High Resolution Site Characterization (HRSC) Technologies & Applications

Vista GeoScience

SUBSURFACE IMAGING SYSTEMS

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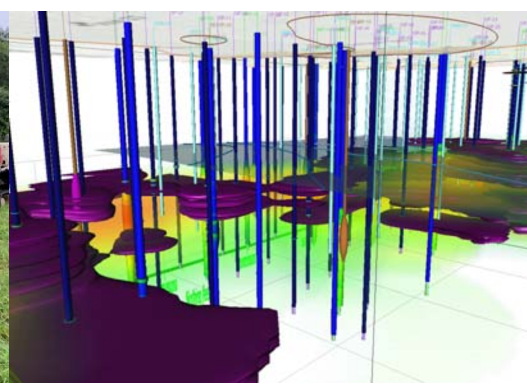

Advanced Site Characterization & Optimized In-Situ Remediation Support Services

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Advanced & Sustainable Site Characterization

A More Sustainable Path to Site Cleanup and Closure

The phrase "High Resolution Site Characterization" (HRSC) has been applied to many different methods, but generally (and in this document) **HRSC** refers to direct sensing tools used with direct push technology (DPT) drilling rigs including combinations of the Hydraulic Profiling Tool (HPT), Electrical Conductivity (EC), Optical Image Profiler (OIP), and Membrane Interface Probes (MIP).

In a recently sponsored study report* prepared for the U.S. Environmental Protection Agency (USEPA), "**High Resolution Site Characterization at Petroleum Underground Storage Tank Release Sites – Applicability, Benefits, and Costs**", the summarized key findings were as follows:

> **In comparison to traditional boring and monitoring well investigations at petroleum release sites, HRSC could:**
>
> - **Provide a more complete understanding of the release site geology and contaminants.**
> - **Increase confidence in corrective action decisions.**
> - **Help achieve No Further Action sooner.**
> - **Results in lower project costs by reducing monitoring costs and better targeting the remedial activities.**
>
> **For three common types of petroleum release scenarios the expert panel concluded HRSC could save on average:**
>
> - **9% to 19% in project costs.**
> - **3 to 8 years in project time.**

The study was focused on UST, refinery, pipeline, and other petroleum release sites. However, these same key findings will apply to chlorinated and other complex sites where these direct sensing tools are used.

*2023, High Resolution Site Characterization at Petroleum Underground Storage Tank Release Sites – Applicability, Benefits, and Costs. Final Report, April 13, 2023; Prepared for U.S. Environmental Protection Agency Office of Land and Emergency Management Office of Communications, Partnerships and Analysis and Office of Underground Storage Tanks; Prepared by: Industrial Economics, Incorporated, Cambridge, MA.

The Tools

Figure 1: HSRC tools.

Hydraulic Profile Tool/Electrical Conductivity (HPT/EC)

This HPT tool injects water to measure pressure, flow, and permeability. Bulk soil conductivity and groundwater Specific Electrical Conductance (SEC) is measured with the EC component of the tool. The HPT/EC tool is integrated into the OIP and MIP tools.

Optical Image Profiler (OIP, OiHPT-UV, OiHPT-G, OiHPT-UVR)

Three different light sources cause petroleum to fluoresce, which is detected and imaged by a CMOS camera chip or photometer. When integrated with the HPT/EC tool, the OIP provides detailed hydrostratigraphic information, in a single log run.

Membrane Interface Probe (MIP, MiHPT, LL-MiHPT)

This multifunction tool heats the soil to drive volatile organic compounds (VOCs) through a membrane, swept by a carrier gas to the surface, and measured by three detectors. This tool is operated in either a standard sensitivity mode, or an ultra-sensitive low-level mode.

Groundwater Profiling Tools (HPT-GWP, HPT-GWS)

This version of the HPT tool allows logging of injection pressure and flow and adds the ability to collect discrete groundwater samples at six-inch intervals.

Cone Penetrometer Testing (CPT)

The cone penetrometer tool is used for measuring geotechnical soil parameters by measuring tip resistance, sleeve friction, and piezometric pressure.

Pneumatic Slug Testing (PST)

The PST system was designed to perform high resolution slug tests in small diameter wells or Geoprobe Discrete Screen-Point samplers at discrete saturated intervals.

Real-Time Data & Subsurface Imaging Reports

REAL TIME DATA REVIEW: Data processed from these sophisticated tools are viewed as borings logs in real-time on the data acquisition computer. At the end of a log run, the logs are printed into readable PDFs, locations are posted on a live Google Earth Map, and all the data is uploaded to a cloud site. From there, office staff have the ability to review the data as it is being generated and make real-time decisions on where to step-out and drill next! The HRSC Logs are viewed on a computer, tablet, or your smart phone, from anywhere!

