GEOPHYSICAL INVESTIGATION REPORT
BUXTON NAVAL FACILITY FORMERLY USED DEFENSE SITE (FUDS) PROPERTY
DARE COUNTY, NORTH CAROLINA

U.S. ARMY CORPS OF ENGINEERS
SAVANNAH DISTRICT

Status: FINAL
Report Date: January 2025

Controlled by U.S. Army Corps of Engineers
Controlled by: CESAS
CUI Category: Environmental Investigation
Limited Dissemination: FEDCON

This page is intentionally left blank

.

EXECUTIVE SUMMARY

The purpose of this investigation was to complete a geophysical investigation of 6.3 acres of the Buxton Naval Facility Formerly Used Defense Site to detect and map abandoned features to include utilities, potential underground storage tanks, concrete pads, and other metallic features associated with the former base.

The methods of investigation used at the site included electromagnetic induction (EMI) and magnetics (Mag). Geophysical sensors that were deployed included the Geonics EM61-MK2 and the EM31-MK2, and the Geometrics G-858 magnetometer.

Using geophysics and GIS data on former building sites and storage tanks (USTs/ASTs), we identified linear features and high geophysical response areas potentially linked to subsurface utilities or infrastructure.

There are a considerable number of metallic items in the ground, presumably related to the abandonment of the facility, which make it difficult to determine associations with petroleum, oil, and lube (POL) features as shown in the GIS data. Numerous crossing linear features and the potential for multiple pipes to be contained within the same trench further complicate interpreting the geophysical data.

This page is intentionally left blank.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

This page is intentionally left blank.

GEOPHYSICAL INVESTIGATION REPORT
Buxton Naval Facility FUDS Property
Dare County, North Carolina

Savannah District

1. INTRODUCTION

This report summarizes the observations and findings of geophysical investigation activities conducted by the U.S. Army Corps of Engineers (USACE) for work performed from June 24th to 28th 2024, at the Buxton Naval Facility Formerly Used Defense Sites (FUDS) Property, Dare County, North Carolina. Electromagnetic Induction (EMI) and Magnetic (Mag) geophysical methods were employed over all accessible areas within a 6.3-acre site requested by the US Army Corps of Engineers, Savannah District. This 6.3 acres represents approximately 16% of the overall FUDS property acreage of 39 acres.

2. SCOPE AND OBJECTIVES

The Buxton Naval Facility FUDS property was used by the U.S. Navy as a submarine monitoring station. The Department of Defense (DoD) acquired 49.99 acres of property on 9 February 1956 through a special use permit with the National Park Service (NPS) and subsequently eight additional acres from private parties for the facility. The Buxton Naval Facility continued to operate until closure on 30 June 1982. The U.S. Coast Guard (USCG) subsequently used the property until 2010, at which point it was returned to NPS.

In September of 2023, the beach along a stretch of the FUDS property was closed by the NPS after naturally occurring barrier island erosion uncovered potentially hazardous infrastructure associated with the US Navy and Coast Guard use of the property (Figure 1) and visitors reported a strong smell of petroleum. All contamination has been based on visual identification where excessive erosion continues on the beach, thus exposing sheens on the beach. A comprehensive sampling contract is underway and is expected to be awarded in November 2024.

The US Army Corps of Engineers, Savannah District requested geophysical investigation services with the purpose of detecting and mapping metallic items in the subsurface associated with utilities and infrastructure left in place after the FUDS property was no longer in use by the Navy/Coast Guard. As of the date of this report (September 2024), the beach has been closed for approximately 12 months.

3. PROJECT DESCRIPTION AND BACKGROUND INFORMATION

The Buxton Naval Facility FUDS property is located within the Cape Hatteras National Seashore in Dare County North Carolina. Figure 2 shows the location of the study area. The geophysical survey area was provided to the USACE field team by the USACE Savannah District based on historical information.

Figure 1: Photo taken March 26, 2024, showing exposed former military infrastructure at the Buxton Beach Access.

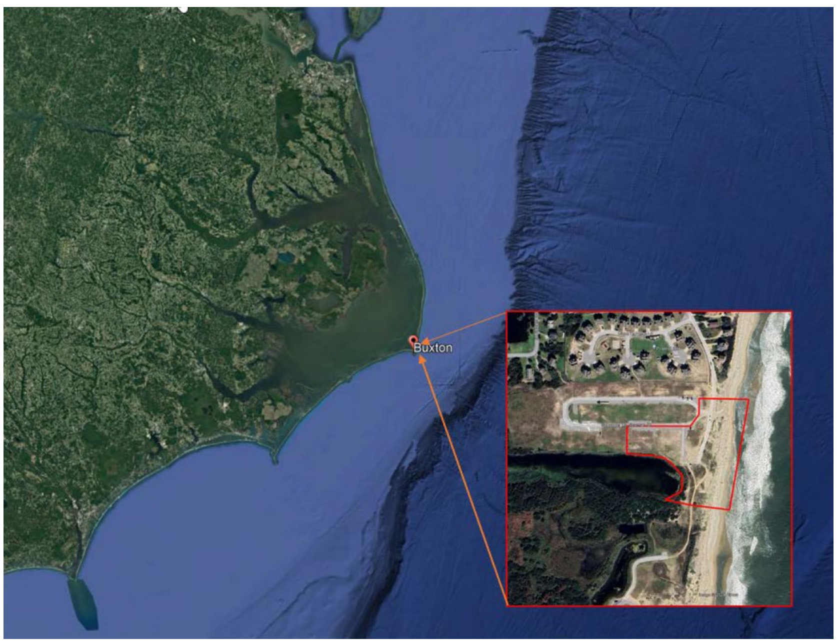


Figure 2: Site Location Map

4. GEOPHYSICAL EQUIPMENT

4.1. ELECTROMAGNETIC INDUCTION (EMI)

Two separate EMI systems were used for this investigation. The beach east of the sand dunes, and the parking lot west of the sand dunes were geophysically mapped using a Geonics EM61-MK2. A Geonics EM31-MK2 was used within the sand dunes. Figures 3 and 4 show the extent of data collection using the EM61-MK2 and EM31-MK2, respectively.

