Use of geophysical techniques and analysis to infer underground structures and unknown voids.

"Digital twin of infrastructure"
–Geoff Zeiss

"BIM for the Subsurface"
– Innovate UK

Albert Boulanger
Smart-X Group
http://smartgrid.info

Position Statement for Geophysical Methods for Underground Mapping

- One Geophysical Method on its own is often not enough
- Need to integrate with other sensors (geophysical, vibro- acoustic, etc.), existing maps, and geotechnical cores.
- Mapping systems like Bentley Subsurface Utility Engineering (SUE) could provide ways to ingest this data.
  - Scale in the era of Big Data
    - Geoff Zeiss influencer, Between the Poles Blog
    - Data Acquisition speed
      - IDS Pegasus:Stream (camera, GPR, 9MPH)
      - T2 Utility Engineers (delivers 3D, consulting, 7MPH)
      - DGT Associates (consulting, 50MPH)
    - Need to create a pipeline to ingest sensor data streams + other data to output 3D.
      - Smart-X Group's work in machine learning and 4D Seismic
- Monitor infrastructure over time (the real win?)
  - Self-repair, spills, catastrophes/accidents, settlement, faults, etc.

Geophysical Methods

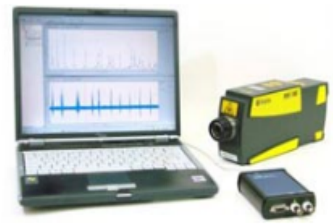
- Geophysical methods, especially when combined with themselves and others like vibro-acoustics, offers low cost means to (repeatedly) survey the underground
  - Not only buried utilities but physical properties of the embedding matrix.
- Multi-sensor Initiatives in the UK (Mapping/Assessing the Underworld) and US (TRB SHRP2) among others.
- These methods are not perfect but compliment the traditional CAD/CAM & GIS
- Offer solutions to technical or "political" boundaries to traditional methods.
- They also offer a separate information source to help validate location and discover the unmapped.

UK's Mapping/Assessing the Underworld Research Activities

Work Packages

Advancing Ground Penetrating Radar Technology

The aim of this work package is to advance GPR technologies specifically in support of the multi-sensor device, for deployment both alone at the surface and in combination with in-pipe GPR transmitters / receivers.
Click here for more information.



Acoustic Technologies Advancement

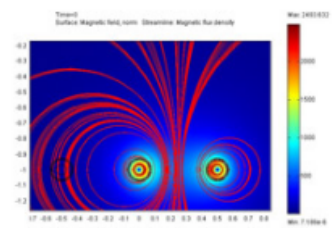
The aim of this work package is to determine the effectiveness and limitations of acoustic technologies for buried utility service location, based on both pipe and ground excitation techniques, when operated alongside the complementary sensor technologies in the multi-sensor device.
Click here for more information.

Low Frequency Electromagnetic Field Technologies

The aim of this work package is to conduct four inter-related studies based on low frequency electromagnetics.
Click here for more information.

Tuning of the Multi-Sensor Device to the Ground Conditions

This work package aims to develop equipment for use in field testing of geophysical soil properties and, in conjunction with the British Geological Survey (BGS), to create a Knowledge Based System that will allow geophysical soil data to be predicted using geographically mapped geotechnical and geological data. Both are intended to inform, and significantly improve, utility location during the planning, site operations and data interpretation phases of site surveys.
Click here for more information.

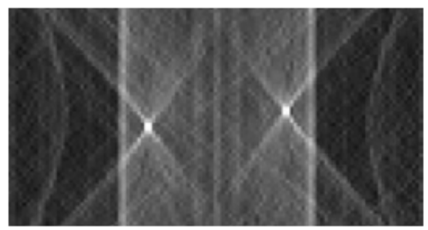


Magnetic Field Technologies

The aim of this work package is to utilise a passive array of magnetic sensors together with advanced signal processing techniques to detect underground electricity cables and other metallic buried infrastructure, even when stacked or laid in close association, and to develop the technique so that it can be integrated in the multi-sensor device.
Click here for more information.

Development of Multi-Sensor Array and Signal Processing

The aim of this work package is to develop a multi-sensor array demonstration unit, bringing together the outputs of the other work packages, which are all specifically focussed on supporting the device's creation
Click here for more information.



Fusion of Sensor Data with Buried Asset Records

The aim of this work package is to fuse geo-referenced information from multiple sensors and to combine this with an integrated database of buried asset records to increase confidence in their presence and location, and to determine missing asset records.
Click here for more information.

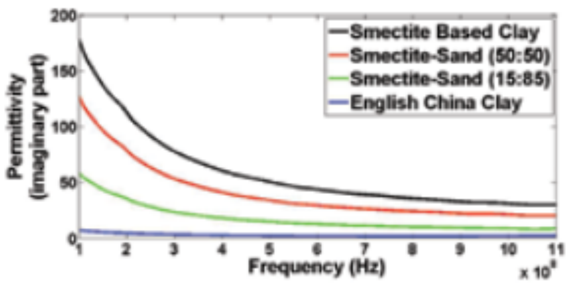
Proving Trials and Specification of a National MTU Test Facility

The aim of this work package is to conduct a comprehensive and rigorous programme of proof tests of the above technologies when combined in the multi-sensor device, and prove the efficacy of accurately tuning the devices to different soils and groundwater conditions. A further objective is to refine the set of criteria compiled in the MTU Phase 1 Feasibility Study for a UK National Test Facility.
Click here for more information.

