SAND2009-5729C

Measuring soil moisture and snow pack with cosmic-ray neutrons

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Project Purpose, Goals and Approach

To develop a cosmic-ray soil moisture/snow monitoring technique that operates at a scale *intermediate* between satellite remote sensing and point measurements

R&D Goals

- Quantify the sensitivity, sample area, penetration depth and correction factors
- Demonstrate the technique in the field
- Develop new techniques

Key Accomplishments

- Development of theory describing sample area, penetration depth and calibration
- Installation of probes at Valles Caldera, Santa Fe paired watersheds

Significance of Results

The cosmic-ray probe can do something that nothing else can: average moisture/snow over tens of hectares

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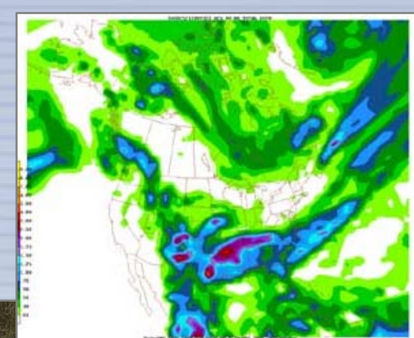
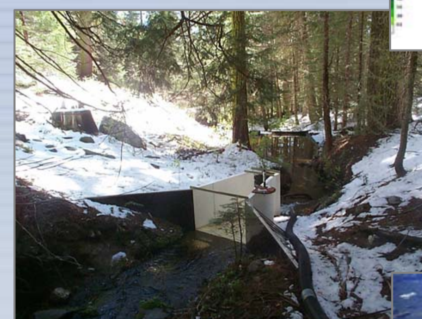
Why measure soil moisture?



- **Modeling weather/climate**

  E.g., drought in central europe, North American monsoon

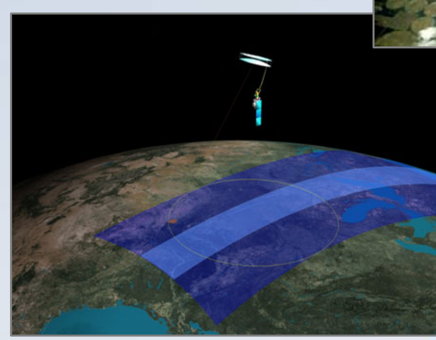


- **Forecasting streamflow**

  NOAA/NWS, USDA/NRCS

- **Agriculture**

  especially important for irrigation scheduling



- **Calibration of satellite sensors**

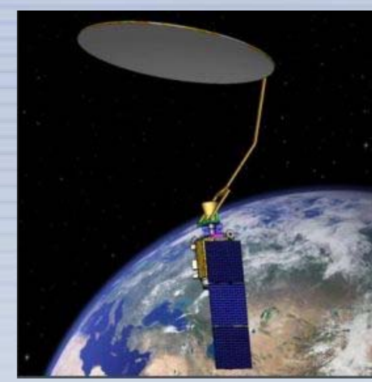
  SMAP (NASA) and SMOS (ESA)

Soil moisture and the problem of scale

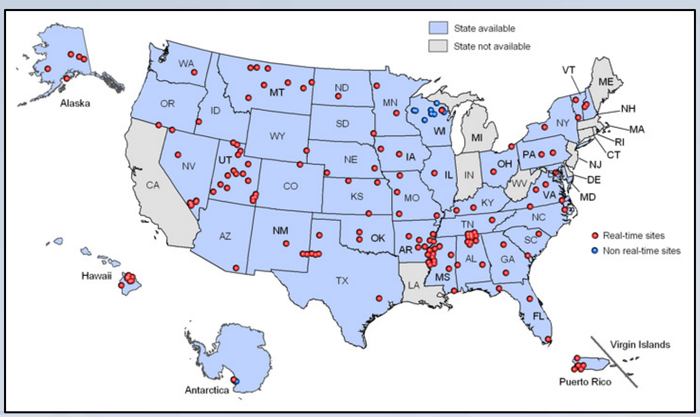
small scale (cm) ⟷ **big scale (10s of km)**

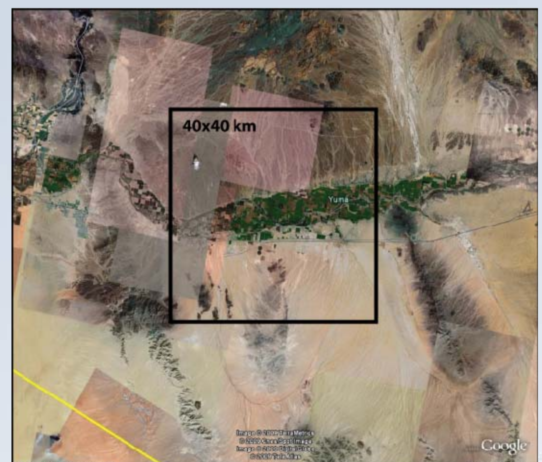
Invasive probes
(e.g. TDR, capacitance, neutron)
- sparse coverage
- highly accurate
- disturbs medium

Passive microwave
(e.g. NASA SMAP, ESA SMOS)
- global coverage
- poor resolution
- many complications
- shallow penetration (2-5 cm)



USDA SCAN network





Significance of snow pack

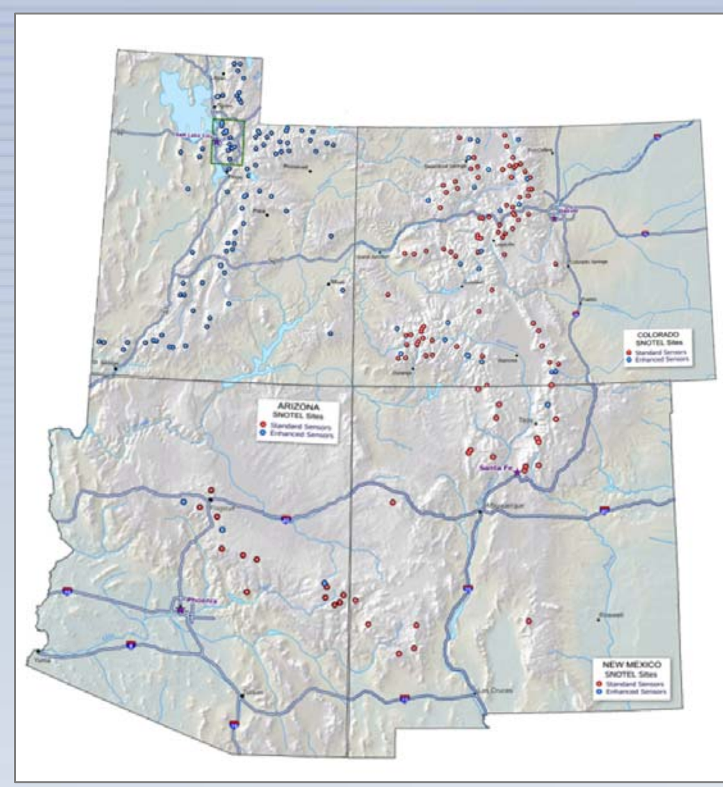
- **50-80% of water consumed in western U.S. is from snow-fed rivers**
- **Seasonal snow pack critical to**
  – Irrigated agriculture
  – Hydropower
  – Municipal water supplies
  – Flood forecasting
  – Ecology/recreation

- **Columbia, Colorado rivers and Rio Grande are good examples of snow-fed rivers in the west**

Measuring snow pack

- **Snow pillow**
  - SWE at a point
- **Satellite**
  - snow extent

- **Active gamma attenuation**
  - attenuation of gammas from pt source
- **Aerial gamma surveys**
  - (eg. NOAA) – passive, but only up to 30 cm of SWE



USDA SNOTEL network

Cosmic-ray technique in a nutshell

- **Passive**
  utilizes cosmic-ray neutrons
- **Non-invasive**
  does not disturb soil
- **Moderately expensive**
  $10-20k
- **Moderate power consumption**
  <0.25 W
- **Small data sets**
  KB per day
- **Can monitor both soil moisture and snow**
  …but not simultaneously
- **Large footprint**
  340 m radius (86% of counts)

