



Soil moisture Sensing Controller And oPtimal Estimator (SoilSCAPE): First Deployment

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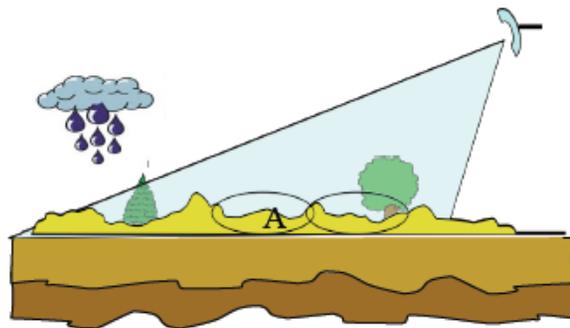
ESTF 2011, Pasadena, CA
06/23/11



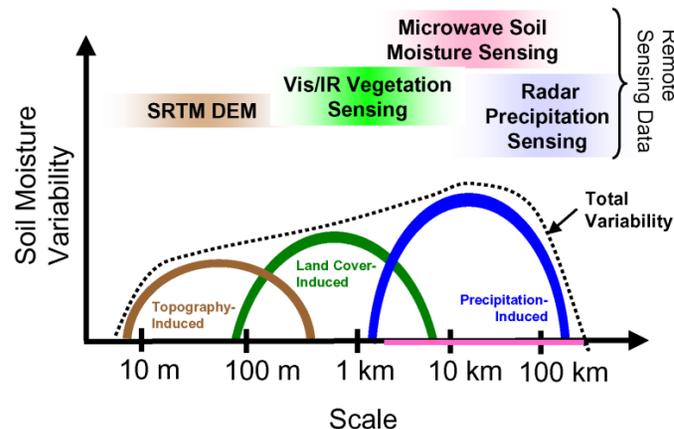
Background and Objectives (1)



Soil moisture Sensing Controller And oPtimal Estimator (SoilSCAPE): develop technologies for near real-time validation of spaceborne soil moisture estimates, and in particular those derived from the Soil Moisture Active and Passive (SMAP) mission



Soil moisture is a key state variable in the hydrologic cycle that varies on **spatial scales** of meters to tens of kilometers, and **temporal scales** of minutes to days.



SMAP's radar and radiometer instruments will each measure soil moisture, but with different spatial resolutions and different sources of uncertainty. Both capture significant landscape heterogeneity due to large pixel sizes. Each heterogeneous pixel can be thought of as containing many homogeneous sub-pixels (areas "A" in the top figure).

Validation of these measurements requires more sophisticated **adaptive temporal and spatial sampling** strategies than the costly (and often impractical) uniform sampling scenarios used today.



Project Elements



- **Wireless communication and actuation system for in-situ soil moisture network**
 - Support SMAP CalVal activities
 - “Ripple-1” wireless nodes demonstrated in field; develop next generation “Ripple-2” with efficient multi-hop features for larger-scale networks
 - Develop web-based command system and data portal
- **Multiscale landscape simulator for soil moisture aggregation/disaggregation**
 - SMAP radar product has 1-3 km resolution, radiometer has 40 km resolution
 - Build heterogeneous radar landscape simulator with capability to include arbitrary vegetation, topography, soil
 - Build landscape hydrology simulator to predict soil moisture field dynamics; interface with radar simulator
 - Numerically and experimentally derive aggregation and disaggregation rules for radar backscatter vs. soil moisture
- **Control system for sensor placement and scheduling optimization**
 - Sensor scheduling
 - Sensor placement
 - Initially decouple placement from scheduling; but eventually a joint estimation problem



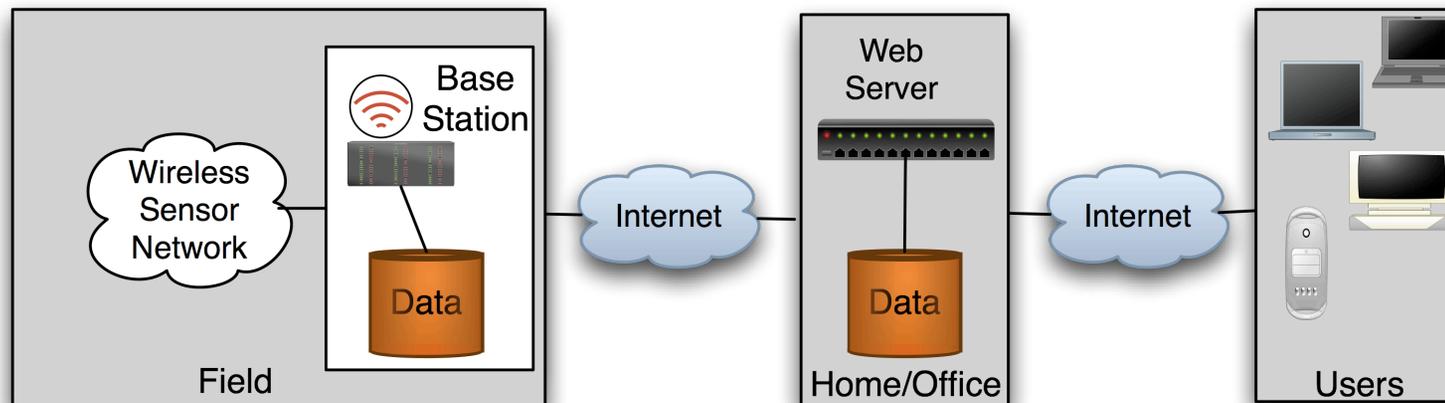
Communication
& Actuation

Landscape
Simulator

Control System



Ripple-1 system architecture



- Unattended field data collection; wireless sensor network has a lifetime on the order of years
- Near real-time data upload, visualization, and inspection
- This system deployed at Canton, Oklahoma in August 2010.



Ripple-1 wireless sensor network design

Design choice: ZigBee Network

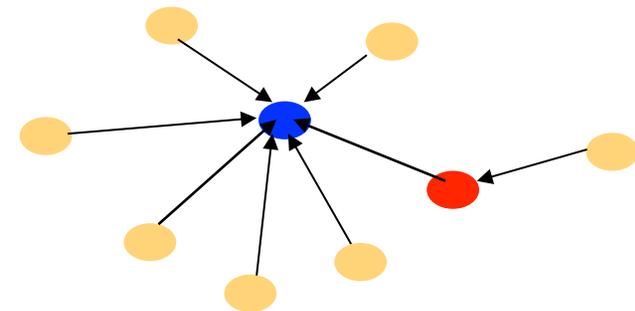
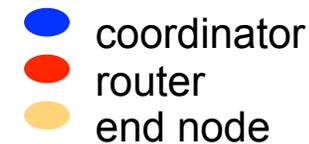
- A multi-hop network consisting of three types of logic devices
- Can auto-configure the topology

Advantage

- Relatively mature technology
- Multi-hopping nature can cover larger areas
- Can potentially shorten our cycle

Disadvantage

- A router cannot be put in “power save” or sleep mode
- Needs larger batteries



Ripple-1 wireless ground module/actuator design

Design choice: Xbee Pro SOC

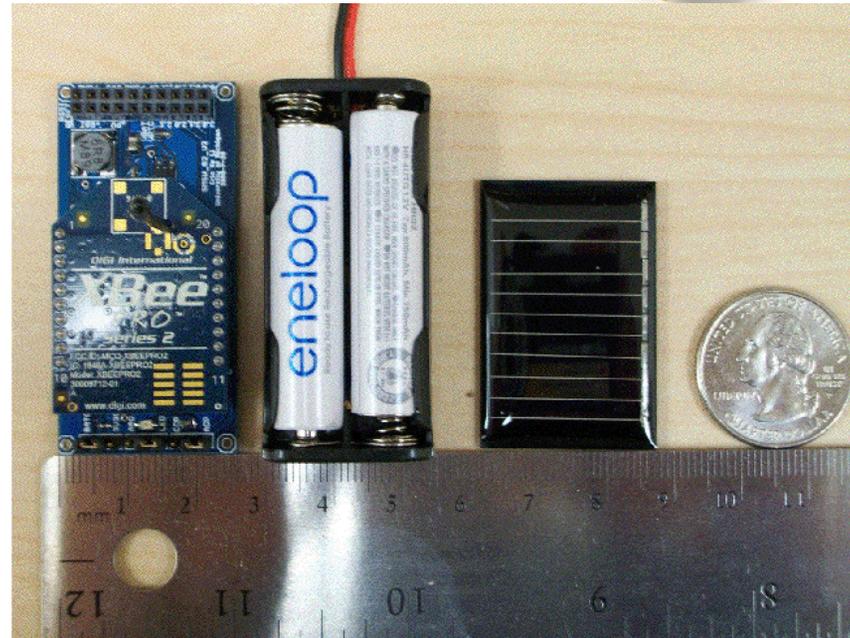
- As MCU and radio

Advantage

- Long range (~500m);
- Low power (295mA @3.3 V (TX); 45 mA @3.3 V (RX); < 10 uA (Sleep))

Disadvantage

- Completely encapsulated;
limited ability to customize





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Ripple-1 network and software configuration

The actuators are heavily duty cycled

- Continuous sampling rate: every 10min
- Wake time: ~1sec; sleep time: 10min
- If using scheduling policy: maximum sleep time 2hr
- Attach three moisture probes per ground module
- Goal: to be able to continue running on 2 AAA batteries for 2-3 months without recharging

The ability to measure on demand

- Actuator can receive scheduling command from the base station and adjust the next wakeup time

Routers

- Much bigger solar panels: ~12' x10'
- Bigger and different batteries



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Ripple-1 deployment: Canton, OK

- August 2010
- ~ 90 miles NW of OKC
- On a cattle farm
- Field covers four different soil types
- Team of 8; 4 days





Deployment at a glance

August 2010 (initial deployment):

- 1 coordinator
- 3 routers
- 21 end devices: 3 depths (4, 13, 30 cm)
- 1 desktop computer
- 1 battery backup (UPS)

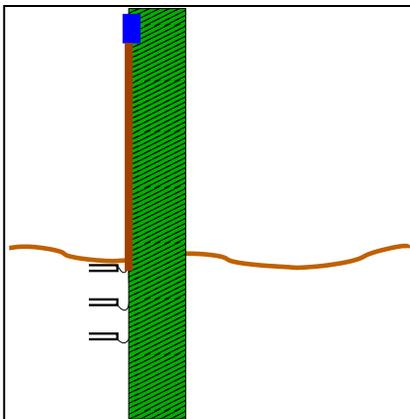
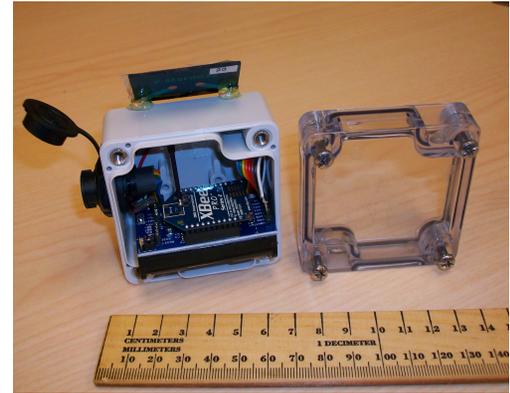
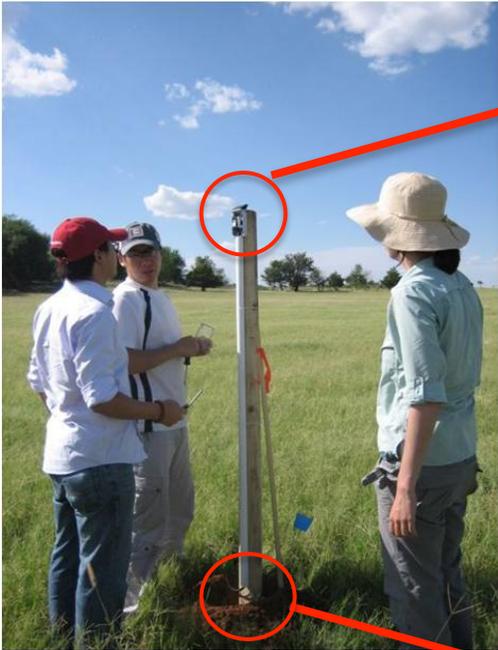




