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Improving UAV Magnetic Surveys with a Theory-Guided Empirical Model for Locating and Characterizing Undocumented Orphaned Oil and Gas Wells

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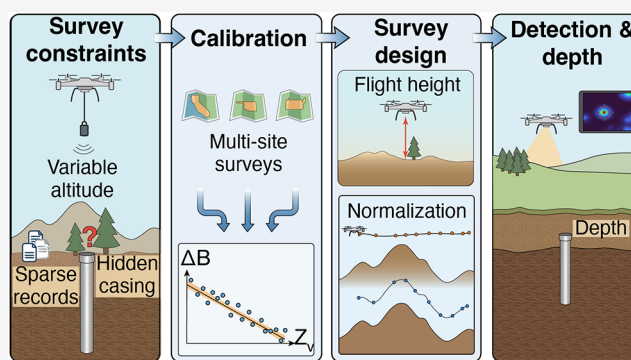
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ABSTRACT: Undocumented orphaned oil and gas wells can pose risks through unintended releases of substances, yet they remain difficult to locate because records are incomplete and surface indicators are often absent. Unmanned aerial vehicle (UAV) magnetometry is increasingly used to identify steel-cased wells, but surveys commonly stop at target detection and provide limited guidance on how sensor height affects anomaly strength, burial-depth estimates, or confidence in non-detection. Here, we develop a physics-informed, calibrated empirical model between peak magnetic-anomaly amplitude and distance from the magnetometer to the top of steel casing. Using anomaly amplitude measured at known sensor height, the model provides three practical outputs: estimated casing-top burial depth where casing is not visible, maximum sensor height at which casing at a specified depth remains detectable, and correction of variable-height anomalies to a common reference height. We calibrate the relationship using multi-altitude UAV surveys at Wildcat Canyon Regional Park, California, and Osage Ranch, Oklahoma, and apply it at Hillman State Park, Pennsylvania, identifying one undocumented-well candidate supported by ground magnetometry and estimating burial depths for three documented wells consistent with independent depth constraints.

KEYWORDS: magnetic anomaly amplitude, casing-top burial depth, transect spacing, survey optimization, altitude normalization



1. INTRODUCTION

Undocumented orphaned oil and gas wells (UOWs) can function as poorly characterized conduits between subsurface zones and the surface, posing site-safety and land-use risks through unintended releases of substances.¹ Reported releases can include light alkanes (C1–C5), associated volatile organic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX), and, in some fields, hydrogen sulfide (H₂S).¹ In this study, “orphaned” refers to oil and gas wells with no legally responsible owner or operator of record, and “undocumented” refers to wells absent from available records or with location records too uncertain for direct field verification.^{1–3} As of April 2022, documented orphaned oil and gas wells accounted for roughly 5–6% of nationwide fugitive C1 light-alkane releases attributed to abandoned wells.^{4,5} As of 2024, about 130,000 orphaned wells had been officially documented in the United States, with an estimated one million more undocumented,^{4,6} together a substantial but minority share of the more than four million oil and gas wells drilled nationwide.^{4,7} Locating these wells is challenging in remote areas with rugged topography and dense canopy and in

urban settings where access and infrastructure constrain surveys.^{3,8} Reliable location is also a prerequisite for inventory, monitoring, and eventual plugging. Where steel casing, the steel pipe installed in a wellbore to maintain borehole integrity, remains, it is strongly ferromagnetic and detectable by magnetic surveys.

Over decades of industrial activity, well locations were commonly recorded using basic compass-and-chain or transit surveys, documented on hand-drawn plats or disparate state forms,⁹ and reported using non-standardized procedures.¹⁰ These practices, coupled with incomplete documentation, lost field notes, and changes in coordinate reference systems, have introduced positional errors into existing well databases.¹¹ As a

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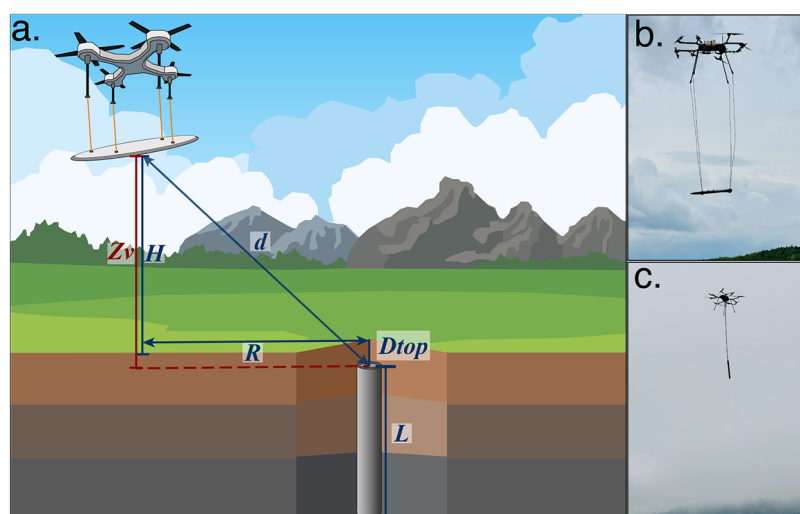


Figure 1. Schematic diagram of an unmanned aerial vehicle (UAV)-based magnetic survey for undocumented orphaned oil and gas wells. (a) UAV magnetic survey geometry. (b) Rope-towed magnetometer configuration. (c) Vertical segmented-rod-mounted magnetometer configuration. Z_v is the vertical distance between the magnetometer and the casing top. H is magnetometer altitude. D_{top} is casing-top burial depth. d is the straight-line distance between the magnetometer and the casing top. R is the horizontal offset, defined as the horizontal distance between the magnetometer and the vertical projection of the casing top. L is casing length.

result, the recorded geographic locations of documented wells could be offset by a few meters to several hundred meters.¹²

