Journal of Applied Geophysics 186 (2021) 104250

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Successful application of drone-based aeromagnetic surveys to locate legacy oil and gas wells in Cattaraugus county, New York

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1. Introduction

Abandoned and unplugged oil and gas wells present a difficult challenge as an environmental and human health hazards and potential economic liability in areas where hydrocarbon exploration and production occurred prior to the adoption of modern laws and regulations pertaining to well plugging and surface reclamation. Recent estimates suggest that in the United States alone there are over 1.2 million undocumented oil and gas wells (Allison and Mandler, 2018); however, the Environmental Protection Agency (EPA) recently estimated that there are 3.11 million abandoned oil and gas wells nationwide, of which approximately 69% are unplugged (EPA, 2018). The problem is particularly pronounced in New York State (NYS), which was the locus of some of the nation's early wide-spread hydrocarbon exploration and production activity in the 19th century, with some recent estimates suggesting that as many as 35,000 oil and gas wells in New York State may exist (Bishop, 2013). The first gas well in the United States was drilled in Fredonia, NY in 1821, and New York's first oil well was drilled in the town of Rushford in 1860. Although NYS was the second state to institute plugging requirements in 1879 (Pennsylvania was the first), they were relatively lax and would be considered crude by modern standards as tree trunks and bowling balls - amongst other implements - were used to "plug" these wells. Many of the wells existed prior to the establishment, in 1963, of a modern regulatory program to ensure the proper plugging of wells. Critically, many of the wells drilled prior to 1963 in NYS were abandoned by their original operators and left unplugged or improperly plugged; these wells are potential conduits for contaminants to reach groundwater, especially if the casing is compromised or non-existant. Unplugged wells have the potential to leak brine, which can impact drinking water, as well as hydrogen sulfide and methane which can impact air quality near the wellsite.

Methane is a potent greenhouse gas (Nisbet et al., 2016) and 11 to 15 million metric tons are released yearly by the oil and gas industry (Alvarez et al., 2018). Although methane is relatively short lived in the atmosphere, it has a global warming potential 86 times greater than carbon dioxide over twenty years (Myhre et al., 2013). It has been estimated that between 40,000 to 70,000 metric tons per year of methane are emitted from abandoned wells in Pennsylvania alone, which accounts for five to 8% of the state's total methane emissions (Kang et al., 2014, 2016), the equivalent of >1 million metric tons of carbon dioxide. The United States Environmental Protection Agency estimates that 17% of abandoned wells nationwide are unplugged (Allison and Mandler, 2018); however, this estimate may be conservative, as many wells remain undocumented. In NYS, the Department of Environmental Conservation's (DEC) Division of Mineral Resources has made some progress toward mitigating and preventing damage caused by leaking oil and gas wells. However, New York State's oil and gas boom largely occurred in the 19th Century (Hill et al., 2004); in 1855 the state was the largest oil and gas producing region in the world. NYS reached maximum oil production in 1938 (barrels) and maximum gas (cubic feet) production in 2006. During the late 19th and early 20th centuries many wells were drilled without proper documentation and were subsequently abandoned without being plugged. Many such wells are classified as having been orphaned, a subset of abandoned wells for which no owner can be determined (DEC-c Orphan & Abandoned Well Plugging, accessed 2020, (NYS-DEC), 2020c). In 2013 it was estimated that there were 61,000 wells drilled prior to regulatory framework, the DEC only has records on approximately 35,000 (Bishop, 2013); although Bishop's (2013) publication in now dated and the DEC currently claims more than 75,000 wells have been drilled in NYS, while the DEC's database records 45,884 wells (Fig. 1).

Methane has a direct influence on global warming, but also has several important indirect effects as well. Increases in atmospheric methane cause increases in tropospheric ozone (O_3), which is produced by sunlight-driven chemical reactions with nitrogen oxides, carbon monoxide, methane, and other hydrocarbons. Around 50% of the increase in background ozone is caused by the abundance of methane in the atmosphere (Royal Society, 2008). Although methane is not direct health concern at low concentrations, ozone has been shown to cause oxidative stress in lungs (Romieu et al., 2008). Moreover, methane is

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https://doi.org/10.1016/j.jappgeo.2020.104250

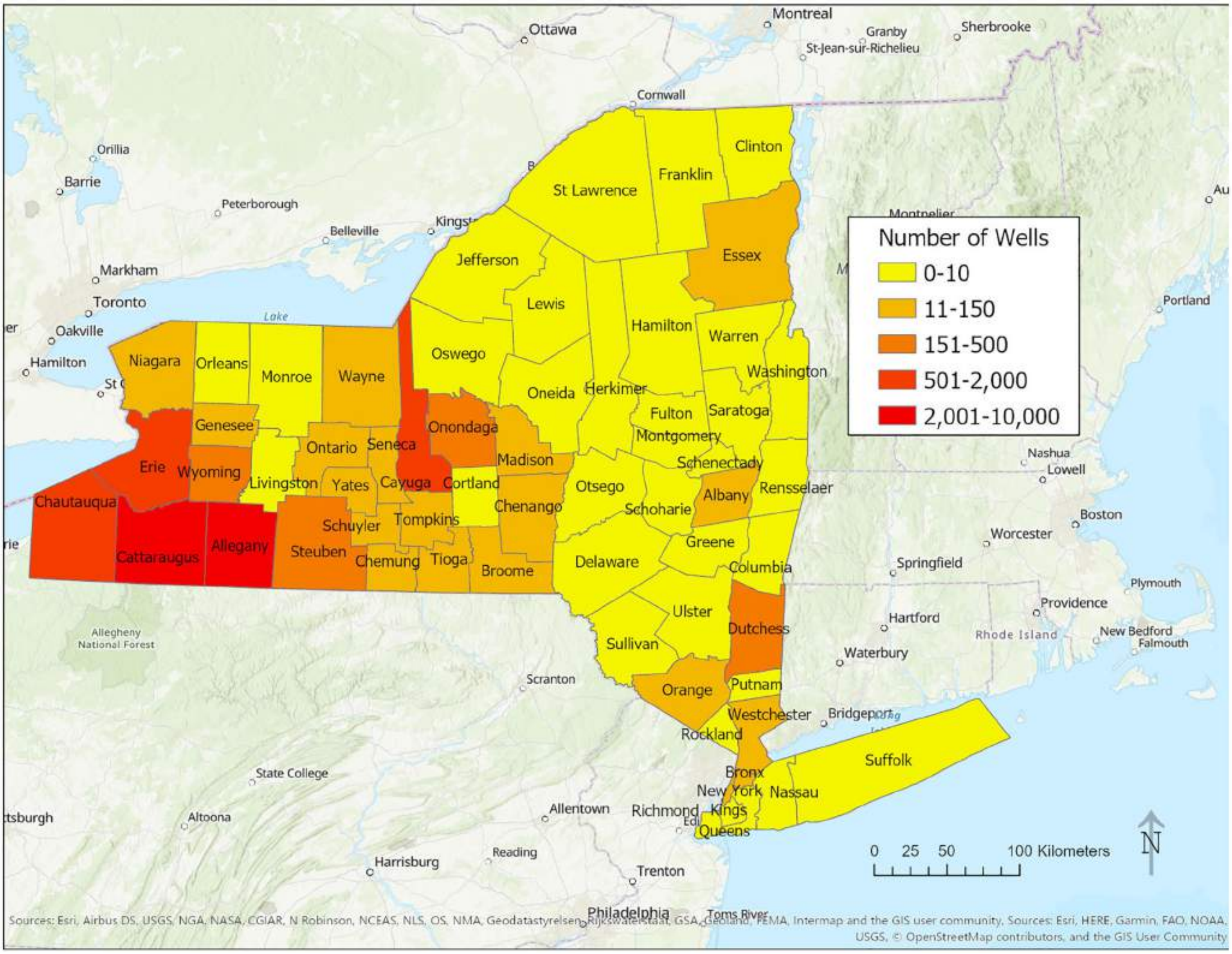

Fig. 1. Wells accounted for in NYS-DEC database by county (data from CUGIR, 2000 & NYS-DEC).

often co-emitted with toxic compounds like benzene, carbon tetrachloride, and chloroform (UNEP, 2011). It is important to decrease the precursors to ozone production, like methane and carbon monoxide, from making their way into the atmosphere by plugging abandoned and orphaned oil and gas wells.