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Landscape Simulator

Control System





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Near-Real-Time Web-Based Data Access

- <http://soilscape.eecs.umich.edu/>
- Data are automatically uploaded to the web page in near-real-time (~30 minute lag)
- Added general information on the deployment site
- Added table showing last update from each node
- Batch data download option (raw and calibrated)
- Added documentation on data calibration

Real-Time Data

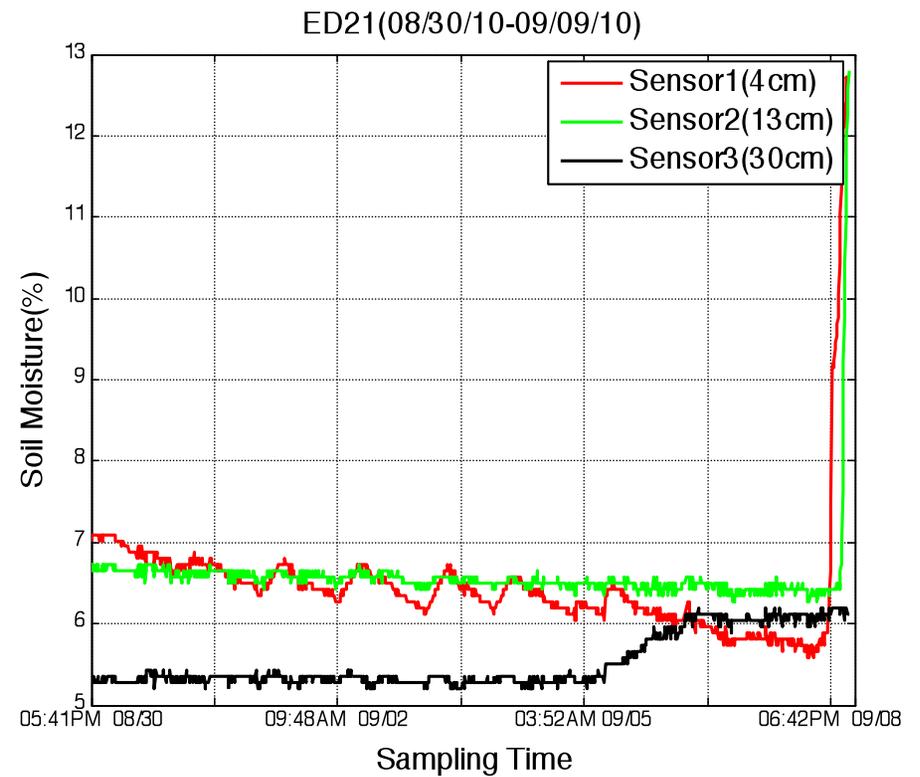
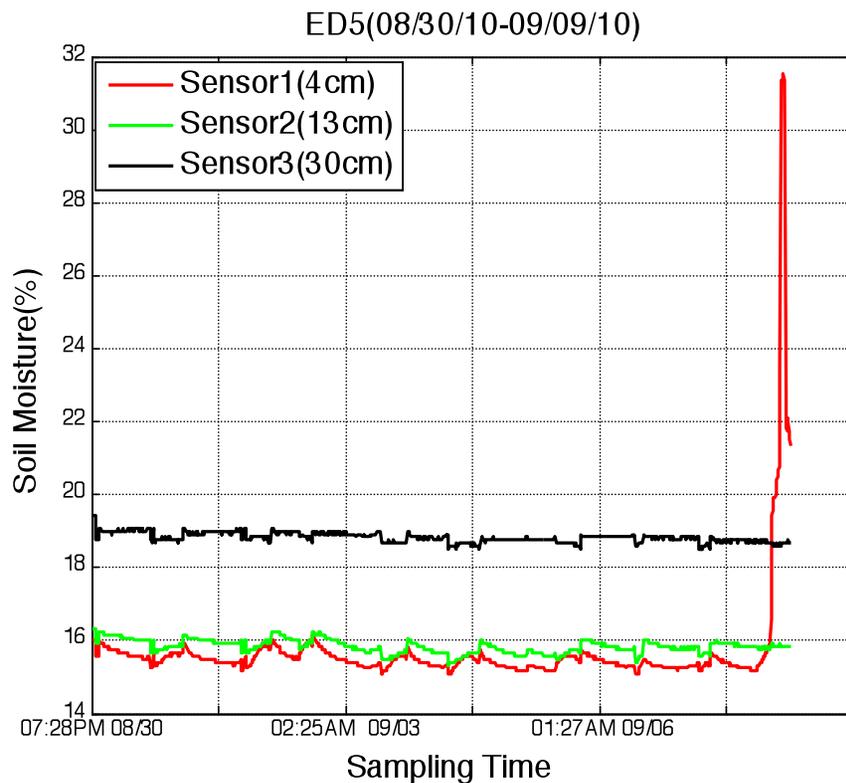


Imagery ©2011 DigitalGlobe, GeoEye, Texas Orthoimagery Program, USDA Farm Service Agency -

Node to View:
Depth to Compare: No. of Nodes to Compare:



Sample data collected at Canton, OK





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Technical problems encountered

- The network would operate normally for some time, but disappear (the end devices stop updating the base station) for a couple of hours at a time.
- Diagnosis:
 - the quality of the router-base station connection was not stable, causing end devices to switch parents
 - this took a long time to complete after a number of re-tries
 - the child-table on the routers took a long time to refresh.
- The 3G was extremely unstable; connection got dropped frequently.
- The 3G card interface regularly failed after some time; the only fix without physically unplug-plugging the card was to reboot the machine.



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Ripple-1: Lessons learned

Hardware solution choice:

- We selected Xbee Pro Series 2, which has ZigBee built-in.
- This significantly shortened the development cycle in rolling out Ripple-1, but very little of the protocol is under our control.

Network design and operation:

- Multi-hopping is very delicate to work with and maintain, especially when the nodes are heavily duty-cycled as ours.
- ZigBee is good for a more stable (indoor) environment, where parent-children associations do not fluctuate frequently over time due to channel quality fluctuation



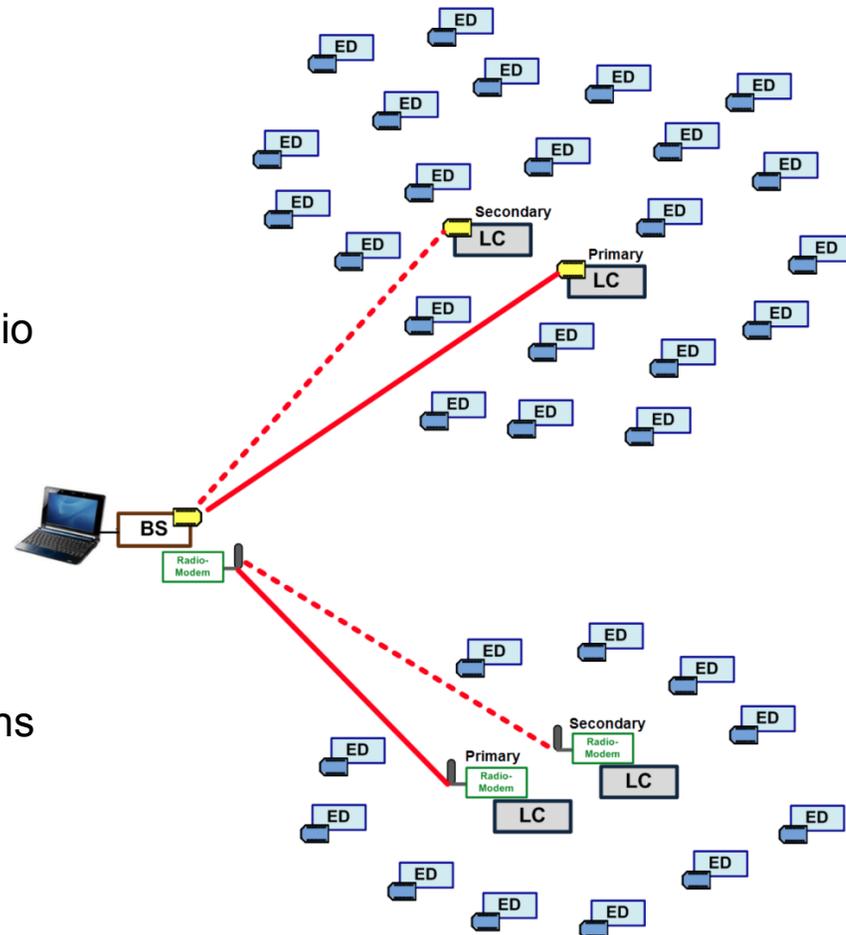
Ripple-2: system architecture

Adopt a two-layer hierarchy:

- (Local) coordinators and end devices form the lower layer
- Base station and (local) coordinators form the upper layer
- Two layers may not use the same radio solution
- Low layer will use IEEE 802.15.4, but not ZigBee

Main advantages:

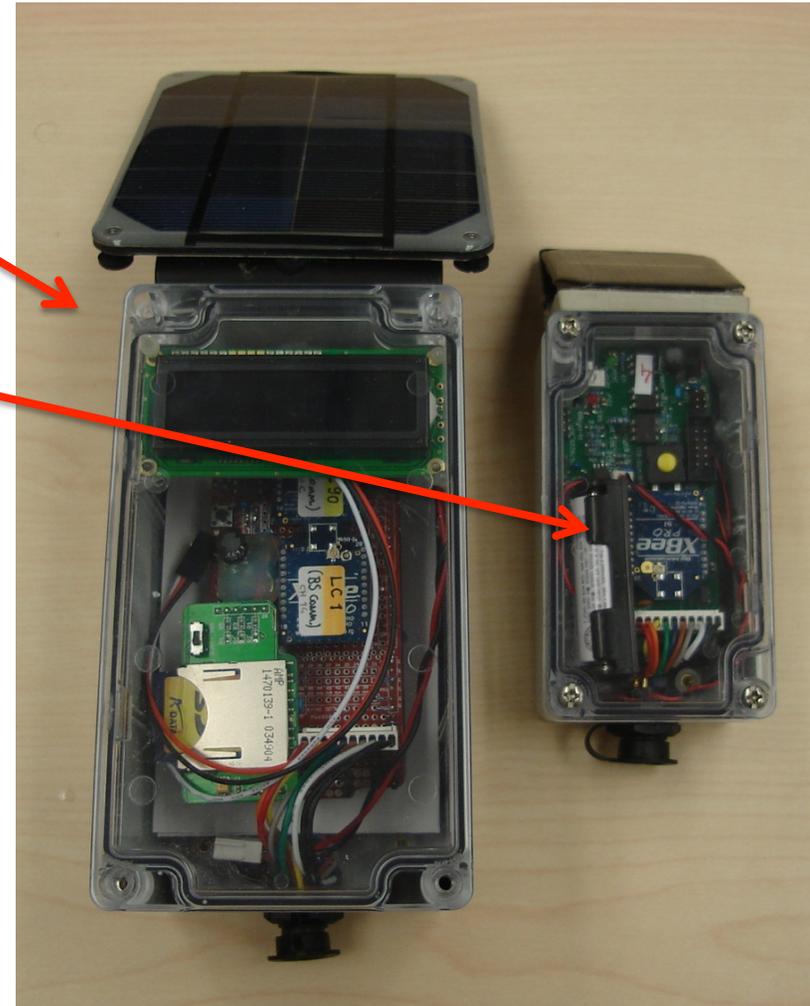
- Flexibility in developing our own protocol on top of 802.15.4 for the lower layer and multiple other solutions for the upper layer
- Two layers are logically separate
- End devices' sleep scheduling much easier to control
- Very easy to scale up the system





