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ESTF, Annapolis, MD
Soil moisture varies on \textit{spatial scales} of meters to tens of kilometers, and \textit{temporal scales} of minutes to days.

SMAP radar and radiometer each observe soil moisture, but with different spatial resolutions. Both capture lots of landscape heterogeneity due to large pixel sizes.

Validation of these multi-scale measurements requires \textit{adaptive temporal and spatial sampling} strategies and upscaling method.

Data also used for AirMOSS EVS-1 mission validation.
SMAP Facts

Objectives:
- Global high-resolution mapping of soil moisture and freeze-thaw state
- Link terrestrial water, energy, and carbon cycle processes
- Estimate global water and energy fluxes at the land surface

Instrument and Measurement Approach:
- L-band radiometer (36 km), L-band radar (3 km)
- Common 6m rotating antenna for 3-day global repeat coverage
- Merge radar and radiometer data for high-accuracy, mid-resolution, soil moisture

Mission Status:
- Launched successfully, January 2015
- Radar failed, July 2015; radiometer working well
- Validated Level 1 and 2 radar (3 km), radiometer (36 km), and joint (9 km) products released

Cal/val Plan:
- Take advantage of several cal/val “partners”
- Number of cal/val sites is ~20
- Core validation sites must meet spatial sampling criteria, data quality requirements, scaling function, and have easy & rapid data access
- SoilSCAPE is a cal/val site for SMAP and was first to provide near-real-time data
Background and Objectives (3)

Generalized SoilSCAPE Framework

SoilSCAPE Sensor Network: Application Interoperability

- Scheduling & Placement Application
- Sensor Network Management
- Water, Energy, Carbon Science Applications
- SMAP/AirMOSS Calibration/Validation Applications

USIF Framework
- * Data Search/Discovery
- * Data Collection & Integration
- * Data Distribution/Visualization

- Security
- Multi-Year Archive
- XML

Other Data Sources

COSMOS

AirMOSS

FLUXNET

SMAP
Specific Objectives of SoilSCAPE:

• Generalized wireless network Framework
  • Support large number of nodes in sparse network
  • Flexible network energy management to meet Earth science mission lifetime requirements
  • Energy-efficient nodes and devices
  • Sustained network reliability and reduced costs
  • Extensible network architecture; deployable in diverse environments
  • Adaptive scheduling of sensor nodes to maximize longevity
  • Accurate geophysical parameter process estimation

• Unified Science Information System Framework
  • Distributed Search/Discovery
  • Data Collection & Integration
  • Data Dissemination for science support (visualization and analysis)
Network architecture design

3 or 4 soil moisture sensors* at different depths (e.g., 5, 20 and 50 cm) called End Device (ED)

Wirelessly send data to Local Coordinator (LC) using custom ‘BETS’ protocol

Send back to USC lab from custom hardware via SMS or 3/4G

Decompress and add to MySQL database, accessible via website

* Decagon EC-5 or 5TM
Technology Overview (2)

Network architecture design

Send data back using custom RPi H/W to USC lab via SMS or 3/4G

Decompress and add to MySQL database, accessible via website Soilscape.usc.edu

SMAP Data System at JPL

Search and discovery portal at ORNL

Files containing the last 7 days of data are created every hour for automatic pull by SMAP Cal/Val team at JPL
116 nodes operational over 7 sites
Data available in near-real-time from soilscape.usc.edu
SMAP nested pixel has 1 km, 3 km, 9 km, and 36 km scales
Network node distribution in SMAP cal/val site in CA (2)

- Network Distribution to support SMAP nested soil moisture pixels
  - Initial deployment focused on 3 km and 9 km cal/val pixels
  - With loss of SMAP radar, focusing also on 36 km pixel.

