Soil moisture (and vegetation?) remote sensing products in Oklahoma

Jason Patton
Plant and Soil Sciences, Oklahoma State University

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The coupling between weather/climate and soil moisture is apparent in models.

(Koster et al. 2004)
Current regular soil moisture measurements are made at single points.
Point measurements may not represent larger scale averages of soil moisture.

(Bramer et al. 2013)
Weather and climate models need soil moisture data for initialization and validation at large spatial scales (>1 km), while in-situ measurements are available at point (~10 cm) scales.

Satellite remote sensing of soil moisture can provide global measurements of soil moisture at large spatial scales.
Outline

I. Soil Moisture and Ocean Salinity mission

II. Soil Moisture Active Passive mission

III. Cosmic-ray Soil Moisture Observing System
**SMOS** is the Soil Moisture Ocean Salinity satellite mission.

European Space Agency

Launched November 2009

**Passive** L-band (1.4 GHz, 21 cm)

43 km average resolution

Sensitive to top 3-5 cm of soil

Polar orbiting:
  - Measurements every 3 days at equator
  - More often at higher latitudes
The “tau-omega” model describes the natural emission of microwave radiation from Earth’s surface.

\[
T_B = T_{soil} (1 - R_{soil}) e^{-\tau/\mu} \quad (1)
+ (1 - e^{-\tau/\mu}) (1 - \omega) T_{veg} \quad (2)
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- \( R_{soil} = f(\)soil moisture, roughness\)"
- \( \tau \) is “vegetation optical thickness"
- \( \tau = f(\)vegetation water content\)
  \( = b \times \) veg water content (VWC)
- \( \omega \) = Veg Scattering Albedo
SMOS uses a multi-angular approach to simultaneously estimate soil moisture and optical thickness.
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\[ T_{B1} = T_{soil} (1 - R_{soil}) e^{-\tau/\mu_1} + \cdots \]
\[ T_{B2} = T_{soil} (1 - R_{soil}) e^{-\tau/\mu_2} + \cdots \]
\[ \vdots \]
\[ T_{Bn} = T_{soil} (1 - R_{soil}) e^{-\tau/\mu_n} + \cdots \]

where \( \mu = \cos(\theta) \)

SMOS also assumes \( \omega = 0 \).
Validation of SMOS has, so far, shown a slight dry bias in most cases, but it does capture dynamics well.

Vegetation optical thickness from SMOS is very noisy, but still may contain some information about vegetation.

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When using SMOS data, be considerate of the sensing depth, noise, radio frequency interference, and the grid spacing.

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SMOS data

L1 (brightness temps) and L2 (soil moisture, tau) available from ESA: https://earth.esa.int/web/guest/-/how-to-obtain-data-7329

Proprietary format, use BEAM or Matlab API (req. 64-bit Linux) to view or convert to more friendly formats:

BEAM: http://www.brockmann-consult.de/cms/web/beam
Matlab Read API: http://smos.array.ca/web/smos/matlab-tool

L3 (3-day/monthly soil moisture) available from CATDS in NetCDF: http://www.catds.fr/

Some L2 (soil moisture & tau *only*) available from the Iowa Environmental Mesonet: http://mesonet.agron.iastate.edu/smos
SMAP is the Soil Moisture Active Passive satellite mission.

Launching January 2015

Active and Passive L-band

3 km and 36 km resolutions
10 km combined active/passive

Sensitive to top 3-5 cm of soil

Polar orbiting:
  Measurements every 3 days at equator
  More often at higher latitudes
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\[
TB = T_{soil} \left(1 - R_{soil}\right) e^{-\tau/\mu} \quad (1)
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\(\tau = f(\text{vegetation water content}) = b \times \text{veg water content (VWC)}\)

\(\omega = \text{Veg Scattering Albedo}\)
The main difference between SMOS and SMAP passive soil moisture retrieval is multi-angle vs. single angle approach.
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<table>
<thead>
<tr>
<th>SMOS</th>
<th>SMAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band</td>
<td>L-band</td>
</tr>
<tr>
<td>Passive-only (43 km pixels)</td>
<td>Radar dissaggregation of passive pixels (36 km to 10 km)</td>
</tr>
<tr>
<td>Multi angle, retrieves $\tau$</td>
<td>Single angle, requires $\tau$</td>
</tr>
<tr>
<td>RFI plagued in regions</td>
<td>RFI mitigation built in</td>
</tr>
<tr>
<td>15 km ISEA grid (oversampled)</td>
<td>EASE-Grid 2.0 (grid spacing approx. matches resolution)</td>
</tr>
<tr>
<td>Already in orbit</td>
<td>Yet to be launched</td>
</tr>
</tbody>
</table>
The baseline SMAP soil moisture retrieval algorithm will require an outside source of vegetation data, will use an NDVI climatology to estimate $\tau$.

$$\text{NDVI} \rightarrow \text{Vegetation Water Content (VWC)} \rightarrow \tau$$

$$VWC = (1.9134 \times \text{NDVI}^2 - 0.3215 \times \text{NDVI}) + \text{stem factor} \times \frac{\text{NDVI}_{max} - \text{NDVI}_{min}}{1 - \text{NDVI}_{min}}$$

$$\tau = b \times VWC$$

(SMAP L2 Passive ATBD)
Under this baseline approach, SMAP may not be sensitive to interannual variability in vegetation.

(Patton, 2014)
SMAP data

All products will be available through NSIDC in HDF-5 format about a year after launch.