Ripple-2: completed system

- Local coordinator uses 6 AA batteries
- End device uses 2 AA batteries
- Currently in process of field validation of Ripple-2 at UM Matthaei Botanical Gardens; will follow up with Canton, OK, upgrade





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Landscape Simulator Highlights:

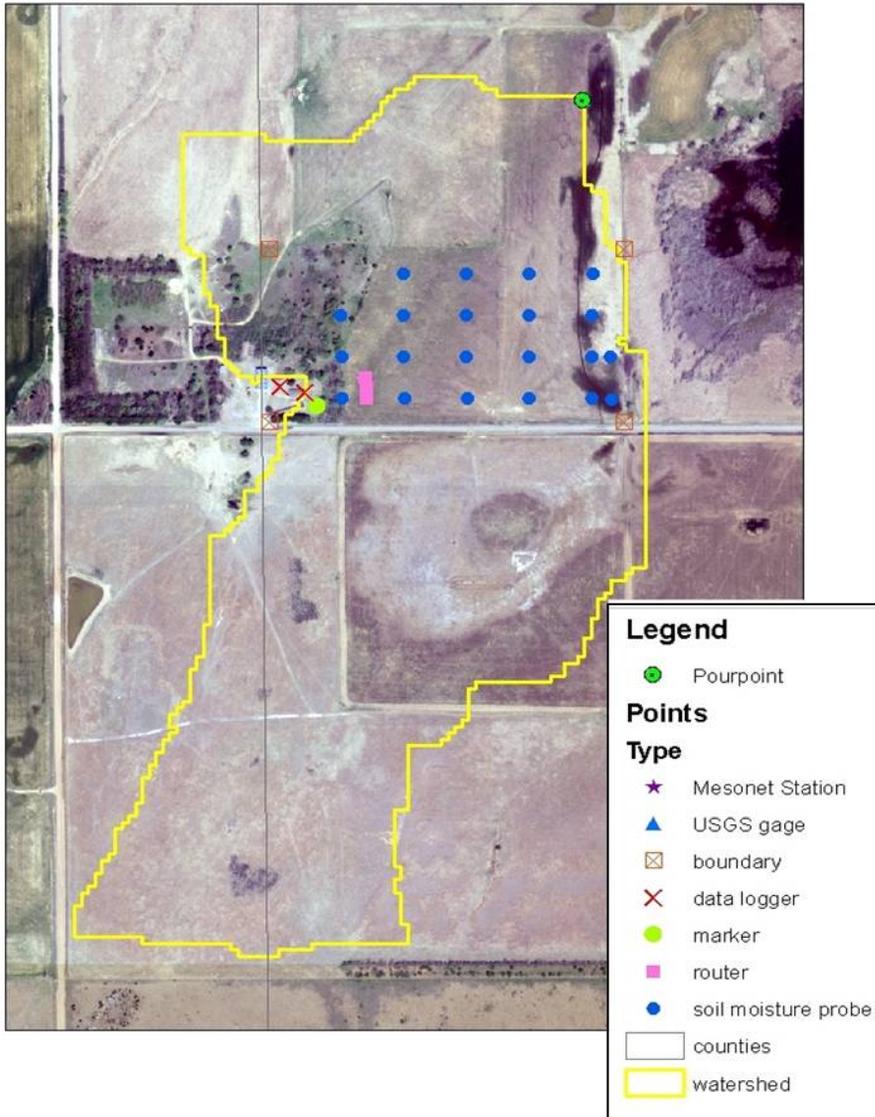
- Hydrologic land-surface model (MOBIDIC) simulations
 - Used geospatial data layers; generated three data sets 2005 (hourly), 2009 (daily), 8/1/10 – 3/20/11 (hourly)
 - Testing and cross-calibration with SoilSCAPE data underway
- Heterogeneous landscape radar simulator
 - Same geospatial data layers as the land surface simulator for the Canton site
 - Performed scaling/aggregation analyses
 - Used soil moisture trends from hydrologic land surface model to simulate backscatter variations across scales



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- Location of SoilSCAPE sensors (blue)
- Delineation of catchment area (yellow)
- Based on 10m resolution DEM



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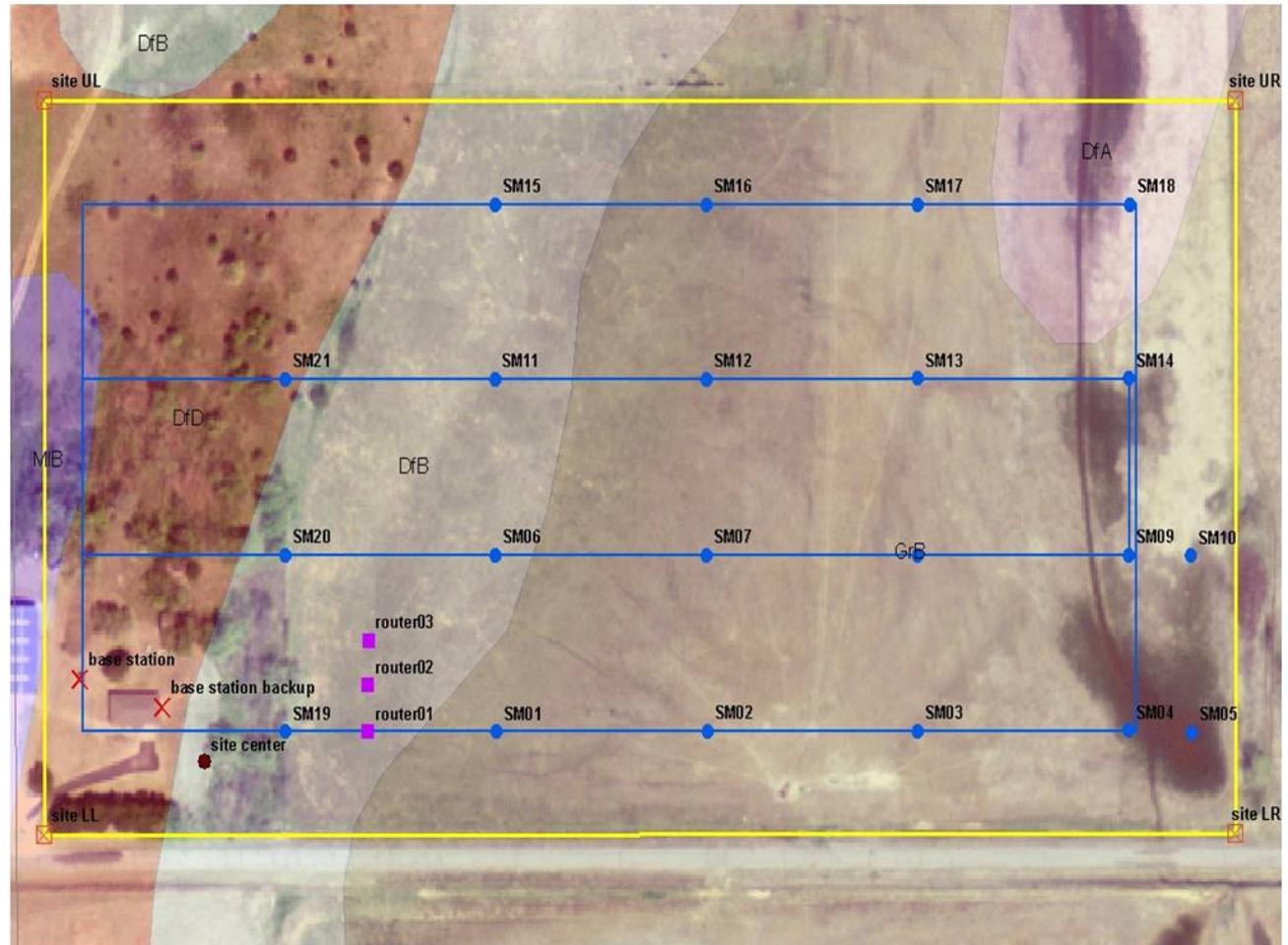
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~ 460m x 250m

Overlaid is the unedited SSURGO soil map





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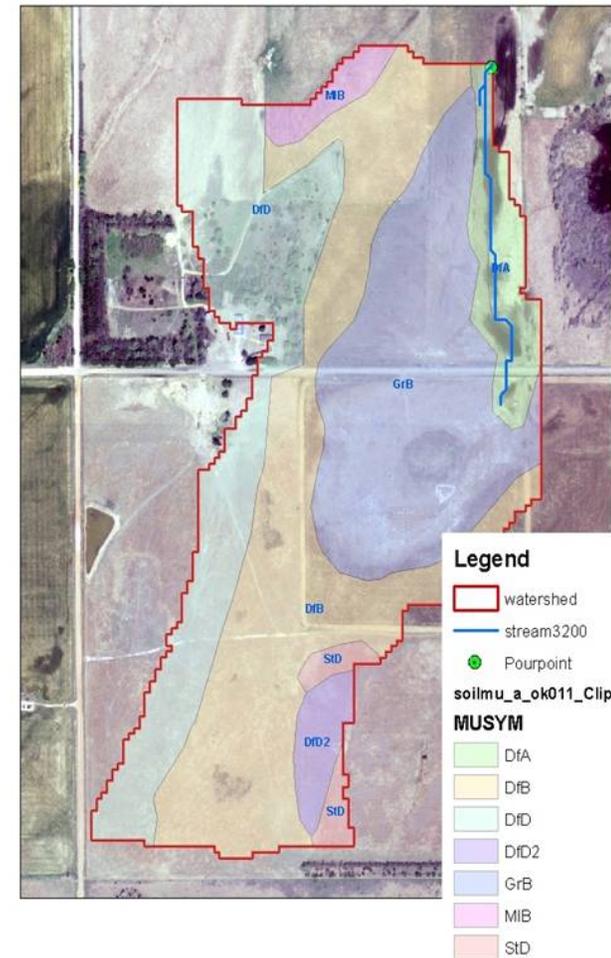
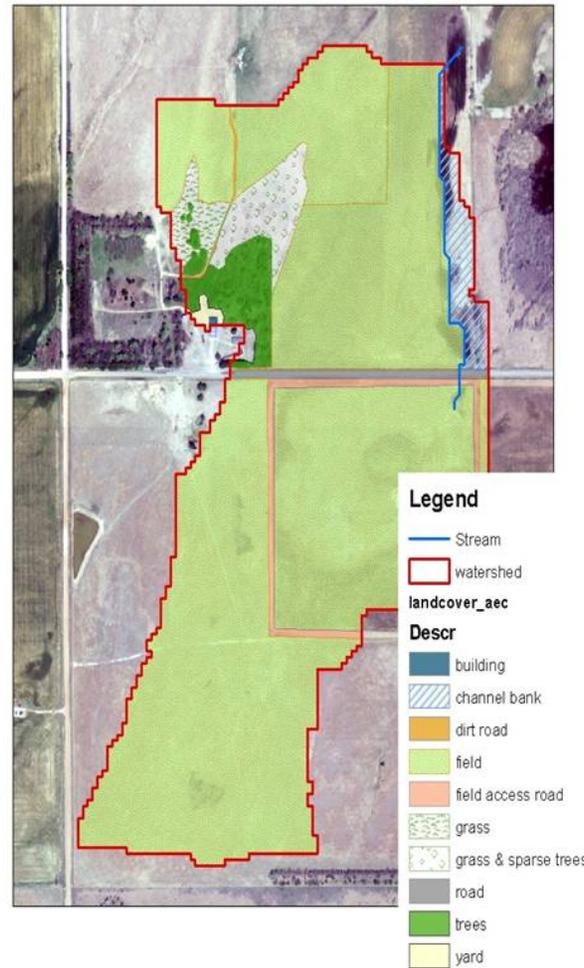