Magnetic surveying provides a practical way to verify uncertain well locations because steel casing commonly produces a compact magnetic anomaly that can be distinguished from broader geologic background and many non-well cultural features after appropriate processing.^{13–15} Crewed aeromagnetic surveys have used this response to locate steel-cased wells across large areas, including fields where database records and surface evidence are incomplete or inconsistent.^{3,11} Unmanned aerial vehicle (UAV) magnetometry extends this capability into a lower-altitude survey regime, providing denser magnetic data than crewed airborne surveys while covering larger or less accessible areas than ground magnetometry.^{16–18} Beyond well location, UAV magnetometry is an established technique used in other applications, including archaeological prospection and unexploded-ordnance (UXO) detection.^{19–21} Previous UAV-based magnetic survey studies have already shown that sensor height, transect spacing, terrain following, canopy and obstacle clearance, and Light Detection and Ranging (LiDAR)-derived terrain products, including digital elevation models (DEMs), are central to survey design.^{2,17,18,22,23} Low-altitude UAV magnetic surveys also require attention to sensor separation, payload motion, attitude variation, heading effects, and electromagnetic interference from the UAV platform.^{24–27}

Although previous studies have established UAV magnetometry as a practical method for locating candidate steel-cased wells,^{17,18,23} most workflows use magnetic anomalies mainly as indicators of target presence or absence. For undocumented orphaned wells, anomaly amplitude can also support screening-level questions that arise when casing is not visible: whether a nondetection is informative, what sensor height is acceptable for an expected casing-top burial-depth range, and what casing-top burial depth is consistent with an observed peak. These questions support interpretation of nondetections, flight-height planning, and prioritization of follow-up ground-based total-field magnetometry, excavation, and plug-and-abandonment (P&A) preparation. Sensor height is central because it controls

anomaly amplitude, but low and spatially uniform magnetometer-to-ground clearance is not always feasible. In rugged or forested settings, low-altitude terrain following requires clearance surfaces that represent both terrain and obstacles. Bare-earth DEMs provide ground elevation but may omit canopy, wires, snags, and small infrastructure relevant to safe flight.^{28–32} When terrain following is unsafe or not used, altitude-hold or barometric control can produce spatially variable above-ground-level sensor height.^{33,34} Visual-line-of-sight and safe-operation requirements can further favor conservative flight profiles.^{35–37} These constraints attenuate anomalies, reduce detectability of deeply buried or short casing, and make amplitudes collected at different heights difficult to compare. Conventional magnetic inversion can provide depth-related information, but it is nonunique and requires assumptions about source geometry, susceptibility or magnetization, and background fields.^{38,39} These requirements make inversion less practical as a routine screening step across many candidate sites.

Here, we build on this established detection capability by developing a physics-informed, field-calibrated empirical model linking peak magnetic-anomaly amplitude to magnetometer-to-casing-top distance. This model extends UAV magnetic surveys beyond target detection by providing three reconnaissance-scale outputs. First, for a detected anomaly acquired at known sensor height, the model estimates magnetometer-to-casing-top distance; where casing is not visible at the surface, this estimate can be converted to casing-top burial depth by accounting for the sensor height above ground. Second, before acquisition, the model supports survey design. Given an expected casing-top burial depth and a selected detection threshold, it estimates the maximum sensor height above ground that would still allow detection, helping balance magnetic sensitivity against terrain, canopy, obstacle-clearance, aircraft-performance, and visual-line-of-sight constraints. Third, for data acquired at variable height above ground, such as altitude-control flights, the model corrects anomaly amplitudes to a common reference height, enabling more consistent comparison of anomalies across a field site. Together, these

outputs add burial-depth estimation, height-dependent detectability assessment, and altitude normalization to UAV magnetic workflows without requiring full site-specific inversion.

2. THEORETICAL BACKGROUND

2.1. Steel Casing Magnetic Signature

A schematic diagram of a typical UAV-based magnetic survey for casing detection is shown in Figure 1a. To reduce UAV-induced magnetic interference, the magnetometer is typically suspended ~ 5 m below the UAV. In this study, we used both rope-towed and vertical rod-mounted configurations (Figure 1b, c), selected based on survey conditions.

Steel casing with predominantly axial magnetization is represented here using an equivalent magnetic pole-pair model.^{13,40} This model is the finite-pole-pair representation of a continuous distribution of axial magnetization and is appropriate at distances large compared with casing diameter. In UAV-based magnetic surveys, we use vehicle altitude H and the magnetometer-to-casing-top distance Z_v instead of the general vertical coordinate z . Here, “casing top” refers to the upper end of the remaining steel casing, not necessarily the original surface wellhead or total well depth. Although scalar total-field magnetometers record field magnitude, for small anomalies the total-field anomaly is approximately the projection of the anomalous field onto the ambient geomagnetic-field direction. Near the peak response of an axially magnetized near-vertical casing ($R \approx 0$), this projection mainly changes the amplitude by a constant factor, so peak total-field anomalies follow the same distance dependence as the modeled vertical component. The resulting vertical-component anomaly is

$$\Delta B_z = \frac{\mu_0 m}{4\pi} \left[\frac{Z_v}{\sqrt{(R^2 + Z_v^2)^3}} - \frac{Z_v + L}{\sqrt{(R^2 + (Z_v + L)^2)^3}} \right] \quad (1)$$

where Z_v is the vertical distance from the magnetometer to the casing top, R is the horizontal offset, defined as the horizontal distance between the magnetometer and the vertical projection of the casing top, L is the remaining casing length, and m is the effective magnetic pole strength, equivalently the axial magnetic moment per unit casing length. The notations and their spatial representations are shown in Figure 1a. With uniform effective axial magnetization, the effective pole strength can be approximated as

$$m = M_{\text{eff}} A_s \approx \frac{\chi B_0}{\mu_0} A_s \quad (2)$$

where M_{eff} is the effective axial magnetization, A_s is the annular steel-wall cross-sectional area of the casing, B_0 is the ambient geomagnetic-field intensity, χ is magnetic susceptibility, and μ_0 is magnetic permeability of free space. The effective magnetization may include both induced and remanent contributions. A more detailed derivation of the steel-casing magnetic signature is provided in Text S1 (Supporting Information).

2.2. Sensitivity Analysis

eq 1 describes the modeled vertical-component response, $\Delta B_z(R)$, produced by an axially magnetized steel casing as a function of the horizontal distance between the magnetometer and the vertical projection of the casing top (R). For the long,

near-vertical casings considered here, the modeled response has a local positive maximum over or near the casing and decreases with increasing offset over the survey distances relevant to UAV transects. This behavior is consistent with previous magnetic well-location studies, which describe steel-cased wells as producing monopole-like or bull's-eye magnetic anomalies that can be distinguished from many dipolar nonwell sources after appropriate processing.^{12,13,15} According to eqs 1 and 2, ΔB_z depends on R , the sensor-to-casing-top distance $Z_v = H + D_{\text{top}}$, and effective pole strength m . In the approximate expression for m , the magnetic response increases with χ , B_0 , and A_s .

