



Fiber-Optic Distributed Temperature Sensing: Theory and Application to Monitoring Problems

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- Dept. of Subsurface Biogeochemical Research (SBR) program
- USGS Toxic Substances Hydrology Program
- USGS Groundwater Resources Program



OUTLINE

Introduction

- The geophysical toolbox
- Temperature data
- Fiber-optic distributed temperature sensing

Studies:

- (1) Waquoit Bay, MA
- (2) Columbia River, Hanford (ERSP)

Potential for application to leak detection

Conclusions & Future Directions



The Hydrogeophysics “Toolbox”

- Electrical - resistivity, induced polarization, self potential
- Seismic – MASW, refraction, reflection, passive seismic/microtremor
- Radar – borehole reflection & transmission, surface reflection
- EM – TDEM, EM Induction
- Gravity – relative, absolute
- Marine: resistivity, chirp seismic, GPR
- Airborne: EM, FLIR, etc.
- Temperature: Fiber-optic distributed temperature sensing

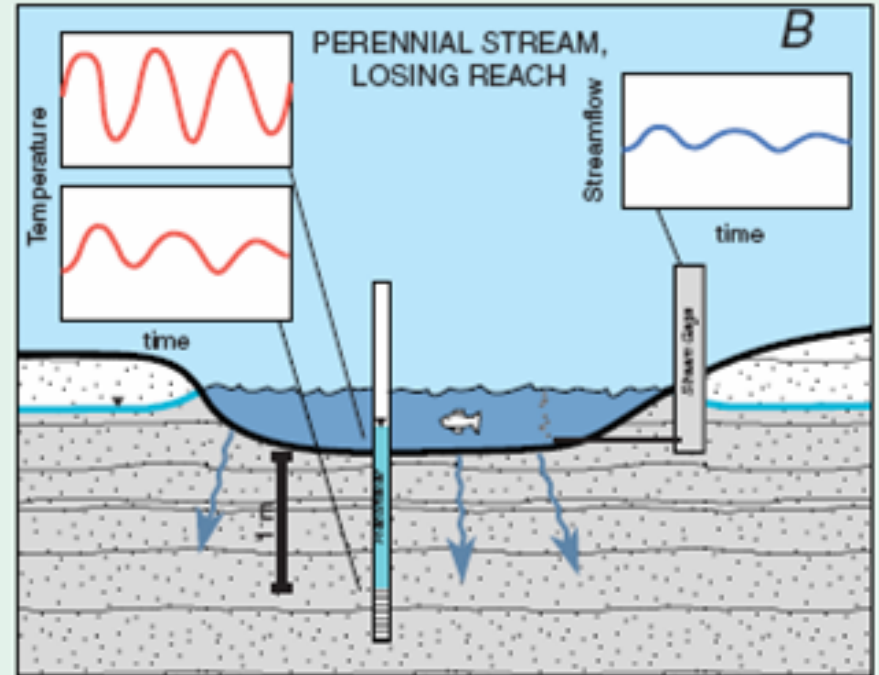
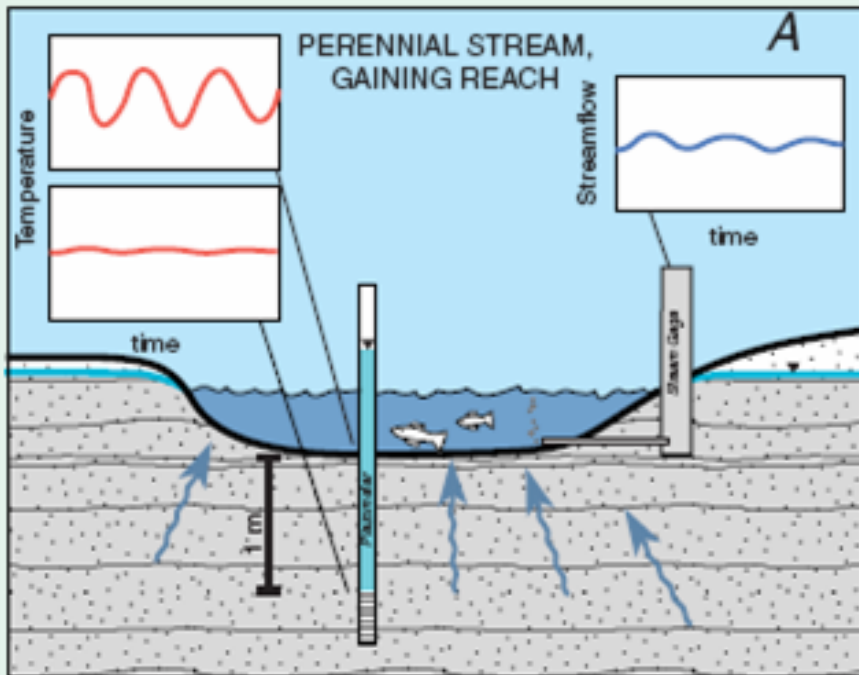


Temperature in the Toolbox

Identifying gaining and losing reaches of streams

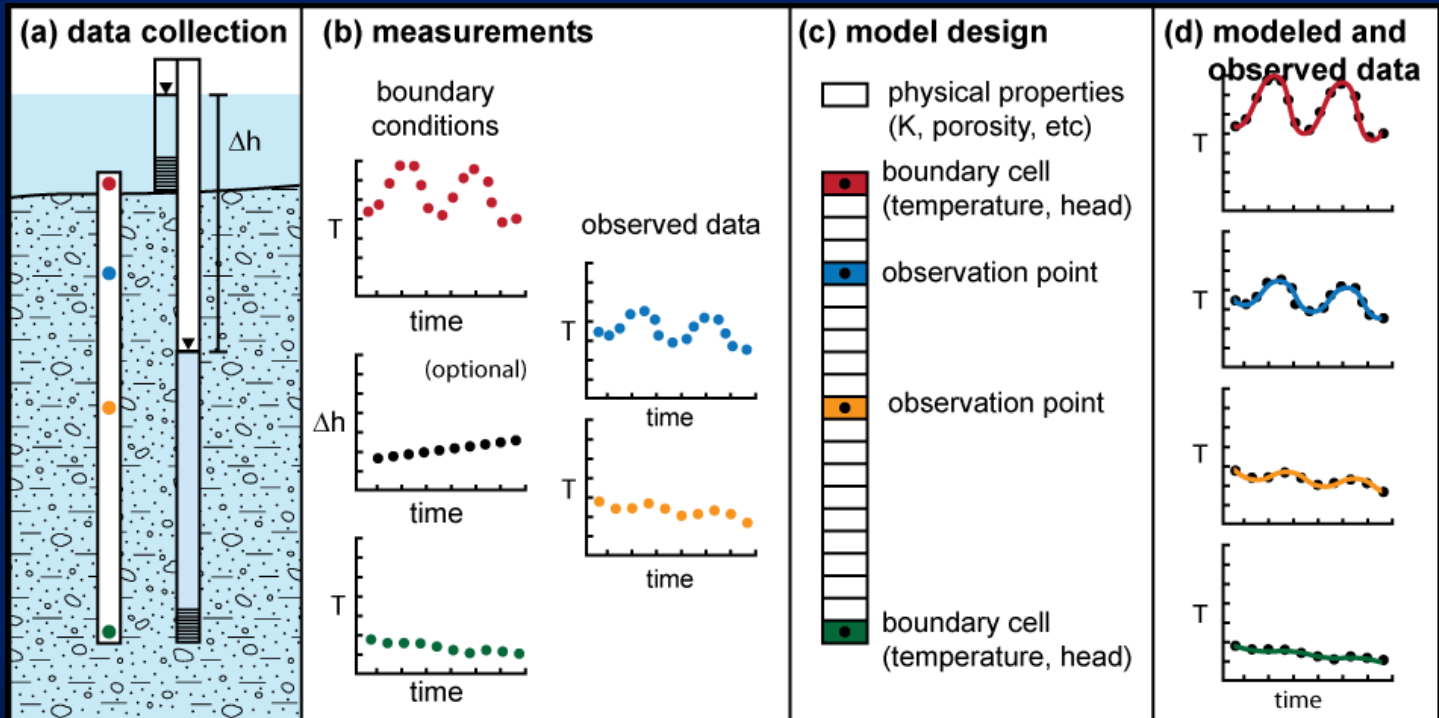
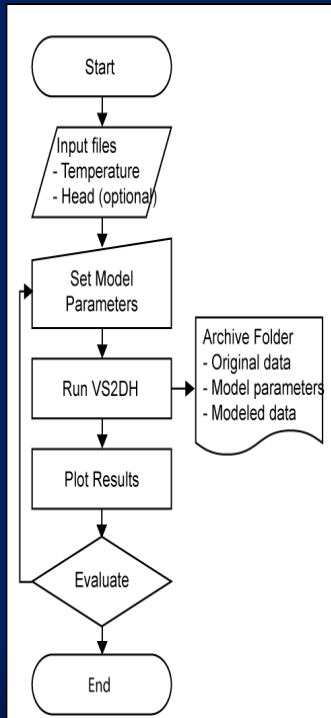
Inference of discharge/recharge rates

Inference of aquifer properties (K)



Temperature Data in Hydrology

Possible to estimate vertical fluid flux from temperature time series at different depths



Voytek et al., *1DTempPro: A tool for analyzing temperature profiles for groundwater/surface-water exchange*, in USGS review

Fiber-Optic DTS (FODTS)

- Commercially available for over a decade
- Principal markets: Petroleum; Fire Detection; Dam monitoring
- Can be installed alongside pipes or inside infrastructure
- USGS demo (20+ sites), 2005-2007
- First papers on technology in hydro literature by Selker et al. (2006)
- Raman-based systems:
 - Current precision: $< \pm 0.01$ deg C (~ 0.1 in practice)
 - Spatial resolution: ~ 1 m (~ 2 m in practice, new instruments and/or cables report 10 cm)
 - Pricing from $\sim \$15K - \$100K$



Applications to Leak Detection

Capitalize on:

- Temperature contrast between leaked fluids and native pore water (or surface water)
- Joule-Thomson effect (cooling at leaks in high-P pipelines)
- Change to thermal properties of porous media with saturation
- Strain and/or vibration/sound associated with rupture or leaks

Advantages:

- High spatial resolution
- Permanent installation
- Mature technology for autonomous monitoring & alarms
- Rapid data collection & minimal processing → actionable info.

Limitations:

- Point measurements (not remote sensing)
- Requires temperature contrast or change in thermal properties

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omnisens
Securing asset integrity

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Pipeline Integrity Flow Assurance

PIPELINE INTEGRITY MONITORING

Omnisens offers comprehensive solution for pipeline



Pipelines are supply chains that become a risk and control distances in the world. Pipeline threats include:

- Gro
- Har
- Cha
- Lea
- Thi
- Wor
- Cor

These three material failure pipeline failure impacts.

Pipeline Integrity monitoring approach

Omnisens systems continuously monitor the entire pipeline independently from the pipeline operation itself. Very small variations in meters along the entire pipeline, analyzed and operators to **anticipate failures at a very early stage** and avoid pipeline failures in high consequences areas.