In parallel with environmental and health concerns, unplugged oil and gas wells pose a threat to the sustainable environmental and economic development of oil and gas reservoirs in older fields in two key ways: 1) decreased pressure in target formations, and 2) increased risk of blowouts and flowbacks. Unplugged wells reduce the pressure of the reservoir and can cause hydrocarbon flow to significantly decrease or go below the formation fracture pressure such that the rock formation no longer fractures hydraulically (Lavrov, 2016). Furthermore, failure to plug wells prior to restimulating older oil fields with new recovery technologies, like hydraulic fracturing, can decrease recovery efforts at a cost to oil companies. Flowbacks and blowouts of brine and oil can occur in nearby wells if recovery efforts are initiated in older formations where abandoned and orphaned wells have not been properly plugged. Finally, environmental contamination traced back to unplugged wells in areas leased by an energy company can result in multimillion-dollar fines from state and federal agencies. Consequently, pre-emptively locating and plugging orphaned oil and gas wells can save millions of dollars in lost and decreased production, as well as avoided fines to energy companies.

In New York State, the DEC Division of Mineral Resources has made efforts to locate, assess the environmental risk, and plug abandoned wells. Staff of the Division of Mineral Resources locate undocumented wells by initial identification of possible well locations on historic lease maps and subsequent visual inspection of identified sites. This workflow has proven difficult because the surface expression of historic wells may be obscured by vegetation and the wells may have leveled or partially excavated. Another confounding factor is the fact that many casings and surface infrastructure were scavenged for metal during World War II. Furthermore, historic lease maps are often difficult to acquire and even when acquired, well locations must be interpreted from hand-drawn maps, a process that inherently introduces location errors. Due to scaling, a hand-drawn point on a map may represent up to a 15 m diameter on the ground. An example of a georeferenced lease map is depicted in Fig. 2; the map was georeferenced using ArcGIS and has an acceptable root mean square (RMS) error, but still contains flaws. It should be noted here that there are >300 well locations on this georeferenced map, but most of these were never drilled. Finally, prior to the

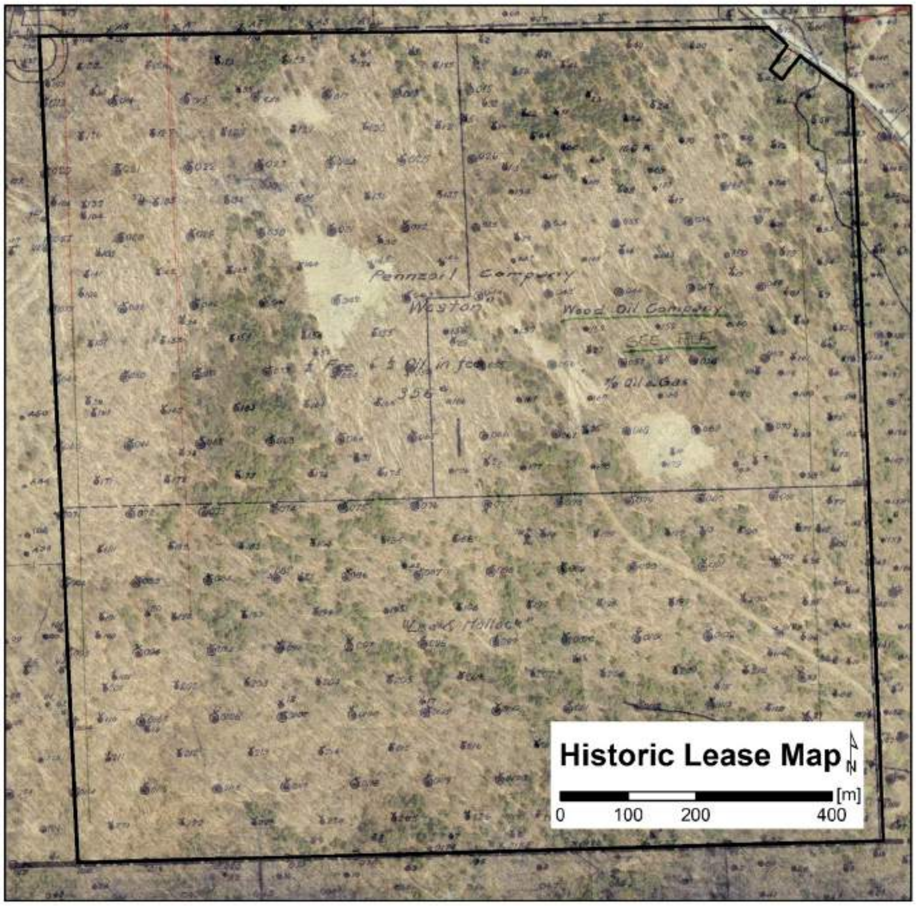

Fig. 2. Georeferenced Pennzoil Lease Map, Olean, New York at 50% transparency overlaying 2016 one foot orthoimagery (NYSDOP, 2016). Black outline is a 0.75-mile shapefile boundary of the survey parcel.

introduction of a strict regulatory framework mandating consistent documentation of wells (NYS-DEC), 2020a, many of the drilled wells were abandoned with undocumented locations and many proposed well locations were not drilled. As a result, New York State DEC personnel face a difficult task of identifying possible well locations and confirming their existence by sight in dense vegetation and uneven terrain. Since 2014, the NYS DEC has plugged a total of 303 wells through the New York Works Well Plugging Initiative (NYWWPI) at a cost of approximately $9,370,000; and since 1990 the NYS DEC has plugged a total of 121 wells through the Oil and Gas Account (OGA) at a cost of approximately $735,000. This leaves approximately 35,000 undocumented oil and gas wells (DEC Completed New York Works Well Plugging Projects, accessed 2020).

In a 2019 proof of concept study, our research group demonstrated that magnetic anomalies associated with the metal casing of abandoned oil and gas wells are detectable in unmanned aerial vehicle (UAV) aeromagnetic surveys collected at an altitude slightly above the regional tree line (Nikulin and de Smet, 2019). We relied on magnetic datasets collected by a commercially-available battery-powered DJI Matrice 600 hexacopter UAV, equipped with a Geometrics Microfabricated Atomic Magnetometer (MFAM) sensor, over a known plugged well location (Butkowsky 1-A, API # 31–007–23,056-01-00) near Binghamton, New York. The well was drilled to a total depth of 10,150 ft. in 2003 and plugged and abandoned in 2017; the well pad was subsequently leveled and at the time of the study, the area was overgrown with light vegetation that obscures any visible evidence of the well. We conducted a series of terrestrial and UAV aeromagnetic surveys over the well site to record the magnetic expression of the well at the ground surface and at altitude, and then calculated the rate of magnetic anomaly dissipation with altitude. Initially, using a standard terrestrial survey design, we located the magnetic anomaly associated with the well, which was ~18,000 nT at 0.15 m AGL. We then positioned the UAV equipped with the MFAM sensor at the center of the magnetic anomaly and proceeded to elevate the assembly at a rate of 1 m/s to an altitude of 100 m above ground level (AGL). We determined that the magnetic anomaly at 40 m AGL, which correlated to an elevation slightly above tree line, was ~400 nT, nearly double the background magnetic field levels at that elevation and signal dissipated to background levels at ~50 m. We concluded that at ~40 m AGL, magnetic anomalies associated with vertical wells featuring metal casing remain pronounced above background levels, allowing their identification in wide-area UAV aeromagnetic surveys. Terrestrial and helicopter-based magnetics surveys are commonly used to locate oil and gas wells and pipelines (Sams et al., 2017; Sapunov et al., 2015; Kaminski et al., 2018).