To quantify the local sensitivity, we compute the dimensionless relative sensitivity,⁴¹

$$S_p = \frac{\partial \Delta B_z}{\partial p} \times \frac{p}{\Delta B_z} \quad (3)$$

which measures the fractional change in ΔB_z produced by a fractional change in parameter p . Positive sensitivity indicates that ΔB_z increases with p , whereas negative sensitivity indicates that it decreases with p . Sensitivities are evaluated at baseline values representative of UAV-based orphaned/undocumented well surveys: $R = 5$ m, $H = 30$ m, $D_{\text{top}} = 1.5$ m, $\chi = 2000$, and $L = 1000$ m. This χ is consistent with typical carbon steel casing susceptibilities.⁴² The ranking indicates that χ sets intrinsic anomaly strength, while the peak response is most sensitive to sensor-to-casing-top distance Z_v among the controllable geometric variables. At the long-casing baseline used here, sensitivity to L is small because the lower effective pole is far from the sensor; L mainly affects the broad anomaly base and becomes more important for short remaining casing segments. Thus, susceptibility χ primarily sets intrinsic anomaly strength, whereas survey geometry, especially sensor-to-casing-top distance Z_v and horizontal offset R , which is controlled in part by transect spacing, controls measured amplitude and detectability.

Casing magnetization also scales with the ambient field B_0 , which ranges from 45,000 to 55,000 nT across the continental United States.⁴³ Over this range the peak anomaly varies by up to ~ 16 nT at $H = 30$ m and ~ 5 nT at $H = 100$ m, comparable to the change from ~ 5 m of altitude fluctuation, so local survey geometry dominates over regional B_0 variability.

One-at-a-time (OAT) tests over realistic ranges ($R = 0$ –50 m, $Z_v = 30$ –100 m, $L = 100$ –1500 m) are summarized in Text S2. Peak anomaly decreases by about 6–10% per 10 m of horizontal offset, limiting amplitude-only localization at 10 m line spacing. Peak anomaly decreases nearly linearly with Z_v over 30–100 m, supporting casing-top depth estimation when sensor height is known and casing properties are bounded. Increasing L mainly raises the broad anomaly base, which can mask shorter casings near long casings or large surface infrastructure.

2.3. Practical Approximations and Error Analysis

For survey planning and robust interpretation, it is useful to relate the peak anomaly to the sensor-to-casing-top distance $Z_v = H + D_{\text{top}}$ and to derive simplified expressions valid for modest altitude variations. For the on-axis ($R = 0$), eq 1 can be written as follows

$$\Delta B_z = \frac{\mu_0 m}{4\pi} \left[\frac{1}{(Z_v)^2} - \frac{1}{(Z_v + L)^2} \right] \quad (4)$$

For the survey geometries considered here, the lower end of the casing is commonly far enough below the sensor that its contribution to the on-axis peak response is small relative to the casing-top term. eq 4 can therefore be simplified by retaining the dominant casing-top term

$$\Delta B_z \approx \frac{\mu_0 m}{4\pi} \left[\frac{1}{Z_v^2} \right] \quad (5)$$

Because the remaining casing is long compared with the sensor-to-casing-top distance, the lower effective pole contributes little to the on-axis peak response. The upper effective pole therefore produces a monopole-like inverse-square response; this is the monopole-equivalent limit of the pole-pair model in Text S1.

UAV flights operate within a limited altitude range around a nominal sensor-to-casing-top distance Z_0 . Linearizing eq 5, using first-order Taylor expansion, with respect to Z_v about Z_0 gives

$$\begin{aligned} \Delta B_z &\approx \Delta B_z(Z_0) + \frac{d\Delta B_z}{dZ_v} \bigg|_{Z_0} (Z_v - Z_0) \\ &= -\frac{\mu_0 m}{2\pi} \frac{1}{Z_0^3} (Z_v) + \frac{3\mu_0 m}{4\pi} \frac{1}{Z_0^2} \end{aligned} \quad (6)$$

For a chosen nominal distance Z_0 and fixed effective magnetic pole strength m , the coefficients in eq 6 are constants over the local linearization interval. Thus, eq 6 can be written as

$$\Delta B_z = -aZ_v + p = -a(H + D_{\text{top}}) + p \quad (7)$$

where $a = \frac{\mu_0 m}{2\pi} \frac{1}{Z_0^3}$, $p = \frac{3\mu_0 m}{4\pi} \frac{1}{Z_0^2}$. eqs 5–7 therefore provide efficient approximations for predicting how peak anomaly amplitude changes over a limited operating-height range.

Compared against the analytical expression (eq 4) over $Z_v = 25$ –90 m and $L = 200$ –2000 m, the inverse-square form introduces <1 nT error and the linear form stays within <7 nT for $L = 1000$ m, comparable to reported low-altitude airborne noise.⁴⁴ Because D_{top} is fixed during a survey and H is adjustable, eq 7 is convenient for modest altitude changes, while eq 5 retains the full inverse-square dependence. Additional comparisons are in Text S3.

3. MATERIALS AND METHODS

Guided by the theoretical scaling and linear approximation, we evaluate the amplitude–distance relationship in four field applications: linear dependence testing at Wildcat Canyon Regional Park, California; multi-height calibration at Osage Ranch, Oklahoma; casing-top depth estimation at Hillman State Park, Pennsylvania; and variable-height amplitude normalization at Osage Ranch. Table 1 summarizes field applications and dates; Table S1 provides complete flight metadata, including active survey duration, sensor AGL, transect spacing, average flight speed, flown distance, and survey footprint. Flight planning was performed in UgCS, and 1 m DEMs for terrain following were derived from USGS LiDAR data.