Omnisens monitoring solutions for pipeline integrity approach

Leak detection
Detection of leakages is performed through continuous monitoring of temperature variations around the pipeline. Detection limits at 10ml/min have been demonstrated over 40 km.

Ground movement monitoring
Monitoring of ground stability using dedicated Strain sensitive cables and geotextiles along the pipeline gives real-time information on the level of strain the pipeline is exposed to.


Intrusion
Third party intrusion, work in construction, digging activities on pipeline are very early threats leading to potential pipeline failure. Threats can be precisely detected, classified and located before damage is done to the pipeline.

sensor net

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DIGITAL PIPELINE LEAK DETECTION



When your assets stretch for hundreds of miles across the remotest of terrains, there's no room for uncertainty. To detect and prevent leaks in long distance pipelines you need near real time updates that let you know precisely what is happening - and where.

Wherever you are monitoring gaps, only Digital Pipeline Monitoring offers accurate, continuous, timely data all along your pipeline to preventative maintenance along the full extent of your pipeline.

- Rapid leak detection with update intervals as low as 10 minutes
- The sensitivity you require to detect the smallest event 0.01°C
- Continuously monitor your entire pipeline via a single kilometre

Oil, Gas and Water Pipeline Monitoring Detection

SensorNet's Digital Pipeline Leak Detection system uses fiber optic technology to monitor your pipeline. Long distance pipelines are monitored with repeater stations situated every 600m providing full coverage at all times. The system is a solution that can be used to detect both liquid and industrial applications such as:

- Gas transmission and distribution
- LNG pipelines and tanks
- Oil transmission and distribution
- Steam pipelines
- Industrial processes (e.g. ethylene, ammonia, water pipelines)

Benefits of Pipeline Leak Detection

Digital Pipeline Leak Detection provides benefits to your organisation - both to Asset Managers, as well as to Operators. Benefits include:

- Improved safety of infrastructure and for operators
- Detected quickly and located accurately
- Enhanced system reliability through reduced inspection time
- Lower risk of environmental damage
- System is fully automated. Can be interfaced with industrial control system using standard protocols

Please click the link below for more information about our Digital Pipeline Leak Detection Monitoring solution. We offer a complete monitoring solution package, including the initial system installation and integration, commissioning. We have offices in Europe, Middle East, Far East. If you are interested, please contact us for more information.

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Technology: Distributed Temperature Sensing (DTS)
Digital Monitoring Solutions: Pipeline Leak Detection

DOWNSTREAM & PROCESS

CASE STUDIES

- Ethylene Pipeline Leak Detection »
- Water Pipeline Leak Detection »
- European refinery flow monitoring and leak detection »
- Digital Steam Leak Detection for »

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Distributed Temperature Sensing (DTS)

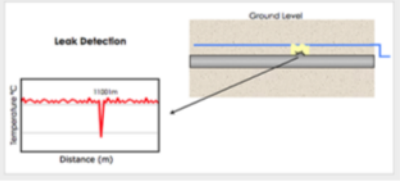
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Applications

Pipelines

SensorTran offers advanced fiber optic-based Distributed Temperature Sensing (DTS) solutions that provide a significant advancement in the integrity and flow assurance management of pipelines. With the ability to quickly detect small leak events and monitor the temperature profile along the complete length of pipelines, these solutions provide an affordable, proven, and reliable means for monitoring both short and long transfer lines, as well as plant-wide pipeline distribution networks. Small leaks along entire lengths of pipelines are detected and located by monitoring small and anomalous local temperature changes and can be readily applied to a wide range of pipeline applications. For gas lines, the escaping pressurized gas creates a local cold zone on the outer surface of the pipeline due to the Joule-Thomson cooling effect, the temperature change, and its location being detected and measured by the system. Cryogenic lines such as LNG, LPG, ammonia, ethylene, etc. also create cold zones which can be easily detected when leaks occur.

Lines carrying heated product such as heavy oil, multi-phase products, molten products, heated water, and steam also lend themselves to these integrity monitoring solutions, due to the local temperature increases which occur as the product escapes.



Fiber Deployment

A wide range of robust optical sensing cables are available to suit specific project and installation requirements. Cables can be supplied and installed within an outer stainless steel tube or Steel Wire Armoured (SWA) cable construction to provide excellent mechanical, chemical, and moisture protection while ensuring good thermal conduction to the fibers. Fiber types are selected suitable for duty with coatings designed to meet temperature limits of -190°C to +70°C.

Numerous alternatives exist for the placement of the optical cables dependent upon the specific project requirements and application thermal time constraints. Installation methods are carefully selected to allow maximum flexibility while affording best mechanical protection. SensorTran offers [specialized installation services](#) to assist customer with the design and installation of comprehensive DTS solutions.

Websites for omnisens, sensor net, ap sensing, sensor tan, etc. (Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US Government.)

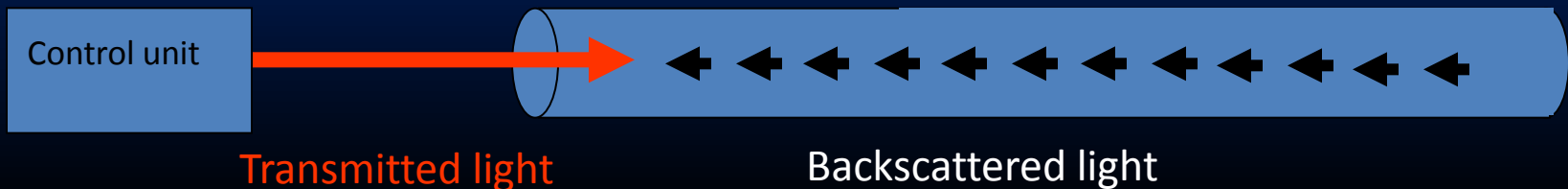
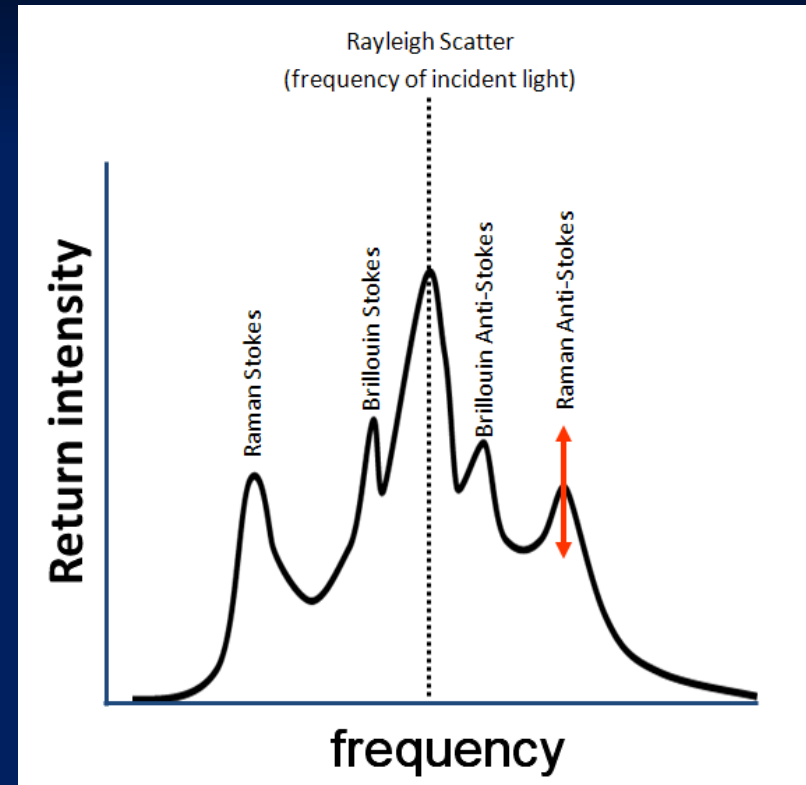
DTS Measurement Physics (1)

- Control unit transmits laser light down cable
- Cable acts as a “light pipe”
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, Raman)
 - *Backscatter spectrum is measured and analyzed to estimate temperature all along the cable*



DTS Measurement Physics (2)

- Control unit transmits laser light down cable
- Cable acts as a “light pipe”
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, Raman)
 - *Backscatter is measured and analyzed to estimate temperatures*
 - *OTDR time-of-flight calculation to localize measurements in space*



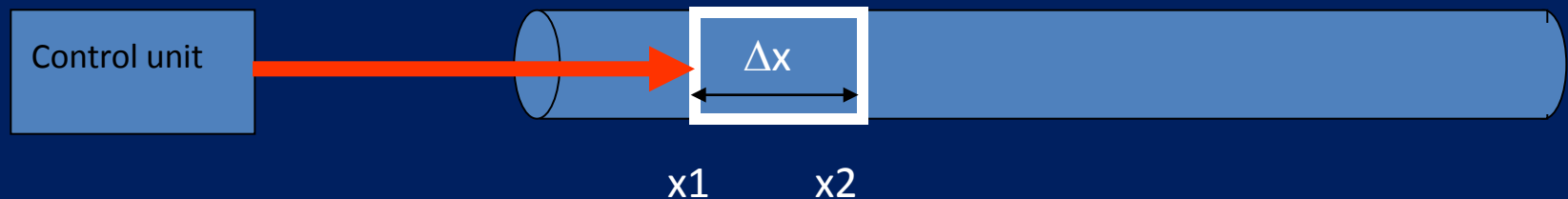
Measurement Physics (3)

OTDR “time of flight”:

- At $t=0$, laser pulse fires, light travels down glass at constant speed, c :



- Light reaches x_1 at $c \times t_1$ and x_2 at $c \times t_2$; best Δx limited by pulse width



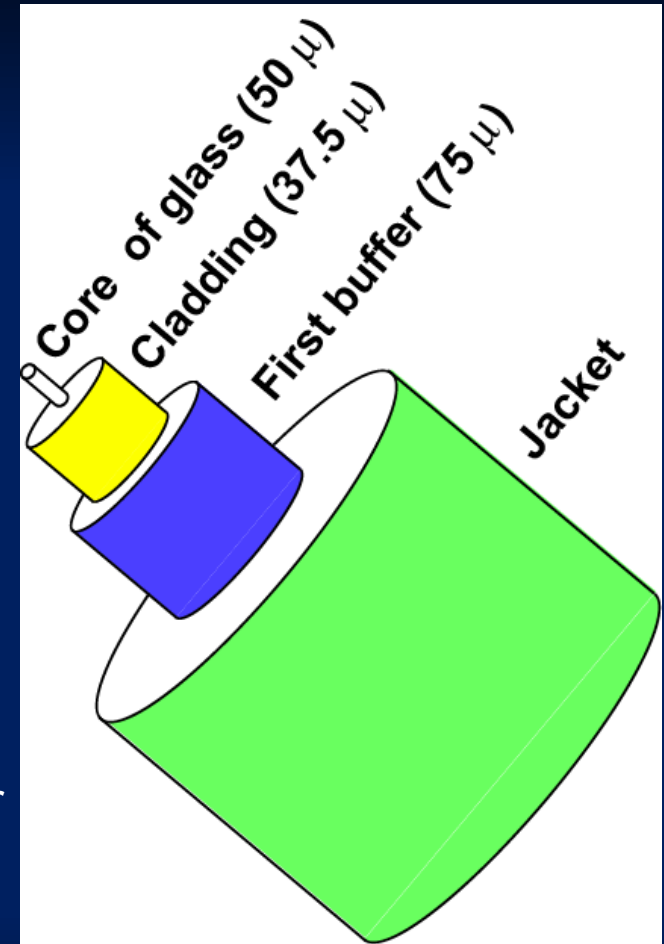
- Can relate backscatter measured over a time window to a spatial interval of the fiber, knowing the speed of light in glass



