Technical Communication

An Introduction to the Use of Airborne Technologies for Watershed Characterization in Mined Areas

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Abstract. Airborne geophysical and imagery technologies can be used to rapidly characterize watersheds. Frequency domain electromagnetics (FDEM) and thermal infrared (TIR) imagery are being used to map surface and subsurface hydrologic features. FDEM is being used to map water-filled fractures and voids that serve as groundwater conduits; TIR is being used to identify locations where groundwater discharges to the surface. The benefits of airborne reconnaissance include: significant cost savings through large-scale data collection, reduced landowner-access issues, improved watershed management practices, efficient targeting of costly, high resolution ground investigations, and superior techniques for locating drilling sites. The papers that follow this overview provide detailed descriptions of the application of these technologies on a case study basis.

Introduction

The National Energy Technology Laboratory (NETL) is testing and evaluating various remote (airborne) sensing technologies to determine their value as watershed characterization tools (Ackman et al. 2001) (Figure 1). Thus far, NETL has conducted 14 airborne thermal infrared (TIR) and eight geophysical surveys in the coal mining regions of West Virginia, Pennsylvania, Maryland, Ohio and an abandoned mercury mine (an EPA Superfund site) in California. To date, more than 1,000 km^2 (400 mi^2) have been surveyed using airborne TIR imagery and geophysics. Two case studies of frequency domain electromagnetics (FDEM) (Hammack et al. 2003a, b) and two case studies of TIR (Sams et al. 2003a, b) will be presented in this special journal edition.

The long-term objective of this research is to develop and/or assess airborne tools that can rapidly and economically: identify groundwater pathways on a large-scale basis (including the natural geologic infrastructure), assess pollution sources, and aid in inventorying water supplies. The short-term objective is to evaluate the combination of airborne and corresponding ground-based technologies for characterizing abandoned mine sites, industrial sites, or other large areas that may be adversely impacting existing and future water supplies. This approach is designed to expand the science of watershed characterization by demonstrating that near-surface (up to approximately 100 m depth) groundwater tables and flow paths (including surface interaction zones, e.g., seeps, springs, stream loss zones) can be rapidly and accurately mapped. This mapping ability will allow managers to effectively prioritize and plan ground-based investigations (drilling, water quality, flow measurement activities, geophysical surveys, etc.) for the entire watershed, rather than just focusing on small project areas. Subsurface zones where man-made (e.g., chemical spills) or geo-chemical pollution interacts or intercepts natural groundwater can be identified. These include: 1) areas (pathways) where clean surface and/or groundwater enters into pollution-generating mine pools, 2) areas where polluted mine water is being discharged from the mine pool, and 3) areas where surface spills (or runoff) and subsequent infiltration enter into the groundwater system.

Airborne technologies can provide large-scale maps of groundwater discharge sites or 3-dimensional depictions of potential groundwater flow paths. Moreover, these technologies have the potential to provide significant insight relative to the management (e.g., pollution prevention, supply and demand) of the

Figure 1. Helicopter with sling load of geophysical instruments

world's water resources. This paper will provide an overview of some of the technology available and will introduce the more detailed papers that follow, recognizing that the field is rapidly progressing and what cannot be accomplished today may be possible tomorrow.

Background

Environmental remote sensing began when NOAA launched meteorological satellites in the 1960s, and continued with land and ocean satellites such as Landsat, SPOT.ERS, JERS, and Radarsat. These early satellites can map and monitor large-scale environmental problems, but their resolutions are too low for detecting small-scale problems (Henderson 2000). During the early years of remote sensing, extracting useful information from raw satellite data was restricted to large companies that could process the digital data in large mainframe computers. Today, with inexpensive computing capabilities, sophisticated data processing, the Geographical Information System (GIS), the Global Positioning System (GPS), and rapid telecommunications through avenues such as the Internet, today's user of remote (airborne or satellite) sensing imagery can be almost anyone anywhere with the appropriate tools. This change immensely increases the user market for such capabilities and for the information and intelligence that can be derived from many previously disconnected data sources (Henderson 1995).