3.1. Data Acquisition Setup

Data were acquired using a Geometrics MagArrow total-field magnetometer towed ~5 m below a Skyfront Perimeter 8 hybrid multicopter to reduce magnetic interference from the UAV. Depending on wind conditions and flight-stability requirements, the sensor was suspended using either a stabilized rope-tow system (Figure 1b) or a semi-rigid segmented rod (Figure 1c). UAV

Table 1. Summary of Field Applications^a

site	purpose	survey date
Wildcat Canyon, CA	linear AGL-amplitude validation	5 aug. 2024
Osage Ranch, OK	multi-height targeted well calibration	20 aug. 2024
Hillman State Park, PA	detection and casing-top-depth estimation	1 may 2024
Osage Ranch, OK	variable-height amplitude correction	11–12 mar. 2024

^aA concurrent UAV LiDAR survey was flown at Hillman State Park to estimate canopy height (Text S6).

navigation was controlled using the onboard GPS, while the MagArrow simultaneously logged its own GPS position for post-processing. For flights using barometric altitude control, only horizontal position, latitude/longitude, was controlled by GPS. Transect spacing was selected relative to sensor AGL, expected anomaly footprint, and survey objective; MagArrow guidance recommends spacing of approximately 1–2 times the distance between the ground and the MagArrow.⁴⁵ Survey purposes and dates are summarized in Table 1; full acquisition metadata are provided in Table S1.

3.2. Data Processing

UAV magnetic data were processed to remove non-survey segments, mitigate MagArrow heading-effect artifacts, reduce high-frequency platform noise, and pick candidate well anomalies. The MagArrow natively records total-field magnetic data at 1000 Hz and GPS positions at 1 Hz as G-864 survey files; the dataset was exported, via Geometrics Survey Manager, at 100 Hz to reduce computational load. Before filtering, measured MagArrow GPS tracks were matched to the planned survey transects, and data outside the planned survey grids were removed, excluding takeoff, landing, transit to and from the survey grid, and other non-survey segments.

The MagArrow uses two orthogonally oriented total-field sensors to avoid dead-zone data loss, but this configuration can retain a heading effect: an orientation-dependent offset as the sensor rotates relative to the ambient magnetic field. In back-and-forth grid flights, this effect appears mainly as low-frequency line-to-line baseline offsets between transects flown in different directions. We mitigated these heading-effect artifacts by subtracting a centered rolling-window background, and remaining high-frequency platform noise was reduced with a fourth-order Butterworth low-pass filter. Similar heading-effect mitigation, line leveling, and platform-noise reduction steps have been used in UAV and airborne magnetic workflows before gridding and interpretation.^{3,18,26,27} Candidate peaks were defined as local maxima in the processed residual field and retained if they exceeded the local background by at least 5 nT;⁴⁶ duplicate picks within 45 m in both UTM easting and northing were represented by the largest-amplitude pick, followed by manual removal of line-edge, infrastructure-related, or other non-well anomalies. Parameter-selection criteria, representative filter settings, path-matching procedures, and peak-picking parameters are provided in Text S5.

4. RESULTS AND DISCUSSION

4.1. Validation of the Linear Approximation

The tested well at Wildcat Canyon Regional Park in California was previously undocumented and was plugged and buried in 2013 following the discovery of surface leakage.⁴⁷ According to the record, the casing is 1,400 m (4,600 ft) in length, has a diameter of 0.1143 m (4.5 in), and is buried approximately 1.5 m (5 ft) below ground level.

We planned flights at four nominal altitudes (35, 45, 55, and 65 m above ground level (AGL)) using straight-line grids with 10 m line spacing at each altitude (Figure 2a, b). To facilitate mission planning, the grid orientation at each AGL was rotated by 2.5°. Because the well is situated on a steep hillside, the

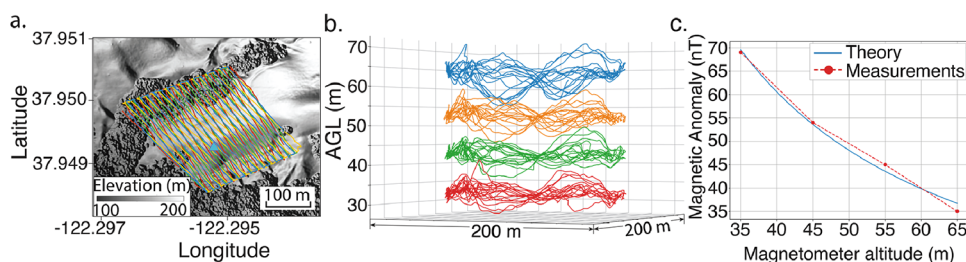


Figure 2. Wildcat Canyon field test validating the altitude–amplitude relationship. (a) Plan view of magnetometer altitude during the test. Flight paths are color coded (red: 35 m AGL; green: 45 m AGL; orange: 55 m AGL; blue: 65 m AGL). (b) Side view of magnetometer altitude along flight lines. (c) Comparison between theoretical anomaly predictions (relative to geomagnetic field) and field measurements.