Left:

Digitized land use/land cover map based on the orthophoto

Right:

Extracted SSURGO soil map. Modifications made to match the orthophoto and the wetness map from field observations





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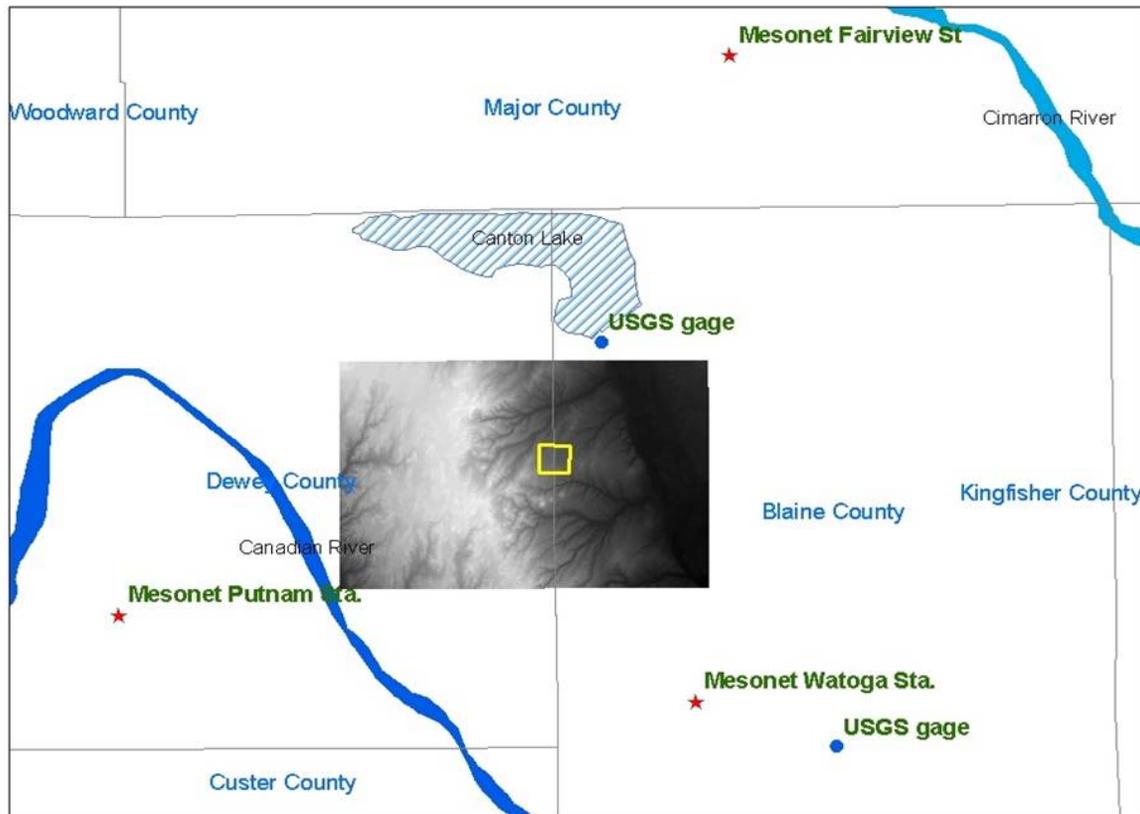


MESONET Stations:

Watoga (20km), Fairview (31km), Putnam (38km)
Hourly met & soil data downloaded for last 5 years

USGS Stations:

0723900 (upstream, 12484sq.mi.), 0723900 (downstream, 12736sq.mi.)



The 2 USGS stations are not very useful for this study; far outside of the catchment



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Simulation

- August 1, 2010 – March 20, 2011
- Time step: hourly
- Some parameters were adjusted so that the results make sense, such as spatio-temporal distribution and range/magnitude of soil moisture, ET, runoff
- Uncalibrated output
- Improve parameterization of basin properties and calibrate output after site visit (April 19-24, 2011)
- Initial results suggest that the input of precipitation might be inaccurate. The installation of a rain gauge is planned and should mitigate this. Additionally, use level III NEXRAD for precipitation, this is still in progress



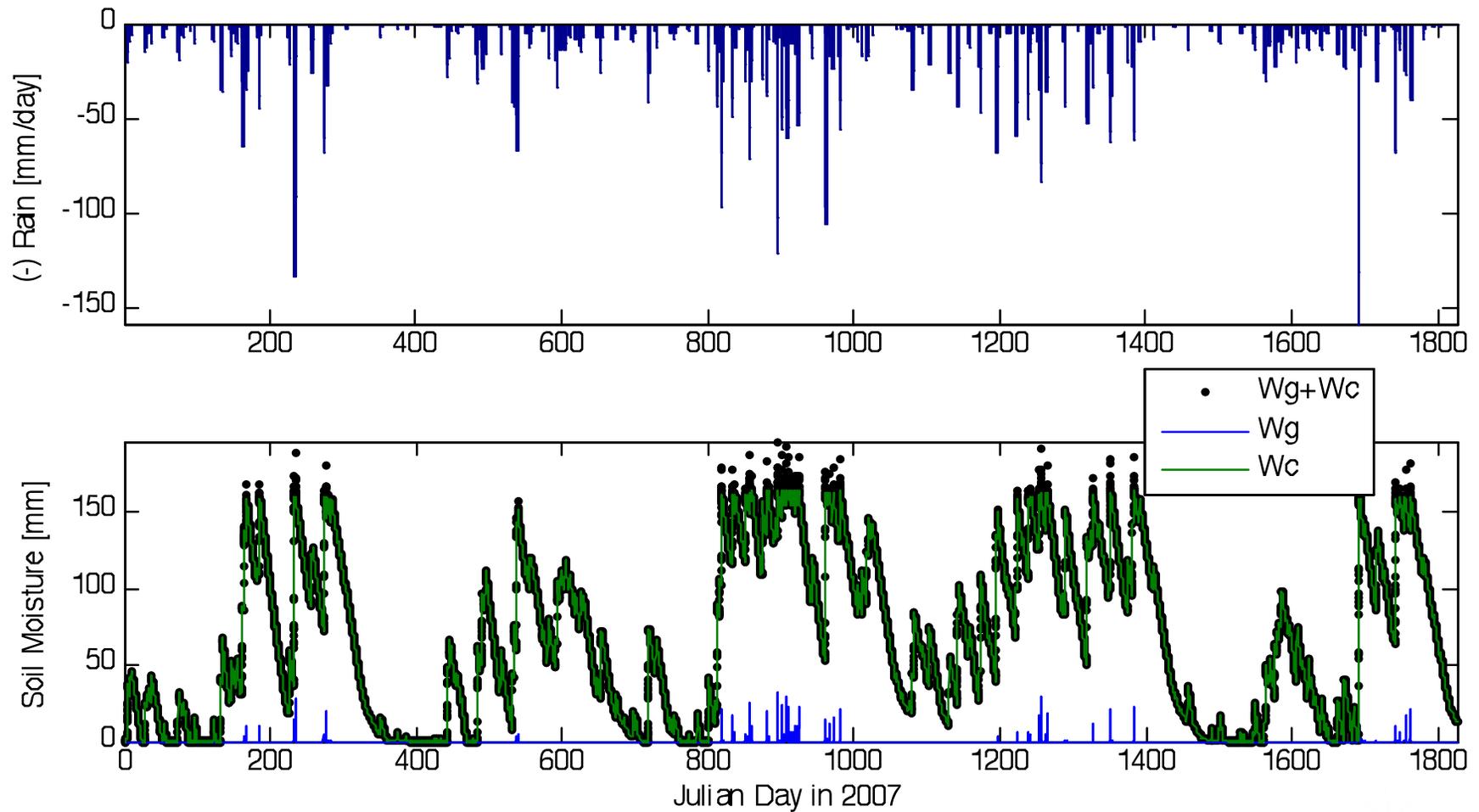
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Output from MOBIDIC (1/3)





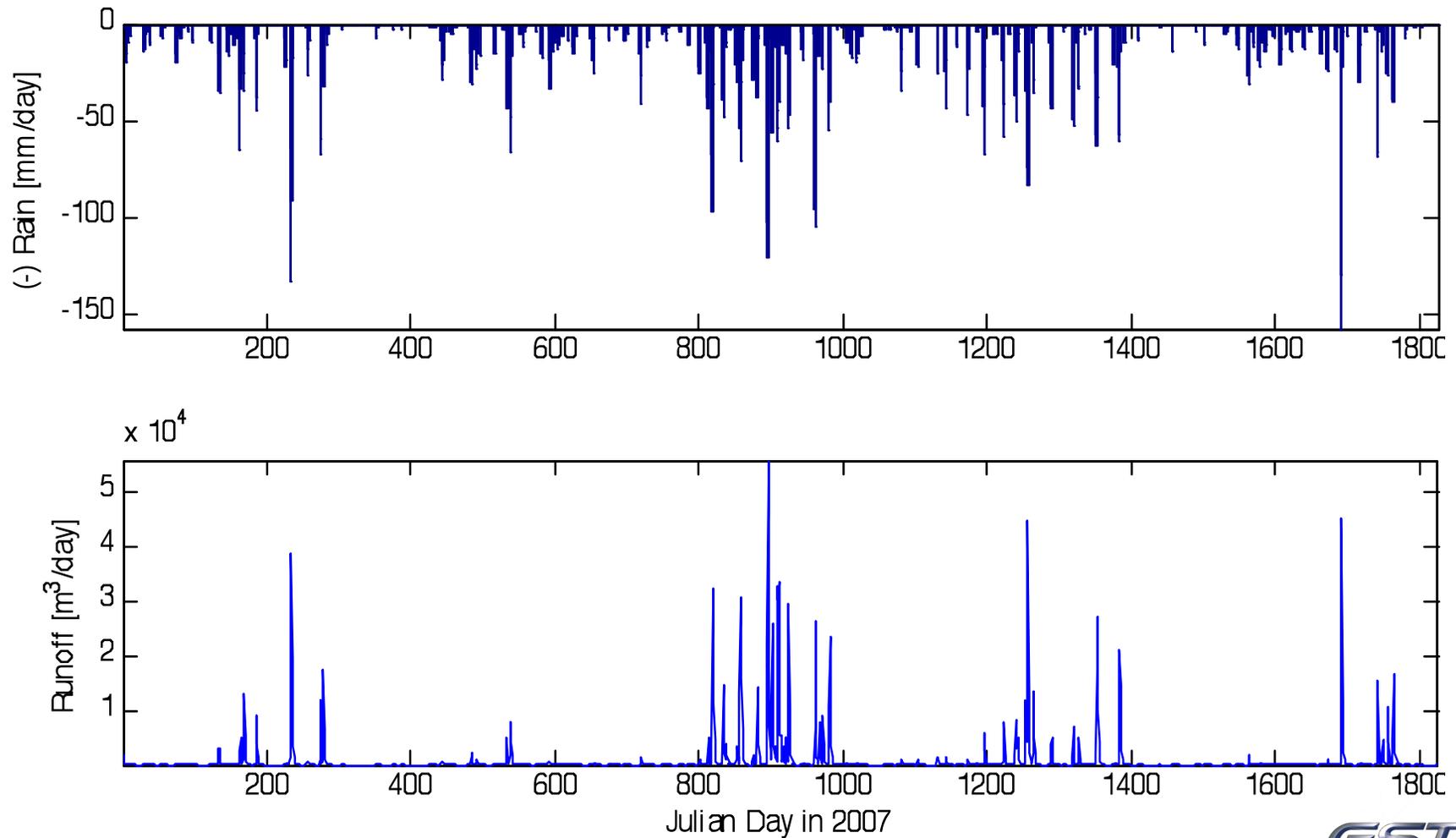
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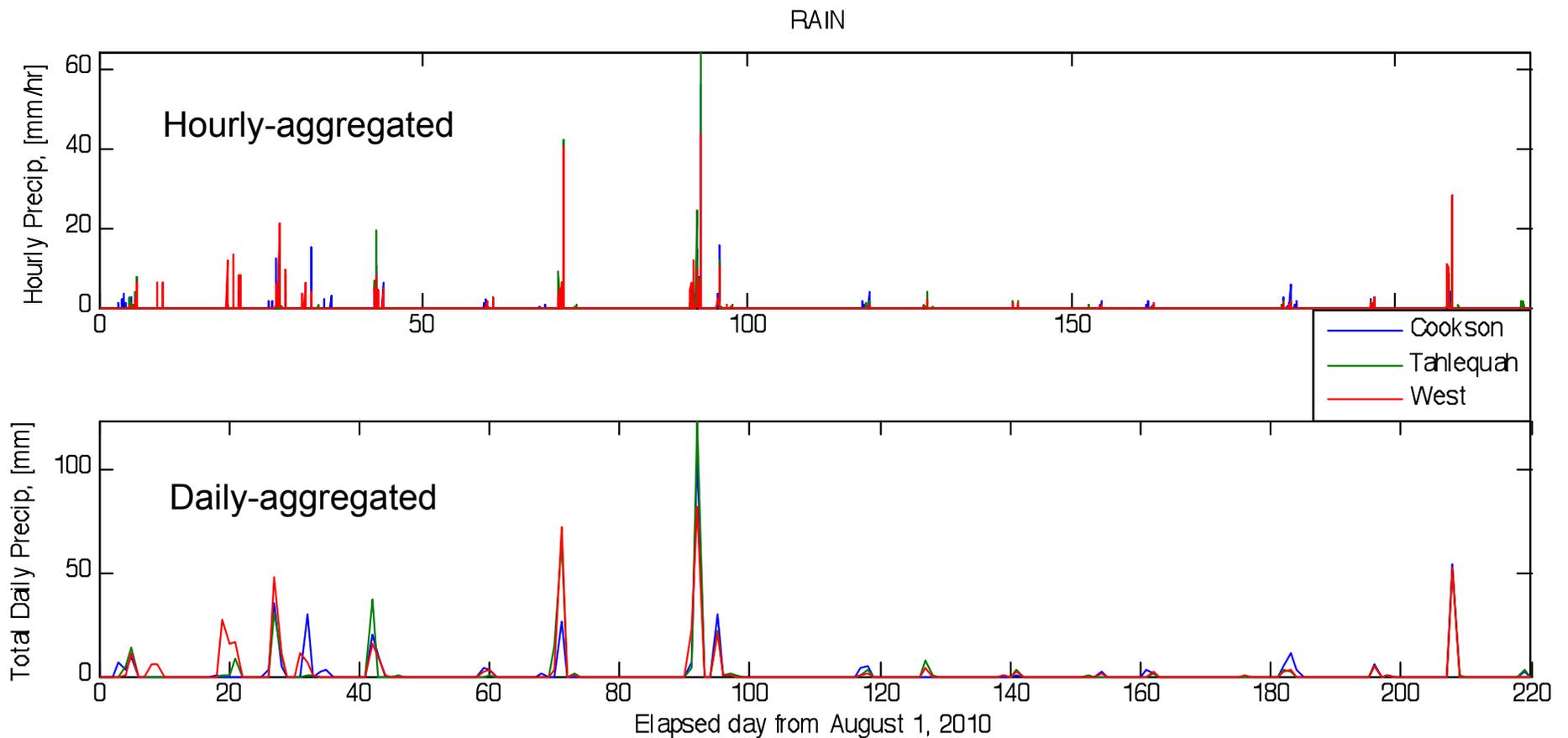


