

DRAFT FINAL REPORT

EVALUATION OF AIRBORNE GEOPHYSICAL SURVEYS FOR LARGE-SCALE MAPPING OF CONTAMINATED MINE POOLS

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Executive Summary

Decades of underground coal mining has left about 5,000 square miles of abandoned mine workings that are rapidly filling with water. The water quality of mine pools is often poor; environmental regulatory agencies are concerned because water from mine pools could contaminate diminishing surface and groundwater supplies. Mine pools are also a threat to the safety of current mining operations. Conversely, mine pools are a large, untapped water resource that, with treatment, could be used for a variety of industrial purposes. Others have proposed using mine pools in conjunction with heat pumps as a source of heating and cooling for large industrial facilities.

The management or use of mine pool water requires accurate maps of mine pools. West Virginia University has predicted the likely location and volume of mine pools in the Pittsburgh Coalbed using existing mine maps, structure contour maps, and measured mine pool elevations. Unfortunately, mine maps only reflect conditions at the time of mining, are not available for all mines, and do not always denote the maximum extent of mining.

Since 1999, the National Energy Technology Laboratory (NETL) has been evaluating helicopter-borne, electromagnetic sensing technologies for the detection and mapping of mine pools. Frequency domain electromagnetic sensors are able to detect shallow mine pools (depth < 50 m) if there is sufficient contrast between the conductance of the mine pool and the conductance of the overburden. The mine pools (conductors) most confidently detected by this technology are overlain by thick, resistive sandstone layers. In 2003, a helicopter time domain electromagnetic sensor was applied to mined areas in southwestern Virginia in an attempt to increase the depth of mine pool detection. This study failed because the mine pool targets were thin and not very conductive. Also, large areas of the surveys were degraded or made unusable by excessive amounts of cultural electromagnetic noise that obscured the subtle mine pool anomalies. However, post-survey modeling suggested that thicker, more conductive mine pools might be detected at a more suitable location.

The current study sought to identify the best time domain electromagnetic sensor for detecting mine pools and to test it in an area where the mine pools are thicker and more conductive than those in southwestern Virginia. After a careful comparison of all airborne

time domain electromagnetic sensors (including both helicopter and fixed-wing systems), the SkyTEM system from Denmark was determined to be the best technology for this application. Whereas most airborne time domain electromagnetic systems were developed to find large, deep, highly conductive mineral deposits, the SkyTEM system is designed for groundwater exploration studies, an application similar to mine pool detection.

Three mined areas in southwestern Pennsylvania were selected to test the ability of the SkyTEM system to detect mine pools. These areas were underlain by partially flooded mines in the Pittsburgh Coalbed where the mined thickness averaged about 3 m and the conductivity of water in mine pools ranged from 2000 to 10,000 $\mu\text{S}/\text{cm}$ (200-1000 mS/m). The depth to the mine pool ranged from 0 to more than 300 m.

Prior to the survey, forward models were generated of the anticipated SkyTEM response to the mine pool at different depths. These models suggested that the SkyTEM system would detect the mine pool at depths of 50 m and 100 m, but not at 150 m or deeper. Unfortunately, the overburden conductivity assumed in these models was less than the actual conductivity that was determined later by induction logs from boreholes within the flight areas. The higher than expected overburden conductivity decreased the conductance contrast between the overburden and the mine pool and made it less likely that the mine pool would be detected by SkyTEM.

A comparison of SkyTEM soundings near a borehole to the induction log from that borehole showed that SkyTEM was accurately determining the depth, thickness, and conductivity of the relatively thick resistive layers in the overburden. However, SkyTEM underestimated the conductivity of thin conductive layers, including the mine pool. There was no SkyTEM response to the mine pool at a depth of 140 m.

SkyTEM conductivity/depth profiles from the three flight areas provided no convincing evidence that the mine pool was detected at any depth. Further, each conductivity/depth profile contained extensive areas where interference from power lines rendered the data useless. Although areas of power line interference can be removed or ignored, it is disturbing that 15-20% of the data must be discarded from flight areas that were purposely picked to be as free from power lines as possible. Areas with more typical power line concentrations would be difficult to survey with any helicopter electromagnetic sensor system.

The conclusion of this study is that helicopter, time domain electromagnetic sensors are not useful for detecting and mapping deep mine pools. Helicopter, frequency domain electromagnetic sensors can detect shallow mine pools when overlain by resistive overburden. The National Energy Technology Laboratory has used helicopter, electromagnetic induction methods (frequency domain or time domain electromagnetic sensors) to survey more than 40 areas with underground coal mines and presumably, mine pools. Conclusions based on this experience are: 1) electromagnetic induction methods are useful for identifying environmental problems at or near the surface and 2) electromagnetic induction methods cannot reliably determine mine water hydrology (including mine pools) beneath more than 50 m of typical coal overburden strata.

A CD attached to this report contains all SkyTEM data from these surveys plus custom viewing software that geospatially relates positions on conductivity/depth sections to locations on topographic maps or air photos.

Introduction

Approximately 5,000 square miles of the Pittsburgh Coalbed in Pennsylvania, West Virginia, Maryland, and Ohio have been mined since the late 1700's; approximately 1,900 square miles of this mined area is currently flooded with water containing high concentrations of acidity, iron, manganese, and aluminum (Donovan and others, 2004). More than 100,000 gallons of contaminated water from the mined areas are discharged to the Monongahela and Ohio River Drainages each minute (Donovan and others, 2004). Currently, only about 23% of the flow is treated prior to discharge (Donovan and others, 2004). The water in the mined-out areas of the Pittsburgh Coalbed is a concern to environmental regulatory agencies because it threatens supplies of surface and ground water. Water from mine pools also can flood active mines and threaten the lives of miners. In contrast, the mine pool is an immense groundwater resource that can supply water for many industrial activities, though treatment may be required prior to use. Recently, the mine pool has been considered as a source of cooling water for coal burning power plants (Veil and others, 2003) and as a heat and cooling source for geothermal heat pumps at surface installations. Watzlaf and Ackman (2006) estimate that the volume of water discharging from the Pittsburgh Coalbed could theoretically heat and cool 17,000 homes and that geothermal heat pump systems using mine water could reduce annual costs for heating by 67% and cooling by 50% over conventional methods (natural gas or heating oil and standard air conditioning). Assessing the resource potential or environmental liability of a mine pool requires accurate maps showing the extent of the mine pool. Maps exist for most mines; these maps have been used by Donovan and others (2004) in conjunction with mine pool elevation data and coalbed elevation maps to estimate the volume and areal extent of the mine pool. Unfortunately, the mine pool maps obtained in this manner are only as good as the mine maps on which they are based. Mine maps reflect conditions extant at the time of mining, not current conditions. Also, mine maps are not available for all mines and where available, sometimes do not reflect the total extent of mining. There is a need for a mine pool detection method that can rapidly survey large areas and accurately map mine pools.

This study evaluated the use of helicopter time-domain electromagnetic surveying for the large-scale mapping of contaminated pools in abandoned underground coal mines in southwestern Pennsylvania. If successful, these surveys could provide information needed to predict the timing and location of mine pool overflows, information needed for in situ or closed-loop treatment of contaminated mine water, information needed to assess the quality, quantity, and location of potential water supplies, and information needed to mitigate the hazards posed by unmapped, flooded workings (Quecreek Mine scenario).