Cable and Fiber (1)

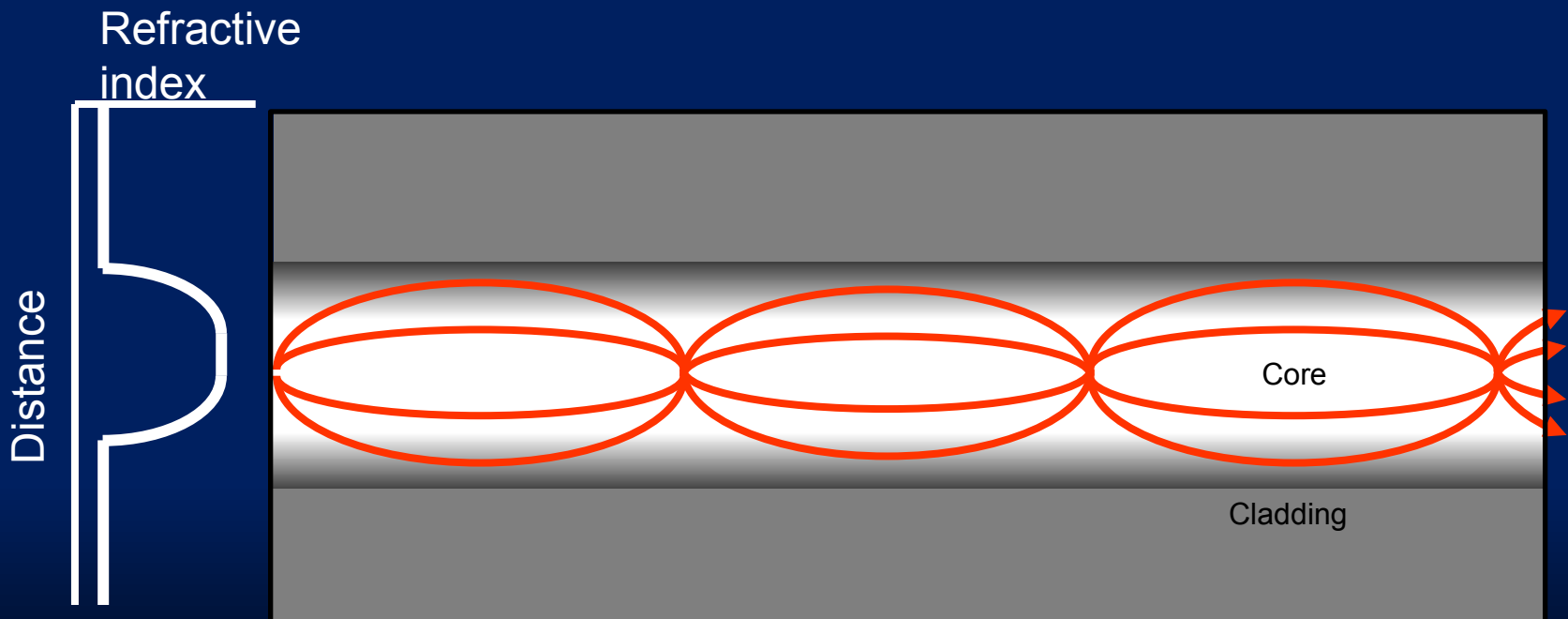
Fiber from inside out:

- **Core:** glass, commonly 50- or 62.5-micron diameter multimode for DTS work; index of refraction varies across the cross section
- **Cladding:** 37.5 micron glass with lower index of refraction
- **First buffer:** 75 micron plastic
- **Jacket/Sheathing:** Many options; can be either “loose tube” or “tight”; keeps water out, protects fiber
 - Loose – gel filled, reduces strain on fiber
 - Tight – more common and cheaper



Cable and Fiber (2)

- Multimode, graded index fiber: A light pipe

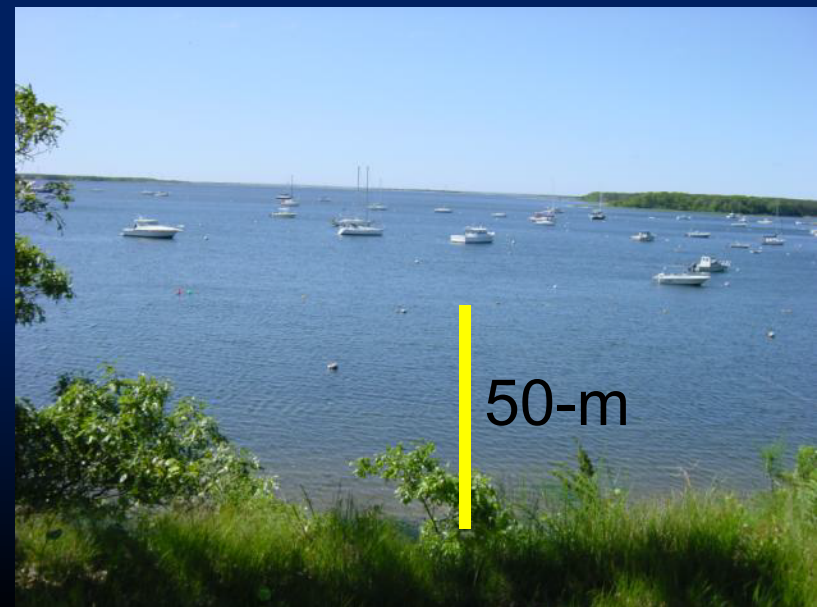


As light approaches sides of the fiber, it refracts back toward the core

Cable and Fiber (3)

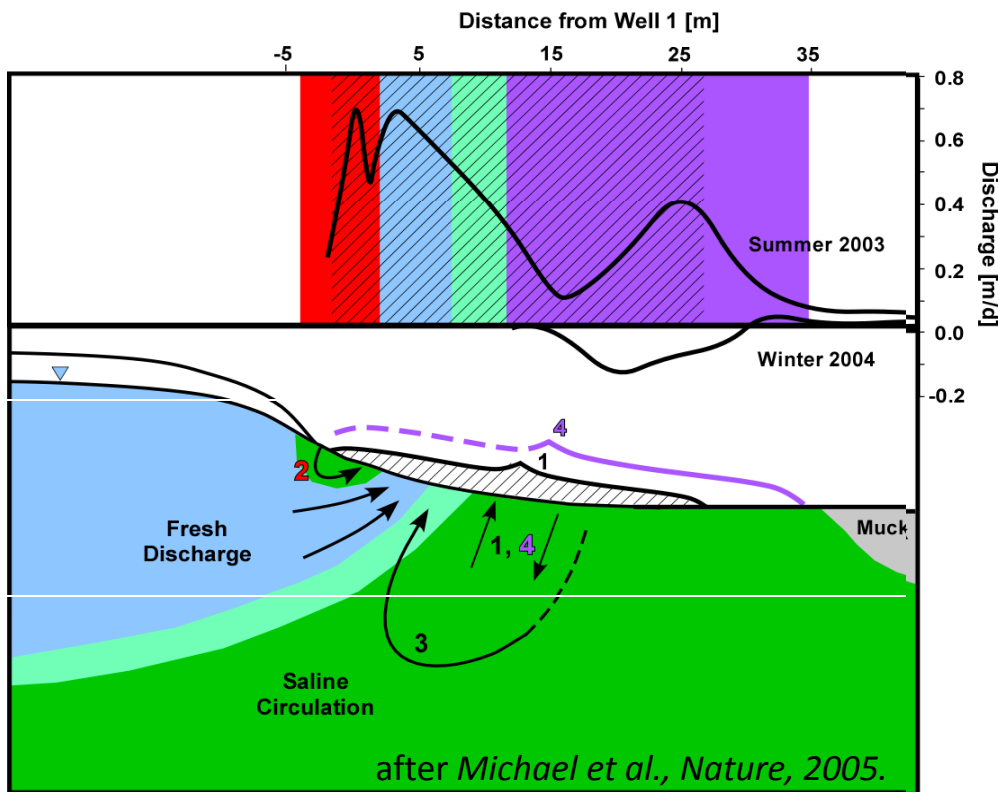
- Cable costs: < \$1/m to \$50/m depending on the amount of armoring, number and types of fibers, etc.
- Cable weight: 10's to 100's of lbs per km depending on armoring
- Major cable manufacturers:
 - AFL, OCC, Brugg

Study 1: Fiber-optic & Resistivity Monitoring of Aquifer-Estuary Interaction, Waquoit Bay, MA



Study 1: Objectives

- Evaluate combination of DTS and fixed-electrode resistivity for characterizing submarine groundwater discharge (SGD) associated with tidal pumping



Zone 1 (cross-hatching) Tidal pumping, extends from the shoreline to approximately 28 m into the bay.

Zone 2: Nearshore circulation due to tides and waves, extends approximately 3 m from the high tide mark.

Zone 3: Dispersive circulation discharges along the bayward edge of the fresh discharge.

Zone 4: Seasonal saline outflow, between 13 and 35 m from shore, but the zone likely extends to the shoreline.

