimes quickly decrease, reaching a minimum in mid-August. Figure 7b shows the NARR soil moisture (0-10 cm) and risetime for each lightning event over the monsoon period for a path between Tucson, AZ and Lordsburg, NM. All the lightning events used to estimate the conductivity for the path occurred in the rectangular box that's highlighted in the maps of Figure 7a. The soil moisture in Figure 7b corresponding to each of the three periods of Figure 7a are shaded olive green, purple and light blue for 7-Jul to 22-Jul, 23-Jul to 7-Aug, and 8-Aug to 23-Aug respectively. The time-variation of NARR soil moisture agrees well with the time-variations in risetime in the three maps. The risetimes for each lightning event (blue dots) are shown to illustrate the inherent variability in the waveform characteristics of lightning. Only through use of a statistical average of risetimes can meaningful information be deduced. A 6th order polynomial fit is drawn overtop the risetimes to show that there is a drop off in risetimes throughout the season that can be estimated even within the large variance of the measurements.

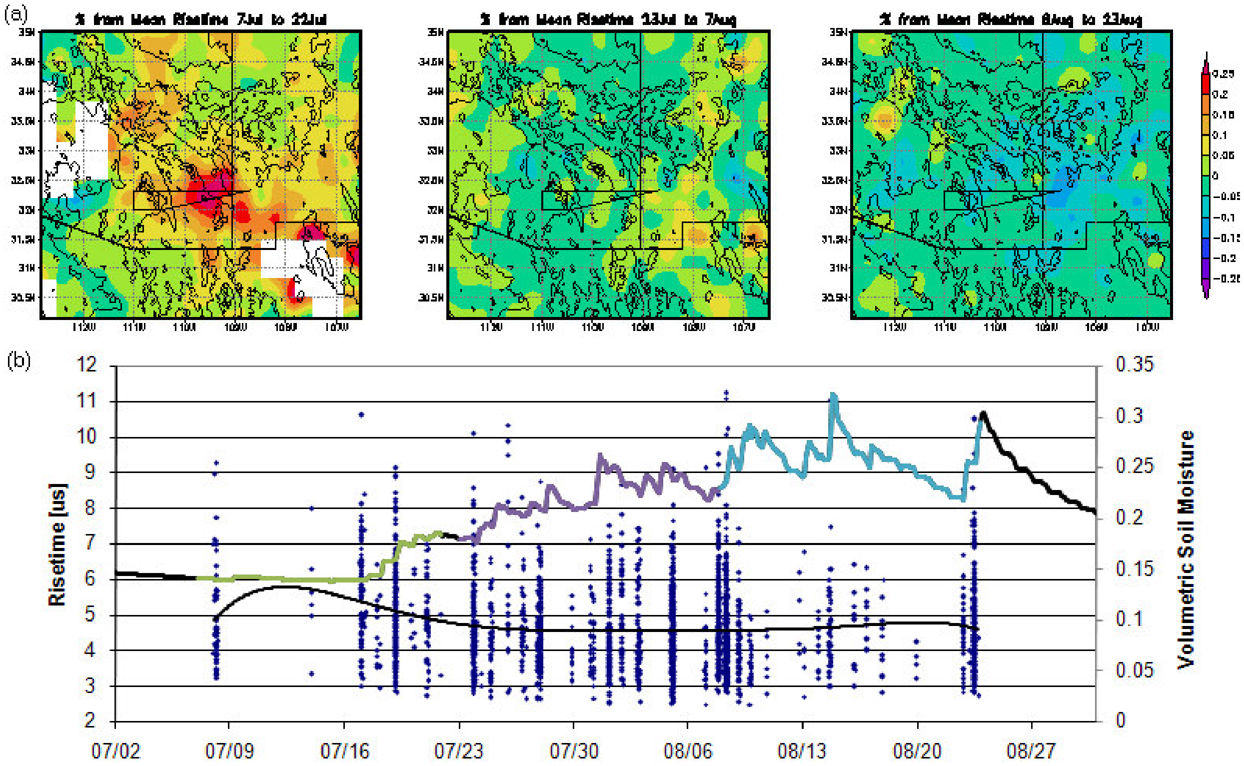

Figure 7. (a) Three successive periods of the variation (in percent) of soil moisture (shaded) over S AZ and S NM. (b) The volumetric soil moisture (0-10 cm) from Tucson to Lordsburg, NM (line) and the risetime (marks) for each lightning stroke in the box (32-32.3N 110.5-111W) labeled on the maps over the 2005 monsoon season.

