The Use of Radar Methods to Determine Moisture Content in the Vadose Zone

Rosemary Knight, James Irving, Stephen Moysey, Paulette Tercier[1], Jonathan Franklin

Geophysics Department
Stanford University

[1]Department of Earth and Ocean Sciences
University of British Columbia

Link to Hanford needs:
An accurate map is needed of the 3D distribution of moisture content.

This is required in order to model/predict the fate and transport of subsurface contaminants.

The focus of our research:
Use surface and subsurface radar methods to extract the required information about variation in moisture content θ_w.

Two approaches for vadose zone characterization with radar:

Approach #1:

radar image → "map" of κ → map of θ_w

i) use radar data to obtain estimates of dielectric constant κ at specific locations

ii) use petrophysical relationships to transform κ -values to θ_w-values

iii) provide estimates of θ_w and estimates of uncertainty in θ_w

<u>The error/uncertainty in information obtained from geophysical data must be incorporated in the "answers" we provide.</u>

Approach #2:
spatial heterogeneity in radar image → spatial heterogeneity in θ_w

- work directly with the radar image to extract information about the correlation structure of θ_w in the subsurface

Research Results and Hanford Challenges

Research Result #1:

- have developed effective method for improving the quality of radar images obtained from surface-based radar measurements: inverse Q filtering

Improving the Radar Image

Frequency-dependent attenuation causes significant wavelet dispersion.

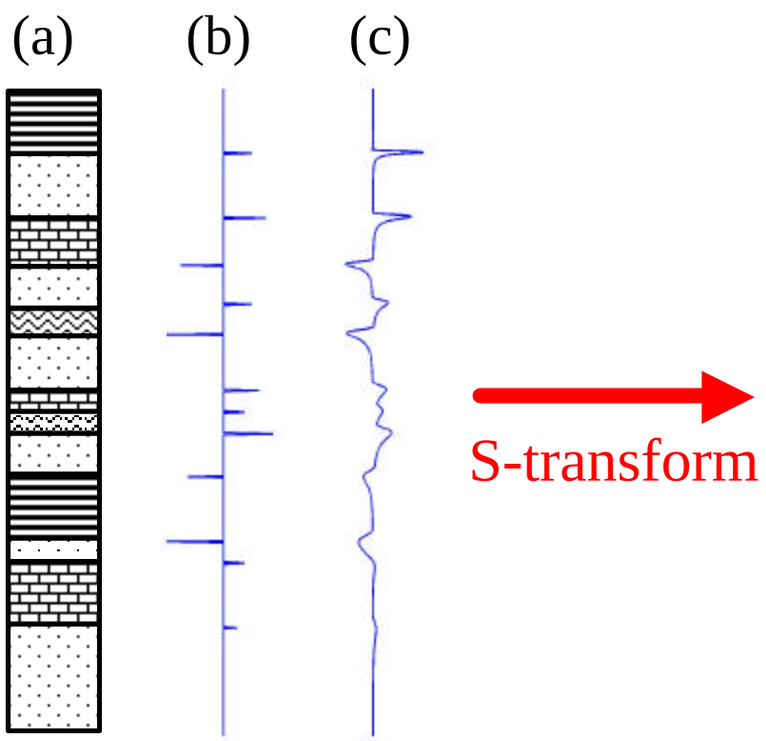
In the GPR image, this appears as a blurry-ness that increases with depth.

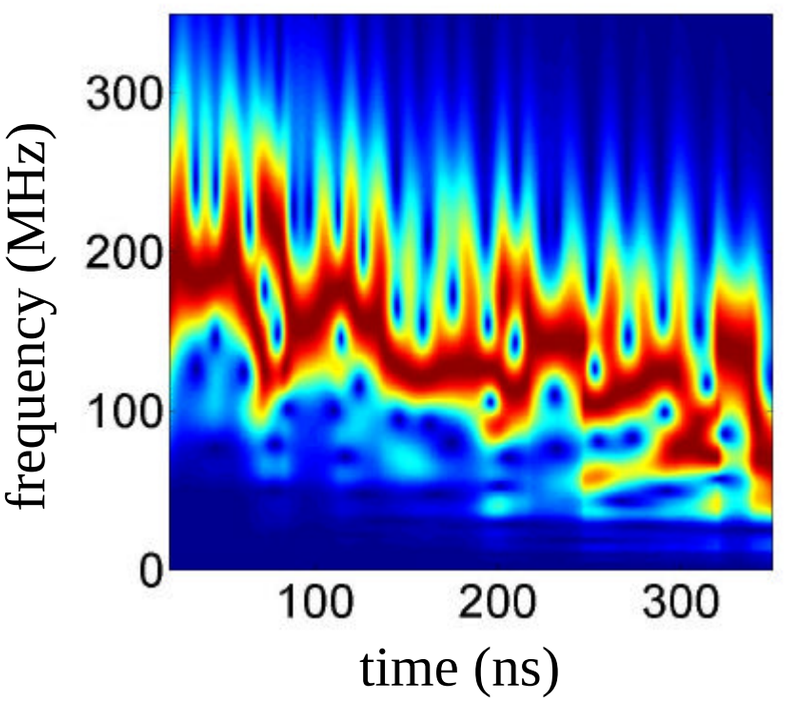
- prevents accurate qualitative interpretation and inversion

our research: correcting for frequency-dependent attenuation

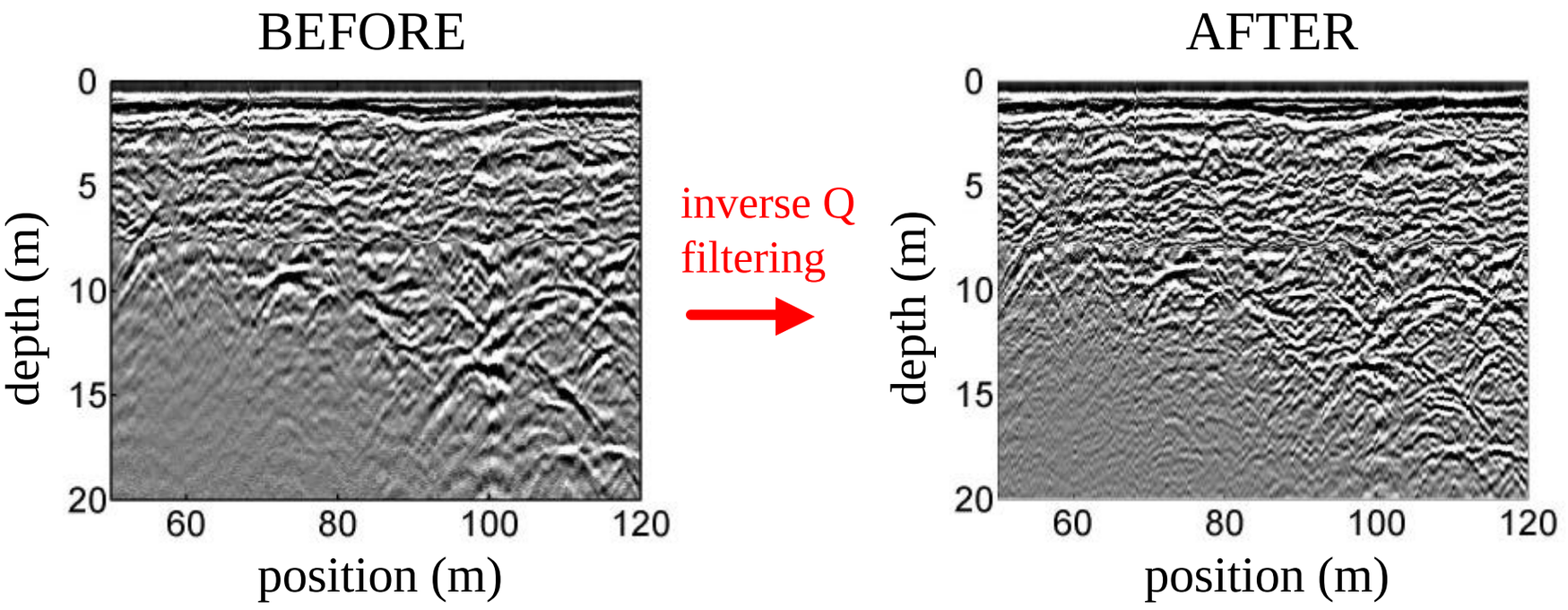
(a) geological sequence
(b) reflectivity series
(c) with frequency-dependent attenuation, Q = 30

- S-transform (hybrid between wavelet and short-time Fourier transforms) is used to examine frequency content of GPR signal with time
- downshift in dominant frequency of signal is used to estimate Q, a measure of frequency-dependent attenuation in the earth





- once Q has been determined, wavelet dispersion is corrected for by inverse Q filtering the GPR data
- resulting GPR image is sharp, and of significantly higher resolution than the original



The challenge at Hanford:

-poor quality of surface radar data, for high resolution imaging

Surface data can be useful in areas where top few meters has been excavated.

Surface data are useful for locating clastic dikes.

To Do 2001/2:

- focus on alternate ways of acquiring radar images
-investigate reflection imaging with borehole radar.