MTU: Ground intelligence

DN Chapman, G Curioni (University of Birmingham)

Figure 2. Variation of the imaginary permittivity with frequency (i.e. dispersion) for different soil types and mixtures



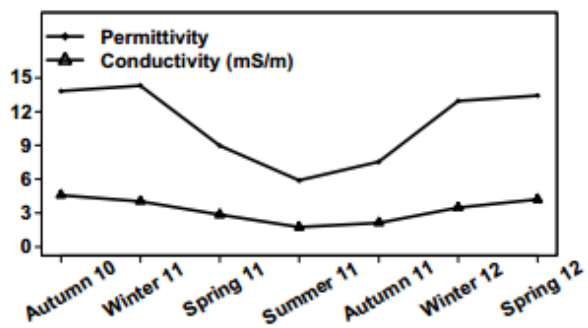
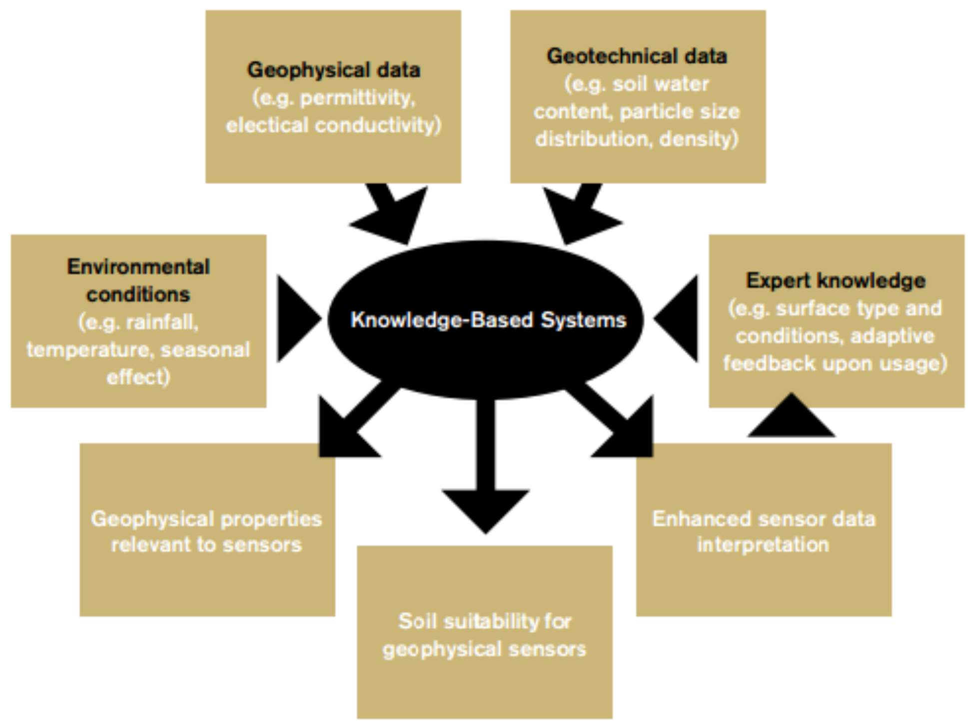


Figure 3. Seasonal means of permittivity and conductivity measured by the TDR monitoring station at the UoB campus

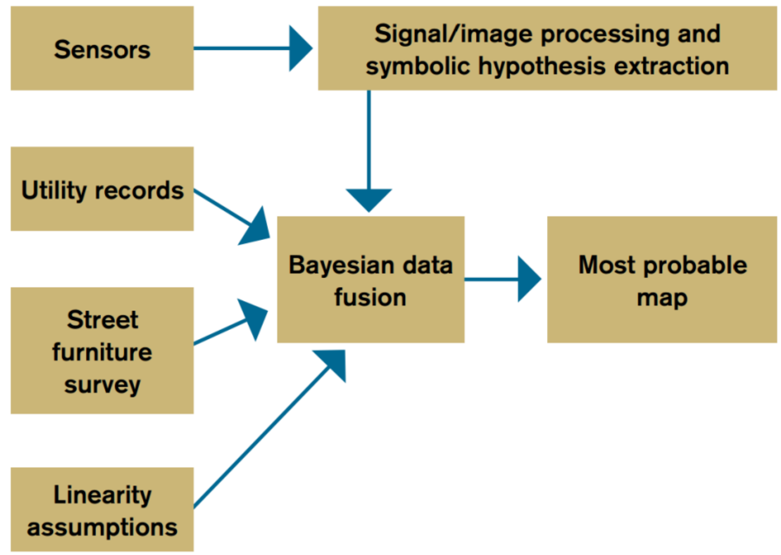
Figure 4. Structure of the Knowledge-Based System



