In situ Sensor Networks for Satellite Soil Moisture Calibration and Validation

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               and many many more!

IEEE GRSS Workshop on Microwave Remote Sensing Agenda
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Presentation Outline

1. Motivation for *in situ* soil moisture Networks
   Context: NASA SMAP mission and surface soil moisture variability

2. Wireless Sensor Networks (WSN)
   SoilSCAPE Project

3. Highlights and Examples of Data/Science-use
1.4 GHz Radiometer at 40 km (-3 dB)
H, V, 3rd and 4th Stokes

1.2 GHz Radar 1-3 km (30% nadir gap)
HH, VV and HV (Failed; 2.5 Months of Data)

Conical scan at 14.6 rpm

Fixed incidence angle at 40°

Contiguous 1000 km swath 2-3 days revisit

Low-frequency microwave instruments with an offset-fed 6 m light-weight deployable mesh reflector.

Implementation

<table>
<thead>
<tr>
<th>Partners</th>
<th>JPL (project &amp; payload management, science, spacecraft, radar, mission operations, science processing)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GSFC (science, radiometer, science processing)</td>
</tr>
<tr>
<td>Risk</td>
<td>NPR 7120.5E Category 2; NPR 8705.4 Payload Risk Class C</td>
</tr>
<tr>
<td>Launch</td>
<td>January 31, 2015 on Delta II 7320-10C Launch System</td>
</tr>
<tr>
<td>Orbit</td>
<td>Polar Sun-synchronous; 685 km altitude</td>
</tr>
<tr>
<td>Duration</td>
<td>3-year Primary Mission (May’15 - Jun’18) w/ 3-year extended mission (Jun’18 – Sep’20) approved</td>
</tr>
<tr>
<td>Payload</td>
<td>L-band radar (JPL)</td>
</tr>
<tr>
<td></td>
<td>L-band radiometer (GSFC)</td>
</tr>
<tr>
<td></td>
<td>Shared 6-m rotating antenna (JPL)</td>
</tr>
</tbody>
</table>
SMAP Science and Application Returns

**Science Returns**

Soil Moisture *Links* the Global Land Water, Energy, and Carbon Cycles

1. Estimating global surface water and energy fluxes
2. Quantifying net carbon flux in boreal landscapes
3. Reduce uncertainty of climate model projections

**Applications Returns**

4. Enhancing weather forecasts
5. Improving flood prediction and drought monitoring

6m conically scanning (14 rpm) antenna for 1000 km swath
Global coverage every 2-3 days

L-band (~21 cm; All-Weather; Canopy Penetration; Sensing Depth)
SMAP Mission Concept

https://smap.jpl.nasa.gov/resources/74/smap-animation-full-version/
1. Soil moisture highly variable across the land-scape

2. Satellite/Instrument FOV and resolution \( \rightarrow \) land-scape heterogeneity is “averaged” within antenna footprint

“Representative” number of in situ ground stations within FOV or posted resolution.
Soil Moisture Variability
Local Scale (~100s [m])

Sacramento, CA
Tonzi Ranch, CA
Soil Moisture Variability
Regional Scale (~1-10 [km])

Localized Precipitation

SoilSCAPE
Kendall & Lucky Hills, AZ

Tombstone, AZ

~10 [km]

Tucson

Google Earth

Kendall

Lucky Hills
Soil Moisture Variability
Regional Scale (~1-10 [km])

Localized Precipitation

[Graph showing soil moisture variability over time with data points for Kendall, AZ and Lucky Hills, AZ.]

[Map indicating locations of Kendall, AZ and Lucky Hills, AZ.]
Presentation Outline

• Motivation for *in situ* Networks
  • Context: NASA SMAP mission and Surface soil moisture

• SoilSCAPE Project
  • Highlights and Examples of Data/Science-use
**SoilSCAPE Overview**

**Background and Motivation**

**SoilSCAPE**: Soil moisture Sensing Controller and oPtimal Estimator (TRL 7)

**What?**

- Clusters of medium-scale (< 500 [m]) *in situ* Wireless Sensor Networks (WSN)

**Function?**

- Measure and report near real-time surface-to-root zone soil moisture (surface down to ~100 [cm])