Output from MOBIDIC (2/3)





Output from MOBIDIC (3/3): 8/1/2010 to 3/30/2011





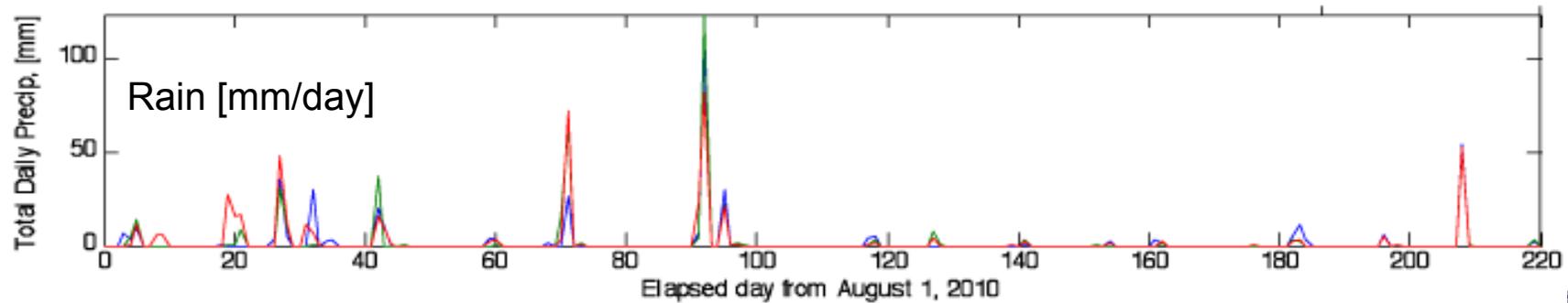
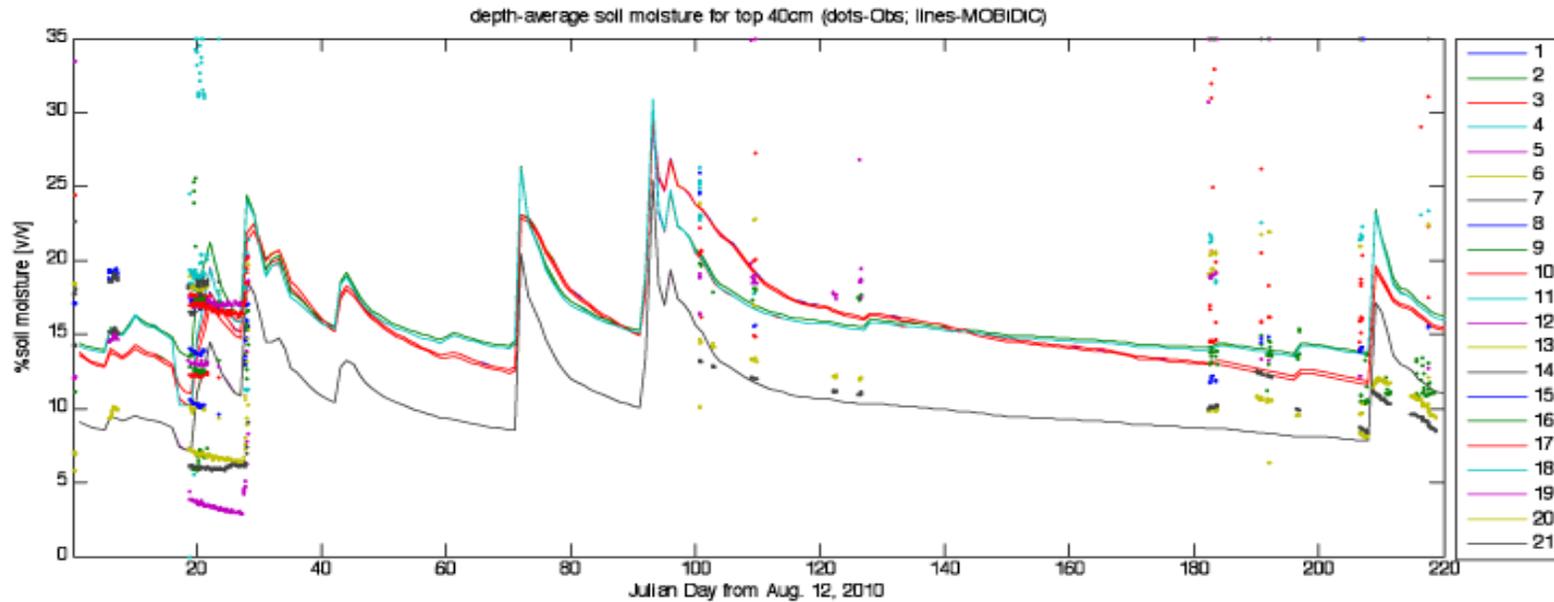
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Daily-aggregated Soil Moisture [% v/v]



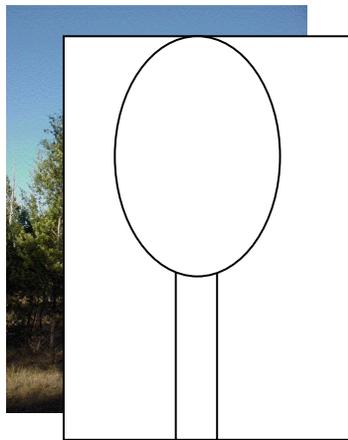


Radar Simulator: land cover type to model

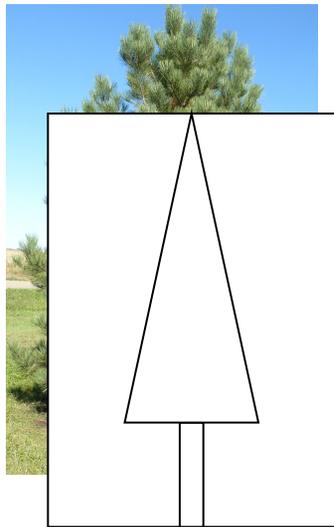
NLCD 2001 Land Cover Classification Legend

- 11 Open Water
 - 12 Perennial Ice/Snow
 - 21 Developed, Open Space
 - 22 Developed, Low Intensity
 - 23 Developed, Medium Intensity
 - 24 Developed, High Intensity
 - 31 Barren Land
 - 41 Deciduous Forest
 - 42 Evergreen Forest
 - 43 Mixed Forest
 - 51 Dwarf Scrub*
 - 52 Shrub/Scrub
 - 71 Grassland/Herbaceous
 - 72 Sedge/Herbaceous*
 - 74 Moss*
 - 81 Pasture Hay
 - 82 Cultivated Crops
 - 90 Woody Wetlands
 - 95 Emergent Herbaceous Wetlands
- * Alaska Only

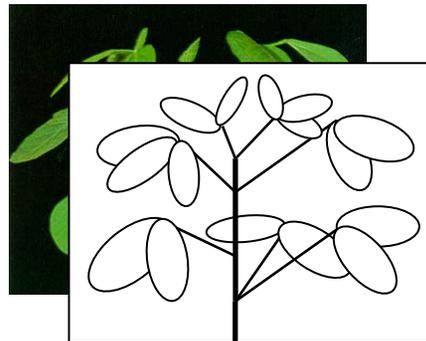
Deciduous tree



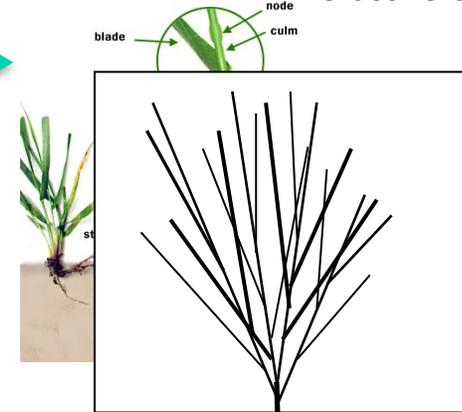
Evergreen tree



Crop – soybean



Grass/ Grassland



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 combination of ancillary data



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Landscape Simulator

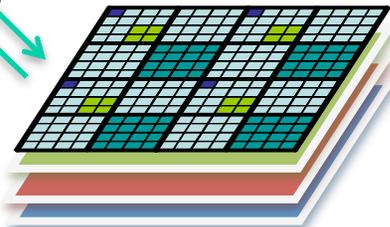
Control System



Architecture of Simulator



Google Earth



PCI Geomatics

Aggregation of sub-blocks

EASI

Text files

NLCD 2001 Land Cover Classification Legend

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 - 95 Emergent Herbaceous Wetlands
- * Alaska Only