Figure 3: EM61-MK2 Data Collection Extent

Figure 4: EM31-MK2 Data Collection Extent

4.1.1. GEONICS EM61-MK2

The EM61-MK2 is a portable 4-channel time-domain metal detector that can detect both ferrous and non-ferrous metallic objects with good spatial resolution and minimal interference from adjacent metallic features. The response to buried metal is a function of metallic composition and amount present, depth of burial, and orientation of the item. The manufacturers (Geonics) website indicates the EM61-MK2 can typically penetrate to a depth of 2-3 meters depending on the size and characteristics of the target, with larger metallic objects like a 55-gallon drum potentially being detected at depths exceeding 3 meters. The detection depth varies significantly based on the size, shape, and composition of the target object.

The EM61-MK2 used for geophysical mapping of the study area consisted of one 1/2- by 1-meter square coil. The bottom coil contains both an EM source transmitter and receiver loop. The transmitter generates a pulsed primary magnetic field. When the loop current is shut off, the collapsing primary magnetic field causes eddy currents to flow in nearby metallic objects. Since there is no energy to sustain the eddy currents, they decay with time. The decay generates a secondary magnetic field that is detected by the receiver coil.

Secondary current voltages are measured by the receiver coil in millivolts (mV) and recorded by an integrated computer based digital logger. Measurements are taken at varying time intervals after the primary pulse, allowing any secondary currents induced in the ground to dissipate, leaving only a secondary field associated with metal to be measured. The EM61-MK2 used in this survey was configured to record four-time gates of the bottom coil response at 216- microseconds (channel 1), 366- microseconds (channel 2), 660- microseconds (channel 3) and 1266-microseconds (channel 4).

The EM61-MK2 was used in the “wheel” mode with the lower coil approximately 40 centimeters above the ground surface (Figure 5).

Figure 5: Geonics EM61-MK2 Instrument

4.1.2. GEONICS EM31-MK2

The Geonics EM31-MK2 is a portable frequency-domain instrument that maps electrical conductivity variations in the subsurface. It can be used to approximate ground conductivity when it's less than about 1000 mS/m. The EM31-MK2 works by generating electromagnetic (EM) energy with one coil, and then detecting the EM fields created by the transmitter with a second coil.

There are two components of the induced magnetic field measured by the EM31-MK2. The first is the quadrature-phase component which gives the ground conductivity measurement. The second is the inphase component, which is significantly more sensitive to large metallic objects and hence, very useful when looking for buried metal items.

The instrument can be operated in either of two dipole modes – vertical or horizontal. The instrument response, as a function of depth, varies significantly between the two modes. The vertical dipole mode provides twice the effective depth of exploration as the horizontal dipole mode – 6 m and 3 m, respectively.

The EM31-MK2 was used in the vertical dipole mode in a normal operating position with the instrument carried on the hip of the operator (Figure 6).

Figure 6: Geonics EM31-MK2 Instrument

4.2. MAGNETICS (MAG)

A Geometrics G-858 magnetometer was used to map the sand dunes and beach as shown in Figure 7.

Magnetometry measures perturbations in the ambient magnetic field caused by contrasts in magnetic susceptibility – the ability of a substance to take on an induced magnetism caused by its immersion in the Earth's magnetic field. The magnetic susceptibility of an item is directly proportional to its iron content; thus, the G-858 magnetometer is only sensitive to ferrous metals. The G-858 was used in the gradiometer configuration with two sensors in a vertical mode (Figure 8).

Figure 7: G-858 Data Collection Extent

Figure 8: Geometrics G-858 Magnetometer

5. GEOSPATIAL POSITIONING

5.1. Trimble R8 Real-Time Kinematic Global Positioning System

Horizontal control was provided with a Trimble R8 Real-Time Kinematic (RTK) Global Positioning System (GPS). The base station was initially set up on the CAHA 13 benchmark established by the North Carolina Geodetic Survey, and two temporary control points (TP-1 and TP-2) were set using a 10-inch nail set flush into the ground just outside the western perimeter of the geophysical survey site. The base station was subsequently set up over TP-1 and a backsight was performed using CAHA 13 to ensure accuracy of the temporary points were within 10 cm. This check yielded a result of 1.2 centimeters (cm). The Trimble R8 Rover was mounted on a tripod directly over the EM61-MK2 coils, and on a backpack situated on the operator’s shoulders for the EM31 and magnetometer. The rover was interfaced with a data logger to record positional data coincident with instrument readings.

Correction data was transmitted from the R8 base to the R8 rover using an external HPB-450 radio modem. Positioning data acquired by RTK DGPS are provided as NAD83 (2011) UTM Zone 18N with units of meters.

GPS backchecks were conducted in the morning and end of day. The GPS rover was mounted on a 2-meter survey stick and bipod. The team recorded the measured location of survey point TP-2. The surveyed point was measured against the known point’s coordinates in the GPS data logger COGO menu using the Compute Distance feature. All positional error checks were under 3 cm.