POST PROCESSING AND BASIC REPORTS: A post project Basic Final Report will include the following:

- Written summary of field activities.
- Log-run Summary Table.
- Quality Assurance/Quality Control (QA/QC), Response Test Methods and Review.
- Color Graphic Logs printed in two scaling formats, with all sensors.
- Color posted and contoured maximum sensor value maps highlighting plume data.
- Final edits of post-processed logs will include estimated hydraulic conductivity (K_{est}) and groundwater specific electrical conductance (SEC) values, were applicable.
- Optional - Excel or ASCII export files of the data, or Direct Image® (DI) Viewer files.

ADVANCED INTERPRETIVE & 3D CSM VISUALZATION REPORTS: An optional Advanced Report includes:

- Scaled Log plots in cross-section of selected sensor responses, corrected to elevation.
- Fence diagrams and cross sections of selected sensor responses and hydrostratigraphy.
- Power Point Report of 3-D Model diagrams of selected sensor responses (isosurface) and hydrostratigraphic plots.
- Integration and plotting of laboratory results with the above information.
- Advanced QA/QC Data Review.

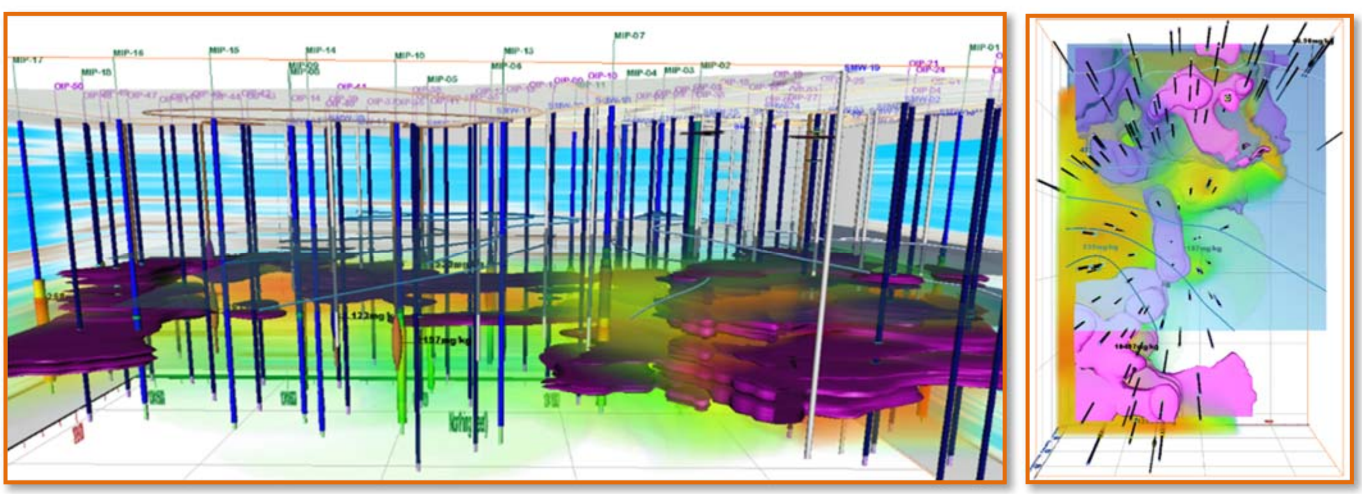

Figure 2: 3D visualization and conceptual site model (CSM) showing confined petroleum LNAPL, VOC plume, hydrostratigraphy, surface elevation model, groundwater elevation model, OiHPT and MiHPT borings, monitor wells, and confirmation soil core borings.

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Hydraulic Profiling Tool & Electrical Conductivity (HPT/EC)

HPT and EC are combined tools that measure injection pressure and flow, static pressure, and soil bulk conductivity. From that data, the software also generates a piezometric profile, logs of estimated K in the saturated zone, and groundwater SEC (Fig. 3).

The **HPT** works by measuring the pressure (P) and flow (Q) required to inject water into the soil as the probe is advanced into the subsurface. The injection pressure and flow logs are good indicators of relative permeability and lithologic properties. The HPT is also used to measure hydrostatic pressure under zero-flow conditions, which allows the development of an absolute piezometric pressure graph for the log and prediction of the position of the water table.