MTU: Assets Matched to Sensors

Vibro-Acoustics
Passive Magnetic
Low Frequency EM
Ground Penetrating Radar

Figure 1. MTU Mobile Laboratory

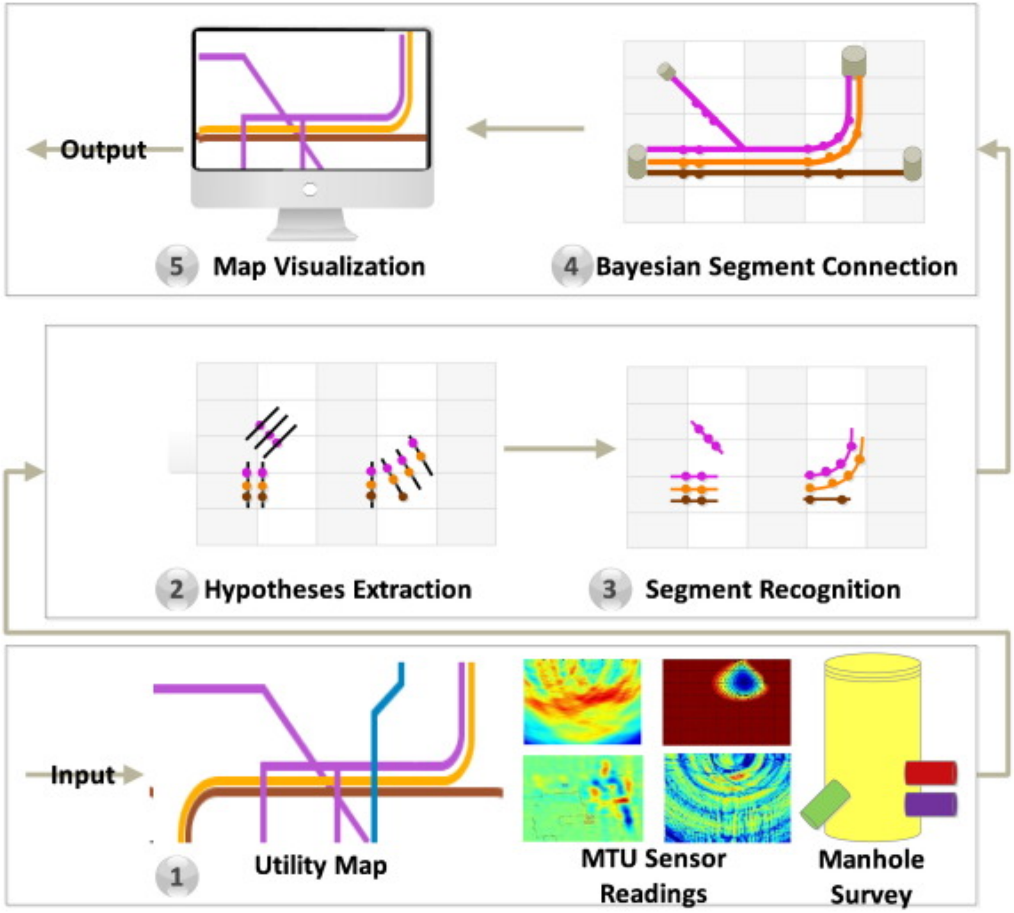


	Road Furniture Cable	Single phase cable	Three phase cable	Pot-ended cable	Plastic gas service pipe	Plastic water service pipe	Metal gas service pipe	Metal water service pipe
V–A	1	1	1	1	2	2	2	2
PMF	2	2	2	1	0	0	1	1
LFEM	2	1	1	2	2	2	2	2
GPR	1	1	2	2	2	2	2	2

	Plastic Gas mains pipe	Plastic Water mains pipe	Metal Gas mains pipe	Metal Water mains pipe	Asbestos cement water pipe	Drains	Telecoms duct shallow	Large Telecoms duct deep
V–A	2	2	2	2	1	2	1	1
PMF	0	0	1	1	0	0	1	0
LFEM	1	1	1	1	1	2	2	1
GPR	2	2	2	2	2	2	1	2

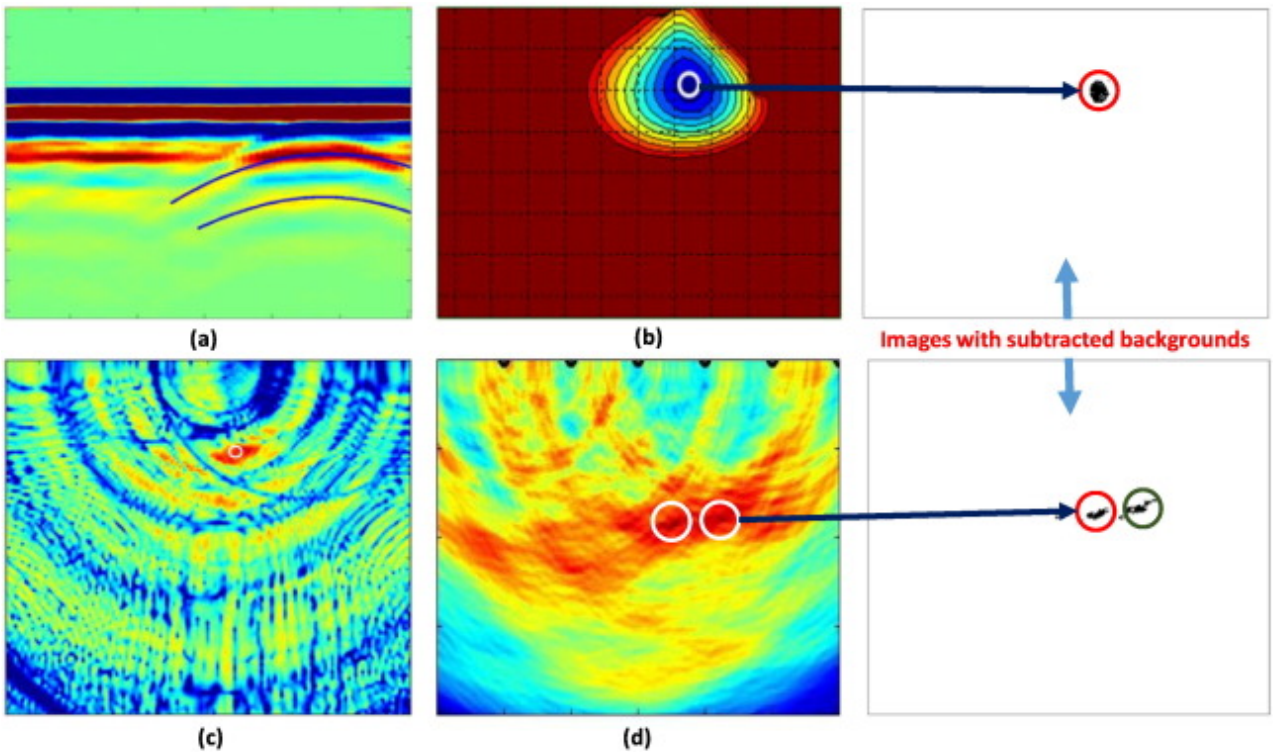
Figure 3. Matrix of operational capability – 2 = confidence of detection, 1 = lesser confidence, and 0 = little or no confidence [V-A, PMF, LFEM and GPR refer to the four sensor technologies]

MTU March 2018 Paper: *Inferring the most probable maps of underground utilities using Bayesian mapping model.*



Model Workflow (Data preprocessing for hypotheses extraction following segment recognition, Bayesian segment connection and refined map visualization.

MTU March 2018 Paper: *Inferring the most probable maps of underground utilities using Bayesian mapping model*.



Images taken from MTU sensors and processed to mark the hypotheses (hyperbolae and circles). The images were created from the raw data collected from **(a)** Commercial GPR, **(b)** Passive Magnetic Field, **(c)** MTU GPR, and **(d)** Vibro acoustics. (Right) Images **(b)** and **(d)** with backgrounds subtracted using image segmentation technique to extract hypotheses.

US: Transportation Research Board

Strategic Highway Research Program SHRP2: R01A,B,C

- R01A: Technologies to Support the Storage, Retrieval, and Use of 3-D Utility Location Data
- R01B: One Pass Multi-sensor Platform
- R01C: Location for Stacked or Deeper Depths
- Relevant Technologies:
  - R01B: Multichannel GPR, time domain electromagnetic induction (TDEMI), and high-frequency seismic imaging.
  - R01C: Seismic, Active/Passive Acoustic, Scanning EM, RFI Tags

ASCE CI 38-02

Australia: AS 5488

Subsurface Utility Engineering

Subsurface Utility Engineering (SUE) services enable project designers to manage risks associated with surprise encounters of buried utilities

American Society of Civil Engineers entitled "Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data" (ASCE CI 38-02).

