EVALUATION OF THE MICRO-FABRICATED ATOMIC MAGNETOMETER DEPLOYED FROM A SMALL AUTONOMOUS ROTORCRAFT FOR LOCATING LEGACY OIL & GAS WELLS

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Abstract

The Pennsylvania Turnpike Commission Southern Beltway Project, a 13-mile highway segment connecting U.S Route 22 to I-79, is part of a larger beltway system designed to improve east-west mobility in the corridor south and west of Pittsburgh. The proposed highway corridor traverses the McDonald Oilfield and was expected to encounter legacy wells. These wells must be located and properly plugged to meet environmental regulations prior to excavation for highway construction. The National Energy Technology Laboratory (NETL) of the U.S. Department of Energy along with US Aerial Video, Inc. conducted aeromagnetic surveys from a small drone rotorcraft during the summer of 2017 employing the novel Geometrics micro-fabricated atomic magnetometer (MFAM) sensor package to locate these legacy wells within the planned highway right-of-way. Over 200 line-kilometers of magnetic data was collected and processed resulting in many monopolar anomalies that may be interpreted as potential steel-cased wells. A list of magnetic targets was submitted to the PA Turnpike Commission for confirmation on the ground.

Introduction

The PA Turnpike Commission (PATC) Southern Beltway system U.S. Route 22 to I-79 connector highway, portions of which are currently under construction, meanders northwest to southeast some 13 miles between two major interchanges, I-576 near Burgettstown to just south of Bridgeville with I-79. There are minor interchanges along its course having on/off ramps, bridges and overpasses together with cut/fill and drainage catchment areas that significantly expand the footprint of the nominal 150 ft. wide four-lane highway.

A magnetic survey was proposed over concerns of encountering legacy wells because the construction corridor passes through the McDonald oilfield, second largest in Pennsylvania. Production in the McDonald field began in late 1886 and peaked at 84,300 BPD shortly thereafter near the end of 1891, mainly from 306 wells. Adjacent fields included the McCurdy, Venice, Hopper, and Moon Run-Crafton (Ingham, 1949). These fields although geographically isolated, shared common Upper Devonian geological origin. The production units are stratigraphic traps where accumulations of oil were found predominantly in more permeable parts of the Gordon, Fourth, and Fifth sands of the Conewango group. The McDonald oilfield is located in the Allegheny Plateau physiographic province, characterized by rolling hills with a maximum elevation of 733 ft. above the Ohio River. The McDonald field covers some 13,000 acres and wells were drilled by cable tool to depths ranging 2100-2500 ft. Over 1200 wells were drilled up until 1916 averaging 2350 ft. T.D. The average length of the original casing strings was 1200 ft. of nominally 6 in. casing. These wells continued in production until 1932, after which 2/3 were abandoned. Secondary recovery ensued on the remaining wells employing gas injection, vacuum, and finally water flooding (Tignor and Nabors, 1949).

Aeromagnetic Well Detection

Aeromagnetic anomalies arising from vertically-oriented steel-cased wells produce a distinctive monopolar anomaly resembling a bulls-eye (Frischnecht, 1985; Hammack, 2006). The location of maximum magnetic intensity interpolated from the resulting grid of the geo-located total field aeromagnetic data will be close to the well location on the ground. Further refinements of the well location can be afforded by applying reduction-to-the-pole or analytic signal processing.

The total magnetic intensity can vary considerably, depending mainly on the length and size of casing, distance from the sensor, degree of magnetization and remanence (Armstrong, 1973; Baer, 1995). Frequently, production tubing and all or most of the casing were pulled from the wellbore and either salvaged for reuse or sold for scrap. These wells will display little or no magnetic response. A weak and broad monopole anomaly usually indicates some quantity of non-retrievable casing remains in the wellbore. Short of excavation, it may be very difficult or impossible to find the wellbore without a wellhead, casing at the surface, or other infrastructure. There are also intact wells impacted by surface mining of coal. Examples of these have been observed and were a subject of investigation from a recent aeromagnetic survey in Hillman State Park, near Burgettstown, PA (Sams, 2017).