6. DATA ACQUISITION

The three geophysical sensors used on this project are sensitive to external noise from varying sources, to include live electrical utilities and metal structures such as fencing, signs, monitoring wells, etc. Effort was taken during the acquisition to acquire the data in a way that would limit the effect of external noise on the data. There are metal/wooden fences located along the eastern edge of the dunes, overhead electrical lines, radio antennas and associated cables, a site trailer, picnic tables, and porta potties. Based on adherence to the digital quality control procedures outlined in the Geophysical Work Plan as well as the individual instrument manuals, QC test results, and general data inspection, the overall quality of the data is good and provides sufficient detail to meet the objectives of this geophysical investigation.

6.1. ELECTROMAGNETIC INDUCTION (EM61-MK2)

EM61-MK2 data was acquired by a single operator along a series of parallel lines spaced approximately 3.25 feet apart (1 coil spacing). Geophysical sensor readings were recorded at a rate of 10 samples per second, and RTK GPS readings were recorded at 1 sample per second. Both geophysical sensor and GPS data were recorded using a Juniper Allegro data logger. Survey lanes on the western side of the sand dunes were marked with pin flags either inserted into the ground or laid flat on pavement surfaces. Survey lanes on the beach and sand dunes were marked using the wheel marks made by the EM61-MK2.

Digital geophysical quality control procedures were followed during data acquisition as outlined in the Geophysical Work Plan. The procedures included allowing the equipment a proper warm-up period of a minimum 15-minutes, as well as completing static, spike, and cable shake tests to ensure the equipment functioned properly.

After data acquisition was completed for the day, data was transferred to a PC for processing and quality control checks.

Figure 9 shows the location of the data acquisition lines for the EM61-MK2.

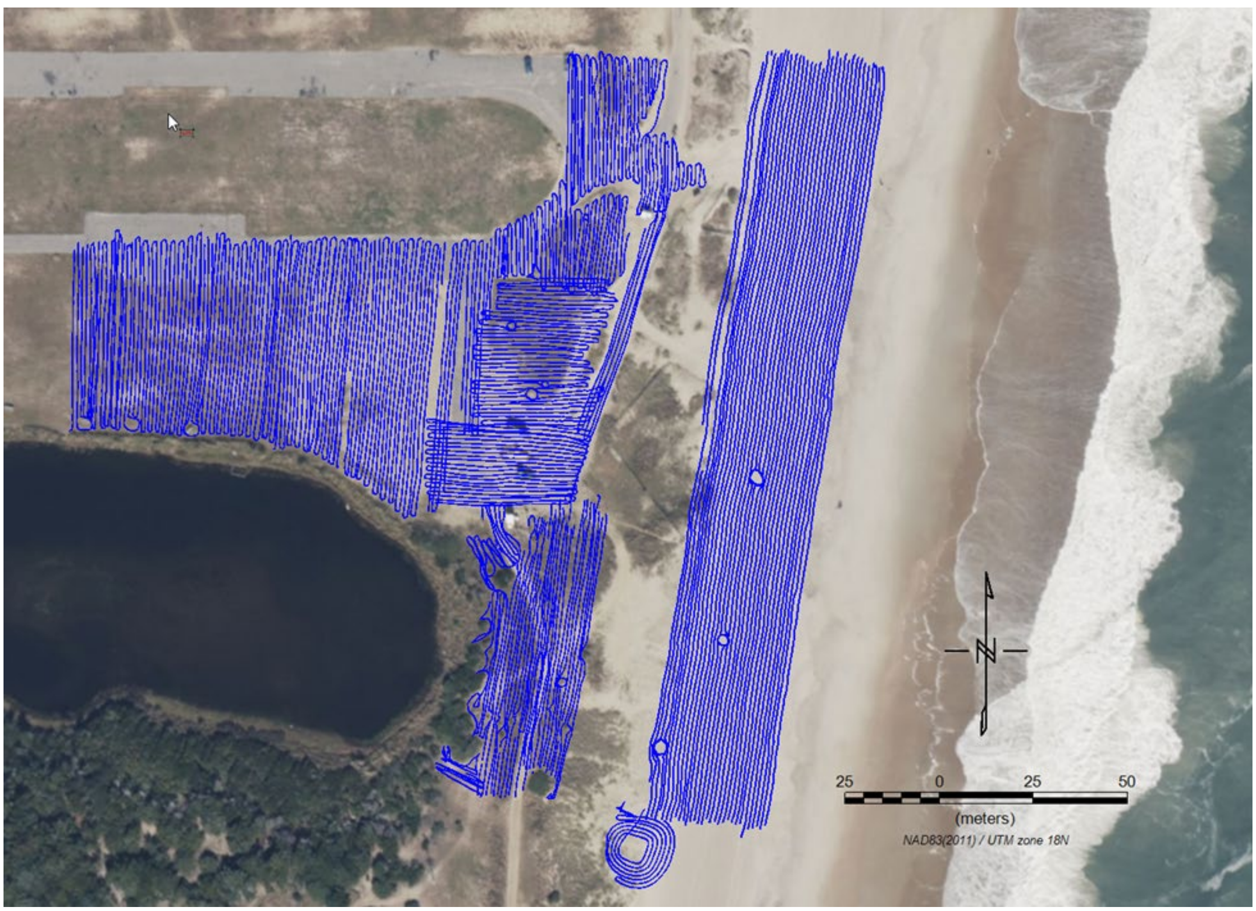


Figure 9: EM61-MK2 Data Acquisition Lines

6.2. ELECTROMAGNETIC INDUCTION (EM31-MK2)

EM31-MK2 data was acquired along parallel lines roughly spaced between 5 to 10 feet apart depending on obstructions as the boom length made navigation more difficult where above ground metal features were present. As with the EM61-MK2, geophysical sensor readings were recorded at a rate of 10 samples per second, and RTK GPS readings were recorded at 1 sample per second. Both geophysical sensor and GPS data were recorded using a Juniper Allegro data logger.