Survey Design

Past Work

Previously, NETL has used helicopter mounted frequency-domain electromagnetic (FDEM) surveys to detect and map flooded portions of underground coal mines in north-central Pennsylvania (Hammack and others, 2003) and elsewhere. However, mine pools deeper than about 50 m are not detected by this technique. In an effort to increase exploration depth, a more powerful helicopter time-domain electromagnetic (TDEM) survey was flown using the VTEM system over flooded coal mines in southwestern Virginia (Hammack and others, 2004a, 2004b). The TDEM survey was unsuccessful, a result that was not surprising given the difficult task of detecting thin, mine pools of low conductivity in an area of multi-seam mining and its associated electrical infrastructure. Further, the helicopter TDEM system used for the southwestern Virginia study was designed for mineral exploration (ie. finding large, highly conductive ore bodies) where more emphasis is placed on exploration depth (requiring a powerful transmitter with a high dipole moment) than on near-surface (0-200 m depth) resolution and noise rejection.

Objective of Present Study

The intent of this study was to use airborne sensing to detect and map mine pools at depths of at least 150 m. Unlike the unsuccessful southwestern Virginia survey, this survey was conducted at a more suitable area using a TDEM system optimized for groundwater mapping.

Selection of Test Areas

The flooded mines selected for the second airborne TDEM survey are in the Pittsburgh Coalbed in southwestern Pennsylvania. The mine pool targets at these localities were better for testing airborne TDEM than those in southwestern Virginia because:

1. only the Pittsburgh Coalbed was mined,
2. the Pittsburgh Coalbed is thicker than the seams that were mined in southwestern Virginia (and so the mine pool would be thicker also),
3. the mine pools are > 10 times more conductive than the mine pools in southwestern Virginia, and
4. mine pool depth increases in a westward direction, providing a thickening wedge of overburden that ranges from 0-m thick at the outcrop to more than 300-m thick beneath hilltops in western parts of the survey areas.

Three areas overlying flooded underground mines in the Pittsburgh Coalbed were selected where:

1. mine height is > 2.5 m,
2. overburden thickness gradually increases from 0 m at outcrop to 300 m,
3. accurate mine maps and structure contour maps (on base of Pittsburgh Coalbed) are available, and
4. mine pool elevations and chemistry are available.

The selected areas are in Greene and Fayette Counties, Pennsylvania and overlie portions of the Gateway Mine, Robena Mine, and Leisenring Mines (Uniontown). Figure 1 is a map showing the locations of the three selected flight areas.

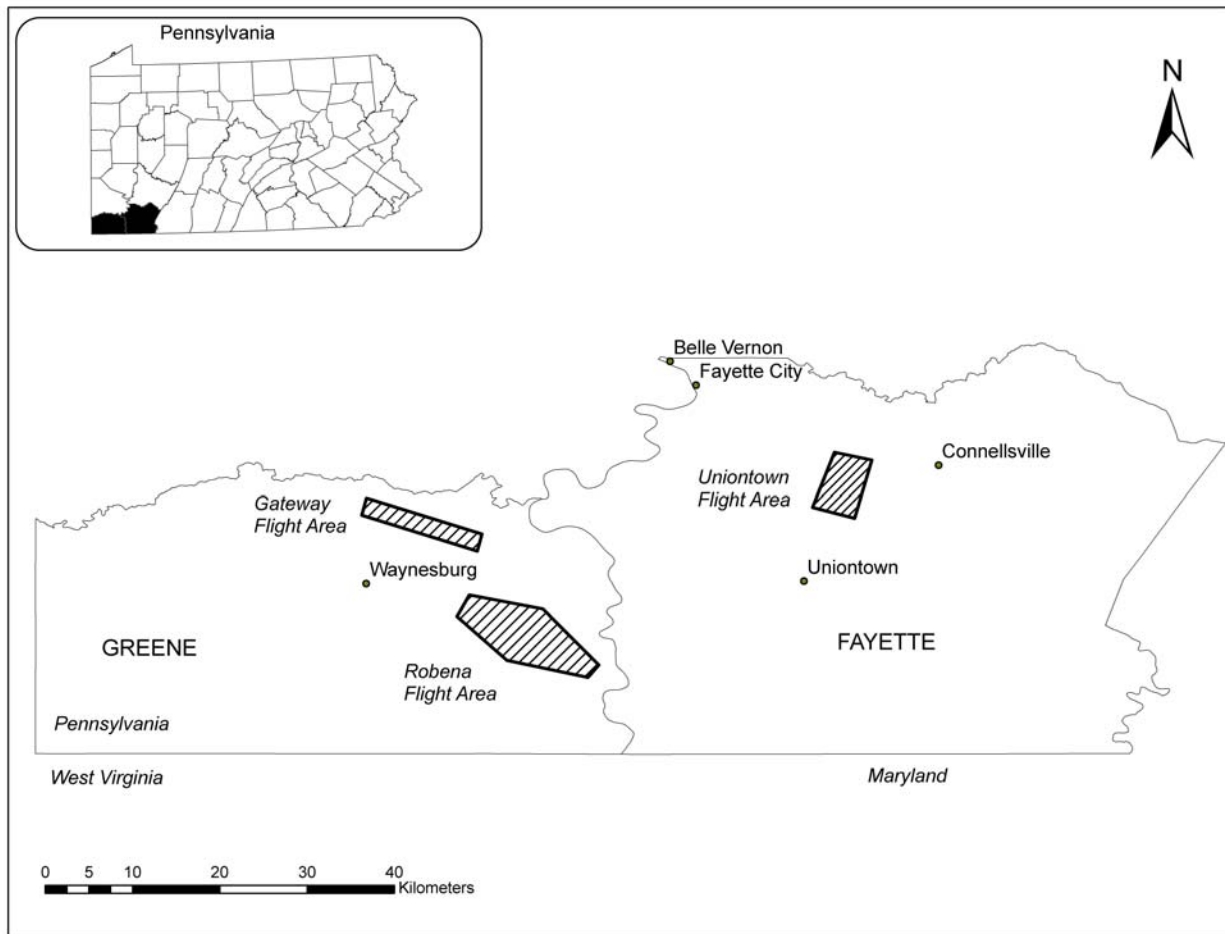


Figure 1. Index map showing the location of three SkyTEM flight areas in southwestern Pennsylvania

Selection of Airborne TDEM System

High levels of cultural, system, and geologic noise were believed to have been major factors contributing to the inability of helicopter TDEM (VTEM system) to detect mine pools in the southwestern Virginia survey (Hammack and others, 2004a; 2004b). Because cultural and geologic noise cannot be decreased, noise reduction has to be achieved by decreasing TDEM system noise. This study evaluated all airborne TDEM systems for exploration depth and noise rejection; the SkyTEM system (Sorensen and Auken, 2004) was chosen for this project primarily because it was designed to have less system noise. The SkyTEM system also has other advanced features not offered by other systems. Table 1 compares SkyTEM specifications with that of VTEM, the system used for the study in southwestern Virginia in 2003. Note that the specifications of the VTEM system have been upgraded since that time, with larger transmitter area, more turns, higher current and improved noise rejection.

