Sensor Networks for Environmental Monitoring

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Outline

Introduction to CENS

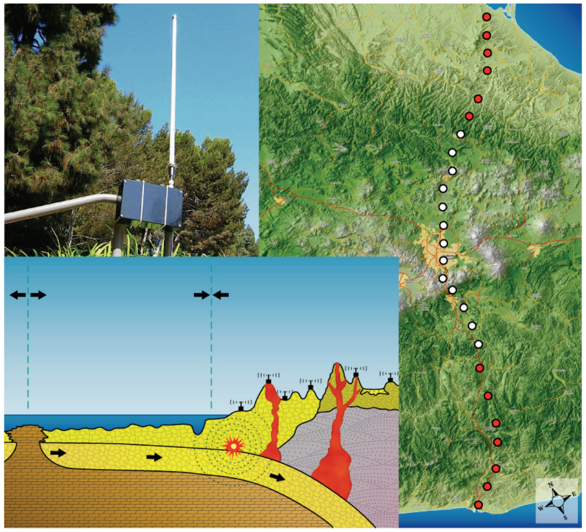
A Brief History of Sensor Networks

Theory Problems

Example Deployments

This work is supported by the
National Science Foundation

ENS Observatories

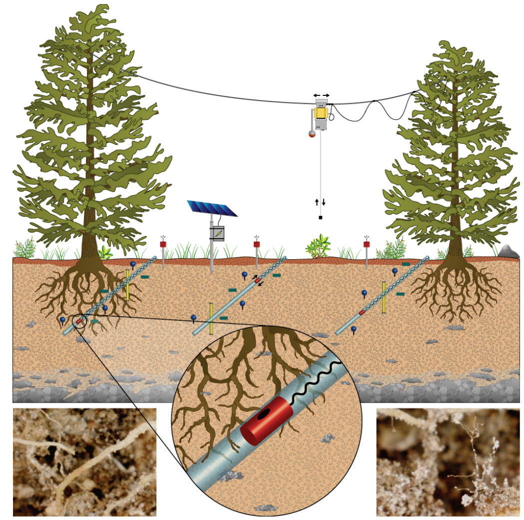


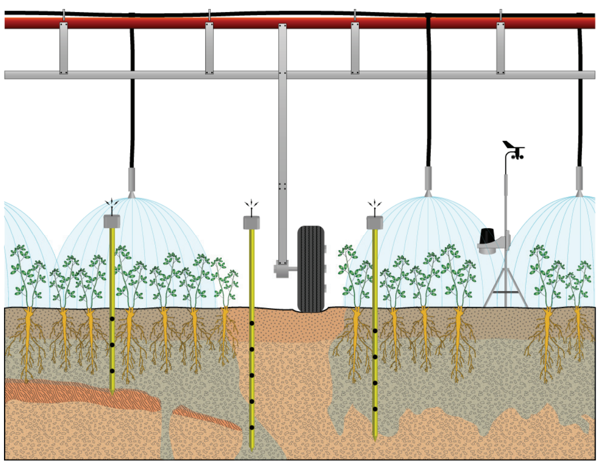
create programmable, distributed, multi-modal, multi-scale, multi-use **observatories**
to address compelling science and engineering issues

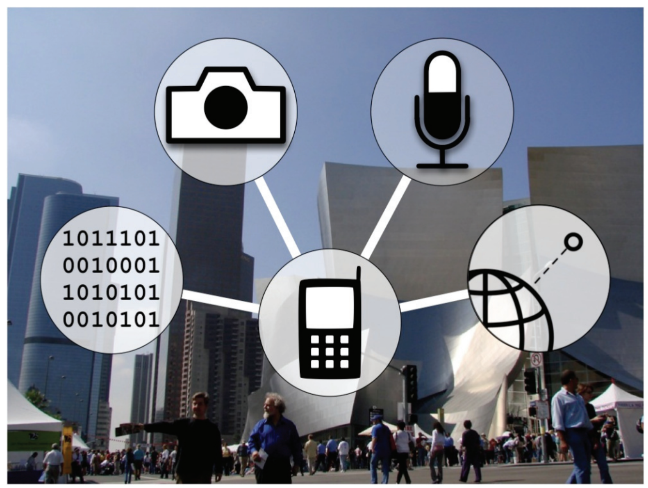
…and reveal the previously unobservable.

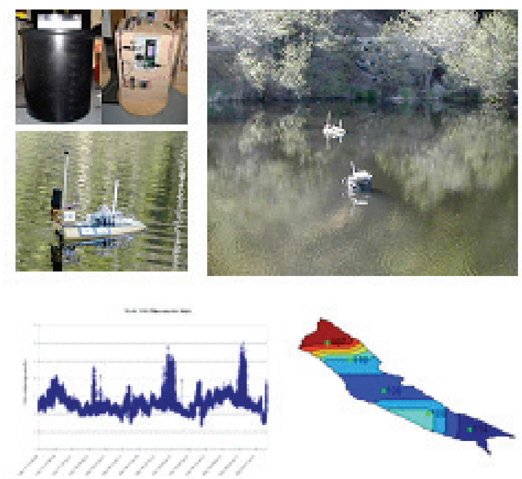
From the natural to the built environment…

From ecosystems to human systems…



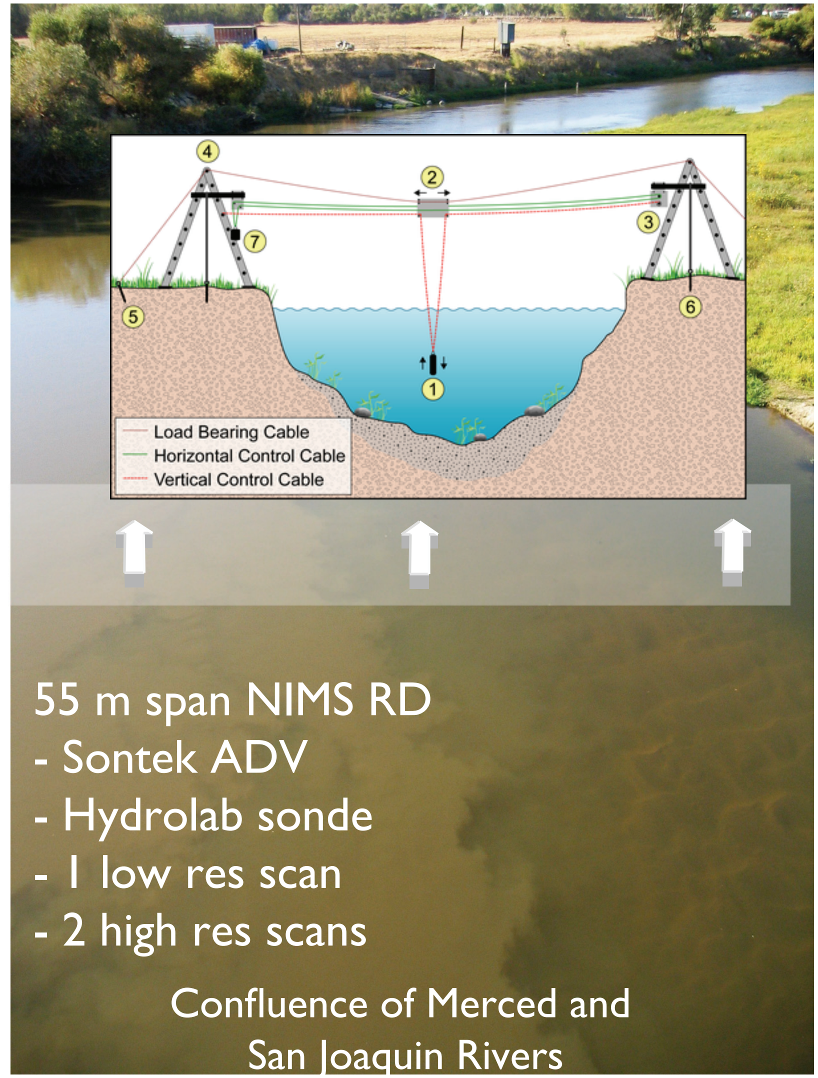




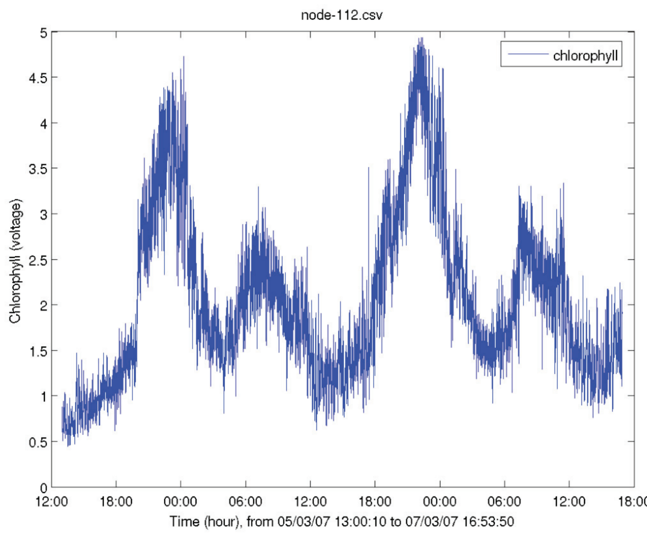


Contaminant Flux Measurement

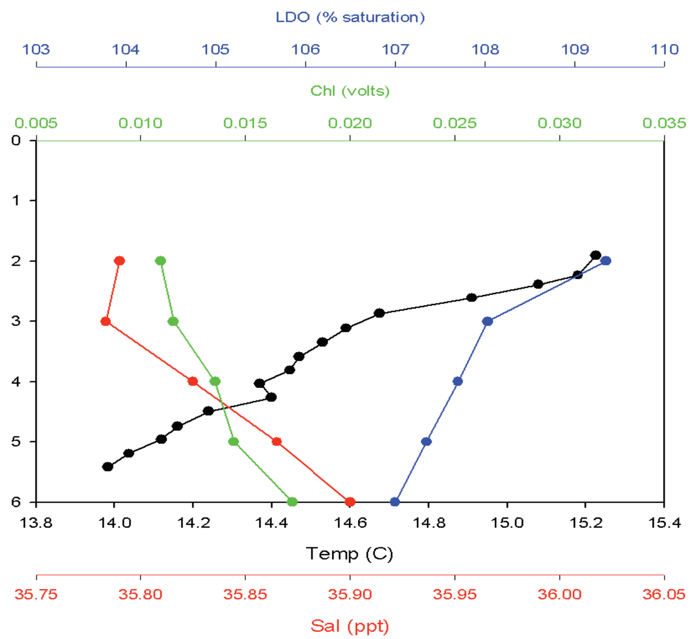
- Directly measure contaminant flux in large river
  - Identify sources and sinks
  - Point source and non-point source contributions
- Measurement
  - Map 3D flow field in river cross-section
  - Map contaminant concentration
  - Integrate product to compute flow
- Requires high spatial resolution
  - Non-uniform contaminant distribution
  - Complex flow and mixing
- Sensor Payload
  - Support standard water quality sensor packages
  - Support angle-resolved flow measurements
- Sensor Location Control and Sampling
  - Control sensor position in river span and depth and include spatially-resolved sample collection
- Autonomous and Rapidly deployable

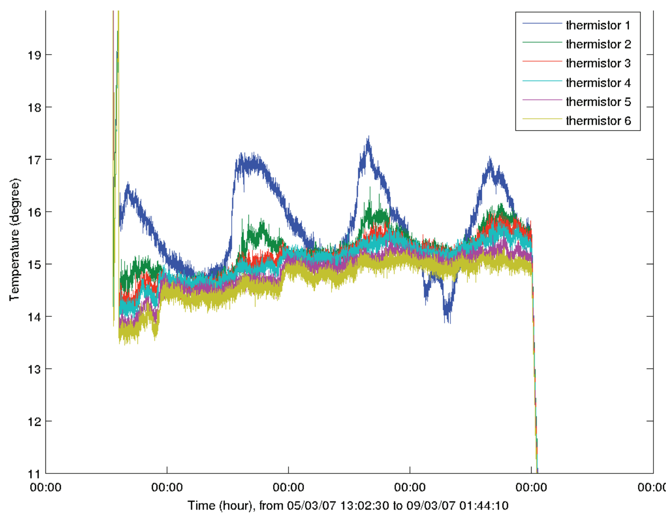


Static sensor buoys and robotic boat with vertical profiling



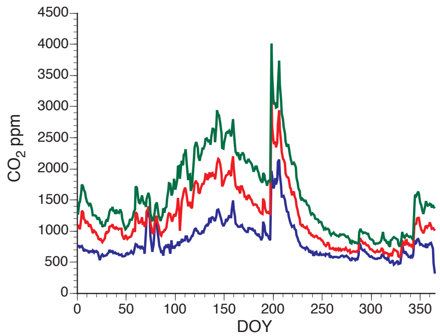
Vertical profile from QBoat, King Harbor (Port Royal)
3/6/07 17:15 start time