With the more recent introduction of commercial, high-resolution satellites with multispectral and hyperspectral sensors, spatial resolutions have been reduced to a typical range of about 2 to 4 m (Coetzee et al. 2002). Hyperspectral remote sensing allows high-resolution measurements of a material's spectra, making it possible to identify an area's specific minerals, rocks, soils, and vegetation, and the changes over time that record an ecosystem's health (Henderson 2000). Specific spectral reflectance and absorption characteristics have been used to indicate the presence and type of a particular mineral, such as hematite or goethite (Bigham 1994). Spectral classification with a field spectroradiometer can be extrapolated to imagery-based sensors so that large areas can be analyzed.

Mapping with high-resolution spectral images is also useful for studying and monitoring acid mine wastes and their impacts on surrounding watersheds. Remote sensing has been used effectively to characterize acid mine drainage (AMD) based upon the spectral properties of mineral precipitates formed in affected streams and lakes (Alexander et al. 1973; Repic et al. 1991; Anderson and Satterwhite 1995). The USGS recently used an airborne multi-spectral technique to differentiate net acidic and net alkaline creeks, based on the distinctly different colors of the mineral precipitates, which are due, in part, to the various types of bacteria associated with these precipitates (Robbins et al. 1996).

Airborne Thermal Infrared

Airborne thermal infrared imagery can clearly identify springs, seeps, and sewage that discharge on land or in shallow water-bodies when the temperature differential between surface features and groundwater is large enough (Sams et al. 2003a,b). Optimal conditions exist when the data is collected at night, in the winter, and with leaf-off conditions. This technique has proven to be very effective at rapidly surveying large areas to identify where natural groundwater and non-point source pollution sites are discharging. The most significant development for commercial applications of this technology occurred about 3 years ago with the introduction of a position and orientation system that provides trajectory data, which is used to record the orientation of the sensor head on the multi-spectral line scanner. This instrument configuration allows data to be georectified for distortions brought about by aircraft attitude (pitch, roll, and yaw). Consequently, thermal anomalies extracted from the imagery are more accurate with respect to map coordinates and can be accurately incorporated with GIS. The reported thermal and spatial resolutions of these surveys are 0.1ºC and 1 m or less, respectively (Howard 2001). However, it must be noted that some thermal anomalies may go undetected due to obscuring vegetation; FDEM can sometimes be used to find such locations.

Airborne Geophysics

The remote spectroscopic techniques described above have undergone significant improvements in resolution during the past decade and been proven both effective and valuable in identifying numerous surface features (e.g., temperature (land and water), mineralogy, vegetation, water quality). However, these technologies cannot provide subsurface data (e.g., subsurface flow paths or plumes, depth to mine pool or water table, surface recharge zones, source of ground water), which are often needed to efficiently and effectively implement remedial or pollution prevention actions. Airborne and ground-based geophysical technologies, which have historically been used for exploration work, are now being used to provide the subsurface, hydrological information necessary to map groundwater features (Hammack et al. 2003a, b).

The current arsenal of geophysical techniques covers a wide range of methods, from gravity, magnetometry, electromagnetics, electrical resistivity, and radiometry, which are all used for mineral exploration, to the advanced seismic techniques that have become essential tools in petroleum exploration (Spies 2001).

Electromagnetic (EM) methods are ideally suited for locating and mapping underground mine pools and groundwater flow paths. EM methods are based on the principle of inducing eddy currents in conductive material by varying the magnetic field in a transmitter wire loop. The eddy currents are detected by measuring their associated secondary magnetic fields in an ultra-sensitive induction coil. Metal detectors used for airport security and treasure hunting are based on the same principle (Spies 2001). EM techniques have been proven useful for: groundwater exploration, mapping industrial groundwater contamination, mapping general groundwater quality (i.e., salinity) and saline intrusion, and mapping soil salinity for agricultural purposes. Factors affecting the use of EM methods include, but are not limited to: target depth from the surface, water quality, previous mining activity, cultural features (e.g., electrical power lines, buried utility lines, bridges), soil characteristics, void fill material or lack of material, geological anomalies and cost.