Notes:

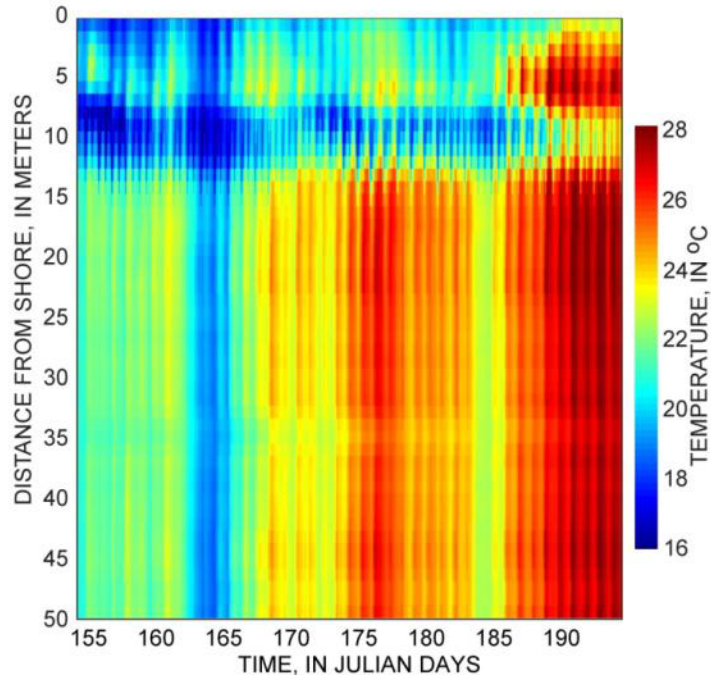
- Expectation: Fresh SGD is cold (summer condition) and electrically resistive
- Groundwater ~11 degrees C

DTS Dataset

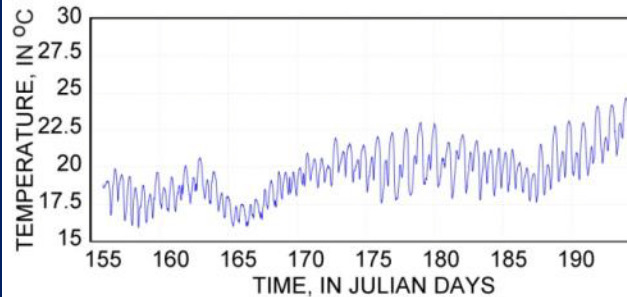
- 40 days continuous data (additional data in HJ paper)
- Temperature data show zone of fresh tidal pumping (cold)
- Seepage measurements (not shown) indicate continuous discharge over tidal cycle, enhanced at low tide
- How to look for non-stationary behavior and correlation with other time series?

Henderson et al.,
GRL, 2009; HJ,
2010

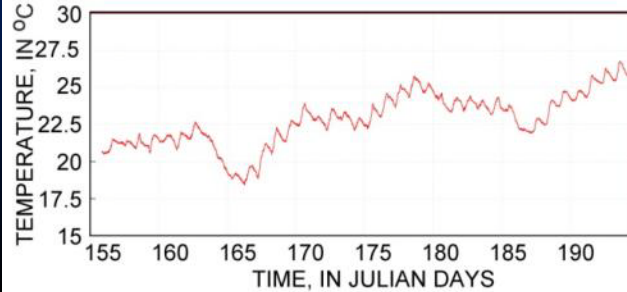
(a) FODTS data



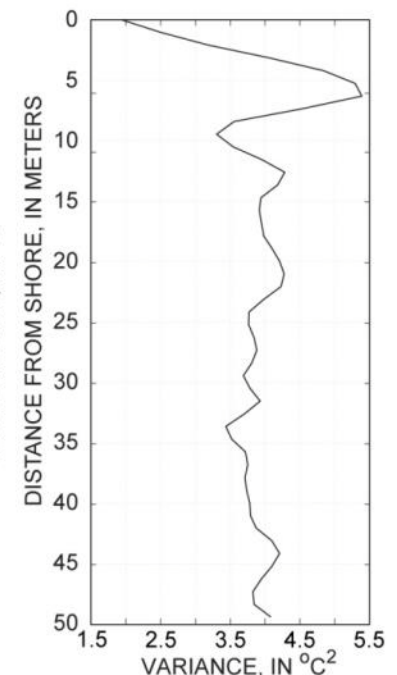
(b) FODTS Time series for 11.5-m location



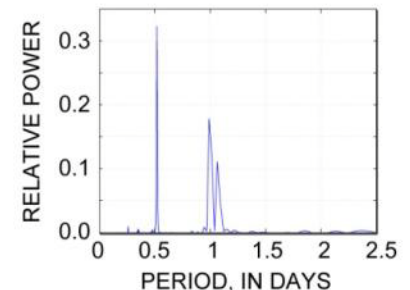
(c) FODTS Time series for 30.5-m location



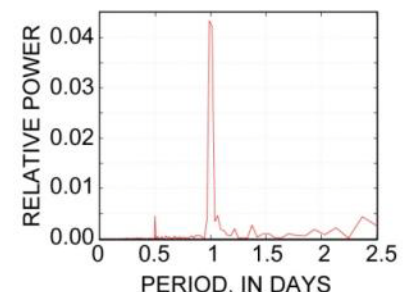
(d) FODTS data variance



(e) Power Spectrum for 11.5 m



(f) Power Spectrum for 30.5 m



Wavelet Analysis

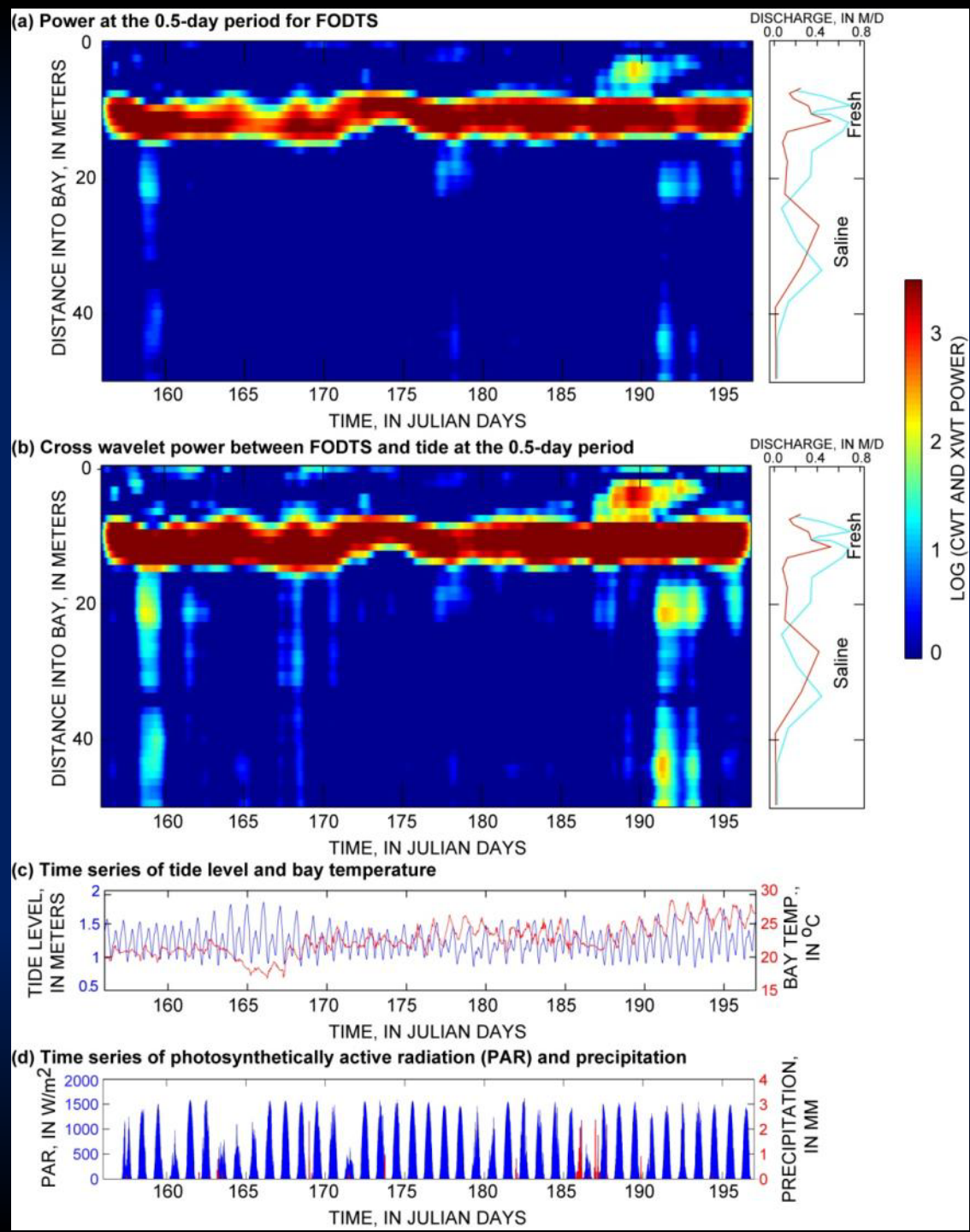
- Continuous wavelet transform (CWT) calculated for all locations

Can provide insight into:

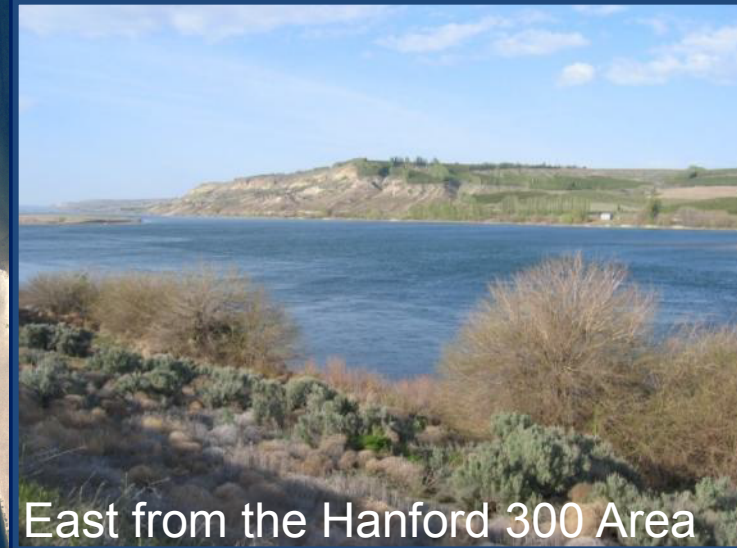
- Frequency content of non-stationary signals
- Large datasets
- Relations between time series
 - Cross wavelet (XWT)
 - Wavelet coherence (WTC)

Note: Slide only summarizes one frequency component (0.5-day)

Henderson et al.,
GRL, 2009



Study 2: Hanford 300 Area



East from the Hanford 300 Area

Contamination legacy: included 241 metric tons of copper, 117 metric tons of fluorine, 2060 metric tons of nitrate and between 33 and 59 metric tons of uranium.

U [VI] contours

Estimated area of contribution (from borehole projection Frtiz et al., 2007)

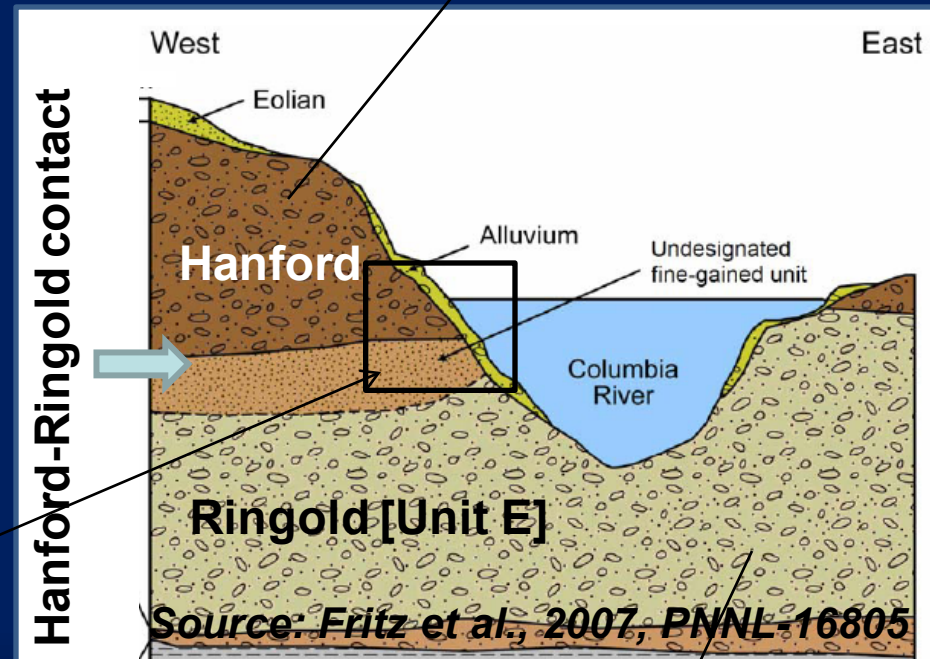
Spatial and temporal variability in exchange between uranium contaminated groundwater and river water?