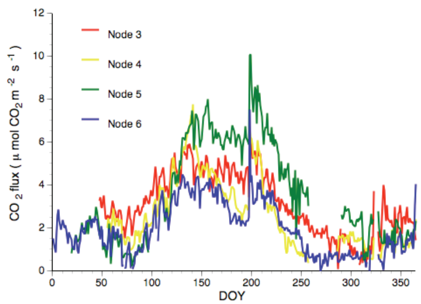


Measuring terrestrial carbon fluxes

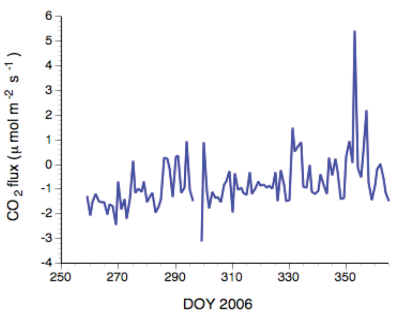
Soil CO_2 concentration

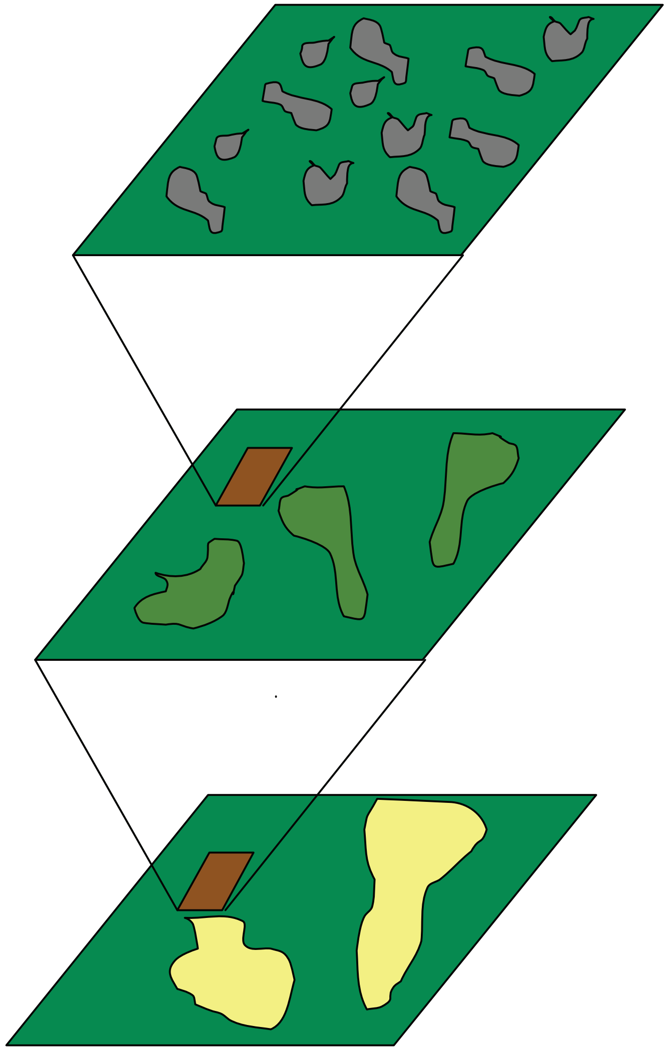


Soil respiration



Canopy photosynthesis





Fine scale

Effects of roots, organic particles, and soil structure

Plot-to field scale

Effect of group of plants, and gradients in soil texture

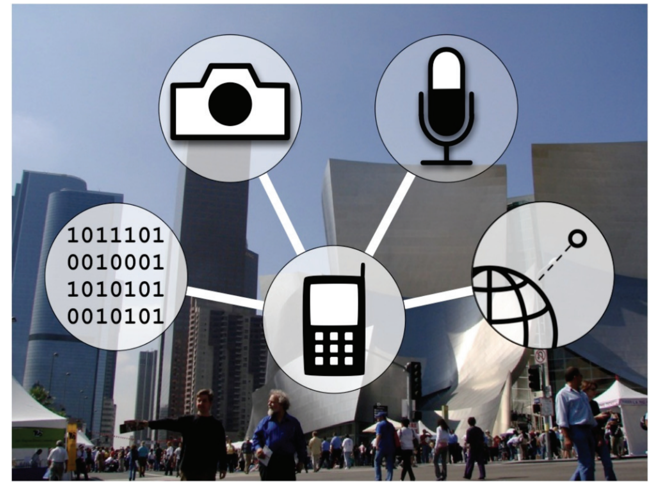
Large-scale

Effect of vegetation systems, and topography

Participatory and Urban Sensing

Enabled by

- Over 2 x 10^9 users worldwide of cell phones.
- Automated geo-coding and pervasive connectivity
- Image and acoustic as data and metadata
- Bluetooth connected external sensors
- Local processing for data quality and triggering
- Spatial interface to data and authoring



Applications

- Personal health: Self-administered diagnostics
- Public health: epidemiology & wellness
- Urban planning and civic engagement
- Culture and creative expression
- Environmental stewardship: Eco-PDA

participatory sensing data promises to make visible human concerns that were previously unobservable…or unacceptable

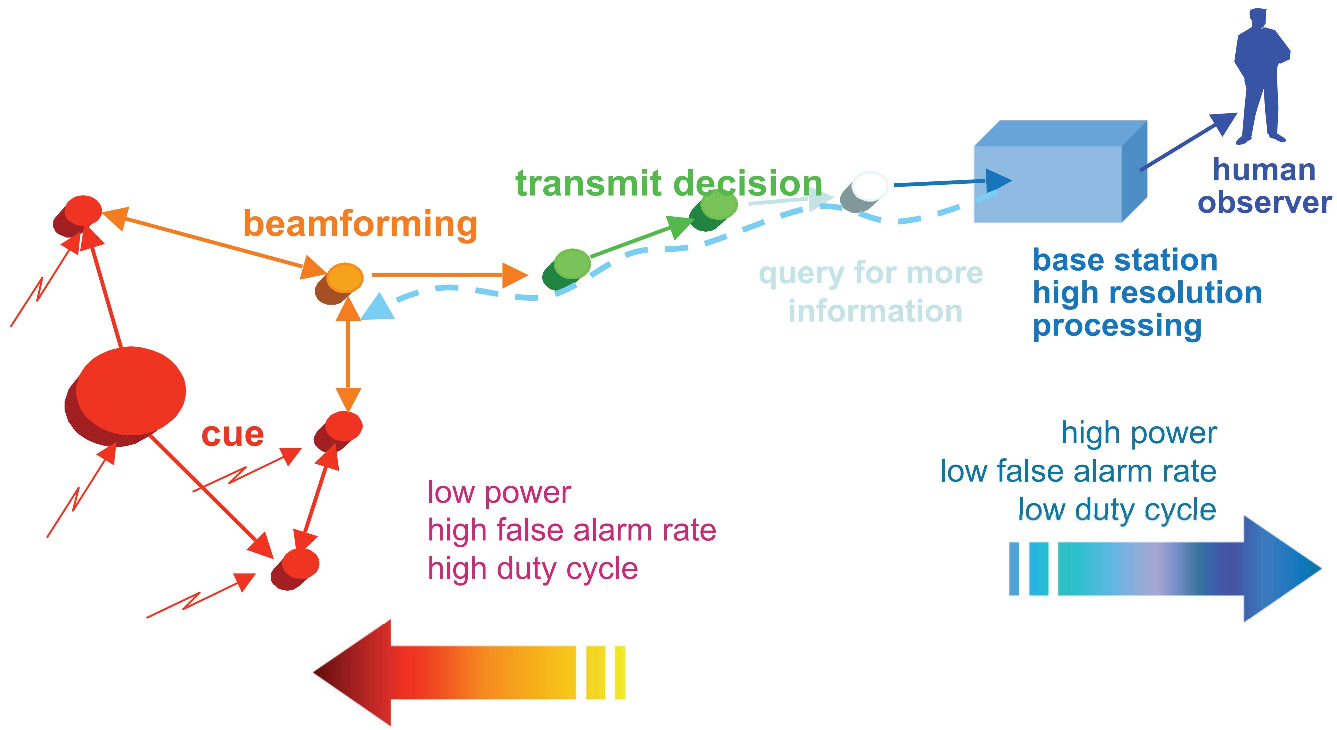
In the Beginning...the Network was Flat

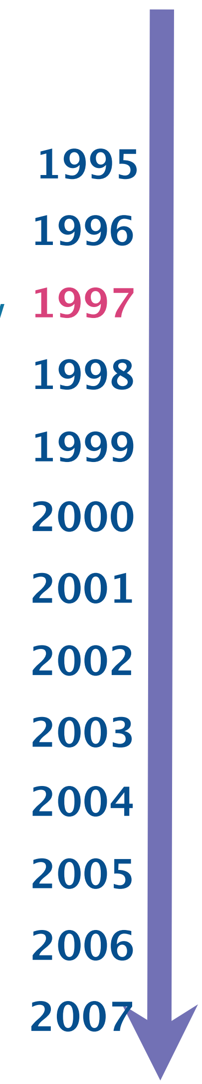
- Much research has focused upon sensor networks with some alternative assumption sets:
  - Memory, processing, and sensing will be cheap, but communications will be dear; thus in deploying large numbers of sensors concentrate on algorithms that limit communications but allow large numbers of nodes
  - For the sensors to be cheap, even the processing should be limited; thus in deploying even larger numbers of sensors concentrate on algorithms that limit both processing and communications
- In either case, interesting theory can be constructed for random deployments with large numbers and flat architectures

Theory for Dense Flat Networks of Simple Nodes

- Redundant communications pathways given unreliable radios
- Data aggregation and distributed fusion
- Scalability
- Density/reliability/accuracy trades
- Cooperative communication
- Adaptive fidelity/network lifetime trades

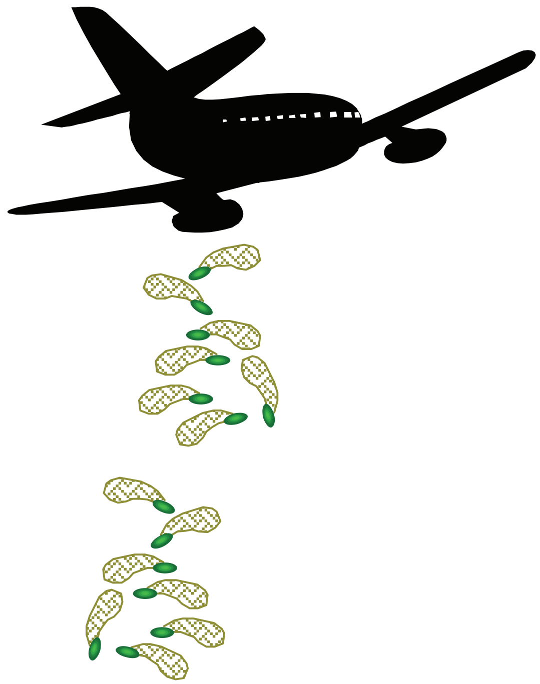
Illustration:
AWAIRS overview
1997





What applications?

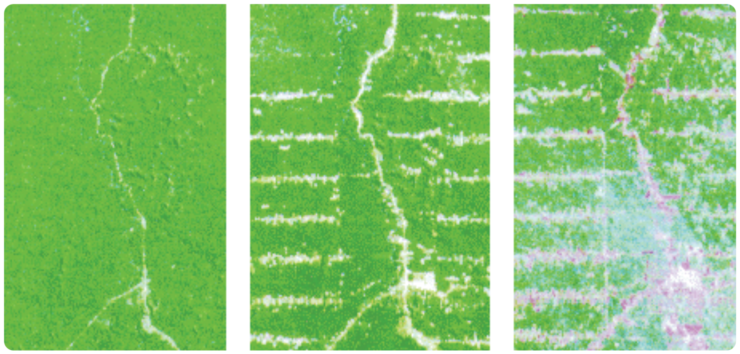
- Early research concentrated on short-term military deployments
  - Can imagine that leaving batteries everywhere is at least as acceptable as leaving depleted uranium bullets; careful placement/removal might expose personnel to danger
  - Detection of vehicles (and even ID of type) and detection of personnel can be accomplished with relatively inexpensive sensors that don't need re-calibration or programming in the field
- Story was plausible…



But was this ever done?