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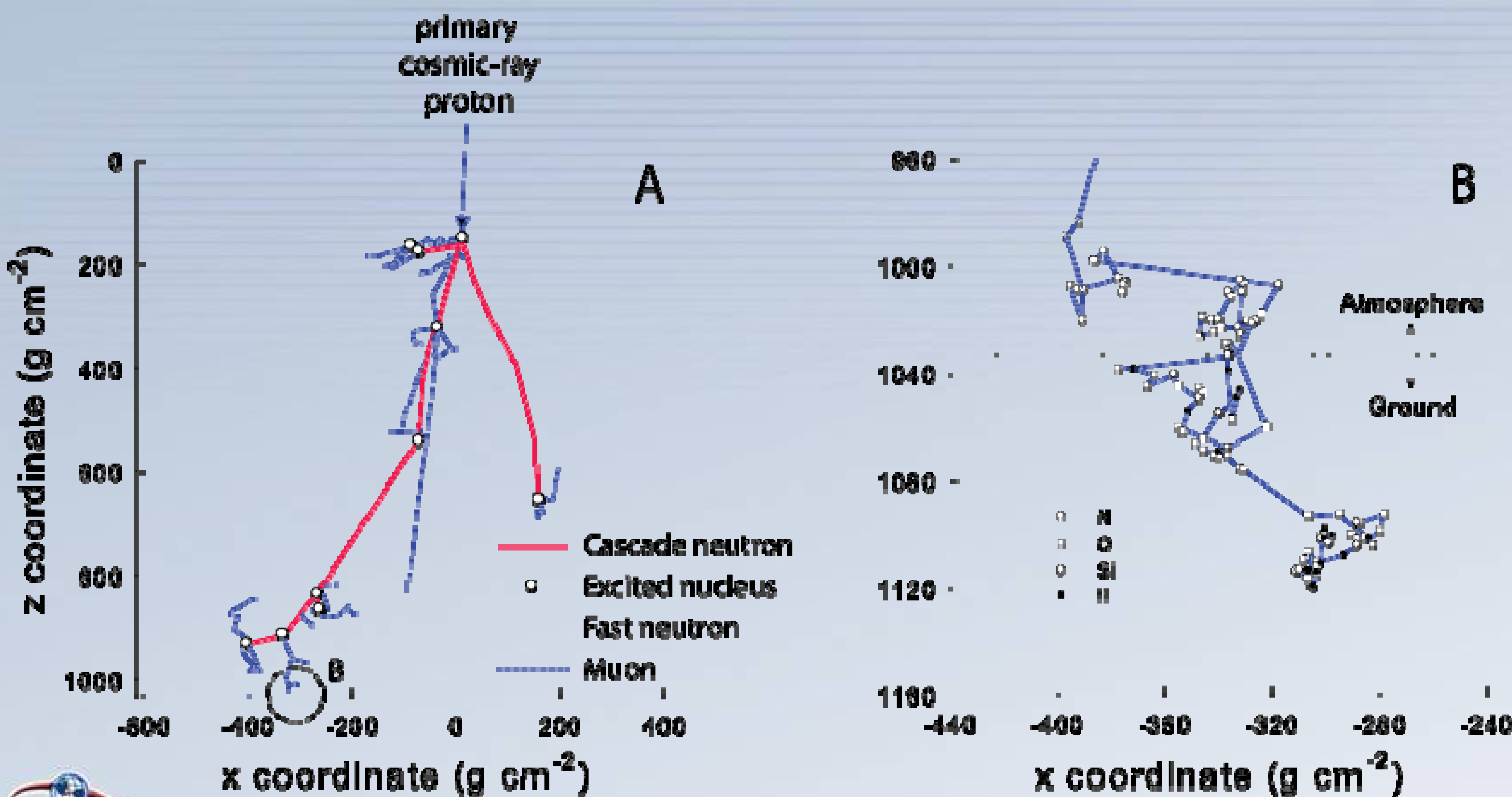
Cosmic rays

Particle cascade simulated in MCNPX



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Sensitivity to soil moisture

fast neutrons

$$\phi \propto \frac{1}{\xi \Sigma_s}$$

$$\Sigma = N\sigma$$

$$N = \text{nuclei cm}^{-3}$$

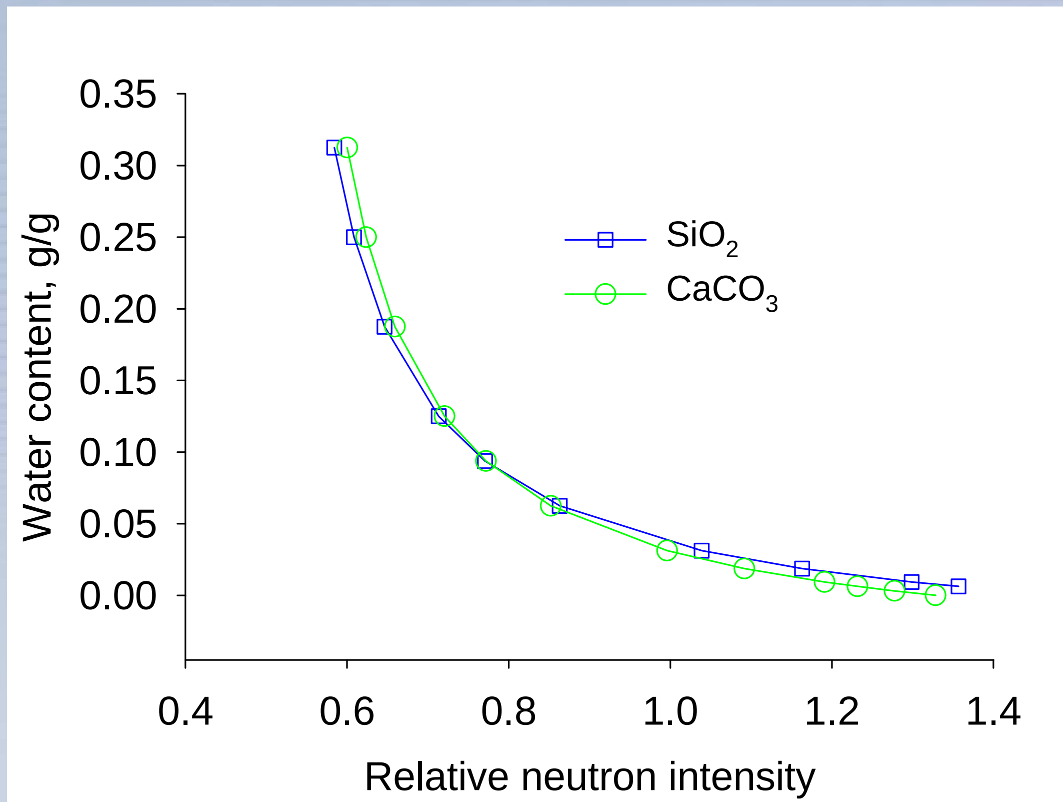
$$\sigma = \text{cm}^2$$

slow (thermal) neutrons

$$\phi \propto \frac{\xi \Sigma_s}{\Sigma_a}$$

	σ_s (barns)	ξ (-)
H	20.0	1.00
C	4.8	0.16
O	4.2	0.12
Si	2.0	0.07

Sensitivity to soil moisture



"Universal calibration" i.e. robust calibration for fast neutrons across a range of soil types

$\eta = \ln E_1 - \ln E_2$

$n = \frac{\eta}{\xi}$

Slowing down length of a neutron

$$L_s^2 = \frac{1}{6}\langle r^2 \rangle$$

Mean square displacement <*r*²>

λ=30 m in air

$$\langle r^2 \rangle = \left(\lambda \sqrt{n}\right)^2$$

Effective number of jumps (*n*)