SMAP proposed 36 km Validation Grid over Tonzi Ranch Area

SMAP 9km Validation Focus (Tonzi Ranch, BLM 1, 2, 3)

- Yellow: Tonzi Ranch
- Red: BLM 1 & 2
- Blue: BLM 3
Network node distribution in SMAP cal/val site in CA (3)

- CA site total count is at 116
- Meeting SMAP sampling requirements for the 9 km validation pixel

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th># of Sensors</th>
<th>Land Cover*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonzi Ranch</td>
<td>North-Central CA</td>
<td>18</td>
<td>Savanna</td>
</tr>
<tr>
<td>BLM I</td>
<td>California</td>
<td>17</td>
<td>Woody Savanna</td>
</tr>
<tr>
<td>BLM II</td>
<td></td>
<td>14</td>
<td>Woody Savanna</td>
</tr>
<tr>
<td>BLM III</td>
<td></td>
<td>5</td>
<td>Woody Savanna</td>
</tr>
<tr>
<td>New Hogan I</td>
<td></td>
<td>19</td>
<td>Open Shrubland</td>
</tr>
<tr>
<td>New Hogan II</td>
<td></td>
<td>14</td>
<td>Savanna/Grass</td>
</tr>
<tr>
<td>Terra d’Oro</td>
<td></td>
<td>28</td>
<td>Vineyard</td>
</tr>
<tr>
<td>Lucky Hills</td>
<td>Southern Arizona</td>
<td>8</td>
<td>Open Shrubland</td>
</tr>
<tr>
<td>Kendall</td>
<td></td>
<td>10</td>
<td>Grassland</td>
</tr>
<tr>
<td>Canton</td>
<td>Oklahoma</td>
<td>22</td>
<td>Pasture/Grassland</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>156</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Savanna & Woody Savanna represent ~ 15% of global land cover; Grasslands & Shrubs ~27%
What is the impact of SMAP radar failure on utility of SoilSCAPE network data?

✧ SMAP radar failed on July 7, 2015
✧ Main purpose of the radar was to enable medium-resolution (9 km) soil moisture products using an algorithm that used both the radiometer (36 km) and the radar (3 km) data
✧ The radiometer products at 36 km are still being produced
✧ Alternate methods are being investigated to get the 9 km product (other radar data, statistical methods, time-series data, etc.)
✧ The SoilSCAPE 3 km and 9 km cells still used:
   o To validate the joint radar/radiometer 9 km product and the 3 km radar product for the 2.5 months when radar data were available; important for algorithm development and validation in the long run
   o To validate new algorithms for disaggregating the 36 km product to 9 km
   o To validate the 36 km product using our recent upscaling method
   o To validate the 36 km product using the SoilSCAPE stations that already exist but are not in the 9 km box
“Textbook” Soil Moisture Response from Tonzi Ranch

Network node distribution in SMAP cal/val site in CA (5)

Node#412

Soil moisture (%)

Sensor 1 (5 cm)
Sensor 2 (20 cm)
Sensor 3 (35 cm)

Rain
Extensive dry period (May-October)

Jitters aren't noise, but rather diurnal soil moisture variation.
SoilSCAPE Data Portal: Visualizations

- Site summary info available for each site in a .pdf “MapBook” page
- More than 1200 page views since Jan 2015

http://mercury.ornl.gov/soilscape

Slide courtesy of Alison Boyer and ORNL DAAC team
“Ripple”-series Architectures (1)

**Ripple-1 architecture:**
- Sensor nodes (end devices) in star-shape multihop arrangement
- Base station (3G) at center, indoor, plugged in
- Xbee Pro SOC module to serve as MCU and radio
- Rechargeable batteries at end devices
- Longevity: days to months
- Sensor nodes per infrastructure node: ~8
- Heat/cold performance: poor

**Ripple-2 and Ripple-3 architectures:**
- End device → Local coordinator → SMS/3G/4G
- Nothing is plugged in; no indoor infrastructure (all unattended except the lab gateway)
- Raspberry Pi single board Linux computer and 3G modem
- Dual-freq network
- Non-rechargeable batteries at end devices
- Home-made protocol: “best-effort time slot (BETS)” allocation
- Longevity: 2 years+
- Sensor nodes per infrastructure node: ~60
- Heat/cold performance: excellent
“Ripple”-series Architecture (2)

Ripple-2 architecture

- All sites employ LC-RPi-3G: LC module + Raspberry Pi + 3G modem
  - ED-LC communication: 900MHz or 2.4GHz
  - New LC board version supports adaptive scheduling
  - Robustness: RPi/modem crash recovery

- All California SoilSCAPE sites employ Ripple2D+ ED nodes

- EC-5 probes made more robust
Ripple-3 architecture: latest SoilSCAPE upgrade

• Significant End-Device hardware upgrades and improvements
  1. On-board short-term memory (~ 1 month)
  2. Multi-level data redundancy: End-Device, Local Coordinator, Raspberry Pi, Database
  3. Intelligent Sensing: probe fault/short detection and flagging
  4. Dual sensor mode compatible: Analog (Decagon EC-5) & Digital (Decagon 5TM)