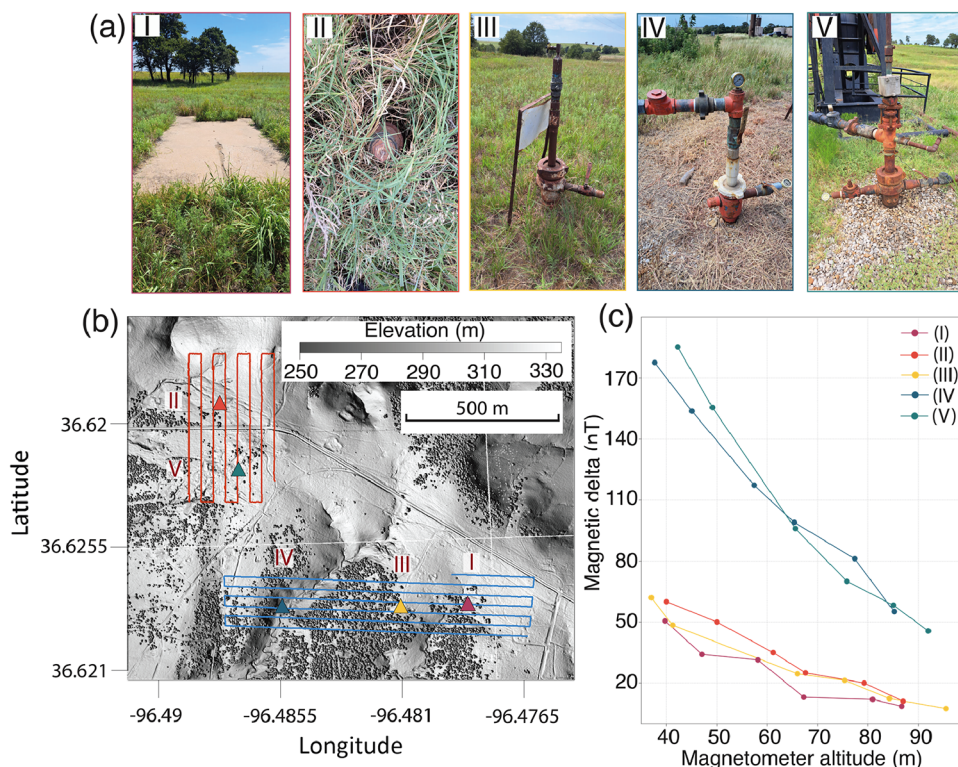


Figure 3. Osage Ranch calibration wells and measured ΔB_z – H relationships. (a) Surface photographs of selected wells. (b) Calibration flight paths. Roman numerals correspond to wells in panel (a). (c) Measured peak anomaly amplitude versus magnetometer AGL for selected wells.

actual flight altitude fluctuated by up to 5 m due to wind, topography, and rapid UAV maneuvers.

Using the recorded magnetometer altitude and known casing parameters, we computed theoretical magnetic anomalies relative to the background geomagnetic field at each AGL. Comparison with the measurements (Figure 2c) shows good agreement. Over the tested AGL range (35–65 m), peak anomaly amplitude varies approximately linearly with altitude.

4.2. Derivation of the Empirical Linear Model

4.2.1. Osage Ranch Field Test Wells. We conducted multi-altitude calibration flights at Osage Ranch, Oklahoma, using gridded paths with 40 m transect spacing at nominal sensor altitudes of 40, 50, 60, 70, 80, and 90 m AGL. Five visually identified wells were selected (Figure 3a, b): a fully buried well, two minimally exposed cut wells, and two wells associated with pumpjacks or nearby surface infrastructure (Figure 3a). Detailed well-construction information, including depth, casing diameter, and surface-structure dimensions, was not available; therefore, for Osage Ranch wells we use

magnetometer AGL (H) rather than Z_v . Wells I–III showed similar quasi-linear amplitude–height behavior with minor differences as exposure increased from buried to approximately 1 m above ground (Figure 3c). Wells IV and V produced larger amplitudes and steeper slopes because pumpjacks and associated ferromagnetic infrastructure were closer to the magnetometer than the buried casing tops.

4.2.2. Establishing the Linear Empirical Model. The sensitivity analysis shows that, within the continental United States, variation in the background geomagnetic field intensity can produce anomaly changes comparable to those induced by a few meters of altitude fluctuation; sparse calibration data from different states can be combined for a reconnaissance-scale empirical fit. We used the Wildcat Canyon and Osage Ranch calibration flights to regress peak anomaly amplitude against sensor-to-casing-top distance. The linear-model slope is unchanged whether distance is expressed as magnetometer AGL (H) or sensor-to-casing-top distance (Z_v); only the intercept differs (eq 7). For Osage Ranch wells, which were above ground or shallowly buried, we approximate Z_v by the

magnetometer altitude above ground level (AGL). For the Wildcat Canyon well, we add the known burial depth (1.5 m) to the measured altitude.

Figure 4 shows two distinct amplitude–altitude clusters: wells that are cut-and-buried or have minimal surface

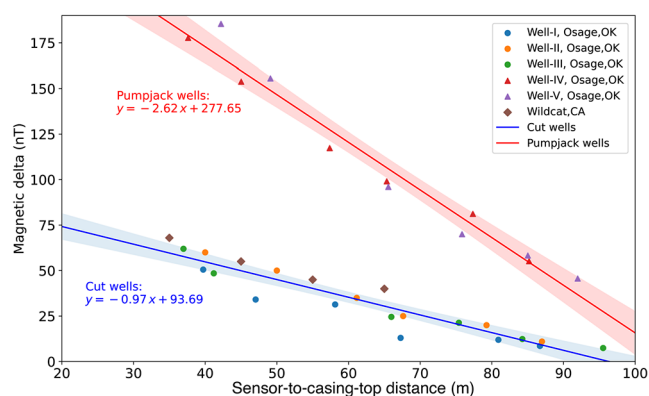


Figure 4. Empirical model relating peak magnetic anomaly amplitude relative to the local background field to sensor-to-casing-top distance, derived from calibration flights at Osage Ranch, Oklahoma, and Wildcat Canyon Regional Park, California. Separate linear regressions are shown for cut/buried wells and pumpjack-associated wells; shaded bands denote approximate 95% confidence bands for the fitted mean response.

structures, and wells connected to pumpjacks. We therefore performed separate linear regressions for these two well types. The fitted lines for both groups are displayed in Figure 4. Thus, we have two calibrated linear empirical models. For cut-and-buried or minimally exposed wells over $Z_v \approx 20$ –95 m, the linear empirical model can be expressed as

$$\Delta B_{\text{peak}} = -0.97Z_v + 93.69 \quad (8)$$

Similarly, for pumpjack wells, the linear empirical model is

$$\Delta B_{\text{peak}} = -2.62Z_v + 277.65 \quad (9)$$

At each altitude H_p , the square roots of the diagonal elements of the variance-covariance matrix ($\text{var}[\widehat{\Delta B}(H)]$) give the standard errors of the fitted mean total-field anomaly amplitude. The shaded bands in Figure 4 show approximate 95% confidence bands, computed as 1.96 times these standard errors.

Pumpjack-associated wells have large ferromagnetic surface structures that generate stronger anomalies and reduce effective sensor-to-source distance during constant-altitude UAV surveys. Therefore, their amplitude-height relation differs from the cut/buried relation. These wells are usually identifiable by field observation or aerial imagery;⁶ when imagery is unavailable, close agreement with the pumpjack regression model can flag anomalies dominated by surface infrastructure rather than isolated buried casing.

4.2.3. Effect of Transect Spacing. eq 8 was calibrated from near-on-axis peaks ($R \approx 0$), where R is the horizontal offset between a measurement location and the vertical projection of the casing top. In a gridded survey with transect spacing s , an unknown target can lie as much as $s/2$ from the nearest transect in the cross-track direction. Off-axis sampling reduces the picked peak and affects both casing-top depth estimation and survey design.