**Why?**

1. Advancement in low-power wireless sensing technologies.
2. *Ground truth soil moisture for NASA Earth Science missions.* (SMAP, AirMOSS, recently CYGNSS)

**How?**

- Custom made low-power “wireless dataloggers”
- Wireless network communication protocols and data-delivery
SoilSCAPE
Network Architecture

Wireless End-Device (ED)
- 4-Digital, 4-Analog probes
- PVC Enclosures
- 900 MHz ISM Xbee Transceiver

Local Coordinator (LC)

Data Server and Delivery
- Project Website
  - SMAP
  - AirMOSS
  - CYGNSS
  - ORNL DAAC

3G/LTE/Satellite
SoilSCAPE
Network Characteristics

**Setup**
- Star-based Network Topology
- **Semi-Sparse**
- Avg. Node Distance ~ 250 [m] (max 750 [m])
- Avg. Node Density ~ 2.5 [nodes ha⁻¹]
- 4 Digital and/or 4 Analog soil probes

**WSN**
- **Efficient** network protocol based on time-division medium access (Best Effort Time-Slot Protocol*)
- Low Duty-Cycle (20-30 min)
- Messages Time-delayed to minimize package collisions
- Zero-hop and no message relay

**Data**
- **Near-real time data** delivery (Avg. 5 min latency)
- 3G/LTE/ Satellite connections
- ~11 Network Sites (CA, AZ, AK, NY, recently CO)
- ORNL DAAC

**Energy**
- **Non-rechargeable batteries**
- Deterministic networking protocol: it is possible to accurately estimate the remaining energy level
- Avg. power consumption <3μW (4 Probes and 20 min schedule)
- Avg. node life-time ~1.8 years

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SoilSCAPE
From “Sparse” to “Semi-Sparse”

- Multiple WSNs within Satellite FOV
- Distributed network of soil sensors → increased representativeness
- Improve Satellite vs. in situ match-ups

“Traditional” Approach

Wireless Sensor Networks (WSN)

Example Sites in CA and AZ

https://www.ncdc.noaa.gov/crn/
SoilSCAPE
Key Components: Local Coordinator (LC)

- Central “node” coordinating all wireless sensors
- Dedicated power module w/ isolated power lines
- Raspberry Pi microcomputer (for “heavier” computing)
- SDI-12 interfaces for peripheral devices
  - Weather station, Sap-flow system, leaf-wetness sensors

Power Module
- MCUs
- Xbee Transceiver
- SDI-12
- Raspberry Pi (A&B)
- 3/4G modem
- USB
- VCC & GND
- Power Module

12V-Power System / Solar Panel
Watchdog Timer (WDT) MCU
Phytos 31
Xbee Transceiver
SDI-12
Raspberry Pi (A&B)
3/4G modem
USB
VCC & GND
Power Module

Real-Time Clock (RTC)
Display

Raspberry Pi Zero (RPI-A)

Raspberry Pi Zero (RPI-B)

LCED Vcc
LCEP Vcc
RPI-A Vcc
RPI-B Vcc
Atmos41 Vcc
DSM Vcc

3.3V
3.3V
3.3V
3.3V
3.3V
5V

WSN / Xbee
TX- WoW Vcc
TX- WoW
USB-Serial
Sat. Modem
3G-Modem

Earth Science Technology Office
SoilSCAPE
Key Components: Local Coordinator (LC)

- LC powered via solar panel and car battery
- Recent addition: mini weather station!
- Data server connection options:
  - Commercial Verizon, AT&T, or iridium modems
- Internal dataloggers

Mini Weather-station
Solar Panel
900 MHz Antenna
LC and Enclosure

Diagram of SoilSCAPE components.
SoilSCAPE
Key Components: Wireless End-Device (ED)

- Designed in-house
- **Non-rechargeable batteries** (2x 19000mAh)
- Low-duty cycle (mostly in sleep mode)
- Power-gating and power-matching techniques to increase energy efficiency (~1.8-2 years)
- “Emergency mode” if no ED-LC communication
- **New Feature**: Wake-up on Radio
SoilSCAPE
Key Components: Wireless End-Device (ED)