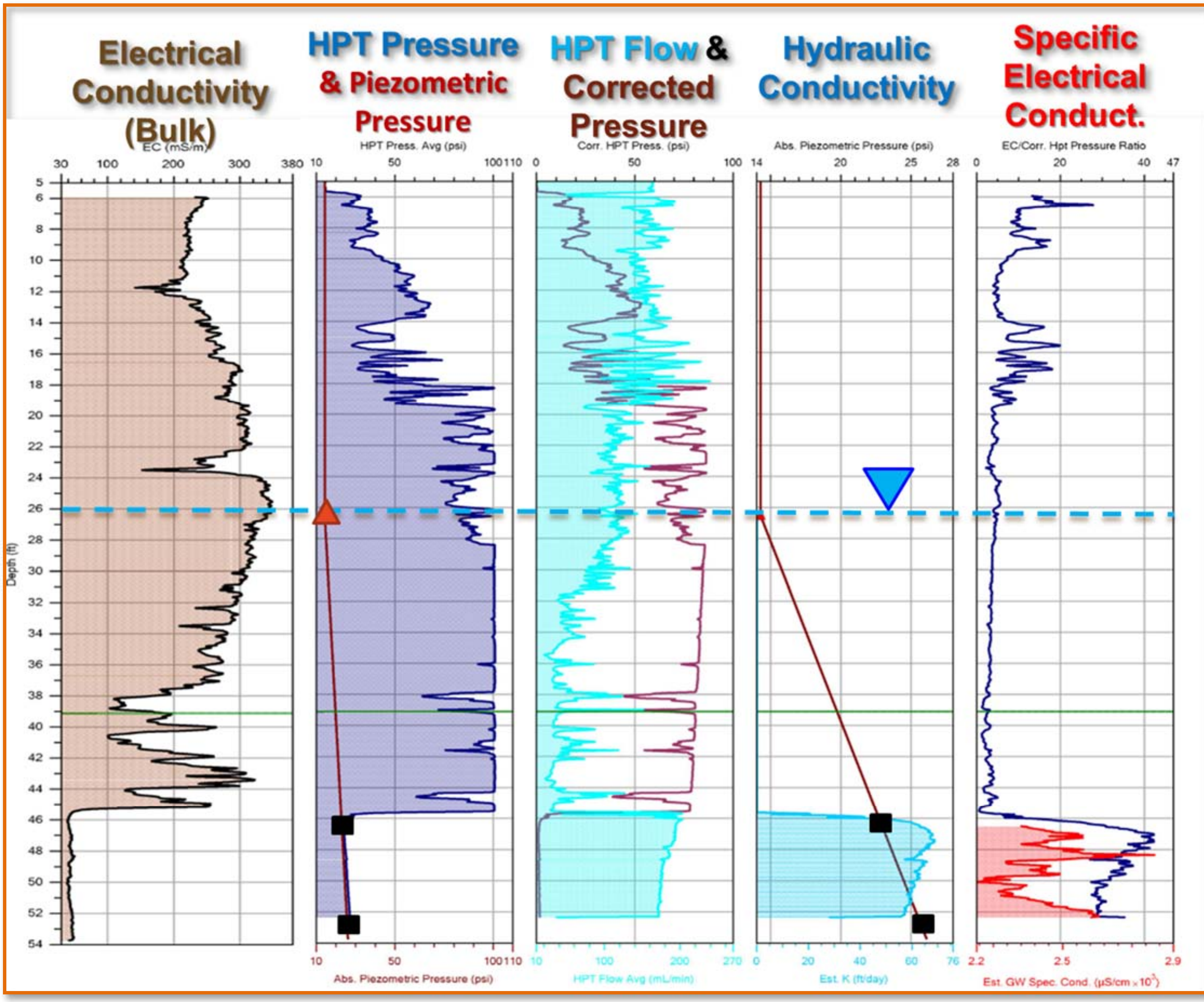


Figure 3: Example logs using HPT/EC.

Formation hydraulic conductivity is estimated from HPT logs using empirical relationships developed for the tool. These estimations are calculated automatically using DI Viewer software. A graph of hydraulic conductivity estimated from an HPT log is shown on Figure 3. Data from this estimate is readily transferable to groundwater flow models.

The rate of advancement of the probe is targeted at no more than 4 feet (ft) (1.22 m) per minute. Therefore, an average daily production of 200-300 ft per day is expected.

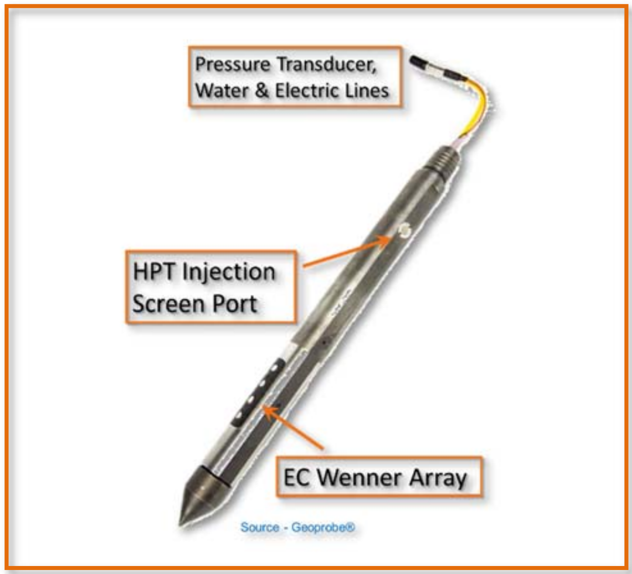
HPT Quality Control: Before and after each log run, the pressure sensor in the HPT tool is tested by measuring differential head pressure in a short water column at the surface. The results of the test are recorded in the log file.

