URTeC: 2153840

Rapid Methods for Locating Existing Well Penetrations in Unconventional Well Development Areas of Pennsylvania

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Summary

Pennsylvania has a 150-year history of oil and gas production-the longest of any state- and this enduring activity has resulted in the drilling of more than 330,000 known wells. However, unknown wells may exist because innumerable wells were drilled during Pennsylvania's early years of intense oil and gas development when incomplete records were kept of well locations. The concern is that early wells are likely to be unsealed because there were no laws that required effective plugging when the wells were abandoned. Now, many unrecorded wells are thought to be in areas of emerging shale gas and shale oil development where open wellbores might provide a pathway for undesired upward migration of fluids and gas from hydraulically fractured reservoirs. Because of this concern, Pennsylvania regulators have asked operators to locate orphaned and abandoned wells within a 1000-ft-buffer of new wells before hydraulic fracturing.

The National Energy Technology Laboratory conducted high-resolution, helicopter magnetic surveys over four large land tracts in western and north-central Pennsylvania where historic oil and gas production has taken place and where unconventional oil and gas resource development is occurring or expected. The project's objective was to evaluate the ability of helicopter magnetic surveys to locate existing wells in heavily vegetated areas of varying terrain. Magnetic surveys locate wells by detecting the unique magnetic signature of vertical, steel well casing, which is depicted on magnetic maps as a "bull's eye" type anomaly centered directly over the well. To mitigate for the likelihood that wellbores exist where most or all casing has been removed, this study augmented helicopter magnetic data with supplemental information from farmline maps, state well databases, historic air photos, and digital terrain models generated from LiDAR datasets- all information that is publically available for areas within Pennsylvania.

The four surveyed areas include: 1) a 7 km^2 (2.7 square mile) tract of privately owned land in Washington County with historic oil and gas production and where gas is now being produced from five, horizontal Marcellus Shale wells; 2) a 17.7 km^2 (6.8 square mile) area of state owned land (Hillman State Park) in Washington County with historic oil and gas production and where the uppermost well casings were often cut off or buried by 1950's era surface coal mining; 3) a 28 km^2 (10.8 square mile) block of state-owned land in the Susquehannock State Forest of Potter County where gas was once produced from the Oriskany Sandstone, but it is now a gas storage field; and 4) a 37.7 km^2 (14.6 square mile) area of state owned land (Oil Creek State Park) in Venango County, which contains more than 900 known wells, including some of the oldest oil wells in the United States. Ground surveys to confirm well targets from the helicopter magnetic surveys have been completed for two of the four areas flown including: 1) the private land tract in Washington County, PA with Marcellus Shale development and 2) the area in Susquehannock State Forest that is now a gas storage field.

At the private land tract in Washington County, the helicopter magnetic survey identified 13 well-type magnetic anomalies within 1000 ft of the five horizontal Marcellus wells located there. The ground investigation confirmed that nine well-type magnetic anomalies were wells while four magnetic anomalies were found to arise from non-

well sources. One additional well with a weak (initially overlooked) magnetic anomaly was found using historical air photos. Of nine confirmed wells, six wells had recorded locations in Pennsylvania's statewide oil and gas wells database (PA*IRIS/WIS). However, the PA*IRIS/WIS locations were sometimes too inaccurate for the wells to be located in the dense underbrush.

At the gas storage field in Susquehannock State Forest, the helicopter magnetic survey identified 81 magnetic anomalies, including 55 well-type magnetic anomalies. A subsequent ground investigation confirmed that 30 of the 55 well-type magnetic anomalies were well locations. All confirmed wells except one were listed in the PA*IRIS/WIS state oil and gas well database and the locations provided were sufficiently accurate to locate the well in the field. The helicopter magnetic survey also identified two gas transmission pipelines with pulsed cathodic protection and multiple short pipeline segments without cathodic protection.

Helicopter magnetic surveys identified 192 well-type magnetic anomalies within Hillman State Park and 742 well-type magnetic anomalies within Oil Creek State Park. The ground investigation to confirm well locations in the two state parks had not commenced at the time of this report.

Preliminary observations from this study are:

1. the PA*IRIS/WIS well database is incomplete for wells drilled between 1890 and 1920, the era of early well drilling at the Washington County Marcellus Area. Only six of nine confirmed wells were listed in this database.
2. the PA*IRIS/WIS well database contained 29 of 30 wells found by the helicopter magnetic survey at the gas storage field in Susquehannock State Forest. Wells in this area were drilled post-1950 to produce from and store natural gas in the Oriskany Sandstone. This area contains active gas storage wells and plugged and abandoned gas wells.
3. high resolution magnetic surveys acquired from low-flying aircraft provide accurate locations for wells with steel casing. However, wells with no steel casing exhibit weak or no magnetic anomaly.
4. the inspection of publically available historic air photos or LiDAR imagery for well signatures can sometimes augment helicopter magnetic surveys by identifying well locations where the steel casing was recovered for reuse or salvage.
5. complete casing strings are not needed for detection by helicopter magnetic survey although the minimum casing requirement for detection is not known.

Introduction

The National Energy Technology Laboratory (NETL) has used high-resolution helicopter magnetic surveys (Fig. 1) to rapidly locate legacy wells in two, 100-year-old oilfields in Wyoming [1] [2]. The 40-square-mile (103.6 km^2) Salt Creek Oilfield near Midwest, Wyoming was flown in 2005 to locate existing wells prior to implementing a $scCO_2$ flood. Concurrent to the helicopter survey, an exhaustive ground search was performed to locate all existing wells on a 1-square-mile (2.6 km^2) subarea of the Salt Creek Oilfield. The comparison of confirmed well locations from the ground investigation with well-type magnetic anomalies from the helicopter survey showed that the helicopter magnetic survey was 100% effective for locating primary production wells (pre-1930 spud dates) but only 83% effective for locating infill wells drilled after 1960 to implement a water flood. A follow-up ground magnetic survey of wells "missed" by the helicopter magnetic survey showed that these wells exhibited an unusually weak magnetic anomaly that would have been difficult to detect at the 100-ft (30.5 m) altitude of the helicopter survey.

Figure 1. A helicopter with two, boom-mounted magnetic sensors was used to detect well-type magnetic anomalies at the Salt Creek Oilfield in Wyoming. The instrument mounted under the aircraft (between the skids) is a differential absorption LiDAR (DIAL) sensor that detects methane in the air column below the aircraft.