ξ=0.15 in air

$$n = \frac{\eta}{\xi}$$

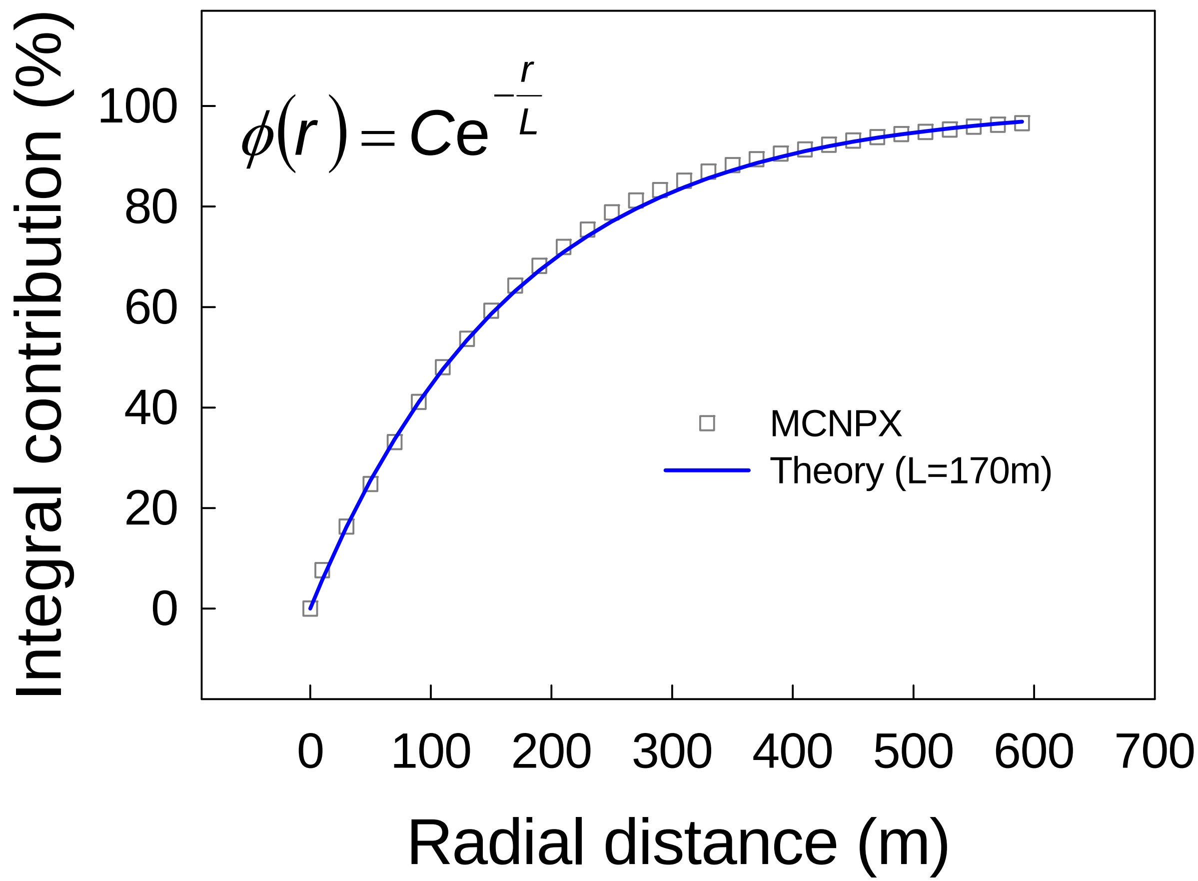
Number of log decrements (*η*)

$$\eta = \ln E_1 - \ln E_2$$

For E1=1MeV, E2=10eV

L = 170 m at sea level

Radius of influence: MCNPX



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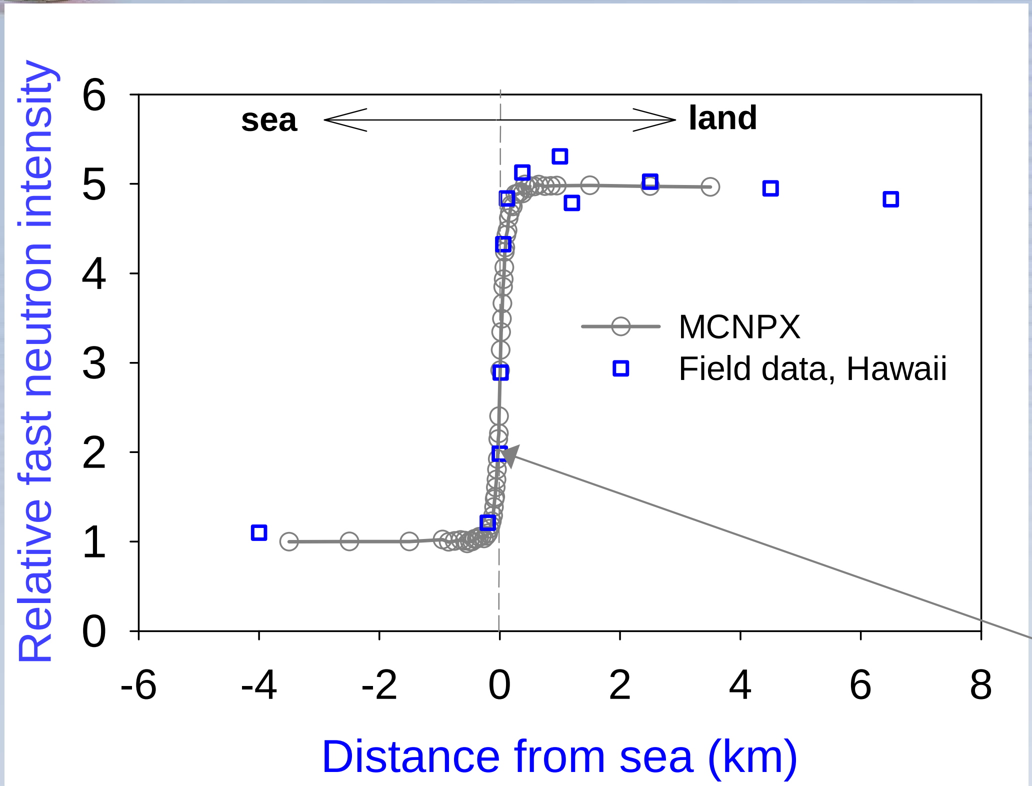
Radius of influence: field data

neutron detectors

Waikoloa, Hawaii
January, 2008

Radius of influence: field data



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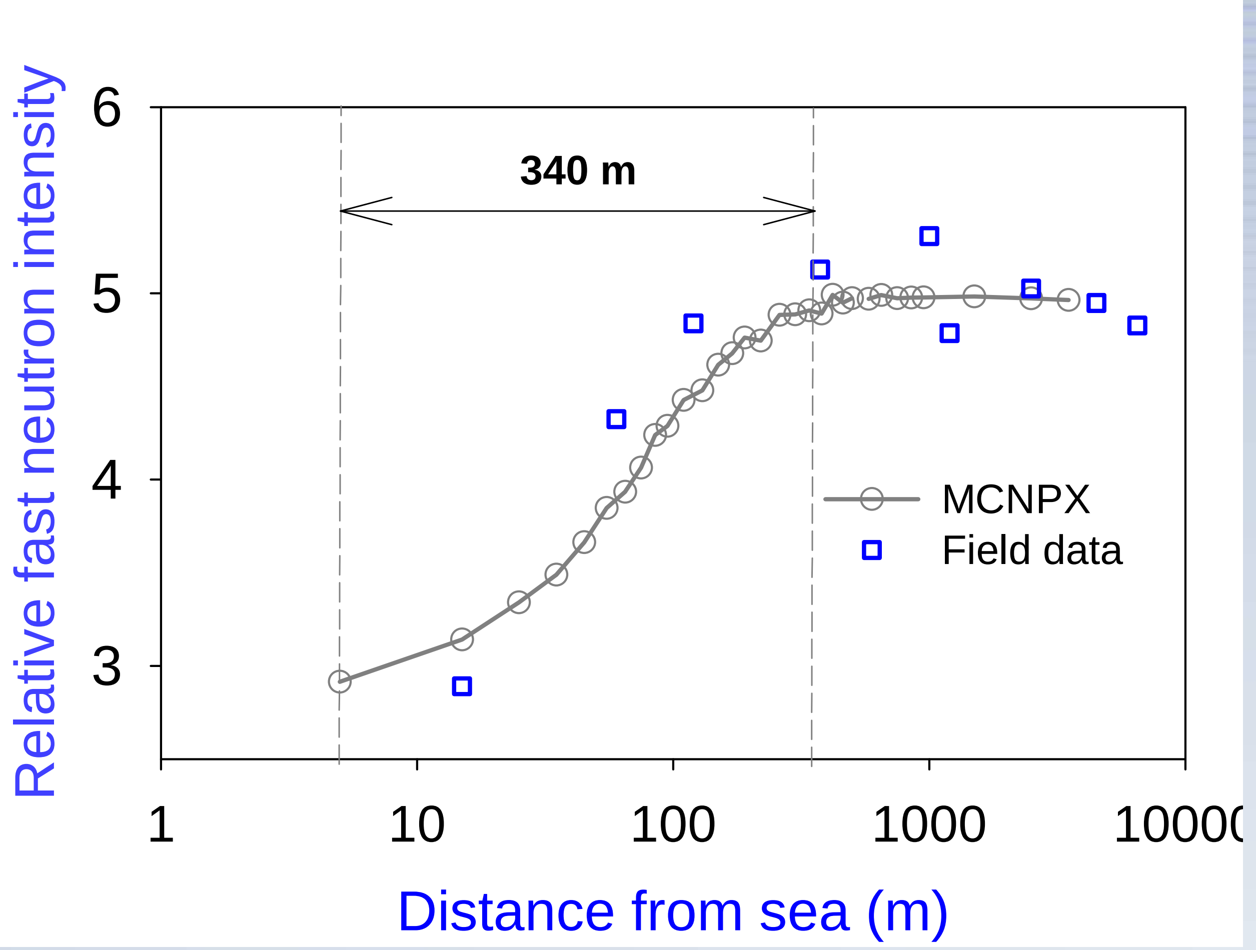
Radius of influence: field data