The sophisticated use of airborne EM was made possible by the introduction of digital systems in the 1980s, which greatly improved the signal to noise ratios. This allowed a greater depth of penetration, which in turn expanded applicability and improved signal fidelity. The wide frequency content of modern systems enables the separation of near-surface and deeper features that cannot be resolved with potential-field techniques such as gravity and magnetometry. Exploration under conductive cover requires high-power, low-noise data acquisition for penetration, combined with a broad frequency range for depth resolution. Such data can be used to calculate and map conductivity as a function of depth. The greater capability of the computers acquiring the digital data has allowed much larger volumes of data to be collected, so that multi-component measurements have now become standard. The extra components provide much more diagnostic information and make interpretation much easier (Smith and Annan 1997).

Airborne EM surveys offer several advantages over ground surveys. The rate of coverage (500-1000 ha can be surveyed per hour) yields lower costs on large surveys. Ground access to the site is not required to complete the survey, and the multi-frequency nature of the systems provides a vertical conductivity profile as well (Hodges 1999). Airborne EM can be used to identify larger targets (e.g., mine pools, water tables, ground water recharge zones, and subsurface flow paths). Ground-based geophysical tools are then used to confirm airborne data and to provide higher resolution data.

Abandoned Mines

Fossil-fuel and mineral extraction can cause AMD. In the U.S., 20,000 km of streams and rivers and 70,000 ha of lakes and reservoirs are polluted with mine effluents (Kleinmann 1989). During the past couple of decades, the obvious surface water pollution has been well documented and significant efforts have been and are continuing to be put forth to address this issue. However, groundwater has become a forgotten element of watershed protection and post-mining scenarios. Depleted mines typically serve as sinks or basins. Underground mine pools can be located either above drainage (i.e., seepage or discharges drain by gravity into surface streams or rivers) or below drainage (i.e., seepage or discharges rise to the surface by hydrostatic pressure and through natural or man-made flow paths). Surface discharges from abandoned underground mine pools are often unknown and/or unmapped and classified as non-point sources of pollution. Underground mines, particularly those below drainage, become large underground reservoirs or impoundments. One reason for the lack of remedial focus on the groundwater (mine pool) in the case of early mining operations is the lack of and/or accuracy of mine maps. Without such maps of where the mine pools could exist, it is difficult to pursue remedial efforts that address mine pools directly. In addition, the lack of accurate mapping of mines and the resulting pools generate potential safety hazards for active and future mining operations due to potential flooding. The 2002 Quecreek Mine accident in Pennsylvania, where nine miners were trapped underground, is an excellent example of what can happen as a result.

In the U.S., current state and federal regulations mandate mapping mining operations and post-mining treatment of water. In general, no efforts are made to engineer the quality of the modern post-closure mine pool during active operations. Although water treatment is required by law for as long as the pollution exists, it is not uncommon for bankruptcy to end post-mining treatment operations. Consequently, polluted abandoned mine pools are still being generated today; however, due to improved mining technology, they are much larger and deeper. Furthermore, issues of volumes and mapping of underground mine pools becomes more complex when the significant aerial extent of underground

workings is coupled with multiple seam mining. Determining the potential interaction of mine pools is extremely difficult and expensive when approaching this objective with only ground-based technologies.

Water Resources

NETL is also currently investigating potential beneficial uses of flooded underground mine voids. One possible application relates to the fact that it is becoming very difficult to locate new power plants in the U.S. because of the enormous volumes of water needed. The electric utility industry is second only to agriculture as the largest user of U.S. water. Steam electric plants use nearly 5,800 m^3/s of fresh water for cooling, boiler blowdown, flue gas cleaning, etc. In addition, another 2,500 m^3/s of saline water is used (USGS 1998). Abandoned underground mine pools could serve as a water source for fossil fueled power plants in either one of two scenarios, recirculation or pump and discharge, depending upon the recharge rate of the mine pool. However, before abandoned underground mine pools can be used, a thorough understanding of fluid (water) dynamics and interactions and a reasonably accurate mapping of the mine pools will be required.

Methodology

Thermal Infrared Imaging

Airborne TIR was evaluated for its ability to locate areas where mine drainage or groundwater is surfacing via seeps, springs, or man-made features (boreholes and mine shafts). The general concept is that the temperature of groundwater (including water from polluted underground mine pools) is typically warmer than the temperature of surface water at night in the late fall and winter months. Our infrared data was collected with a Daedalus AADS1268 multispectral scanner using a single TIR detector configuration (8.5 to 12 μm wavelength). The data were radiometrically calibrated and converted to apparent temperature. It was collected from an altitude of approximately 700 m and has temperature resolutions 0.1°C. Data were collected using both helicopter and fixed-wing platforms.