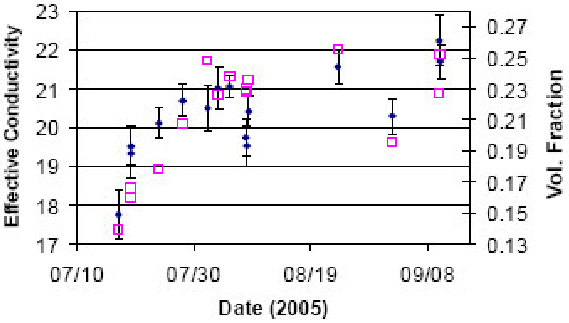

Figure 8. Time-evolution of estimated electrical conductivity (blue symbols with 1-sigma error bars) and NARR-estimated soil moisture (0-10 cm) in south-western Arizona for the summer of 2005.

Soil moisture estimates obtained along a path from Tucson to Lordsburg, NM in southeastern Arizona during the summer of 2005 using lightning data as the "probe" are shown in Figure 8 (blue symbols with 1-sigma error bars). The 1-sigma standard error bars of conductivity (100/risetime) are based on the variability of risetime seen in figure 7b. Only lightning "events" with greater than 35 strokes are shown. The "conductivity" units are arbitrary, but the data are linearly scaled to visually overlay on the volume fraction of water for the 0-10 cm depth (magenta squares) produced by NARR for the same region and time periods. Figure 8 shows good correspondence between the two measurements, given the uncertainties in both datasets.

Lightning-based estimates of changes in soil moisture have unique and useful properties for tracking long-term changes in water storage. Given the long wavelengths (large penetration depth) of the lightning signal, a depth-integrated measurement of soil moisture can be obtained. Also, each measurement (storm) provides an independent estimate of the relative electrical conductivity (and therefore water content), with no requirement for models involving temporal integration of near-surface measurements or estimates of soil hydraulic properties. Finally, the necessary lightning data have been archived since 1995, providing a 13-year historical dataset that can be useful for assessment of climate variability.

However, it is clear that lightning-based measurements are not available for all locations on a continuous basis. This limitation is addressed by the radio-based method discussed below.

4. RADIO TRANSMISSION METHOD

In addition to its effect on lightning waveforms, the signal transfer behavior shown in Figure 1 also produces measurable changes in the signals produced by anthropogenic transmitters. For example, the carrier signal for an amplitude-modulated (AM) transmitter at 700 kHz measured over a 100 km path with average conductivity of 10 mS/m will exhibit a 70% signal loss, as can be seen from Figure 1. The distinct benefit of radio signals is that there are thousands of continuous transmitters distributed throughout North America.

During the summer of 2007, soil moisture estimates using radio transmissions (referred to as the RadioTX method) were evaluated in the San Pedro Basin using a small network of LF/MF radio receivers. Results for the period of July 1 through September 30 are shown in Figure 9. The source was a commercial AM radio station operating at 830 kHz in Tucson, Arizona, and the relative signal values (proportional to electrical conductivity) were obtained between receivers in Benson and Tombstone, Arizona (40 km separation).

Independent measurements of the relative amplitude were obtained every three hours. Estimates for periods commencing at 17, 20, 23 UTC are overlaid on Figure 9a. There is greater variability between these three estimates early in the season, so the measurement durations were steadily increased from July 1 until August 5 to improve the signal-to-noise ratio. Even after August 5, the measurement duration used less than one second of the available observation time (per hour), which indicates that reliable estimates can be made every minute, if desired.

The 0-10 and (averaged) 0-40 cm soil moisture estimates for the primary overlapping NARR region are shown in Figure 9b. Note that there is a very good correspondence between the datasets in Figure 9a and 9b starting with a significant precipitation event on July 22, and continuing through August 7. After that time, the electrical conductivity (relative magnitude) falls off more-slowly than the near-surface NARR estimate, presumably because of the increased soil moisture at greater depth as a result of persistent rainfall over the previous few weeks.