- Designed in-house
- Non-rechargeable batteries (2x 19000mAh)
- **Low-duty cycle: mostly in sleep mode**
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ED Current [A] Consumption

- Recharge Super-Capacitors (3.6V)
- Sleep Mode

Sensing, Sending/Receiving

(measured with Keithley Sourcemeter 2400)
SC MCU initialized

Initialization of variables & hardware

TX-WOR Activation (if enabled)

LCED Transaction (WSN LC-EDs)

- Activate LCED MCU & XBee radio
- LCED MCU waits for ED messages
- (wait numMillSecTXWOR)
- Request ED data from LCED MCU
- Save ED data at LC internal datalogger
- Deactivate LCED MCU & XBee radio

RPI Transaction

- Activate RPI & 5V-power rail for Data Server modem
- Send ED data to RPI
- RPI stores ED data as a file at SD-card
- RPI tries to transmit this file (and any other file at the queue) to Data Server using 3G/4G/Satellite link
- Get weather-station data (if enabled)
- Send weather-station data to RPI (if enabled)
- RPI stores WS data as a file at SD-card
- RPI tries to transmit this file (and any other file at the queue) to Data Server using 3G/4G/Satellite link

Wait for the next cycle
SoilSCAPE
Operational flowcharts

MCU initialized

Initialization of variables & hardware
- Charge supercapacitors
- Activate XBee, get XBee ID, deactivate XBee

Local Measurements
- Activate power to probes & take readings (S1..S8)

ED_MEAS Transmission
- Deactivate power to probes & activate XBee radio
- Transmit ED_MEAS message to LC

Wait for LC_CTRL message
- If timeouts after multiple tryouts, enter in Emergency Mode (long cycles: e.g., 6h),

ED_CTRL Transmission
- Send ED_CTRL message to LC and deactivate XBee
- Save ED_MEAS in local datalogger
- Charge supercapacitors

Wait for the next cycle
SoilSCAPE Deployment and Installation Considerations

- Preserve soil texture profile! Important!
- Low profile
- Barbed-wire fence sometimes required.
SoilSPCA
Deployment and Installation Considerations

Typically 3 constraints:

1. Land access and permissions (Private vs. Public land)
2. Site Characteristics:
   - Soil texture (sand, clay, and bulk density)
   - Topo (slope, aspect, elevation)
   - Vegetation Cover
3. Satellite/Instrument Overpass and FOV
Typically 3 constraints:
1. Land access and permissions (Private vs. Public land)
2. Site Characteristics:
   • Soil texture (sand, clay, and bulk density)
   • Topo (slope, aspect, elevation)
   • Vegetation Cover
3. Satellite/Instrument Overpass and FOV
<table>
<thead>
<tr>
<th>Site Name</th>
<th>State</th>
<th>Land Cover</th>
<th>Project Support</th>
<th>Data Range</th>
<th>Data Access</th>
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</thead>
<tbody>
<tr>
<td>Tonzi Ranch</td>
<td>CA</td>
<td>Woody Savanna</td>
<td>SMAP, AirMOSS</td>
<td>Jan’12-Present</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>BLM-1</td>
<td>CA</td>
<td></td>
<td></td>
<td>Jan’13-Jan’18</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>BLM-2</td>
<td>CA</td>
<td>Woody Savanna</td>
<td>SMAP, AirMOSS</td>
<td>Jan’13-Jan’18</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>New Hogan Lake-1</td>
<td>CA</td>
<td></td>
<td></td>
<td>Jan’12-Jan’18</td>
<td>ORNL ✗</td>
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<tr>
<td>New Hogan Lake-2</td>
<td>CA</td>
<td></td>
<td></td>
<td>Jan’12-Jan’18</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>Kendall</td>
<td>AZ</td>
<td>Grasslands</td>
<td>SMAP, AirMOSS</td>
<td>Aug’15-Present</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>Lucky Hills</td>
<td>AZ</td>
<td>Shrubs</td>
<td>SMAP, AirMOSS</td>
<td>Aug’15-Present</td>
<td>ORNL ✗</td>
</tr>
<tr>
<td>Happy Valley</td>
<td>AK</td>
<td>Arctic Tundra</td>
<td>AirMOSS, ABoVE</td>
<td>Aug’16-Present</td>
<td>Internal</td>
</tr>
<tr>
<td>Alamosa-Z1</td>
<td>CO</td>
<td>Crops/Pasture</td>
<td>CYGNSS</td>
<td>Nov’19-Present</td>
<td>Processing</td>
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<tr>
<td>Alamosa-Z4</td>
<td>CO</td>
<td>Grassland</td>
<td>SMAP</td>
<td>July’19-Present</td>
<td>Processing</td>
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<tr>
<td>Millbrook</td>
<td>NY</td>
<td>Mixed Forest</td>
<td>SMAP</td>
<td>July’19-Present</td>
<td>X</td>
</tr>
</tbody>
</table>

