Ground Network Design and Dynamic Operation for Validation of Space-Borne Soil Moisture Measurements

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Technology Relevance: SMAP

SMAP Primary Science Objectives:
- Global high-resolution mapping of soil moisture and its freeze-thaw state to:
  - Link terrestrial water, energy, and carbon cycle processes
  - Estimate global water and energy fluxes at the land surface
  - Quantify net carbon flux in boreal landscapes
  - Extend weather and climate forecast skill
  - Develop improved flood and drought prediction capability

Mission Approach:
- GSFC L-band radiometer
- JPL L-band radar
- Common 6m rotating antenna for 3-day global repeat coverage
- Merged radar and radiometer data for high-accuracy, mid-resolution, soil moisture
- 670 km polar sun-sync

Development Status:
- Entered Phase B in January 2010
- Science Definition Team (SDT) selected in 2008
- Algorithms and Cal/Val workshop held in June 2009 and March 2010; Applications workshop September 2009
- Now completing mission trade studies

Development Objectives:
- Just completed KDP-B; now in Phase B
- Phase B will focus on further trade studies, risk reduction, requirements and interface maturation
- 2nd Algorithms Workshop March 2010
- Cal/Val Field Campaigns Summer 2010 (Oklahoma, Canada, Australia)
- Launch planned for late 2014
Soil moisture Sensing Controller And oPtimal Estimator (SoilSCAPE): develop technologies for near real-time validation of spaceborne soil moisture estimates

The Challenge for SMAP Validation:

- SMAP’s radar and radiometer will measure soil moisture with different spatial resolutions
- Soil moisture varies on multiple spatial scales
  - \( O(10 \text{ m}) \) due to vegetation cover and topography
  - \( O(100 \text{ m}) \) due to topography and soil type
  - \( O(1000\text{ m}) \) due to cloud cover and precipitation
- Deploying validation sensors at all scales and with high density is infeasible
  - \( \checkmark \) Old paradigm doesn’t work
- Need smart and adaptive time and space sampling
  - \( \checkmark \) Balance cost and accuracy
- This problem is at the boundary of the conventional instrument domain and information technologies domain
SoilSCAPE Objectives are:

1. Optimal design of sensor node placement and scheduling controller based on modeled and measured soil moisture spatial and temporal statistics.

2. Derivation of large-scale remote sensing estimates of heterogeneous soil moisture, compatible with ground sensor network estimates of true mean of soil moisture field via a landscape simulator.

3. Design and implementation of large-scale wireless communication & actuation system to configure sampling within the in-situ sensor network and to produce estimates of the soil moisture field mean.
Control System overview:

- Design of sensor node placement and scheduling based on soil moisture spatial and temporal statistics
  - Implemented through a “centralized control” architecture
  - Initially will decouple sensor placement solution from sensor scheduling solution

\[
\binom{N}{k}
\]

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Centralized Control Architecture