SUE Quality Levels

- **Quality Level D: Records Research / Data Collection**
- **Quality Level C: Above-ground survey**
- **Quality Level B: Utility Designation(Geophysical methods here)**
- **Quality Level A: Test Hole / Potholing**

USDOT: Federal Highway Administration

$4.62 return on $1.00 investment

Canada: Ontario Sewer and Water Contractors Assoc.

$3.41 return on $1.00 investment

Going from sensing to objects

- Sense underground from multiple sensors:
  - Geophysical
  - RFID, etc.
  - Vibro-acoustic
- In parallel or iteration:
  - Fuse with other sensors, existing maps, and geotechnical cores using kriging, deep learning, and Bayesian models
  - Object extraction from matrix using segmentation
- Sense over time to track changes and establish baseline

The Smart-X {Cities, Buildings, Grids} Group

- Our group's expertise is machine learning, statistics, and data analytics on large datasets.
- These datasets also come from real time monitoring applications, like smart buildings and grids.
- Can process sensing data of underground structures
  - Extract properties of structures of interest or in the embedding matrix
  - Monitor changes.

Monitoring Over Time: 4D

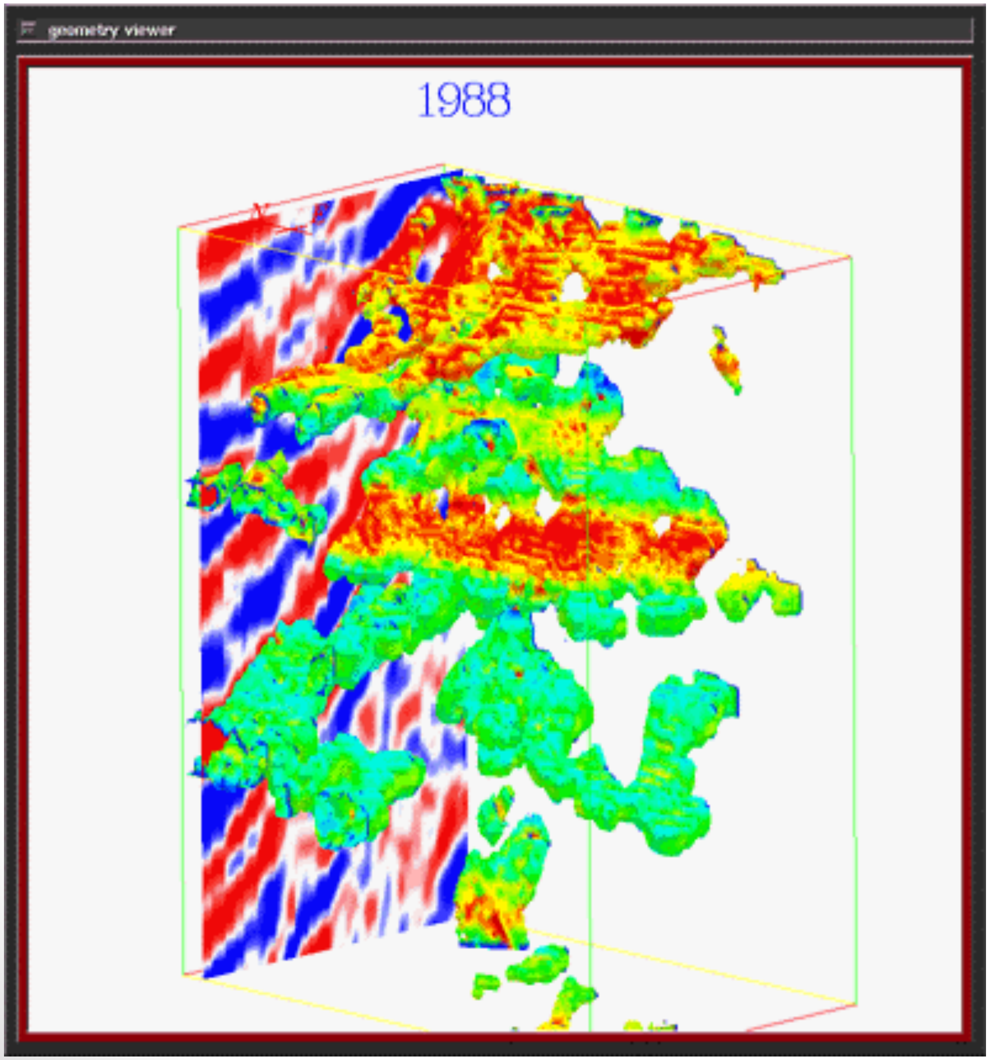
- We propose regular, and where appropriate, continuous geophysical mapping and monitoring of underground infrastructure
  - baselining
  - enhance situational awareness
  - forecasting, and predictions
  - ATU Self-Repairing Cities ASSESSING THE UNDERWORLD
- Compliment Accenture's Underground Infrastructure Mapping platform.

4D History

- The Smart-X {Cities, Buildings Grids} Group pioneered a 4D (or time-lapse) method to use geophysical data to monitor for changes over time in underground “structures” in the 90’s
  - Primarily used seismic data for oil and gas applications
    - also with ground penetrating radar (GPR) data.
  - The method used 3-D segmentation to isolate voxels contained in structures of interest
    - Collect just their statistics for advanced analysis
  - Tetrachloroethylene spill using (GPR): isolate the spill plume structure and deduce and analyze properties just within the structure.