Hanford Geology

- Hanford-Ringold contact: important interface controlling flow/transport
- Intensively studied inland away from the river corridor
- Cobble layer in streambed complicates permeability measurement and installation of piezometers

Improvements in hydrogeological framework required along corridor of surface-water/groundwater exchange

Pebble to boulder size gravels and interbedded sands



Highly heterogeneous, granule to cobble size gravels interbedded with fine sand and silt.






Water
depths

Survey
geometry



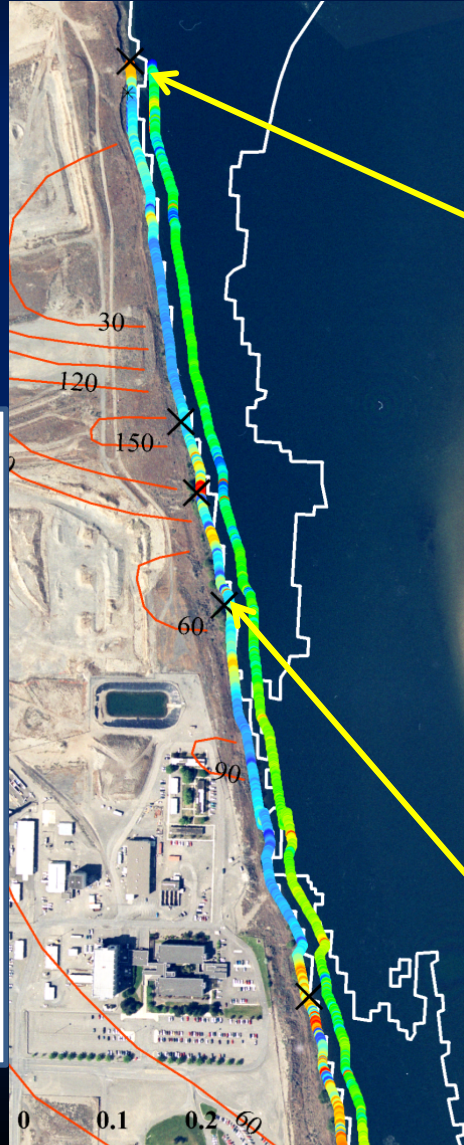
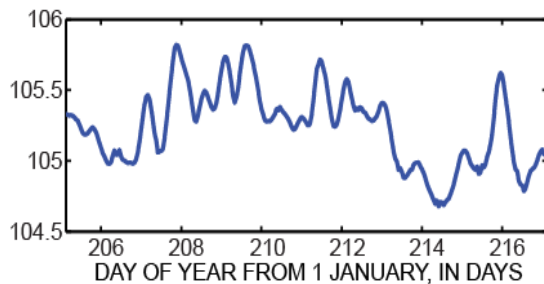
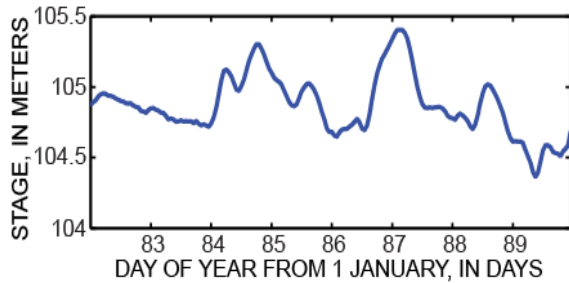
Summary of Field Data Acquisition

- 30 km of waterborne IP line
- 4.5 km of DTS line, ~1 to 2-m spatial resolution, 5-min interval, ~0.1°C temperature precision
- Water depths varied from 1-14 m (in channel)
- Focus on near shore where water depth of a few meters only
- *Also waterborne seismic and GPR, land-based res/IP; 1D vertical temp, not reported here*

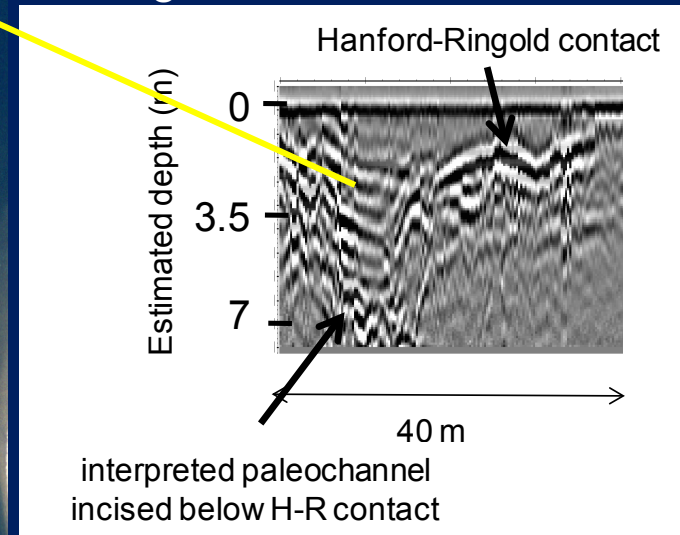
	IP
	DTS
	Contributing area?

DTS Data Visualization (Winter vs. Summer)

Non-stationary river stage variations driven by seasonal effects and daily dam operations on Columbia River



Paleochannels locally eroded beneath Hanford-Ringold contact

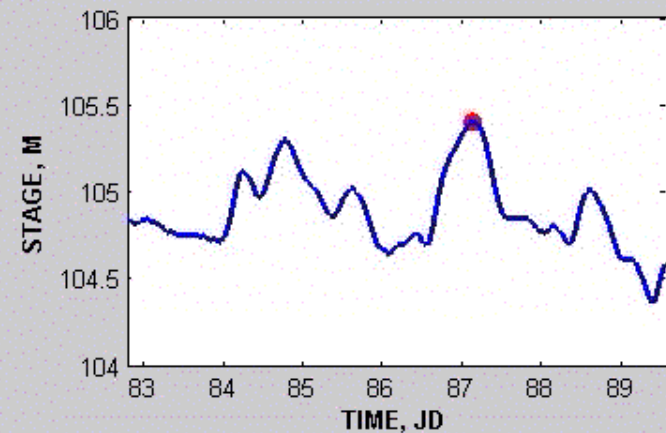


Identified uranium "seeps" (Fritz et al., 2007)

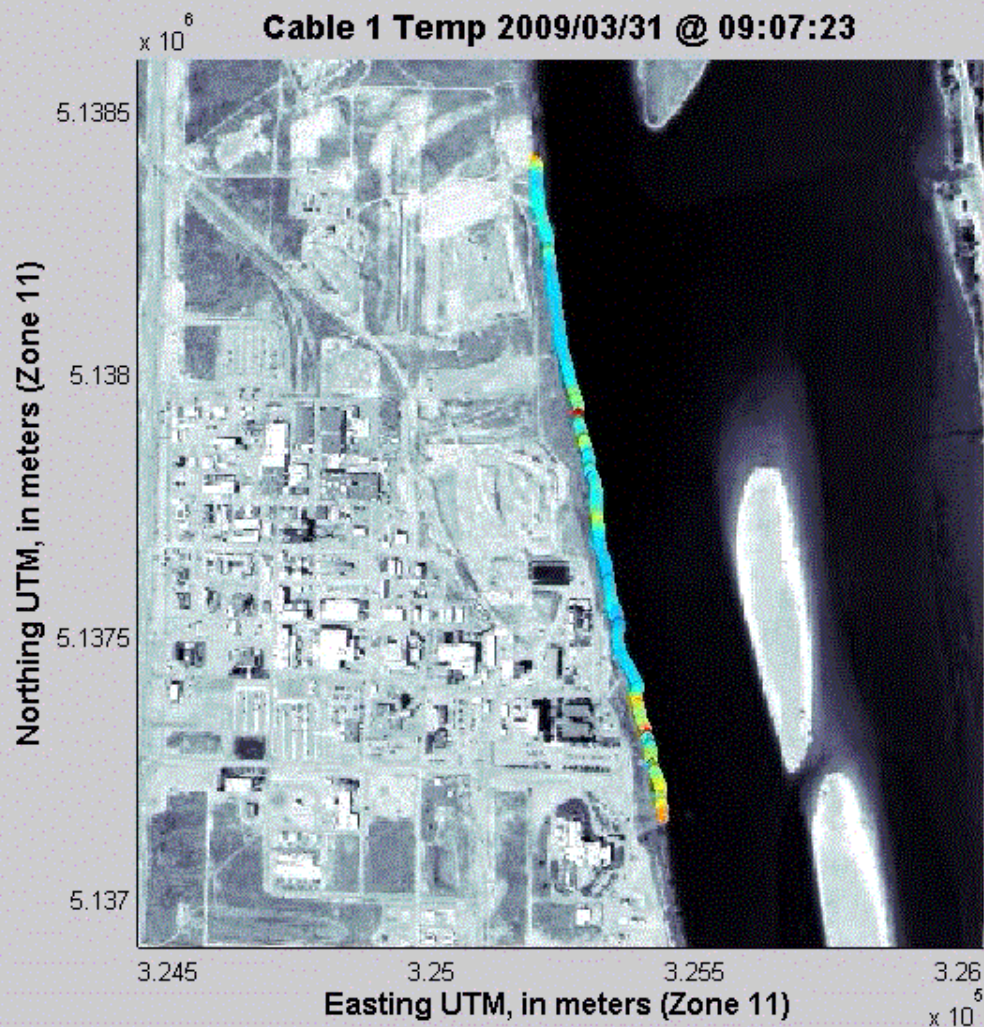
Results: DTS Monitoring of GW/SW Exchange - Winter (March 24-31, 2009)