Equipment functional checks were performed every time the instrument was turned on in accordance with the instrument operating manual.

After data acquisition was completed for the day, data was transferred to a PC for processing.

Figure 10 shows the location of the data acquisition lines for the EM31.

Figure 10: EM31-MK2 Data Acquisition Lines

6.3. MAGNETICS

Data acquisition of the sand dunes and beach was also accomplished with the G-858 magnetometer using much of the same the same techniques as the EMI data collection, with parallel lines spaced between 5 to 10 feet apart. A Simple Survey Mode of operation was selected, with geophysical sensor readings recorded at a rate of 10 samples per second, and RTK GPS readings were recorded at 1 sample per second. Both geophysical sensor and GPS data were recorded using the G-858 console. Survey lanes on the beach followed the wheel marks made during the previous EM61-MK2 survey, while lane spacing was visually approximated within the sand dunes given difficulties with topography and obstructions.

Typical digital geophysical quality control procedures were followed during data acquisition based on the Geometrics Operating Manual and USACE Engineering Manual EM-200-1-15. The procedures included allowing the equipment a proper warm-up period of a minimum 15-minutes, as well as completing static, spike, and cable shake tests to ensure the equipment functioned properly.

After data acquisition was completed for the day, data was transferred to a PC for processing and quality control checks.

Figure 11 shows the location of the data acquisition lines for the G-858.

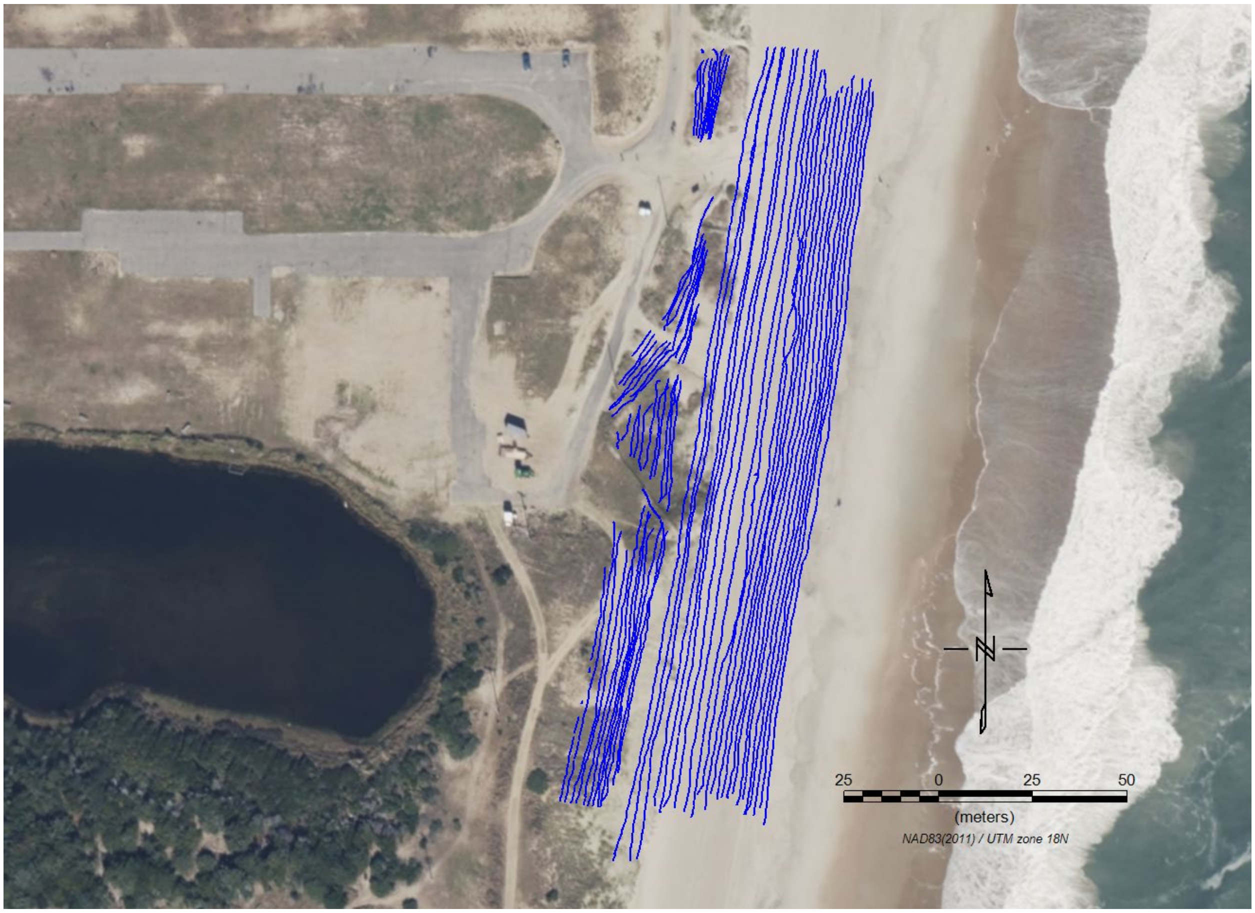


Figure 11: G-858 Data Acquisition Lines

7. DATA PROCESSING, VISUALIZATION, AND INTERPRETATION

Different geophysical methods require separate pre-processing tools as outlined below. Once pre-processing was completed, the data was imported into Seequent's Oasis montaj program for further processing, visualization, and interpretation.