Pre-determined parameter input files

EASI
Engineering Analysis and Scientific Interface

Text files

(Verification with Matlab)

FORTRAN



backscatter cross section of each sub-block



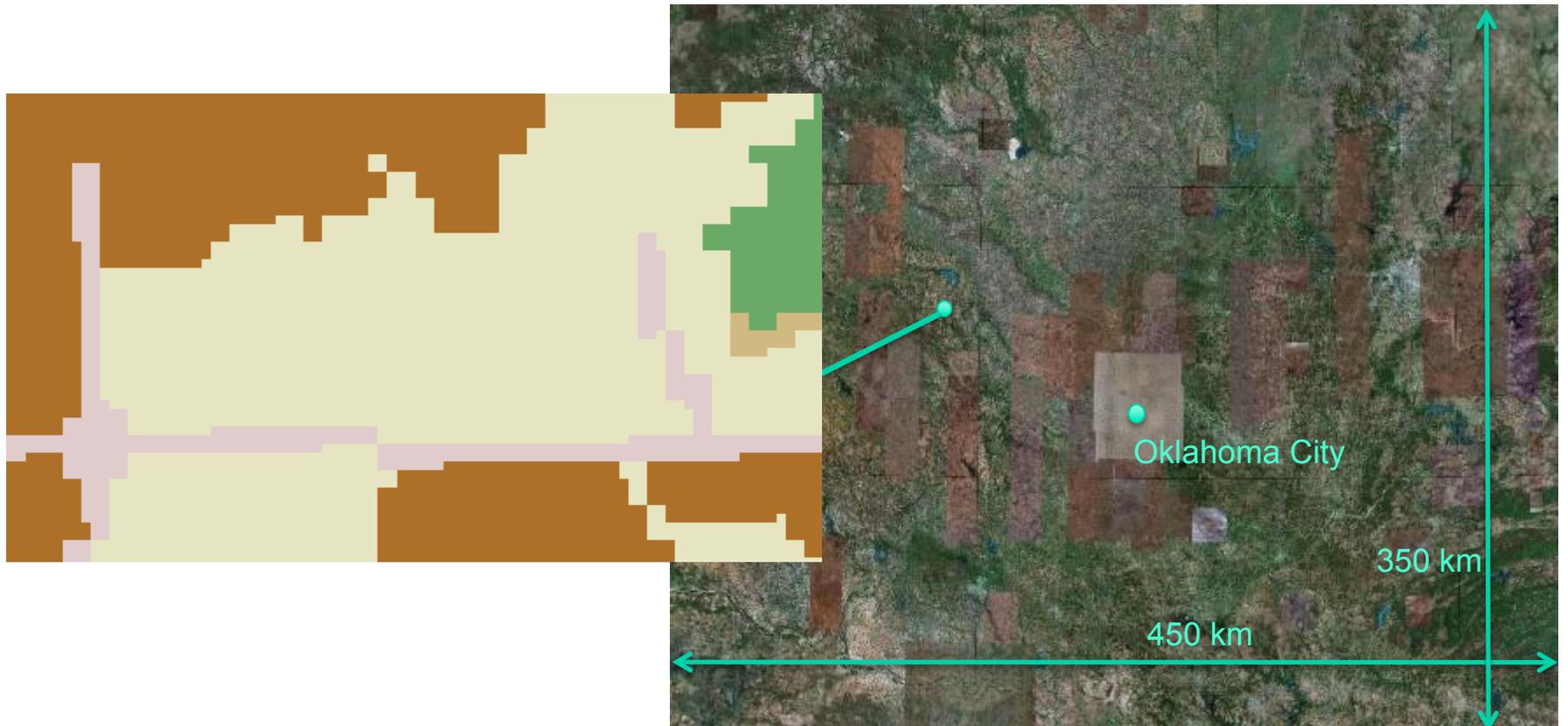
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Location: Canton Test Site – data layers (1/4)



Area around Oklahoma City, OK

1. Google Earth
2. Soil type from USDA
3. Land cover type from NLCD 2006



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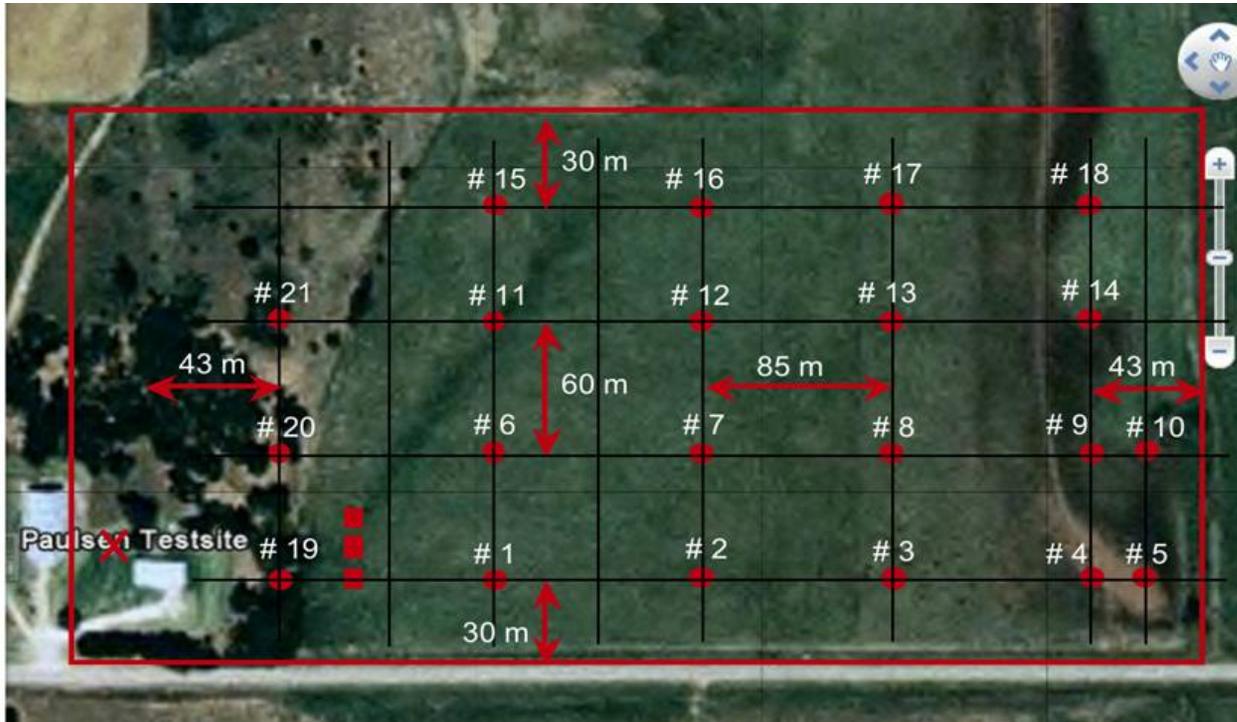
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Location: Canton Test Site – data layers (2/4)

Measured soil moisture from in-situ soil moisture sensor network



Prototype deployment:

- 21 nodes in field
- 3 routers
- 1 base station

Ideally:

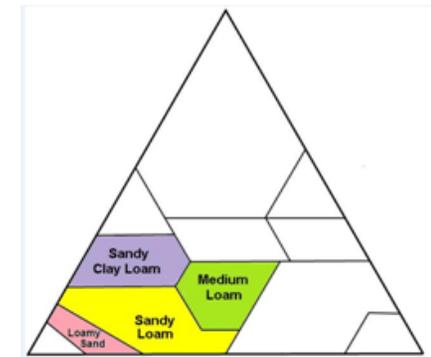
- Measurement of soil moisture every 10 mins

Location: Canton Test Site – data layers (3/4)

Soil type measurement from probes taken in the field on last site visit



USDA Soil Texture Classification



Oklahoma Site: Soil Texture



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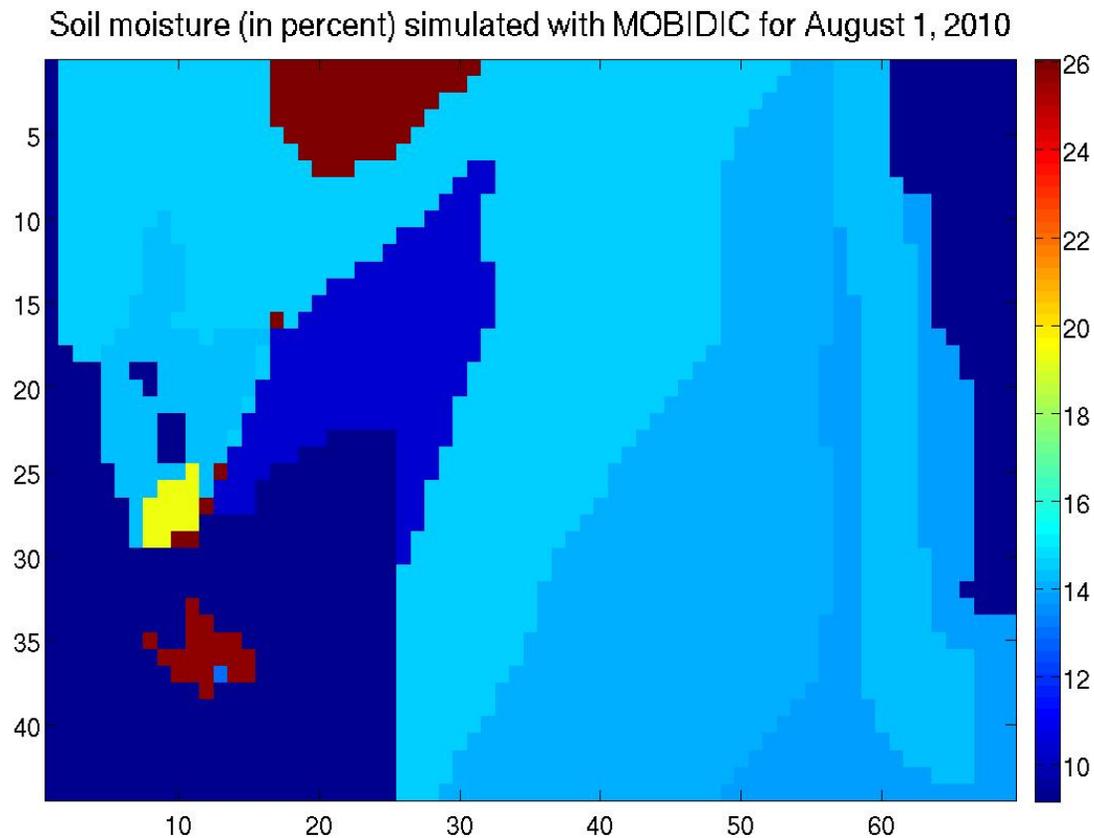
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Location: Canton Test Site – data layers (4/4)

Simulated soil moisture from MOBIDIC of MIT over test site



Inputs from 3 MESONET stations [Watoga (20km), Fairview (31km), Putnam (38km)]:

- Rain (mm/hr)
- Air temperature
- Relative Humidity
- Solar Radiation
- Wind speed
- Pressure