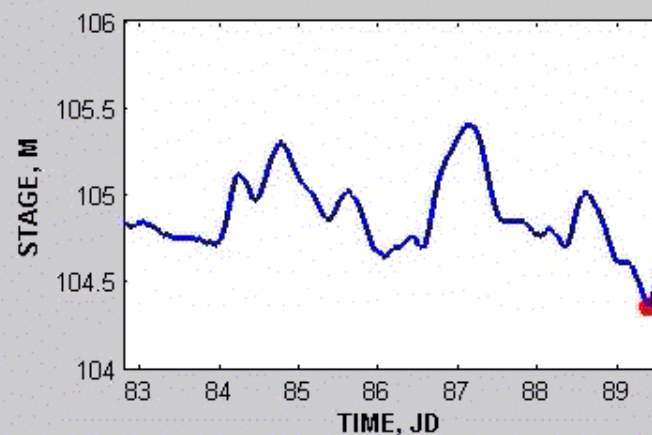
High stage



Results: DTS Monitoring of GW/SW Exchange - Winter (March 24-31, 2009)

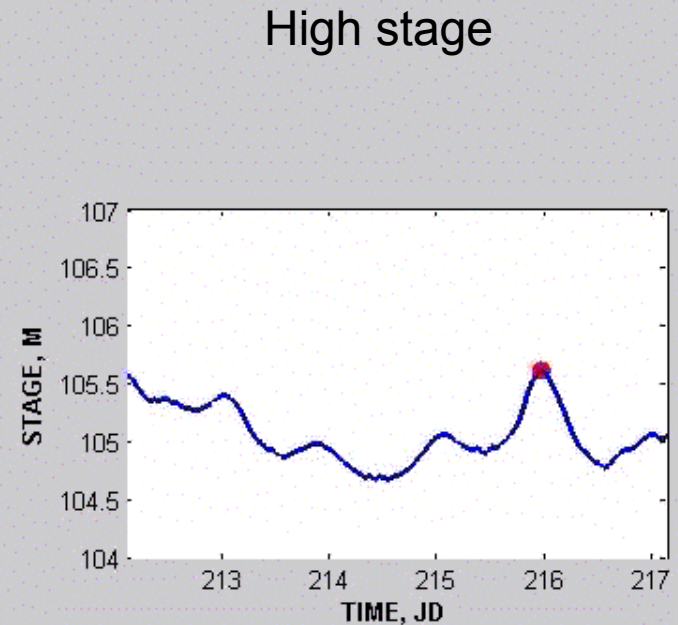


Low stage

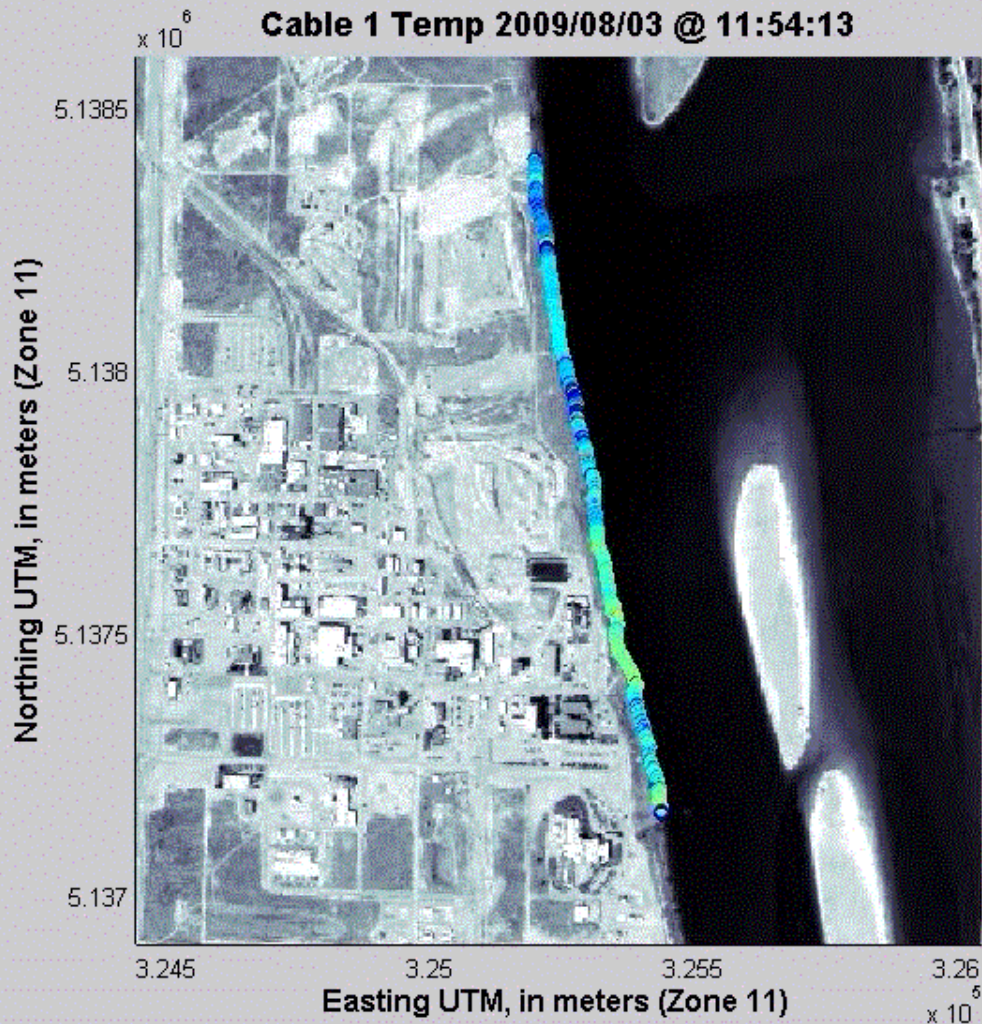


Warm anomalies indicative
of focused groundwater
discharge

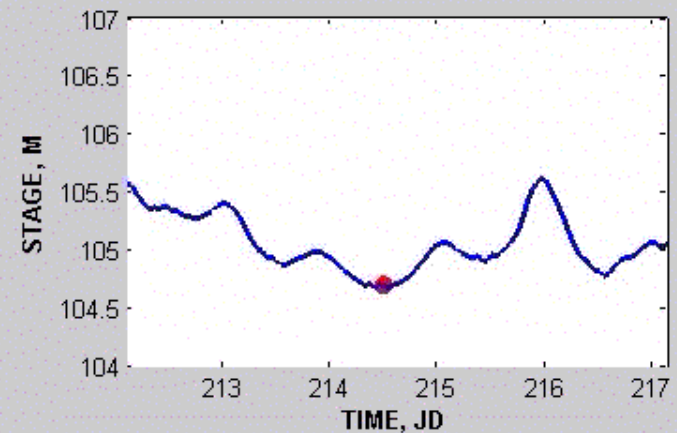
Results: DTS Monitoring of GW/SW Exchange - Summer (August 1-6, 2009)



Results: DTS Monitoring of GW/SW Exchange - Summer (August 1-6, 2009)