- Military surveillance
  - Largest deployment (1000 nodes or so) was hierarchical and required careful placement; major issues with radio propagation even on flat terrain
  - Vehicles are really easy to detect with aerial assets, and the major problem with personnel is establishment of intent; this requires a sequence of images
  - The major challenge is urban operations, which demands much longer-term monitoring as well as concealment
- Science applications diverge even more in basic requirements
  - Scientists want to know precisely where things are; cannot leave heavy metals behind; many other issues
- Will still want dense networks of simple nodes in some locations, but will be system component

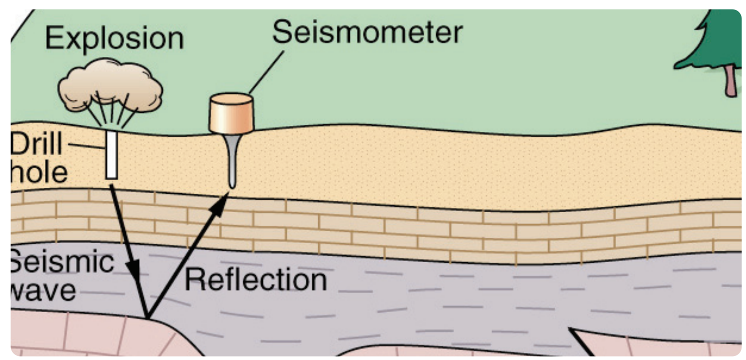
Environmental Monitoring Applications
Spatial variations and heterogeneity



Impact of fragmentation on species diversity

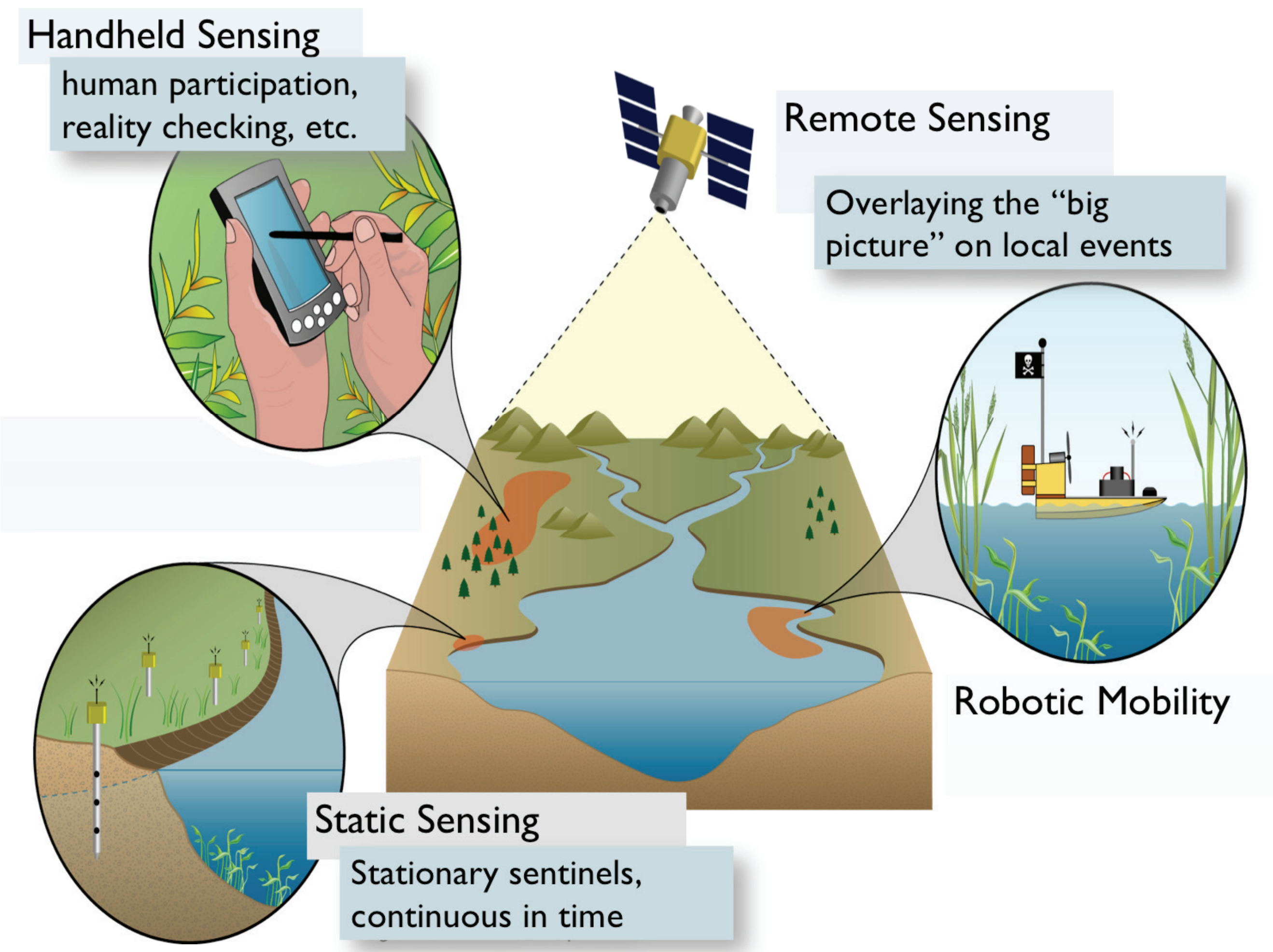
Precision agriculture, water quality management

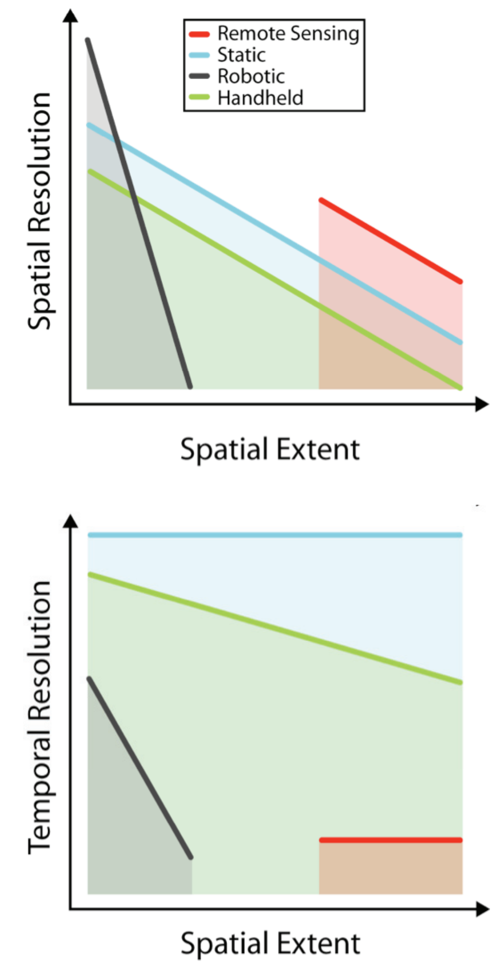
Algal growth as part of eutrophication



Earth structure inhomogeneities

Multiple observation scales perspective

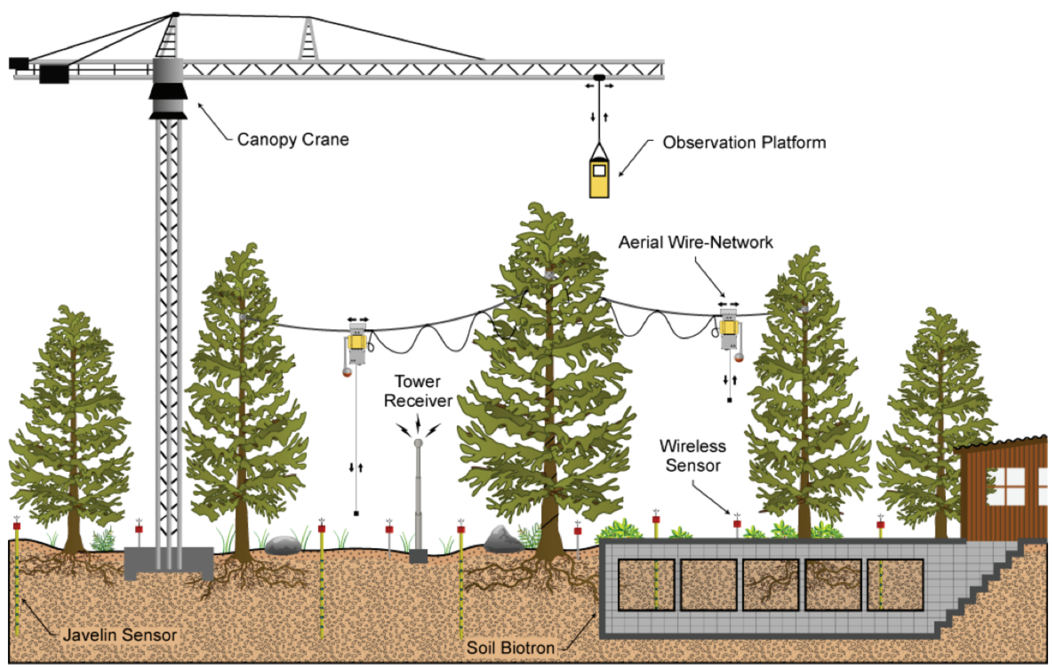




Evolution to More Intelligent Design

- Many problems with flat resource-constrained networks
  - Software is nightmarish
  - Always undersample physical world in some respect
  - Logistics are very difficult; usually must carefully place, service, and remove nodes

- The major constraint in sustained science observations is the sensor
  - Biofouling/calibration: must service the nodes
- Drives us towards tiered architecture that includes mobile nodes
  - Many new and exciting theory problems



Evolution of H/W Platforms and Research Community

Programs/Publications

DARPA DSN
Under-sea Networks
Ubiquitous Computing
Distributed Tracking
DARPA LWIM

1996 — LWIM Paper (ACM ISLPED)

DARPA AWAIRS

1997

1998

Robotic Ecology (DARPA ISAT 1999)

1999 — DARPA SensIT — SmartDust, Diffusion (MobiCom 1999)

2000 — DARPA PACC — TinyOS (OSDI 2000)

2001 — Embedded Everywhere (NRC Report 2001)

2002 — DARPA NEST — NSF CENS STC — NSF CASA ERC

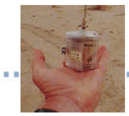
2003 — ACM SenSys and ACM/IEEE IPSN

2004 — NSF NeTS-NOSS

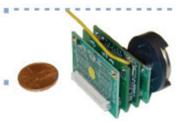
2005 — ACM TOSN

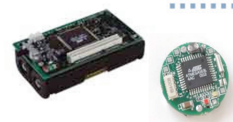
2006 — NSF Cyber Physical Systems?

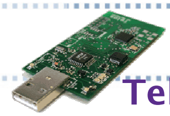
H/W Platforms


LWIM-III (UCLA)


WINS (UCLA/ROckwell)


MICA (Berkeley)

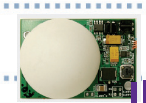

MICA2 (Berkeley/Crossbow)