The area chosen for our follow-up study was Cattaraugus County in Western New York, where wide-spread hydrocarbon exploration and production activity occurred in the late nineteenth and early twentieth century. DEC continues to conduct efforts to locate and assess abandoned oil and gas wells. These efforts are guided by the surface owner's willingness to allow staff to enter the property and perform a physical search. As part of an inspection effort in fall 2018, staff were tasked with locating 17 wells on an approximately 355-acre parcel. Through the use of historic well records, it was determined that there were potentially hundreds more wells drilled

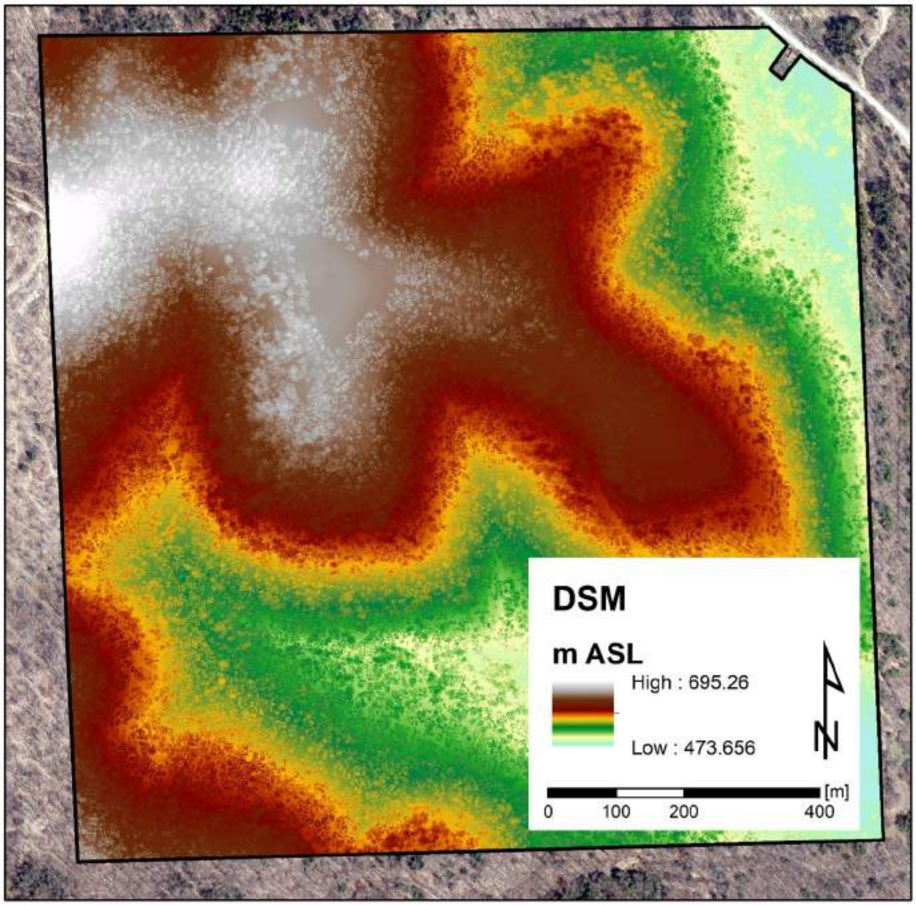

Fig. 3. Digital Surface Model (DSM) of survey area in Olean, NY. Relatively flat clearings are visible at several highpoints in the northeastern portion of the parcel. The large flat field in the northwest was a logistically important area of survey operations, allowing for visual line of sight and an unimpeded takeoff and land area.

on the property (Fig. 2). Discussions with the landowner yielded interest in having all of the wells found on the property. After spending several hours traversing the hilly, wooded terrain with limited success, DEC staff suggested the use of an aeromagnetic survey to assess the property in its entirety due to the promising results shown in the previous preliminary studies (Nikulin and de Smet, 2019; Veloski et al., 2018). An UAV aeromagnetic survey would save considerable time and limit the risk of injury to staff. The parcel had several clearings at the highest elevations, providing ideal take-off and landing sites for the unpiloted aircraft system (UAS), and adequate line of sight for coverage of the entire parcel. A UAV is simply a drone, while a UAS included the UAV, the ground control station, and the remote pilot in command (PIC) controlling the autonomous flight. From an aerial geophysical perspective this is an ideal experimental test site as there are potentially many closely spaced unmapped unknown wells and there is a great amount of terrain variation, which increases the difficulty of survey logistics and of detecting and identifying individual wells since the signal amplitude of multiple closely spaced wells might overlap, confounding interpretation. In essence, this site was not chosen because it was an easy survey location, but because it was difficult.

2. Methods

New York State (NYS) has high-resolution 1 m LiDAR data coverage throughout most of the state and the survey area in Cattaraugus County was collected in 2017 by the Federal Emergency Management Agency (NYSGPO, 2017). NYS LiDAR data is available as .las files, which were used to generate post-processed derivative data products such as digital elevation models (DEM) and digital surface models (DSM). A DSM is a 3D digital model of the first returns from LiDAR, which includes all natural and anthropogenic objects, like trees and buildings (Fig. 3). A DEM encompasses the subsequent returns as well at the earth's surface where vegetation and anthropogenic structures have been removed to produce what is often called a ‘bare earth’ model (Fig. 4). Subtracting the DSM from the DEM produces a critical derivative data product, a digital obstacle model (DOM). The DOM is essential to avoid terrain obstructions like trees and infrastructure while planning low-altitude missions (Figs. 4 and 5), while the DEM is necessary to maintain constant altitude AGL. Maintaining consistent altitude AGL is of the utmost importance as the earth's total magnetic field rapidly decays at $1/r^3$ and shifts in altitude AGL will result in poor data quality and increase the difficulty in post-processing. The anomalous field due to the well casing may have a different distance dependence and decay more or less due to depth of casing.

One of the limiting factors of the Nikulin and de Smet (2019) proof-of-concept study was the relatively short total flight time allowed by the battery-powered UAS used in the initial aeromagnetic surveys over the Butkowsky 1-A well site. In our follow-up efforts to adapt the developed methodology to wide-areas surveys, UAS-based magnetic data were collected by a UMT Cicada gas-electric hybrid hexacopter platform (https://umt.aero/cicada/), equipped with the Geometrics MFAM development kit sensors. This UAS weighs 16.5 kg (36.38 lb) and has a maximum takeoff weight of 19 kg (41.89 lb) (Fig. 6b), which is similar to the weight of a terrestrial magnetic gradiometer system with batteries and global navigation satellite system (GNSS) receiver (Fig. 6a). We housed and protected