The physical design of the SkyTEM system (Fig. 2a) places the receiver in a “null” or minimum position with respect to electromagnetic fields emitted by the transmitter. Even when the transmitter is “off”, transient currents can still flow in transmitter coils and give rise to errant responses in the receiver. A receiver placed in the “null” (minimum coupling) position is much less sensitive to electromagnetic fields produced by the transmitter and, therefore, is less susceptible to this type of noise.

The VTEM system used in the southwest Virginia study had the receiver loop mounted inside the transmitter coil; (Fig. 2b), a position of maximum coupling and maximum sensitivity to transient currents in the transmitter coil. At the time of the southwest Virginia survey, VTEM was testing a prototype electronic compensation module to correct the receiver response for spurious off-time transmitter currents.

The SkyTEM system alternates low-moment and high-moment soundings to explore near-surface and deeper strata. Low-moment soundings are acquired using a higher frequency (240 Hz) and have quicker turn-off times enabling measurements with higher frequency response, lower noise, and provide better information about the near surface. SkyTEM high-moment soundings provide similar information to that obtained by VTEM.

The SkyTEM system provides redundant devices on opposite sides of the transmitter frame for collecting critical navigational information. For example, the system obtains location data from two GPS devices, altitude data from two laser altimeters, and frame tilt from two attitude sensing devices.

Altitude data from laser altimeters are suspect in areas with tree cover because the laser is often reflected by tree tops and not the ground. This is overcome by recursive filtering that examines altitude readings along a short segment of the flight line and selects the maximum altitude reading, which is assumed to be the true altitude. By comparison, the VTEM survey in southwestern Virginia used a conventional radar altimeter and no altitude corrections were made for areas of tree cover.

Table 1. A comparison of the specifications for the VTEM system used in 2003 and SkyTEM (2006) helicopter time domain electromagnetic systems. Note that significant improvements have been made to VTEM since 2003

Transmitter	VTEM	SkyTEM
Transmitter-Receiver Configuration	Concentric loops	Virtual concentric loops (center of receiver loop is 2 m above and 8 m behind center of transmitter loop)
Transmitter Diameter and Shape	18.5 m (Round)	15 m X 15 m (Octagonal)
Transmitter Area	266 m ²	Low moment (1 turn): 283 m ² High moment (4 turns): 1132 m ²
Waveform Shape	Trapezoid	Exponential rise; linear ramp off
Transmitter Current	150 amps	Low moment: 40 amps High moment: 92 amps
Peak Dipole Moment	166,000 A m ²	Low moment: 11,000 A m ² High moment: 104,000 A m ²
Pulse Width	7.5 ms	Low moment: 1.04 ms High Moment: 8.34 ms
Base Frequency	30 Hz	Low moment: 240 Hz High moment: 30 Hz
Receiver		
Receiver Loop Diameter	1.1 m	Approx. 0.5 m Effective area: 31.4 m ²
Receiver Bandwidth	50 kHz	338 kHz
Sampling	26 channels	Low moment: 21 channels High moment: 28 channels
Recording time (after turnoff)	100 μ s - 14 ms	Low moment: 18.1 μ s - 1.1 ms High moment: 59.8 μ s - 5.5 ms

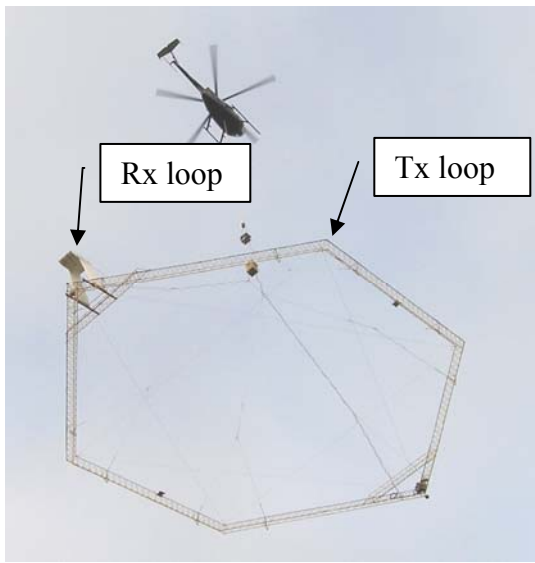


Figure 2a. SkyTEM system showing transmitter loop (Tx) with receiver loop (Rx) in position of minimum coupling (null position).

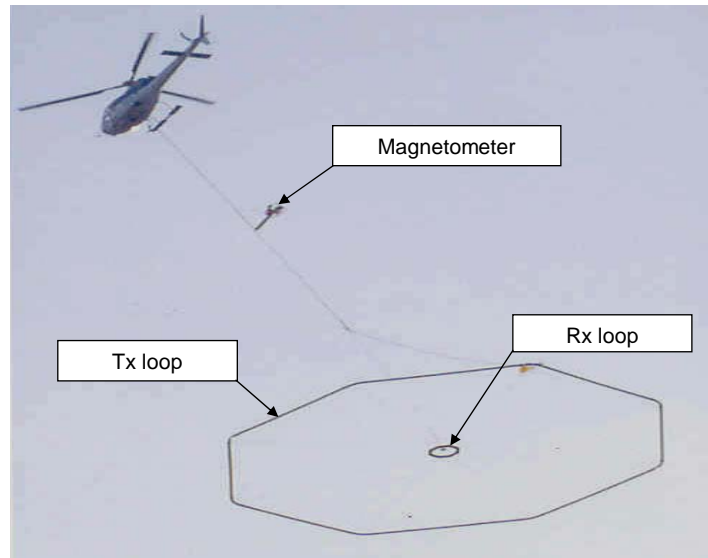


Figure 2b. VTEM system showing transmitter loop (Tx) with receiver loop (Rx) in position of maximum coupling.

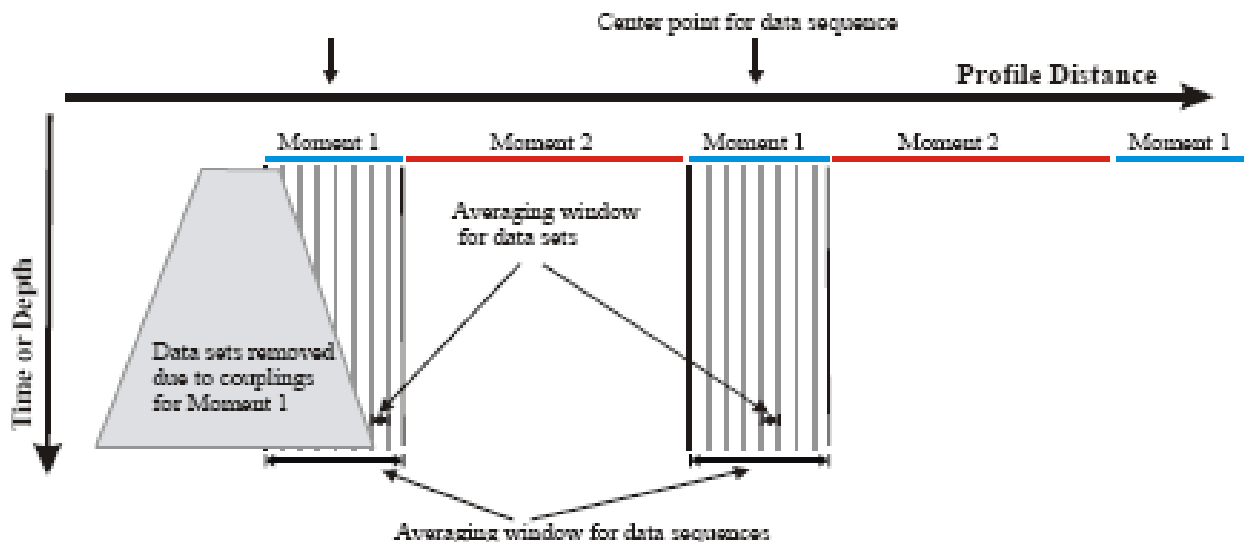


Figure 3. Schematic showing SkyTEM data collection with respect to distance along flight line. Moment 1 and Moment 2 refer to the low moment and high moment soundings, respectively.