The following programs were used to transfer raw data from the data loggers to a computer: Geonics DAT61MK2 for EM61 data, Geonics DAT31 for EM31 data, and Magmap for G-858 data.

After transfer, data was converted to ASCII format, followed by integration of the sensor and GPS data, and exporting to a .xyz file format. At this point, the integrated data/positioning .xyz files were then imported into Oasis Montaj.
Within the Oasis Montaj environment, the unified xyz file facilitated the creation of a gdb database file. Distinct databases were constructed for each day of collection and assigned the UTM zone 18N Coordinate System, NAD83 (2011), meters.

7.1. ELECTROMAGNETIC INDUCTION PROCESSING (EM61-MK2)

The imported data in Geosoft underwent latency and drift corrections. A latency correction of 0.35 seconds was uniformly applied across all datasets. Drift correction was conducted on individual datasets collected each day using a median filtering routine. A specific background area was identified for each dataset and the Subwindow Statistics QC QA Tool was used to evaluate the leveling routine. Raw channels 1 through 3 were individually leveled by varying the percentages of lowest and highest values to ignore. Leveling was considered complete once the Subwindow Statistics Tool returned a mean value of the respective raw data channel as close to zero as possible. A rolling window width of 101 seconds was used over the entire leveling process.

Leveled data from channels 1 thru 3 were summed and gridded using a minimum curvature routine with a grid cell size set to 0.25 meters, blanking distance set to 1.3 meters, a starting coarse grid of 4, starting search radius of 16 cells, tension set to 0.5, while all other parameters remained at default settings.

Visual representation of the gridded images was enhanced using a linear transform distribution color scale, with set minimum and maximum values of -100 mV and 200 mV respectively. These gridded images were then synthesized into a comprehensive master map, incorporating an aerial overview of the entire site.

7.2. ELECTROMAGNETIC INDUCTION PROCESSING (EM31-MK2)

The EM31 data collection time was approximately 50 minutes, and pre- and post-data collection readings at the calibration site showed no major drift; therefore, no drift corrections were applied to the EM31 data. In addition, no latency corrections were applied as there are no discernable chevron patterns in the gridded data to indicate a latency issue.

Both the quadrature and in-phase components were gridded using a using a minimum curvature routine with a grid cell size set to 1 meter, blanking distance set to 3 meters, a starting coarse grid of 16, starting search radius of 8 cells, tension set at 0.5, while all other parameters remained at default settings.

Visual representation of the gridded images was enhanced using a linear transform distribution color scale, with set minimum and maximum values of 0 and 30 millisiemens per meter (mS/m) for quadrature data, and -2 to 5 parts per thousand (ppt) for the inphase data.

7.3. MAGNETICS PROCESSING (G-858)

After transferring the field team's raw data files to a processing computer, the data processor used Magmap2000 software to position the sensor data and export to ASCII format files. These data files were imported into Geosoft's Oasis Montaj processing environment and were projected to the project coordinate system (UTM zone 18N, NAD83 (2011), meters). Once in Geosoft, corrections for positional offset of the GPS antenna from the Mag sensors and a latency correction were applied to each dataset. Data were processed for each sensor as well as the gradient response. The Analytic signal of the gradient response was calculated using the standard Oasis Montaj functions.

Data from the top sensor, bottom sensor, gradient and analytic signal were assessed, however, the analytic signal provided the best resolution on this site. Data were gridded using a using a minimum curvature routine with a grid cell size set to 0.15-meter and blanking distance set to 1.45 meters.

Visual representation of the gridded images was enhanced using a linear transform distribution color scale, with set minimum and maximum values of -200 and 800 nano Tesla per meter (nT/m).

8. RESULTS

The first step in data interpretation was to combine gridded data from the three geophysical sensors onto a single map to identify and trace linear features. Figure 12 portrays the EM61-MK2 EMI and G-858 Magnetic data along with the outline of the geophysical survey area. The EM31-MK2 data was not portrayed on Figure 12 as it is co-located with a portion of the G-858 data. This was followed by identification of areas of elevated geophysical response exhibiting multiple peaks in which linear features are not easily discerned. To assist with interpretations of the geophysical data, GIS features including the locations of former building/structure foundations and underground/above ground storage tanks were plotted on top of the geophysical data (Figure 13).

The approximate locations of former building/structure foundations are shown in gray with a transparency set such that the underlaying geophysical data is visible, underground/above ground storage tanks are shown in dark green, three large circular potable water tanks are shown in black, and the oil change ramp in yellow.

Because of the possibility of multiple utilities being co-located in a single trench, and the resolution capabilities of the geophysical sensors used on his project, anomaly size (width or area) alone could not be used as a criterion for making decisions regarding a potential association with former POL sites/tanks, or to recommend follow-on environmental investigations.