Coordinator

Actuator / Comm. 1
Actuator / Comm. 2
Actuator / Comm. 3
Actuator / Comm. N

Ground

Sensors

```
Control System overview:

• Sensor placement assuming continuous-time sampling
  • Conducted studies on simulated data
  • Developed a cluster-based placement scheme

• Field mean estimation problem assuming a fixed placement
  • With a fixed placement, computed scheduling policies for sensors
  • Modified the estimation policy to estimate the mean value of soil moisture over the field of interest

• Methodology to address the joint placement and scheduling problem
  • Had previously developed scheduling controller independent of placement
  • Placement and scheduling problem are inter-related
  • Optimal placements should take into account the dynamic scheduling costs
  • Identified a methodology that incorporates the dynamic aspects of scheduling into the static placement problem
Sensor placement algorithms using simulated data

- **tRIBS** (TIN-based real-time integrated basin simulator; TIN: triangulated irregular network) is a landscape hydrology simulation tool developed at MIT; has been used here to investigate space/time soil moisture dynamics.

- Assuming perfect measurements in time, address sensor placement as a stand-alone problem.

- Exploit special properties of data.

- Investigate a cluster-based placement scheme to better exploit the data features.

- Experimental results.
The stand-alone sensor placement problem

- A field with $N$ possible locations to place sensors $V = \{v_1, v_2, \ldots, v_N\}$
- Signal to be sensed assumed to be a random process; random variable $X_i$ at location $v_i$
- If we place a sensor at $v_i$ we observe perfectly $X_i$; otherwise we need to provide an estimate $\hat{X}_i$

- Want to select $K$ locations to place sensors
  \[
  (P) \quad A^* = \arg \min_{A \subset V, |A| = K} E[\text{err}(X_V, \hat{X}_V)]
  \]

- $\text{err}()$ is some error measure; most commonly used is the MSE
  \[
  E[\text{err}(X_V, \hat{X}_V)] = \|X_V - \hat{X}_V\|^2
  \]

- This is a joint optimization: simultaneously determine the best subset and the best estimate
- Can limit the solution space, e.g., only consider linear estimates
One very commonly used approach

• Assume the underlying spatial random process is Gaussian
  • The best estimate for an unobserved location is the conditional mean of a Gaussian random variable, a linear estimator
    \[ \hat{x}_V = u_V + \sum_{V_A} \sum_{A_A}^{-1} (x_A - u_A) \]
  • Can use metrics like entropy and mutual information as alternative objective functions (though an approximate one to MSE) for subset selection

(MaxEN)

\[ A^* = \arg \min_{A \subseteq V, |A| = K} H(X_{V \setminus A} | X_A) \]
\[ = \arg \max_{A \subseteq V, |A| = K} H(X_A) \]

(MaxMI)

\[ A^* = \arg \max_{A \subseteq V, |A| = K} MI(X_{V \setminus A}, X_A) \]
\[ = \arg \max_{A \subseteq V, |A| = K} H(X_A) - H(X_{V \setminus A} | X_A) \]

• They remain NP-hard
• Simple greedy algorithms shown to have good performance

\[ \text{(MaxEN)} \]

\[ \text{(MaxMI)} \]
How the greedy algorithms work

- Use certain training data to compute the mean, variances, and covariances at (and among) all locations

- Greedy placement:
  - At each step $t$, select one location that maximizes EN/MI (or minimizes MSE) given the set of locations already selected
  - Repeat till we have selected $K$ locations

- Estimation/Prediction:
  - Conditional mean, also known as Gaussian regression

- How well does the Gaussian assumption hold for soil moisture data?

- How does this affect the design of good sensor placement and field estimation algorithms?
tRIBS simulation of soil moisture fields

- A 2km x 2km basin with 2400 locations (9 depths each) on a regular square grid
- Over a three-month period (simulated time), one snapshot per hour, a total of 2208 snapshots used in our experiments
Properties of the data: is the (surface) soil moisture process Gaussian?

- Three randomly selected locations
- Surface soil moisture only
- Moisture readings amplified 1000x
- Top: histograms of moisture at these locations (black) and the estimated Gaussian kernel (red)
- Bottom: estimated pdf
- Observation: these are clearly non-Gaussian
Temporal changes at these locations

- The same three locations as in previous slide
- Figures show the change over time at these locations
- Figures show, qualitatively, how soil moisture is correlated between them
- Spikes correspond to rain events
Observations