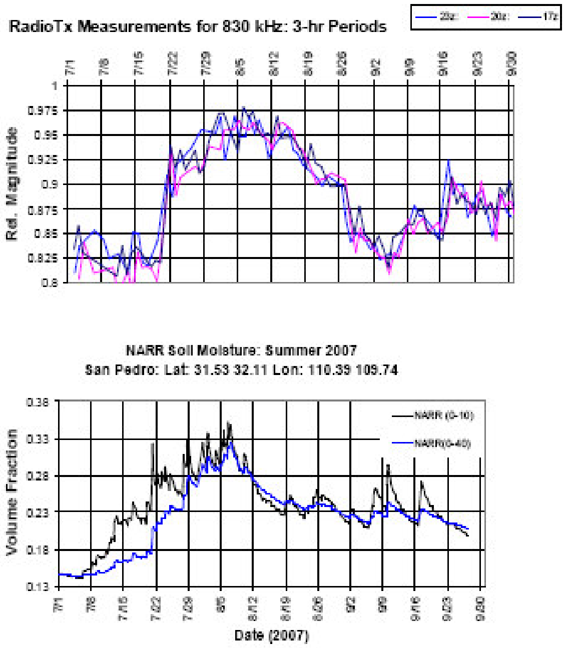

Figure 9. Inferred electrical conductivity change (a) and NARR estimated soil moisture (b) for the summer 2007 monsoon season in the San Pedro Basin, Arizona.

Continued quantification and validation of the RadioTX method is ongoing. Measurements through November 2007 will be directly compared with in-situ soil moisture measurements at various depths, obtained by the USDA/ARS. Relative magnitude measurements will be converted to changes in soil moisture using the relationships shown in Figure 2. A second field campaign in central Oklahoma is planned for spring and summer of 2008.

5. SUMMARY

Through use of the known effects the finite ground conductivity has on the propagation of MF/LF electromagnetic waves, this paper introduces two related methods for estimating soil moisture. The first method involves the use of lightning impulse risetimes. It was shown that changes in land surface model (LSM) estimated soil moisture (from NARR) is related to changes in the average risetime of lightning waveforms using data from the NLDN sensor at Lordsburg, NM over the summer of 2005. The second method uses narrow-band anthropogenic radio transmissions. Using an 830 kHz AM transmitter in Tucson and two sensors in the San Pedro Basin, it was shown that changes in the attenuation between the two sensors were well-correlated with changes in soil moisture.

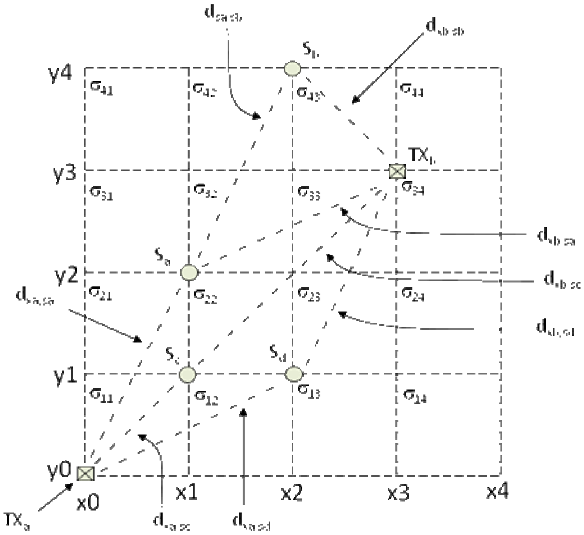

Figure 10. Illustration of how transmitters (TX) and sensors (S) can be used to construct the conductivity (σ) on a square grid assuming a known conductivity and distance between transmitters and sensors.

The long-term objective of this work is to provide continuous real-time measurements of changes in soil moisture throughout North America. The spatial domain over which the measurements will be "averaged" depends on the geometry and separation between the radio transmitters and the measurement stations. Figure 10 Illustrates how the geometry between different transmitters (TX_i) (AM radio or lightning) and sensors (S_i) can yield conductivity (σ_{ij}) profiles at different "grid boxes". If one uses the existing measurement capabilities and sensor locations of the NLDN and Canadian Lightning Detection Network (CLDN) (a total of ~190 sensor sites), the spatial resolution would be about 100x100 km. Increasing the number of measurement sites in the U.S. by an additional

200 should result in 30-50 km resolution. This approach would clearly be a cost effective way to obtain continuous wide-area estimates of soil moisture.

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