<u>Research Result #2</u>:

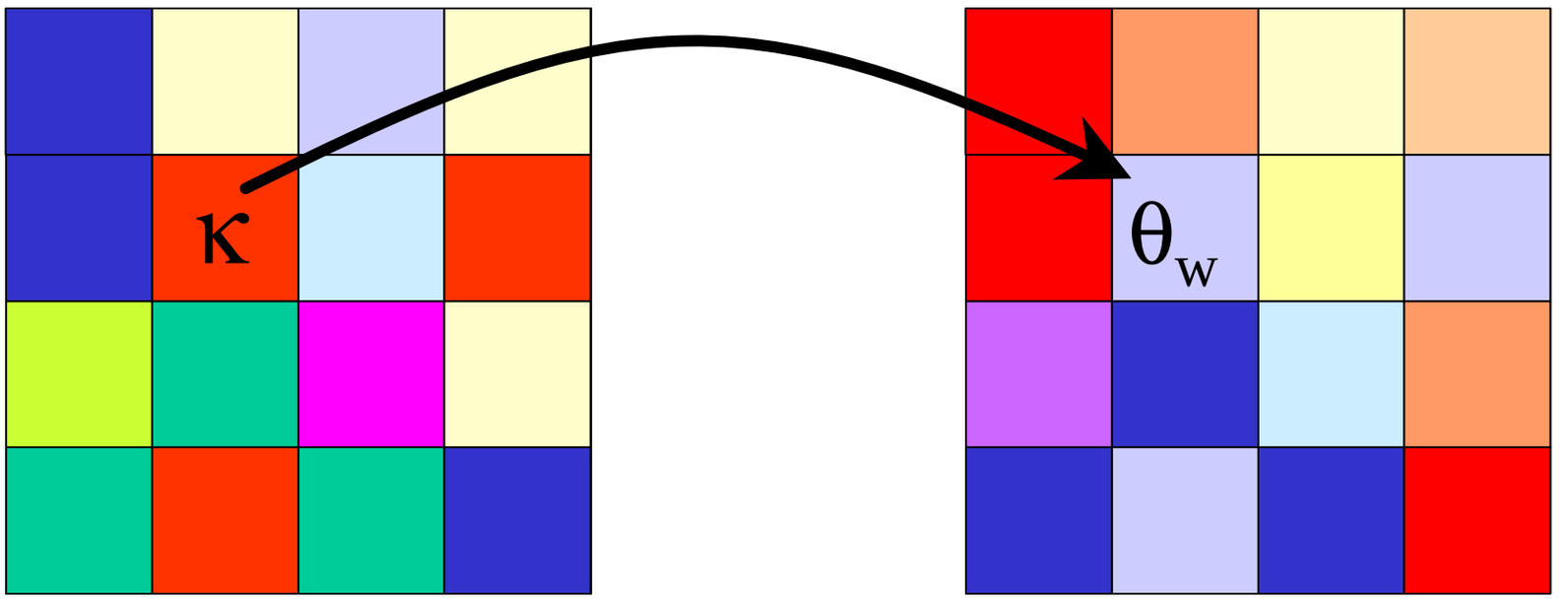
Approach #1:

radar image → "map" of κ → map of θ_w

- have developed a framework for quantifying error and uncertainty in θ_w estimates

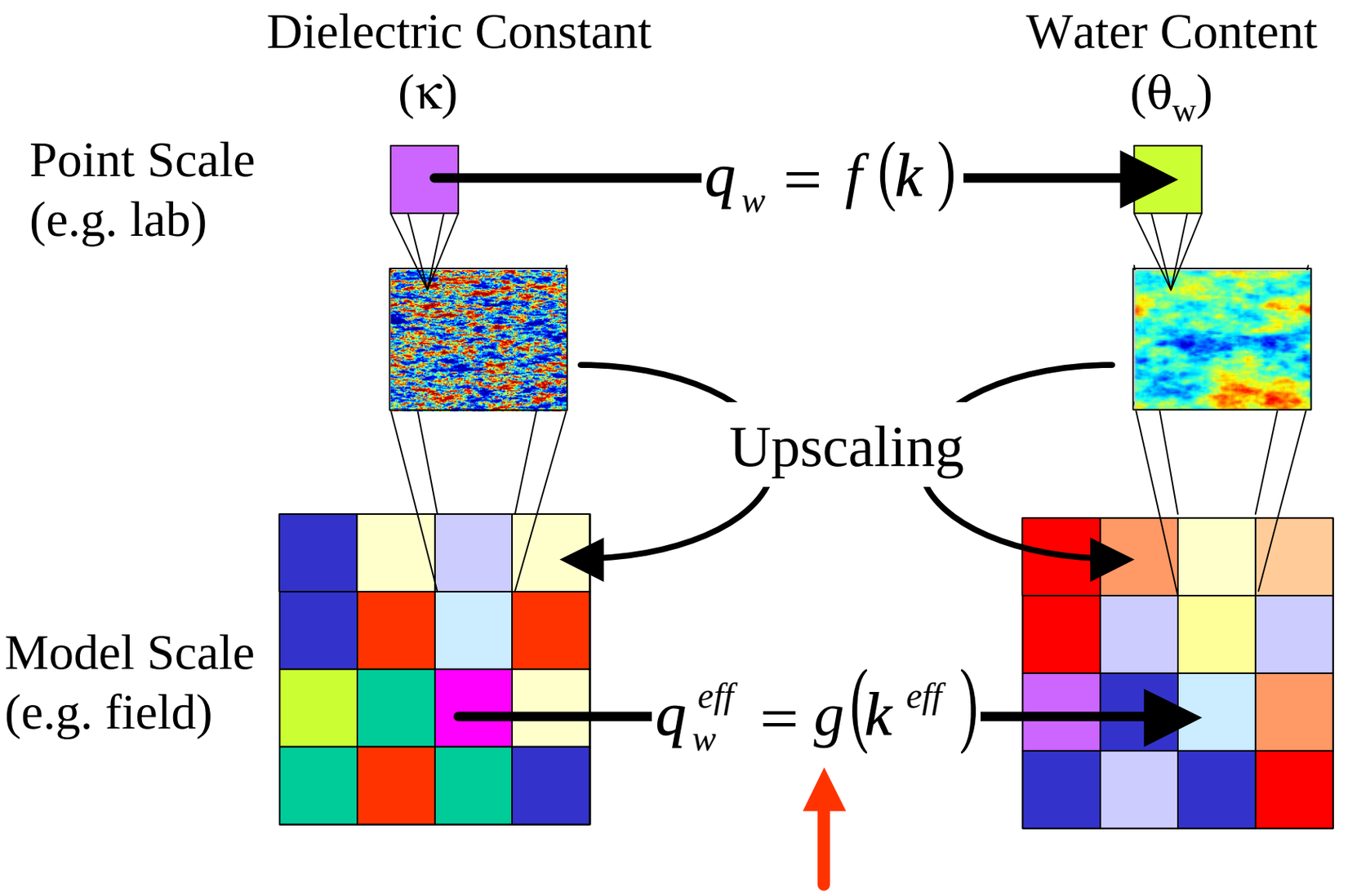
-can be used with surface or borehole radar data

Wanted: water content from field scale dielectric measurements



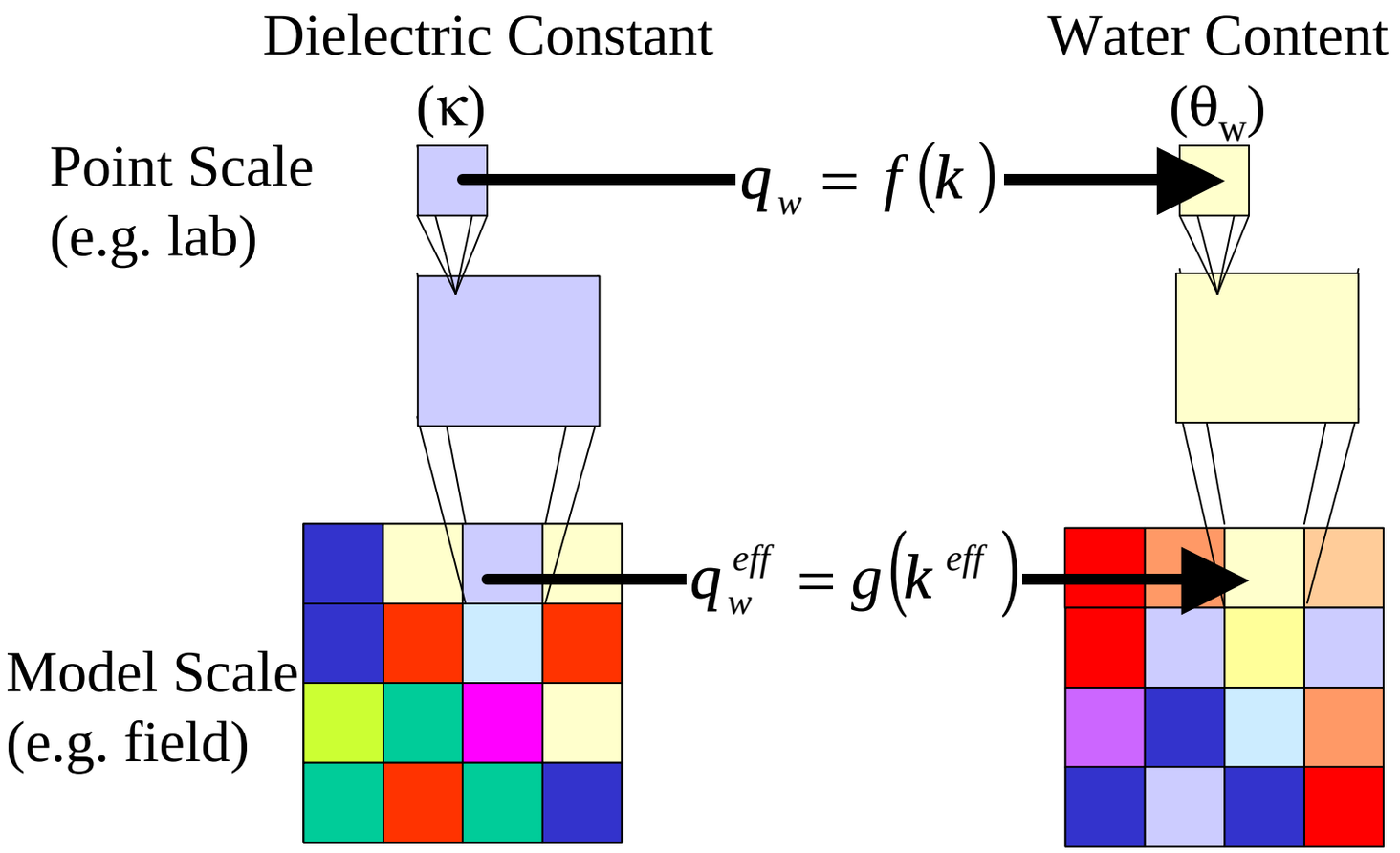
What is error/uncertainty in θ_w?