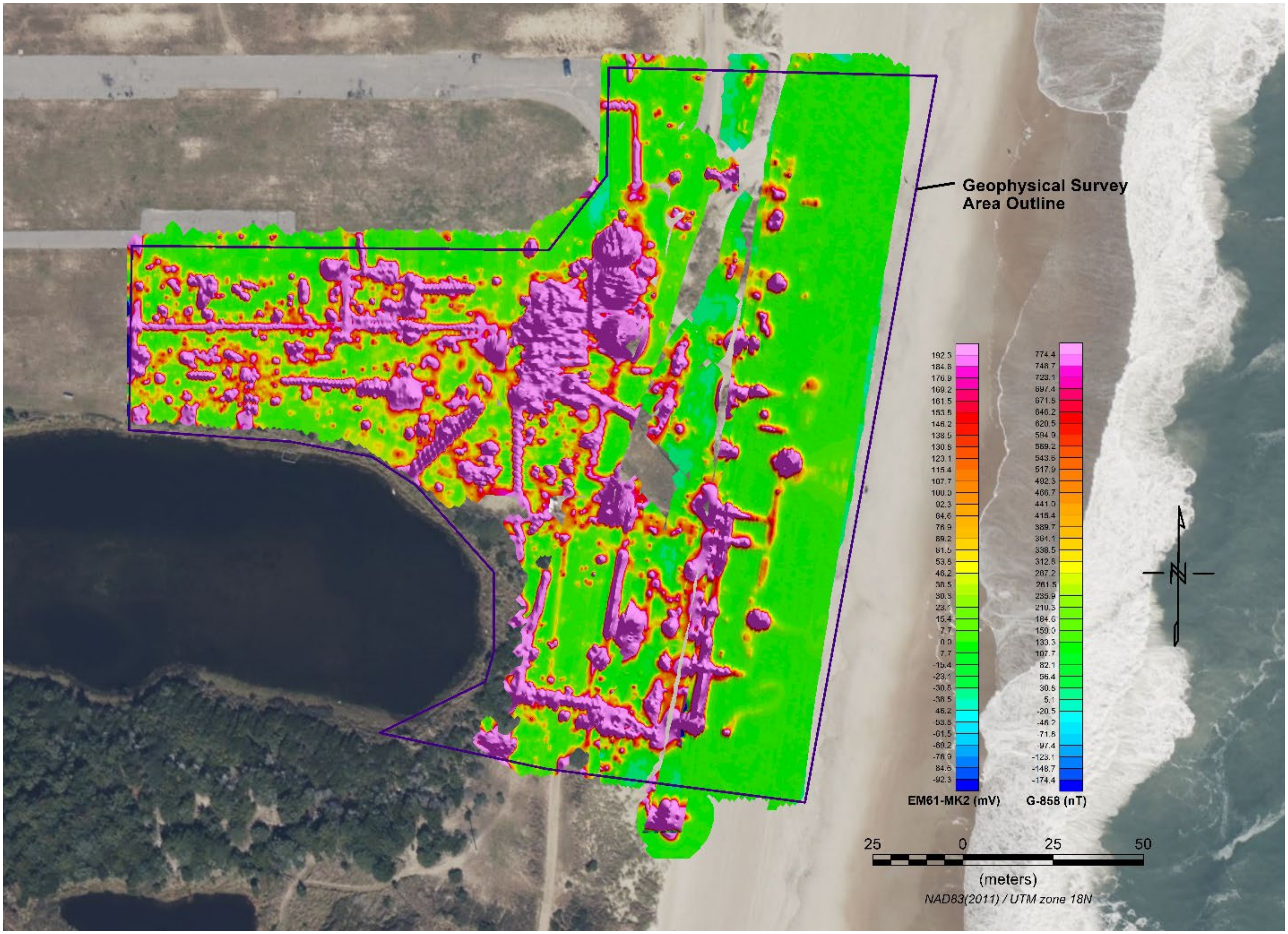


Figure 12: Composite Geophysical Map of EM61-MK2 and G-858 Data

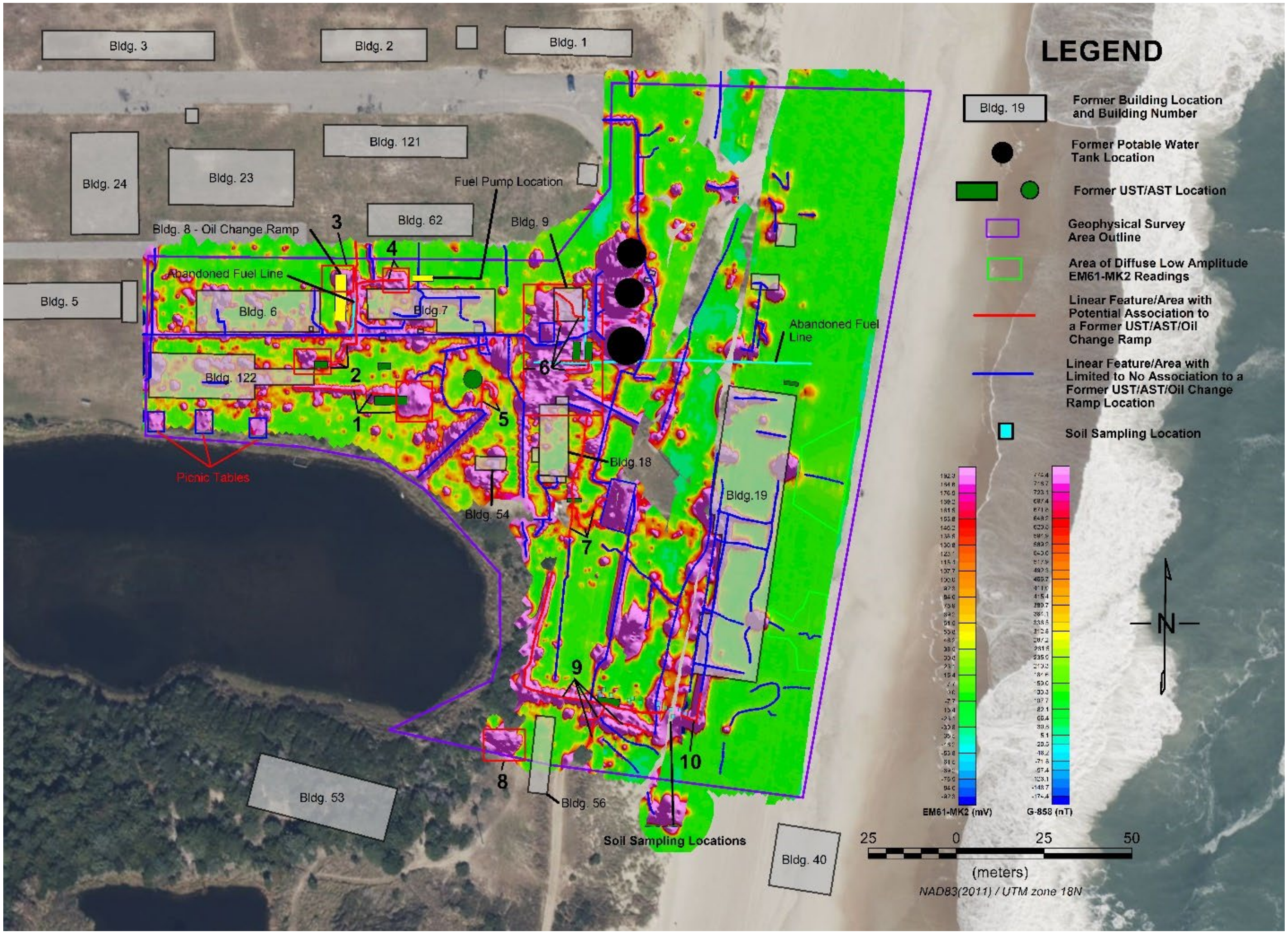


Figure 13: GIS Features Overlain on the Geophysical Data

Geophysical anomalies were interpreted to have a potential association with a known UST/AST or the Oil Change Ramp if the anomaly either terminated at the documented GIS location or passed within 1 m such that the mapped geophysical response and the GIS location overlapped to some extent. Linear features and areas of multi-peaked elevated amplitude that met this criterion are color-coded red. All other geophysical anomalies considered to have little to no association with the former underground/above ground storage tanks/oil change ramp are colored blue. A description of selected geophysical anomalies of concern are described below. Figure 14 shows a composite of all the interpreted geophysical anomalies overlain with the former building footprints (gray infill boxes), the former oil change ramp (yellow infill box), and former ASTs and USTs (green infill outlines). Figures 15 thru 17 portray the data interpretations at a smaller scale for better definition.

Geophysical feature 1 consists of an area surrounding multiple peaks in the EM61-MK2 data immediately adjacent to a former AST location (Figure 15). In addition, geophysical feature 1 also includes two linear anomalies trending east-west from the former AST location. There is a third linear anomaly with an identical signature located within the footprint of the former public works garage; however, the discontinuous nature of these 3 linear anomalies makes it difficult to assume all 3 are related.

Geophysical feature 2 also consists of an area of multiple peaks in the EM61-MK2 data immediately adjacent to a former AST location as well as linear anomalies which emanate from the former AST and trend northwards past the location of the former oil change ramp location (Figure 15). The GIS database supplied by Savannah District contains a feature class labeled "AbandonedFuelLines" which shows an abandoned pipeline trending north-south and just east of the oil change ramp (Figure 15). It is believed this GIS feature class is related to a pipeline removal effort conducted in March 2000.