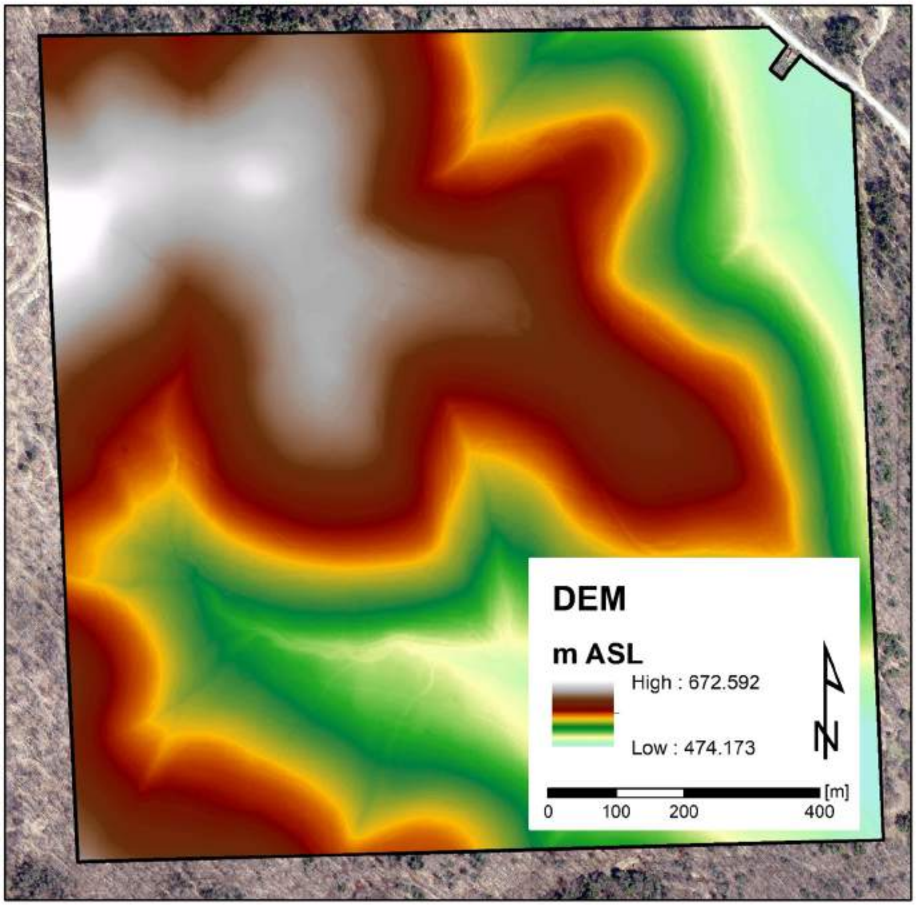

Fig. 4. Digital Elevation Model (DEM) of survey area in Olean, NY.

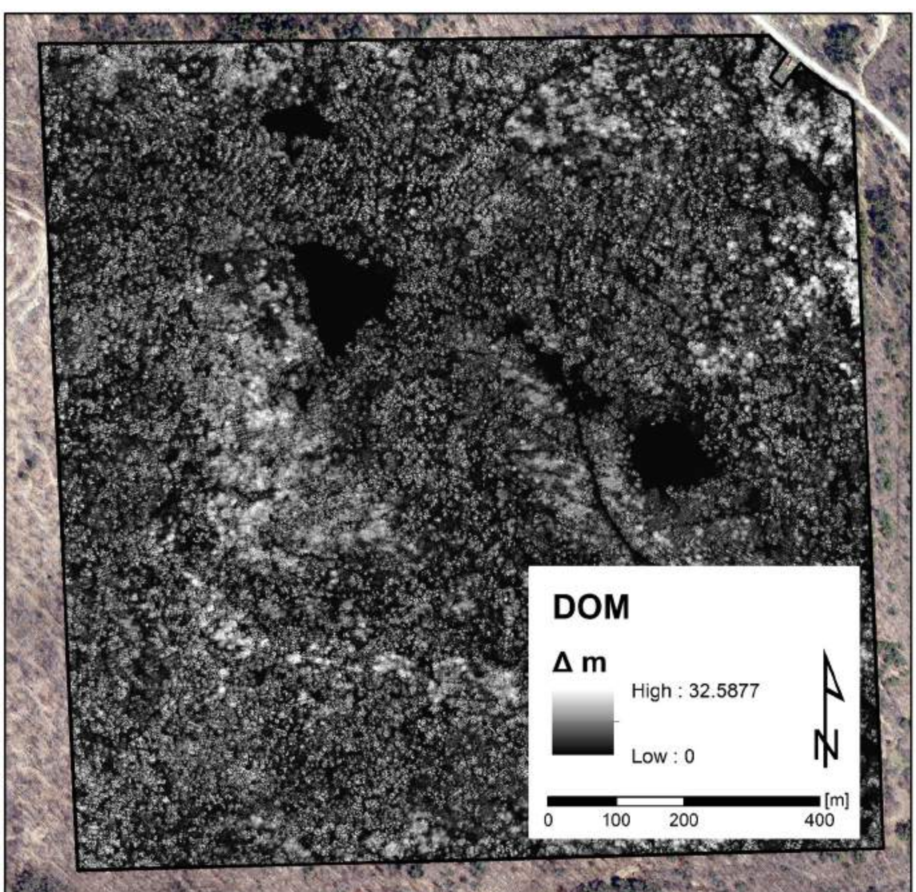

Fig. 5. Digital Obstacle Model (DOM) of the survey area in Olean, NY.

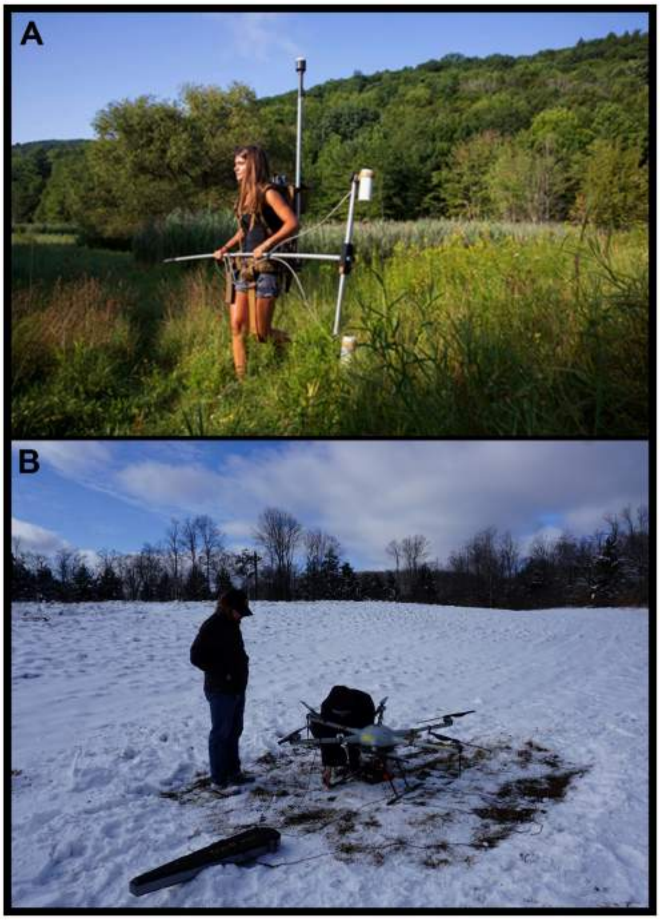

Fig. 6. (a) Terrestrial survey with Geometrics G-858 cesium vapor gradiometer, and (b) UAV-based aerial magnetic survey. Bottom photos was from the December 7, 2019 survey. Magnetic base station can be seen in the left along the tree line.

the MFAM development kit including the GNSS receiver in the non-magnetic, light, and durable UMT MagPike enclosure case, specifically manufactured for this purpose. The MFAM development kit consists of two laser pumped cesium vapor total field scalar magnetometers that can collect data at a sample rate of 1000 Hz and a sensitivity of $5\text{pT}/\sqrt{\text{Hz}}$. The sensors were side by side and their measurements were averaged. The MFAM was powered with an 1800 mAh Zippy lithium polymer battery that only contains small amounts of weakly magnetic nickel. The MFAM was tethered to the UAS with thin, strong, and flexible polypropylene rope braided poly cord at a 4 m fixed offset. We had previously determined the optimal tether distance to maintain the highest signal-to-noise (SN) ratio for UAS-based magnetic data acquisition (Nikulin et al., 2020).