In 2007, a second helicopter magnetic survey (Fig. 2) was performed just a few miles south of the Salt Creek Oilfield at the 14-square-mile (36.2 km^2) Naval Petroleum Reserve No. 3 (NPR No. 3). Here, the purpose was to determine accurate locations for 1,353 recorded wells and an unknown number of unrecorded wells [3]. The helicopter magnetic survey at NPR No. 3 used the same helicopter platform and magnetic sensor system as the previous survey at Salt Creek Oilfield although the NPR No. 3 survey was flown at a lower altitude and with closer spacing between parallel survey lines. The lower altitude was to mitigate for wells with weak magnetic anomalies such as those that were missed by the helicopter magnetic survey at Salt Creek Oilfield. The flightline spacing was decreased to improve spatial resolution and prevent overlap of magnetic anomalies because wells at NPR No. 3 were closely spaced in some areas. The helicopter magnetic survey at NPR No. 3 located 2,355 magnetic anomalies, which included both well and non-well targets [3]. The NPR No. 3 well inventory contained 1,353 well locations. However, only 889 of 1,353 well locations (66%) matched well-type magnetic anomalies from the helicopter survey to within 50 ft., an indicator of spatial inaccuracies inherent in historic well location databases. The remaining 1,466 magnetic anomalies could not be associated with well locations in the NPR No. 3 well inventory and are likely to be unrecorded wells or from non-well magnetic sources. Like the survey at Salt Creek Oilfield, a ground search for existing wells was performed on a 0.2-square-mile (0.52 km^2) subarea of NPR No. 3 that contained 75 closely spaced wells according to the well inventory [3]. However, the ground search only found 29 well locations of which 28 locations were co-located with well-type magnetic anomalies identified by the helicopter survey. Forty six wells in the NPR No. 3 database for the test area could not be located on the ground and were not targeted by helicopter magnetic data. Of the 46 unfound and untargeted wells, 42 were less than 530 ft. in total depth and were designated as plugged and abandoned. Because no well-type magnetic anomalies were detected at these 42 well locations

Figure 2. Helicopter magnetic survey to locate oil and gas wells at Teapot Dome Oilfield (Naval Petroleum Reserve No. 3) near Midwest, Wyoming

during either the helicopter or the more sensitive ground magnetic surveys, it can be assumed that most, if not all casing was removed when these wells were abandoned. If one ignores the plugged and abandoned well locations that have no magnetic signature, the helicopter magnetic survey successfully located 28 of the 29 wells that were found by an intensive ground search (96% effective).

Results from helicopter magnetic surveys in Wyoming suggest that this method is a rapid way to survey large areas and accurately locate existing wells, particularly old wells whose locations are most likely to be unknown or inaccurately known. The current study was undertaken to determine if the helicopter magnetic surveys that have successfully located wells in Wyoming oilfields can also be applied to legacy wells in western Pennsylvania where wells are older, the terrain is more rugged, and dense vegetation obscures surface evidence of abandoned well locations. The motivation for this research is that there are estimated to be 330,000 abandoned wells in Pennsylvania drilled over the Commonwealth's 150-year history of oil and gas development [4] and PADEP estimates that more than 250,000 of these wells are not properly plugged [5]. However, more wells may exist because innumerable wells were drilled during Pennsylvania's intense early oil and gas history when incomplete state records were kept of well locations. Moreover, these early wells may not be sealed because there were no laws at that time that mandated effective plugging when wells were abandoned. Now, many unrecorded and possibly unplugged wells are thought to be in areas of emerging unconventional oil and gas development where their wellbores may provide a pathway for undesired upward migration of fluids and gas from hydraulically fractured reservoirs. Current development in the Marcellus Shale and the deeper Utica/Point Pleasant Formations is thousands of feet below the deepest penetrations of early wells, and the risk of unwanted fluid and gas migration is minimal. However the risk will increase with the expansion of unconventional gas and oil well drilling into Upper Devonian/Lower Mississippian formations that are closer to the penetration depths of the legacy wells. Because of

this concern, Pennsylvania regulators have asked operators to locate orphaned and abandoned wells within a 1000-ft-buffer of new wells prior to hydraulic fracturing [5].

Methods

The National Energy Technology Laboratory conducted high-resolution, helicopter magnetic surveys over four large land tracts in western and north-central Pennsylvania (Fig. 3) where historic oil and gas production has taken place and where unconventional oil and gas development is occurring or expected. The four surveyed areas include: 1) a 2.7 square mile (7.0 km^2) tract of privately owned land in Washington County with historic, shallow oil and gas production and where gas is now being produced from five horizontal, Marcellus Shale wells; 2) a 6.8 square mile (17.7 km^2) area of state owned land (Hillman State Park) in Washington County with historic, shallow oil and gas production and where the uppermost well casings were sometimes removed or buried by 1950's era surface coal mining; 3) a 10.8 square mile (28 km^2) block of state-owned land in the Susquehannock State Forest of Potter County where gas was once produced from the Oriskany Sandstone, but it is now a gas storage field; and 4) a 14.6 square mile (37.7 km^2) area of state owned land (Oil Creek State Park) in Venango County, which contains more than 900 recorded wells, including some of the oldest oil wells in the United States. The Washington County Marcellus Site (private land) was flown in March, 2012 and the three state land surveys were flown in August, 2014. Ground surveys to confirm well targets from the helicopter magnetic surveys have been completed for two of the four areas flown including: 1) the private land tract in Washington County with Marcellus Shale development and 2) the Oriskany gas storage field in Susquehannock State Forest.

