Using Distributed Temperature Sensing (DTS) to Assess Soil Moisture In Agricultural Settings

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安装光纤电缆在内华达州梅森谷附近的替代农业田地里。
Outline

I. Introduction and Motivation

II. Theory and Thermal Model

III. Methods for measuring soil moisture

  • Remote Sensing: Plane, Satellite
  • Ground-based: Geophysical, Probe
  • DTS Active or Passive

IV. Field application: Walker Basin, NV

  • Passive DTS vs. Thermal Diffusivity
  • Thermal Diffusivity vs. soil moisture

IV. Conclusions and Future Direction
Soil Moisture

- Near surface water and energy balance
- Evapotranspiration, climate modeling
- Agricultural water management
- Landfill Engineering
- Nutrient/ contaminant transport
- Nuclear repository engineering
- Efficacy of Geophysical methods
III. Methods for Estimating Soil Moisture

Methods for measuring soil moisture

• Remote Sensing: active and passive microwave, electromagnetic resistivity
• Ground-based: Geophysical, Heat dissipation probe (HDPs)
  ➤ Typically limited to top few mm of depth (remote sensing)
  ➤ or limited to point measurements in space (hand probes)
• Thermal methods: Active or Passive DTS
  ➔ GOAL: Develop an integrated, near surface method for assessing soil moisture over large areas that is detailed in time
Heat in the Subsurface

- Surface
- Depth 1
- Depth 2

Temperature vs. Time Graph:
- Surface line
- Depth 1 line
- Depth 2 line

- Amplitude reduction
- Phase shift
II. Soil Thermal Regime

1D Heat Transfer (Conduction):

\[ \frac{\partial T}{\partial t} = K_T \frac{\partial^2 T}{\partial z^2} \]

Solution:

\[ T(z, t) = T_A + A \exp \left( \frac{z}{d} \right) \sin \left( \omega t + \phi + \frac{z}{d} \right) \]

Phase shift:

\[ \Delta t = \frac{z}{\omega d} \]

Damping depth:

\[ d = \sqrt{\frac{2K_T}{\omega}} \]

Thermal Diffusivity:

\[ K_T = \frac{\lambda}{\rho c} \]

Jury and Horton, 2004, 6th Ed.
Thermal Diffusivity $K_T$

Water Content 0.3  0.4  0.5  0.6

36.0
28.8
21.6
14.4
7.2

Sand n=0.4
Sand n=0.6
Clay n=0.6
Peat n=0.9

Jury and Horton, 2004, 6th Ed.
Distributed Temperature Sensing

Rayleigh Scattering

Stokes \(\rightarrow\) Raman (Stokes) \(\rightarrow\) Brillouin in frequency

Brillouin in amplitude

Anti-Stokes \(\rightarrow\) Raman (Anti-Stokes)

Amplitude/Intensity

Tyler, et al., J Glaciology, 2008
Ongoing DTS Soil Moisture Studies

**ACTIVE:**
- Apply a heat pulse, and measure $T(t)$
  (analogous to HDP, e.g. Mori et al. 2003, Ren et al., 2003)
- Provides more certainty in values than passive.
- Oregon State University (Selker),
  Lawrence Berkeley National Laboratory (Freifeld)

**PASSIVE:**
- Use natural thermal cycles for heat signal (e.g. Horton et al. 1983)
- Easier to calibrate, operate and maintain.
- UNR, OSU, Univ. of Delft (Van de Geisen)

- DTS systems may yield thermal diffusivity and soil water content over large spatial domains at high frequency, without the need for distributed sensors.
IV. Field Application: Walker Basin
Improving water use efficiency
Installing fiber optic cable

- 1000m of armored cable installed at 15cm depth
- Dragged and seeded
Temperature vs. Time

\[ \theta = 7\% \]

\[ K_T \approx 30 \text{ cm}^2/\text{hr} \]

Soil temperature

Air temperature

\[ \Delta t \]

Soil temperature

Air temperature

7/26

7/27

7/28

Time

Air Temperature (°C)

Soil Temperature (°C)

Dry Soil
During Irrigation

<table>
<thead>
<tr>
<th>Date</th>
<th>Soil Temperature (°C)</th>
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<tbody>
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<td>30</td>
</tr>
<tr>
<td>7/27</td>
<td>28</td>
</tr>
<tr>
<td>7/28</td>
<td>26</td>
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DRY: $\theta = 7\%$

IRRIGATED: $\theta$ varies from 14% to 26%

During irrigation events, the soil temperature varies significantly, with the irrigated soil experiencing a higher range compared to the dry soil.
Soil Moisture & Thermal Diffusivity

- Soil Moisture (\%): 25, 20, 15, 10, 5
- Thermal Diffusivity (cm²/hr): 100, 80, 60, 40, 20

- Irrigation event:
  - 7/26
  - 7/27
  - 7/29

- Drying:
  - 7/28

- DRY SOIL:
  - 7/26
  - 7/29
Conclusions

• DTS is an effective, easy to install, tool for measuring integrated soil T over a wide range of time and area.

• Simple thermal model shows promise of passive method for assessing soil moisture and initial data illustrate that thermal diffusivity ($K_T$) tracks soil moisture content ($\theta$).

• Future Work: Improved signal processing to derive heat capacity (greater sensitivity to $\theta$).

• Passive DTS yields integrated effective $K_T$ over top 15cm, which provides a significant estimate of $\theta$ storage for models.

• Active DTS (heated cable method e.g. Selker et al.) may be much more accurate because heat pulse is a step function; however, it is limited to a single depth and time.
Thank You!

U.S. Bureau of Reclamation