Uncertainty in q_w leads to uncertainty in predicted contaminant transport rates.



Can we substitute f(k) for g(k) ???

Case 1: Homogeneous & Isotropic

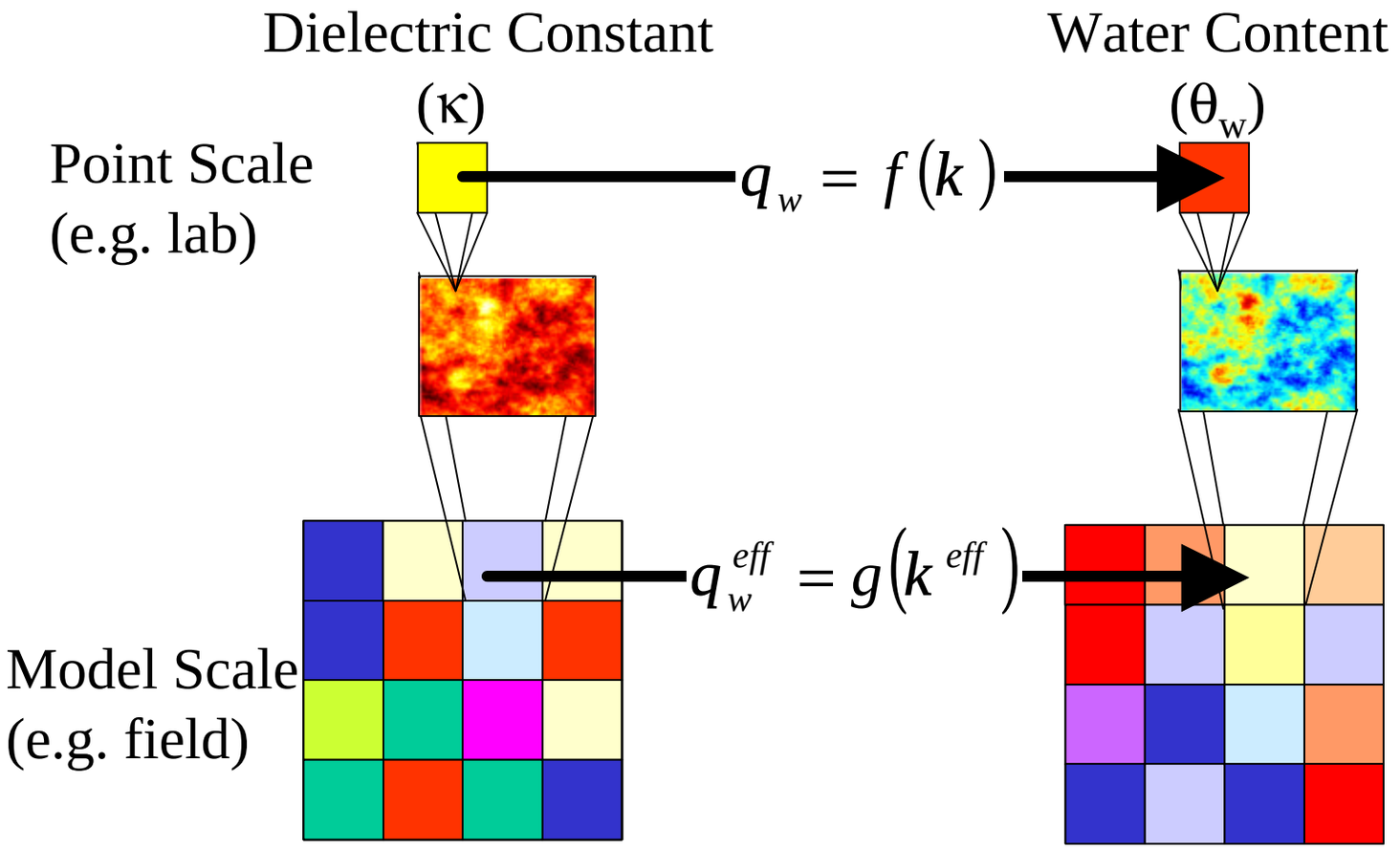


In this case, no error in water content because g=f :

$$q_{w_i} = f(k_i) = g(k^{eff}) = q_w^{eff}$$

$$error = e = q_w^{eff} - \hat{q}_w^{eff} = 0$$

Case 2: Heterogeneous & Isotropic



In this case, if we assume g=f :

$$e = q_w^{eff} - \hat{q}_w^{eff} = q_w^{eff} - f(k^{eff})$$

Key question: Can f be upscaled?

Case 2: Heterogeneous & Isotropic

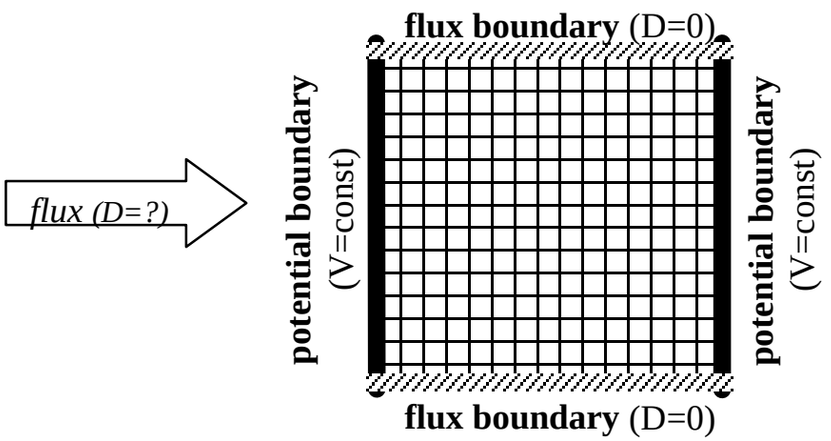
Numerical Modeling to Investigate Upscaling:

- *100 realizations for each modeled system*

water content: arithmetic average

dielectric constant:

$$\nabla \cdot \left(k \nabla V \right) = 0$$

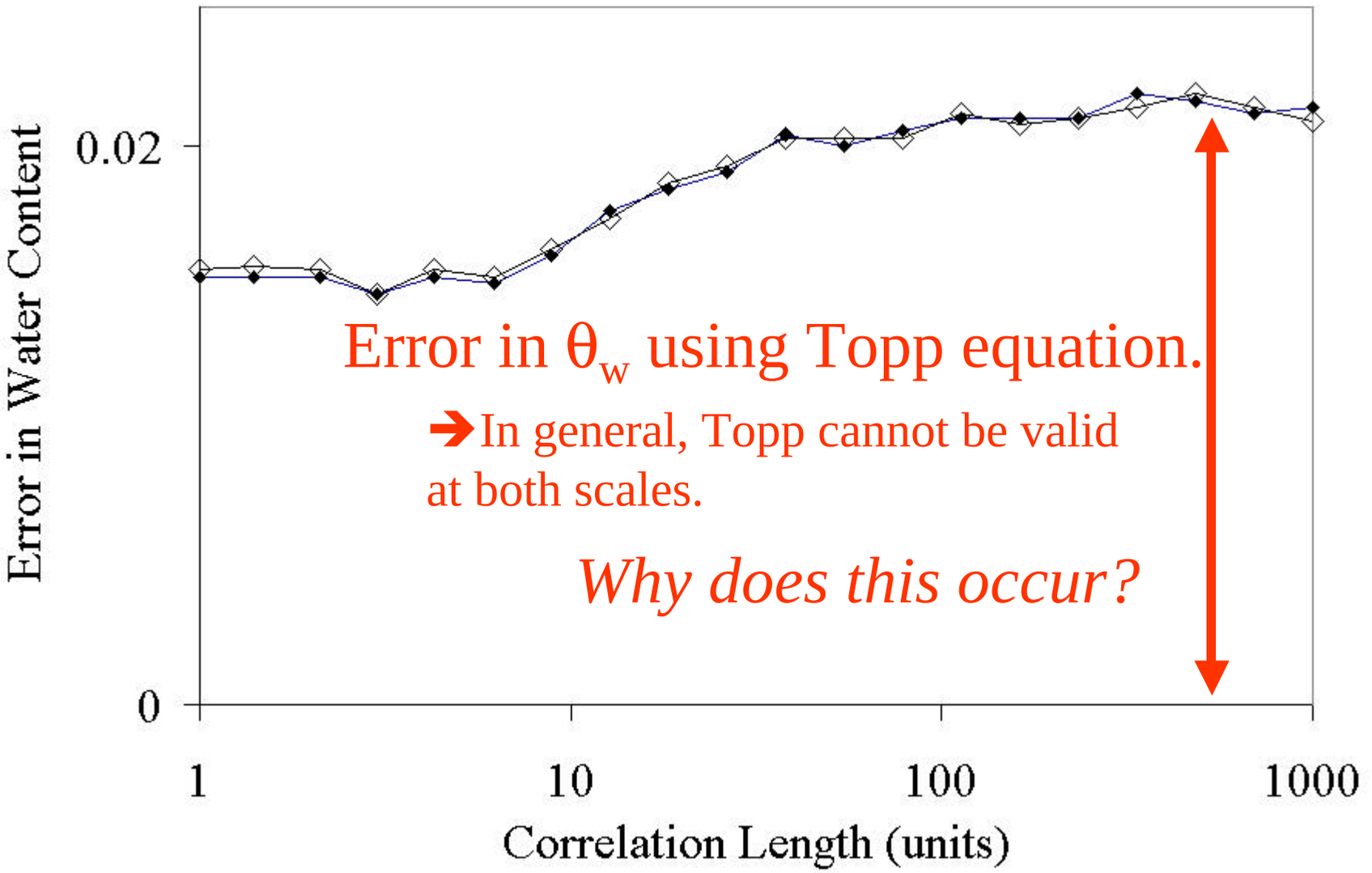


$$k_{eff} = \frac{D}{\Delta V}$$

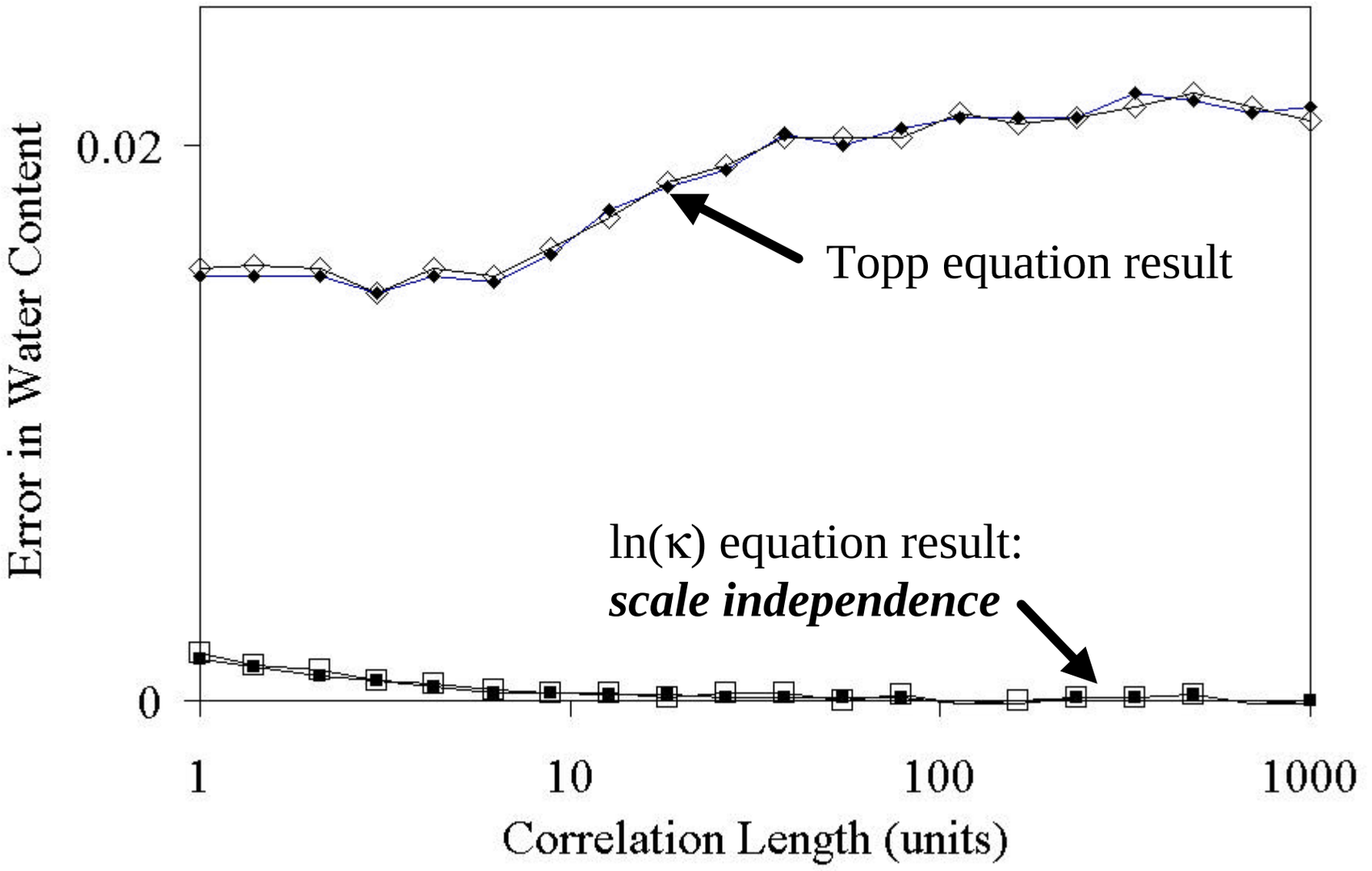
D = displacement current

ΔV = voltage difference

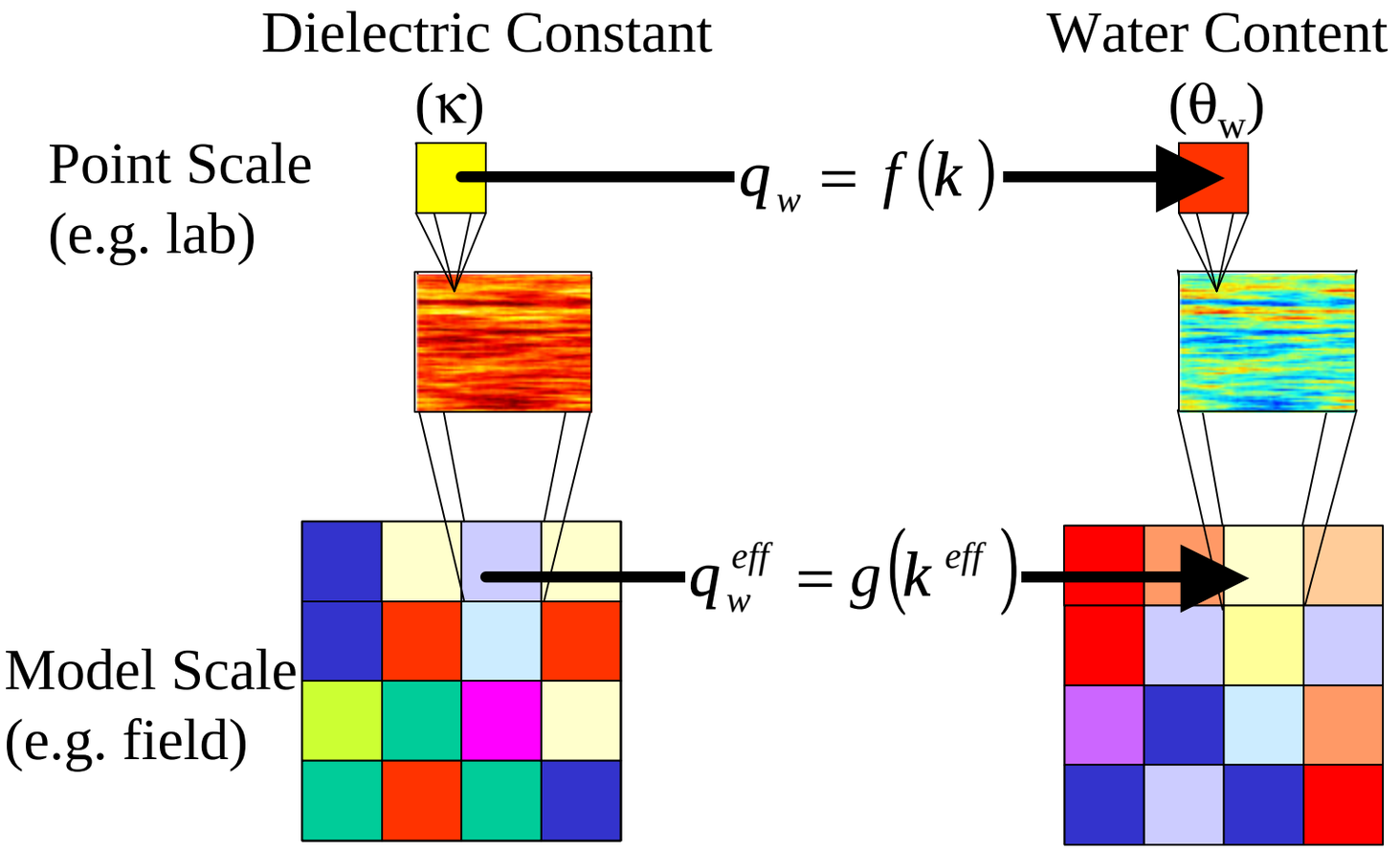
Case 2: Heterogeneous & Isotropic



Case 2: Heterogeneous & Isotropic



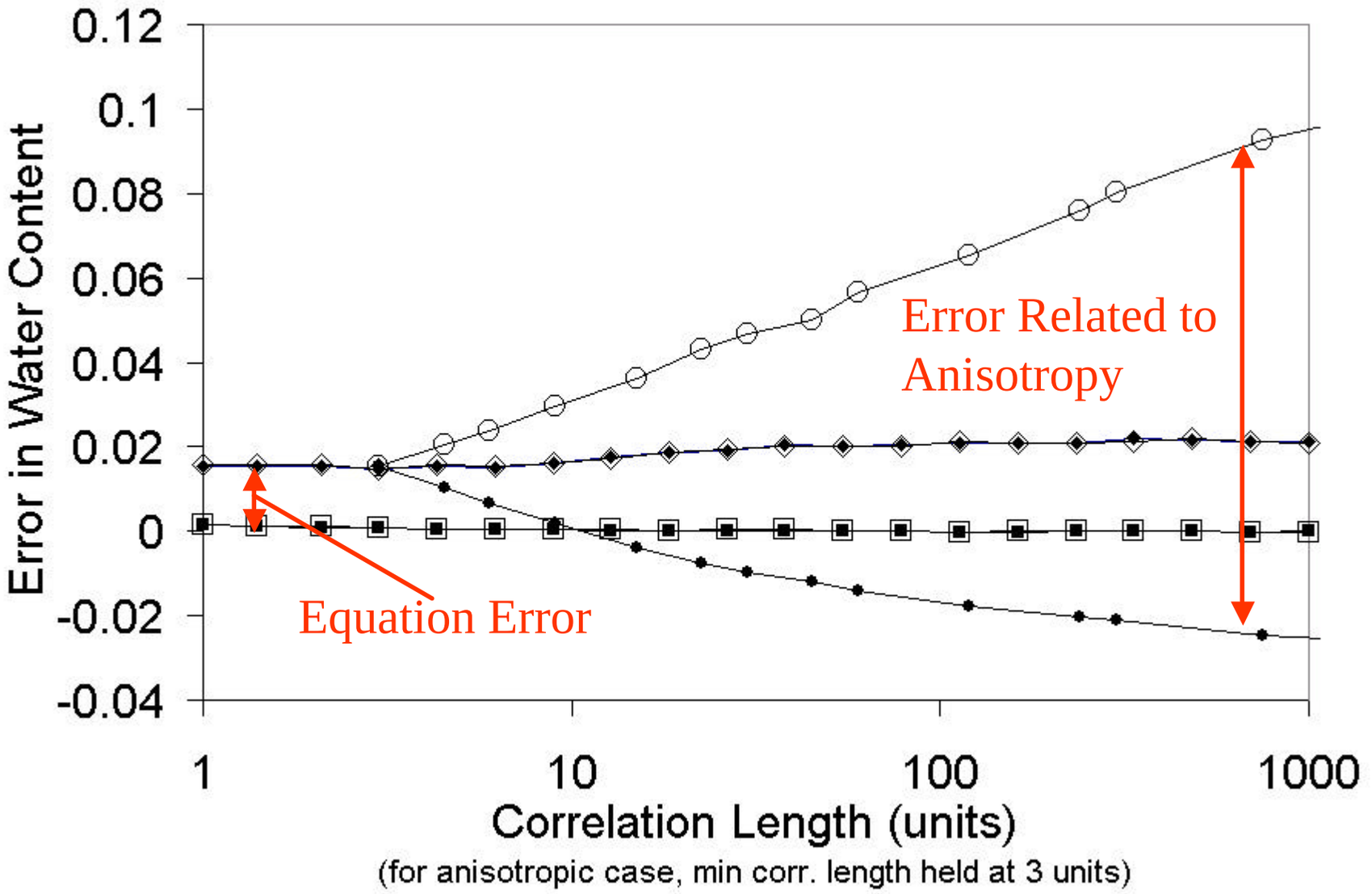
Case 3: Heterogeneous & Anisotropic



Calculate error in q_w^{eff} when we assume g=f :

$$e = q_w^{eff} - \hat{q}_w^{eff} = q_w^{eff} - f\left(k^{eff}\right)$$

Case 3: Heterogeneous & Anisotropic



The challenge at Hanford:

How best to acquire radar/dielectric images from Hanford?
borehole? cone-based?

To do: planned for completion 2002