• All upgrades have been implemented & operational since 08/18/2015
Ripple3 End Device Enhancements

• Reliability
  • Significant number of Ripple2 maintenances due to EC-5 probe fault: impact on the ED node (battery) and on data quality (noisy/bad data)

• Data redundancy
  • Measurements are saved in 4 places: ED node, LC module, RPi module, and at the Data Server

• Support for modern digital probes
  • Ripple3 supports 5TM digital probe
  • Can be software-adapted to support the SDI-12 specification

• Future: Extensibility and converting Ripple3 into a low-cost datalogger
  • To be used to cover very large areas
  • LC+ED integrated; no LC-ED network
  • Implementation: Ripple3 + Rpi + 3G modem + power module
  • Multiple soil measurements during the day
  • Few 3G transmissions to the Data Server (application-specific)
  • No solar panel and lifetime ~1 year
# “Ripple”-series Architecture (5)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Ripple-1 thru 2D</th>
<th>Ripple2D+</th>
<th>Ripple3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Management</td>
<td>Rechargeable battery ED&amp;LC; plugged in base station</td>
<td>Non-rechargeable battery at ED, solar at LC</td>
<td>Non-rechargeable battery at ED, solar at LC</td>
</tr>
<tr>
<td>Longevity</td>
<td>Days to weeks</td>
<td>2+ years</td>
<td>3+ years expected</td>
</tr>
<tr>
<td># of Sensor ports per ED</td>
<td>3 (analog)</td>
<td>4 (analog)</td>
<td>8 (4 analog, 4 digital)</td>
</tr>
<tr>
<td>Isolated power lines</td>
<td>No</td>
<td>No, shared</td>
<td>Yes, 8 isolated lines</td>
</tr>
<tr>
<td>User-defined probe power profile*</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>User-defined probe measurement valid range*</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Detection/isolation of short-circuited probes*</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Detection of unresponsive probes</td>
<td>No</td>
<td>No</td>
<td>Yes, for digital probes</td>
</tr>
<tr>
<td>Internal datalogger</td>
<td>No</td>
<td>No</td>
<td>Yes (128k B)</td>
</tr>
</tbody>
</table>

* Not available in any existing commercial hardware
“Ripple”-series Architecture (6)

Data-server algorithms become more efficient in reconstructing missed/flagged data.

Real case: water infiltration

Can a sensor node auto-flag its own measurements?

Ripple-3 has this “intelligent sensing” feature:
• All data still transmitted but bad data are flagged
• Criteria: power consumption signature, valid data range, spatio-temporal soil moisture gradient heuristic (user-defined and uploaded to the node)
## Sensor and Node Deployment Statistics

<table>
<thead>
<tr>
<th>State</th>
<th>Site</th>
<th>Number of Nodes</th>
<th>Node Density (nodes ha(^{-1}))</th>
<th>Maximum distance from LC (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>Tonzi Ranch</td>
<td>19</td>
<td>1.45</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>New Hogan 1</td>
<td>14</td>
<td>1.66</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>New Hogan 2</td>
<td>18</td>
<td>1.05</td>
<td>346</td>
</tr>
<tr>
<td></td>
<td>Terra d' Oro</td>
<td>27</td>
<td>1.50</td>
<td>317</td>
</tr>
<tr>
<td></td>
<td>BLM 1</td>
<td>17</td>
<td>4.73</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>BLM 2</td>
<td>16</td>
<td>5.09</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>BLM 3</td>
<td>3</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Arizona*</td>
<td>Lucky Hills</td>
<td>7</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Kendall</td>
<td>10</td>
<td></td>
<td>480</td>
</tr>
</tbody>
</table>

* Upgraded to Ripple 3 for Arizona.
**Expansion to Walnut Gulch, AZ (1)**

- New network site in Tombstone, Arizona: deployed August 2015
- Science objectives
  1. Support ongoing SMAP Cal/Val activities in Walnut Gulch Experimental Watershed* (WGEW)
  2. Support regional & small scale studies in WGEW
  3. Technology expansion & adaptation