Airborne Electromagnetic Conductivity

The hardware and software developments in this arena have been very active and it is a challenge to stay abreast of the technological developments. The airborne EM conductivity survey data that we have acquired during the past three years have used several systems, though all were owned by same vendor; each system was a technological advancement over the previous systems. The Dighem^{VRES} is representative of the earlier analog/digital systems used by NETL. It was a 5-frequency, electromagnetic transmitter and receiver with an 8-m coil separation, which was towed by helicopter over the targeted areas (Figure 1). This instrument was flown at a constant altitude of 30 m (~100 ft) above the ground, following the contours of the terrain. The Dighem^{VRES} was designed specifically for conductivity mapping and features 5 coplanar coil pairs that allow the calculation of conductivity at 5 widely separated frequencies (400 Hz, 1600 Hz, 6400 Hz, 25 KHz, and 100 KHz) (Hammack et al 2003b). Because the frequencies are separated by a factor of four, the skin depth, or the thickness of the strata being sensed, decreases by a factor of two for each successively higher frequency. For example, a conductivity survey at 400 Hz senses the conductivity of geologic strata between the surface and a depth of approximately 90 m, whereas a survey at the next higher frequency (1600 Hz) would only sense the conductivity of strata between the surface and 45 m depth. This co-planar coil geometry was optimized for the resolution of horizontally layered geology and the detection of water tables and mine pools. Airborne conductivity data can be displayed as separate contour maps for each of the 5 frequencies overlain on a topographic and/or digital orthographic quarter quadrangle (DOQQ) background. The multiple frequency nature of the data permits a 3-dimensional interpretation of the conductivity distribution.

Most recently, the EM survey of the Kettle Creek watershed in Pennsylvania in July and August 2002 used the new RESOLVE electromagnetic data acquisition system, which is all digital construction , self calibrating and uses the more accurate laser altimeter. Like the Dighem^{VRES}, the Resolve system consists of 5 co-planar transmitter/receiver coil pairs operating at frequencies of 393 Hz, 1,530 Hz, 6,200 Hz, 28,200 Hz, and 107 kHz; however, this new system also has one coaxial transmitter/receiver coil pair that operates at a frequency of 3,230 Hz. Separation for the 5 coplanar coil pairs was 7.9 m; separation for the coaxial coils was 9 m. A complete description of the Resolve system is available at: http://www.fugroairborne.com/Services/airborne/em/resolve/index.shtml.

Although significant improvements in instrumentation, computer hardware and software and other aspects of helicopter EM technologies have occurred in the past 3 to 5 years, the pilot remains one of the most critical factors in conducting a successful mission. The application of this technology lends itself to a variety of geographic locations and topographic conditions. Consequently, the ability to fly a mission over steeply dipping topography while

Figure 2. Moving map capabilities, which combine GPS and GIS technologies, can significantly reduce the time required for field investigations

attempting to maintain a constant altitude of about 30 m and avoid cultural features (e.g., power lines, communication towers) can be very challenging and requires experienced pilots.

Differential Global Positioning System

Carrier-phase, differential GPS is an integral part of airborne remote sensing. GPS was used in our studies to: guide the helicopter along parallel swaths (flight lines), precisely correlate results from TIR imagery and geophysical surveys with location, append results from the current study to existing GIS databases, guide field workers attempting to correlate mine workings with observed anomalies, and ground-truth airborne imagery/geophysics (Figure 2).