Oak Ridge National Lab (ORNL) DAAC

[https://daac.ornl.gov/LAND_VAL.guides/SoilSCAPE.html](https://daac.ornl.gov/LAND_VAL.guides/SoilSCAPE.html)
Presentation Outline

- Motivation for *in situ* Networks
  - Context: NASA SMAP mission and Surface soil moisture
- SoilSCAPE Project
- Data Science-use Highlights and Examples
SoilSCAPE
Science-use Highlight: Example Comparison with SMAP

SMAP 36 and 9 [km] Soil Moisture (L3SMP) 08/08/2018

- 2 single soil moisture stations, ~ 10 [km] apart

Figures from NASA WorldView
https://worldview.earthdata.nasa.gov
SMAP 36 and 9 [km] Soil Moisture (L3SMP) 08/08/2018

- 2 single soil moisture stations, ~ 10 [km] apart
- Poor comparisons with closest SMAP 36,9 [km] soil moisture

Figures from NASA WorldView
https://worldview.earthdata.nasa.gov

Errors and Standard Deviations

<table>
<thead>
<tr>
<th></th>
<th>Kendall</th>
<th>Lucky Hills</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAP 36 [km]</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>SMAP 9 [km]</td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

SMAP requirement Error StnDev. ≤ 0.04 [m^3/m^3]
SoilSCAPE
Science-use Highlight: Example Comparison with SMAP

SMAP 36 and 9 [km] Soil Moisture (L3SMP) 08/08/2018

- 2 single soil moisture stations, ~ 10 [km] apart
- Poor comparisons with closest SMAP 36,9 [km] soil moisture
- SMAP vs. in situ match-ups improves with more sensors
- “Averaging” one of many “Up-scaling” methods
  - Open and on-going topic

Figures from NASA WorldView
https://worldview.earthdata.nasa.gov

<table>
<thead>
<tr>
<th></th>
<th>Kendall</th>
<th>Lucky Hills</th>
<th>Mean of all sites (20 sensors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAP 36 [km]</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>SMAP 9 [km]</td>
<td>0.08</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

SMAP requirement Error StnDev. ≤ 0.04 [m$^3$/m$^3$]
SoilSCAPE
Science-use Highlight: SMAP Radar Soil Moisture Retrieval

- 3 [km] SMAP SAR-based Soil Moisture Estimation
- SMAP has ~14 core cal/val sites
- Excellent match-up between SMAP* and SoilSCAPE (red line; Error StnDev ~ 0.03 [m$^3$ m$^{-3}$])

SoilSCAPE
Science-use Highlight: Permafrost Active Layer Retrieval

“zero curtain”
Soil Temp. ~ 0 [°C]

Good indicators of freeze/thaw states
Dielectric const. (or soil moisture) stays saturated when thawed

Time-invariant variables assumed in ALT Retrieval using August and October AirMOSS data:
1. Surface roughness (h)
2. Active layer thickness (ALT)
3. Bottom of active layer (ε₂) remains saturated

SoilSCAPE
Science-use Highlight: Permafrost Active Layer Retrieval

- Retrieval of active layer soil properties at SoilSCAPE site in Happy Valley, Alaska

SoilSCAPE
On-going research tracks

In situ networks & SoilSCAPE

- Soil Moisture Up-scaling
- Expanded Functionality
- "Smart" WSN
- How to "average-up" to Satellite scale?
- WSN + WSN Operations
- Coordination with other sensing platforms
- ML-based spatiotemporal scheduling
Thank you!