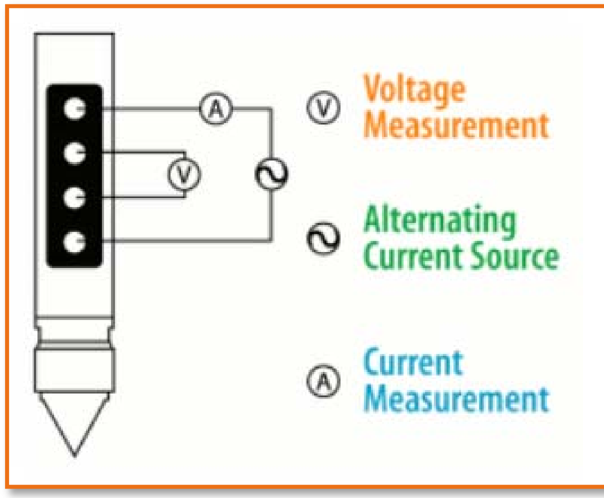
EC is integrated into all of the subsurface imaging tools to measure soil conductivity. Soil conductivity and resistivity (the inverse of conductivity) have long been used as tools to classify soils or rock formations. Soil conductivity, in general, varies with grain size. Finer grained soils, such as silts or clays, tend to produce higher EC signals than coarser grained sand and gravels.

As shown on Figure 4, specific values are not assigned to each soil type; however, each soil type typically provides a different response on a specific site. The coarser grained sediments will allow the migration of contaminants and the finer grained sediments will trap and store contaminants. The EC gives the investigator real-time, on-screen logs allowing onsite decisions. When used in conjunction with HPT data, relative permeability of the soils is also identified, adding powerful information to the soil characterization task.

EC Quality Control: The continuity of the dipole array and response is checked before and after each log run. The test response information is recorded in each log file verifying the check was done.

HPT-GPW and HPT-GWS are two other versions of the HPT tools are available that include additional screen ports to log HPT data and collect groundwater samples at multiple discrete intervals in a single boring.





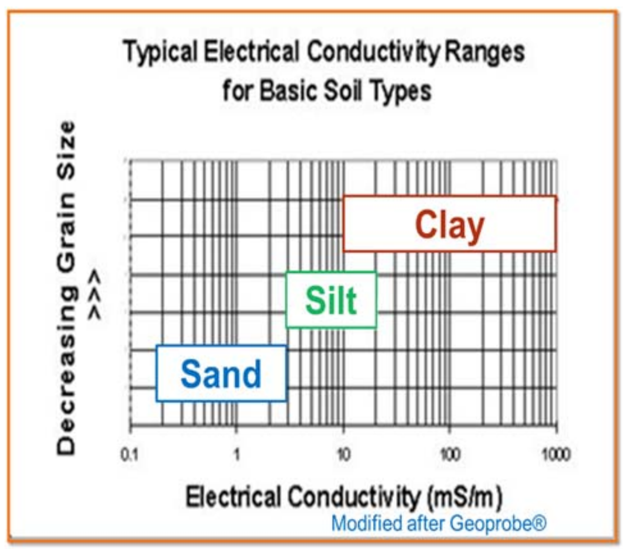


Figure 4: HPT/EC diagrams and soil conductivity relative to grain size.

Membrane Interface Probe (MIP, MiHPT)

MIP is used for field screening and rapidly mapping sorbed and dissolved phase VOCs, typically petroleum and chlorinated solvent contamination. The MIP will quickly delineate both the horizontal and vertical extent of contamination and identify relative concentrations down to parts per million (ppm) or parts per billion (ppb) levels using the Low-Level MIP option. The MIP systems are combined with the HPT and EC, known as the **MiHPT**.

The MIP is driven by DPT and continuously logs VOC detections as it is pushed through the soil at a constant rate. The MIP heats the soil and water to increase the vapor pressure of the contaminants. The VOCs pass across a semi-permeable membrane and are carried to the surface by an inert gas via small diameter tubing. At the surface, the VOC mass is passed through selective chemical detectors to provide a continuous correlation between contaminant detection and the depth of the probe at the point of detection. Vista's standard MIP sensor detection system utilizes three laboratory grade detectors that are built into a ruggedized instrument. The detectors include:

- **Photo Ionization Detector (PID)**
- **Flame Ionization Detector (FID)**
- **Halogen Specific Detector (XSD)**

Operated in Standard Mode, the MIP system detect common VOCs at levels ranging from 0.2 to 2.0 ppm. If lower detection limits are required, the MIP system is operated in Low Level mode (see next section.)

The MIP tool is integrated with an EC dipole and HPT injection port to simultaneously log hydrostratigraphy and lithology.

The probe is typically pushed at an average rate of approximately 2 centimeters (cm) per inch, or 15 seconds per foot.

Quality Control: All instruments are continuously monitored by the software and the operator is notified of out-of-spec conditions. A response test using a standard (e.g., tetrachloroethene [PCE], trichloroethene [TCE], benzene, etc.) in water is run before and after each log run by exposing the membrane to the standard. The use of the standard aids in demonstrating instrument sensitivity and condition of the replaceable membrane. The results of the response test are recorded in the digital log files with each log run.