To quantify this effect, we down-sampled the dense 10 m Wildcat Canyon survey at sensor AGL ≈ 35 m to emulate 20 – 60 m transect spacing (Figure 5). Relative to the 10 m baseline, measured peak amplitude was $\sim 87\%$ at $s = 20$ m, $\sim 78\%$ at $s = 30$ m, and $\sim 57\%$ at $s = 40$ m. The theoretical

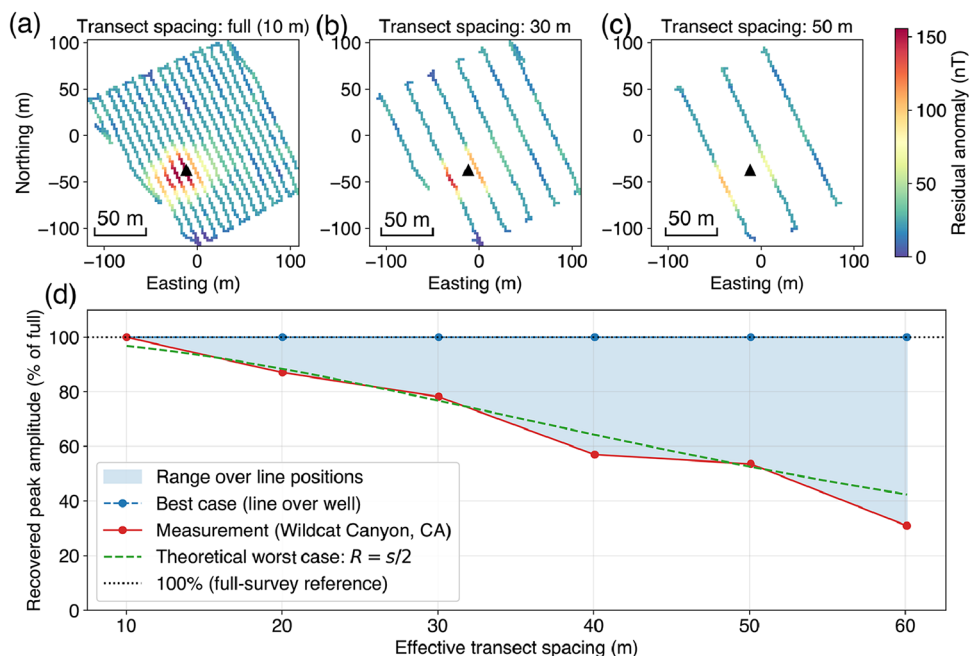


Figure 5. Effect of transect spacing on anomaly recovery, from line-removal of the dense 10 m Wildcat Canyon calibration survey. (a–c) Residual total-field anomaly for the full 10 m survey and line-thinned versions emulating 30 and 50 m spacing, shown for the worst-case line position (well midway between retained lines); the black triangle marks the known cut-and-buried well. (d) Recovered peak anomaly amplitude versus effective transect spacing, as a percentage of the full-resolution value. Red: measurements; blue dashed: best case (a line directly over the well); green dashed: theoretical worst-case recovery when $R = s/2$; shaded band: range over all line positions.

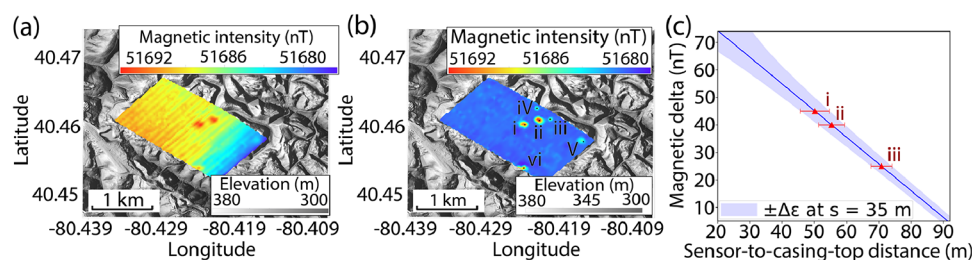


Figure 6. UAV magnetic survey at Hillman State Park, Pennsylvania, and application of the empirical model. (a) Raw total-field intensity overlaid on the U.S. Geological Survey (USGS) 1-m DEM. (b) Processed total-field anomaly map with auto-picked candidate well locations (black dots; labels i–vi). (c) Sensor-to-casing-top distance estimation for documented wells i–iii. The blue line denotes the empirical linear model for cut/buried wells, and the light-blue shaded band denotes the $\pm\Delta\epsilon$ envelope for a transect spacing of $s = 35$ m. Red triangles denote the point estimates obtained by projecting the measured peak anomaly amplitudes for Wells i–iii onto the empirical model; horizontal red bars show the corresponding sensor-to-casing-top distance ranges after accounting for a possible cross-track offset of up to 17.5 m.

worst-case curve ($R = s/2$) is consistent with the half-transect-spacing detectability limit reported in prior UAV magnetic surveys;^{18,22} deviations at $s \geq 40$ m likely reflect altitude variation from wind and UAV maneuvers over steep terrain. Multi-altitude results are in Figures S7 and S8.

As shown in Figure 5, off-axis sampling may bias casing-top depth estimation. When casing lies off-line, the picked peak is smaller than the on-axis value, so eq 8 returns an apparent sensor-to-casing distance larger than the true $Z_v = H + D_{\text{top,true}}$. Combining the off-axis form of eq 1 with the on-axis form of eq 8 at the worst-case offset $R = s/2$ gives

$$\Delta\epsilon = (H + D_{\text{top,est}}) \left\{ \left[1 + \left(\frac{s}{2(H + D_{\text{top,est}})} \right)^2 \right]^{3/4} - 1 \right\} \quad (10)$$

Because true D_{top} is unknown, eq 10 is evaluated using $D_{\text{top,est}}$ from eq 8. The same relation also constrains survey design. For detection threshold T , eq 8 gives the on-axis bound $Z_v \leq (93.69 - T)/0.97$. For expected maximum casing-top burial depth $D_{\text{top,max}}$, the worst-case picked peak at $R = s/2$ must still exceed T , giving the maximum permissible transect spacing at chosen sensor altitude $H \geq H_{\text{min}}$, where H_{min} is the minimum feasible sensor altitude set by canopy/obstacle clearance, aircraft performance, regulatory constraints, and survey-time constraints

$$s_{\text{max}} = 2(H + D_{\text{top,max}}) \sqrt{\left[\frac{93.69 - T}{0.97(H + D_{\text{top,max}})} \right]^{4/3} - 1} \quad (11)$$

If the square-root term is negative, on-axis detection at the assumed $H + D_{\text{top,max}}$ is already below T . eq 11 gives the largest spacing that still allows worst-case detection; tighter spacing or lower altitude increases the detection margin. The chosen H and s must also satisfy aircraft, clearance, and survey-time constraints.