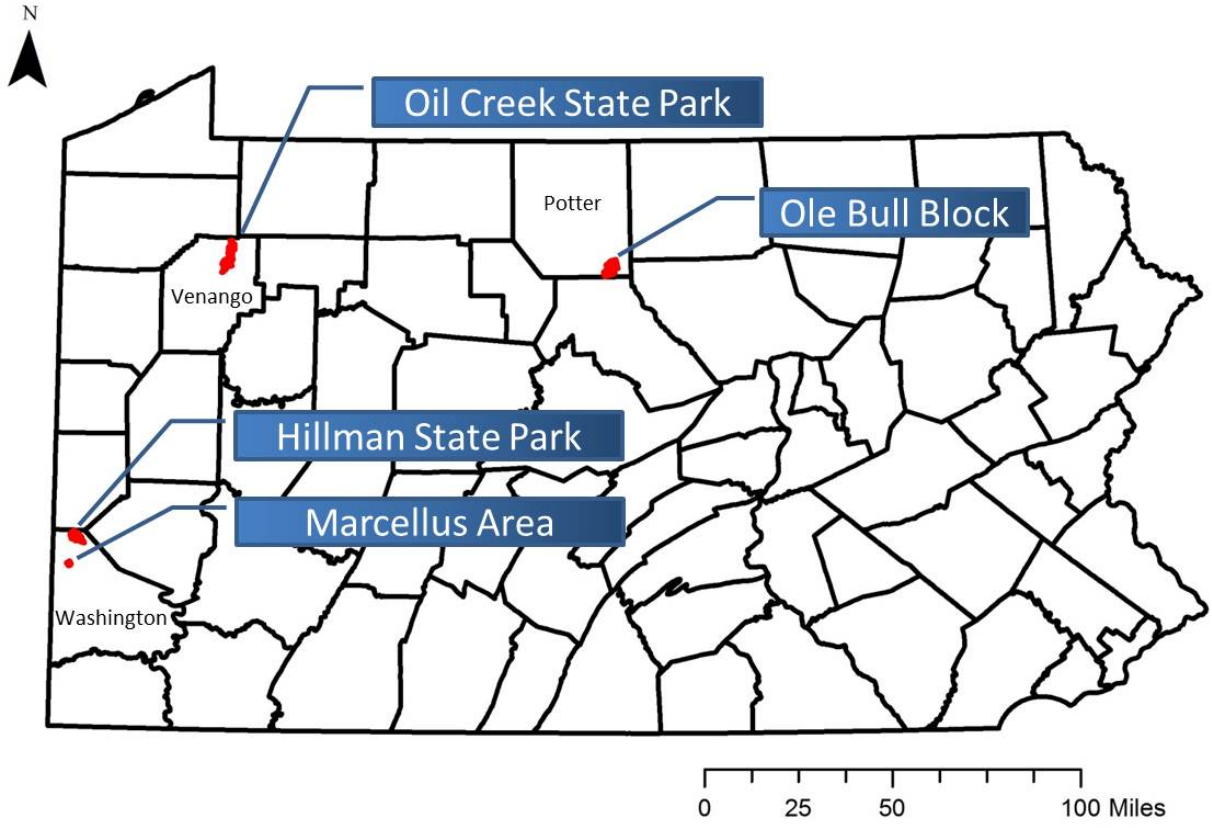

Figure 3. Helicopter magnetic surveys for well detection were flown in four areas of Pennsylvania where historic oil and gas production has taken place and where unconventional oil and gas production is occurring or expected.

Helicopter Magnetic Surveys

Survey Design

A turbine-powered helicopter was used having boom-mounted, dual magnetic sensors spaced 41 ft (12.5 m) apart and oriented orthogonal (90°) to the flightpath (Fig. 4). The helicopter-mounted system permitted slow flight at low altitude with excellent terrain compliance and short turn-around distance. Slow flight increases data density along the flightpath; low altitude flight improves the likelihood of detecting weak magnetic anomalies. The four survey areas were flown with the CGG (formerly Fugro) MIDAS system, an updated version of the system that was used for earlier NETL well location surveys in Wyoming. The survey plan consisted of flying multiple parallel swaths in a north-south direction because this orientation will exhibit the maximum peak-to-peak amplitude for a given magnetic anomaly [6]. At the Washington County Marcellus Site, the helicopter magnetic survey was flown with a nominal interline spacing of 82 ft (25 m). The interline spacing was increased to 98.4 ft (30 m) for surveys at Hillman State Park, Oil Creek State Park, and the Ole Bull Block in Susquehannock State Forest. Tie lines (for interline data levelling) in all four survey areas were flown orthogonal (90°) to the survey course and at 820 ft (250 m) spacing. The flight plan avoided occupied dwellings, terrain/obstruction conflicts, power lines, and busy roads.

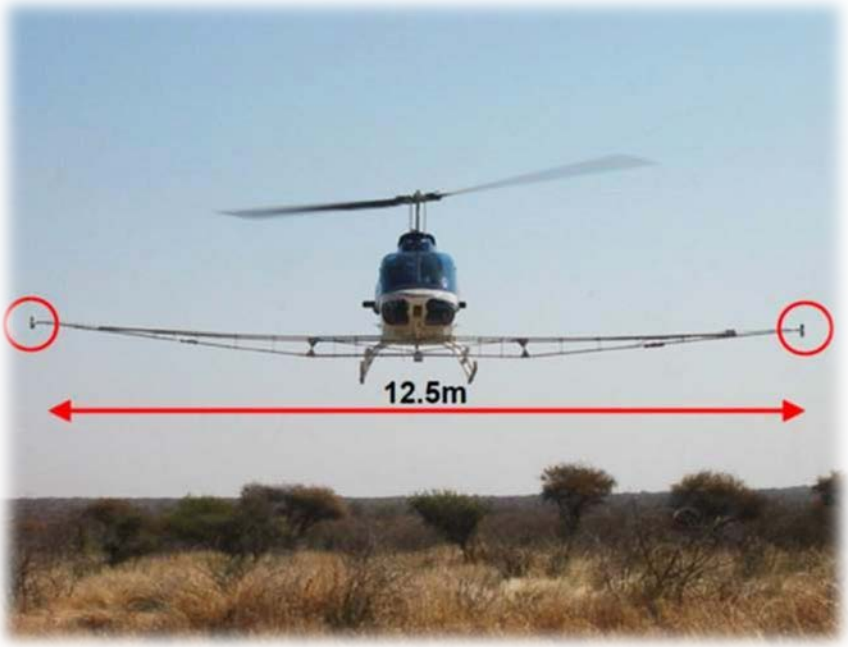

Figure 4. Helicopter magnetic surveys in this report were conducted using the CGG MIDAS system with two boom-mounted cesium ion magnetometers. Photo courtesy of Greg Hodges, CGG Airborne.

Processing/Interpretation of Helicopter Magnetic Data

The deliverables from the airborne contractor (CGG Airborne Surveys) included a DVD-ROM containing a data archive, grids, maps, geophysical report and video archive along with two paper copies of the report. Printed maps, including a horizontal-gradient-enhanced, total magnetic intensity map, a calculated magnetic vertical gradient map, and a measured transverse magnetic gradient map were provided. A Geosoft™ line database was provided by the airborne contractor that contained all data channels acquired during the survey.

Magnetic surveys locate wells by detecting the unique magnetic signature of vertical, steel well casing, which is depicted on magnetic maps as a “bull’s eye” type anomaly centered directly over the well. Although the “bull’s eye” magnetic anomaly can be seen in the map products provided by the airborne contractor, additional processing can enhance these features. Levelled, compensated, and diurnally-corrected Total Magnetic Intensity (TMI) data provided by the airborne contractor were processed by NETL to produce a cell based grid using a minimum

curvature method. The resulting grid was then filtered using a pseudo-analytic signal algorithm and further processed into a color-draped, shaded relief image to assist in the visual identification of potential well anomalies. Analytic signal processing effectively removes negative frequency components of the magnetic signal and enhances the edges of features giving rise to these signals. Shading gives a 3-D visual impression to anomalous features. Collectively, these enhancements provide image maps that emphasize even the most subtle of magnetic anomalies. NETL used data processed in this manner to identify well-type magnetic anomalies that served as targets for the ground investigation that followed.

The video of the ground beneath the helicopter taken during magnetic surveys contains timestamps and fiducials that are synchronized with the magnetic data stream. The video record can be used to identify magnetic sources in a few open areas but most of the surveyed areas had tree canopy. In forested areas, the coordinates for magnetic anomalies were converted to file formats that are compatible with GPS receivers, GIS, and Web-based viewing software. Universal exchange format facilitates uploads to various compliant GPS models as waypoints for field navigation to aid in the reconnaissance. These waypoints may then be converted to keyhole markup language (kmz) and ArcGIS™ shapefile formats for sharing with colleagues and industry partners as layers in Google Earth™ and ESRI GIS software products.