Materials and Methods

The magnetic sensor used in this study was a Micro-Fabricated Atomic Magnetometer (MFAM) built by Geometrics, Inc. MFAM is a solid-state, laser-pumped atomic magnetometer. The redundant, dual sensors were positioned such that the flightpath was orthogonal to the optical axis to optimize signal and to avoid the narrow dead zone at normal flight attitudes. The MFAM electronics and sensor package were housed in the Arrow, an early prototype towed-bird apparatus on loan from Geometrics, Inc. A second prototype towed-bird was later built by US Aerial Video, Inc. to house an evaluation version of MFAM originally designed for bench testing and to conduct all the well finding work for the PATC.

The aerial vehicle was an electric-powered DJI Matrice M600 Pro hexacopter with a DJI A3 Pro flight controller. A belly mounted, stabilized, HD video camera was used to monitor and record the flights. An additional fixed, forward-looking, 1.3 GHz long range camera was added for redundancy and was mounted in-line with the planned flightpath to improve situational awareness. The pilot in command (PIC) and Visual Observer (V/O) were positioned at the highest possible elevation to allow the PIC and V/O to always maintain visual line-of-site with the aerial vehicle. A pair of plastic pulley wheels were fastened, one at each end of the MFAM Arrow which was slung below the M600 suspended by 1/4-inch polyethylene tubing threaded through the pulleys. This early suspension method successfully countered unwanted attitude excursions caused by accelerations (change in airspeed and turns) and slipstream. As configured, mission endurance was about 20 minutes, which provided approximately 10 line-km of survey at 9 m/s groundspeed under no-wind conditions. With MFAM operating at 1 kHz and typical survey groundspeed, the distance between data samples on level ground was just under 1 cm.

Surveys were designed using a combination of Google Earth Pro and UgCS. KML layers depicting the areal extent of the survey exported from Google Earth were imported to UgCS, where a flight plan was designed. The flight lines were extended 20 m beyond the survey boundaries. The resulting flight plan was then uploaded to the DJI rotorcraft. The system navigated and maintained altitude via waypoint navigation computed from a terrain database. Up to 99 elevation control points were generated depending on elevation compliance requirements and the size of the survey. A +/- 1 m terrain conformity was selected for missions where terrain was more precipitous, but this could sometimes exceed the allowed number of control points. The magnetic survey lines were flown magnetic north-south in a serpentine fashion. A minimum of 4 adjacent lines having 30 m spacings were collected for gridding (6 m cells). The sensor elevation ranged from 30-37 m AGL; most of the survey blocks flown at 37 m, depending on terrain and obstructions. The flights were planned so that the aircraft would slow in anticipation of turnarounds to 4 m/s, then accelerate on completion of course reversal to 9 m/s. On average, flight blocks covered about 0.20 km^2. Position information was afforded by a GPS receiver operating at 1 Hz installed alongside the MFAM electronics package. A timestamp event was generated internally by the MFAM electronics. The internal timestamp was then used to synchronize the GPS timestamp to compensate for an approximately 400 mS delay between the GPS output and the generated event. The firmware version provided by Geometrics only captured the $GPRMC sentence, and therefore, contained no altitude information.

Diurnal was recorded using a GEM Systems, GSM-19 Overhauser magnetometer base station operated at ¼ Hz and used to correct the MFAM total magnetic intensity data. The magnetic base station was deployed from the same location for those flight blocks completed over multiple days.

The magnetic data was pre-processed using a custom parsing algorithm written in National Instruments LabVIEW. The ASCII formatted MFAM output files were first processed to extract the time and position information from the GPS sentence and then converted to UTM coordinates. These values were reinserted at the correct record position in accordance with an internally-generated timestamp event. The resulting parsed file was then exported as comma-separated values containing channel headers for import into Geosoft® Oasis Montaj and transformed into a line database. Additional processing steps included linear interpolation of the x, y positions and lag correction. The dataset was then edited to crop the ends of each flightline to remove high frequency noise artifacts caused by oscillation of the sensors induced by deceleration and attitude changes in turns. The resulting single line dataset was split into separate lines according to changes in direction or x, y breaks, so that the substantial heading error could be corrected on a line by line basis. Finally, magnetic targets were selected from the gridded, line data using the grid peaks utility in Geosoft®. Reduced-to-the-pole or analytic signal processing was sometimes applied resulting in modest improvements in positional accuracy of potential well targets. A table of exported target locations could then be entered in a GPS-linked, portable GIS application (ESRI® ArcPad™) for navigation in the field.