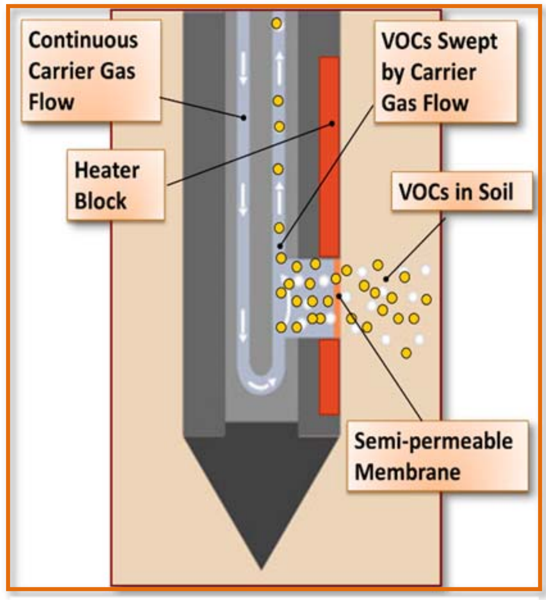


Figure 5: Schematic of MIP probe tool showing carrier gas flow and VOC capture through the membrane.

Figure 6: Detector instrumentation for MIP system with PID, FID, and XSD selective detector suite.

Low-Level MIP (LL-MiP, LL-MiHPT)

LL-MIP is a technology that increases the sensitivity of the MIP logging tool and is typically applied to mapping chlorinated solvent or mixed plumes. The primary feature of LL-MIP technology is that the carrier gas stream that sweeps the internal surface of the MIP membrane is pulsed, or paused, at selected intervals. This results in an increase in the concentration of a VOC contaminant delivered to the MIP detectors and a 10x or better increase in sensitivity. LL-MIP is also performed with the standard MiHPT probes, which is known as **LL-MiHPT**.