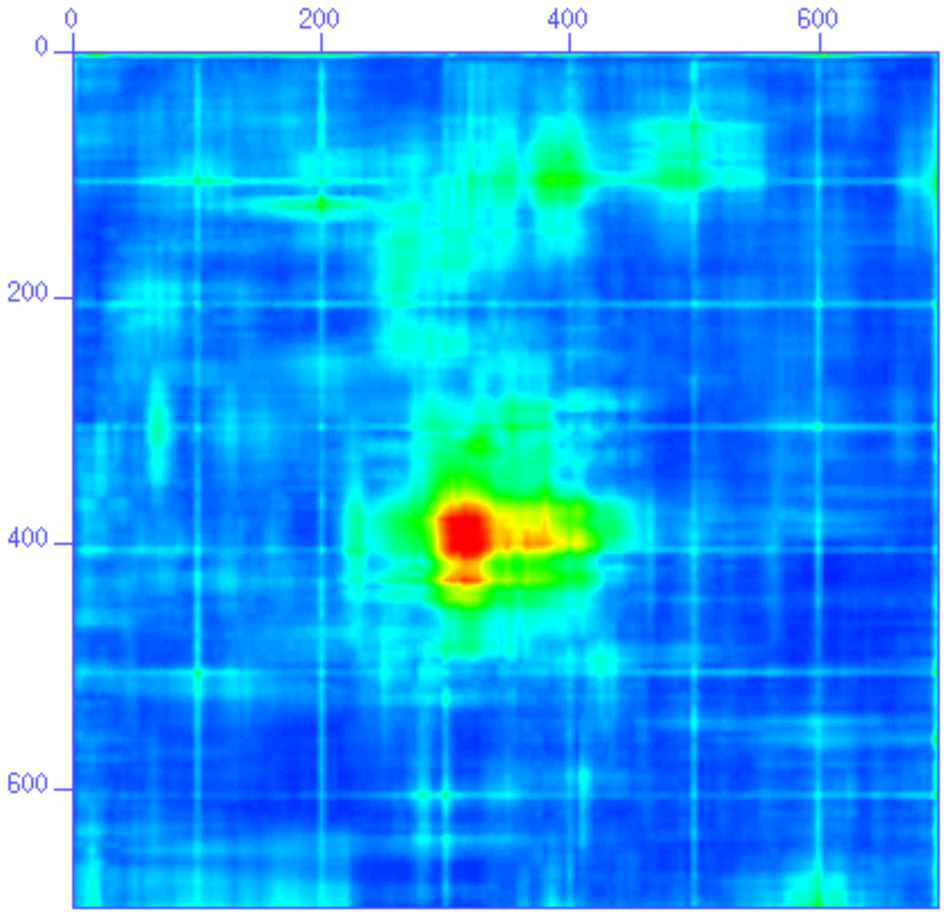
4D Monitors Shrinkage Due to Production

Examples of 4D (Time Lapse) Processing
(view in presentation mode for animation)



Oil and Gas stacked reservoirs isolated by region growing in a 1988 seismic survey and 1994 survey. Changes in oil, gas, and, water content as well as shrinkage of the stacked reservoir are easily identified.

4D applied to construction of hydrologic conductivity model

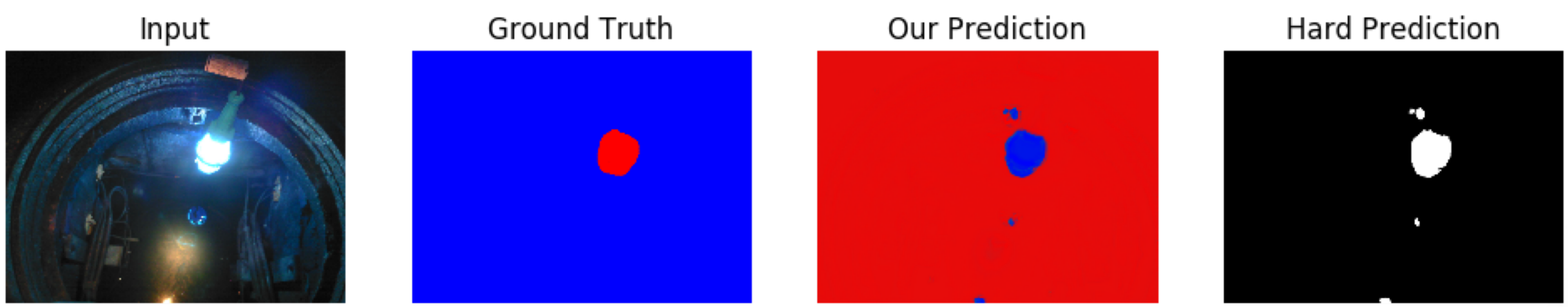


Time slice – 72

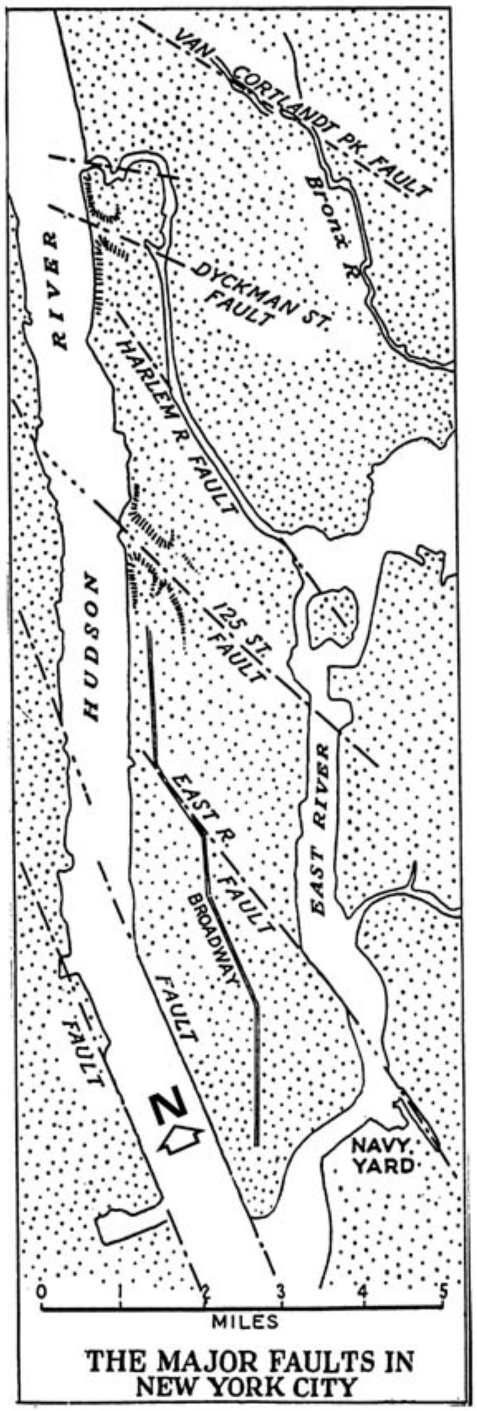
By tracking the DNAPL through the cube of data (actually here only 1.5 meter of the 2.5 meter is shown) we can determine what the path was that the DNAPL took through the sand. This path is considered to be a hydrologic conductive zone, and by inference, must have some different properties from adjacent zones which were not invaded by the DNAPL. The Movie is a series of time slices (or depth slices) through this hydrologic model. The index corresponds with the depth (from top sand)