Using the high-endurance hybrid UAS platform allowed us to plan wide-area missions that covered ~100 acres in a single 1-h UAS flight. In fact, this metric could be further expanded in terms of flight time and aerial coverage and remains constrained by line-of-sight rules imposed on small UAS operators by the US Federal Aviation Administration. QGroundControl mission planning software was used to preprogram GNSS-guided autonomous missions where waypoint navigation allowed the UAS and magnetic sensors to maintain constant altitude AGL (Fig. 7). This was critically important as elevation changes in the survey area approached ~200 m (Figs. 2 and 3). There were ~400–500 waypoints per survey mission depending upon terrain changes specific to the survey (Fig. 8). Data were collected at an altitude of 45 m AGL in north-to-south and south-to-north transects spaced 20 m apart. The GNSS error of the DJI Matrice 600 UAV is $\pm$0.5 m vertical and $\pm$ 1.5 horizontal. Three missions were flown at a speed of 7 m/s in three 600 $\times$ 600 m grids and nearly 60 line-kilometers of magnetic data was collected during these surveys (Fig. 9, Table 1). Additionally, a fixed forward looking visible-light camera was used to monitor potential obstacles along the flight path in addition to visual control of the UAS by the remote pilot-in-command.

While the raw aeromagnetic datasets revealed some of the larger anthropogenic anomalies, there were considerable errors and

Fig. 7. Google Earth image of preprogrammed autonomous flight path terrain awareness.

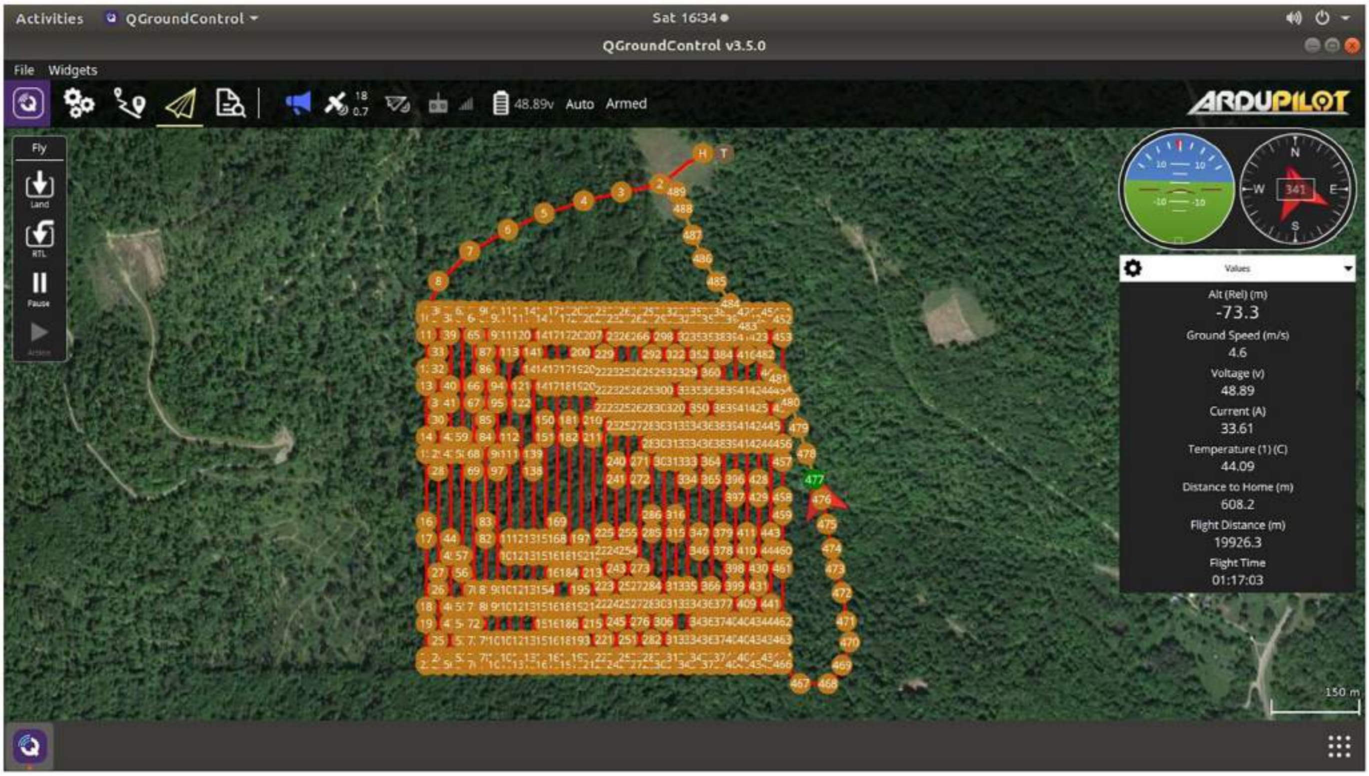

Fig. 8. Mission plan with elevation waypoints using QGroundControl. Each 600 × 600 m survey consisted of between 400 and 500 waypoints due to the variable topography.

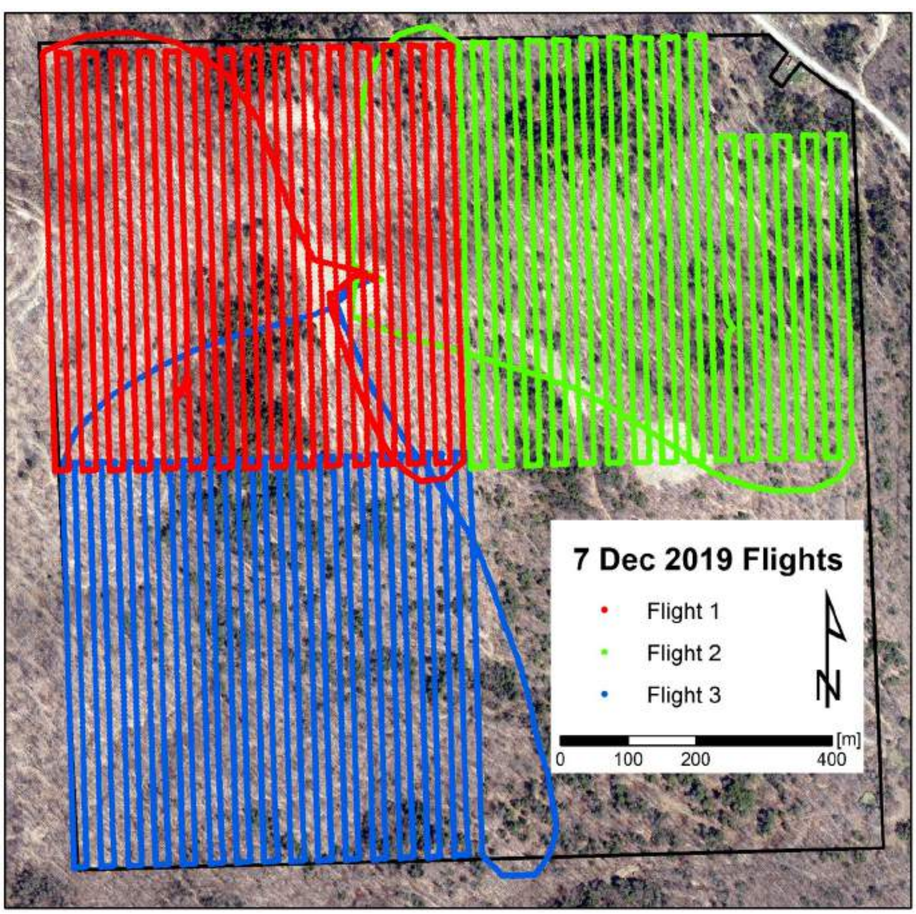

Fig. 9. Three 600 × 600 m missions flown on December 7, 2019. One foot orthoimagery base map from NYSDOP (2016).