Low stage

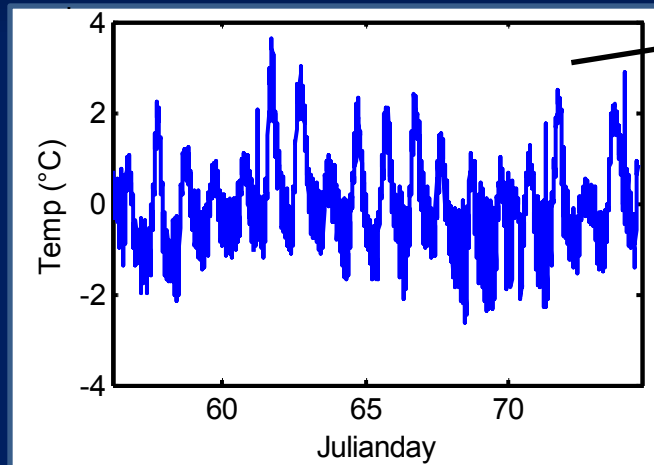


Cold anomalies indicative
of focused groundwater
discharge

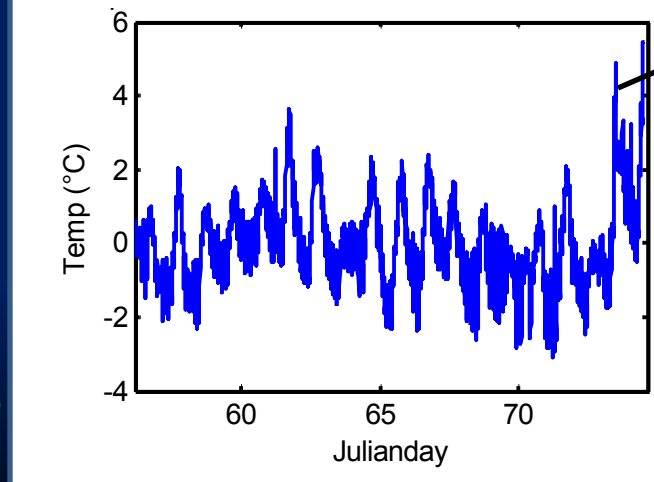
Time-Frequency Analysis

Non Exchange Area

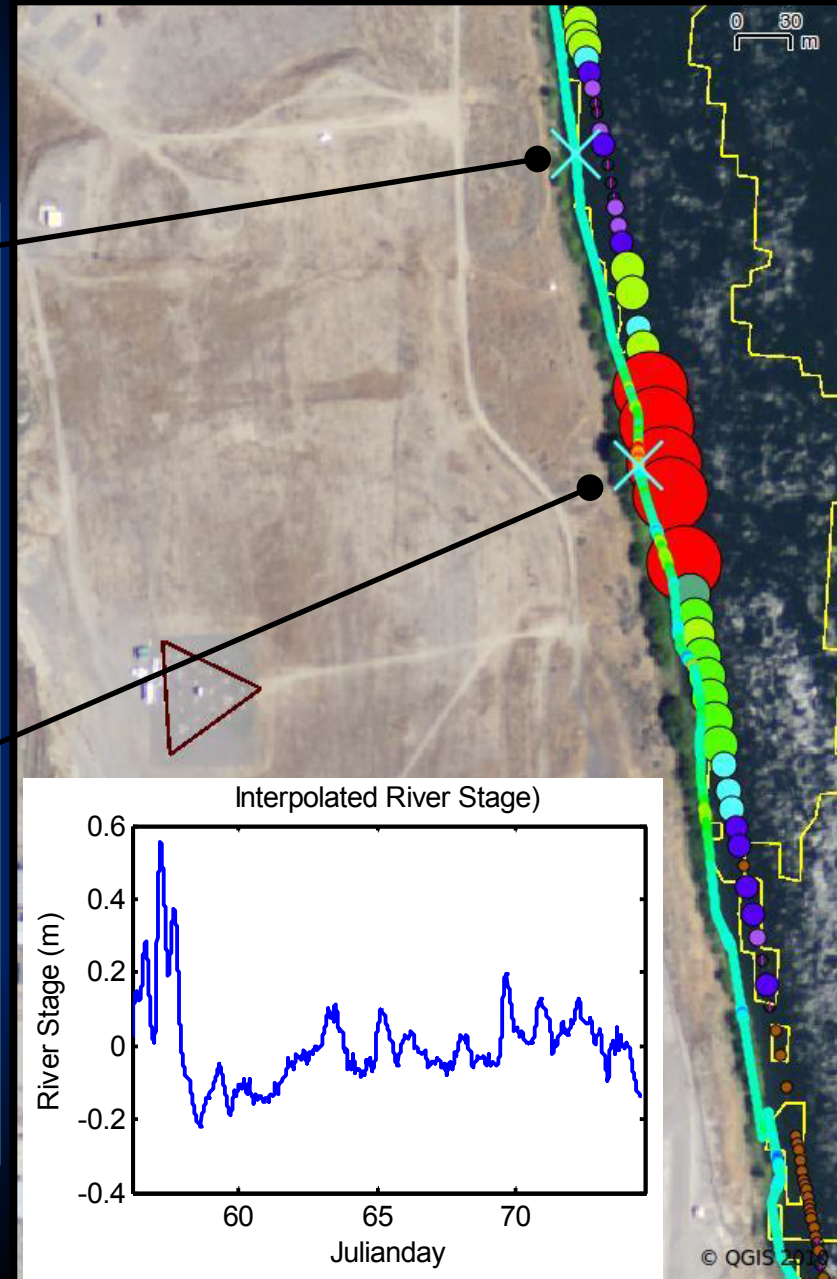
De-trended time series



Focused Exchange Area



Stockwell (S)
Transform on
selected time
series and stage
data

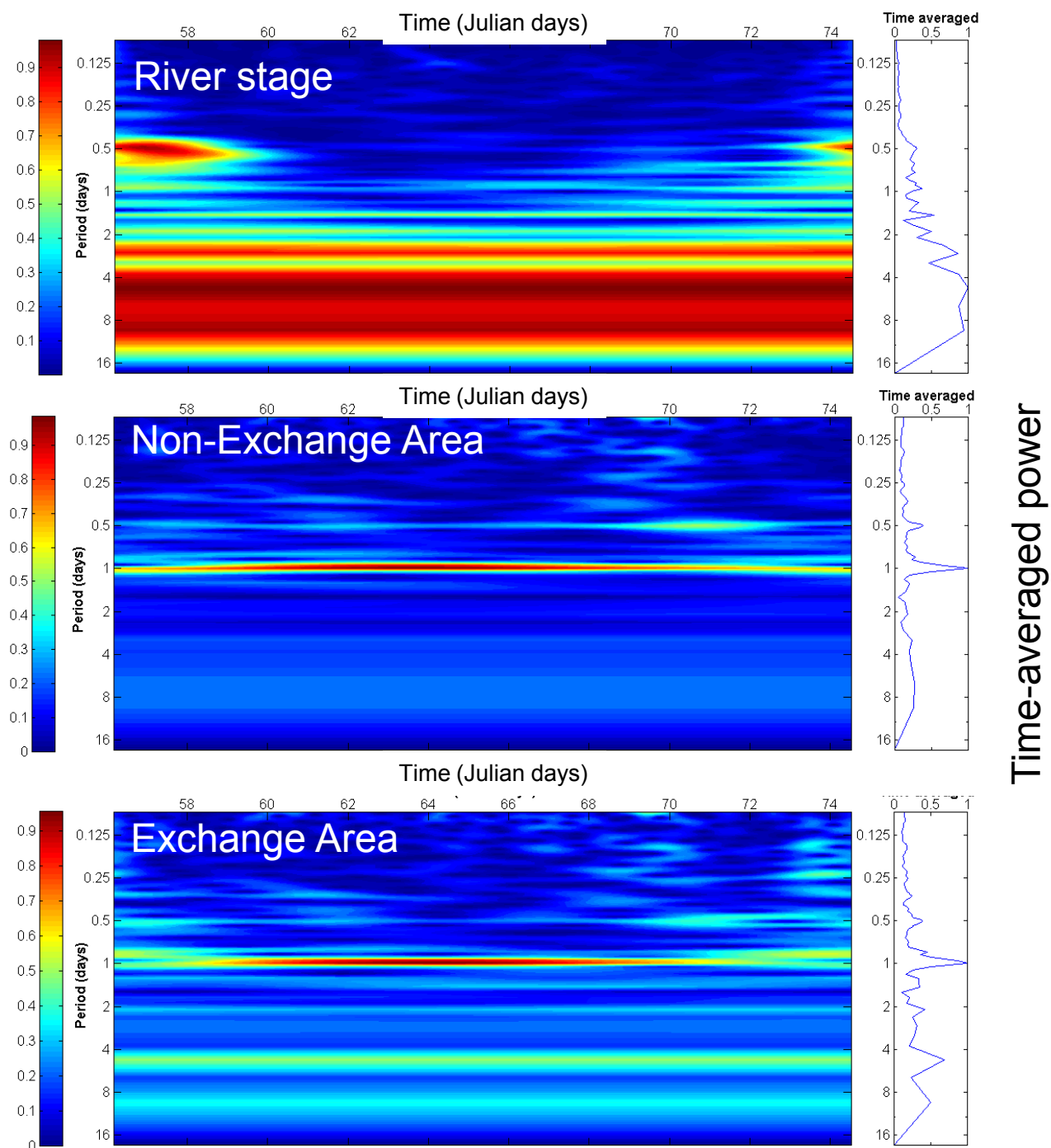


S-Transform Analysis

-Exchange areas contain long periods that are strong signals in stage data

-These periods only weak in non exchange area

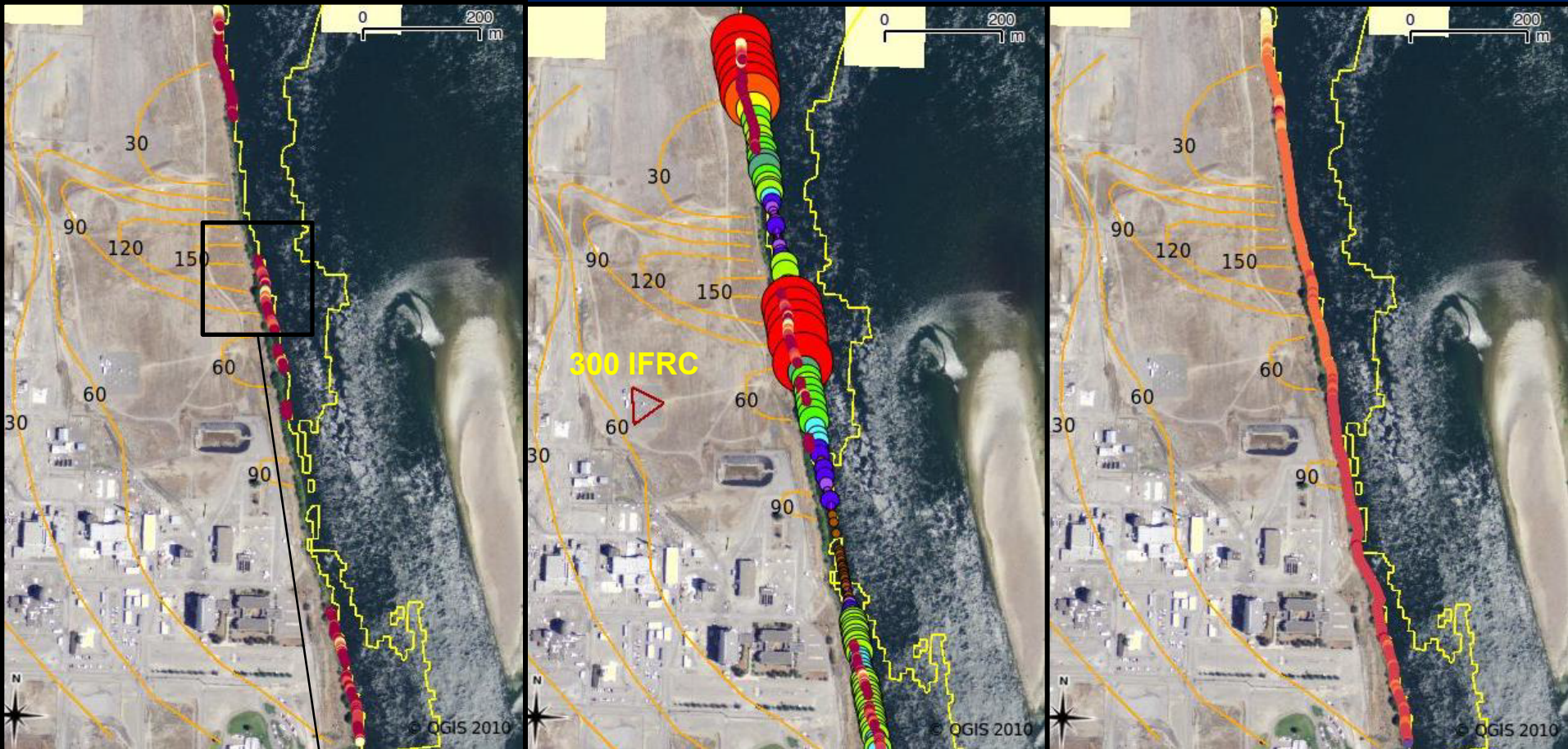
-Temperature variations at exchange locations are being driven by stage variations



S-Transform Analysis at Selected Frequencies

4 day period in river stage

1 day period (solar heating)