Survey Design

Rural areas were selected for SkyTEM flights to avoid power lines that interfere with electromagnetic surveying. Where possible, flight lines were oriented along directions that would minimize the amount of elevation change (parallel to valleys or ridges). Adjacent flight lines were spaced about 200-m apart. However, the pilot was encouraged to deviate from preplanned flight lines when the lines were over interference sources (power lines, fences, pipelines etc.) and inhabited areas (the Federal

Aviation Administration prohibits flying sling loads over inhabited areas). The nominal altitude for the survey was 30 m. However, altitude was at the pilot's discretion and safety was the foremost consideration. Flight speed was approximately 20 knots or 23 mph (37 km/h).

SkyTEM Data Processing

A transient consists of 128 voltage measurements that are collected from the receiver coil at logarithmic spaced time gates after the turn-off of the transmitter current. At the average speed of the aircraft, the horizontal distance between individual transients is approximately 4 cm for the low moment and 33 cm for the high moment. Transients are grouped together to form alternating low moment or high moment data sequences that are visually inspected to identify transients coupled to man-made objects so that such data can be removed. Once coupled data have been removed, the data sets are averaged to reduce noise and to obtain the final soundings used in the inversion. Final soundings are the average of ≈ 1000 individual transients and are plotted at the center point for the data sequence (30-40 m apart along the flight line, Fig. 3).

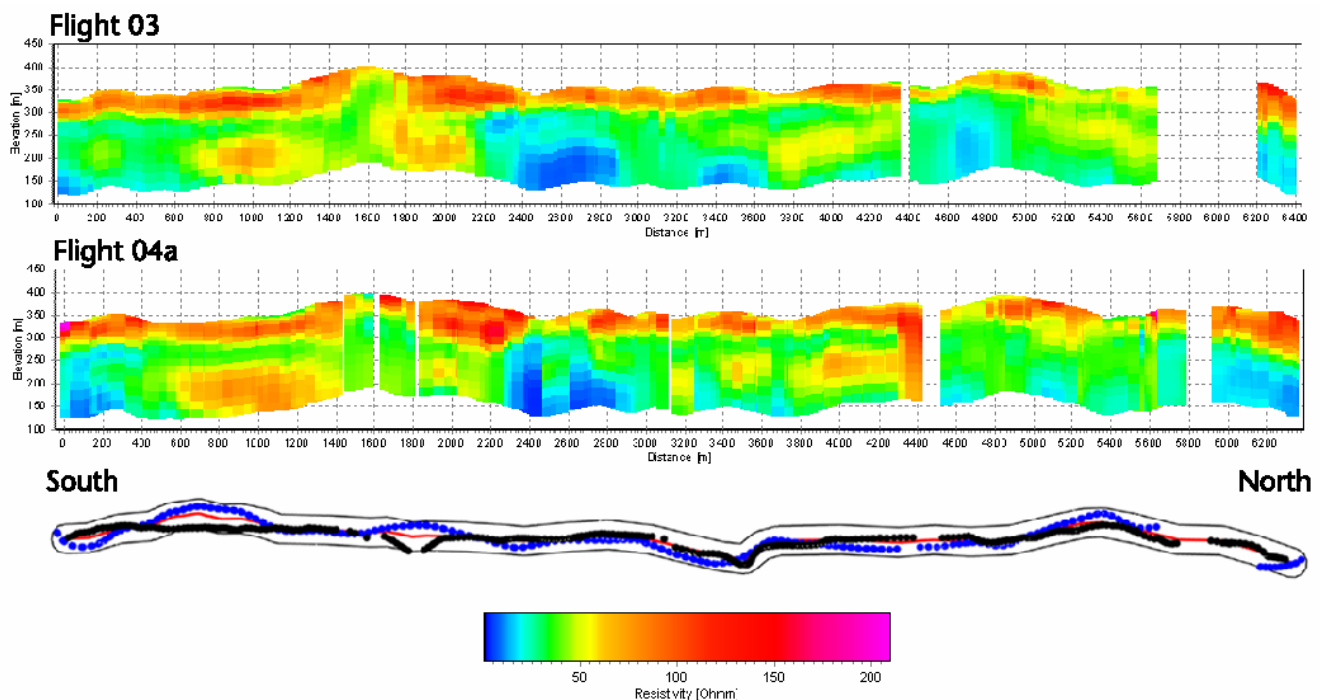


Figure 4. Two flight lines were flown over the same area from opposite directions. Flight line 03 is black and flight line 04a is blue on the map at the bottom of the figure. In some areas, the two flight lines do not coincide and a red intermediate line can be seen. Sounding locations from the black and the blue line were projected onto the red line for display. The resistivity/depth profiles shown are SkyTEM results from each respective line projected onto the intermediate red line

Final sounding data are inverted using a 1-D laterally constrained inversion where inversion parameters are tied together laterally with a spatially dependent covariance. Two types of inversions are generated: 1) a parameterized inversion containing four or five layers with horizontally constrained thickness and resistivity, and 2) a smooth inversion containing 15 or more layers of fixed thickness with loosely constrained vertical resistivity and tightly constrained horizontal resistivity. Both high moment

and low moment data are jointly inverted. Layer interfaces and resistivity are best determined from the parameterized inversion. However, the smooth inversion does not require a starting model and subtle variations in resistivity are more easily discerned. The enigma is that only the parameterized inversion is likely to detect the mine pool conductor while only the smooth inversion works with the rapidly changing topography of the selected study areas. SkyTEM data presented in this report were processed using the multilayer smooth inversion because the parameterized inversion does not provide stable results for the surveyed areas.

Output from the inversions are displayed using custom viewing software that geospatially relates positions on the conductivity/depth sections (or resistivity/depth sections) to locations on topographic maps or air photos. The inversion viewing software plus all inverted data from this study are included on the CD attached to this report.

Quality Assurance

Calibration

For each take-off during the survey, the SkyTEM system acquired data for a short period of time over a calibration site, an easily recognizable area that was close to the refueling site and free from electromagnetic noise sources. The SkyTEM response over the calibration site was compared with other data from the same area to be certain that the system was functioning satisfactorily and that there had been no electronic drift. SkyTEM response differences of less than 10% were considered satisfactory; response difference was attributed primarily to the difficulty of accurately hovering at a predetermined altitude. No data were rejected by this test.