Table 1
Total and within transect flight duration. Total within survey flight time 3:22:40 and total flight time 3:49:18 for three flights. All flight times in UTC time.

Flight	Takeoff	Start transects	End transects	Landing	Within survey	Total flight	Line-km
1	17:05:18	17:11:19	18:19:43	18:23:25	1:08:24	1:18:07	20.52
2	18:54:22	18:57:29	19:58:09	20:03:32	1:00:40	1:09:10	18.18
3	20:17:35	20:19:16	21:32:52	21:39:36	1:13:36	1:22:01	20.83

artifacts introduced to the datasets as a result of sensor motion and diurnal magnetic field variations (Fig. 10). The UAV-based magnetics data underwent a standardized processing routine to highlight anomalies associated with well casings and dim other anthropogenic magnetic anomalies. Initially, raw data files were parsed by down sampling from 1000 to 1 Hz and attaching the GNSS data from the NMEA $GPGGA sentence, which contains time, latitude northing, longitude westing, and altitude information. Next anomalous dropouts related to sensor errors, or polar dead zones, were removed. Time variations in the MFAM data were diurnally corrected with the aid of a Geometrics G-858 cesium-vapor magnetometer that was used as a base station continuously collecting at 1/15 Hz (Fig. 11). Heading errors of up to 15 nT in the raw total magnetic field intensity, or strength, data can be seen as large stripes (Fig. 10) and were corrected with a statistical line leveling algorithm. The 12th generation International Geomagnetic Reference Field (IGRF) regional total magnetic field values were calculated for the date, location, and elevation of our surveys (Thébault et al., 2015), in order to determine the residual total magnetic intensity (TMI). These point data were then converted to a raster grid of 5 m pixels using kriging interpolation. The raster grid was low-pass filtered using a 3 × 3 unweighted moving average kernel convolution. The effect of the local magnetic-field direction at the survey location was removed with a reduction to the pole filter (RTP) to create a TMI RTP raster (Fig. 12). A final TMI RTP map of 5 nT contours was created to easily locate the peak amplitudes of potential wells (Fig. 13). Wells targets were localized at peak amplitudes, similar to Kaminski et al. (2018). (See Figs. 14 and 15.)

3. Results & discussion

Previous research by Nikulin and de Smet (2019) compared ground and UAV-based magnetic surveys to determine optimal flight parameters like altitude, speed, and line spacing over a single well. In

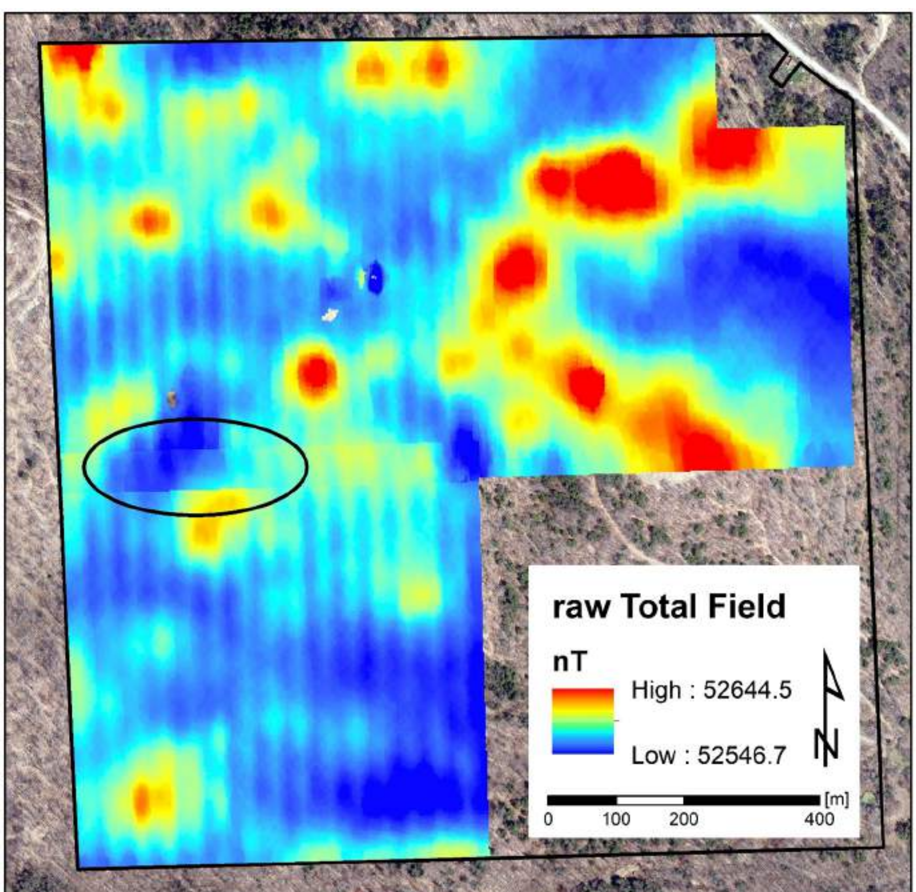

Fig. 10. Raw uncorrected total magnetic field intensity. Note the ~15 nT heading errors, and ~10 nT between grid diurnal shift circled before base station correction.

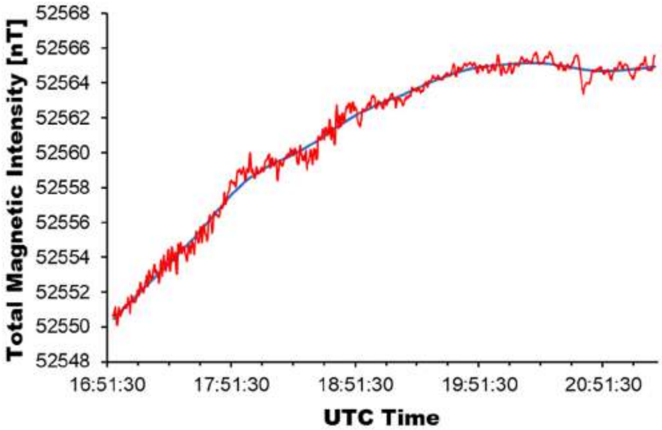

Fig. 11. Diurnal variation in the intensity of the total magnetic field recorded at 1/15 Hz with a Geometrics G-858 magnetometer base station. The total magnetic field intensity changed by >15 nT throughout the survey. Raw data in red and data smoothed over 3 min (13 point) moving average in blue. Smoothed average was used in diurnal correction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this follow-up study we successfully conducted a wide-area UAS magnetic survey to detect and map orphaned and abandoned oil and gas wells in Cattaraugus County, New York. Each individual mission covered 0.36 km^2 and lasted 69–82 min (Table 1). We collected 1.08 km^2 (267 acres) of magnetic data in three missions in less than four hours and located dozens of previously undocumented well anomalies (Figs. 14 and 15); previous DEC terrestrial surveys had located and GPS mapped 11. We visited nine well anomalies and ground verified that eight were in fact wells. The target location error average is 11.71 m from the predicated well location to actual well location from our eight samples (minimum 0.97 m, maximum 22.68 m). We found one false positive, an approximately 10 m tall iron deer stand. It should be noted here that there are 278 potential wells in the historic lease map in the survey area. This survey demonstrates that many of those wells were never drilled and highlight the difficulty of using historic data.