Results

Initial testing was limited on an early evaluation version of MFAM to where the magnetometer remained stationary while the effects of the aerial vehicle on the magnetic signal were evaluated. The MFAM firmware had not yet been written to enable on-board data storage on digital media, but did allow capture of data in the form of TCP packets transmitted over an ethernet cable. MFAM was found to be very sensitive, and in stand-alone testing, showed a well-defined 60 Hz waveform even in an environment far removed from powerlines. The intensity of this noise ranged between 3 and 5 nT and was easily removed from the signal by applying a low-pass filter.

Additional testing involved tethering the aerial vehicle and hovering above the sensors while varying distance, heading, and power settings on the electric motors. The effects observed when changing power settings were used to simulate climbs and descents. Noise levels induced during these operations provided information for the design of a platform that would yield both an acceptable signal quality and aerodynamic stability. An upgrade to the firmware followed that allowed recording of data to a micro-SD card along with a Webpage application to control data acquisition through any Wi-Fi enabled device capable of running a Web browser. These firmware changes set the stage for flight testing.

Initial flight testing was performed over a private parcel containing 2 known steel-cased gas wells using the MFAM Arrow towed-bird prototype (Figure 1), provided by Geometrics as part of a beta testing agreement with NETL. These results were very encouraging. It was then decided to test the quality of the MFAM Arrow data by comparing with results obtained from an aeromagnetic survey previously flown using the CGG Midas® system for locating abandoned wells in Hillman State Park, PA (Figure 3). The Midas® survey was flown from a piloted helicopter using dual boom-mounted, Scintrex CS-3, 10 Hz cesium magnetometers sensors. The targets from this survey were verified during an extensive ground-truthing effort (Sams, 2017). Well finding was especially challenging in this section of Hillman State Park because the casing from the abandoned oil wells had been cut off and buried beneath overburden excavated during surface mining for Pittsburgh #8 coal between 1940-1960. The surface in this area was further disturbed during an extensive remediation effort that followed.

The test area selected at Hillman State Park measured 0.2 km^2 and contained 3 steel-cased oil wells detected in the CGG Midas® survey and verified on the ground. The top image in Figure 3 shows a contour colormap subset of the Midas aeromagnetic survey. The total magnetic intensity of the easternmost well anomaly was subdued because most of its casing had been removed. For locating wells, the MFAM Arrow data, corrected for heading error and diurnal, was comparable to the Midas® data. The MFAM data did appear to show more details owing to the higher along-line sample rate (1000 Hz).

A second prototype towed-bird apparatus was built (Figure 2) to house a modified version of the MFAM evaluation kit. Included in the electronics package was a Wi-Fi enabled board for acquisition and storage of data on micro-SD card, as well as a WASS-enabled GPS unit. The assembly was suspended on pivoting rods 1.15 m below the aircraft. These suspension members attached to the aerial vehicle were made from carbon fiber or 3D printed from nylon filament. The towed-bird assembly, including electronics package, battery, and mounting hardware weighed 2.0 kg. The original MFAM Evaluation Kit (LCS050G) electronics package alone weighed 1.1 kg. A new enclosure was CNC manufactured from FR4 fiberglass to replace the aluminum enclosure, saving additional weight. The internal 1500 mAh battery (11.7 V lithium ion polymer) was replaced by a 2500 mAh external battery having a remote charging port, providing enough energy for about 8 hours of continuous operation.

The second prototype towed-bird was used to collect aeromagnetic data to locate legacy wells for the PATC. The new design had better in-flight stability than the Arrow and incorporated features for monitoring system health and mission readiness. More than 200 line-km of data was collected over 5 areas along the proposed highway right-of-way. The contour colormap in Figure 4 shows an example mosaic of processed aeromagnetic data collected over 13 separate flights for the PATC Southern Connector block 55A2. 45 magnetic targets were selected from block 55A2 for investigation on the ground as potential steel-cased wells. It should be noted that many targets were located within flight boundaries that often extended beyond the proposed construction boundaries. Aerial imagery and historic well maps were used in initial screening to prioritize targets for ground truthing. Evidence for at least one pipeline was seen in the data, along with a recent unconventional gas wellpad containing an unresolved cluster of 5 closely-spaced wells (most intense feature). At the time of this report, NETL had only engaged in a minimal ground truthing effort, locating 8 suspected legacy wells. A more comprehensive ground investigation organized by the PATC has been underway.