Ground Verification of Helicopter Survey Results

Survey Design

The objective of the ground reconnaissance was to confirm if well-type magnetic anomalies identified during the helicopter survey were actually wells. A 2- or 3-person field team used a tablet PC running GPS-linked moving maps to navigate to the approximate location of well-type magnetic targets (Fig. 5). The ground search was often hindered by a thick tree canopy, which degraded the accuracy of GPS receivers and created uncertainty about the ground location of the airborne anomaly. When the anomaly location was reached, the well was often obscured by nearly impenetrable undergrowth. The ground investigation found that the magnetic source (eg. well casing) was often offset from the helicopter magnetic target by several meters, an artifact of aeromagnetic data processing which assigns targets to a location along the flightline having the highest TMI. When the flightline was not directly over the magnetic source, the airborne target was offset slightly from the ground location. When the flightline was directly above the magnetic source, there was no discernable offset.

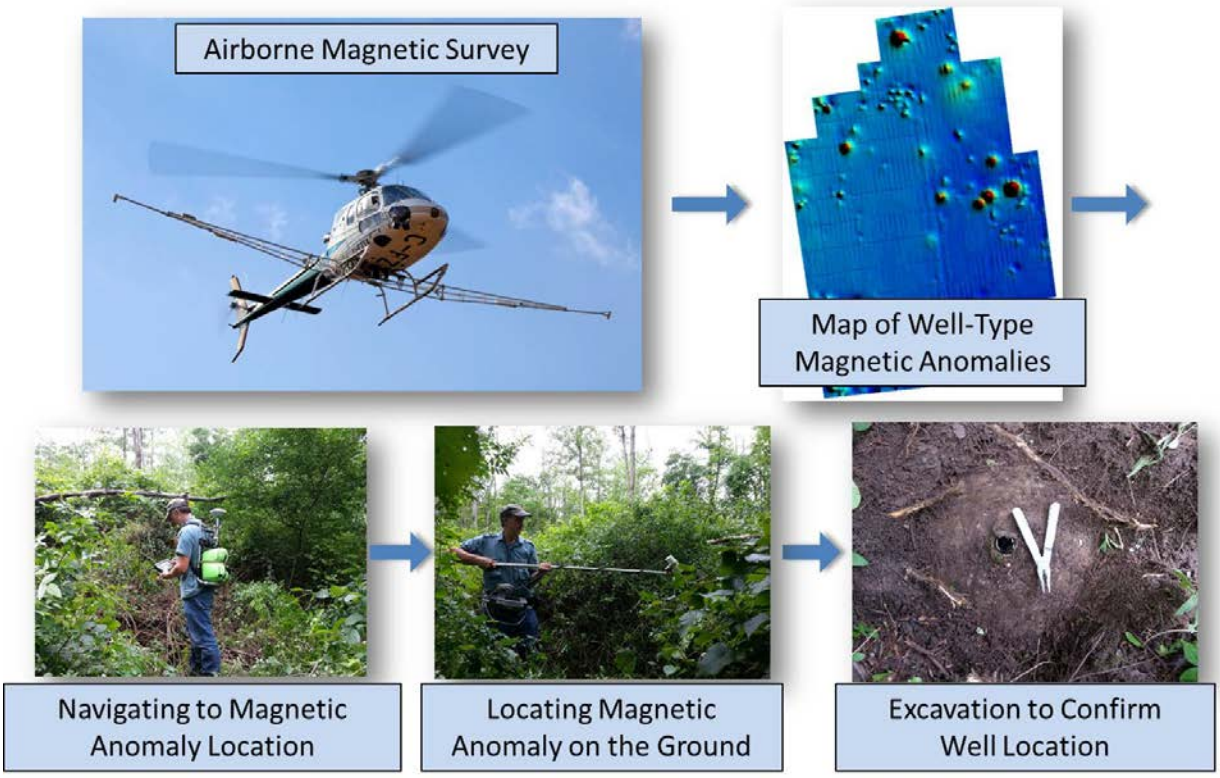

Figure 5. The steps used to confirm well locations. Photos from Washington County Marcellus Site.

For well casing that was either concealed by vegetation or was cut off below ground, a Geometrics G-858 portable magnetometer was used to locate the origin of the strongest TMI, which was frequently at the well. The G-858 could be used to collect a continuous stream of magnetic intensity data at a 10-Hz acquisition rate for use in walking surveys. Positional data for walking surveys was afforded by a backpack mounted, differentially-corrected GPS receiver that would output to the G-858's console data recorder. The instrument offered a "search mode" that was found to be useful to home-in on strong magnetic sources. Search mode permits the operator to observe the total magnetic field value at the sensor location on a strip-chart display of the unit's data logger console, along with audible pitch changes linked to signal intensity trends in real-time. Operating the magnetometer in search mode identified several buried wells that were confirmed by excavation.

Results

Marcellus Site, Washington County, PA

The Pennsylvania Department of Environmental Protection (PADEP) has asked oil/gas operators to locate existing wells that are within 1000 ft. (305 m) of new wells prior to hydraulic fracturing [5]. The Washington County Marcellus Site contains five horizontal Marcellus Shale wells; the 1000-ft-buffer area (Fig. 6) around these wells comprises an area of approximately 1.15 square miles (3 km^2). Within the 1000-ft-buffer area, the helicopter survey identified 36 magnetic anomalies including 21 magnetic anomalies that the airborne contractor listed as having "unknown" origin, the category that would include well-type magnetic anomalies (Fig. 7, 8). From the 21 "unknown" anomalies, NETL identified 13 magnetic anomalies that had the characteristic "bull's eye" magnetic signature of vertical steel well casing. The ground investigation confirmed that 9 of the 13 well-type magnetic anomalies were abandoned oil/gas wells and that four anomalies were from non-well sources. Only six of the nine confirmed well locations were recorded in Pennsylvania's statewide oil and gas wells database (PA*IRIS/WIS). This study found that PA*IRIS/WIS locations were often more than 164 ft (50 m) from actual well locations, which was sometimes too distant for the well to be found in areas with heavy vegetation (Fig. 9).

Although the ground investigation extended slightly outside the 1000-ft-buffer area where there was evidence of nearby wells, it did not cover the entire flight area. Six additional wells were found outside the 1000-ft-buffer area

using a combination of airborne magnetic data, LiDAR (topographic footprint-showing a pad or access road), and historic 1930's aerial photography (showing derricks and engine house). Within the ground investigation area (both inside and outside the 1000-ft-buffer area), a LiDAR well signature was clearly visible at seven well sites and derricks and engine houses were visible in historic geo-referenced photographs at six well locations. Two wells with weak helicopter magnetic anomalies might have been overlooked without the air photo that showed a derrick and pump house at each of these locations in 1939. In total, 19 well locations were confirmed by the ground investigation; at six locations, the well was not visible and a portable magnetometer was needed to locate the well casing, which was either buried or concealed by dense underbrush.