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Center pivot irrigation

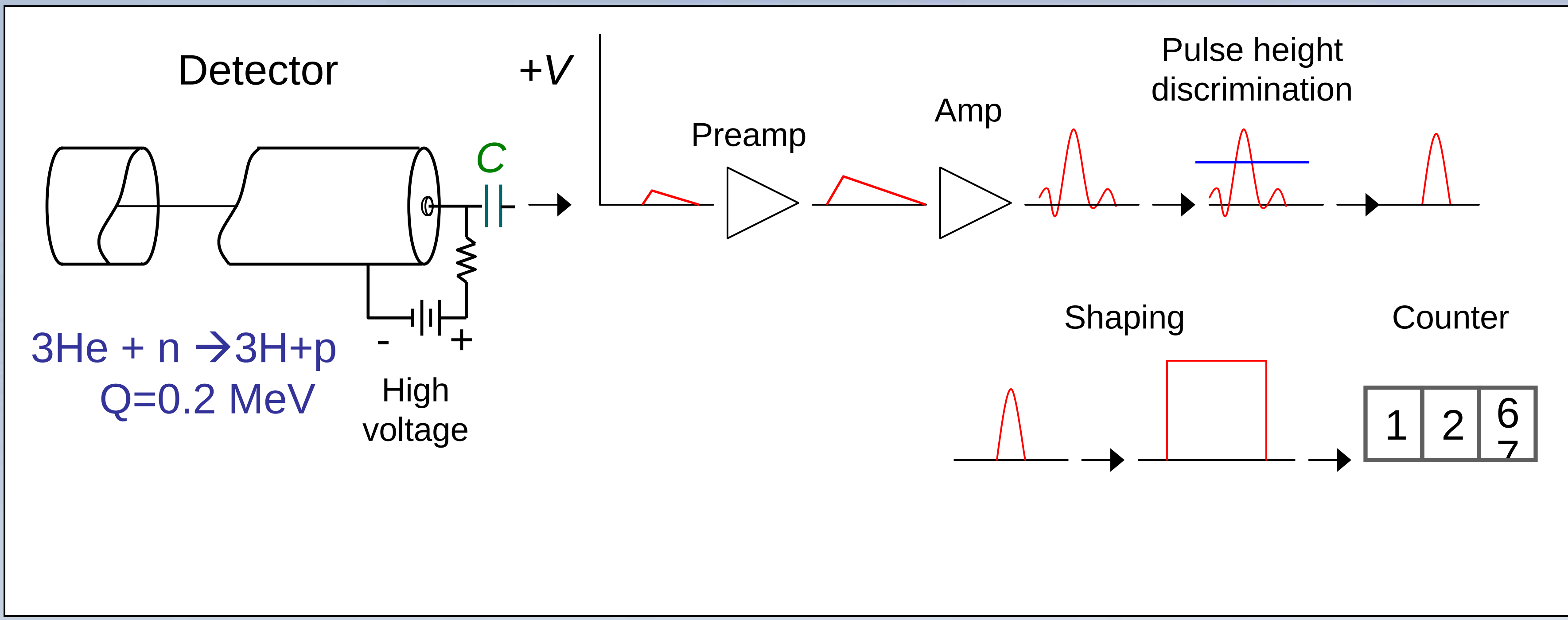
- **Cosmic-ray probe covers about one "quarter section"**

Center pivot irrigation over the Ogallala Aquifer (west Texas)

Summary of characteristics

- **Radius of influence**
  - Proportional to slowing down length
  - ~170m at sea level
  - Inversely proportional to barometric pressure
  - Independent of moisture content
  - Increases with distance above ground
- **Penetration depth**
  - Proportional to neutron mean free path in soil
  - 10-40 cm depending on water content
- **Precision**
  - Depends strongly on land elevation and detector dimensions
  - Counting statistics: Poissonian, i.e. $N^{1/2}$
  - Precision: typically ~3% with integration time of ~1 hour

Neutron detection system: 3He tubes



These detectors are “dumb”, i.e. no directional of spectral or directional information

Field instrument

- **Two counters: one bare, one moderated with 1” HDPE**
- **Solar powered**
- **Ancillary measurements: barometric pressure, temperature**

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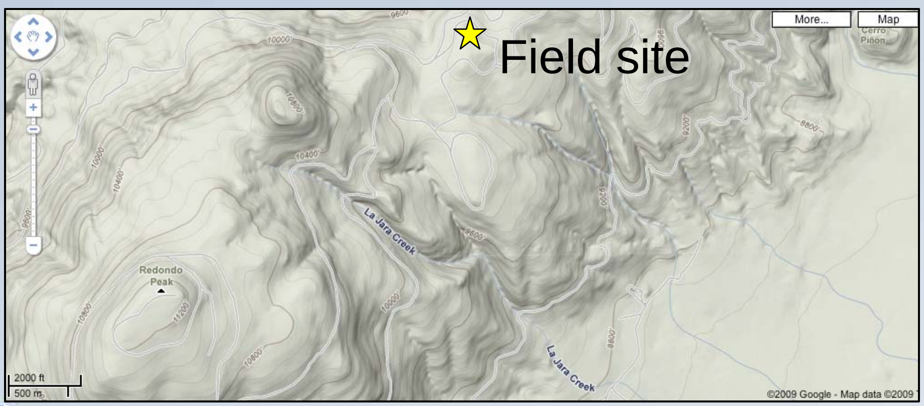
Field sites

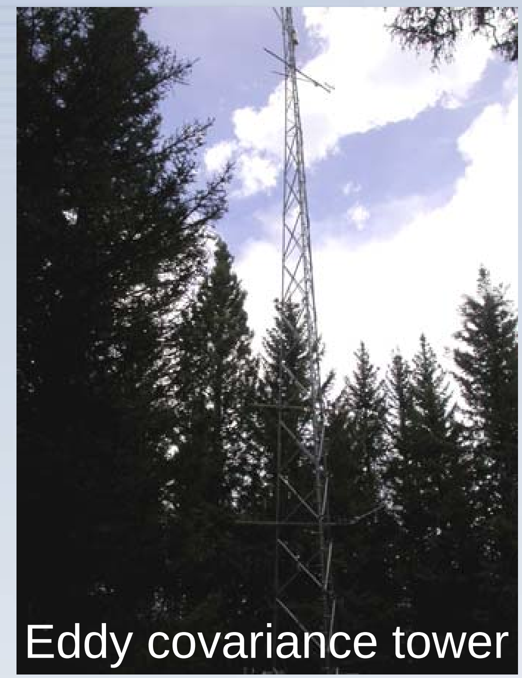
Questa
Mt Walter
Taos
Ranchos de Taos
Cimarron
Springer
Cuba
Espanola
Chimayo
Los Alamos
Santa Fe Baldy
Santa Fe
Valles Caldera National Preserve
Santa Fe Municipal Watershed
Rio Rancho
Bernalillo
Corrales
Mt Taylor
Albuquerque

Valles Caldera

Selected for:

- Elevation (>3000 m)
- Presence of nearby meteorological equipment
- Gauged streams
- Good location for snow pillow
- Accessibility and convenience