Conceptual design of data acquisition system to better constrain dielectric anisotropy.

Apply methodology for error estimation to an example from Hanford assuming use of borehole or cone-based radar.

Expand study of uncertainty to cases of large-scale heterogeneity (non-effective media).

Research Result #3

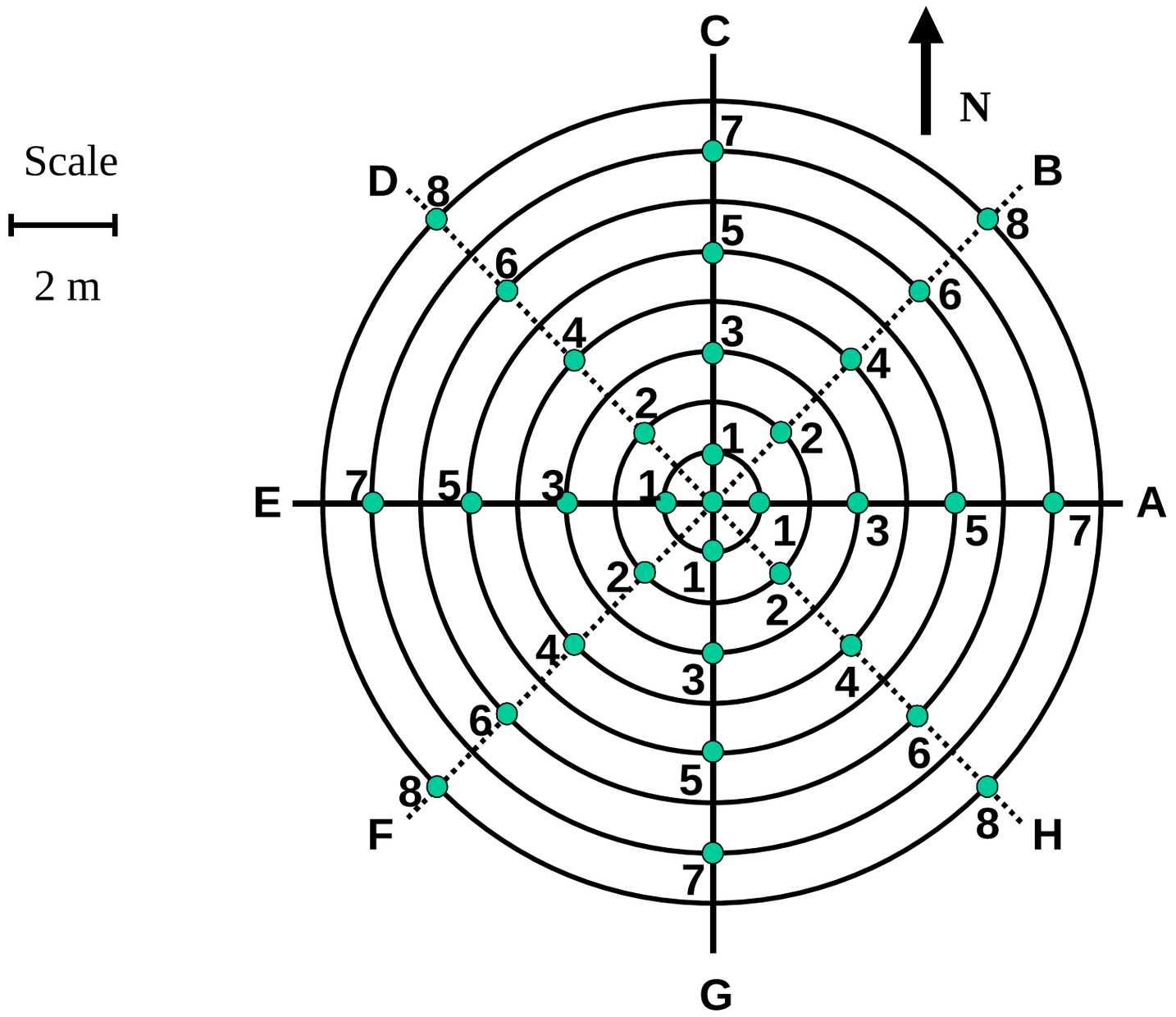
Approach #2:

spatial heterogeneity in radar image → spatial heterogeneity in θ_w

have developed/used geostatistical framework for analysis of radar images (Rea and Knight, WRR, 1998)

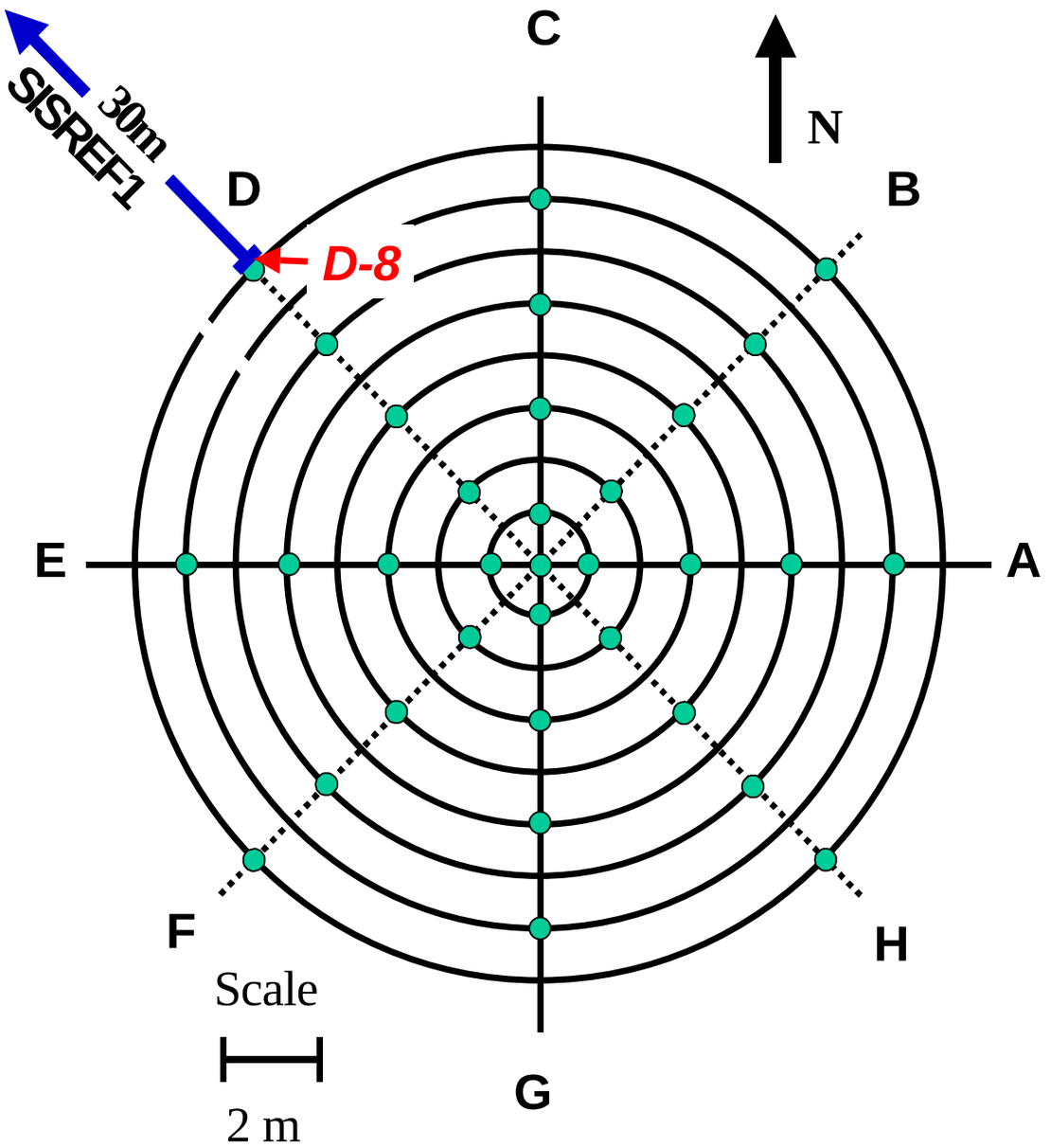
-Hanford: have found very good agreement between variogram for θ_w obtained from neutron probe data and variogram obtained from surface-based radar image