Handwritten records for one well within the 1000-ft- buffer area suggest that it was abandoned in 1902 as a dry hole and that an attempt was made at that time to recover the casing. During casing recovery, an unknown length of casing became lodged and was abandoned in the well at an unknown depth. Despite the removal of some casing, this well was easily located by the helicopter magnetic survey and its location was confirmed by a ground magnetic survey. Further, a DC resistivity survey using a 56-electrode array centered over the well-type magnetic anomaly identified a narrow, vertically oriented, conductive anomaly at the same location as the magnetic anomaly. The resistivity survey showed the conductive anomaly to be at a depth of about 60 ft (18.3 m) - presumably the upper part of the casing left in the well.

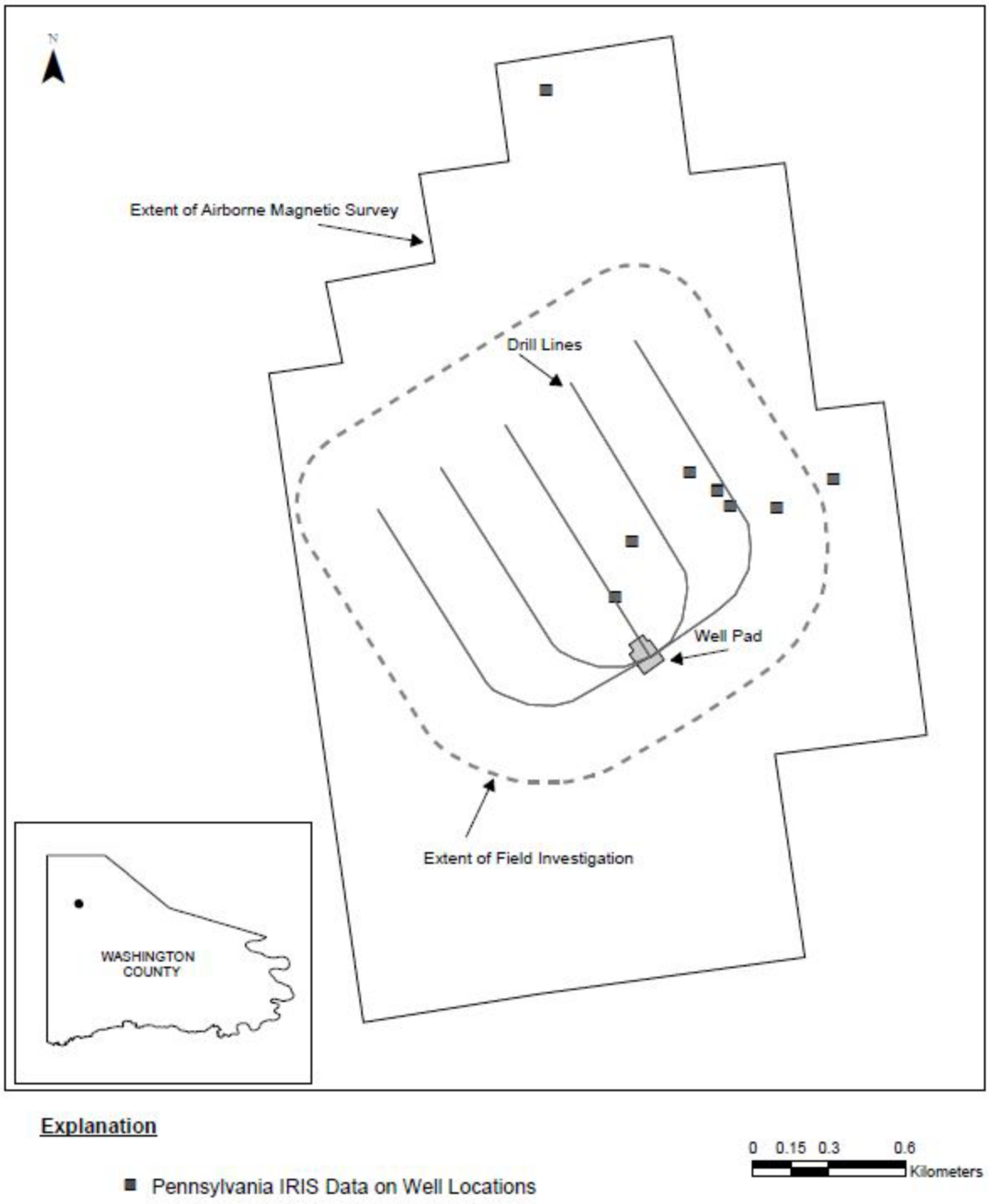

Figure 6. Map of Washington County Marcellus Site showing the extent of the flight area, the location of five horizontal Marcellus Shale wells, and the PADEP recommended 1000-ft-wide buffer (dashed line) around the Marcellus Shale wells where operators are requested to locate existing wells. Black squares are PA*IRIS/WIS well locations.

Figure 7. Helicopter magnetic survey of the Washington County Marcellus Site. Pilot flew as close to the ground as possible to maximize the magnetic response of wells.