Application of GIS Data

An additional level of corrective action was performed on the infrared data sets to improve their accuracy with respect to map coordinates. Ground control points (GCPs) were used in conjunction with a polynomial rectification procedure to warp the imagery to reduce distortions. GCPs consist of features (e.g., buildings, road intersections) seen in the imagery data and selected for the purpose of defining the coordinates of a specific location. The map coordinates defining the GCP location are obtained from a corresponding location in the DOQQ. Once a sufficient number of GCPs are defined in the imagery, a polynomial rectification is performed that results in each pixel being assigned a coordinate based on its row and column position in the array.
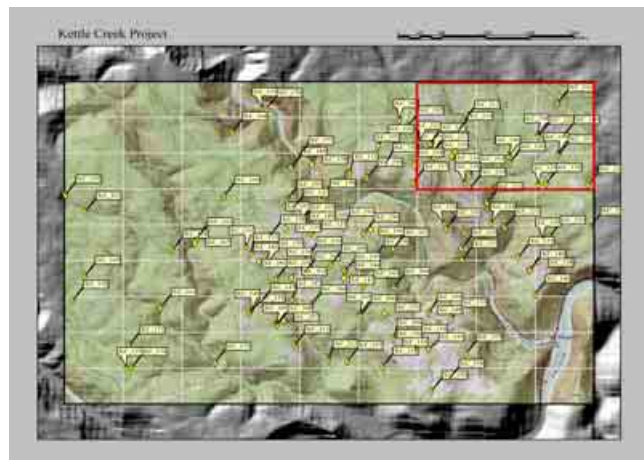

Figure 3. Yellow locations depict TIR targets prior to field investigations; each TIR target has a GPS (latitude and longitude) address.

The method is highly dependent on the accuracy and distribution of the selected GCPs. Next, a classification algorithm is run on the rectified imagery to generate a thematic image. A raster to vector algorithm is then applied to extract specific features (e.g., mine drainage seeps and discharges) as vector polygons (Figure 3). Finally, the polygons may be incorporated into a GIS along with other map layers of the same projection for further analysis.

Results

It is extremely difficult to provide a full appreciation of the utility and capability of airborne data in hard copy format, such as in this paper. NETL anticipates generating a remote sensing web site during 2003 that will display all of our remote sensing studies and will be accessible at: www.netl.doe.gov. The following discussion provides a sampling of the types of remote sensing data that is available for addressing energy-, water-, and mining- related issues.

Airborne Thermal Infrared Imaging

As discussed elsewhere in this issue, TIR imagery has been very successful in locating groundwater discharge locations. Approximately 200 thermal anomalies were selected from the various TIR and GIS data sets and validated in the field. Using hand-held GPS instruments, it was found that the accuracy of the mapping was within 5 m. Field data included water quality, site descriptions, digital photographs, latitude and longitude, and other pertinent data. In the eastern coal regions, the typical thermal anomalies were found to be fresh water, AMD, or sewage. Figure 4 shows a processed airborne TIR image and a corresponding photograph of the anomaly taken from the ground. The red and yellow color scheme depicts areas of higher ground temperature.
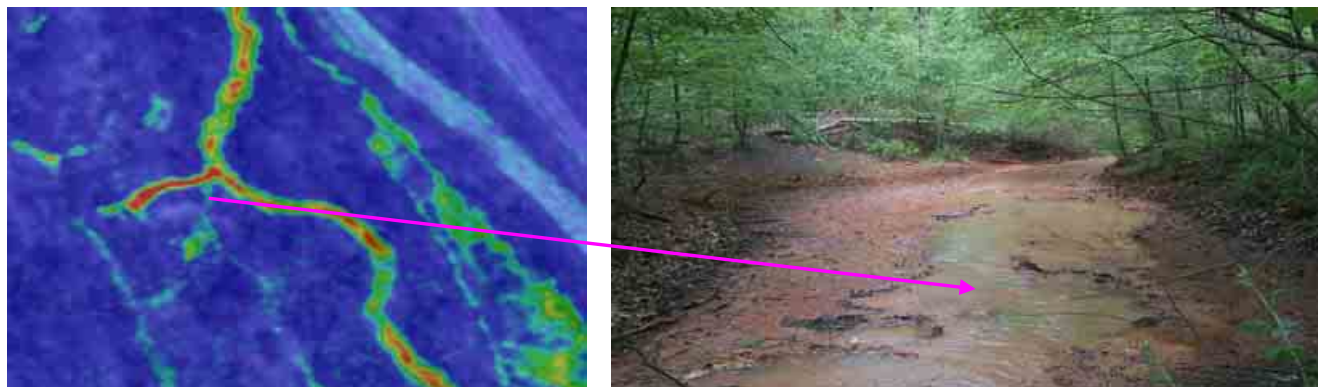
Figure 4. Thermal anonomaly showing georectified airborne TIR data (left), with red and yellow indicating the warmest temperatures in the selected pseudocolor scheme; ground photo of the thermal anomaly (right), which in this case depicts an AMD discharge.
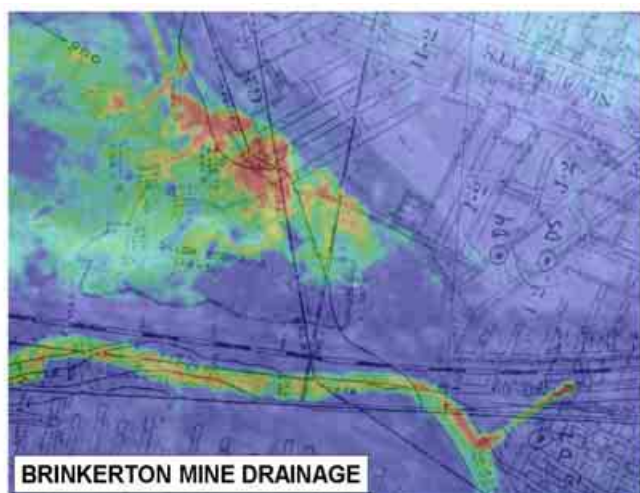