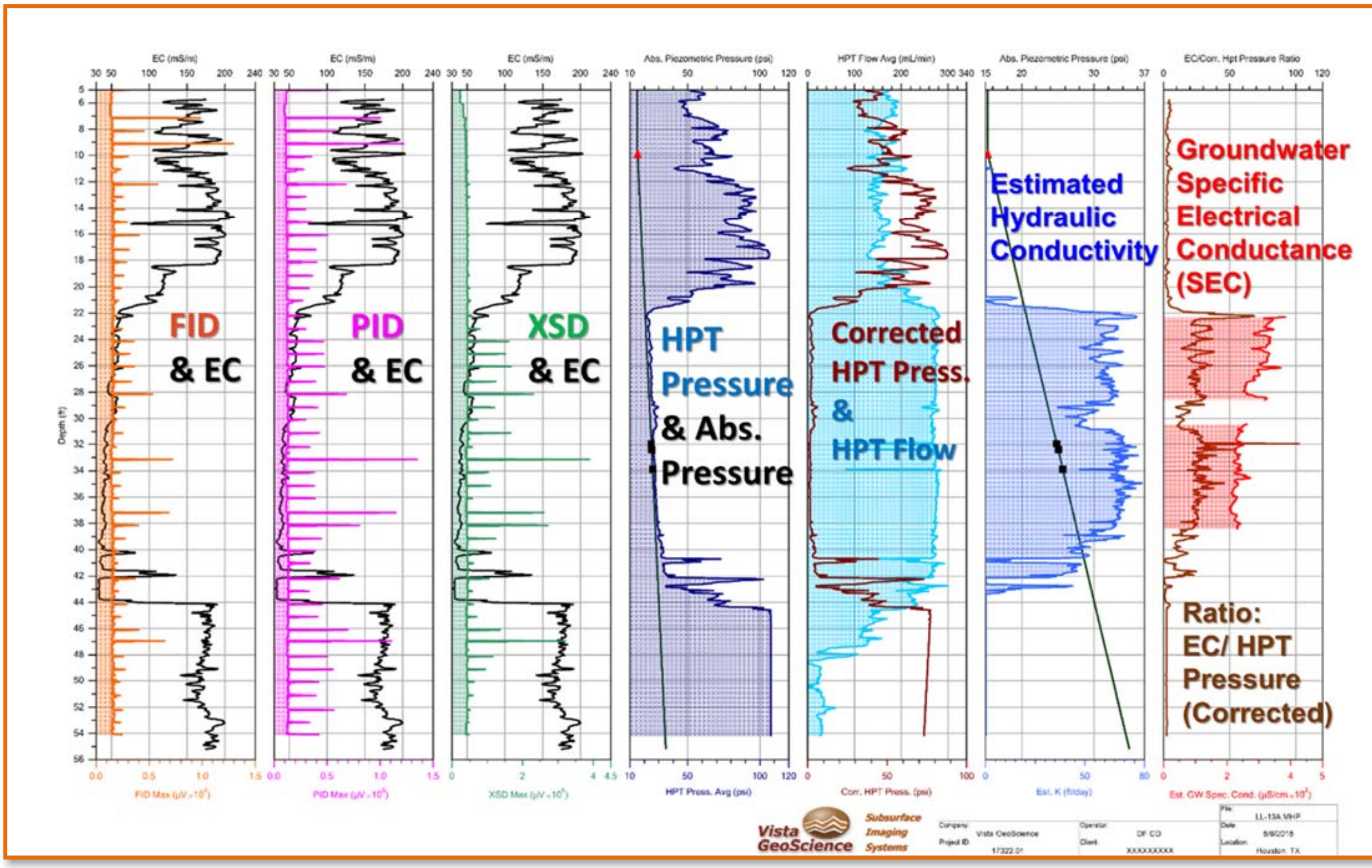


Figure 7: Sample MiHPT log run in Low-Level mode showing the chemical sensors (FID, PID, XSD) along with Electrical Conductivity, Injection Pressure & Flow, Corrected Pressure, Absolute Piezometric Pressure, Estimated K, and groundwater SEC, all completed in a single boring push!

Typically, advancing the probe is paused at one-foot intervals to collect the concentrated samples. The result is the saw tooth pattern seen in the detector responses on the log graph shown on Figure 7. A switching valve creates separate flow paths for the MIP trunkline and detectors; trunkline flow is stopped and restarted without affecting detector baseline or stability. When the trunkline flow is restarted, the contaminant mass (peak) is quickly swept to the surface and is routed to the detectors giving a 10x or better magnified response to any VOCs present. Low Level mode takes approximately 20-40% longer to run than the standard mode; therefore, a decrease in daily footage rate is expected.

Optical Image Profiler (OiHPT-UV, OiHPT-G, OiHPT-UVR)

The OIP tools that detect non-aqueous phase liquids (NAPLs) now come in three configurations with different combinations of excitation light source options and sensors. The OIP tools are configured with HPT and EC to simultaneously capture lithology and hydrostratigraphy.

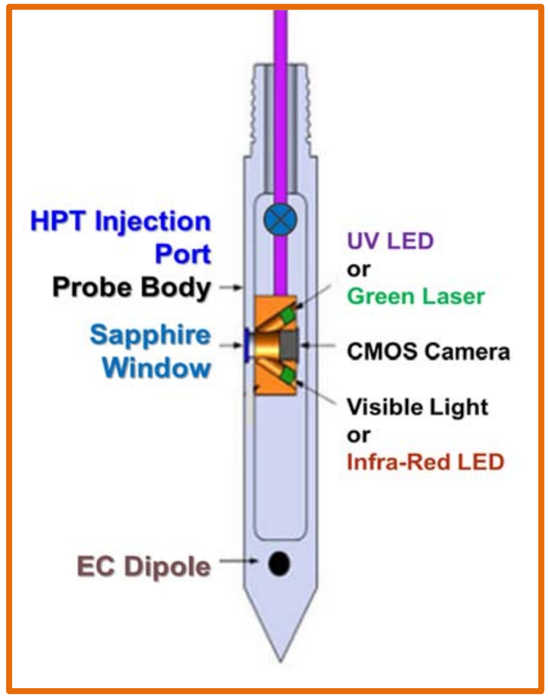


Figure 8: OIP-G/OiHPT-G tool diagram.

OIP-UV, OiHPT-UV was developed for the detection of lighter non aqueous phase liquids (LNAPL) fuels (gasoline, diesel, motor oil, condensate, etc.) that will fluoresce when exposed to a 275 nanometer (nm) ultraviolet (UV) light source. During the advancement of the probe, images of the soil are taken through a sapphire window utilizing an onboard camera (CMOS sensor) as seen on Figure 8. The image color is analyzed by the software for presence of fluorescing light colors consistent with that of known fuels. The fluorescence is measured as the amount of fluorescence within the area of the image, or percent area fluorescence (%AF).

Previous to the OiHPT-UV's development, the only other tools for measuring petroleum NAPL was the laser induced fluorescence (LIF) system. The OIP tool provides very similar data