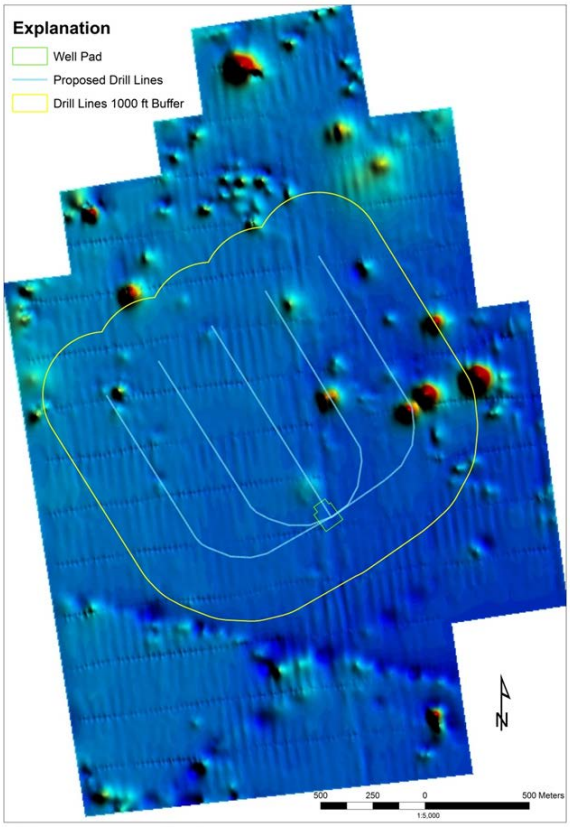

Figure 8. Helicopter magnetic map of the Washington County Marcellus Site

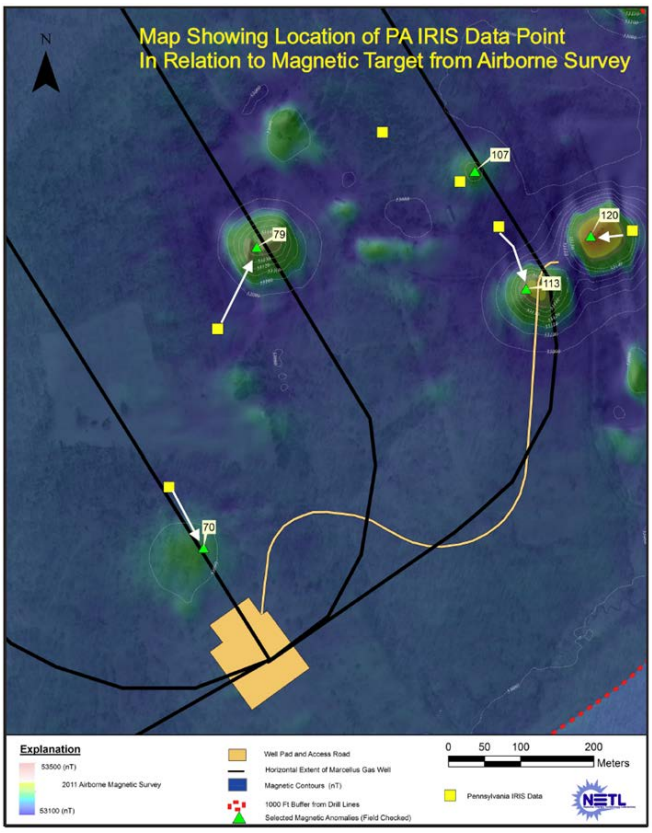

Figure 9. Helicopter magnetic map showing the offset between PA*IRIS/WIS well locations (yellow square) and actual well locations (green triangle).

Hillman State Park, Washington County, PA

Hillman State Park is a 6.8 square mile (17.7 km^2) area in northern Washington County that had historic oil and gas development in the late 1800's and was surface mined for coal in the early 1950's. The surface mining that occurred here poses significant challenges to well location methods that rely on the magnetic signature of vertical steel well casing because: 1) the upper casing for wells in surface mined areas is likely to be cut off just below the level of the mined coal, and 2) mine spoil was cast into low-lying areas where it buried wells under 0- 50 ft (0-15 m) of soil and rock. In both cases the magnetic intensity from the steel well casing is reduced, making detection more difficult.

The Farmline Map of 1911 showed 186 oil and gas well locations within park boundaries although the PA*IRIS/WIS database contains only 36 well locations for the same area. The airborne contractor's magnetic anomaly picker identified 148 potential well locations based on results of the helicopter magnetic survey. NETL manually performed a line-by-line examination of the helicopter magnetic data to identify subtle anomalies that may have been missed by the contractor's anomaly picker software. This examination identified 46 more well-type magnetic anomalies and excluded many dipole magnetic anomalies that are unlikely to be well locations. An additional 104 potential well locations were added using information from PA*IRIS/WIS databases, Farmline Maps, historic air photos, and LiDAR well signatures. A total of 298 potential well locations within Hillman State Park were identified for ground confirmation by a follow-up investigation, which is underway but in its early stages (Fig. 10).

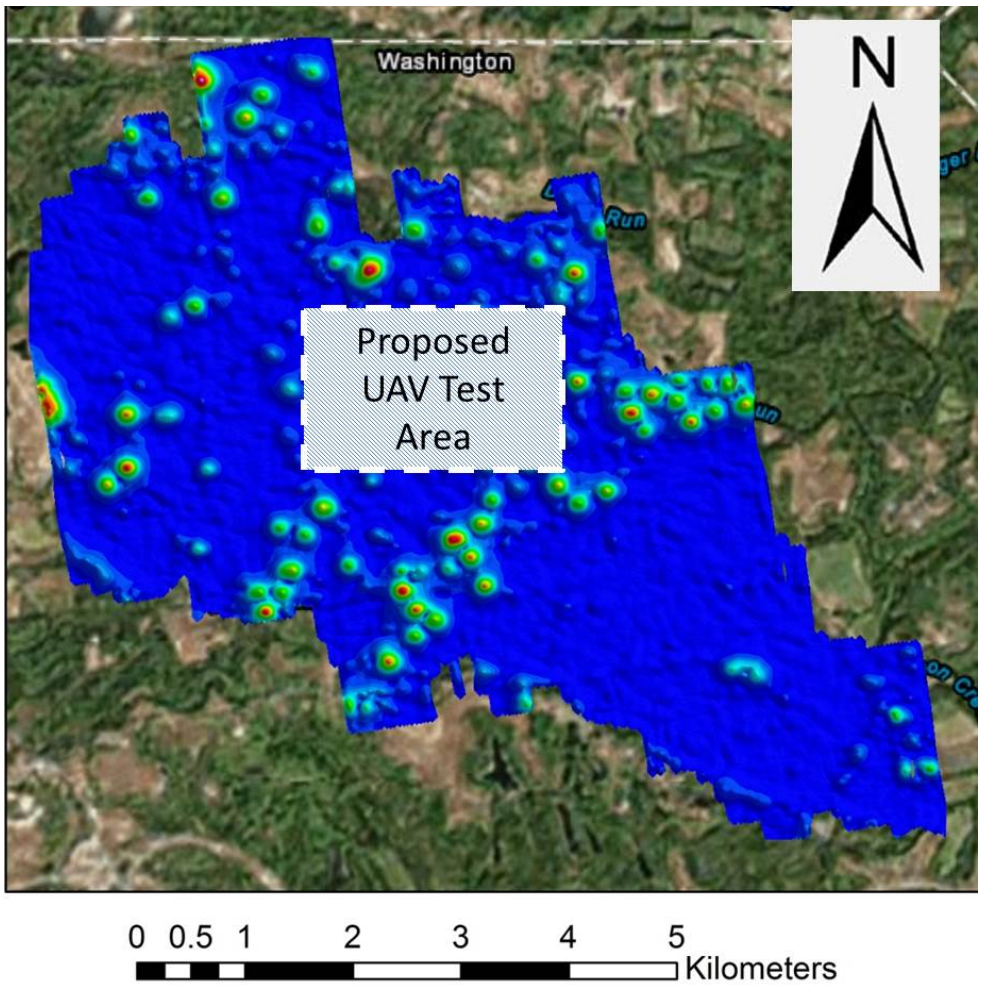

Figure 10. Helicopter magnetic map of Hillman State Park, Washington County. Shaded area is a potential site for testing the ability of unmanned aerial vehicles (UAV) to locate legacy wells.

The Commonwealth of Pennsylvania is considering using part of Hillman State Park to evaluate new methods for locating existing wells. Hillman State Park is considered a good site to test well location methods because:

- NETL's well locations, which are based on a helicopter magnetic survey and publically available information sources and will be confirmed by a subsequent ground investigation, can provide a basis for evaluating new well location technologies.