- Locations with similar features (soil type, vegetation cover, etc.) will show high correlation
- Most of these are relatively stable features over time
- May expect relative soil moisture values to hold steady even as absolute values vary over time
- Shown in bottom figure: histogram of a location’s numerical rank in each snapshot
What does the clustering look like (W=8)
Placement using coarse-grained ordering

- Use a subset of simulated data for training, compute the mean, variances, and covariances at (and among) all locations

- Sensor placement:
  - Solve the placement problem independently for each cluster
  - Can allocate more sensors to clusters with higher average moisture (variance) levels
  - Place $K_i$ sensors in cluster $i$, with $\sum_{i=1}^{W} K_i = K$
  - Within each cluster can use any existing scheme (e.g., max EN/MI)

- Field estimation:
  - Will use Gaussian regression
Clustered vs. global placement: size of the selected subset

- Using the first 1500 snapshots for training and the last 700 for testing (out of 2208)
- Clustered schemes show advantage when placing sensors $K \geq 200$
Clustered vs. global placement: performance improvement

- 250 sensors are placed
- Regardless of training amount, clustering results in better performance

1500 training snapshots

1000 training snapshots
A quick glance at the actual placement (20 sensors) under different schemes: Many features are similar between EN and MI approaches.

- Global MaxEN (blue)
- Clustered MaxEN (red)
- Global MaxMI (blue)
- Clustered MaxMI (red)
Non-Gaussian Dynamic Mean Estimation with a Fixed Placement

- Currently, the scheduling objective is to estimate soil moisture evolution at $K$ fixed lateral locations using sensors placed at those locations.

- However, we are also interested in using the $K$ sensors to estimate a mean value of the soil moisture over the area of interest.

- Statistics are not Gaussian; estimation costs are dynamic.
Mean Estimation: Solution Methodology

- Solve the scheduling problem independently for each sensor location.

- Exploit the correlation among soil moisture values at different locations to find local estimates, \( \hat{X}_i \) (location), using past measurements from all locations (Joint Estimation).

- Find the joint statistics of the field mean \( M \) and the local values of soil moisture at sensor locations.

- Use the joint statistical model of the soil moisture at sensor locations and the field mean to convert the local estimates to a mean field estimate \( \hat{M} \).

- Performance of scheduler (dynamic problem) depends on placement (static problem), and vice versa.

- Currently developing solution of joint placement and scheduling problems.
Landscape Simulator Overview

- Proof-of-concept heterogeneous landscape simulator
  - Developed architecture of simulator
  - Implemented unified multi-layered multi-species vegetation model adaptable to various land cover types
  - Created a data base of input files using land cover types of NLCD 2001

- Visualization in Google Earth
  - Layers of information co-registered on whole Earth

- Preliminary aggregation studies
  - Investigated how coarse-resolution remote sensor measurements relate to finer-resolution measurements
Example: Oklahoma locations

1. Google Earth
2. Land cover type from NLCD 2001
3. Digital Elevation Map (DEM) / National Elevation Dataset (NED)
4. Soil type from USDA

Area around Oklahoma City, OK
From land cover type to model

Available information & ancillary data is used to adapt model to specific landscape (via parameter input file)

- **Current**: selection of pre-determined input files based on land cover type
- **Prospective**: generate input file based on more diverse combinations of ancillary data
From land cover type to model: One model

Model is general enough to represent various land cover types
Model:

- Can simulate multi-layer vegetation and multiple vegetation types simultaneously
- Builds on existing single species forest model (Durden et al., 1989)
  - Scattering from layers of arbitrarily oriented dielectric cylinders above a rough dielectric surface
  - Extended to multi-layer multi-species discrete scatterer model with rough surface representing ground
  - Simulation of full Stokes matrix and polarization signature
- Analysis is based on wave theory; distorted Born approximation
  - Scattering and transmission matrices are formed, from which Stokes matrices are calculated
Model (2):

Species-specific parameters:

- Set of 27 parameters define geometry and structure of single species:
  - Soft- or hardwood
  - Dielectric characteristics of leaves, branches, trunks, soil
  - Densities, lengths, radii
  - Probability density function (pdf’s) for orientation of branches, trunks

- Allometric relations exist for different species, ideally unique relationships
  - Knowledge of plant anatomy results in species-specific relations for modeling
Single species geometry:

Model considers four scattering mechanisms:

- Direct backscatter from crown layer (DC)
- Direct backscattering from ground (DG)
- Specular crown scattering followed by ground reflection (CG) modified for surface roughness
- Specular trunk scattering followed by ground reflection (TG)
Single species setup:

- Total Stokes matrix found by summing the matrices of the different scattering mechanisms

\[
M_{Total} = M_b + T_b T_t M_g T_t T_b + T_b T_t M_{bg} T_t T_b + T_b T_t M_{tg} T_t T_b
\]

M: Stokes matrix for backscattering
T: Stokes matrix for transmission through layer
b: Branch layer
t: Trunk layer
g: Ground
Multi-species geometry:

- Introduction of more species will result in N layers
- Determination of layer composition, including that of overlapping layers is an important step
- Model proceeds with methodical calculation of layer scattering, attenuation and interaction
Multi-species setup:

- Total Stokes matrix for multi-species model:

\[
M_{Total} = M_b + M_g + M_{bg} + M_{tg} + M_{li}
\]

\[
M_b = M_{bL1} + T_{L1} M_{bL2} T_{L1} + T_{L1} T_{L2} \cdots T_{LN-1} M_{bLN} T_{LN-1} \cdots T_{L2} T_{L1}
\]

\[
M_g = T_{L1} T_{L2} \cdots T_{LN-1} M_{gLN} T_{LN-1} \cdots T_{L2} T_{L1}
\]

\[
M_{bg} = T_{L1} T_{L2} \cdots T_{LN-1} M_{bg1LN} T_{LN-1} \cdots T_{L2} T_{L1} + T_{L1} T_{L2} \cdots T_{LN-1} M_{bg2LN} T_{LN-1} \cdots T_{L2} T_{L1} + \cdots
\]

\[
M_{tg} = T_{L1} T_{L2} \cdots T_{LN-1} M_{tg1LN} T_{LN-1} \cdots T_{L2} T_{L1} + T_{L1} T_{L2} \cdots T_{LN-1} M_{tg2LN} T_{LN-1} \cdots T_{L2} T_{L1} + \cdots
\]

\[
M_{li} = M_{liL1s1L2s2} T_{L1} + M_{liL1s1L3s2} T_{L2} T_{L1} + \cdots + T_{L1} M_{liL2s1L3s2} T_{L2} T_{L1} + \cdots + T_{L1} M_{liL2L3} T_{L2} T_{L1} + \cdots
\]

TL1, ...TLN: can contain combination of crown and trunk layer, depending on geometry
Architecture of Simulator

Google Earth

PCI Geomatics

EASI

Aggregation of sub-blocks

Text files

backscatter cross section of each sub-block

Text files

FORTRAN

Model

Pre-determined parameter input files

Text files

EASI Engineering Analysis and Scientific Interface

(Verification with Matlab)

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FORTRAN

Model

Pre-determined parameter input files

Text files

EASI Engineering Analysis and Scientific Interface

(Verification with Matlab)

Text files
Select area and read data out via text files.

Pre-determined parameter input files

Aggregation of sub-blocks

EASI Engineering Analysis and Scientific Interface

backscatter cross section of each sub-block

FORTRAN Model
pre-determined parameter input files

PCI Geomatics

EASI - Engineering Analysis and Scientific Interface

Aggregation of sub-blocks

backscatter cross section of each sub-block

FORTRAN Model

Text files

Text files
Run the Fortran model...

Pre-determined parameter input files

Text files

PCI Geomatics text files

EASI Engineering Analysis and Scientific Interface

Aggregation of sub-blocks

EASI backscatter cross section of each sub-block

FORTRAN Model

Pre-determined parameter input files
New data layer co-registered on Earth

Pre-determined parameter input files

PCI Geomatics

Aggregation of sub-blocks

Text files

EASI

Engineering Analysis and Scientific Interface

Text files

(Verification with data layer co-registered on Earth)

FORTRAN

Model

backscatter cross section of each sub-block
Architecture, con’t.

- Backscatter cross section from each sub-block is calculated.
- Aggregation types can be investigated: blocks of 4 (light green), 16 (dark green), 64, etc., to achieve a statistically representative mean value for the backscattering cross section of the scene (e.g., for one SMAP pixel).
- Final result can be exported to PCI & Google Earth for visualization.
- Will be used in the future as basis for *disaggregation* analysis for SMAP retrievals.

Sub-block
30 x 30 m
(Resolution of NLCD 2001 land cover type information)

~3 km SMAP resolution cell
First results: HH backscatter coefficient in dB for L-band

1. Google Earth
2. Land cover type from NLCD 2001
3. Backscatter coefficient