4.3. Survey Design Optimization and Well Characterization

4.3.1. Optimizing Survey Design and Detection Confidence in UAV-Based Surveys. When well locations and burial depths are unknown, eq 8 helps set flight altitude and interpret nondetections. For survey design and non-detection assessment, we use a conservative ~ 10 nT detection threshold, approximately twice the 5 nT candidate peak-

picking floor used during automated processing and above the < 7 nT linearization error. At this threshold, 35 m sensor AGL keeps casing detectable to 48.5–51.3 m BGS for 35 m line spacing (worst to best case from eqs 8 and 11). A nondetection at this threshold is evidence against shallow detectable casing, but remains inconclusive where severe corrosion, atypical casing materials, nonstandard geometry, or nearby metal could weaken or mask the signal.

In practice, detection confidence is often constrained by operational requirements rather than instrumentation limits. The MagArrow magnetometer is typically towed ~ 5 m below the UAV, so safe canopy and terrain clearance increases sensor altitude and reduces anomaly amplitude. The empirical model provides a direct way to translate these safety constraints into expected signal levels and to select the lowest feasible operating altitude consistent with a target detection threshold, while also informing line spacing choices given the expected anomaly footprint.

We evaluated this planning framework at Hillman State Park, Pennsylvania, a rugged reforested site with historical oil development and later coal mining.^{3,8} Five documented buried wells lie within the test area. Wells i–iii have estimated burial-depth ranges of 15–25 m BGS Wells i and (ii) and 25–50 m BGS Well (iii); Wells iv and v have documented locations only. USGS LiDAR-derived DEMs give ground elevation but not current vegetation height, so we flew a targeted UAV LiDAR survey (Rock R3 Pro) to measure canopy height (~ 30 m). We then selected a terrain-following flight at 40 m vehicle AGL (35 m sensor AGL) with 35 m line spacing to balance safety, efficiency, and sensitivity.

4.3.2. Casing-Top Burial-Depth Estimation at Hillman State Park. Raw and processed Hillman magnetic data are shown in Figure 6a,b. Auto-picked anomalies i–v align with the five documented orphaned wells, and anomaly vi occurs at a previously undocumented location later confirmed by ground magnetometry, suggesting an additional undocumented-well candidate. For Wells i–iii, which have independent burial-depth ranges of 15–25 m BGS Wells i and (ii) and 25–50 m BGS Well (iii), we projected peak anomaly amplitudes onto eq 8 to estimate magnetometer-to-casing-top distance (Figure 6c). Because the wells may lie between survey lines, we used the half-line spacing (17.5 m) as the worst-case cross-track offset in eq 10. The resulting sensor-to-casing-top distances are 48–57 m, 53–61 m, and 71–77 m for Wells i–iii, corresponding to casing-top burial depths of 13–22 m, 18–26 m, and 36–42 m. These estimates agree with the independent depth ranges and support use of the empirical

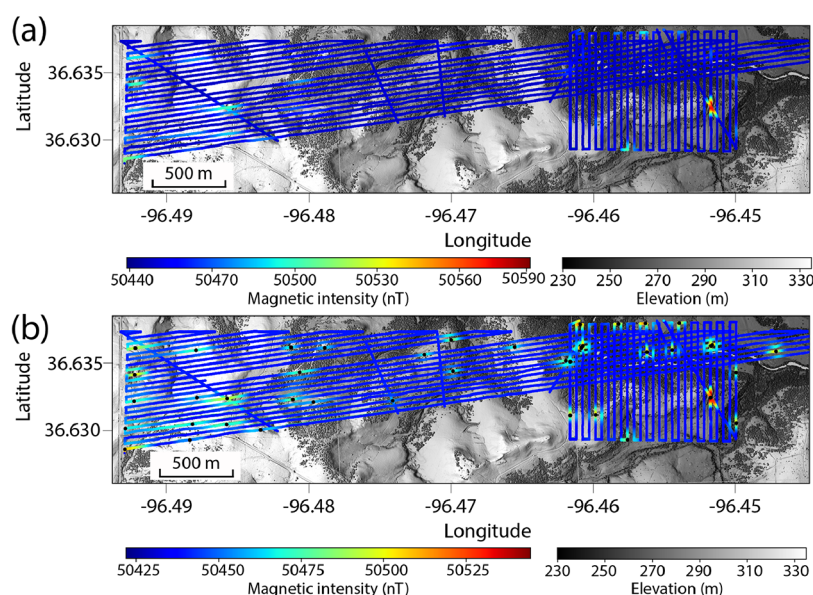


Figure 7. Altitude normalization of non-terrain-following data using the empirical linear model. (a) Processed UAV magnetic anomalies before correction. (b) Anomalies normalized to 45 m AGL. Black dots indicate auto-picked well anomalies.

relation for screening-level casing-top burial-depth estimation, follow-up field planning, P&A preparation, and land-use or infrastructure-siting decisions.⁴⁸

4.4. Altitude Normalization of Variable-Height Anomalies

Data acquired without terrain following, such as constant-barometric-altitude control or fixed-wing surveys, can show anomaly-amplitude changes driven by sensor height rather than casing length or burial depth. During the UAV-based magnetic survey at Osage Ranch, Oklahoma, two areas were flown using constant barometric altitude control rather than DEM-based terrain following or downward-facing radar altimetry. As a result, the magnetic data were collected at highly variable AGL. We reconstructed the AGL profiles from MagArrow GPS elevations and a USGS DEM; sensor height ranged from ~15 to 97 m AGL, leading to large amplitude variations not attributable to differences in well conditions. We therefore use the cut/buried empirical model to normalize picked anomalies to a common reference height. For a picked anomaly measured at sensor altitude H , the normalized amplitude is $\Delta B_{\text{ref}} = \Delta B_{\text{obs}} + s_c(H_{\text{ref}} - H)$, where $s_c = -0.97$ nT m⁻¹ and $H_{\text{ref}} = 45$ m. Normalization enhances anomalies collected above the reference height and reduces amplitudes collected below it, improving field-scale comparison (Figure 7). Because the cut/buried slope is shallower than the pumpjack-associated slope, this correction is conservative for pumpjack-associated anomalies.