Telos

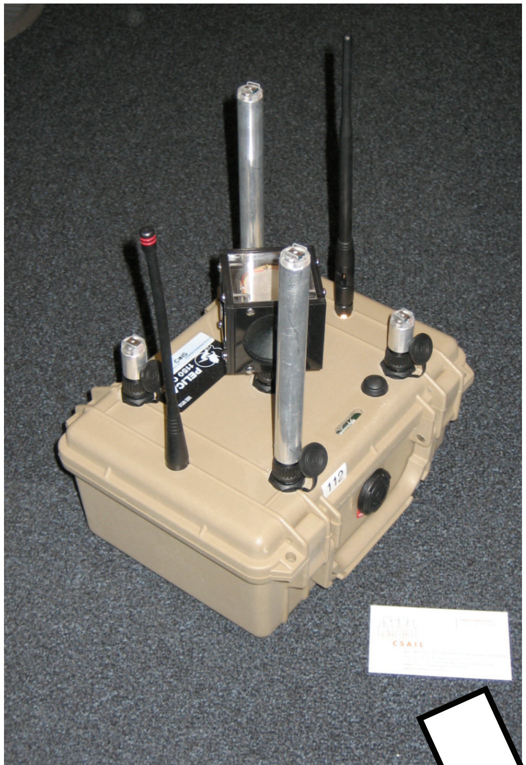

HelioMote


Cyclops


LEAP

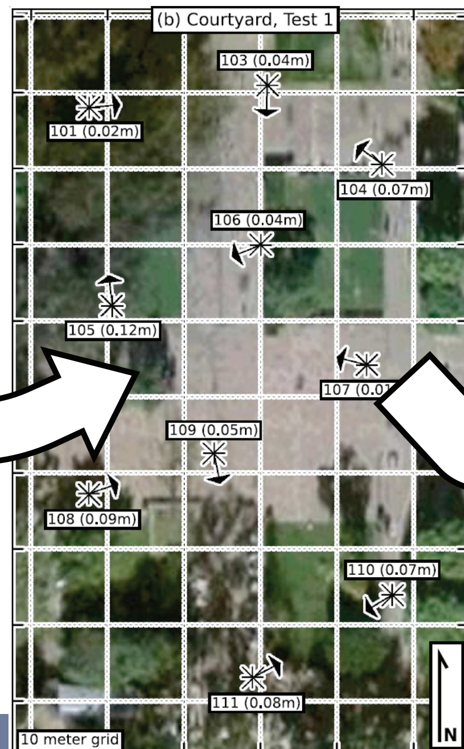

Illumimote

Acoustic ENSBox

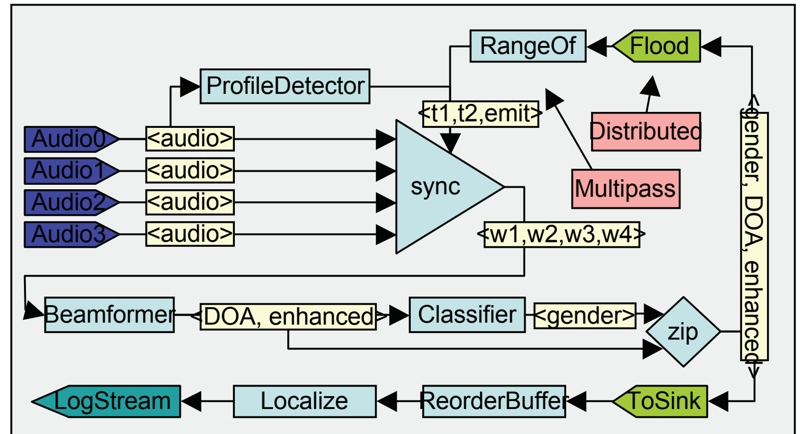


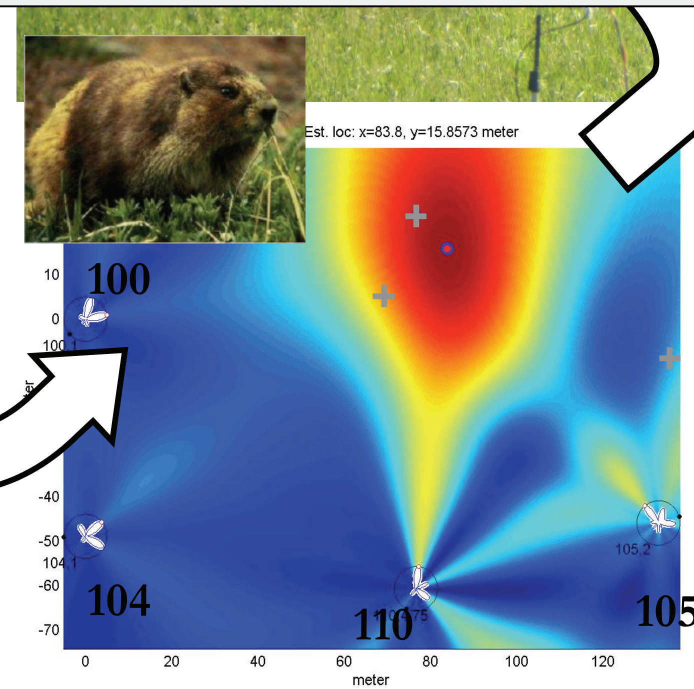
Platform Development

Platform Software



WaveScope: New programming model





First User Applications

Some Theory Problems

- Data Integrity
  - Sufficiency of network components/measurements to trust results
- Model Uncertainty
  - Effects on deployment density, number of measurements needed given uncertainty at different levels
- Multi-scale sensing
  - Information flows between levels; appropriate populations at the different levels given sensing tasks
  - Local interactions assume increased importance
- Logistics management
  - Energy mules
  - Mobile/fixed node trades

Data Integrity

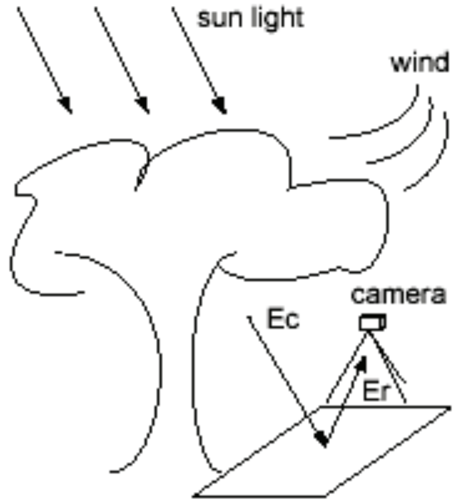
- Can use models of sensor behavior to assure data integrity
  - Empirical results indicate that many of the most common sensor faults are well-described with a linear model
  - Can then show that can perform reconstruction with only small oversampling if most sensors are accurate
  - Developing tools to diagnose sensor faults, using tools from modern statistics; expands tools sets that identify network faults
- Can use models of the physical phenomenon to identify the most reliable sensors
  - Bayesian techniques can be quite reliable given weak assumptions such as smoothness
  - Better knowledge of the model can result in improved performance
- Hybrid combinations are also possible

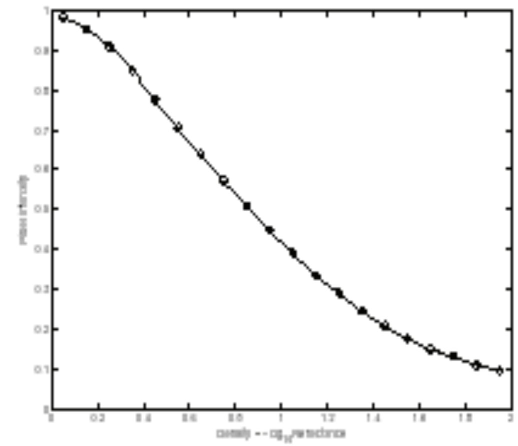
Multi-Scale Example: Fiat Lux

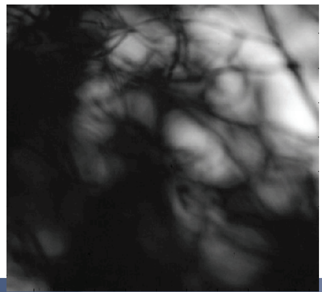
- Top level: camera/laser mapper providing context and wider area coverage
  – Direct locations for PAR sensors to resolve ambiguities due to ground cover
- Modular model construction
  – Begin with simple situations: pure geometric factors, calibration of instruments
  – Progress to add statistical components: swaying of branches, distributions of leaves/branches at different levels of canopy, ground cover
- Resulting model is hybrid combination of:
  – Deterministic causal effects
  – Partially characterized causes (statistical descriptions)
- Level of detail depends on goals
  – Reconstruction, statistics or other function of observations

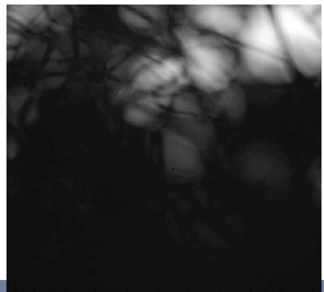
Early Experiments

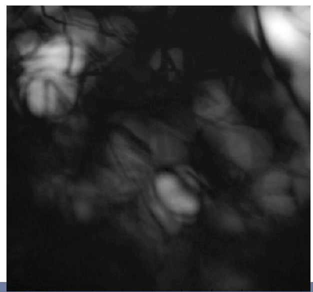
- Sensors with different modes and spatial resolutions
  - E.g. PAR sensor and camera
  - PAR measures local incident intensity
  - Camera measures relative reflected intensity
- Provides better spatial and temporal resolution, at cost of requiring careful calibration
- Analogous to remote sensing on local scales











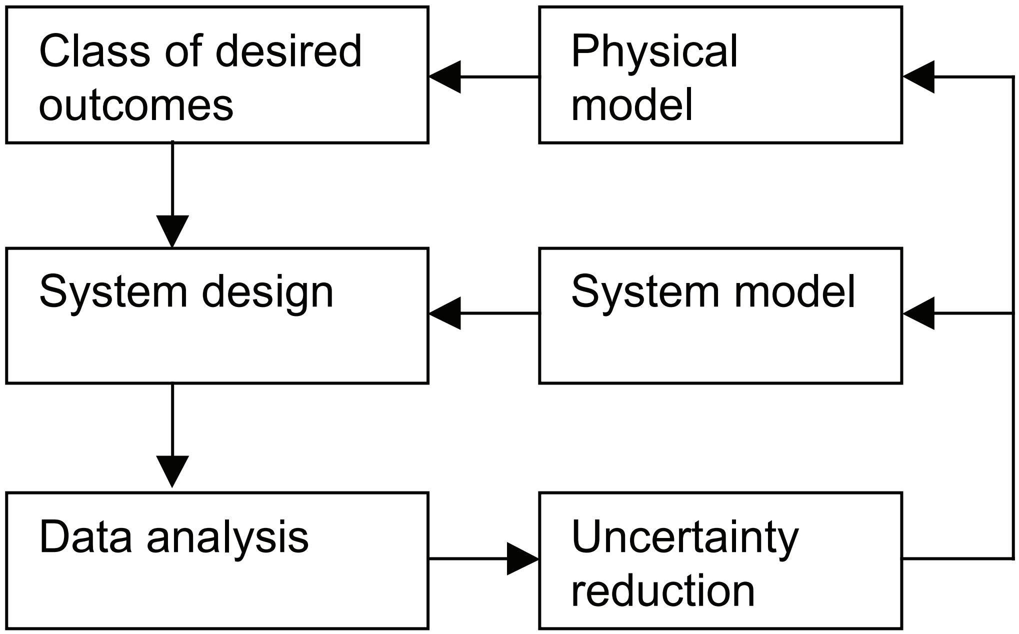
- A homogeneous screen is placed to create a reflection Er proportional to incident light Ec.
- Camera captures the reflection on its CCD
- The image pixel intensity is transformed to Er using camera's characteristic curve.

Practical Design Constraints

- Validation (=debugging) is usually very painful
  - One part design, 1000 parts testing
  - Never exhaustively test with the most reliable method
- So how can we trust the result given all the uncertainties?
  - Not completely, so the design process deliberately minimizes the uncertainties through re-use of trusted components
- But is the resulting modular model/design efficient?
  - Fortunately not for academics; one can always propose a more efficient but untestable design
- **Our goal: building systems for *sequence* of deployments that evolve with user goals**

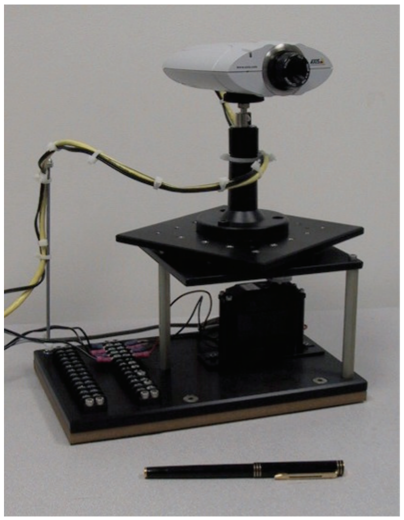
Universal Design Procedure

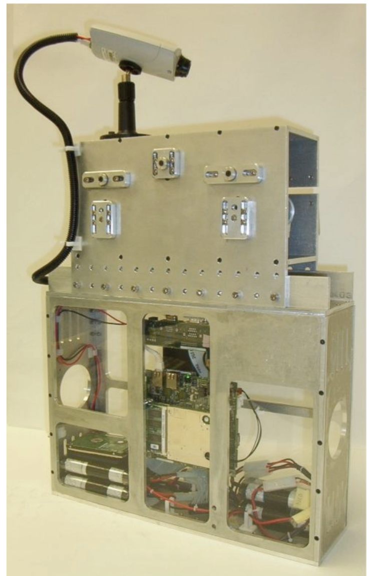
- Begin with what we know
  - E.g., trusted reference experiment, prior model(s)
- Validate a more efficient procedure
  - Exploit prior knowledge to test selected cases
  - Construct tools to assist debugging
- Bake-off the rival designs or hypotheses
  - Requires tools for rapid evaluation of data
  - End result is solution of an inference problem
- Iterate
  - Different model components become trusted at different stages