Deep Learning

- Hitting new watermarks in accuracy and predictability.
- Deep learning combined with big data ingest is making advances where little progress has been made in the application of prior machine learning methods



Detection of lightbulbs to reduce artifacts in Thermal Imaging of Manholes using DL

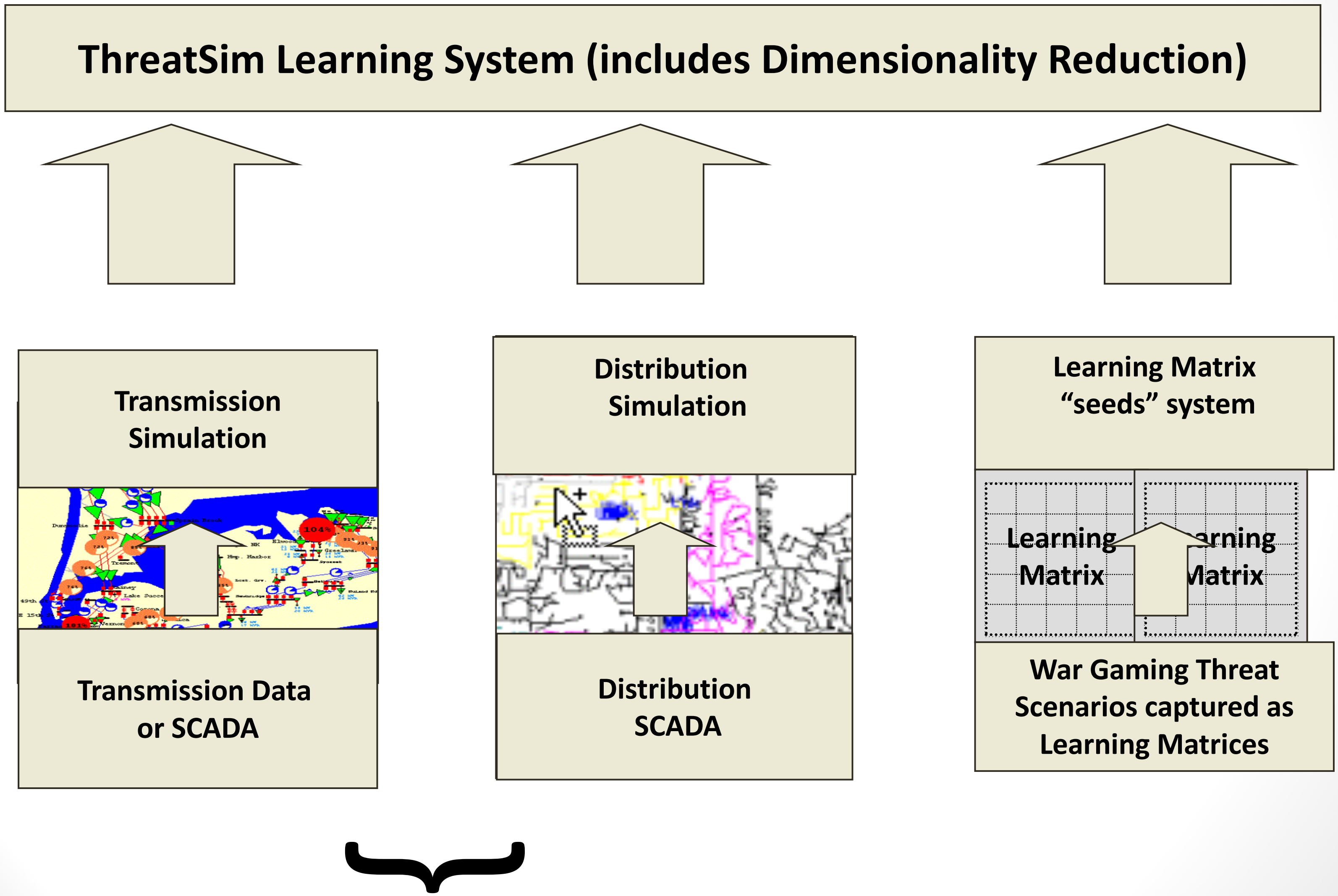


A Proposal

- We propose to apply and further develop advanced geophysical mapping, 4-D sensing, and data analytics in the real time integrated mapping of smart cities
- Study area centered on Columbia's Manhattanville development. The 125th Street fault runs though the development and adds impetus to the monitoring of the area.