Figure 1: Geometrics MFAM Arrow prototype towed-bird used in early flight testing.

Figure 2: MFAM towed-bird prototype designed and built by NETL and US Aerial Video, Inc. used to locate legacy wells for the PATC.

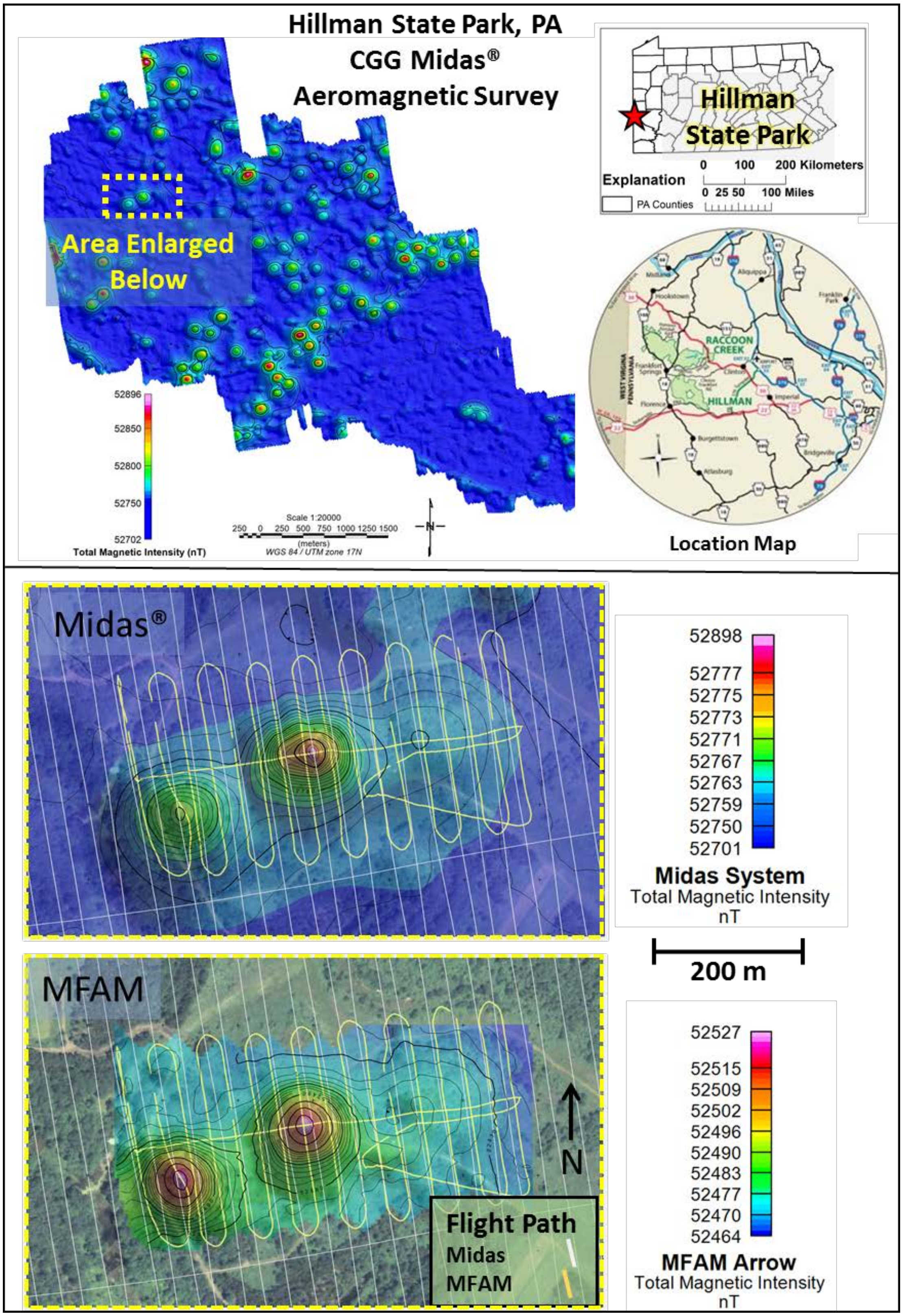

Figure 3: Comparison of aeromagnetic survey results from Midas® System (piloted helicopter) to MFAM drone survey over a control location in Hillman State Park, PA having 3 buried legacy wells.