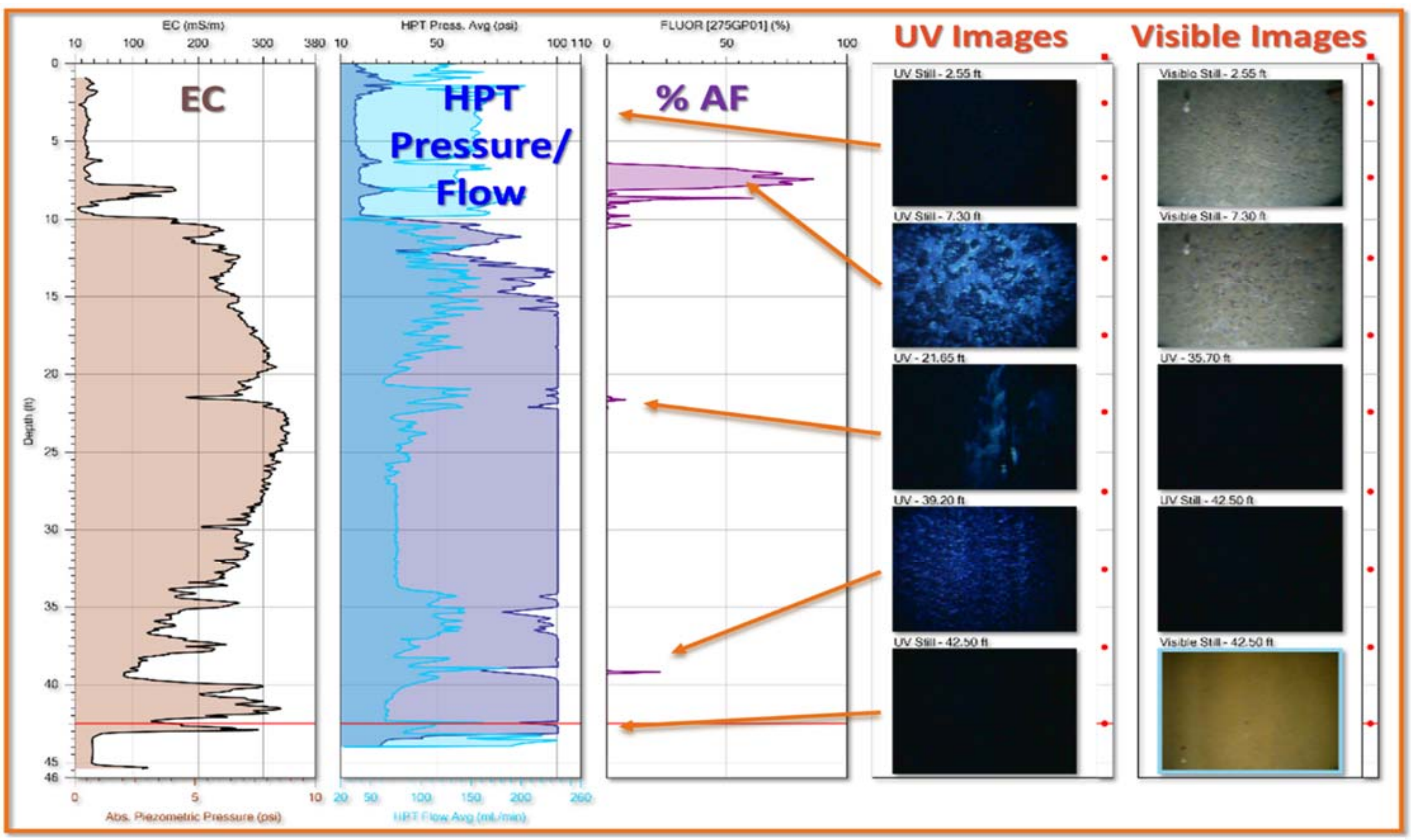


Figure 9: The above log shows bulk soil conductivity, injection pressure and flow, and %AF of the LNAPL, in a perched zone, as well as two thin confined sandy stringers. Selected UV fluorescence and visible light captured images are shown to the right of the %AF log.

and response characteristics to the LIF/UVOST system, but at a lower cost. Instead of a laser source, the OIP tool uses a modern light emitting diode LED source, both ultraviolet and visible light. At selected depths, the operator stops the probe and captures still images using visible light and UV light as seen on Figure 9. The rate of advancement of the probe is targeted at no more than 4 ft (1.22 m) per minute. Therefore, an average daily production of 200-300 ft per day is expected. Colors are filtered to select petroleum fluorescence, but occasional mineral fluorescence may interfere with the response, which is interpreted through examination of the images.

OIP-G, OiHPT-G Green Laser system is designed for identifying the fluorescence of heavier polycyclic aromatic hydrocarbons (PAHs), such as with creosote, crude oil, or coal tar, as seen on Figure 10. Since heavier PAHs absorb the shorter wavelength UV light, a longer wavelength excitation light is required, which causes stronger fluorescence of the PAHs in the yellow to red light wavelengths. An optical filter in the probe removes the interference from the shorter wavelengths, including the green light, which allows the detection of heavier NAPLS that may be found as solid petroleum compounds (often DNAPLS). Soil texture is also be viewed by switching to the Infra-Red (IR) light source.

Figure 10: Example images from the OIP-G system.

OIP-UVR, OiHPT-UVR tool is the most recent version of the OIP and was developed to see refined products that only have single-ring aromatic hydrocarbons. These single-ring aromatic hydrocarbons fluoresce in the invisible ultra-violet range between about 300-375 nm, which may include some kerosene or aviation fuels. The camera chip will only detect visible light, so a photometer sensor was added to the **OiHPT-UV** system to detect this unique fluorescence signature.