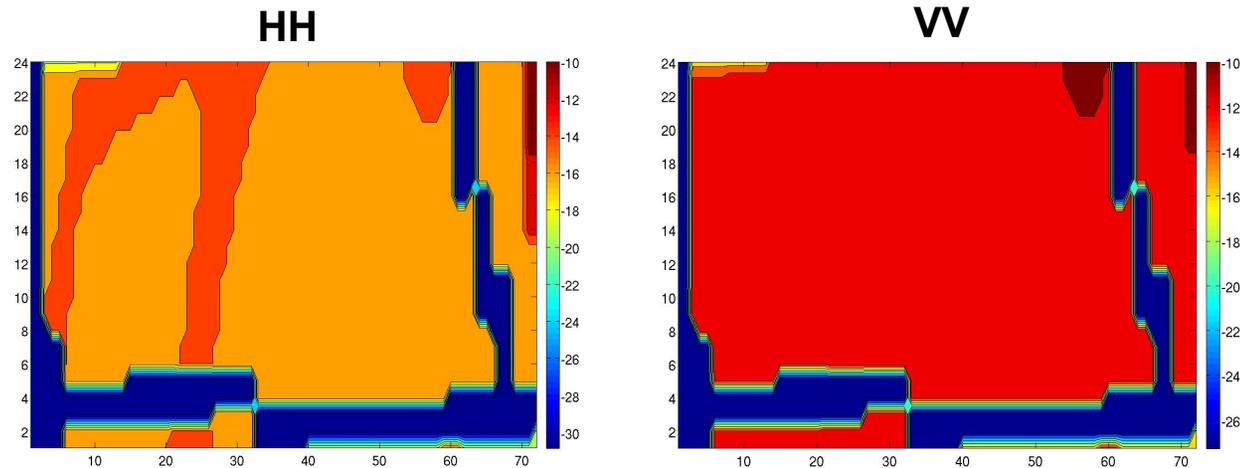
Output:

- Volumetric water content (VWC) in percent



Scenario 1: Dry condition

- Different land cover types according to NLCD 2006
- Different soil types according to soil maps
- Soil moisture distribution from August 1, 2010 from MOBIDIC data
 - #0: Loamy sand with 13.98%
 - #1: Sandy loam with 10.32%
 - #2: Sandy with 14.62%
 - #3: Sandy loam with 13.83%
 - #4: Sandy clay loam with 25.89%
- Slope of 10 degrees in # 0 (loamy sand)





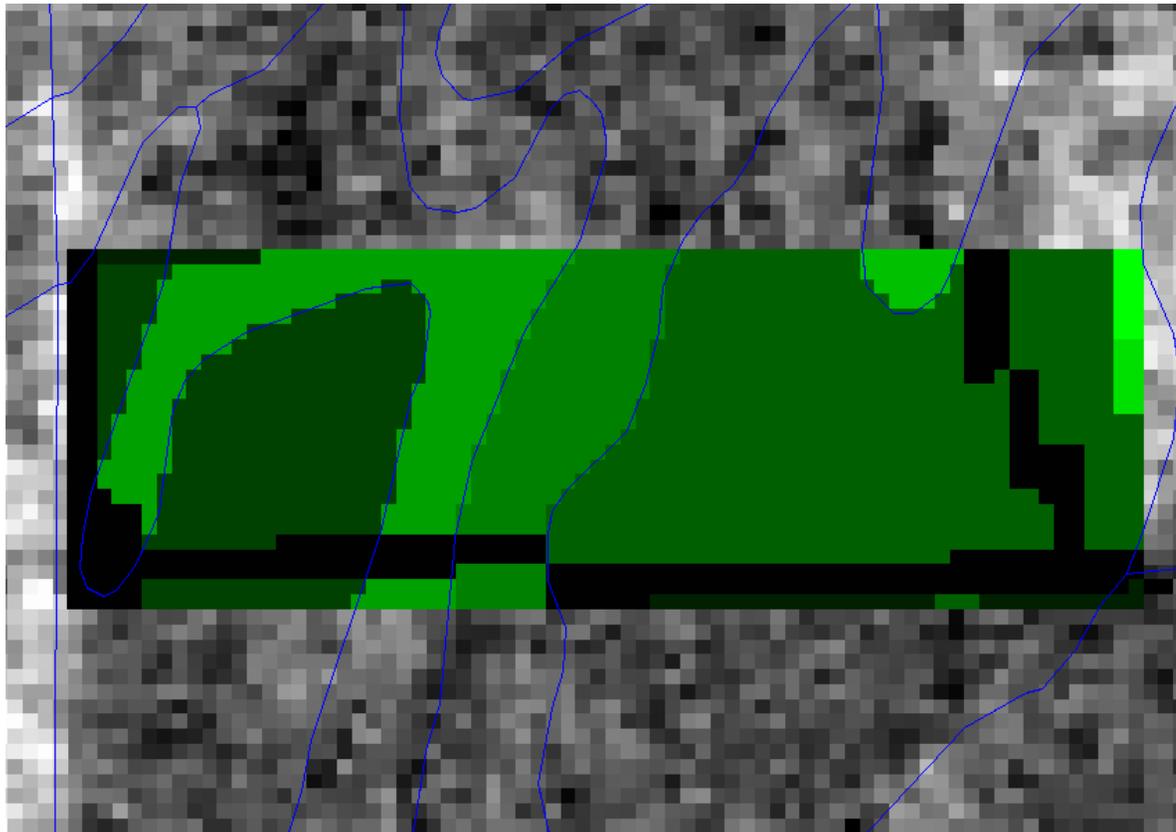
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Aggregation results for Scenario 1 (closest in time):



PALSAR – HH
recorded on June
10, 2010

Resolution: 12.5m x
12.5m

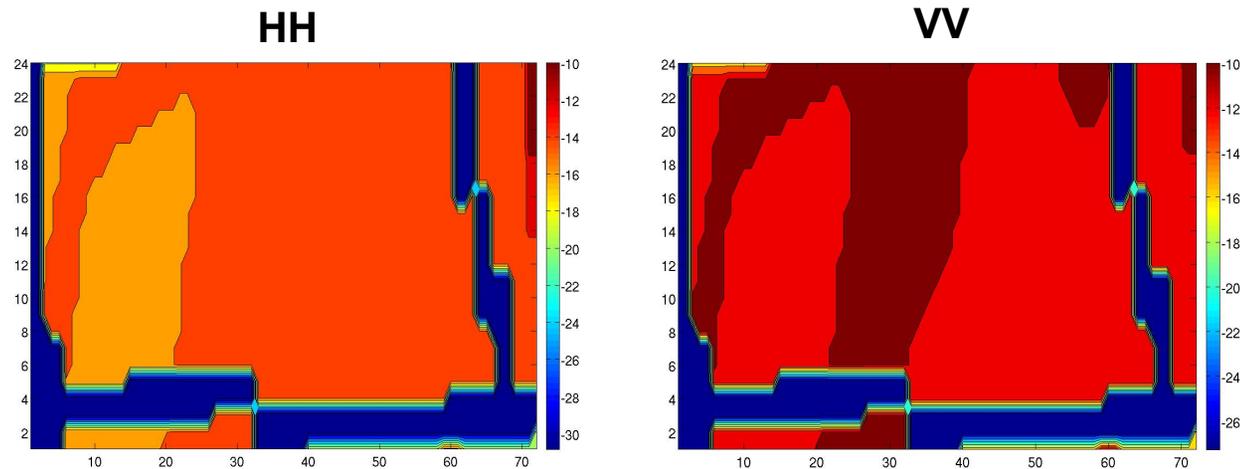
Simulated radar
backscatter for HH
(only single pol avail)

No PALSAR available
From 8/1/10-3/20/10,
therefore no ideal
comparison possible



Scenario 2: After rain

- Different land cover types according to NLCD 2006
- Different soil types according to soil maps
- Soil moisture distribution from September 1, 2010 from MOBIDIC data
 - #0: Loamy sand with 20.45%
 - #1: Sandy loam with 15.85%
 - #2: Sandy with 19.97%
 - #3: Sandy loam with 19.64%
 - #4: Sandy clay loam with 29.83%
- Slope of 10 degrees in # 0 (loamy sand)





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Aggregation results for scenario 2:





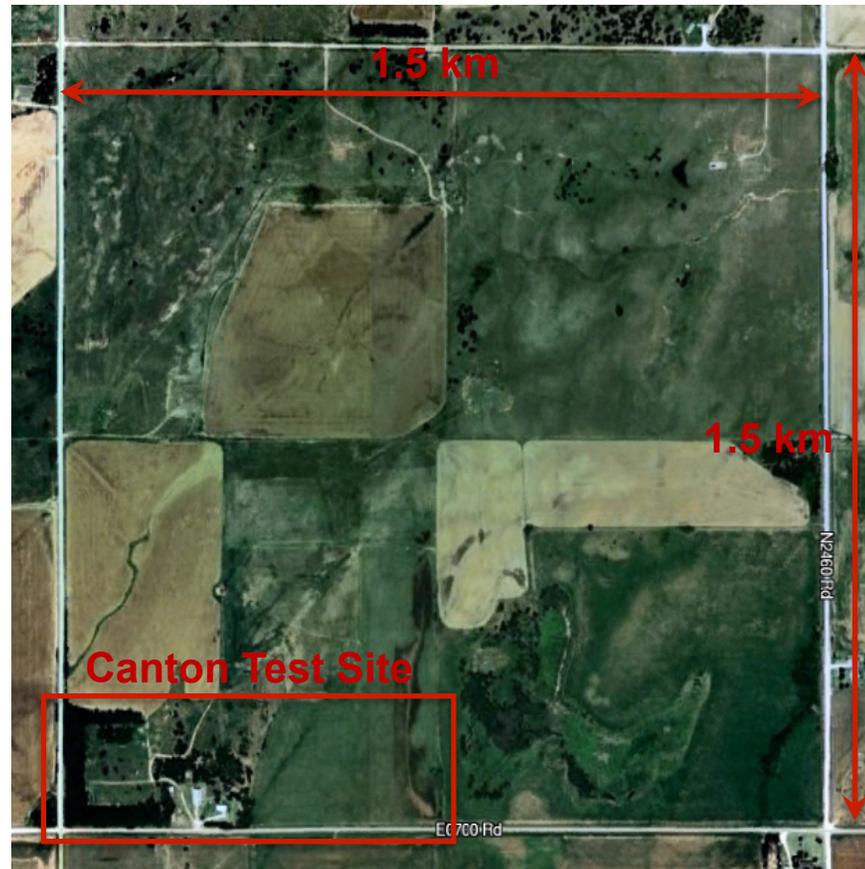
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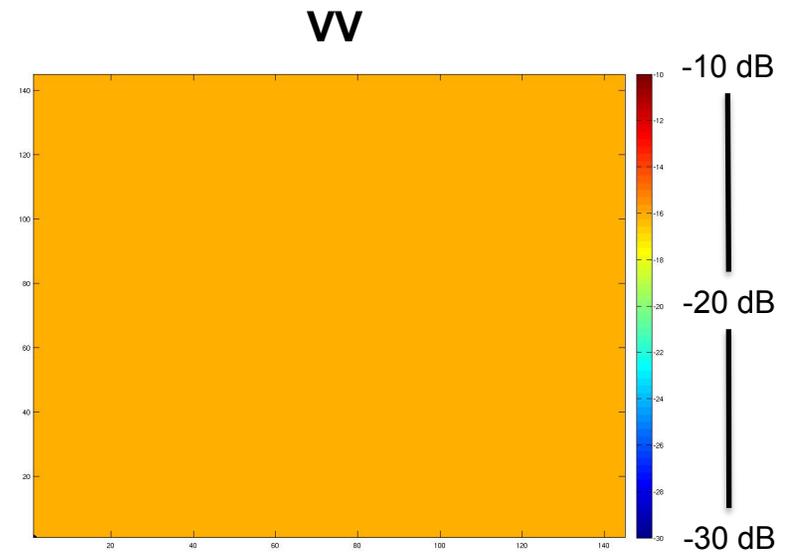
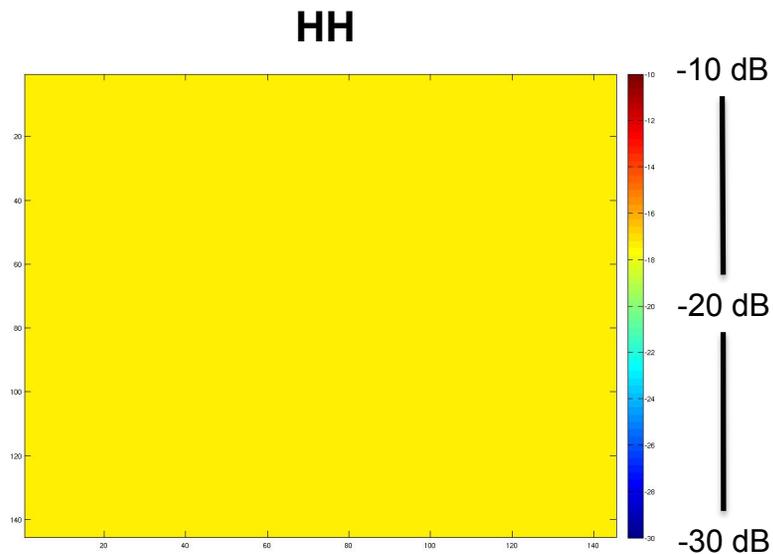