Location of maximum stage forcing

No discrimination

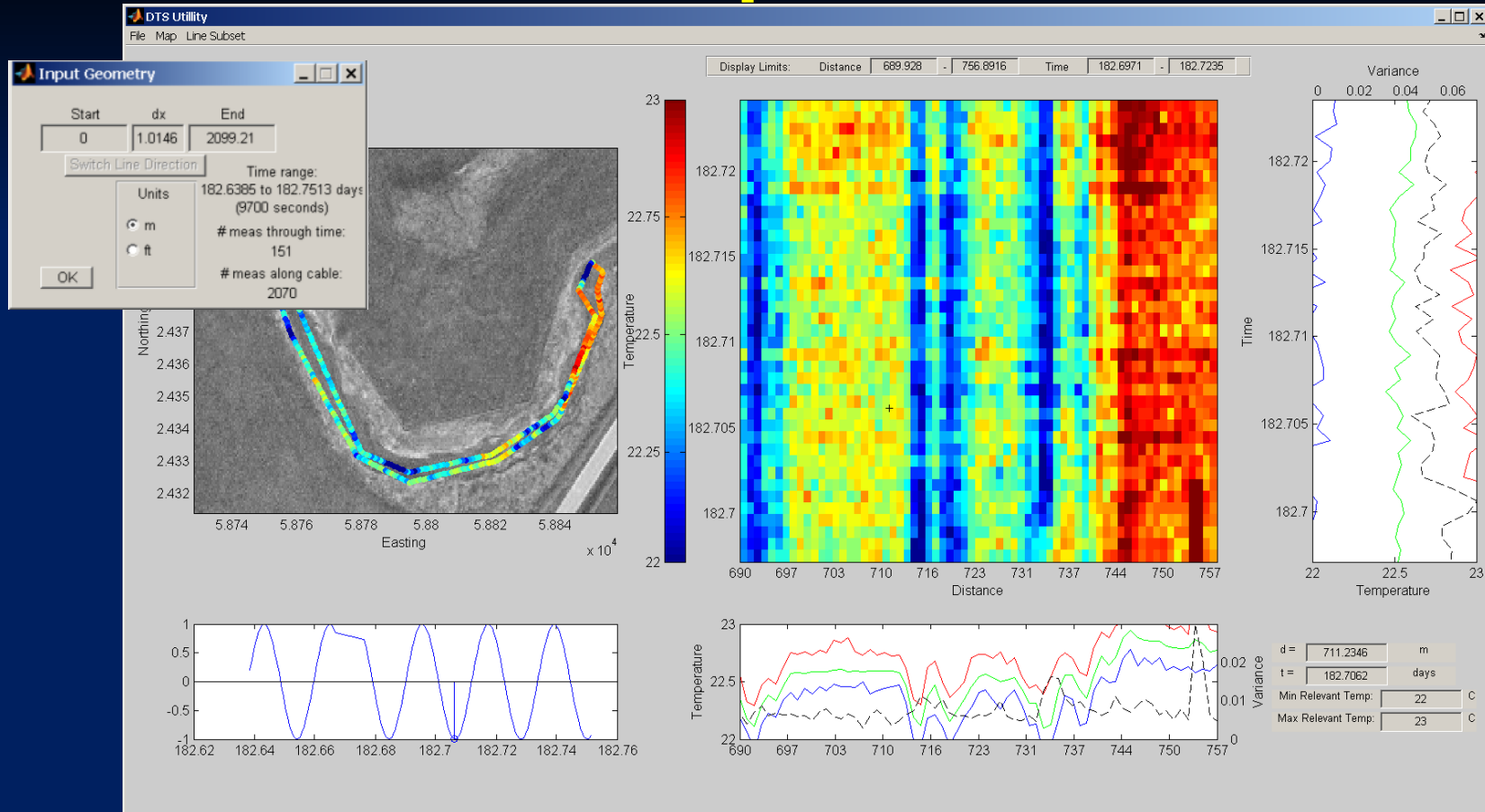
Summary

- FODTS synergistic with other geophysical methods (e.g., electrical results commonly require adjustment for soil temperature)
- High resolution in space and time
- Data amenable to time-series and signal-processing analyses
- Data amenable to numerical simulation (coupled flow and heat-transport)
- Capable of triggering alarm events
- FODTS is low-power, safe; permanent installations are feasible
- Mature COTS technology & software for leak detection



Additional slides

Tools in development: DTSTool GUI

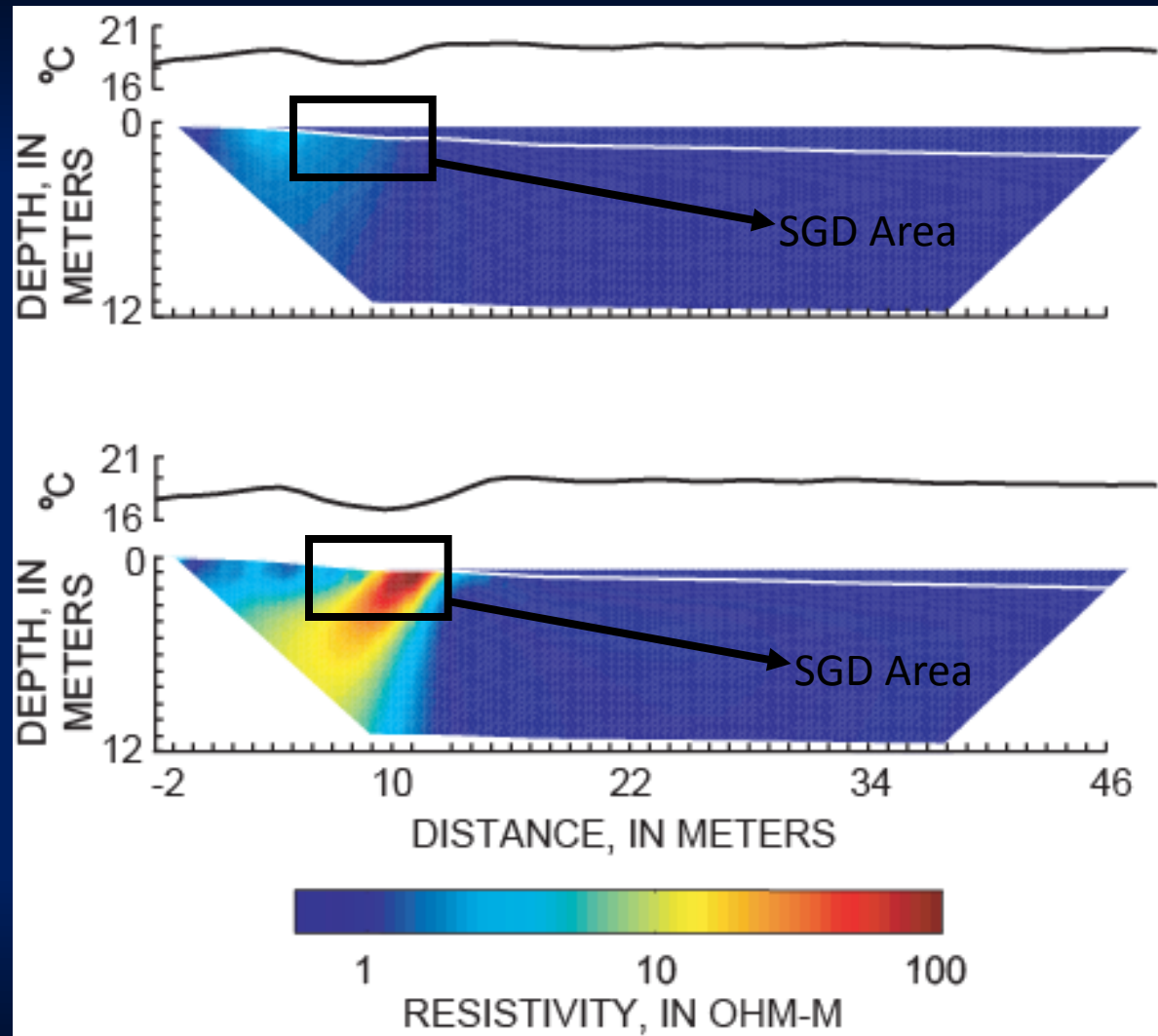


- Import data in Lios, Agilent, Sensortran, and Sensornet format
- Edit to temporal or spatial subsets
- Remove bad data based on value, location, or time interval
- Calculate statistics, e.g., min, max, std deviation, for profiles or time series
- Generate animations and saves to .avi format
- Compare to other time series and calculate cross correlation
- Perform dynamic calibrations to multiple thermistor bath time series

Koch, Elwaseif, Day-Lewis, and Slater, in development

Resistivity Tomography

High-Tide



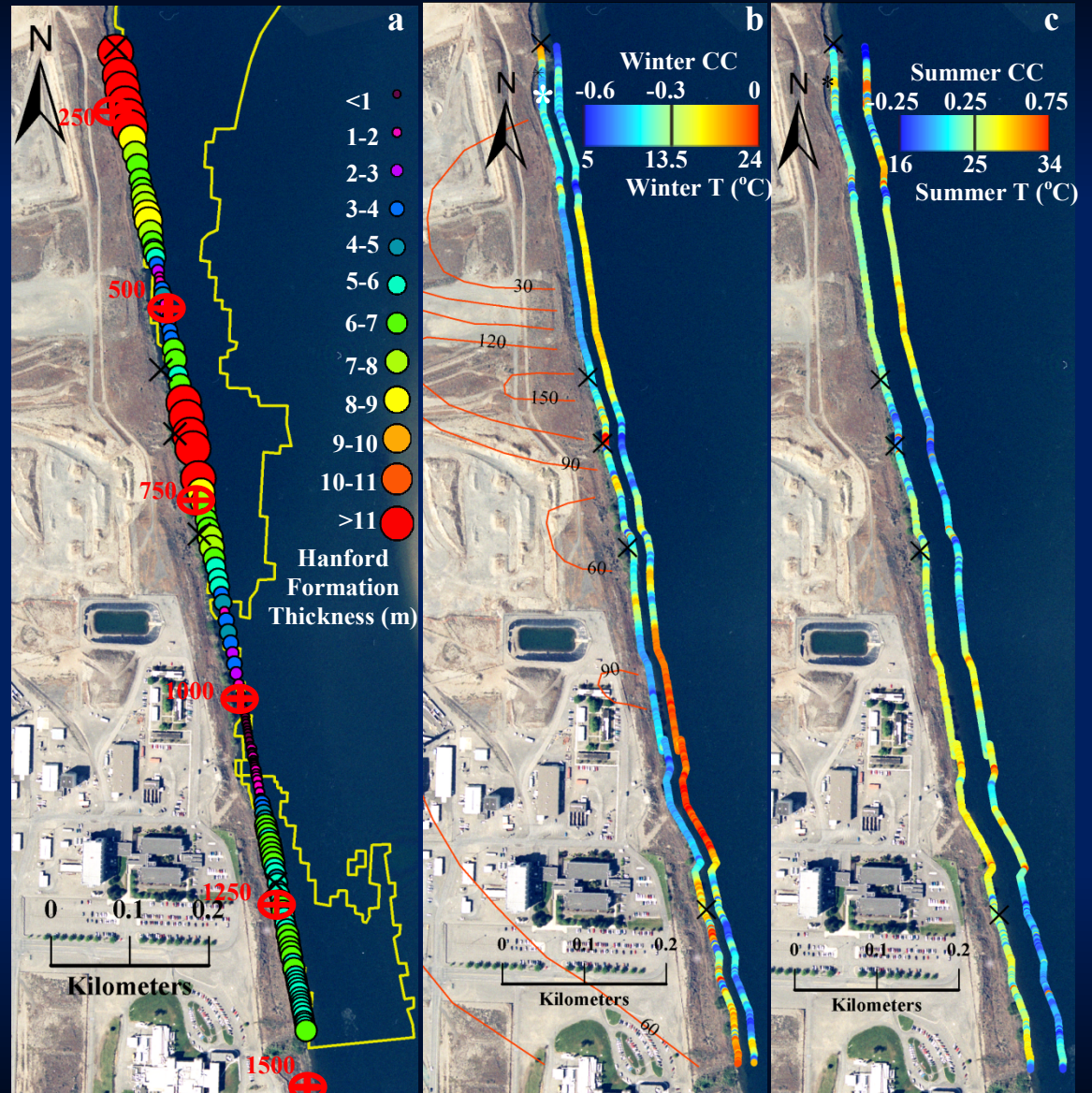
Low-Tide

→ Variable resolution in space and time

Focused Exchange and Area of Contribution

- IP resolves hydrogeologic framework and provides cross-sectional imaging
- DTS provides high-resolution in space and time
- Temperature anomalies coincide with known uranium seeps, *but there are many additional temperature anomalies/seeps*

Estimated variation in thickness of uranium contributing area from IP



(DTS artificially offset for visualization)