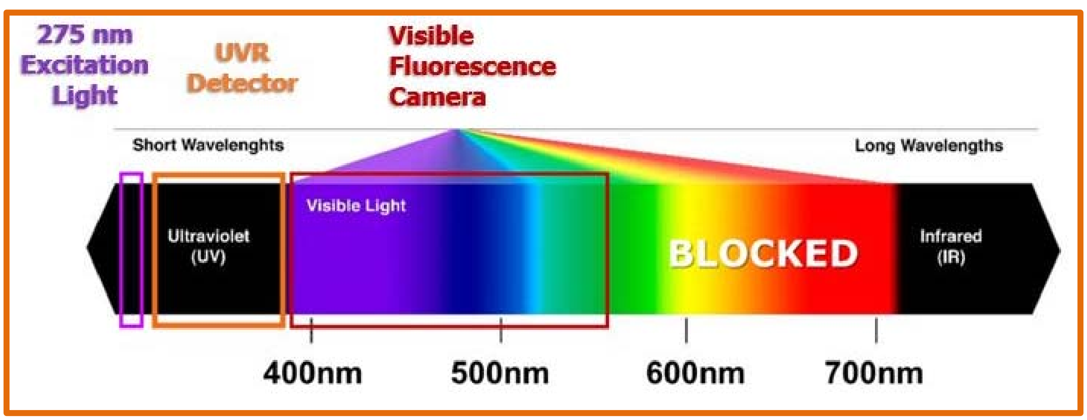


Figure 8: Electromagnetic spectrum showing fluorescence detector ranges.

Quality Control: The fluorescence response of the tool is checked using liquid petroleum standards in a quartz cuvette placed up against the sapphire window before and after each log run. A patterned image is also imaged, as is a black image, to test the focus and quality of the image. The response results and captured images are recorded in the log file.

High Resolution Soil and Groundwater Sampling

While the subsurface imaging tools provide millions of data points across a site, the tools only provide qualitative and relative numbers. Confirmation sampling is part of quality control in HRSC standard operating procedures to ensure that the responses are detected in the soil and groundwater, as well as not showing false positives. Quantitative data is needed for certain project objectives, e.g., remediation design to determine treatment reagent dosing, etc. Once the tools have identified highly focused areas of interest, high resolution soil and ground water sampling is recommended to collect additional information, and the optimal placement of monitoring and or treatment wells.

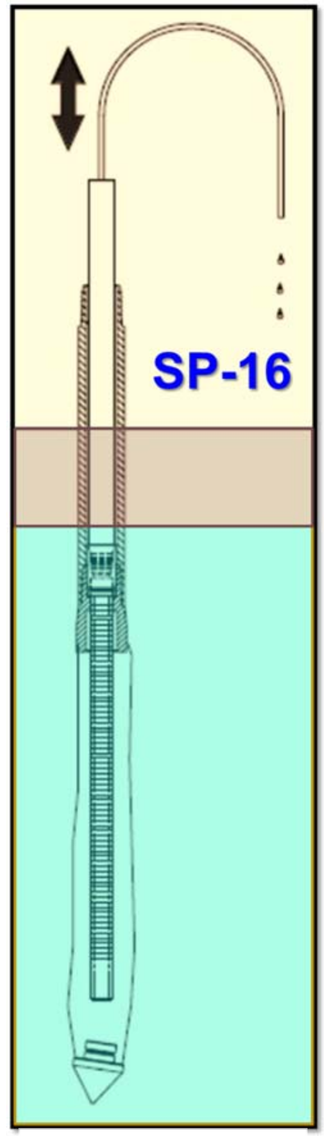


Figure 13: Discrete groundwater sampler.

Continuous Soil Core Collection

For confirmation sampling, continuous soil core sampling is completed using a Geoprobe® **DT32 or DT22 Dual-Tube** sampling system. The advantages of dual-tube sampling is having an outer casing pushed while collecting continuous soil cores with an inner rod string. The benefits of using the Geoprobe® DT32 or DT22 Dual-Tube sampling system is that there is no tripping in and out of the bore hole, smeared slough, or cross contamination from pushing contaminants to deeper intervals as when using conventional core tubes. The outer casing may also be outfitted with an expendable cutting shoe to allow for small diameter PVC or pre-packed well screen installation after continuous coring is complete. Pressure grouting is also possible with the dual tube system since the outer casing is in place during the entire coring process.

Figure 12: Collecting discrete samples from 40 feet of continuous soil core.

Discrete Groundwater Sampling

Discrete groundwater samples are collected economically at specific depths using retractable Screen Point **(SP-16, SP-22) samplers**, or by nesting temporary tubing implants with short-screened intervals in DPT core holes. The temporary wells are completed through the dual-tube system allowing nested screens and grouted intervals. The HPT tools described in the earlier sections identify the permeable flow zones and aquitards for optimizing sampling for well screen intervals.

Figure 9: Screen Point Samplers with screen extended.