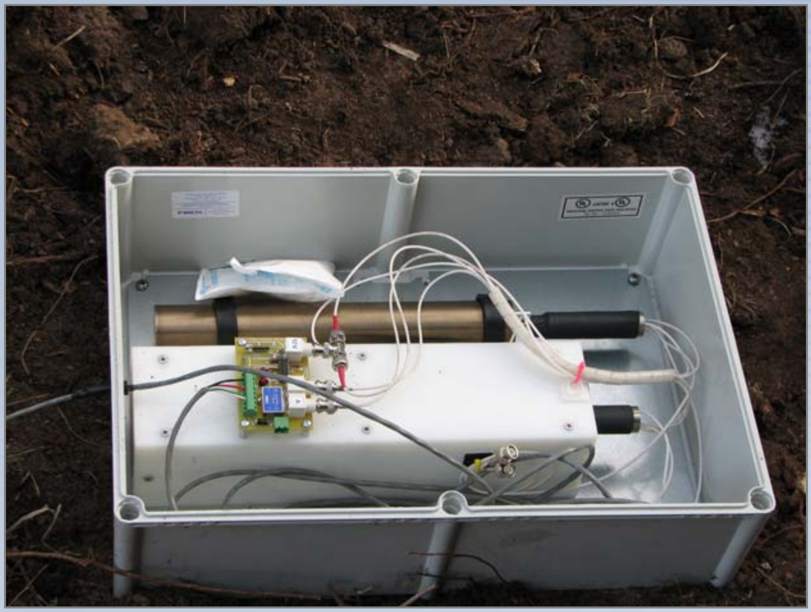

Eddy covariance tower

Ground truthing: snow pillow

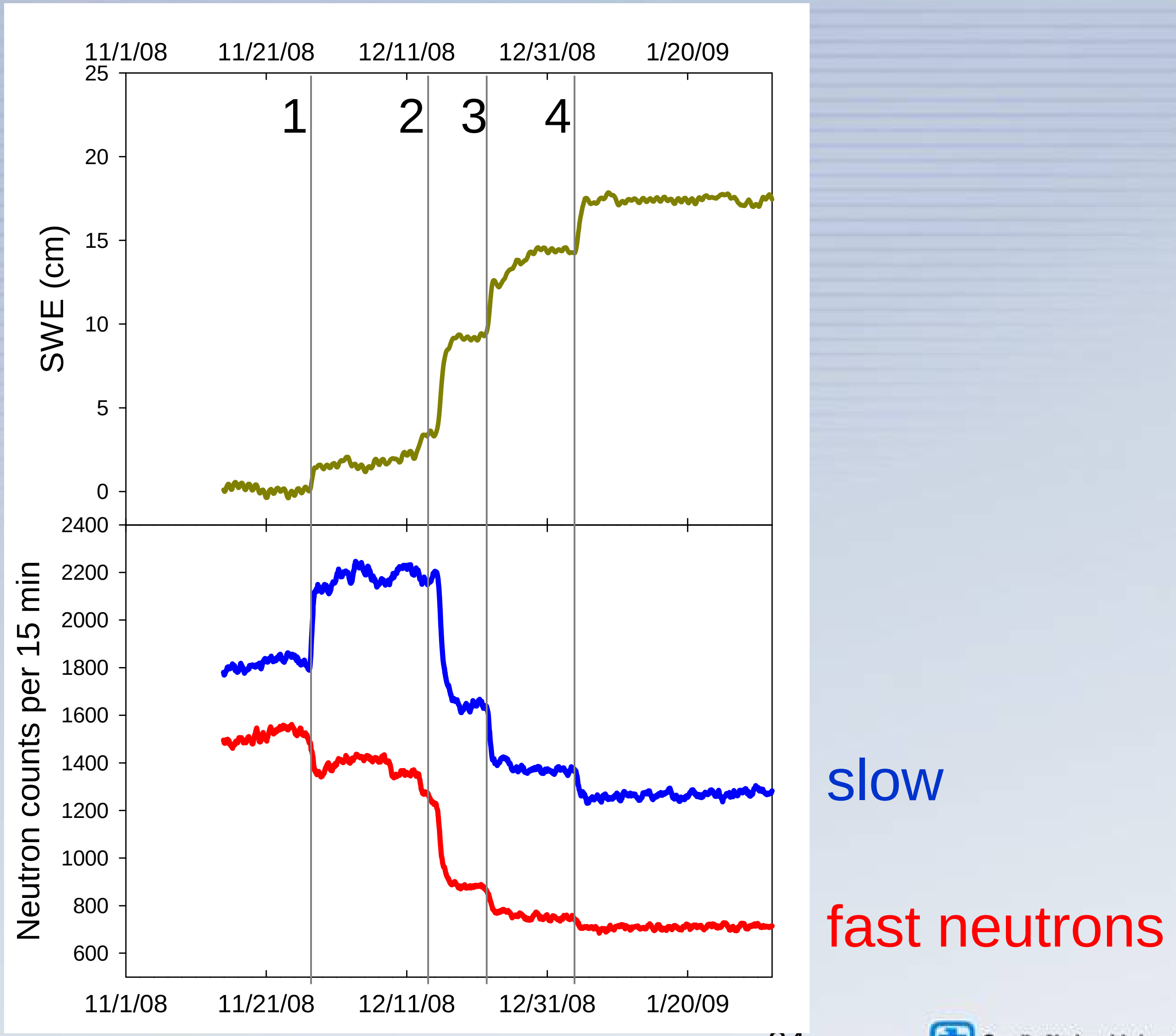
Richard Armijo, USDA/NRCS
NM State Snow Surveyer