Design Iterations for NIMS

- Begins as use of articulated sensors/antennas for senior design course



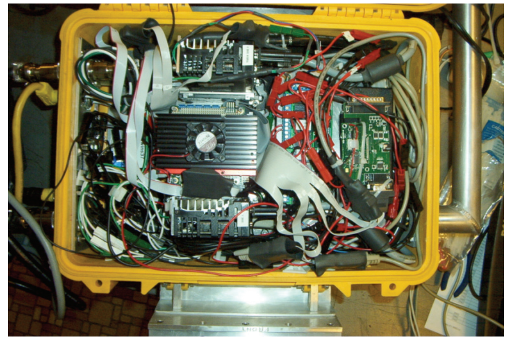


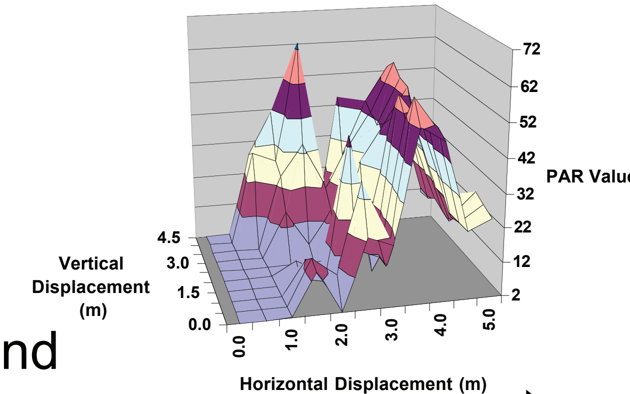
- Hire course grads to work on how to get articulated camera views in trees; build prototype with ugrad team supervised by grad students

- Work all summer towards a field deployment at Wind River

Design Iterations for NIMS

- First deployment at JR with camera,PAR sensor and microweather station

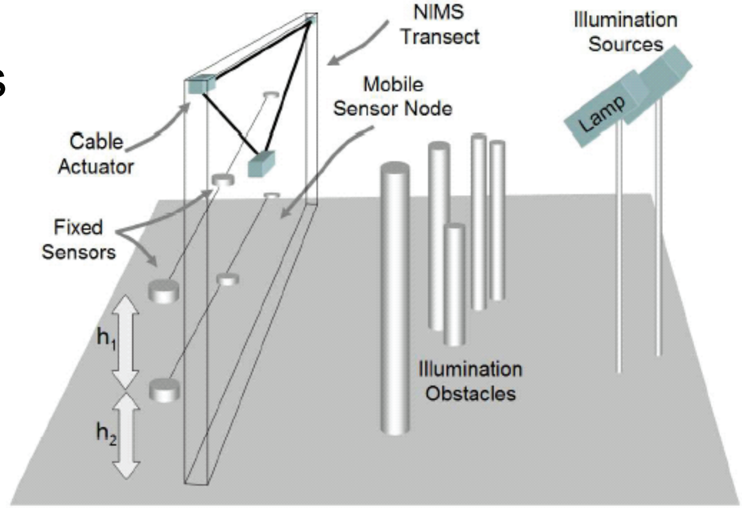




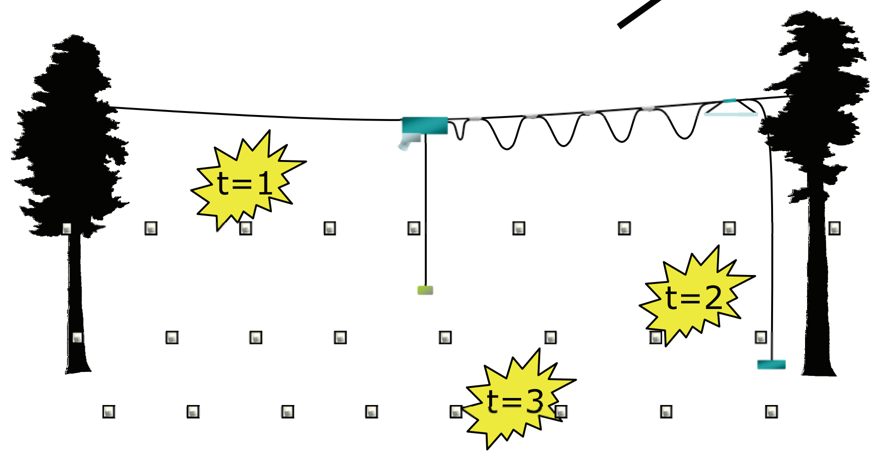
- Numerous issues and opportunities with fixed deployments

Design Iterations for NIMS

- Grad course project leads to reduced-mass laboratory system

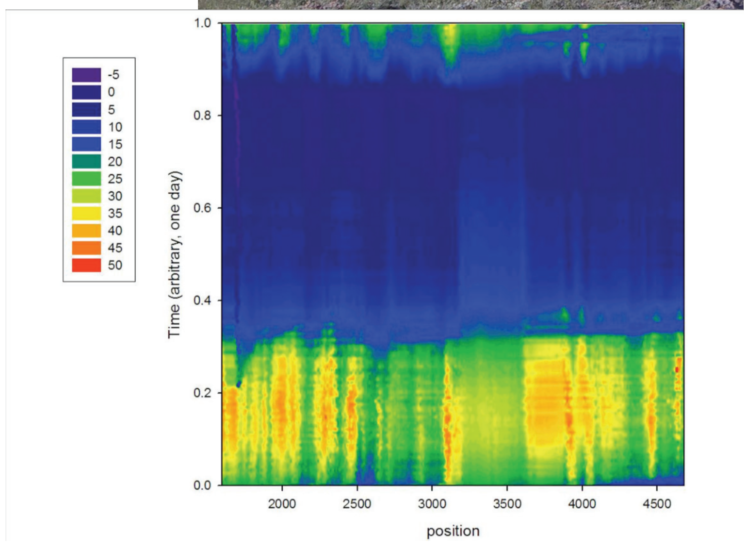


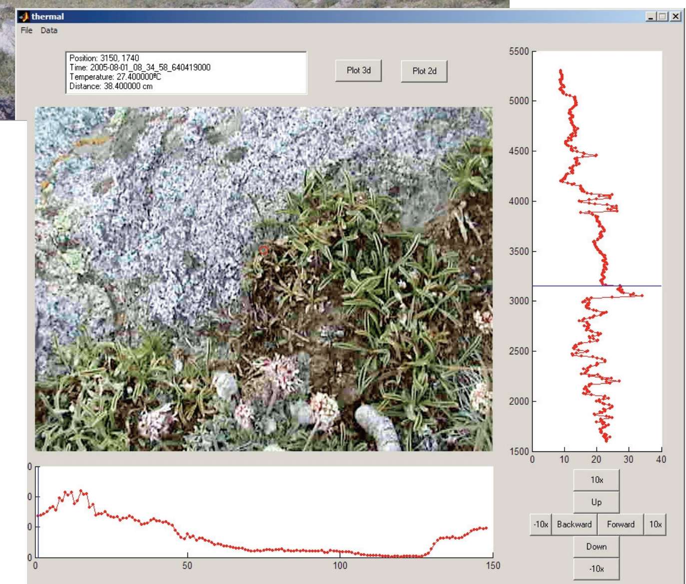
- Begin adaptive sampling projects, with light patterns as challenging project



Design Iterations for NIMS

- Development and deployment of NIMS RD with active roles by domain scientists at all stages

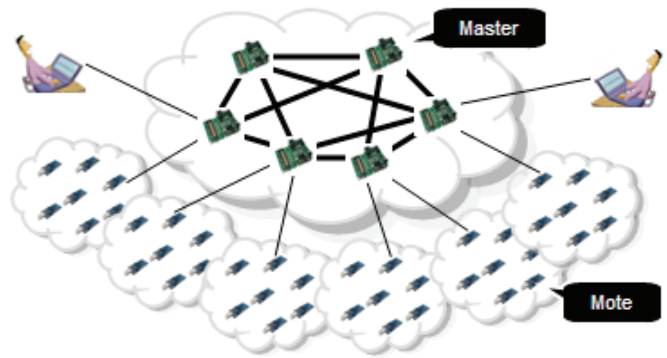


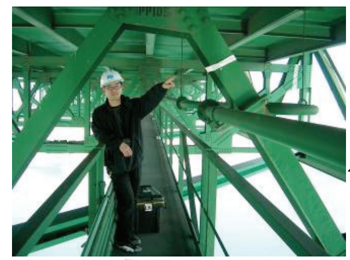


- From lab to Medea creek, White Mountains, Merced River, NIMS/NAMOS

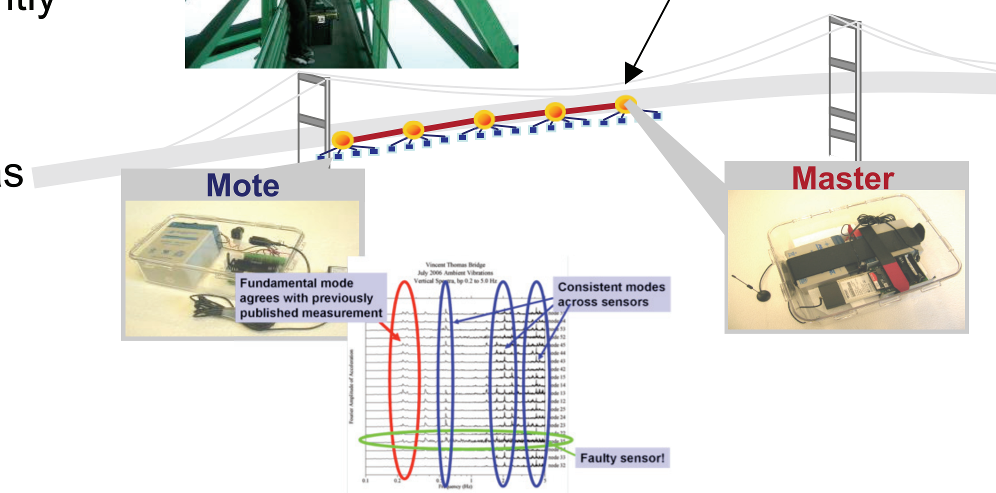
Tenet: Tiered Sensing Systems

- Goal
  - Develop an architecture that simplifies programming large-scale sensing systems
  - … and improves overall manageability
- Approach
  - Large-scale sensing systems will be tiered for greater capacity
  - Judiciously separate functionality across tiers
  - Applications run on relatively unconstrained upper-tiers
  - Requires no mote programming
  - Can run multiple applications concurrently
- Achievements
  - Code released: Jan 2007
  - 24-hour deployment on Vincent Thomas Bridge
- Future Directions
  - Geonet, structural deployments
  - Extensible Sensing System
  - NAMOS