*The USDA-ARS Walnut Gulch Experimental Watershed (WGEW) is operated by the Southwest Watershed Research Center (SWRC) is a 150 km² watershed. It has been extensively studied since 1953 and is one of the most intensively instrumented semiarid experimental watersheds the world.*
Expansion to Walnut Gulch, AZ (2)

- Two new sites identified, with help from local USDA-ARS research teams*
  - Lucky Hills (LH)
    - Open shrubland
    - 8 End Devices
    - Sensors from 5cm to 75cm
  - Kendall (KN)
    - Grassland
    - 9 End Devices
    - Sensors 5cm to 50cm
- Long term, both LH & KN have been heavily monitored (TDR, Flux towers, etc.)

* Special thanks to: John Smith, Russ Scott, Joel Biederman, Leland Sutter from USDA-ARS and UA
Expansion to Walnut Gulch, AZ (3)

- **Existing soil moisture infrastructure**
  - Very limited and over a decade old
  - Does not quantify soil moisture variations at the sub 500m scales
  - Affects understanding controls on ecohydrological state and fluxes within the watersheds

- **SoilSCAPE Impacts**
  - Capturing local soil moisture heterogeneity due to topography, soil type, and solar aspect variation
  - Better understanding of channel erosion and soil moisture with sensors in proximity
Expansion to Walnut Gulch, AZ (4)

- Near-real time data delivery (30min sampling schedule)
- Web-based visualization (beta) and free data download
- Continued integration with ORNL DAAC
Interface with legacy hardware

- Legacy technology integration and demonstration at a 3rd site underway: SoilSCAPE network as add-on to existing sensors and dataloggers

- Database and web interface improvements

- Forwarding and data integration within ORNL DAAC
• SMAP and AirMOSS calibration and validation (Cal/Val)
• California data used in all SMAP data product cal/val activities
  o Radar-only at 3km, Radiometer-only at 36 km, and Radar-Radiometer at 9 km
  o Overall excellent agreement with SMAP products

SMAP Radiometer-only Soil Moisture vs. Up-scaled SoilSCAPE Soil Moisture (April 1\textsuperscript{st} 2015 – March 31\textsuperscript{st} 2016)

<table>
<thead>
<tr>
<th>Errors (cm\textsuperscript{3}/cm\textsuperscript{3})</th>
<th>RMSE</th>
<th>Bias</th>
<th>ubRMS E</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF vs. SMAP</td>
<td>0.04</td>
<td>-0.00</td>
<td>0.0448</td>
</tr>
</tbody>
</table>
Scaling analysis: Validation Results

SoilSCAPE Random-Forests-based scaling algorithm produces significantly improved soil moisture mean estimation relative to alternative upscaling techniques.

SoilSCAPE algorithm predictions are consistently closer to field data than are alternative upscaled estimates.

<table>
<thead>
<tr>
<th>Method</th>
<th>RMSE  (m$^3$/m$^3$)</th>
<th>Bias  (m$^3$/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
<td>0.033</td>
<td>0.023</td>
</tr>
<tr>
<td>SoilSCAPE (Random Forest)</td>
<td>0.026</td>
<td>0.008</td>
</tr>
<tr>
<td>Arithmetic Average</td>
<td>0.032</td>
<td>0.023</td>
</tr>
<tr>
<td>Inverse Distance</td>
<td>0.041</td>
<td>0.034</td>
</tr>
<tr>
<td>Theissen</td>
<td>0.067</td>
<td>0.063</td>
</tr>
<tr>
<td>Timestab</td>
<td>0.036</td>
<td>0.021</td>
</tr>
<tr>
<td>Kriging</td>
<td>0.033</td>
<td>0.022</td>
</tr>
</tbody>
</table>
Up-scaled Soil Moisture: Greater Tonzi Ranch Area

RF 100m Estimates

04/01/2015

RF 9km EASE grid Aggregates

0 % 50 %
Summary

• Networks at Tonzi ranch, CA, have demonstrated continuous operation for well over two years

• Technology demonstration expanded and extensibility shown in Walnut Gulch, Arizona, with significant device upgrades

• Have designed, implemented, and demonstrated operation of open architecture

• Continued support of SMAP and AirMOSS cal/val activities

• Plans for near future: Boreal and arctic science support (esp. permafrost for ABoVE campaign)
http://soilscape.usc.edu/