Noise Measurement

At each of the three survey areas, the SkyTEM system was taken to a high altitude to determine the system's response where there could be no detectable signal from the ground. The measured response at high altitude is the noise background for the SkyTEM system, which consists of the environmental noise for the area (natural electromagnetic noise (spherics) and noise from cultural sources) plus the noise from the SkyTEM system itself. At all times, the noise level determined by the high altitude measurement was a factor of 100 lower than measurements taken during actual surveys. This low noise background provided assurance that changes in the SkyTEM response due to the presence or absence of a mine pool would not be obscured by noise.

Proof of Repeatable Measurements

To demonstrate the repeatability of SkyTEM results, a flight line in the Uniontown Survey Area was repeated. Because it was not possible for the pilot to fly exactly the same flight line, a map (bottom of figure 4) shows the locations of SkyTEM final soundings as blue or black dots depending on whether they were part of flight line 03 (blue) or flight line 04a (black). Inversion results from both lines were projected onto the red line (intermediate between flight lines 03 and 04a) and the results are displayed as two resistivity/depth sections that overlie the map. The gaps in the sections are where data were removed because of cultural interferences. The two resistivity/depth sections are remarkably similar and demonstrate the repeatability of the SkyTEM data and its processing.

Data Quality Manager

The collection, processing, and interpretation of airborne electromagnetic data are highly specialized skills that can be performed only by a small number of people worldwide. Therefore, an expert with extensive experience in airborne electromagnetic surveying was contracted to provide independent oversight (“bird dog”) for this project. Richard Irvine of Condor Consulting, Inc., an internationally known expert in airborne geophysical surveying, was on site during the initial surveys to ensure that quality data were collected.

RESULTS OF SKYTEM SURVEYS

Modeling the Response of SkyTEM to Mine Pool

Because mine pools in the Pittsburgh Coalbed are thicker and more conductive than those in southwestern Virginia, they exhibit greater conductance (conductance \approx conductivity \times thickness). Increased conductance should make the mine pool easier to detect by TDEM and other electromagnetic sensing techniques. For TDEM to detect the mine pool, the difference between the conductance of the mine pool and the conductance of overlying or underlying strata must be sufficiently different. This is commonly termed “contrast”.

Subtle differences in conductance often are obscured within the noise of TDEM systems. We expected that the contrast between the mine pool and surrounding strata would be low and selected the helicopter TDEM system with the lowest noise for this survey. The selected SkyTEM system was developed in Denmark for hydrologic studies, which are typically low-contrast targets like mine pools.

Forward modeling programs were run by Esben Auken of the University of Aarhus in Denmark to determine if contrast was sufficient for the mine pool to be detected using SkyTEM. Inputs to the forward model included specifications (geometry, waveform, dipole moment, base frequency etc.; Table 1) for the SkyTEM system and the expected geoelectrical section (layer thicknesses and conductivity) for the mine pool and overburden strata. Because no induction logs from the Pittsburgh Coalbed overburden were available when the initial forward models were generated, simple three-layer models consisting of overburden, mine pool, and underlying strata layers were used. Models were made with the overburden layer thicknesses of 50, 100, and 150 m (Table 2, Fig. 5). The overburden layer was given a bulk resistivity of 50 ohm m (20 mS/m) based on the average resistivity (from down-hole induction logs) of the overburden above the Upper Freeport Coalbed in Preston County, West Virginia. The mine pool layer, which included water, coal pillars, roof-fall material (gob), and conductive underclay was assigned a bulk resistivity of 5 ohm m (conductivity = 200 mS/m) and a thickness of 6 m in all models. The lowest layer, termed underlying strata, was given an infinite thickness and a resistivity of 50 ohm m (20 mS/m).

Table 2. Thickness and resistivity of layers used to generate forward models

Layer resistivity	Layer thickness (m)		
	Model 1	Model 2	Model 3
Overburden (50 ohm m)	50	100	150
Mine pool (5 ohm m)	6	6	6
Underlying strata (50 ohm m)	∞	∞	∞

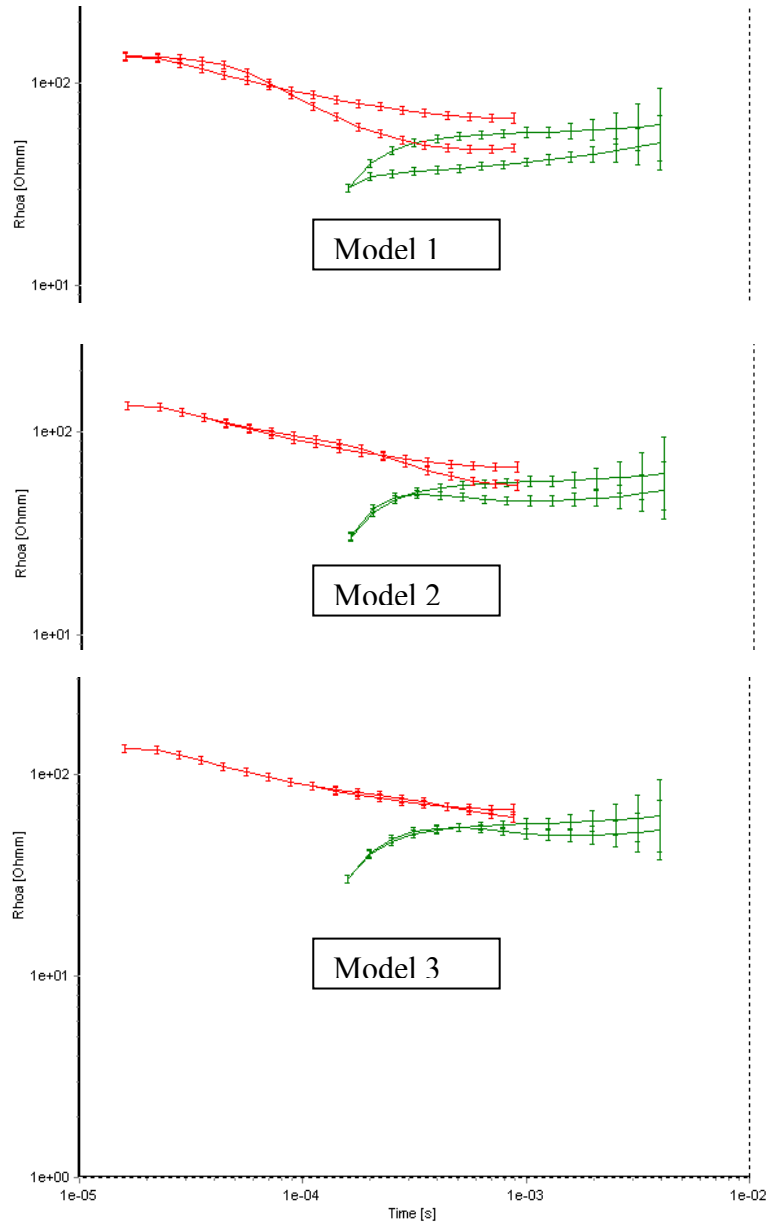


Figure 5. Modeled response of SkyTEM to layer thickness and resistivity described in Table 1. For each model, the red curves represent the low-moment response: upper curve is the response with mine pool layer present; lower curve is the response without mine pool layer. The green curves are the predicted high-moment responses: upper curve is with mine pool layer present; lower curve is without mine pool layer. Error bars are uncertainties due to representative amounts of noise that are included in the model.