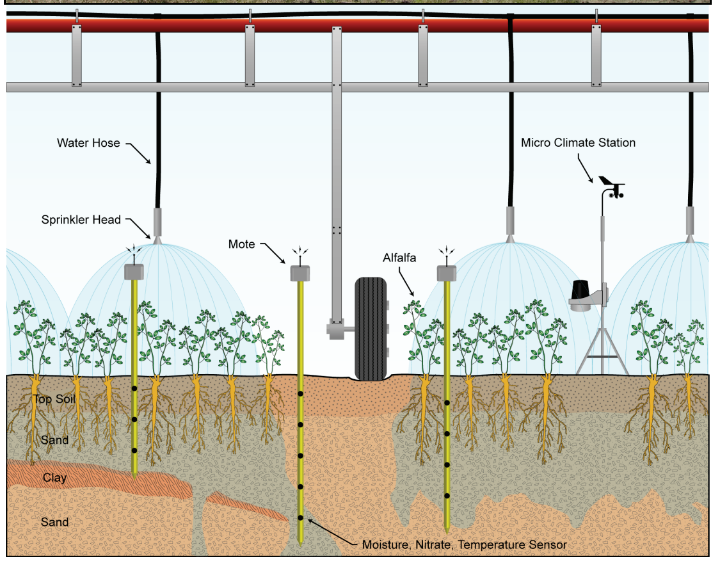




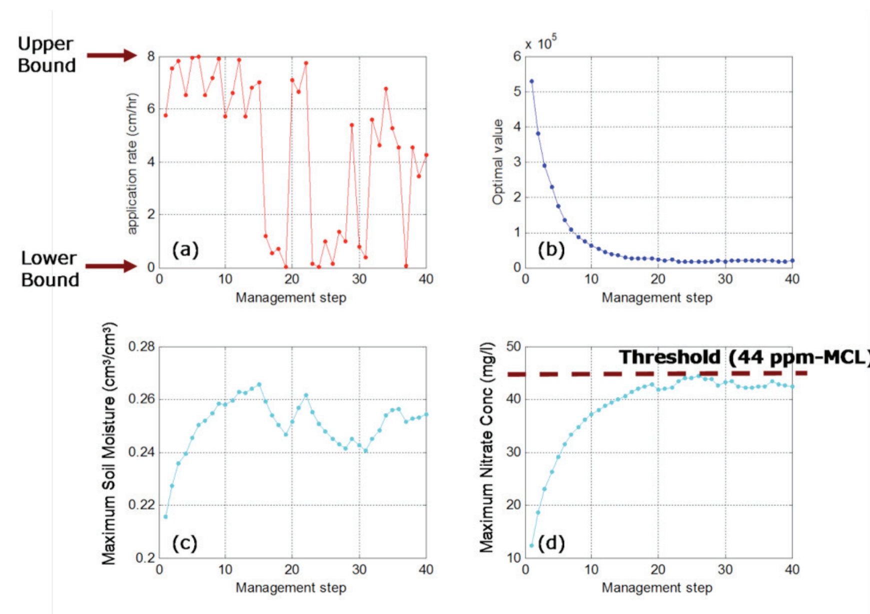
Deployment on Vincent Thomas Bridge



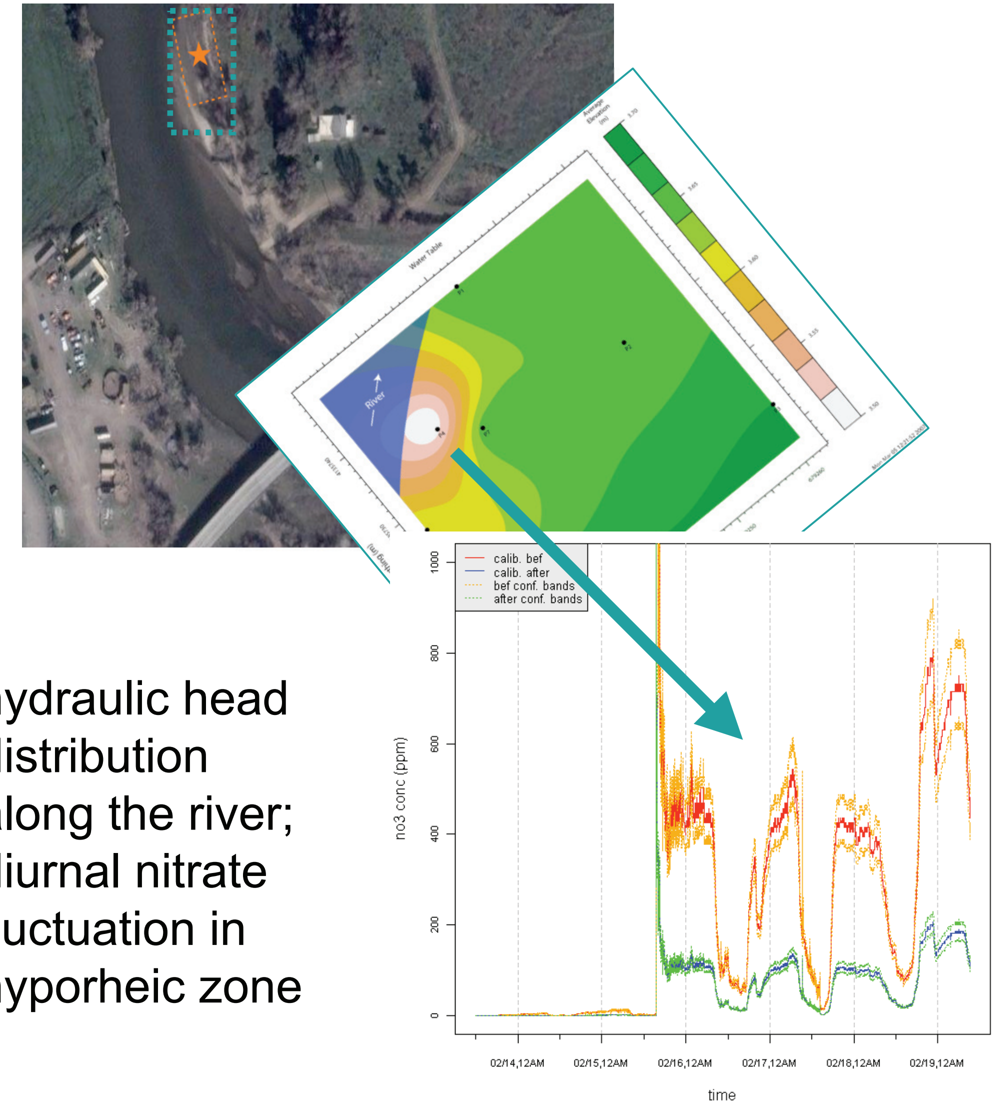
Precision Agriculture with Reclaimed Water



- Palmdale water reuse experimental site
- Microclimate + soil pylons (moisture, temp, **short-term nitrate and ammonium**)
- sensor **feedback**, model calibration, model forecast, system **control**



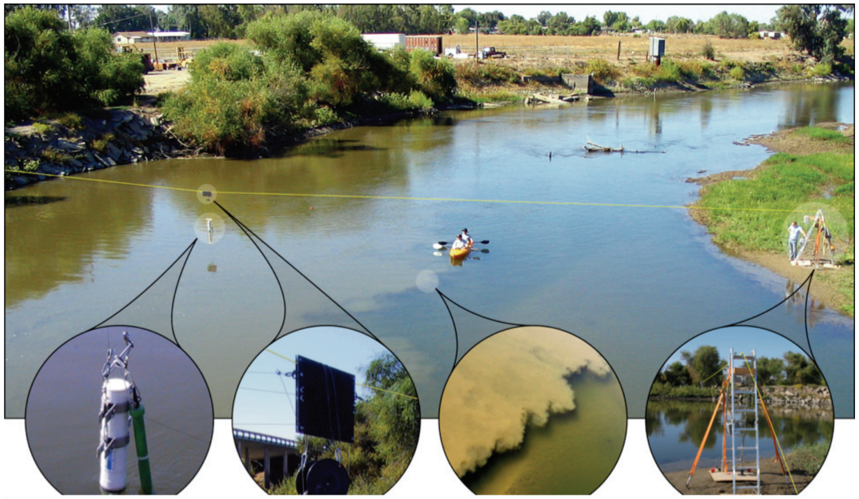
Multiscale River Observations:
Groundwater-Surface Water Interactions

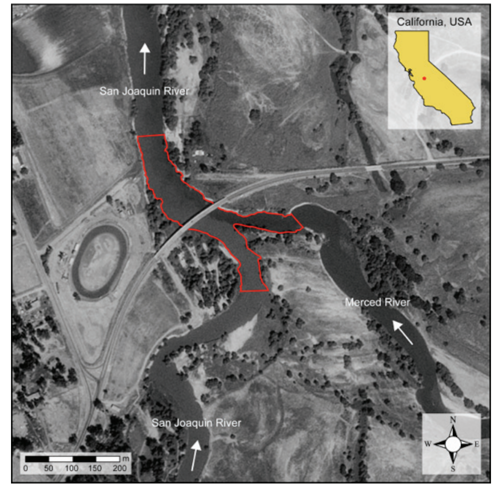


hydraulic head distribution along the river; diurnal nitrate fluctuation in hyporheic zone

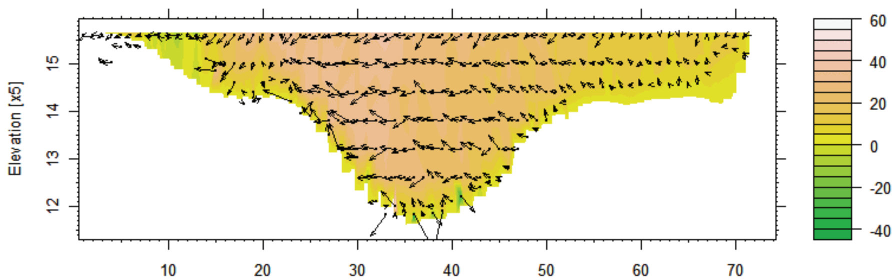
- Missing component of the mass balance on the San Joaquin River
- Stationary network (P, T, nitrate, ammonium)
- Diurnal cycles in hyporheic zone: ammonium peaks in afternoon while nitrate drops; potential causes:
  - River-hyporheic zone exchange
  - Transient hydraulics beyond the P sensors

Multiscale River Observations:
Precision Mixing and Mass Balance Assessment

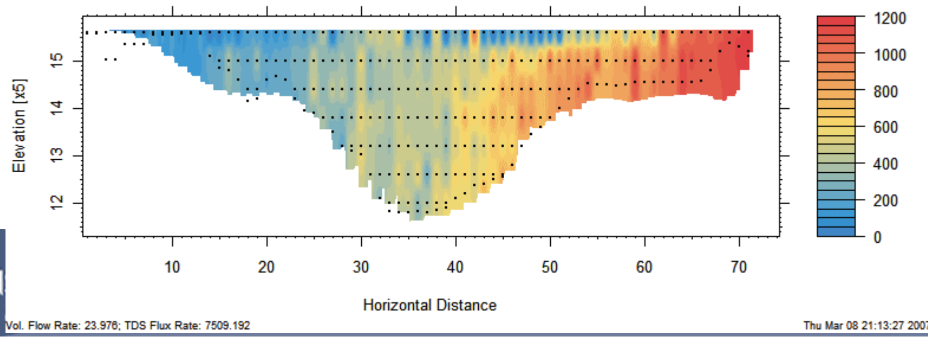




velocity vectors



specific conductance

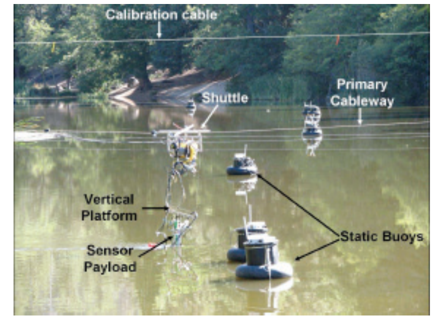


- San Joaquin-Merced River confluence
- Coupled velocity and water quality parameter fields yield mass fluxes
- Reservoir operation and 3D water quality
- Groundwater accretion

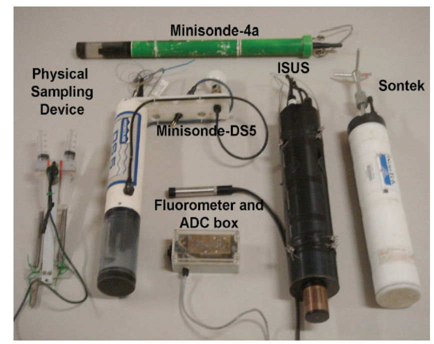
Aquatic Networked Infomechanical Systems (NIMS)

- NIMS aquatic applications expanding
  - Contaminant transport, phytoplankton dynamics, marine algal blooms
  - Multiple, simultaneous transects operating in lake, river, stream systems
  - NAMOS/NIMS Robot Teams
  - Typical payloads: over 10 sensors
  - Wide span (~100m), high resolution (0.1 - 0.5m), precise location control
- NIMS aquatic system evolution
  - Now relies on in-field adaptation to static and dynamic 3D phenomena structure
  - Introduce physical sampling for contaminant/microbe identification
- NIMS Systems
  - NIMS RD commercialized in 06/07
  - New NIMS-AQ system - enables NIMS benefits over wide span river systems - integrating autonomous sonar sounding

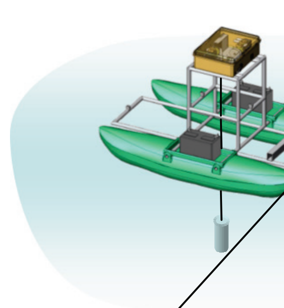
San Joaquin R.



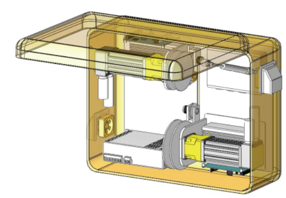
NAMOS/NIMS



Sensor Payload.