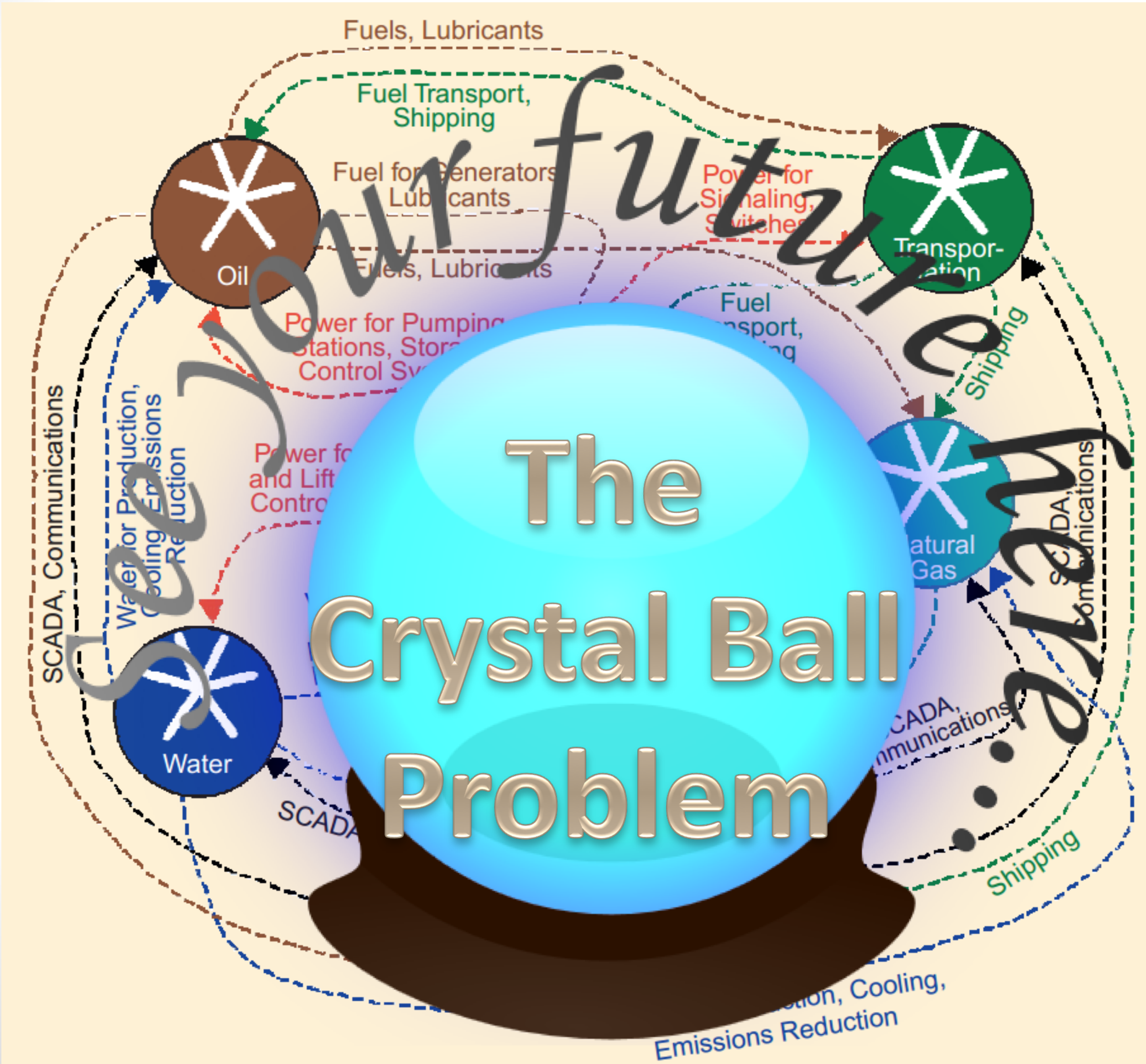
Manhattan fault map from Lobeck (1939)

Initial Concept After 2003 Blackout: ThreatSim



Single or multiple simulations of aspects of assets under threat

About Dependencies and a Warning



Resilient Infrastructure Initiative

S. M. Rinaldi, J. P. Peerenboom and T. K. Kelly, "Identifying, understanding, and analyzing critical infrastructure interdependencies," in IEEE Control Systems, vol. 21, no. 6, pp. 11-25, Dec 2001.

References

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  http://www.mappingtheunderworld.ac.uk/ http://assessingtheunderworld.org/
- Transportation Research Board (TRB) second Strategic Highway Research Program (SHRP 2) Multi-Sensor Platforms for Locating Underground Utilities (R01B):
  http://www.trb.org/Main/Blurbs/165612.aspx
- M. Bilal, W. Khan, J. Muggleton, E. Rustighi, H. Jenks, S. R. Pennock, P. R. Atkins, and A. Cohn, "Inferring the most probable maps of underground utilities using Bayesian mapping model," *J. Appl. Geophys.*, vol. 150, pp. 52–66, Mar. 2018.
- A Deep Neural Network to identify foreshocks in real time
  https://arxiv.org/abs/1611.08655
- Preparing for the Day the Earth Moves
  http://www.nytimes.com/2011/03/20/nyregion/20critic.html
- Earthquakes May Endanger New York More Than Thought, Says Study
  http://www.earth.columbia.edu/articles/view/2235
- Lamont 4D Visualization Applied to Ground Penetrating Radar
  http://www.ldeo.columbia.edu/~aboulang/4d4/radar/index.html
- Chapter from the Lamont 4D Seismic Handbook
  http://www.ces-enterprise.com/vpatch/bp/attachments/handbook/4D_seismic_23to28.pdf
- Online talk on Lamont's 4-D Seismic Method
  http://www.ldeo.columbia.edu/~aboulang/4d4/talks/eage/tool-index.html
- Lobeck, A. K., 1939, Geomorphology. An introduction to the study of landscapes: New York and London, McGraw-Hill Book Company, Inc., 731 p.

EXTRAS

Technologies

From TRB Report 2265 Innovations to Locate Stacked or Deep Utilities

Table B.1. Potential Technologies to Detect and Map Utilities

Technique	Utility Material	Property Measured	Soil Type	Detection Limit	Critical Property	Development Needed	State of Development
Acoustic holography	Any	Seismic velocity or attenuation	Any	Approximately 30 ft or less	Seismic velocity or attenuation contrast	High	Low
Active EM detection	Conductive	Radiated EM signal	Any	Less than 50 ft	Radiated field strength—imposed on line	Available now	NA
Frequency-domain EM	Generally conductive	Induced EM field	Nonconductive	Less than 10 ft	Conductivity contrast	Available now	NA
Capacitive EM	Any	Low-frequency EM	Any	Less than 20 ft	Dielectric contrast	Moderate	Low
Gas detection—chemical	Gas filled or containing volatile	Concentration	Any	Less than 50 ft	Gas or contaminant concentration	Moderate	Low
Ground-penetrating radar	All	Reflected EM field	Nonconductive	Less than 30 ft	Conductivity/permittivity contrast	Available, but modifications in progress	High
Induced polarization	Conductive	Electrical potential	Any	Approximately 30 ft	Conductivity contrast	High	Low
Infrared thermometry	Any	Temperature	Any	Approximately 10 ft	Temperature contrast	Available	NA
Leak detector	Fluid filled	Sound	Any	Less than 20 ft—leak-size-dependent	Radiated pressure field	Available in several forms	NA
Magnetic field	Magnetic	Magnetic permeability	Nonmagnetic	Less than 25 ft	Magnetic susceptibility contrast	Available	NA
Metal detector	Conductive	Induced EM field	Relatively nonconductive	Less than 25 ft	Conductivity contrast	Available	NA
Nuclear magnetic resonance	Contains polar molecules	Spin resonance	Relatively dry	Unknown	Variations in water content	Moderate to high	Existing systems are used on very large targets.
Passive EM detection	Conductive	Radiated EM field	Any	Signal-strength dependent, typically less than 15 ft	Radiated field strength	Available	NA
Pressure waves	Fluid filled	Pressure or acoustic wave	Any	Rated to 500 ft	Radiated pressure field	Available	NA
Resistivity	Any	Current/resistivity	Relatively nonconductive	Approximately 30 ft	Conductivity contrast	Available	NA
Seismic reflection	Any	Seismic velocity	Any	Approximately 30 ft or less	Seismic impedance contrast	Moderate to high	Needs to be done at higher frequencies.