Results from Model 1 (Fig. 5) suggest that SkyTEM can detect the mine pool layer at a depth of 50 m. This conclusion is based upon the separation between the curves that represent the SkyTEM response with and without the mine pool layer. Separation occurs at late times in the low moment (red curves) and at early times in the high moment (green curves) responses. Model 2 results (Fig. 5) indicate that SkyTEM should be able to detect the mine pool layer at a depth of 100 m also. Separation of the SkyTEM response curves attributable to the presence of the mine pool layer occur at the latest times in the low moment response and at intermediate times in the high moment response. In Model 3 (Fig. 5), there is no separation between the SkyTEM response with the mine pool layer and the response without the mine pool layer. Error bars overlap suggesting that noise will prevent the mine pool layer from being detected. To summarize modeling results, the SkyTEM system theoretically should be able to detect the mine pool at depths less than or equal to 100 m. However, SkyTEM theoretically will not be able to detect the mine pool at 150-m depths unless noise can be curtailed.

Comparison of Inversion Results with Induction Logs

Foree Oil Company provided down-hole induction logs from two wells drilled to extract gas from gob areas of the Robena and Gateway Mines. A steel casing was set into the Gateway Mine well before logging, rendering induction logs from this well useless. However, the induction log for the well into the Robena Mine contained a conductivity/depth section that was complete except for about 5 m at the surface. SkyTEM flew two lines that intersected at the well location where the induction log was acquired (Fig. 6). Smooth, multilayer inversions of SkyTEM data from these two lines in the vicinity of the well are compared with the induction log in figure 7. The two soundings are located approximately two meters apart, well within the footprint of the SkyTEM system, so similar results were expected and obtained. The sounding for line 2021 is almost identical to the line 2099 sounding (Fig. 7, left graph); slight differences between soundings can be seen in the graph with an expanded conductivity scale (Fig. 7, right graph) These differences can be attributed to data averaging and to the inversion process which “pulls” some information from neighboring soundings.

SkyTEM soundings were not expected to reflect the rapidly varying conductivity changes of the induction log (associated with thin layers, Fig. 7) because soundings are derived from measurements obtained from a much larger area than that of the induction log. Similarly, progressively deeper sounding data are obtained from correspondingly larger rock volumes whereas induction logs have the same sampling volume at all depths (if changes in sampling volume of the induction log due to changes in conductivity can be ignored). Rather, SkyTEM soundings were expected to respond to gross changes in conductance (\sim conductivity \times layer thickness). Therefore, in the right graph, a 10-point moving average algorithm was applied to the induction log to smooth local conductivity variations. The resultant induction log should be comparable with the multilayer, smooth inversion of SkyTEM soundings. The results show that SkyTEM soundings predict the conductivity of the most resistive layers very well though the conductivity of conductive layers is underestimated (Fig. 7, right graph). When asked to comment on the goodness-of-fit between the inverted SkyTEM soundings and the induction log, Greg Hodges, the Chief Geophysicist for Fugro Airborne Surveys stated that “the smooth layer inversion is pretty good” although the “calibration is off” and “the smoothed average conductivity is 10 mS/m too low.” Further, he mentioned that he would have expected to have seen a “bit of response to the conductive layers” in the inverted SkyTEM data. Multilayer, smooth inversions of SkyTEM soundings do not exhibit a discernable response to any conductive layers in the smoothed induction log. More

importantly, the multilayer, smooth inversions of SkyTEM soundings do not detect the conductive mine pool layer that is evident in the induction log at a depth of about 140 m.

Esben Auken of Aarhus University has shown the author a parameterized inversion of these soundings that was a better fit for the induction log (data not available). Although the parameterized inversion has the greatest potential for detecting the mine pool conductor, it could not be used because the highly variable topography within the selected areas would have made the inversion unstable. However, ongoing refinements to the parameterized inversion may allow it to be used for areas of rugged topography soon.

Representative conductivity/depth profiles from the three flight areas are shown in figure 8. In this figure, the elevation of the Pittsburgh Coalbed is shown as a dashed, black line; the mine pool elevation is shown as a dashed yellow line; and areas of no mining (solid coal pillars) are shown as a solid red line. If the SkyTEM surveys had detected the Pittsburgh Mine Pool, a thin, conductive layer (yellow or red) would be visible along the black dashed line where it is overlain by the dashed yellow line i.e. flooded mine workings. No conductive layer would be expected in the unmined areas denoted by the red line.