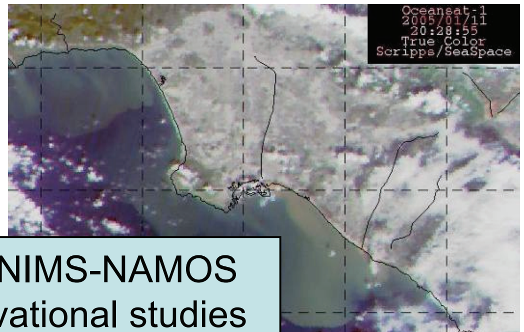


NIMS-AQ

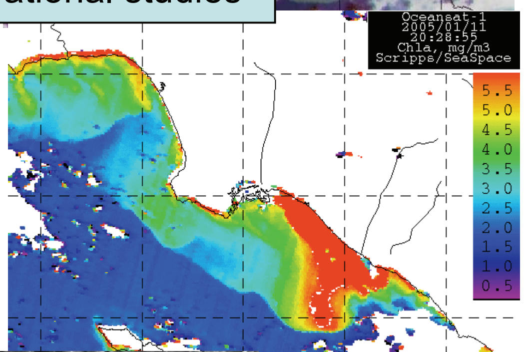


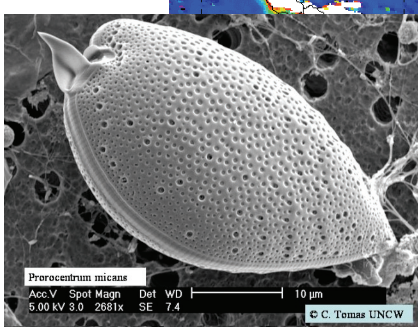
Commercial NIMS Embedded Module

Networked Aquatic Microbial Observing System (NAMOS) Overview

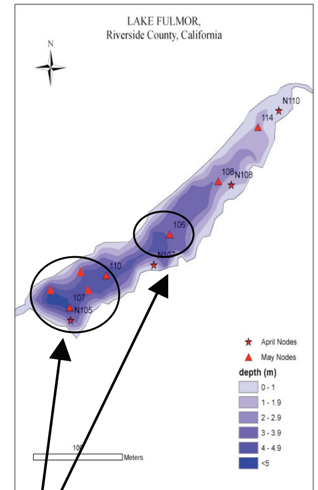


Joint NIMS-NAMOS observational studies





Extend in-situ sensor networks to other freshwater/estuarine ecosystems for the study of HABs.



Multi-scale analysis of small-scale heterogeneity within spatial patterns of plankton assemblages.

New robotic boat for larger-scale measurements and vertical profiling.


Stationary buoys
(T, EC, chlorophyll-a)
Robotic boat sensor
platform (3D sampling
capable)
Redondo Beach
© 2007 Europa Technologies
Google
Pointer 33°50'52.15" N 118°23'51.32" W elev 0 m Streaming |||||||||| 100% Eye alt 2.13 km

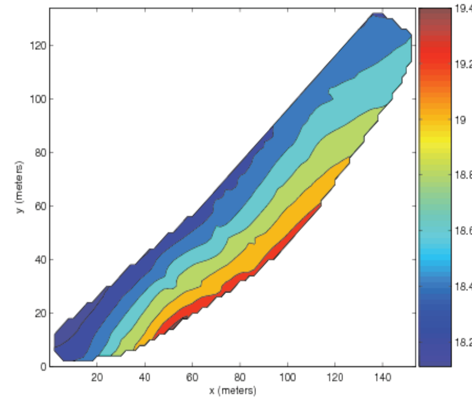
Iterated Deployment

- Field reconstruction by spatially distributing samples using a mobile robot
- Robot is energy limited
- Non-parametric regression
- Optimal density and bandwidth

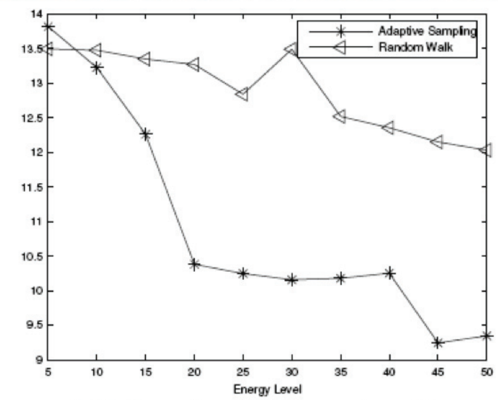
$$f^*(x) \propto tr^{\frac{2d}{d+8}}\{\mathrm{H}_m(x)\}\sigma^{\frac{8}{d+8}}(x)$$

$$h^* = C(K)\left(\frac{\sigma^2(x)d}{nf(x)tr^2\{H_m(x)\}}\right)^{\frac{1}{d+4}}$$

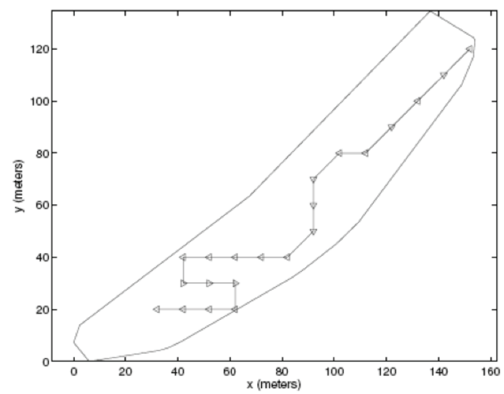
- Optimal path planning on set of samples using a gain function related to integrated mean square error



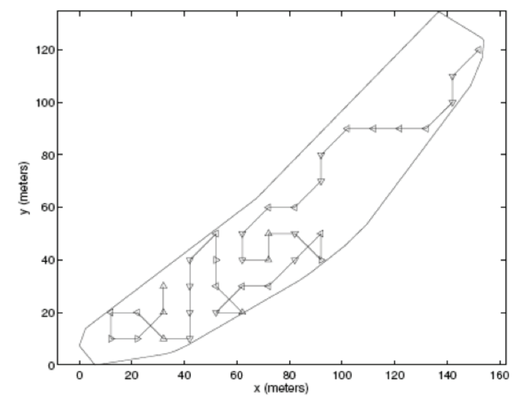
Reconstruction



IMSC reduces sharply with adaptive sampling



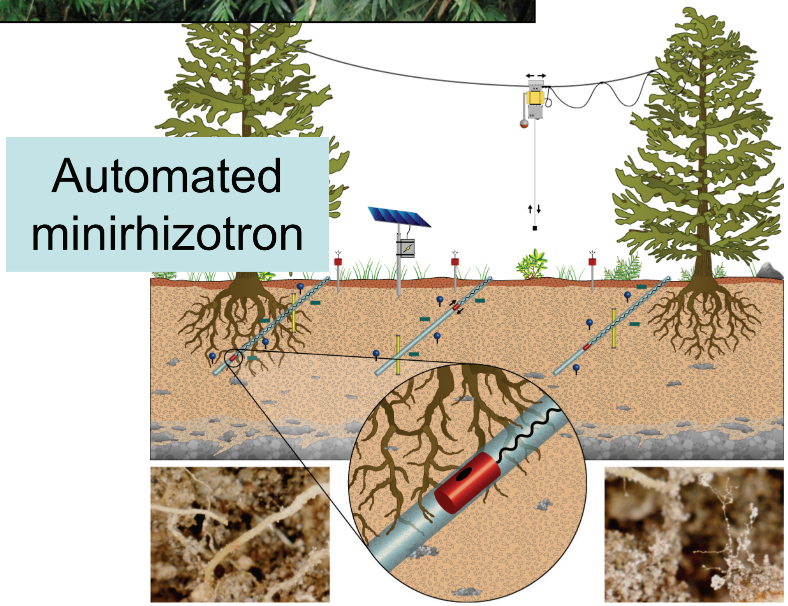
Initial low energy



Initial high energy

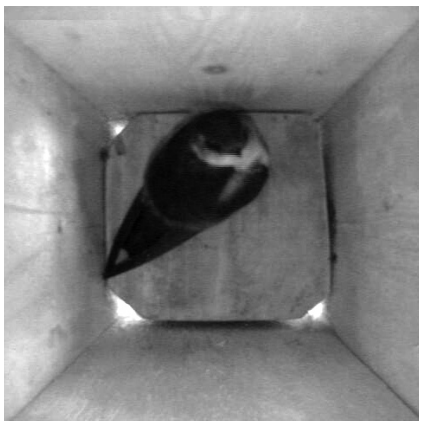
TEOS: Terrestrial Ecology Observing Systems Overview

- CENS technology
  - 2^{nd}, 3^{rd} generation NIMS and AMR mobile nodes
  - Cyclops
  - Integrated data analysis and management
- TEOS ecologists multi-scale and multi-modal approaches
  - soil root and microbial activity
  - ground surface energy dynamics,
  - microclimates below and within canopy
  - above canopy energy and carbon fluxes
  - phenological responses to environmental factors



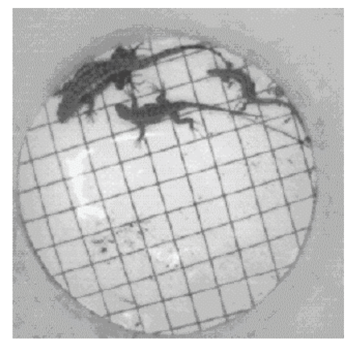
Imagers as Biological Sensor - Animals

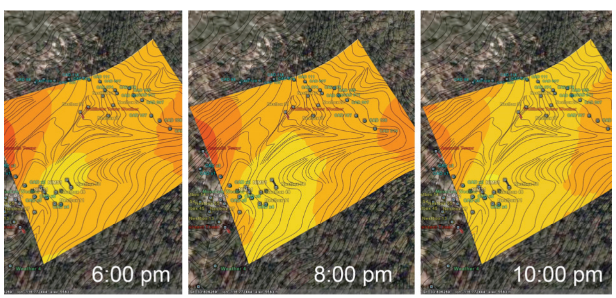
- **Visible light cameras** can capture quantitative information on the behavior of animals: time-to-fledging for cavity nesting birds to reptile diversity.
- All while **minimizing observer bias and disturbance**



Nestboxes – Automatic and assisted classification of events in bird reproduction coupled with microclimate information.

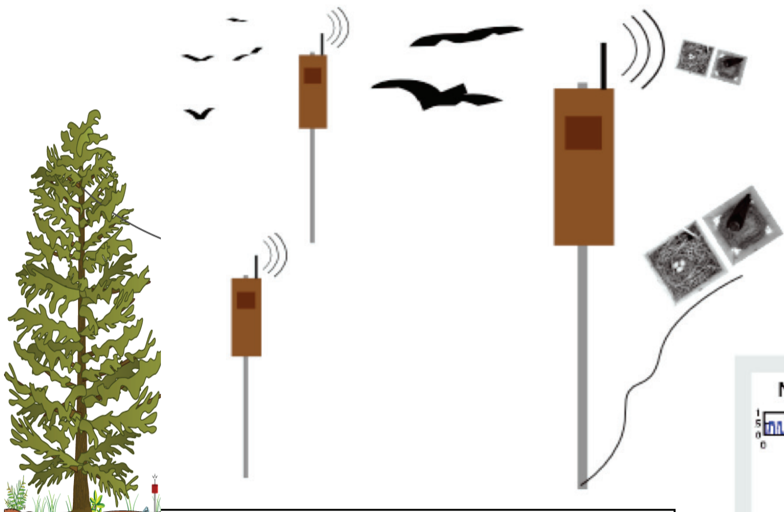
Pitfall traps – Cyclops reduces time for sampling, mortality of organisms, and documents escapees.

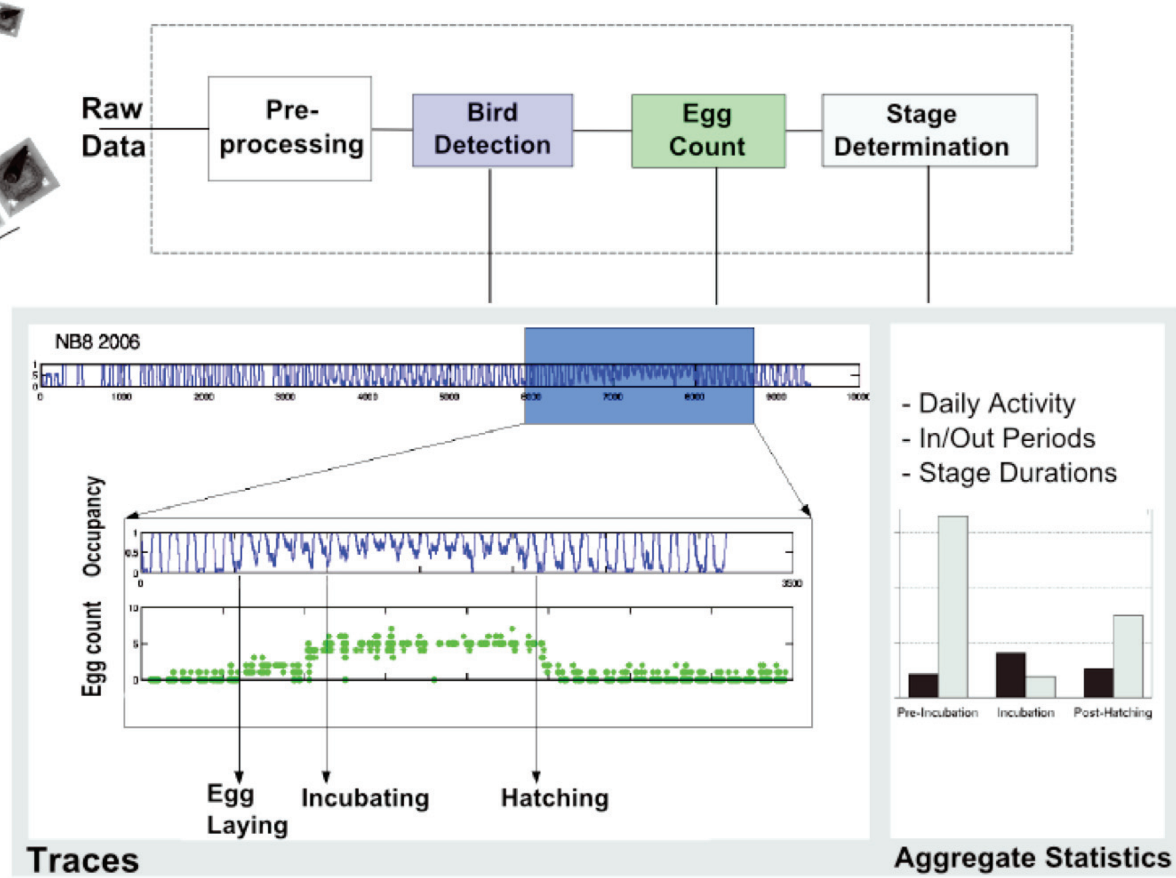




Microclimate array – Coverage of the JR airshed provides the “backdrop” on which to document organism behavior