- The partly forested landscape altered by surface mining will present a variety of logistical, navigational, and detection challenges to potential well location methods
- A RC model aircraft airport within the park is favorably located to serve as a staging area for well location methods that use unmanned aircraft,
- Area is state owned and uninhabited-no issues with private landowners.

Figure 11. A well location targeted by the helicopter magnetic survey lies beneath this small pool at Hillman State Park

Ole Bull Block, Susquehannock State Forest, Potter County, Pennsylvania

The Ole Bull Block comprises a 10.8 square mile (28 km^2) area in Susquehannock State Forest where gas was once produced from the Oriskany Sandstone, but it is now a gas storage field. The airborne contractor's automatic anomaly picker identified 81 magnetic anomalies within the survey block. NETL selected 55 anomalies (Fig. 12) from this list that had magnetic characteristics of vertical, steel well casing and these locations were either visited in the field or confirmed from aerial photographs (most active gas storage well locations were confirmed by aerial photography and not visited). The investigation found 30 well locations; 29 wells were in the PA*IRIS/WIS database although database well locations were sometimes offset as much as 164 ft (50 m) from the actual well location.

In addition to well locations, the helicopter magnetic survey identified two natural gas transmission pipelines with pulsed cathodic protection (to prevent pipeline corrosion), multiple smaller pipeline segments that serve gas storage wells, and one gathering line that connected wells that are now plugged and abandoned. In helicopter magnetic maps, the pulsed cathodic protection results in a patchwork of areas with and without magnetic fields (Fig. 12) on either side of the pipeline. When the cathodic protection current is on, a magnetic field is detected at the helicopter's location for the duration of the current pulse. No magnetic field is detected for the flightline segment flown when no current is flowing in the pipeline.

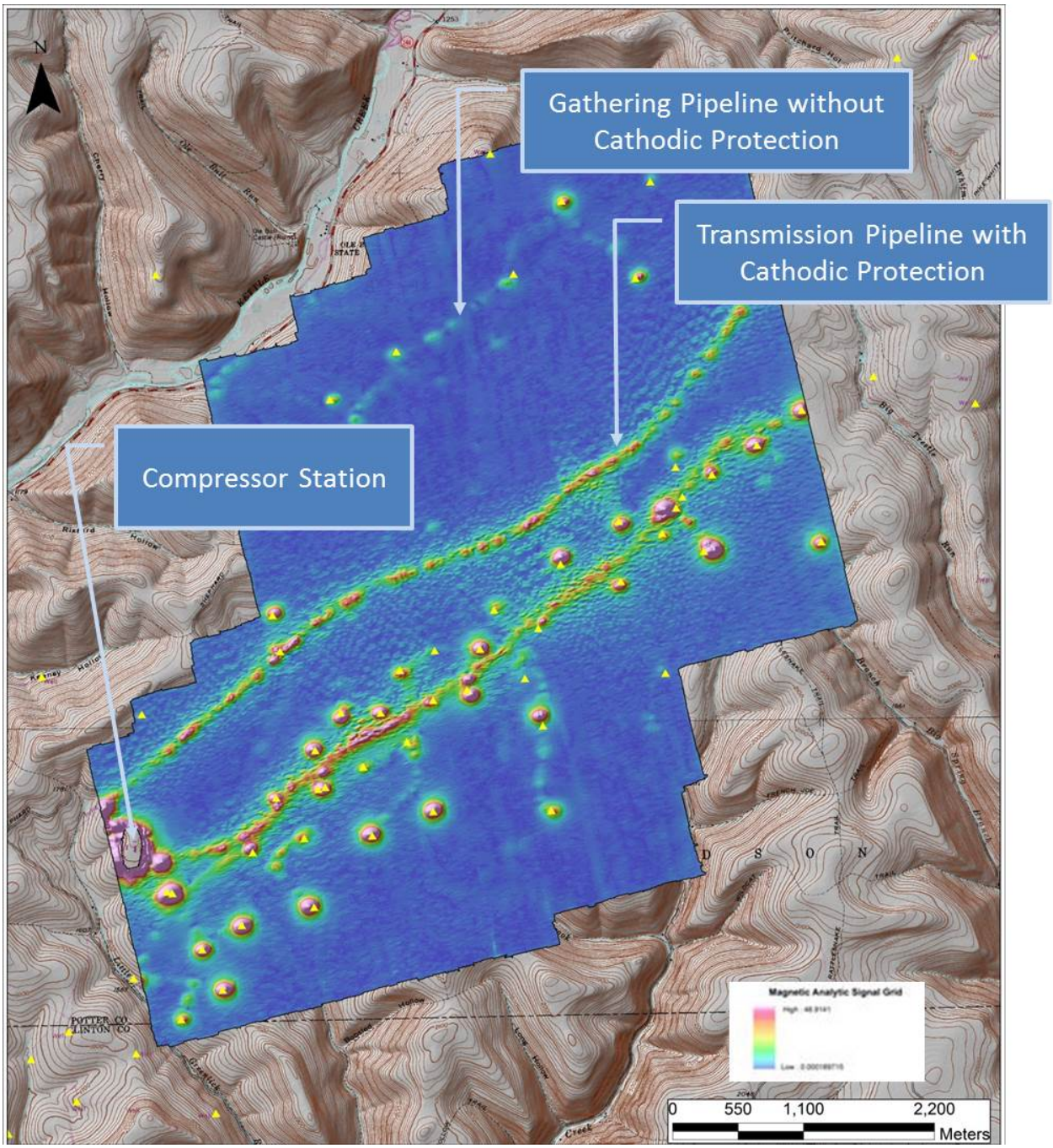

Figure 12. Helicopter magnetic map of Ole Bull Block in Susquehannock State Forest that contains two gas transmission pipelines with pulsed cathodic protection, multiple gathering pipelines without cathodic protection, and 30 well locations. PA*IRIS/WIS well locations are designated by a yellow triangle.

Oil Creek State Park, Venango County, Pennsylvania

Oil Creek State Park is a 14.6 square mile (37.7 km^2) area that contains some of the oldest oil wells in the world. The Drake Well, located just outside the northern boundary of Oil Creek State Park, was drilled in 1859 and its success brought the nation's first oil boom to this area. Between 1859 and 1865, 100's of oil wells were drilled along the floodplains and lower slopes of Oil Creek and its tributaries. Although the oil boom within Oil Creek State Park was over by 1871, there have been periods of intermittent drilling activity until the present. The most recent drilling targeted gas in the Silurian age Medina Group, which was produced from regularly spaced wells, drilled in the 1990's. NETL chose this area to test the well finding ability of helicopter magnetic surveys because the dense concentration of 1859-1870 era wells along Oil Creek offers the ultimate challenge to this method of well finding. The magnetic response of these wells is expected to be weak because the wells were shallow (~500-ft-deep) and wood may have been used instead of steel for the well's conductor, casing, and flow lines. Further, the close well spacing in certain areas may cause overlap of magnetic anomalies from adjacent wells. Moreover, the area contains abundant ferrometallic relicts from past oil production and its ancillary activities that can obscure the magnetic response of vertical steel well casing. The steep terrain adjacent to the deeply incised Oil Creek required a high performance helicopter to maintain the low-altitude flight needed to detect weak magnetic anomalies.