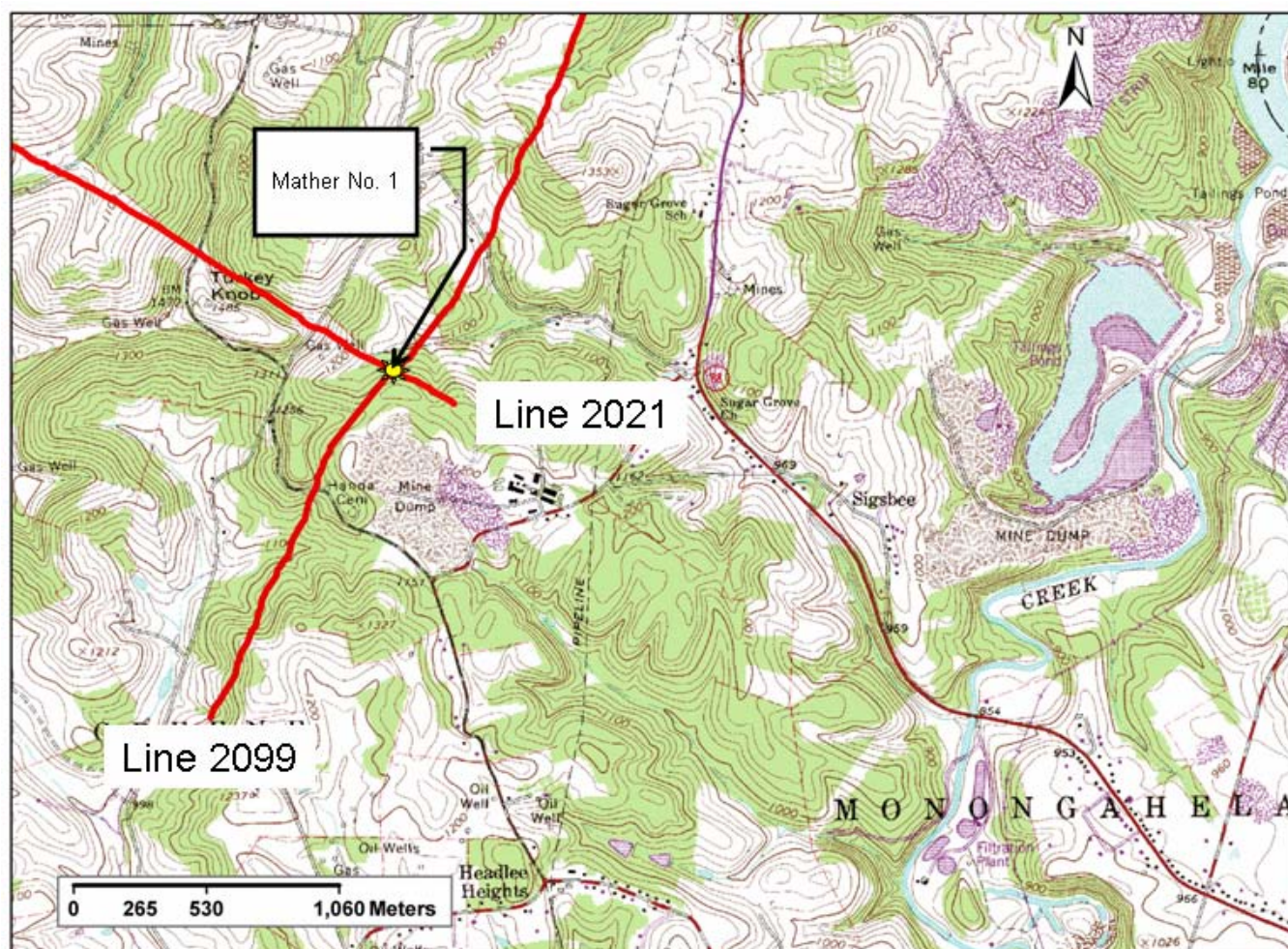


Figure 6. Mather No. 1 gas well is located at the intersection of SkyTEM flight lines 2021 and 2099 in the Robena Mine Flight Area.

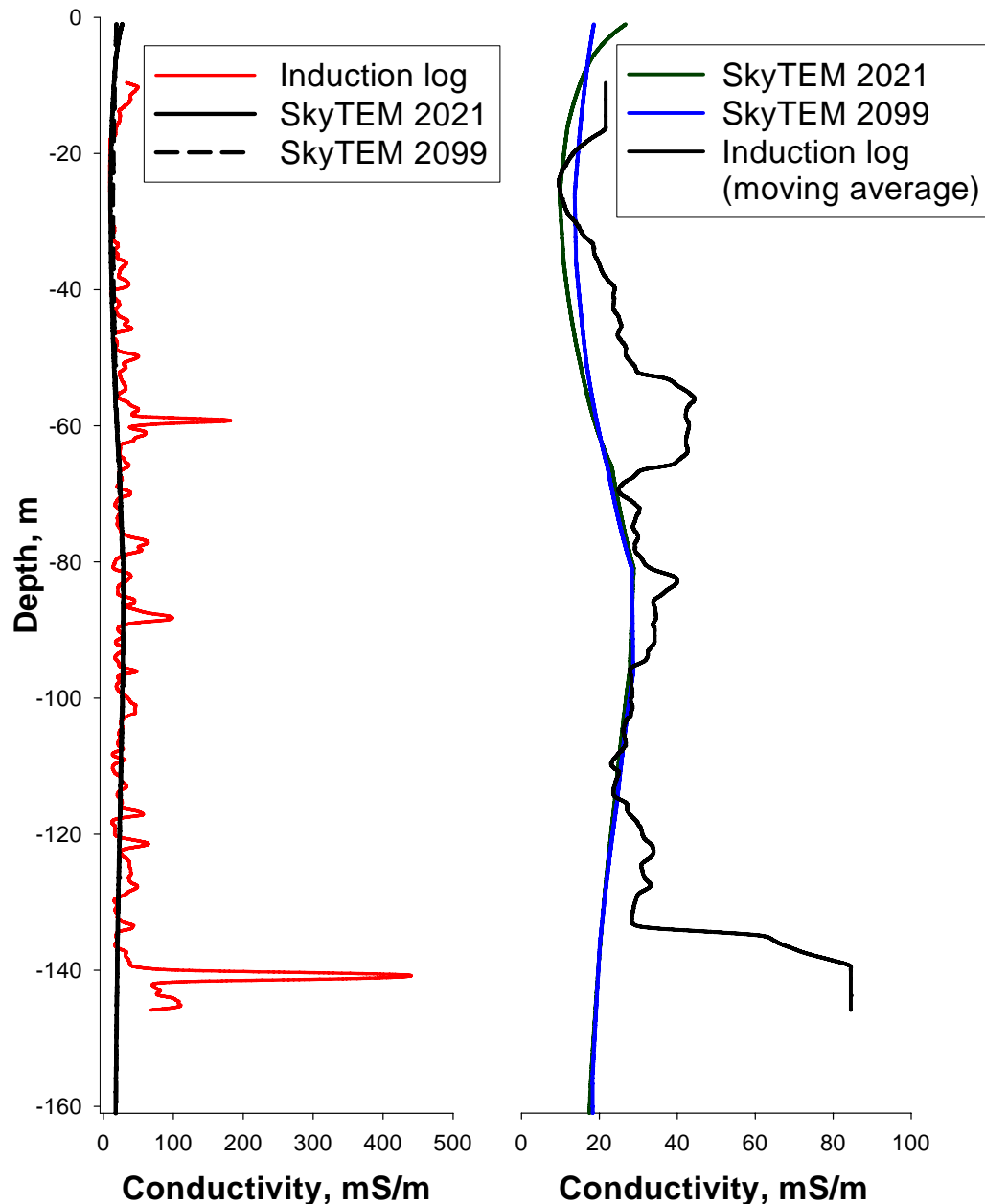


Figure 7. Comparison of induction log from Mather No. 1 Well with conductivity/depth profile (smooth inversion) from two SkyTEM soundings at same location. Left graph shows SkyTEM results compared to raw induction log; right graph shows SkyTEM results compared to induction log data that has been smoothed using a 10-point moving average algorithm. Note differences in conductivity scale.

The SkyTEM surveys did not detect mine pools known to be present in the Pittsburgh Coalbed beneath the three study areas. However, there is some indication that the SkyTEM survey may have detected previously unknown mine pools in the Sewickley Coalbed in the eastern part of the Robena Mine Flight Area (Fig. 8, dashed oval area in center profile). This cannot be confirmed because no maps of mines in the Sewickley Coalbed currently exist for this location though topographic maps show nearby adits and surface mines at the same elevation (Fig. 9). The potential mine pool in the Sewickley Coalbed was detected at a maximum depth of 70 m (230 ft, about the same depth as the Quecreek Mine). If

SkyTEM is actually responding to an existing mine pool, this would represent the maximum depth that a mine pool has been detected from aircraft. Arguing against the possibility of a successful mine pool detection are results from the Uniontown Flight Area where the mine pool is at or near the surface in many areas but was not detected by SkyTEM (Fig. 8, bottom profile).