Geophysical feature 3 consists of a single large amplitude anomaly which underlays the current parking lot asphalt (Figure 15). The aerial extent of this geophysical anomaly mimics that of a manhole cover found elsewhere on the site and is likely a similar feature.

Geophysical feature 4 consists of an area surrounding multiple peaks in the EM61-MK2 data immediately adjacent to the former public works shop location and an east-west trending linear anomaly which trends towards the former oil change ramp (Figure 15).

Geophysical feature 5 consists of two somewhat linear anomalies which emanate from the location of a former AST (Figure 15).

Geophysical feature 6 is a very large area measuring approximately 35 meters length by 18 meters wide consisting of numerous elevated geophysical anomalies located between the former public works shop and the former potable water tank locations. Within this area were two former ASTs, a former building, and a concrete pad which is visible on the ground surface. There are two linear geophysical anomalies immediately adjacent to the former AST, and two linear geophysical anomalies underneath the former building

(Figures 15 and 16). The GIS feature class "AbandonedFuelLines" related to a pipeline removal effort conducted in March 2000 shows a north-south trending abandoned pipeline immediately east of the former Building 9, as well as a much longer east-west trending abandoned pipeline immediately south of the two AST locations mentioned above (Figures 15 and 16).

Geophysical feature 7 consists of three linear geophysical anomalies located radially around a former AST and east-southeast of the former wood shop (Figure 17).

Geophysical feature 8 is located at the southwest edge of the study area and consists of multiple peaks in the EM61-MK2 data immediately west of the former warehouse. The full extent of the geophysical anomaly may not be accurate as portrayed in Figure 17 since data collection ended at this location after the limits of the study area were reached, and due to obstructions caused by large bushes.