Instrument trailer

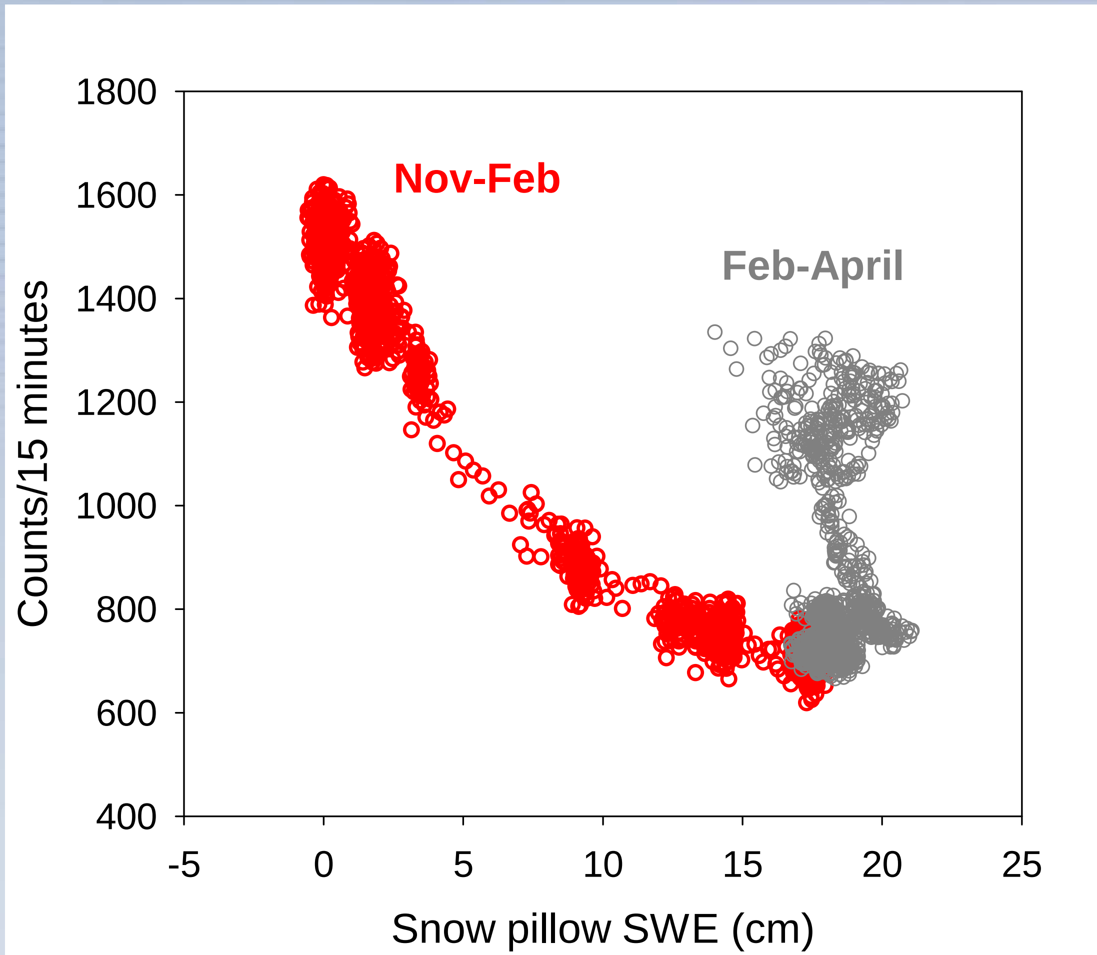
Submerged detectors



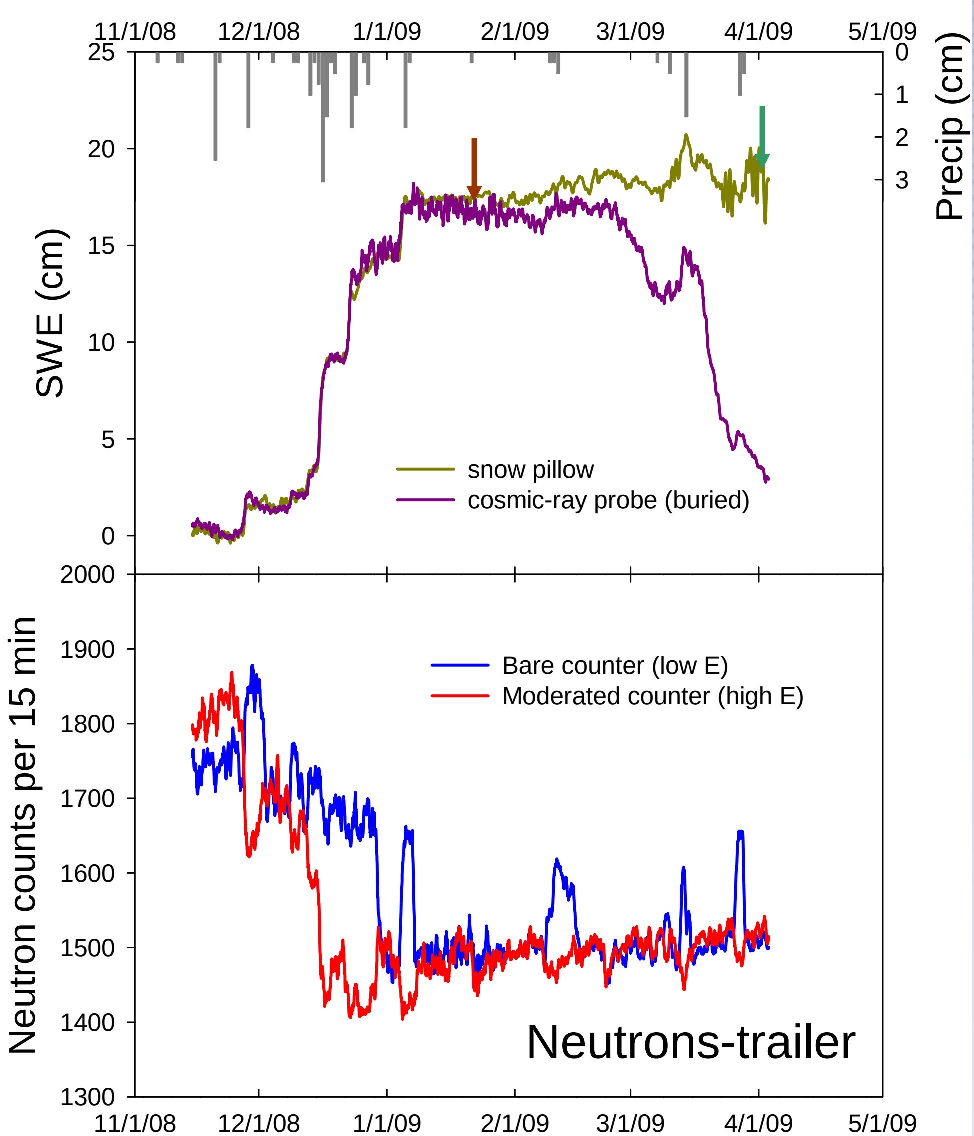
Buried probe vs. snow pillow



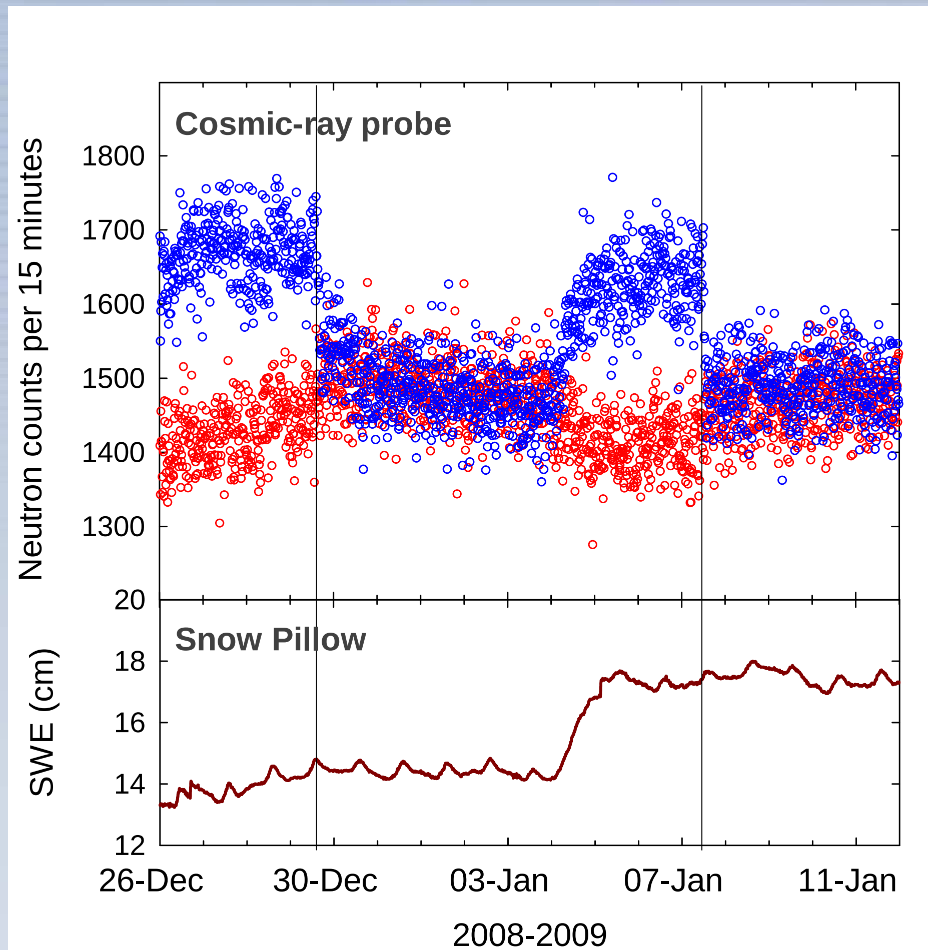
Buried probe vs. snow pillow



Winter time series



Snow event at Valles Caldera