Sisson and Lu - Well Locations

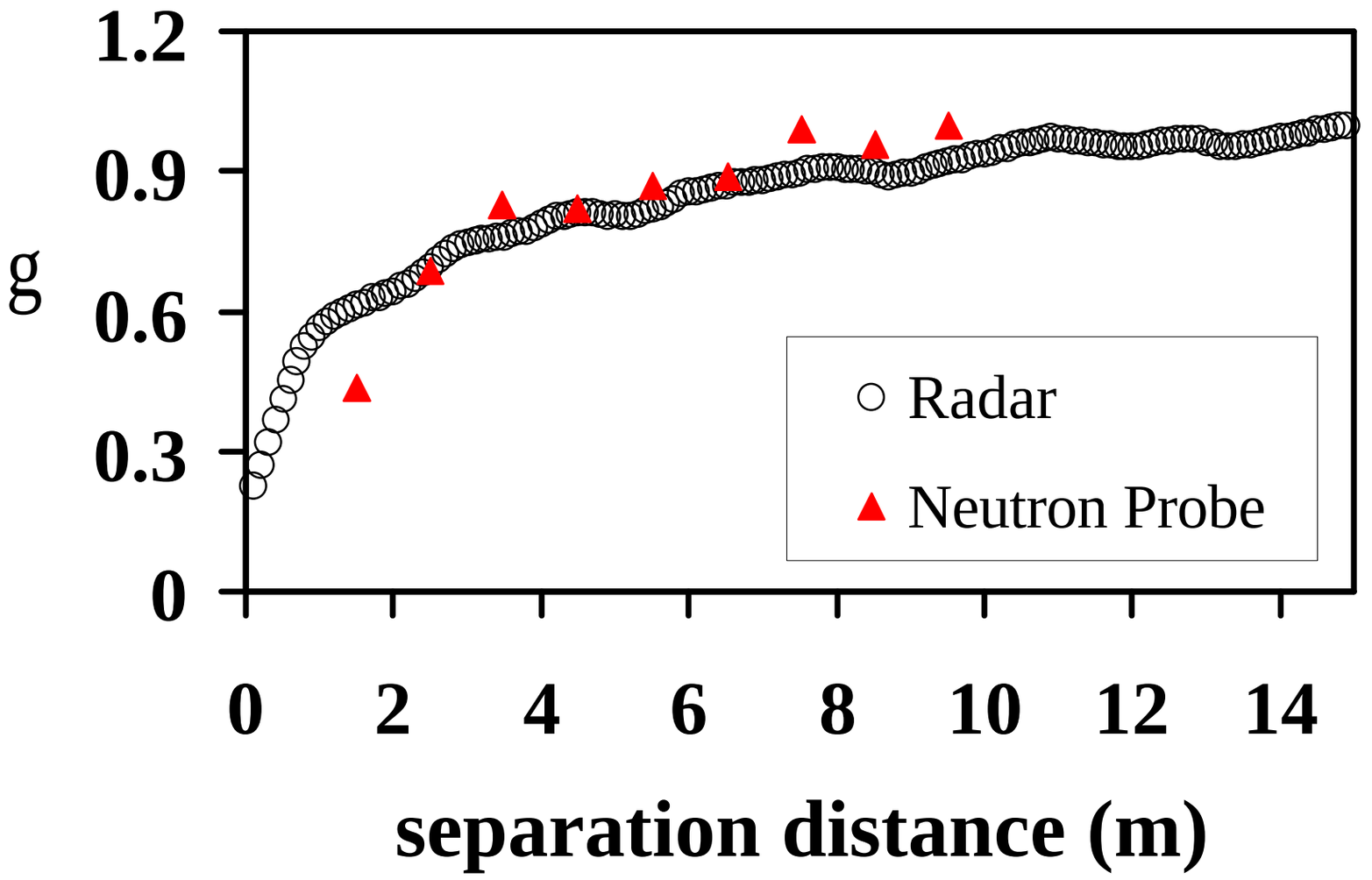


neutron probe data collected in all wells to a depth of 20m

Sisson and Lu - GPR Line



Semivariogram for radar data and neutron probe



The challenge at Hanford:

Surface radar data can only image top ~10m.

To Do: planned for completion 2002

How can information from the top 10m be used?

Can this geostatistical method be used with borehole radar images?

Other Ongoing Research - planned for completion 2002

Approach #2:
spatial heterogeneity in radar image → spatial heterogeneity in θ_w

We need a fundamental understanding of the link between the heterogeneity of the subsurface and that captured in the radar image.