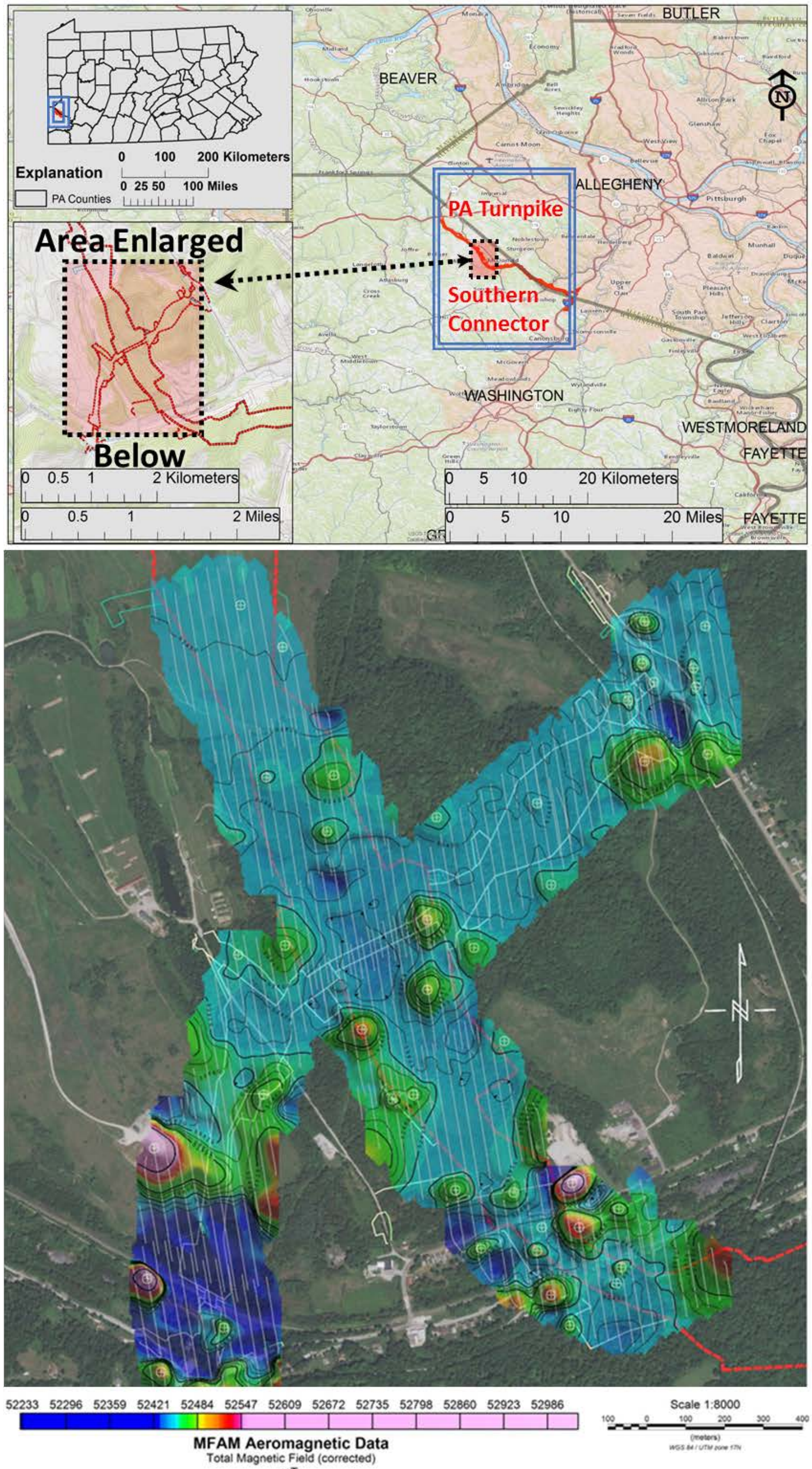

Figure 4: Aeromagnetic survey map showing MFAM data collected over PA Turnpike block 55A2.

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