<table>
<thead>
<tr>
<th>Data Product Short Name</th>
<th>Short Description</th>
<th>Gridding (Resolution)</th>
<th>Latency*</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1A_Radar</td>
<td>Radar raw data in time order</td>
<td>-</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1A_Radiometer</td>
<td>Radiometer raw data in time order</td>
<td>-</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1B_S0_LoRes</td>
<td>Low resolution radar $\sigma_o$ in time order</td>
<td>(5x30 km)</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1B_TB</td>
<td>Radiometer $T_B$ in time order</td>
<td>(36x47 km)</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1C_S0_HiRes</td>
<td>High resolution radar $\sigma_o$ (half orbit, gridded)</td>
<td>1 km (1-3 km)**</td>
<td>12 hours</td>
</tr>
<tr>
<td>L1C_TB</td>
<td>Radiometer $T_B$ (half orbit, gridded)</td>
<td>36 km</td>
<td>12 hours</td>
</tr>
<tr>
<td>L2_SM_A</td>
<td>Soil moisture (radar, half orbit)</td>
<td>3 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L2_SM_P</td>
<td>Soil moisture (radiometer, half orbit)</td>
<td>36 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L2_SM_A/P</td>
<td>Soil moisture (radar/radiometer, half orbit)</td>
<td>9 km</td>
<td>24 hours</td>
</tr>
<tr>
<td>L3_F/T_A</td>
<td>Freeze/thaw state (radar, daily composite)</td>
<td>3 km</td>
<td>50 hours</td>
</tr>
<tr>
<td>L3_SM_A</td>
<td>Soil moisture (radar, daily composite)</td>
<td>3 km</td>
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<tr>
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<td>50 hours</td>
</tr>
<tr>
<td>L4_SM</td>
<td>Soil moisture (surface &amp; root zone)</td>
<td>9 km</td>
<td>7 days</td>
</tr>
<tr>
<td>L4_C</td>
<td>Carbon net ecosystem exchange (NEE)</td>
<td>9 km</td>
<td>14 days</td>
</tr>
</tbody>
</table>

* Mean latency under normal operating conditions (defined as time from data acquisition by the observatory to availability to the public data archive). The SMAP project will make a best effort to reduce these latencies.

** Over outer 70% of the swath.
COSMOS is the Cosmic-ray Soil Moisture Observing System

NSF project based out of University of Arizona

Passive neutron counting sensor

700 m sensing area

Sensitive to top 10-30 cm of soil (dependent on soil moisture)

http://cosmos.hwr.arizona.edu/
COSMOS is being deployed across the US, already two (project-sanctioned) sensors in Oklahoma.
COSMOS counts “fast” neutrons, which are related to soil moisture because hydrogen slows neutrons.
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COSMOS requires careful calibration, which can change over time in areas with large changes in vegetation water content.

\[ \theta_v(N) = a_0 N - a_1 - a_2 \] (1)

where: 
- \( \theta_v \) is the volumetric soil moisture; 
- \( a_0, a_1, a_2 \) are constants that are insensitive to soil type; and 
- \( N_0 \) is the maximum counting rate over dry soil (i.e. the rate that would be detected if the soil was perfectly dry). As the water content of the soil increases, the number of neutrons scattered by the soil towards the COSMOS sensor decreases.

Theoretically only one parameter, \( N_0 \), must be found to calibrate a COSMOS sensor for a particular site. We determined this calibration for the sensor at the IVS using the soil moisture measurements described in Section 3.1. Three of these calibrations are shown in Figure 3. The original calibration when the sensor was installed in September, 2010, is shown in black. At that time the IVS was covered with a crop of soybean. The two other calibrations were made during the 2011 growing season when the IVS was planted with maize. Note the difference in the three calibrations and especially the unreasonably–high soil moisture values for the May 19, 2011 calibration. The original September calibration is too dry in May and too wet in August.

At the same time that we took soil moisture samples we also sampled the amount of vegetation. The variation of \( N_0 \) as a function of the amount of vegetation, quantified by both the vegetation column density (mass of fresh vegetation per area) and the water column density (mass of water contained within vegetation tissue per area) is shown in Figure 4. Note the following. First, \( N_0 \) decreases as the amount of vegetation increases. From the COSMOS sensor's point of view, the counting rate for perfectly dry soil must be decreased in order to account for the additional water that is held in the vegetation. Second, the effect of vegetation on \( N_0 \) is non-linear. Third, there appears to be some hysteresis: the change in \( N_0 \) as the maize crop grew and accumulated mass is different than the change in \( N_0 \) during the period when the maize crop began to senesce and dry out. Perhaps the distribution of water within the canopy (among leaves, stems, and fruit) is important. Fourth, it appears that the effect of vegetation can be modeled, at least empirically.

4. CONTRIBUTION TO SATELLITE VALIDATION

As stated in Section 1, there is a need for additional soil moisture measurements to validate satellite products. COSMOS sensors have the potential to provide this soil moisture information. The following points should be considered.

1. Due to the sheer number of planned COSMOS sensors, it will be possible to organize dense sub–networks in specific regions of the U.S. where SMAP validation activities will occur.
2. Once installed, COSMOS sensors require little maintenance but may have to be regularly calibrated for growing vegetation.
3. COSMOS network data is provided free–of–charge with little latency (<1 day).
4. The large footprint (support) of COSMOS measurements as compared to traditional in–situ soil moisture (Hornbuckle et al 2012)
COSMOS data, publications, etc.

http://cosmos.hwr.arizona.edu/
Thank you

jason.c.patton@okstate.edu