During ground verification surveys it was determined that some wells were emitting both carbon monoxide and low explosive levels (LEL) of methane as measured with a Multi Gas Clip Simple Plus 4-gas detector. The EPA (2018) estimates that an average of 0.67 kg of methane is emitted from each abandoned unplugged well per day and that its global warming potential 86 times greater than carbon dioxide over twenty years (Myhre et al., 2013). If all the orphanded and abandoned oil and gas wells in NYS were plugged the equivalent of nearly 750,000 metric tons of carbon dioxide could be removed from the atmosphere, which is the equivalent of removing the cars of Buffalo for one year.

It should be noted that each survey flight used approximately 2 l of fuel, or approximately 1/2 of the fuel tank of the UMT Cicada UAS. Therefore, flights could easily cover a much greater area and we estimate that if we excluded the take-off, approach, and landing sequences and increased flight speed, we could cover the entire ~1.44 km^2 parcel in a single 2–2.5-h aerial survey. We chose not to collect tie-lines that would have decreased the survey area of the missions, a common choice in UAV aeromagnetic surveying

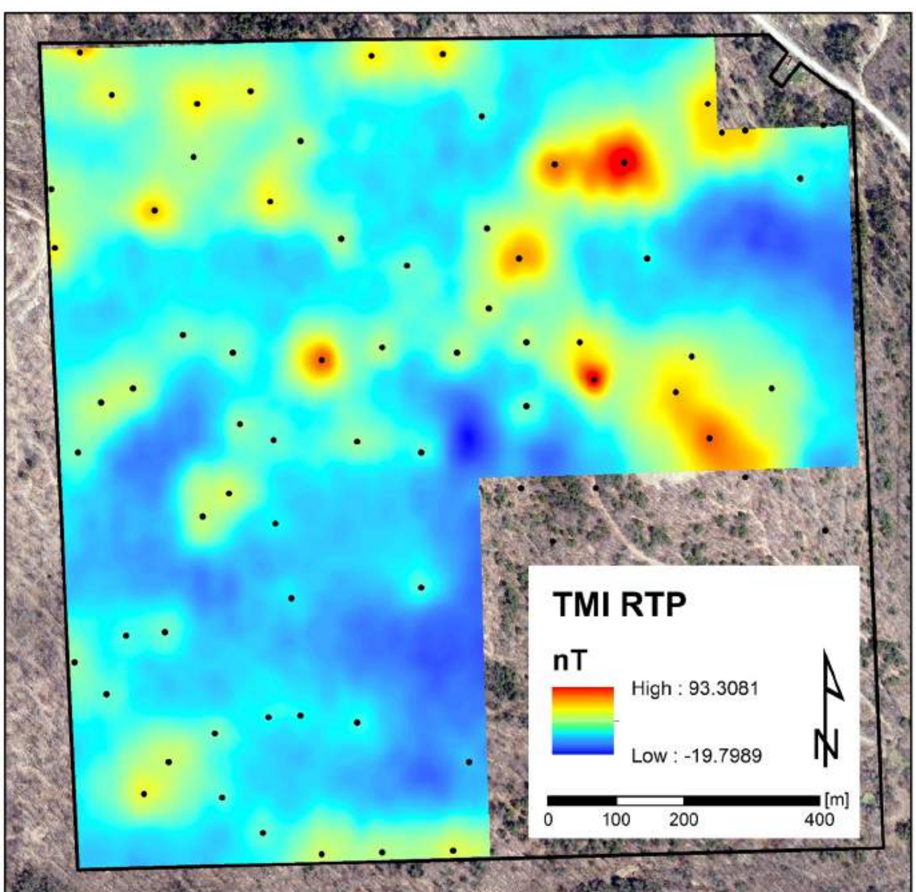

Fig. 12. Processed residual total magnetic intensity (TMI) data reduced to the pole (RTP) with well interpretations at peak amplitudes.

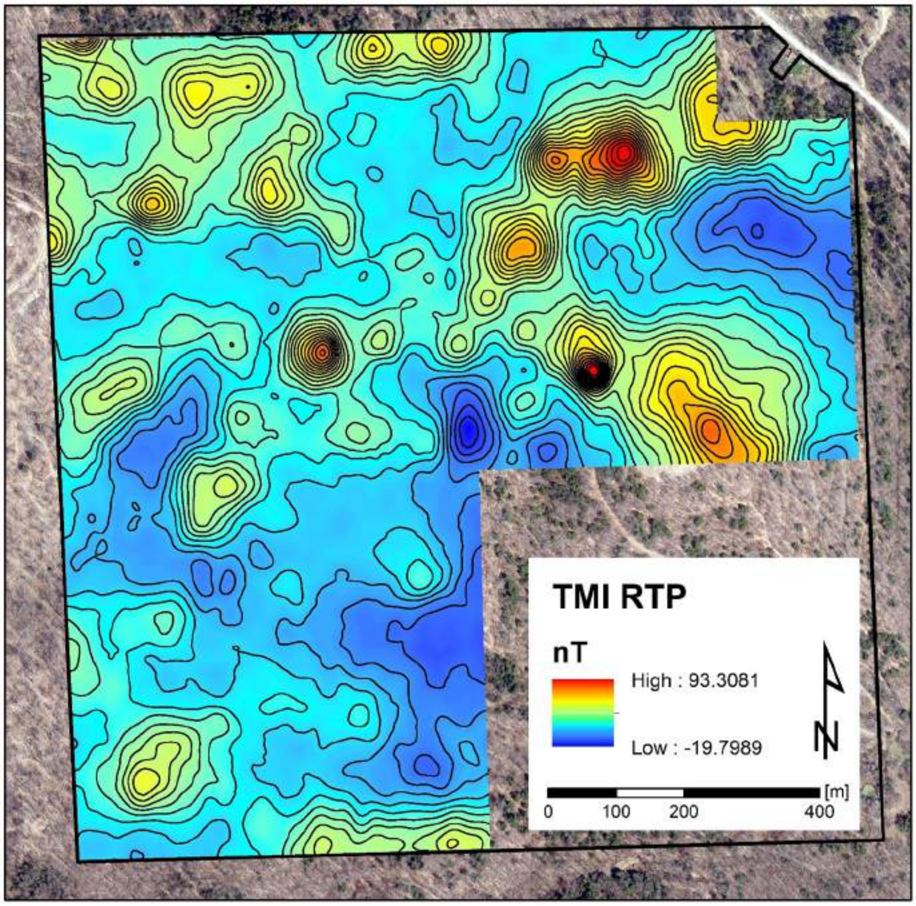

Fig. 13. TMI RTP with 5 nT contours.

(Walter et al., 2020); but there are some artifacts in Fig. 12 that could have potentially been eliminated with these extra data. At this stage, we were conservative with mission planning and were restricted by FAA Part 107 visual line-of-sight rules. An approved FAA 107.31 visual line of sight aircraft operator waiver would theoretically allow longer missions in the future and should be considered when planning such surveys. Landowners can fly over their own land without a license for recreation, but if it is for commercial purposes they would need an FAA 107 license and would be restricted to the same air space regulations. However, even with the current limitations, UAS-conducted aeromagnetic surveys targeting abandoned oil and gas wells provide a largely-unparalleled solution to stakeholders tasked with well mitigation activities and offer a significant improvement over both terrestrial and piloted aeromagnetic surveys.