Aggregation results for larger area around Test Site in Canton:





Example of pixel aggregation: HH and VV backscattering coefficient



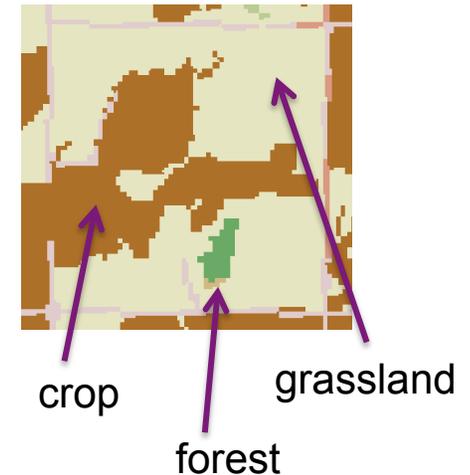
Backscatter coefficient

- 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 of 8 x 8 sub-blocks
- e) Block containing all sub-blocks



Effect of aggregation on soil moisture retrieval

- “True” soil moisture set to 4% throughout the simulation domain
- Used the largest aggregated area (entire domain), representative of satellite footprint to estimate soil moisture
- Made different assumptions about land-cover and soil types during retrieval
- Large differences are observed in retrieved soil moisture over the footprint, if a single land-cover or soil type is assigned to entire domain, ignoring heterogeneity



Assumed Land cover type	Assumed Soil type	Retrieved Soil moisture (% vol)
Grassland	Sandy	14
Grassland	Sandy loam	16
Grassland	Sandy clay loam	18
Crop	Loamy sand	10
Deciduous forest	Loamy sand	0 (inconclusive)



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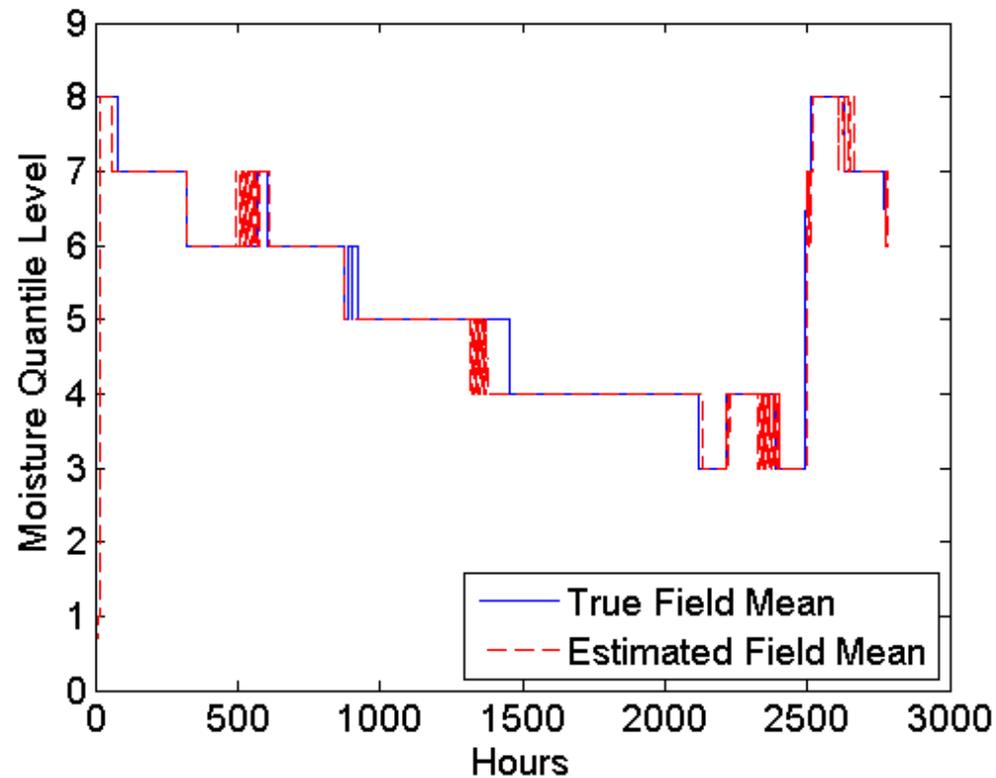


Control System Highlights

- Performance evaluation of sensor scheduling and estimation methodologies
 - Conducted experiments on MOBIDIC data for Canton site, OK
- Initial formulation and studies on the placement problem with sensor failures
 - Evaluation of placements under random sensor failures
 - A heuristic modification of the placement algorithm to address possibilities of sensor failures



Mean Estimation with Optimal Scheduling for Canton site



Quantization levels: [<8 , 8-9.5, 9.5-11, 11-12.5, 12.5-13.25, 13.25-14, 14-14.75, 14.75-15.5, 15.5-16, 16-17.5, >17.5]; Total number of quantiles: 11

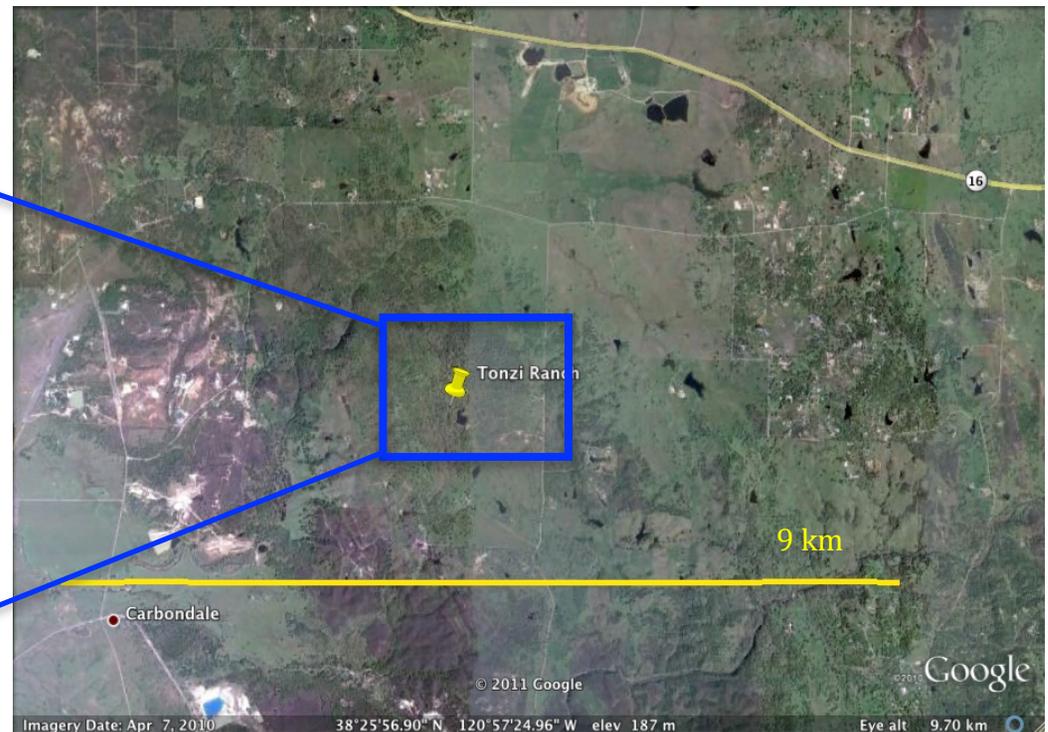


Future Installation Site (Extended Network)



Tonzi Ranch

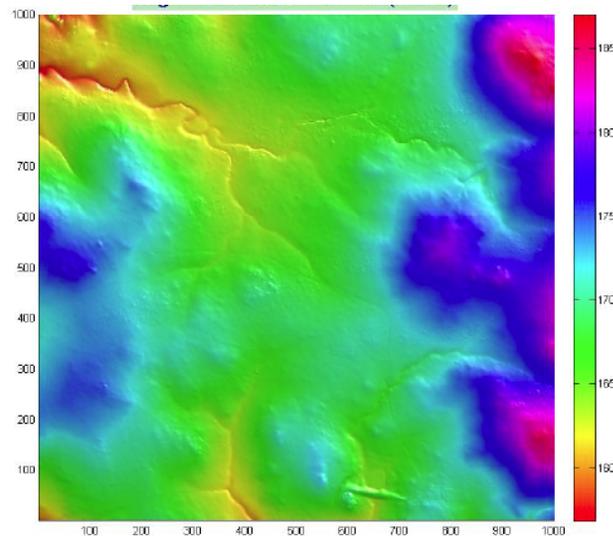
- Flux tower site, part of Ameriflux network
 - Established in 2001; western savanna ecosystem
 - Mild topography; heterogeneous canopy cover of pine, oak, grass
 - Strong control of soil moisture on ecosystem productivity
 - Annual rainfall ~600 mm



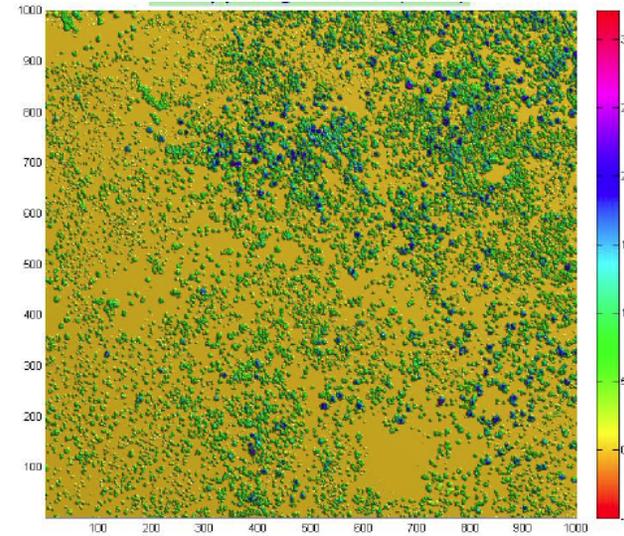


Tonzi Ranch

- Flux tower site, part of Ameriflux network
 - Established in 2001; western savanna ecosystem
 - Mild topography; heterogeneous canopy cover of pine, oak, grass
 - Strong control of soil moisture on ecosystem productivity
 - Annual rainfall ~600 mm



Tonzi Ranch DEM, for a 1km² area around the flux tower



Tonzi Ranch canopy height map



Summary



- Deployed first full-scale SoilSCAPE network prototype
 - Demonstrated Ripple-1 concept; identified shortcomings
 - Developed more robust network architecture: Ripple-2
 - Ripple-2 currently undergoing checkout; Canton site will be upgraded shortly after
 - Will start large-scale (~150 node) network deployment at Tonzi Ranch late summer
- Developed and adapted landscape radar and hydrology simulators
 - Adapted for Canton site; partially integrated the two simulators
 - Performed preliminary aggregation studies
 - Developing mathematical formalism for relating coarse-scale retrievals to fine-scale landscape heterogeneity
- Demonstrated accuracy of soil moisture field mean estimation methodology using small number of sensors and policy-controlled sensor scheduling