(continued on next page)

Technologies (cont)

Table B.1. Potential Technologies to Detect and Map Utilities (continued)

Technique	Utility Material	Property Measured	Soil Type	Detection Limit	Critical Property	Development Needed	State of Development
Seismic refraction	Large diameter	Seismic velocity	Any	Approximately 30 ft or less	Seismic impedance contrast	Available but not for utility mapping	High
Seismic tomography	Size dependent	Seismic velocity or attenuation	Any	Approximately 30 ft or less	Seismic velocity or attenuation contrast	Available but not for utility mapping	High
Spontaneous potential	Conductive	Electrical potential	Any	Approximately 30 ft	Conductivity contrast	Available but not used for utilities	Moderate
Sonic	Hollow pipe	Sound	Any	Less than 50 ft	Radiated pressure field	Under development by Mapping the Underworld (MTU)	Low to medium
Sonic and subsonic acoustics	Any, preferentially large diameter	Seismic impedance or scattering	Any	Less than 150 ft	Acoustic impedance contrast	High	Low
Spectral analysis of surface waves (SASW)	Any	Ground motion	Any	Less than 30 ft	Seismic velocity contrast	Available but not used for utilities	Moderate
Time-domain EM	Generally conductive	Induced EM field	Nonconductive	Less than 10 ft	Conductivity contrast	Available and improvements possible	Low to moderate
Ultrasonic acoustics	All	Acoustic impedance	Any	Less than 10 ft	Acoustic impedance contrast	High	Low

Note: NA = not available.

UK's Mapping the Underworld

Mapping the Underworld

Home | About | News | Blog | People | Work Packages | Links | Affiliated Research | Publications | Discussion Forum | Contact Us

Project Summary

It is estimated that up to 4 million holes are cut into the UK road network each year in order to install or repair buried service pipes and cables. Failure to identify accurately the location of existing buried assets results in numerous practical problems, costs and dangers for utility owners, contractors and road users. Mapping the Underworld seeks to develop the means to locate, map in 3-D and record, using a single shared multi-sensor platform, the position of **all** buried utility assets without excavation.

» 25 year Vision!
» MTU Brochure
» Click here to watch the MTU animated video

Research began on the full research project to develop a multi-sensor location device, as part of the Mapping the Underworld Programme, in November 2008.

This project aims to build on the promising results of a feasibility study and use every possible advantage to see through the ground and focus on the targets. The research into the multi-sensor device is subdivided into eight complementary Work Packages, all of which focus on the device's creation and performance assessment. This project is made possible by a four-year ~£3.5M grant from the Engineering and Physical Sciences Research Council (EPSRC)

For more information, click here

Recent News Articles

- Mapping the Underworld Final Dissemination Seminar
- Mapping the Underworld and BBC Radio 4
- Mapping the Underworld on Radio 4
- A New Era In Location, Protection & Safety
- MTU/PIG Event 8 Sept 2011 - Pipeline Location and Condition Assessment

Recent Blog Articles

- Mapping the Underworld on Radio 4
- MTU animated video
- Pathways to impact video and podcast
- Wheel Process Video
- GPR Hardware Video
- February Event: In Pictures
- GPR2008 Proceedings Available

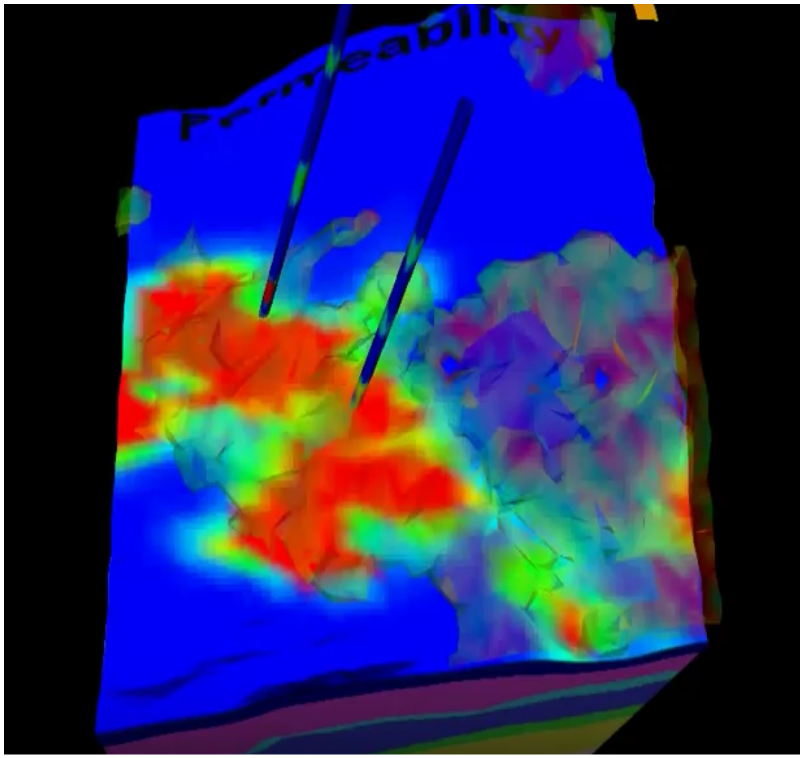
Contact Information: Mark Hamilton, Mapping the Underworld Project Manager | Telephone: 0121 414 3544 or 07795 811 539 | Email: m.hamilton.3@bham.ac.uk
Web Design by Darren Langley

EPSRC Engineering and Physical Sciences Research Council | University of Birmingham | University of Bath | University of Leeds | The University Of Sheffield. | University of Southampton | UKWIR

MTU Centre of Excellence
(MTU training QCF)

http://www.construction-skills-academy.co.uk/mtuce/

VRML (3-D Virtual world models) of 4-D analysis



Movies:

https://www.youtube.com/watch?v=GnB-B94rVl8
https://www.youtube.com/watch?v=1jky-Ro9w40
https://www.youtube.com/watch?v=iBhRfPdFrPM&t=109s
https://www.youtube.com/watch?v=9l6qZF9ObCU

VRML models:

http://tiger.aboulanger.com/vrml/cave/vrml-index.html