A terrestrial survey conducted over the area with the same spatial resolution (transect spacing), would take at least 15.66 h, or approximately two 8-h work days to conduct, assuming a walking speed of 1 m/s, or 3.6 km/h. While this rate of magnetic data collection is possible, it is derived from relatively small surveys and its application to a wide-areas survey is inaccurate, given the terrain, dense vegetation, and the size and weight of a conventional terrestrial magnetometer systems. Furthermore, the 15.66-h survey time estimate assumes constant data acquisition with no breaks for the operator or battery replacement times factored into the calculation. From de Smet's professional experience, conducting terrestrial magnetic surveys in difficult environmental conditions has a more reasonable maximum estimate of 10–15 km/day for a single operator. Consequently, a terrestrial survey of the size and scope collected in Olean, NY would likely take at 4–6 working days and could only be conducted in the seasonal transitions between Fall-Winter and Winter-Spring when brush undergrowth is slightly less dense, and the air temperature allows for longer working days. During other times of the year, environmental conditions, dense vegetation, or thick snow cover in this region make wide-area terrestrial magnetic surveys time- and cost-prohibitive.

UAS-based aeromagnetic survey methods have several key advantages both over terrestrial and piloted aeromagnetic surveys: in particular, ease of use, more efficient, lower cost, portability, repeatability, possible even in logistically challenging areas, much smaller environmental impact for surface disturbance, and operator safety. Currently, licensed operation of UAS platforms requires less training to receive accreditation than a traditional FAA pilot license. The initial purchase cost and maintenance of a helicopter or piloted aircraft magnetic system is an order of magnitude more than a UAS-based magnetic system (Versteeg et al., 2007). The operating costs of UAVs are much less, because they do not require a hanger for storage, a pilot, or aircraft fuel (Versteeg et al., 2007). A UAS is much more portable than any piloted platform, requires less maintenance, and less storage space - further reducing overall operational costs. Furthermore, because UAS surveys fly GNSS-guided autonomous missions, which are more repeatable and therefore more reproducible than piloted missions, they might allow for the measurement of change over time. UAS surveys can be conducted in areas too logistically difficult for either terrestrial or helicopter-based surveys. Moreover, hybrid UAS surveys are relatively weather tolerant and can be conducted is the heat of the summer or as this survey demonstrates in the cold of winter with a foot of snow on the ground. Finally, mindfully designed and executed UAS surveys are safer than piloted missions and even in the event of a crash an unpiloted

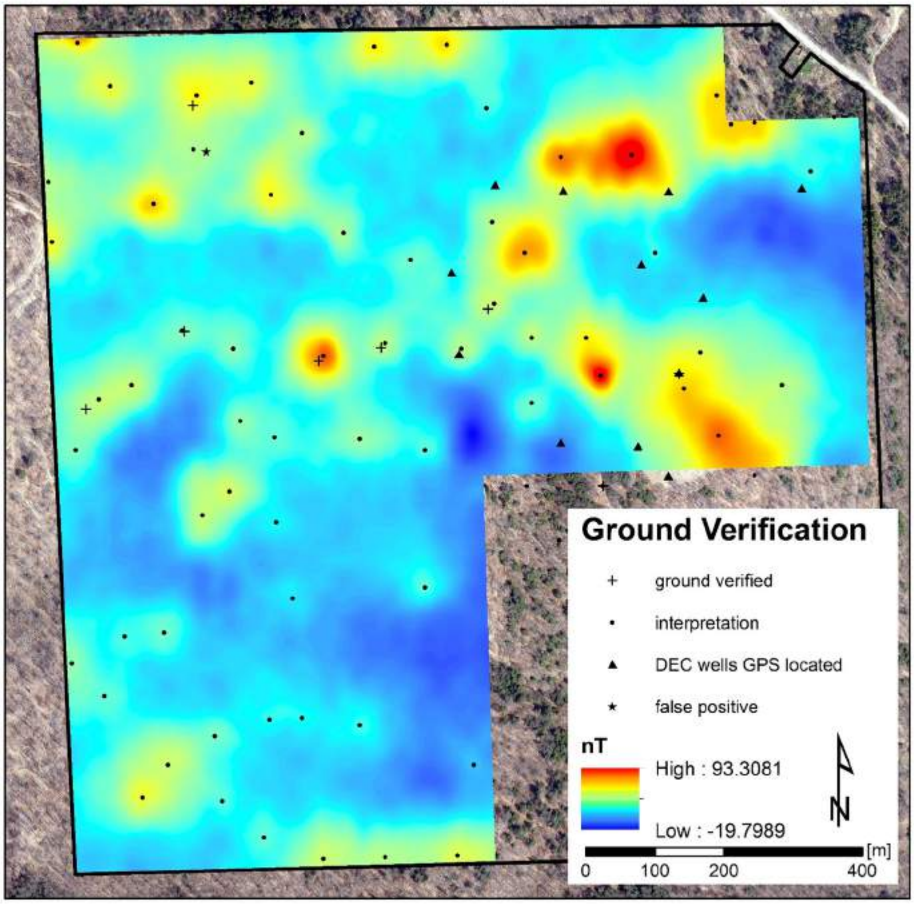

Fig. 14. Results of ground verification survey and previously GPS mapped wells by the (NYS-DEC), 2020b.

Fig. 15. Unplugged previously unknown well located with UAV-based magnetics. GNSS receiver staff is 2 m for reference.

system poses a reduced threat to the operator, ground personnel, residents, and structures.

4. Conclusions

Our study demonstrates that hybrid UAS aeromagnetic surveys are more operationally efficient than terrestrial or piloted aeromagnetic surveys to detect and map orphaned and abandoned oil and gas wells. There are, however, several challenges associated with UAS aeromagnetic surveys that should be noted. Depending upon the survey location logistics can increase the difficulty of surveying. Depending upon the UAS platform used batteries can be a logistical and practical limiting factor. A battery-powered UAS capable of lifting the required payload, for instance, can only reasonably collect data for 15–20 min. Furthermore, operation of the UAS systems introduces some magnetic noise, however, this is not different than either terrestrial or helicopter-based surveys. Overall, we find that UAS-based aeromagnetic survey methods have several key advantages when compared to terrestrial survey: increased survey speed and size, lower cost, greater operational efficiency, and increased survey safety. UAS magnetic surveys are much faster than traditional terrestrial survey methods, which greatly decreases exploration time per unit area and although the initial investment in UAS-magnetic sensors and a UAS platform are relatively high the long-term costs are much lower because larger areas can be surveyed in much less time. Critically, UAS aeromagnetic surveys can be conducted over hazardous environments and difficult terrain that may otherwise be effectively inaccessible for terrestrial or piloted surveys at low altitudes. As UAS platforms become a common part of the geophysical toolkit other magnetic applications will become common, like: unexploded ordnance detection (Nikulin et al., 2020), geological mapping and mineral exploration (Malehmir et al., 2017; Parshin et al., 2018, 2019; Walter et al., 2020), fault structure analysis, buried infrastructure like pipelines, drainage tiles, utilities location, drilling hazards, groundwater pollution, carbon capture utilization and storage, and due diligence surveys.

Declaration of Competing Interest

None.

Acknowledgments

We would like to thank Vitalii Gitchenko, Pavlo Kosolapkin, Anton Smirnov of UMT for their contribution of time and aerospace engineering expertise. We would like to thank Ted Loukides and Catherine Dickert on the NYS DEC. We would like to thank the reviewers, especially Ed Biegert, for their comments that helped greatly improve the quality of this paper. Support for this research was provided by de Smet & Nikulin's startup funds from the State University of New York at Binghamton.

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