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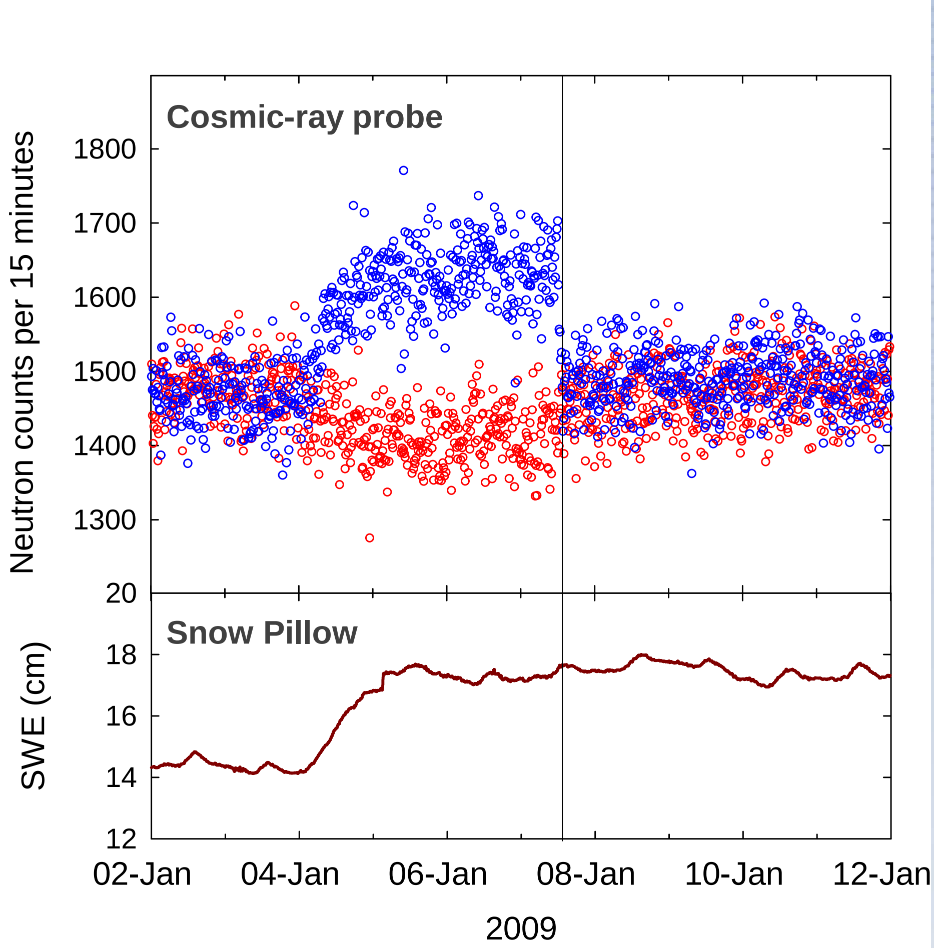
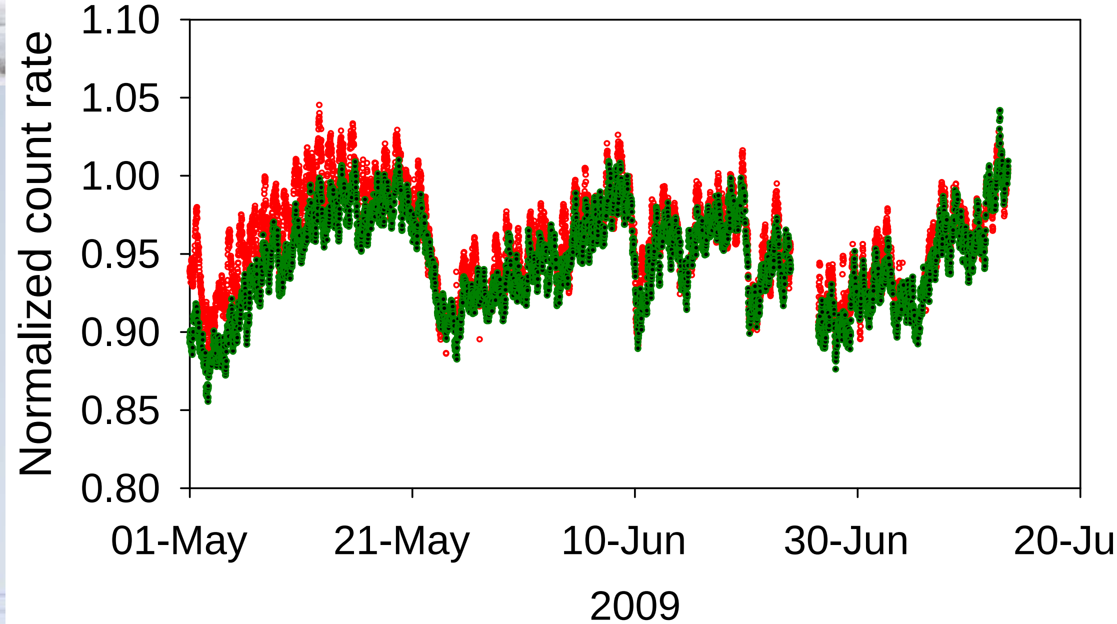
Snow on the roof

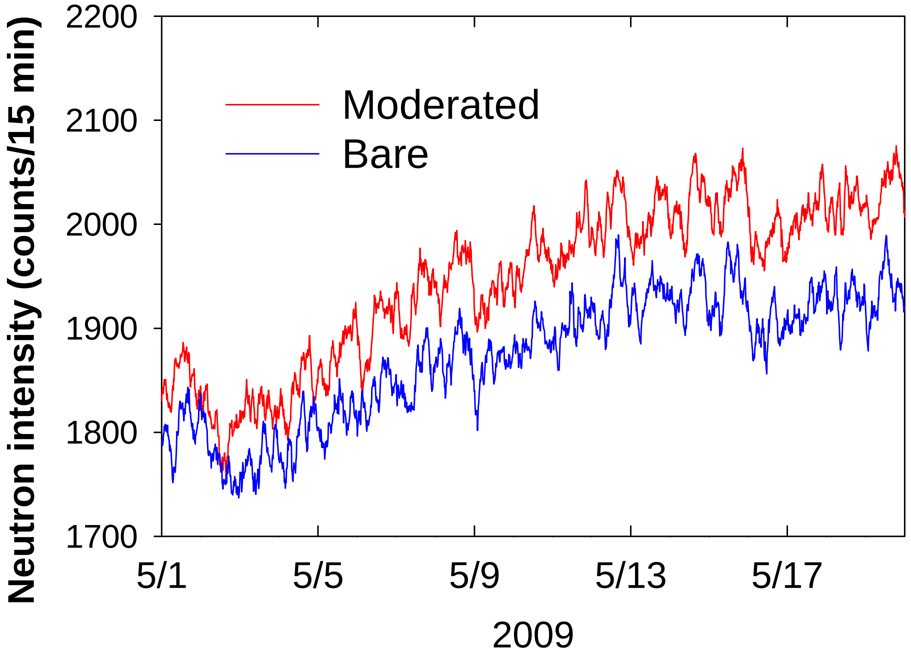


How sensitive to local effects?

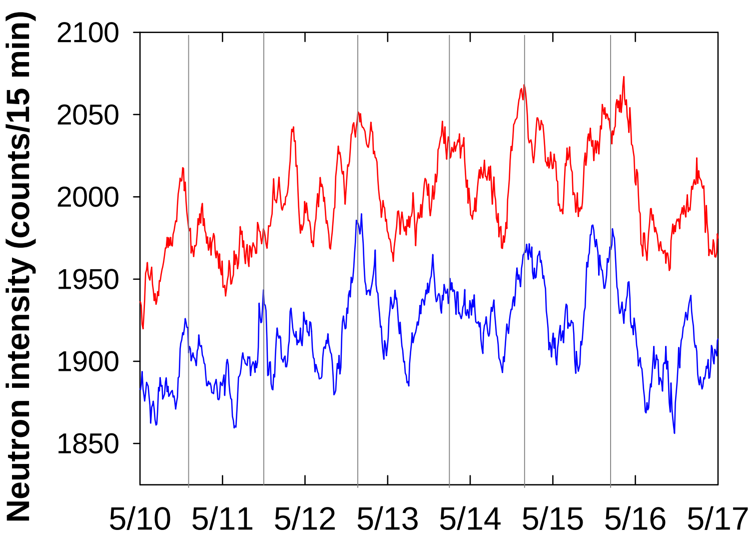
Similar responses from submerged and trailer probes



Diurnal cycle?