5. IMPLICATIONS

Previous magnetic, aeromagnetic, and UAV studies have established that steel-cased oil and gas wells can be located from localized magnetic anomalies, including where records are incomplete, surface evidence is absent, vegetation is dense, or land use has altered the original well site.^{3,8,11,13–15,17,18,23} This study builds on that established detection capability by adding a theory-guided, field-calibrated amplitude-distance relation that translates peak magnetic-anomaly amplitude and known sensor height into practical UAV-survey interpretation. Starting from the finite-casing response, we retain the dominant casing-top term and linearize the peak-amplitude

relation over operational UAV heights; the slope and intercept are calibrated from multi-altitude field data. The resulting model is not a universal inversion: fitted coefficients absorb casing material, diameter, magnetization, local background, processing workflow, and survey configuration. Its value is a rapid, low-input interpretation layer for surveys where casing length, remaining segment, casing condition, magnetization, and burial depth are poorly constrained. For the cut/buried regression, eq 8 predicts ~50 nT at $Z_v = 45$ m and ~21 nT at $Z_v = 75$ m, consistent with prior UAV well-location amplitudes at comparable heights.^{17,18} The calibrated model therefore adds a quantitative interpretation layer to UAV magnetic well-location surveys, rather than introducing a new detection workflow.

Approximation-error and field-calibration results support this operational simplification. Over $Z_v = 25$ –90 m and $L = 200$ –2000 m, reducing the finite-casing response to the casing-top inverse-square form introduced <1 nT error, and the linearized form stayed within <7 nT for $L = 1000$ m. Sensitivity analysis shows that B_0 variability over the continental U.S. changes predicted peak anomaly by up to ~16 nT at 30 m AGL and ~5 nT at 100 m AGL, comparable to about 5 m of sensor-height variation. Thus, for practical U.S. UAV surveys, sensor height and survey geometry generally dominate over regional B_0 variability.

At Hillman State Park, the model estimated casing-top burial depths of 13–22 m, 18–26 m, and 36–42 m for three documented wells, consistent with independent depth constraints and previous evidence that mining removed upper casing and buried remaining casing beneath spoil or sediment.⁸ Casing-top burial depth does not by itself determine whether intervention is required; together with location information, it helps plan ground magnetic confirmation, access and excavation logistics, P&A preparation, land-use planning, and siting or construction of new infrastructure where the presence or absence of buried wells affects planning and execution.⁴⁸ The model also helps interpret nondetections: if a casing should have exceeded the threshold but no anomaly is observed, casing may be absent, removed,

non-steel, weakly magnetized, off-line, or masked by nearby metal; if the predicted anomaly is below threshold, the nondetection is inconclusive. Pumpjack-associated wells require separate interpretation because above-ground ferromagnetic structures dominate their anomalies. Agreement with the pumpjack regression can therefore flag infrastructure-dominated anomalies, and physically unrealistic depths from the cut/buried regression warn against interpreting such anomalies as isolated buried casing. This interpretation is consistent with prior UAV work showing that intact surface infrastructure, exposed casing, and pumpjacks produce high-amplitude organized magnetic anomalies.^{22,23} Finally, normalization of variable AGL Osage Ranch data reduced geometry-driven amplitude differences and improved field-scale comparison and interpretation.

The empirical model has practical limits. It is most reliable for approximately vertical steel casing when the picked peak is close to the casing axis, the remaining casing is long enough that the lower pole contributes little to the peak response, and the survey is flown within the low-altitude operating envelope typical of sUAV magnetic surveys. In U.S. operations, this envelope is generally bounded by the 400 ft (122 m) AGL Part 107 limit;³⁷ over the tens-of-meters sensor-to-casing-top distances evaluated here, the approximation-error analysis shows that the amplitude–distance relation can be represented by a local linear model. The fitted coefficients should be checked or refit for substantially different regions, instruments, or processing workflows. Nearby pumpjacks, tank batteries, pipelines, or closely spaced wells can mask weaker casing anomalies. Soil type and water-table position are not expected to strongly attenuate the static magnetic field from steel casing, but they can affect casing degradation, surface expression, access, and follow-up observations.^{1,49} Severe corrosion, non-steel casing, or nonstandard geometry can reduce magnetic response, causing overpredicted detectability or overestimated casing-top burial depth; nondetections therefore require local recalibration or ground confirmation where such conditions are plausible.

Overall, this study adds amplitude-based interpretation to UAV magnetic surveys of steel-cased oil and gas wells. By simplifying the finite-length casing response into a field-calibrated linear empirical model over operational sensor heights, the approach provides a rapid, low-input alternative to full magnetic inversion when casing length, remaining segment, condition, magnetization, and burial depth are poorly constrained. Applied to peak anomaly amplitude and known magnetometer height, the model supports three practical uses: casing-top burial-depth estimation, pre-survey selection of sensor height and transect spacing with post-survey non-detection assessment, and variable-height amplitude normalization. These capabilities move UAV magnetic surveys from location-focused screening toward practical interpretation and planning for undocumented orphaned oil and gas wells.

■ ASSOCIATED CONTENT

Data Availability Statement

The UAV magnetic survey data and processed Rock R3 Pro UAV LiDAR-derived canopy-height products supporting the analyses reported in this study are available from the corresponding author upon reasonable request.

■ Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.6c02007>.

Expanded derivation of steel-casing magnetic signature (Text S1); extended sensitivity and approximation-error analyses (Texts S2–S3); field-site maps and survey layouts (Texts S4 and S6); data-processing diagnostics (Text S5); barometer-based altitude-control profiles (Text S7); and multi-altitude transect-spacing analysis (Text S8) (PDF)

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Notes

The authors declare no competing financial interest.

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