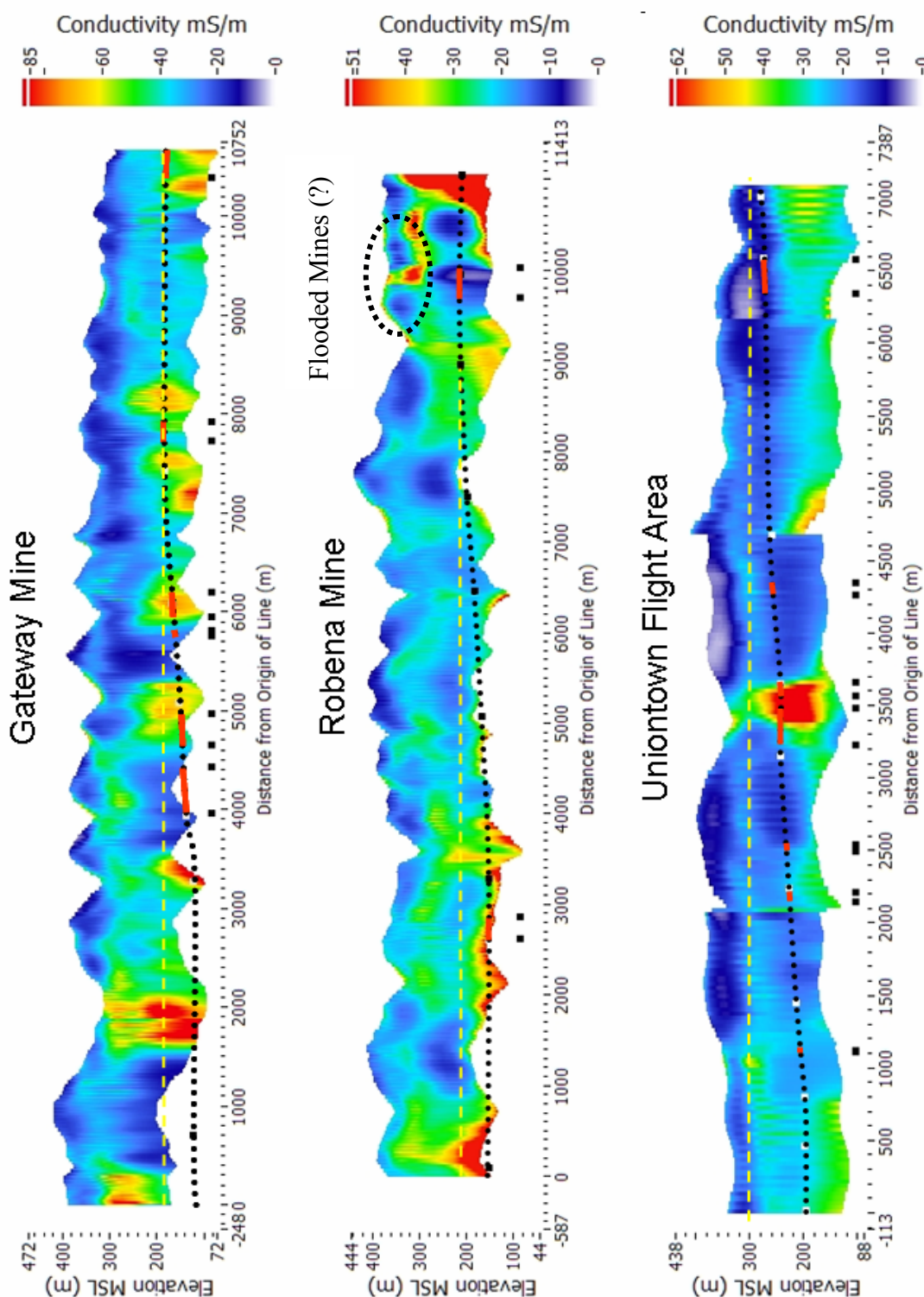


Figure 8. Conductivity/depth sections for selected flight lines from the Gateway Mine, Robena Mine, and Uniontown Flight Areas. Black dotted line shows the elevation of the Pittsburgh Coalbed, which has been mined except for areas denoted by solid red line (unmined coal pillars). The dashed yellow line denotes the piezometric surface of the mine pool at the time of the surveys.

CONCLUSIONS

Airborne time domain electromagnetic (TDEM) surveying systems should not be considered for mapping underground mine pools because: 1) there is insufficient difference between the mine pool conductance and the conductance of the overburden strata for the mine pool to be detected, and 2) broadband receivers used by TDEM surveys are too susceptible to powerline interference to be practical for any surveys except wilderness surveys.

Forward models of the SkyTEM response to the mine pool suggested that it would be detected at depths of 50 m and possibly 100 m but not at 150 m. Actual surveys found that the overburden conductivity is greater than assumed in the models and that the target mine pool could not be detected at any depth. There are no foreseeable changes that can be made to TDEM instrumentation or survey execution that would improve mine pool detection. Significant improvements to the parameterized inversion that would allow stable outcomes in areas of wide ranging topography may invite the re-examination of these survey data. Currently, airborne frequency domain electromagnetic (FDEM) surveying systems only have detected mine pools at shallow depth in north-central Pennsylvania where the mine pool is overlain by resistive sandstone. In this case, the conductance contrast between the mine pool and overburden layer is much greater and the depth is much less than that of this study.

Many soundings were removed from SkyTEM data because of powerline interference even though the flight areas had been selected to be as free of powerlines as possible. The removal of corrupted soundings resulted in large segments of flight lines with no data. Surveys in more populated areas would exacerbate this problem. Airborne frequency domain electromagnetic (FDEM) surveying systems are less susceptible to powerline noise because they employ notch filters on their receivers that exclude most powerline noise.

Although FDEM can detect mine pools at shallow depth (<50 m) when there is sufficient conductance contrast between the mine pool and overburden, too few mine pools fall under this category to make airborne FDEM a practical technique for mapping mine pools.

RECOMMENDATIONS FOR FUTURE WORK

The attractiveness of airborne systems is their ability to survey large areas more quickly and inexpensively than their ground-based analogues. Airborne systems also avoid landowner issues that are sometimes difficult to resolve. Future attempts to detect underground mine pools should not abandon the advantages of airborne surveys but should look for ways to overcome the deficiencies of the electromagnetic induction methods. One suggestion would be to avoid electromagnetic induction completely by directly introducing an alternating current into the mine pool via electrical cables into drill holes or mine portals. Conductive pathways between two current injection points could be detected from aircraft by sensing the magnetic fields generated along the path of current flow. A two- or three-axis magnetic field sensor carried as a helicopter sling load would be able to detect the magnetic fields along the current flowpath and still offer a rapid means of surveying large areas. The perennial problem of powerline interference could be minimized by using an injected current frequency that is greater than 1000- Hz and at a harmonic minimum for powerlines. Notch filters on the output from the magnetic sensors would remove noise at frequencies other than the one selected. A ground-based analogue of this sensing technology is currently offered as a service by Willowstick Technologies, Inc. It has been used at

the Rocky Mountain Oilfield Testing Center to detect the flowpath for a water flood through a 100-m deep, oil-bearing formation (unpublished internal report, RMOTC, 2006).

Although SkyTEM surveys did not detect thin conductors (mine pools), SkyTEM surveys are able to map thick, resistive units such as channel sandstones. The comparison of the smooth, multilayer inversion of SkyTEM soundings to a down-hole induction log from the same location showed that SkyTEM results accurately depicted the depth, thickness, and conductivity of resistive sandstone layers. Large scale mapping of sandstone units would be valuable for coal mine planning (predicting areas where coal was eroded or load estimation for roof support plans). It also may be useful for road construction and oil/gas production.

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