Figure 5. TIR image combined with DOQQ and mine map

The application of GIS and GPS technologies was also found to be very valuable. The combination of DOQQ's, TIR imagery and mine maps show shallow (<9 m of overburden) mine entries as the source of seepage in a wetland (Figure 5). Also shown in Figure 5 is a major (avg. 0.2 m^3/s) and well-known mine discharge (lower right-hand corner). A small drain shaft was dug in the 1940's to convey water out of the mine complex by artesian flow and through a short flume that discharges into the adjacent stream channel, shown across the lower portion of the image. The GIS configuration shown in Figure 5 identifies where segments of a wetland and a surface stream are located relative to the underground mine. The red and yellow segments of the wetland area indicate artesian discharges of mine water that are emerging in the wetland; these discharges were unknown until the TIR data was collected.

In addition, very small discharges can also be accurately located; the size of the smallest distinguishable anomaly (a single pixel) is related to the spatial resolution of 1 m. TIR data provides only relative surface temperatures; flow rates or volumes or water quality cannot be determined with these data. However, as implied above, the addition of various GIS layers (e.g., streams, mining operations, topographical and geological features, hyperspectral or multispectral data) can help in conducting a preliminary review of what could be expected in terms of water quality based on relative locations and elevations, prior to field investigations.

Discussion

The application of AEM technologies is and will continue to be limited by urban sprawl. The U.S. Federal Aviation Administration prohibits the flying of sling loads (geophysical equipment in this case) over civil structures, such as: houses, churches, schools, and other structures. Cites and towns in the Appalachian coal fields (e.g., Pittsburgh, PA), which were built over existing coal mines, will likely never have the mine pools located beneath them mapped by airborne EM. In addition, utility lines (electric and gas and water) can have detrimental effects on EM data; areas of interest can be masked. The nature of the instrumentation and manner of collection permits TIR data to be collected over populated areas. However, density of cultural features (buildings, roads, bridges, shopping centers, etc.) can significantly increase the time required for data processing and interpretation. Airborne surveys of disturbed rural areas (e.g., mining impacted or industrial plumes) are considered to be the optimal environmental application of remote sensing technologies.

Finally, the improved fidelity of data has resulted in improved visualization of data. Although the number of software packages available for remote sensing data is limited, improvements in the available packages are occurring almost continuously. It is a challenge to stay abreast of the remote sensing

software. The use of remote sensing data involves both commercially available and custom software for processing raw data into a generic format for the end-user. The end-user will, depending on data type, further process the remote sensing data and/or incorporate it into a GIS database. Typically, there will be several different software packages that can be used prior to or after incorporation of data into a GIS database. These additional software packages are typically specialized, compatible with GIS software and provide additional insight (visualization) of the remote sensing data.

Acknowledgements

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