i) Numerical Modeling
ii) Cliff-face Studies

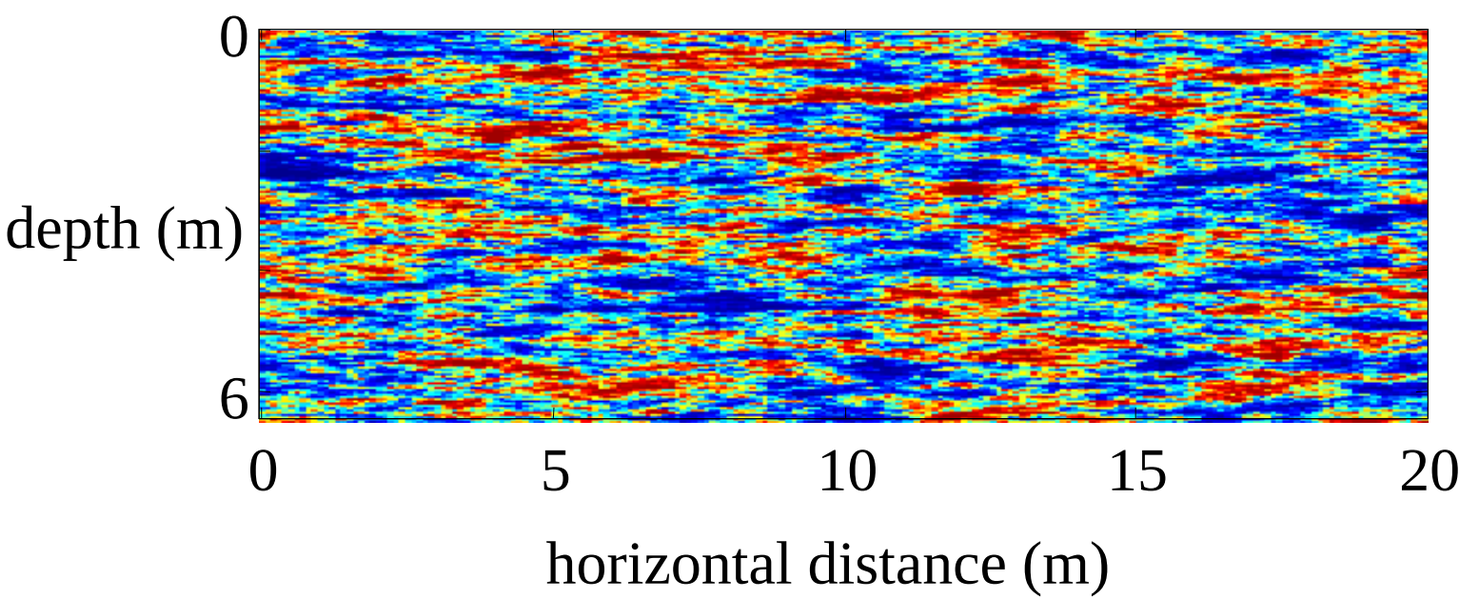
i) Numerical Modeling

generated a model of water content distribution

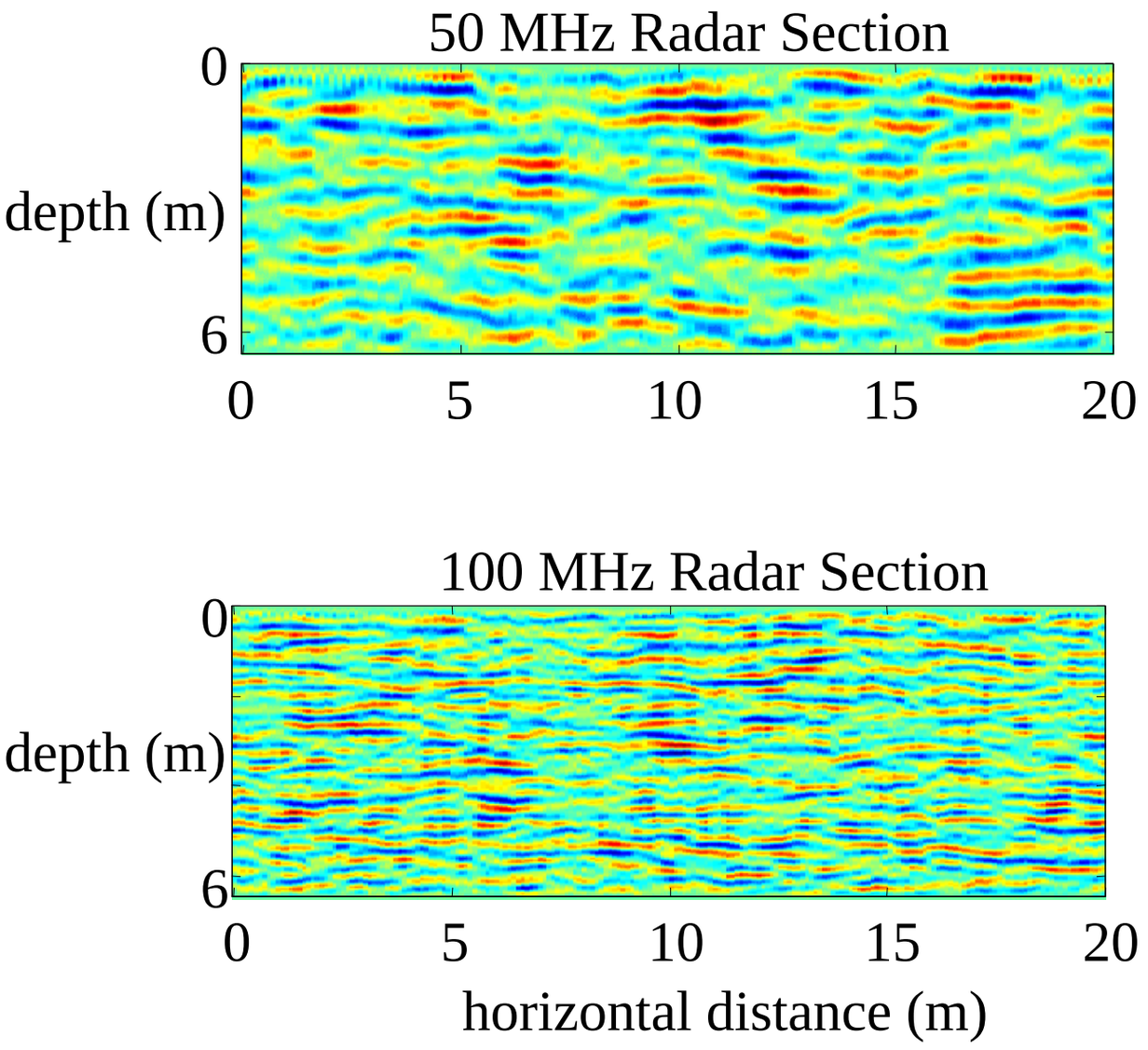
$0.029 < \theta_w < 0.346$

correlation structure: vertical range = 0.21m
horizontal range = 2 m

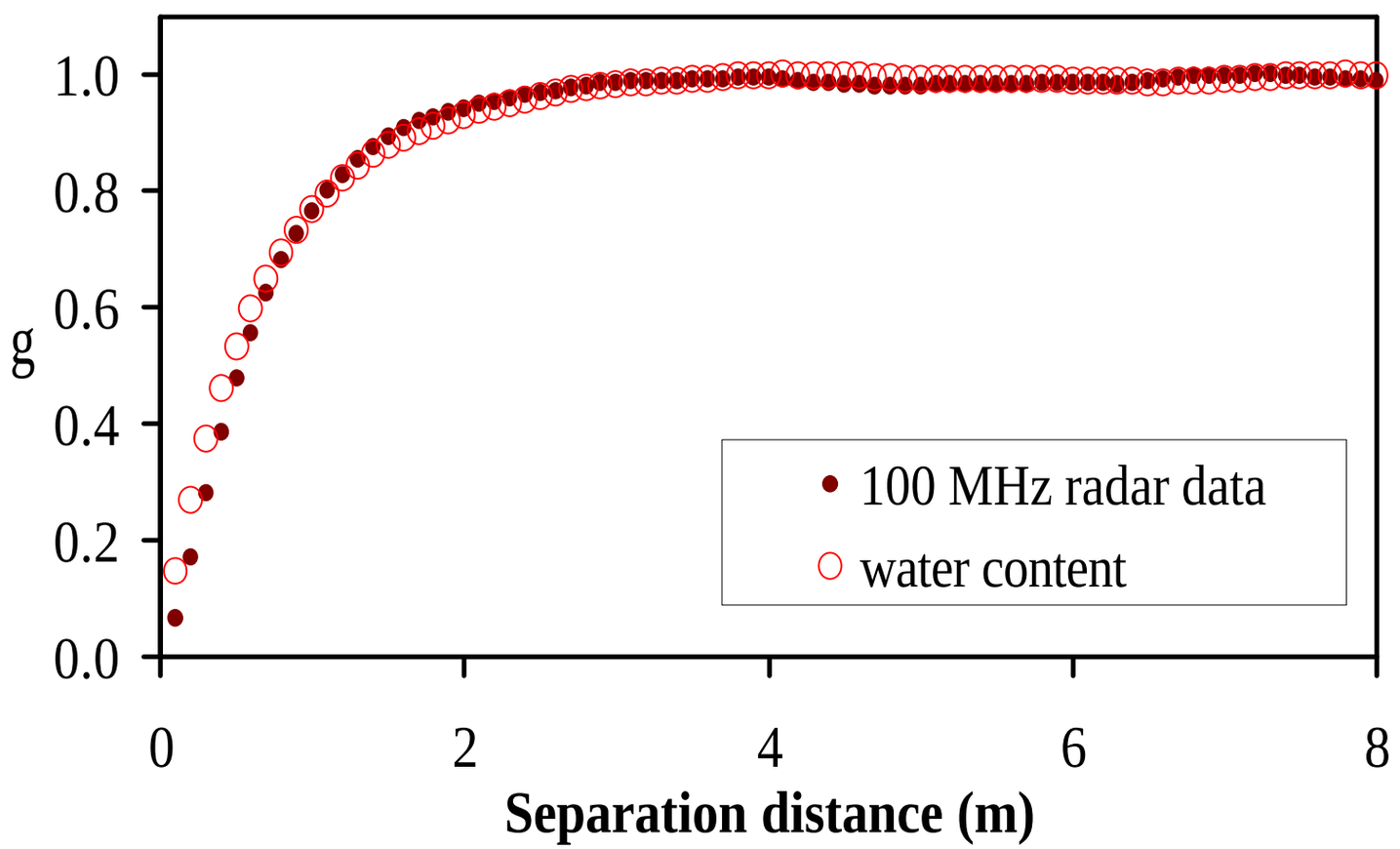
Subsurface Model of Water Content



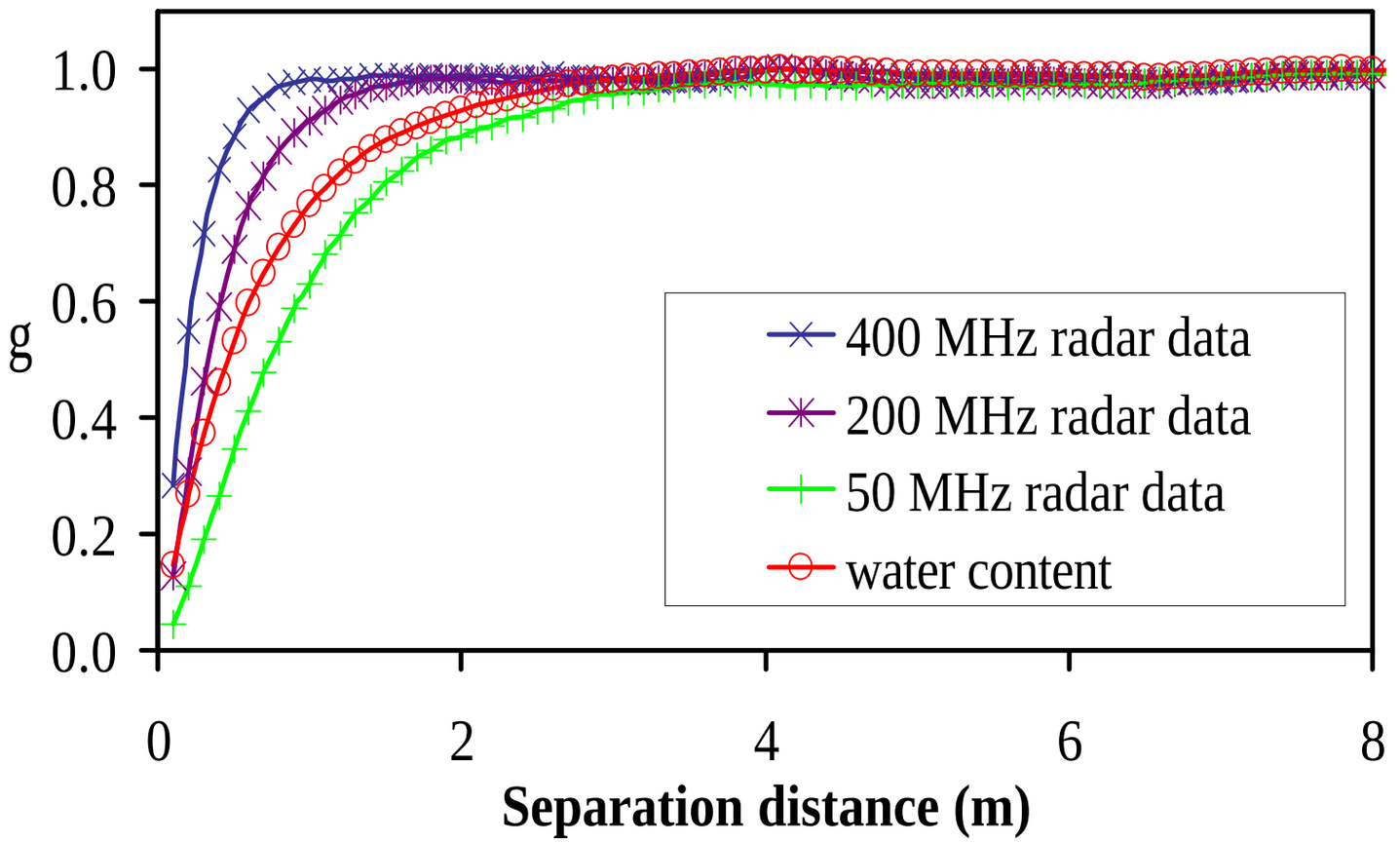
1-D convolutional model used to generate corresponding radar sections