The helicopter magnetic survey of Oil Creek State Park identified 742 well-type magnetic anomalies that will be the target of a ground investigation that has not yet commenced (Fig. 13). These anomalies were identified from a line-by-line examination of the helicopter magnetic data, which permitted the selection of well-type (monopole) magnetic anomalies from the many dipole magnetic anomalies that arise from non-well sources.

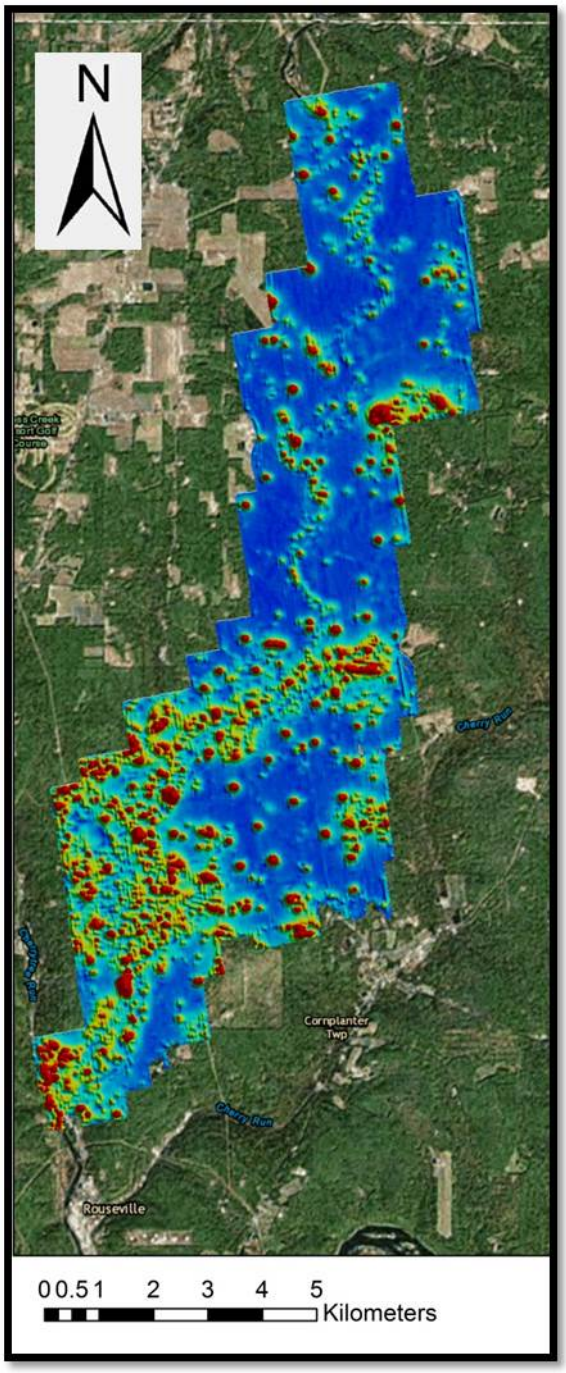

Figure 13. Helicopter magnetic map of Oil Creek State Park, Venango County, PA

Conclusions

In Pennsylvania, there are four sources of publically available information that should be consulted first when trying to locate abandoned and orphaned wells. These sources include: 1) Farmline Maps (where available), 2) PA*IRIS/WIS wells location database, 3) historical air photos, and 4) LiDAR digital elevation models.

NETL's experience indicates that Farmline Maps contain the most complete catalog of wells drilled prior to 1910. In the Washington County Marcellus Area, the Farmline Map provided a well location where the helicopter magnetic map showed a weak magnetic anomaly that was initially overlooked because it was near a stronger magnetic anomaly associated with a pipeline. Seeing the well location on the Farmline Map caused us to reconsider the magnetic anomaly, which was later confirmed to be a well. When Farmline Maps are accurately georeferenced, they provide well locations that often permit the well to be found. This link shows Pennsylvania areas with Farmline Maps and where these maps can be obtained. (http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/resrefs/farmline_maps/index.htm)

The PA*IRIS/WIS wells location database was found to be almost complete (29 well listings for 30 confirmed wells) for the Ole Bull Block in Susquehannock State Forest where wells were drilled after 1950. However, the PA*IRIS/WIS well locations database contained only six of nine confirmed wells at the Washington County Marcellus Area where wells were drilled prior to 1920. This study found that PA*IRIS/WIS well locations were often offset more than 164 ft (50 m) from actual well locations, which is too far for the wells to be found in heavy vegetation. The PA*IRIS/WIS wells location database is available at (http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/pa_iris_home/index.htm).

Historical air photos were found to be helpful at the Washington County Marcellus Area where they provided locations for wells where some or all casing had been pulled and where the helicopter magnetic anomaly was weak or absent. The image and shadow of a well derrick with pump house are unmistakable in these photos and provide an unimpeachable well location if the photo is accurately georeferenced. Historical air photos do not provide a complete record of well locations, however, because well structures on the surface may have been removed before the air photos were taken. Historical air photos are available at (http://www.pennpilot.psu.edu/).

Digital terrain models generated by gridding last return LiDAR data can identify subtle topographic features beneath the forest canopy that are indicative of well sites. When looking for a well signature in LiDAR constructed topography, NETL looks for a small road ending at a level area (possible well site). This LiDAR signature was observed at seven confirmed well sites in the Washington County Marcellus Area. Pennsylvania state-wide LiDAR data can be downloaded from (http://www.pasda.psu.edu/uci/SearchResults.aspx?originator=%20&Keyword=pamap%20lidar&searchType=keyword&entry=PASDA&condition=AND&sessionID=62847488020153213956).

Helicopter magnetic surveys are the current gold standard for obtaining a nearly complete catalog of abandoned oil and gas well locations. However, magnetic surveys cannot detect wells where all casing has been pulled for salvage or reuse, a common practice during early days of oil and gas production and particularly during the World Wars. Results obtained from the Washington County Marcellus Area showed that wells can be detected by helicopter magnetic surveys if some casing still remains in the well. Although effective, helicopter surveys are expensive, limiting their use to large, inaccessible areas where the cost can be justified. For this study, helicopter magnetic survey costs ranged from $11,000/square mile for the 32.2 square mile combined surveys of Hillman State Park, Oil Creek State Park, and Ole Bull Block to $41,000/ square mi for the 2.7 square mile survey of the Washington County Marcellus Site. There is a cost advantage to flying large areas. Future research will be directed at installing magnetic sensors on small, unmanned aircraft, thereby significantly reducing the cost of airborne magnetic surveys without decreasing their well detection capability. Moreover, unmanned aircraft can safely fly at lower altitude, which will increase the magnetic signal from well casing, and improve well detection.

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