   a) Block of 1 x 1 sub-blocks
   b) Block of 2 x 2 sub-blocks
   c) Block of 4 x 4 sub-blocks
   d) Block containing all sub-blocks

- The final aggregation stage is similar to what SMAP radar sees
- Landscape detail is lost
- Current aggregation simply shows linear averaging; in reality SMAP data might correspond to some other (nonuniform or nonlinear) aggregation
First results: VV backscatter coefficient in dB for L-band

1. Google Earth
2. Land cover type from NLCD 2001
3. Backscatter coefficient
   a) Block of 1 x 1 sub-blocks
   b) Block of 2 x 2 sub-blocks
   c) Block of 4 x 4 sub-blocks
   d) Block containing all sub-blocks

- VV results are similar to HH
- This aggregation simply shows linear averaging; in reality SMAP data might correspond to some other (nonuniform or nonlinear) aggregation
Ongoing Activities

• Improve modeling and finalize landscape simulator:
  • Search for and integrate more available information
  • Use more ancillary data to build input files of sub-blocks to make modeling as realistic as possible
  • Integrate topography (slope, etc.)

• Investigate forward-mode multi-scale aggregation/disaggregation
  • Can a coarse resolution measurement be represented as a weighted sum of the fine-resolution ones? What statistical rules apply?
  • Study sensitivity of answer to above question to perturbations in soil moisture
Wireless Comm and Actuation System Overview

- Developed and successfully tested “Ripple-1” wireless sensor nodes for field deployment at U of M Matthaei Botanical Gardens

- Started on the design of “Ripple-2” ground unit platform to provide better energy efficiency for router nodes

- Webpage released, with a backend database to store and retrieve real-time soil moisture data collected at the Botanical Gardens
Functional view

- Soil moisture observations provided by sparse set of sensors in the field
- Each sensor sends data to coordinating center via a wireless network
- Base station assimilates data, generates control, and sends that to actuators at sensor locations
Field Deployment: Matthaei Botanical Gardens

Thirty Ripple-1 sensor node were built and successfully deployed at Matthaei during our AIST-05 project. Figure shows the Zigbee network formed by these sensor nodes.
Ripple-1 ZigBee Network

• A multi-hop network consisting of three types of logic devices

• An end device is heavily duty cycled; the base station is plugged in; the router currently needs more power than desired

• Can remotely access sensors and control data collection

• Can remotely set the sensor and transceiver on cyclic sleep mode to better control energy consumption
AIST-05: The Ripple-1 Node

- Xbee Pro SOC module serves as MCU and radio
  - Long Communication Range: up to 1 mile (1600 m)
  - Low Power Consumption
    - 295mA @3.3 V (TX)
    - 45 mA @3.3 V (RX)
    - < 10 uA (Sleep)
Global architecture of the Ripple system

- **In target field**
  - A sensor network consisting of multiple wireless ground units and sensors
  - An indoor base station; data stored in a database
  - Scheduling policy run on the base station

- **On UM campus**
  - Web site hosted on a server ([soilscape.eecs.umich.edu](http://soilscape.eecs.umich.edu))
  - Real-time data query and display
  - Enable mobile access
Plans for Deploying at SMAP 2010 Field Sites

• SMAP has deployed a network of ground sensors in Marena, OK, this spring
  - Primary goal is to benchmark various in-situ sensors against each other
  - May also investigate issues related to scaling of soil moisture measurements, but limited scope

• We plan to deploy networks concurrently
  - Marena, OK (interleaved with SMAP sensors)
  - Canton, OK (our network only)
  - Sites are within ~ 100 miles of each other, but Canton has more heterogeneity and allows better testing of optimal placement strategies
Summary

• Tested several candidate approaches for sensor placement optimization
  – Implemented and verified empirical placement strategies; started developing analytical joint placement/scheduling methodology

• Built landscape simulator
  – Simulator architecture developed, implemented, and tested; preliminary scaling studies performed

• Developed wireless sensor actuation and communication nodes
  – Multihop architecture investigated

• Ongoing collaborations with SMAP algorithms and całval team
  – Continually collaborating with team; will install in one or two of SMAP całval nodes (one in Oklahoma, another TBD)

• Various project elements at TRLs of 3 to 4