Comparison of horizontal variogram for water content and 100 MHz radar data

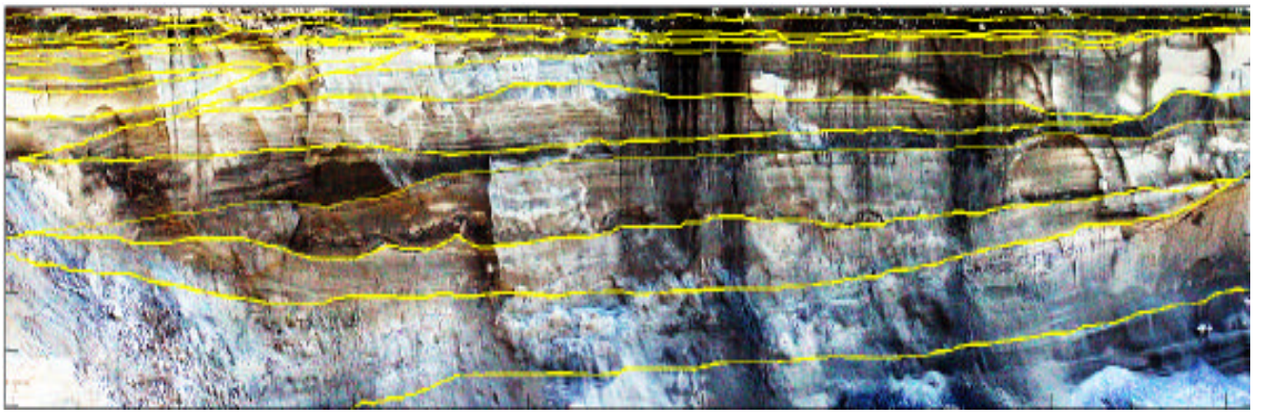


Comparison of horizontal variogram for water content and radar data

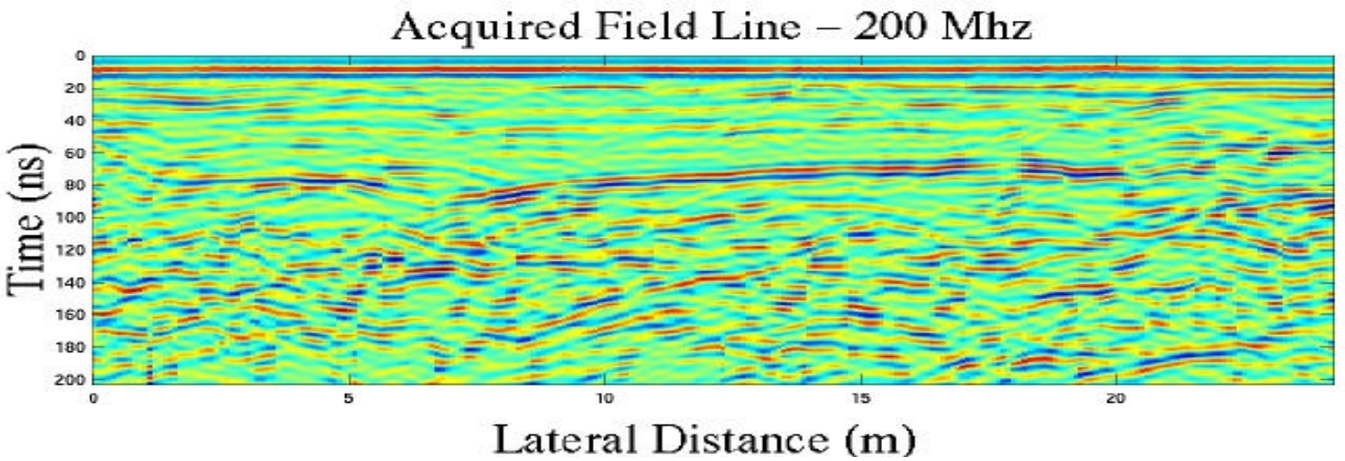


ii) Cliff-face studies

25 m



Photograph



Radar Section

GPR Modeling Package:

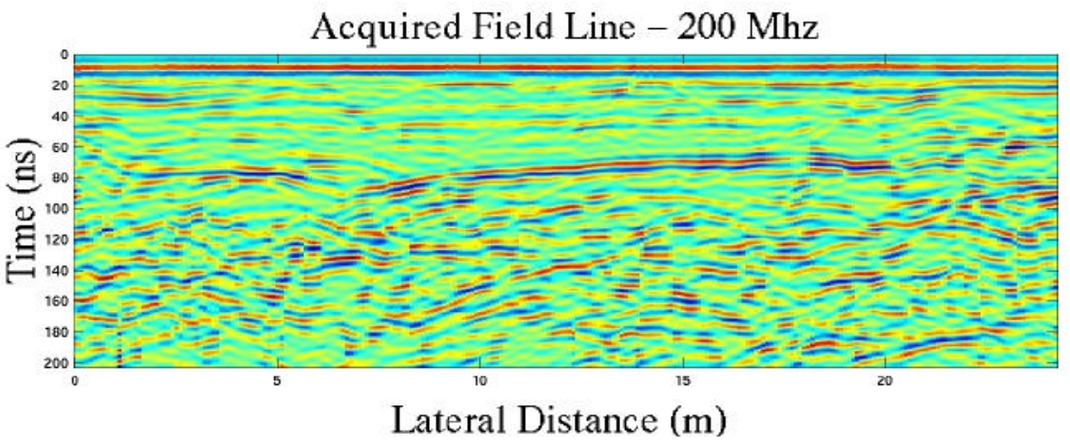
-generates a full-wavefield radar image assuming a line source, and pure TE-mode wave propagation

-equations solved in the time-domain on a shot-by-shot basis using either finite difference or pseudo-spectral methods

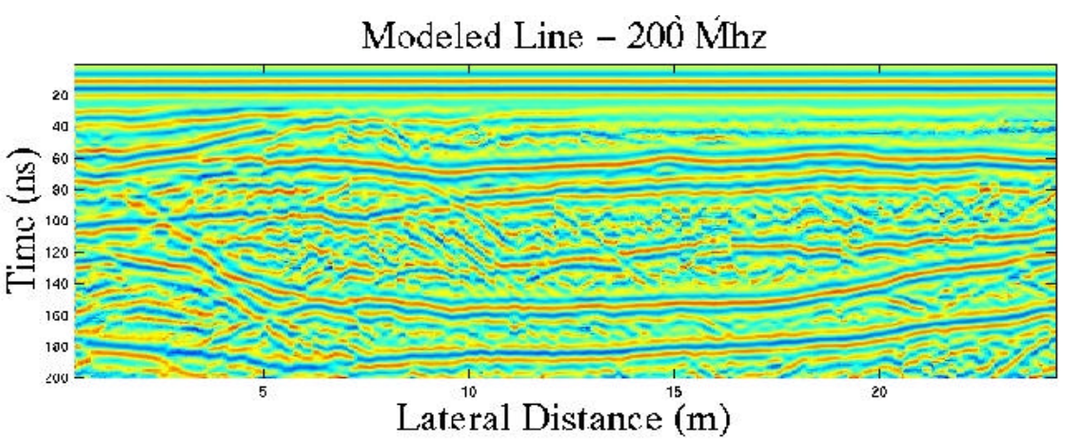
-includes only conductive losses

-also capable of plane wave, exploding reflector and sequential 1D modeling

Comparison of acquired and modeled 200 MHz radar section:



Acquired 200 MHz radar section



Modeled 200 MHz zero-offset radar section

Conclusions:

Our objective:

Use surface and subsurface radar methods to extract the required information about variation in moisture content θ_w.

Completed Research:

- improved clarity of surface radar images
- framework for quantifying uncertainty in θ_w
- comparison of variogram from neutron probe data and radar data for θ_w estimates at Hanford

Hanford Challenge:

Acquiring high quality radar images

Ongoing Research:

- extension of error/uncertainty estimates - with Hanford example
- borehole or cone-based imaging
- the fundamental link between the radar image and subsurface properties