Imagers as biological sensors: *end-to-end*



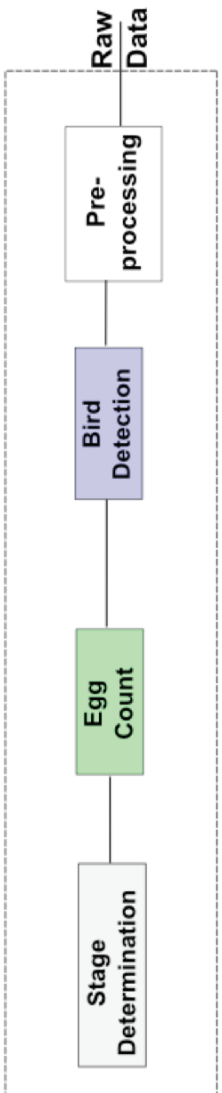


Avian biologists are interested in bird nesting activity during the breeding season. Typically this involves manual inspection of nestboxes in the field.

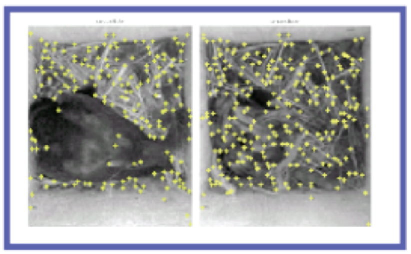
Imagers can provide similar observations for longer periods of time over larger geographic locations.

A scalable solution would provide high-level statistics to the biologist in an automated fashion.

Imagers as biological sensors: *inference*

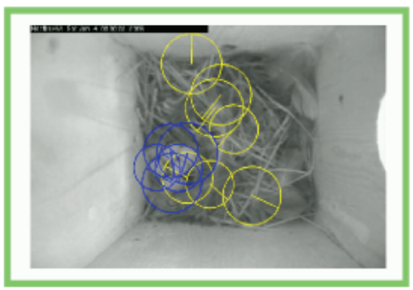


Cropping and normalization of image reduce noise and unnecessary processing .



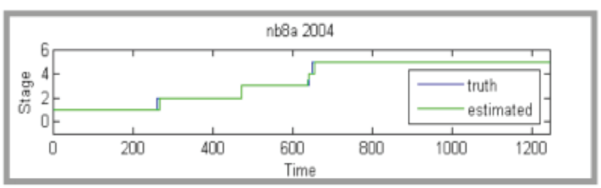
Use the absence of corner points as an indicator of bird presence

A moving threshold overcomes changes in background, lighting conditions, etc.



Scale Invariant Feature Transform (SIFT) finds potential egg locations.

Using mean/variance around regions of interest, the location is identified as having an egg or not.



A Hidden Markov Model (HMM) is used to enforce temporal constraints on egg counts and determines stage transitions.

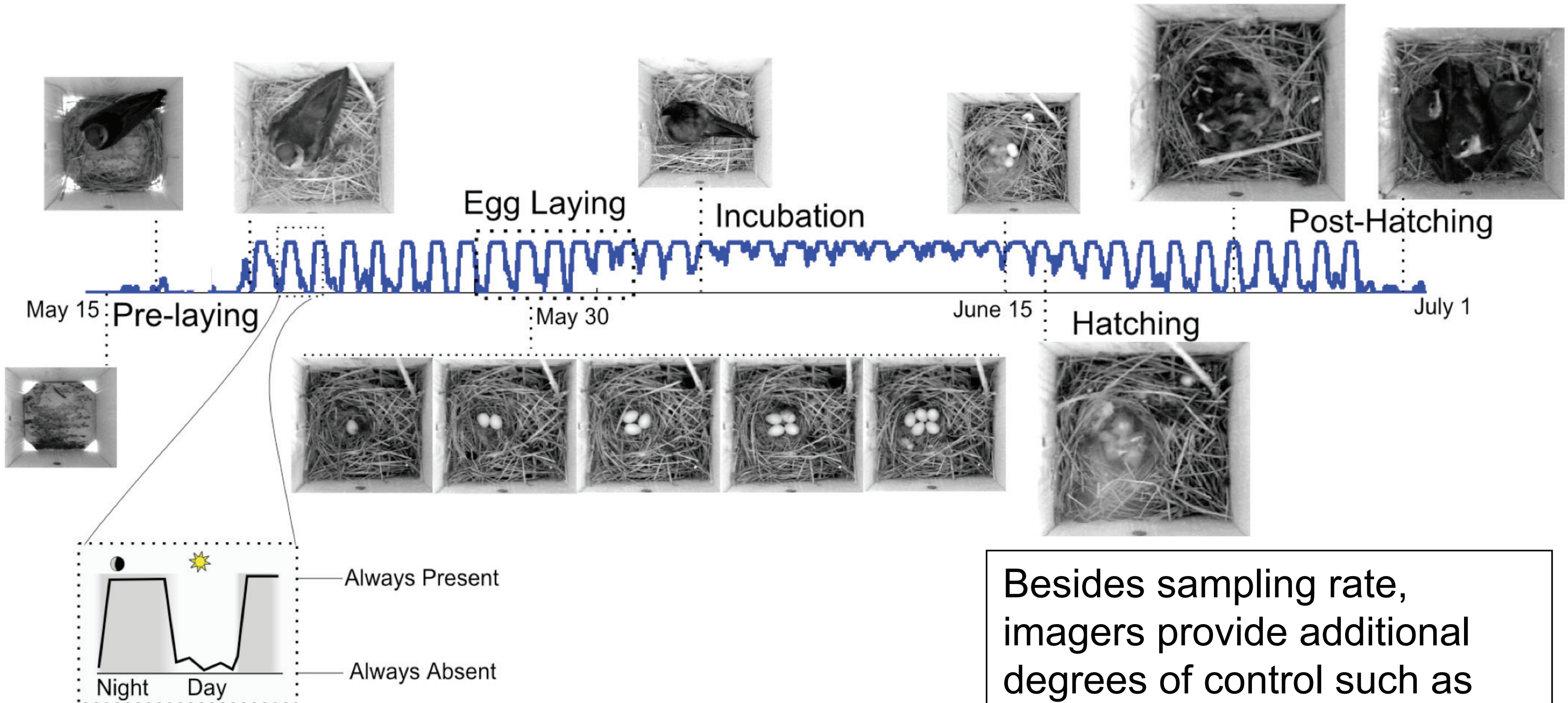
Automated inference is challenging. We can overcome some of these challenges by:

Viewing inference as a multi-step process.

Using vision algorithms that are “robust” (invariant) to dynamics of the environment.

Temporal and spatial consistencies to reinforce observations

Imagers as biological sensors: *context*



Blue line is inferred presence/absence from a sequence of 5000 images that has been smoothed and plotted over the duration of the nesting season and overlaid with snapshots of the nest.

The juxtaposition highlights the evolution of nesting activity and brings forth "micro" / "macro" trends, such as diurnal activity patterns and nesting stages, that can be used for context-based sensing

Besides sampling rate, imagers provide additional degrees of control such as resolution (size of image) that can be leveraged to improve inference of "interesting behavior" (*sensor output*). A mechanism to do this is *context.*

Imagers as Biological Sensor - Plants

Visible light cameras can capture colorimetric, shape, and time-sequenced data on plant growth and phenology and are easily mounted on poles, sent underground, or attached to mobile robotic platforms to collect images.

MossCam – Detecting color change as it is related to Carbon exchange in drought-tolerant (and other non-moss) species.

AMR – Rhizotron images of roots and mycorhizae are correlated with soil carbon fluxes.

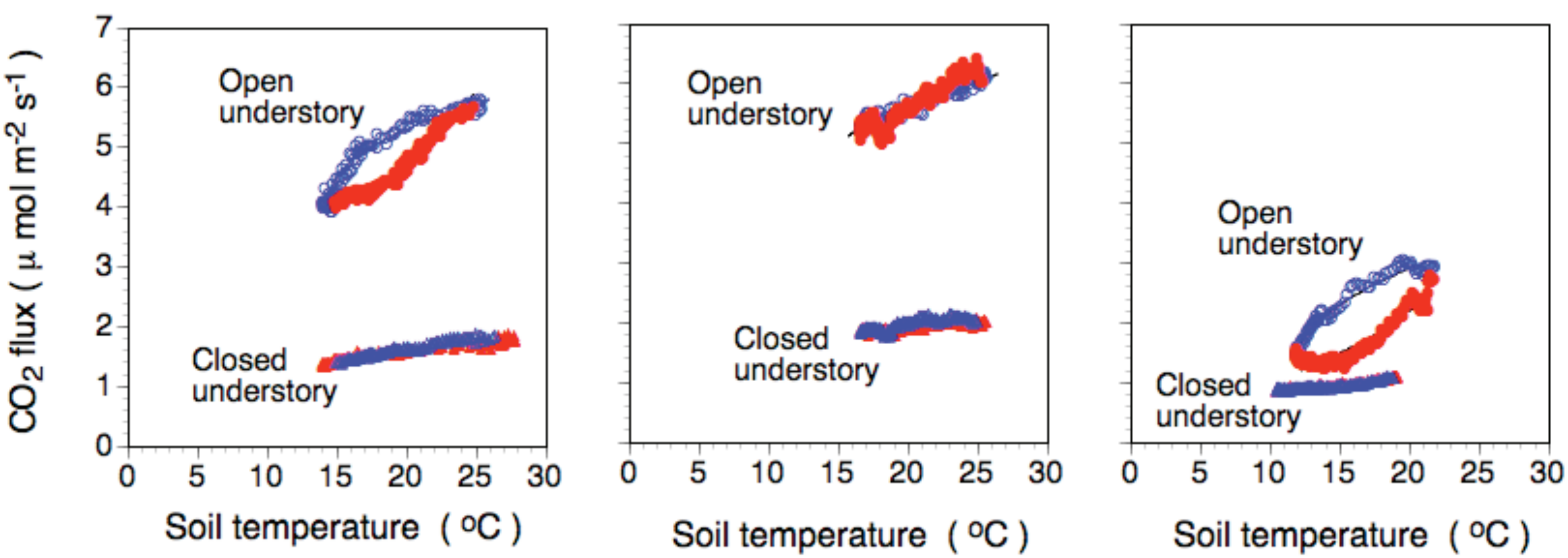
FlowerCam – Detecting annuals and perennials, “greening up”, and phenological changes associated with local climate.

TEOS: Terrestrial Ecology Observing Systems

- Unexpected patterns in soil respiration
- Seasonal changes in hysteretic responses of soil respiration
- Potentially leading to a new generation of soil respiration models.

closed forest understory

open forest understory



Lessons from the field...

Early themes

Thousands of small devices

Minimize individual node resource needs

Exploit large numbers

Fully autonomous systems

In-network and collaborative processing for **longevity:** optimize communication

New themes

Heterogeneity

Tiered systems architecture to optimize system as a whole

Inevitable under-sampling (in time or space) with homogeneous sensing

Exploit multiple modalities, multiple scales, and *mobility*

Interactivity

Coupled human-observational systems: online tasking, analysis, visualization

In-network and collaborative processing for responsiveness, data quality, rapid and iterative deployment

Monitoring the monitors: calibration, self test, validation

Conclusion

- New and interesting problems arise from real deployments
  - Even seemingly simple natural phenomena are usually amazingly complicated to model
  - Approach through sequence of related experiments and models