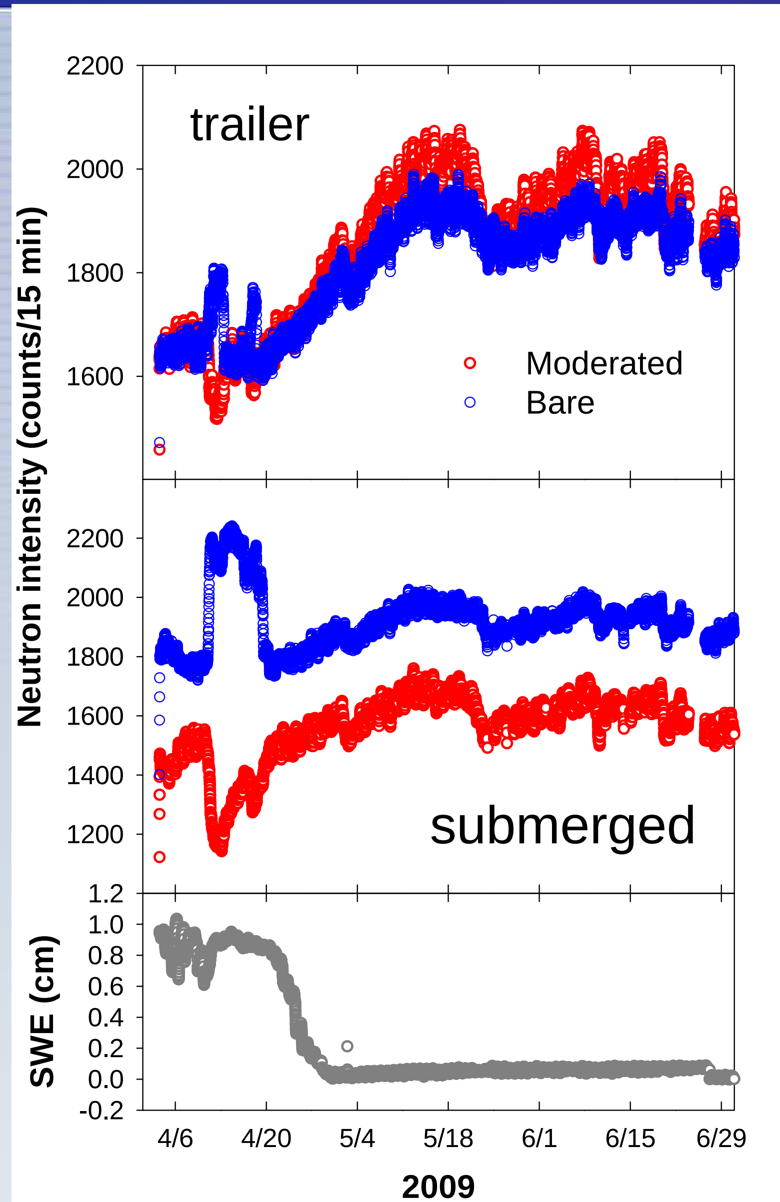


Peak neutron intensity: 1-4 pm



Spring-summer transition

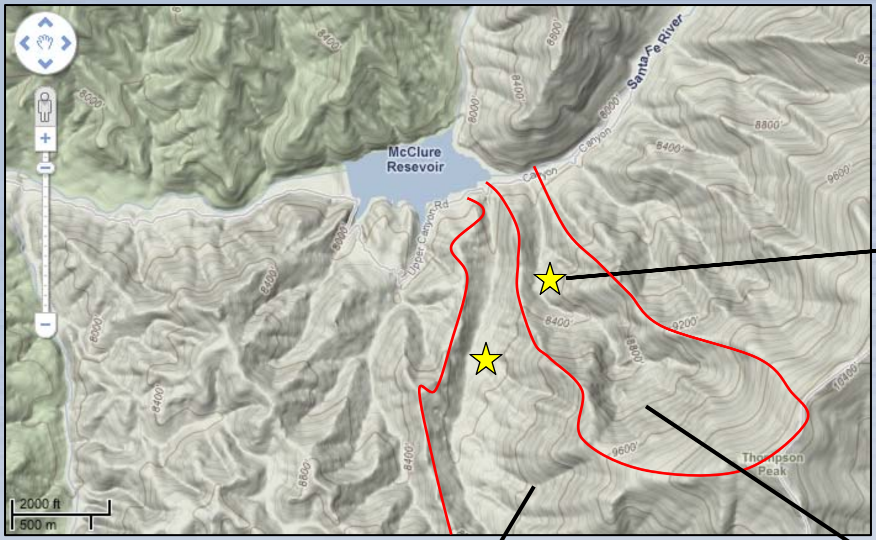
- **How do you distinguish rain events from snow?**
  - Air temperature
  - Ultrasonic depth gauge
  - Thermal neutron enhancement

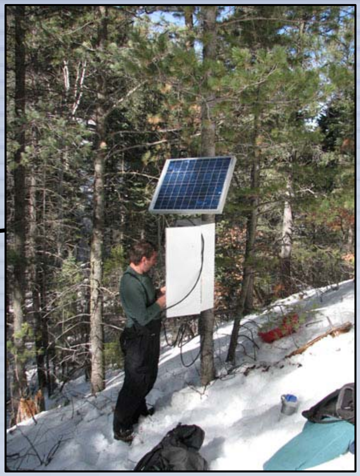


Conclusions from VCNP

- **Subaerial probe**
  - Bare counter especially sensitive to snow overhead, but…
  - Otherwise, fairly insensitive to presence of non-hydrogenous materials
- **Buried probe**
  - Excellent for point measurements of SWE
    - low cost (<$6k)
    - portable
    - easy to install
  - Bare/moderated counter setup discriminates snow from soil moisture
- **Optimal configuration for snowy environments: one buried counter (bare), one subaerial counter**
- **Next year:**
  - Does the signal saturate after 10-15 cm of SWE?
  - Will we get thermal neutron peak w/o roof effect?

Santa Fe paired basin study






Treated basin


Control basin

Measurements

Darin Desilets (Sandia):

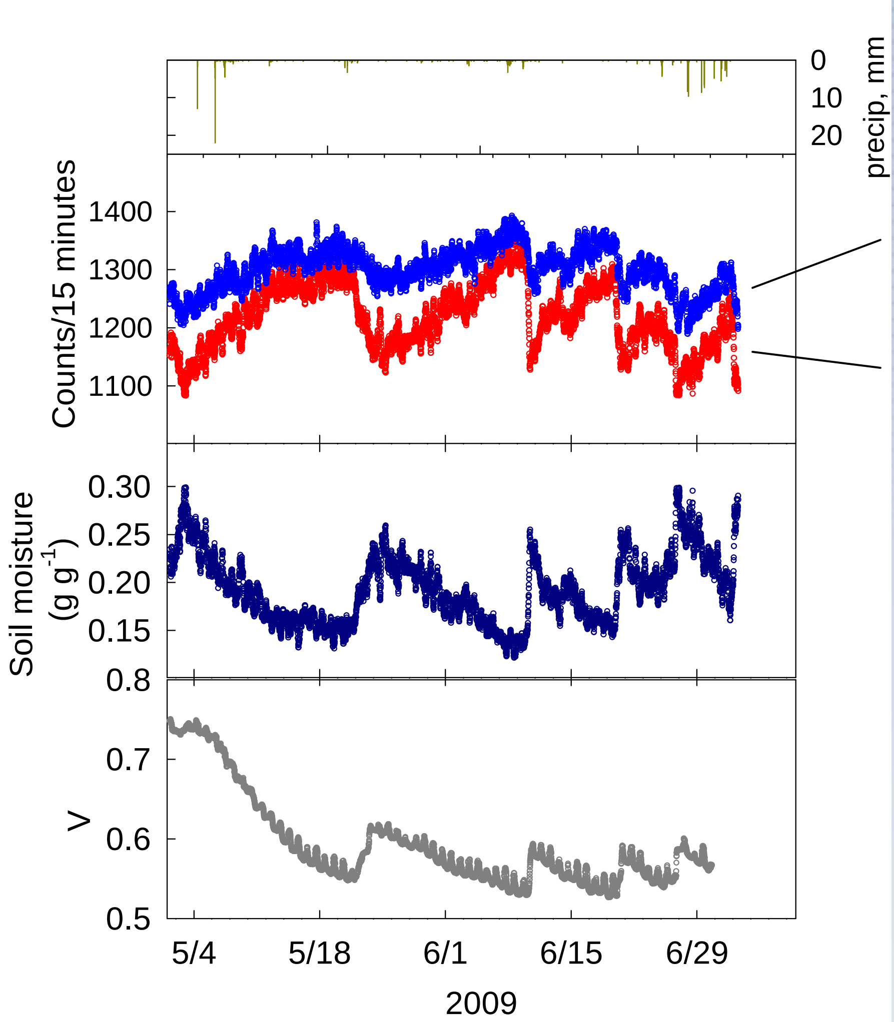
- **Moisture/snow pack with cosmic-ray probe**
- **Campaign style snow and soil moisture surveys for calibration/ground truthing**

Amy Lewis/John Kay (DBS&A):

- **Hourly discharge**
- **Daily chloride load**
- **Precipitation**
- **Stream discharge**

Also nearby: Elk Cabin SNOTEL, USDA RAWS

Santa Fe data: SF1, May-July 2009



precipitation

bare counter

moderated counter

gravimetric water content

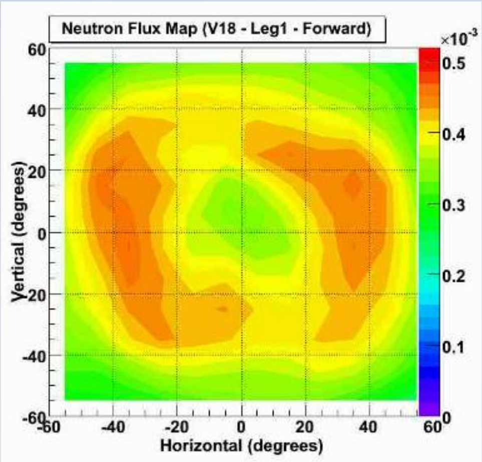
capacitance probe

The future: neutron scatter camera

- 60 degree field of view
- Ability to "image" neutron fields
- Potential to measure canopy intercepted water
- Potential for measuring soil moisture at scale of tens of meters

Nick's neutron scatter camera

TEAMS Facility, KAFB



Flux map

Permafrost and global warming

Field measurements in the arctic?

- **Facilities and contacts: DOE ARM facility (Barrow, Alaska)**
- **Technology leadership at Sandia in radiation monitoring technology**
- **New DOE priorities in climate change/carbon cycle**
- **Advanced modeling capabilities at Sandia**

Summary

- Cosmic-ray method operates at a scale covering tens of hectares
- Calibration is robust across different soil types
- Field data support the use of cosmic-ray neutrons for soil moisture and snow measurements
- Buried probes are a viable alternative to snow pillow for point measurements
- Method is ready for research applications—especially those where dynamics are important
- Other neutron detection methods will open new possibilities