Question: rakbar@mit.edu
Radar:
- Tunable 1.215-1.34 GHz
- 350 μsec
- 15 μsec TX, 9 μsec delay between H and V-pol
- H and V-pol freq. of set by 3 MHz
- Noise Equiv. $\sigma^0 < -30$ dB

Radiometer:
- 1.413 GHz, 24 MHz BW
- ~ 350 μsec Integration Time between radar PRI (multiple packets for image formation)
- Dedicated RFI detection and mitigation subsystem
- NEDT < 1 K (*1st year in orbit)

Reflector Antenna:
- 6 [m] diameter Mesh-reflector
- 13-14.6 rpm
- Corrugated feed-horn antenna

Benefits of using Radar and Radiometer

Radar → High Resolution
- SMAP SAR 1-3 [km]

Radiometer → Low(er) Resolution
- SMAP Radiometer 36 [km] Posted FOV
- “Enhanced” BG-method* 9 [km]

Emission vs. Scattering
Different yet complementary sensitivities to
- Soil Moisture (i.e., permittivity)
- Surface Roughness
- and Vegetation

Marker size proportional to amount of vegetation.

**Where Do I get SMAP Data?**

Answer: National Snow & Ice Data Center (NSIDC) DAAC

https://nsidc.org/data/smap/smap-data.html

Only ~2.5 Months of Radar Data

“Enhanced” Resolution* Product also available

- Based on Backus-Gilbert Interpolation method**
- Takes advantage of Spinning Antenna and Overlapping Samples
- 9 [km] TB and Soil Moisture

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**Table 4. SMAP data products.**

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
<th>Gridding (Resolution)</th>
<th>Latency**</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1A_Radiometer</td>
<td>Radiometer Data in Time-Order</td>
<td></td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L1A_Radar</td>
<td>Radar Data in Time-Order</td>
<td></td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L1B_TB</td>
<td>Radiometer T_B in Time-Order</td>
<td>(36x47 km)</td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L1B_S0_LoRes</td>
<td>Low-Resolution Radar σ_o in Time-Order</td>
<td>(5x30 km)</td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L1C_S0_HiRes</td>
<td>High-Resolution Radar σ_o in Half-Orbits</td>
<td>1 km (1–3 km)*</td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L1C_TB</td>
<td>Radiometer T_B in Half-Orbits</td>
<td>36 km</td>
<td>12 Hrs</td>
</tr>
<tr>
<td>L2_SM_A</td>
<td>Soil Moisture (Radar)</td>
<td>3 km</td>
<td>24 Hrs</td>
</tr>
<tr>
<td>L2_SM_P*</td>
<td>Soil Moisture (Radiometer)</td>
<td>36 km</td>
<td>24 Hrs</td>
</tr>
<tr>
<td>L2_SM_AP*</td>
<td>Soil Moisture (Radar + Radiometer)</td>
<td>9 km</td>
<td>24 Hrs</td>
</tr>
<tr>
<td>L3_FT_A*</td>
<td>Freeze/Thaw State (Radar)</td>
<td>3 km</td>
<td>50 Hrs</td>
</tr>
<tr>
<td>L3_SM_A</td>
<td>Soil Moisture (Radar)</td>
<td>3 km</td>
<td>50 Hrs</td>
</tr>
<tr>
<td>L3_SM_P*</td>
<td>Soil Moisture (Radiometer)</td>
<td>36 km</td>
<td>50 Hrs</td>
</tr>
<tr>
<td>L3_SM_AP*</td>
<td>Soil Moisture (Radar + Radiometer)</td>
<td>9 km</td>
<td>50 Hrs</td>
</tr>
<tr>
<td>L4_SM</td>
<td>Soil Moisture (Surface and Roof Zone)</td>
<td>9 km</td>
<td>7 days</td>
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<tr>
<td>L4_C</td>
<td>Carbon Net Ecosystem Exchange (NEE)</td>
<td>9 km</td>
<td>14 days</td>
</tr>
</tbody>
</table>

* Over outer 70% of swath.
** The SMAP Project will make a best effort to reduce the data latencies beyond those shown in this table.
* Product directly addresses the mission L1 science requirements.

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