Geophysical feature 9 consists of four linear geophysical anomalies all centered around a former UST and west of the location on the beach where a small diameter pipe (approximately 1.5-inch diameter) was recently removed (Figure 17). The GIS database supplied by Savannah District contains a feature class labeled "BuxtonPipeRemovalMay2024" which shows the locations of soil samples taken after removal of a small diameter iron pipe south-southwest of the former Building 19 location. The pipe was removed prior to this geophysical survey.

Geophysical feature 10 is a linear geophysical feature located east of geophysical feature 9 and in the location of the same small diameter iron pipe recently removed prior to this geophysical survey (Figure 17).

There are two areas on the eastern side of the beach/study area where low amplitude scattered readings in the EM61-MK2 data were noted in Figure 17 by the lime green polygons. These readings are believed to be associated with cables anchored to two concrete structures recently exposed after storms in 2023.

Determining the presence or absence of USTs from the EM61 data is difficult at best. The response to buried metal is a function of metallic composition and amount present, depth of burial, and orientation of the item. Consideration was given to trying to categorize non-linear responses as UST/non-UST based on response amplitude as well as the size/shape of the area above background; however, these interpretations would be non-unique. Based on the GIS data, only fuel oil tanks were buried underground, and ranged in size primarily from 250 gallons (27 documented) to 1,000 gallons (1 documented). A search of standard UST sizes and volumes across North America returned dimensions of 3 feet by 5 feet for a UST with a capacity of 300 gallons, and 4 feet by 11 feet with a capacity of 1,000 gallons. USTs containing hazardous materials can be single to triple-wall steel, which can affect the dimensions, thus these sizes are only approximate.

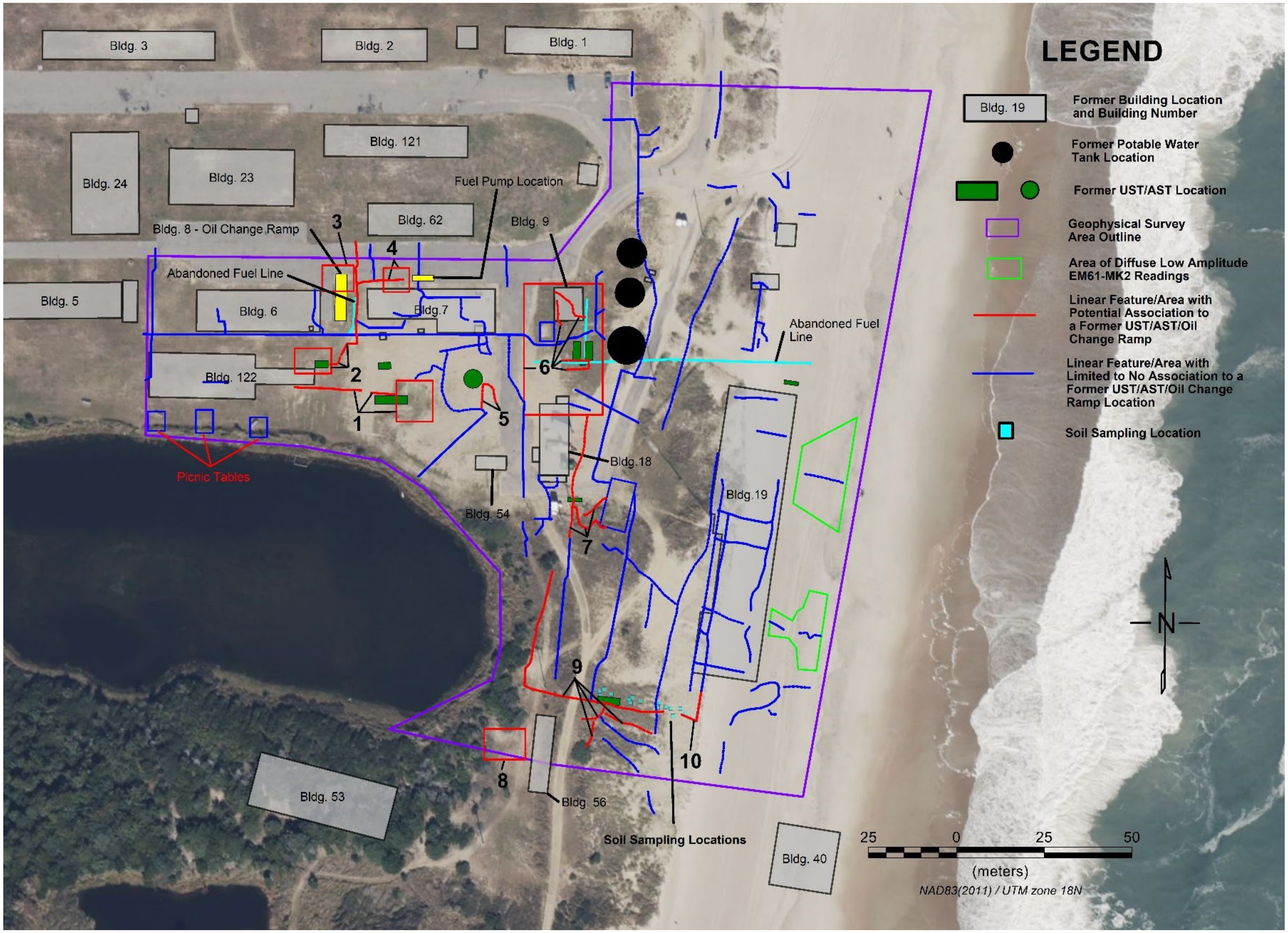


Figure 14: Composite Interpretations from Geophysical Data

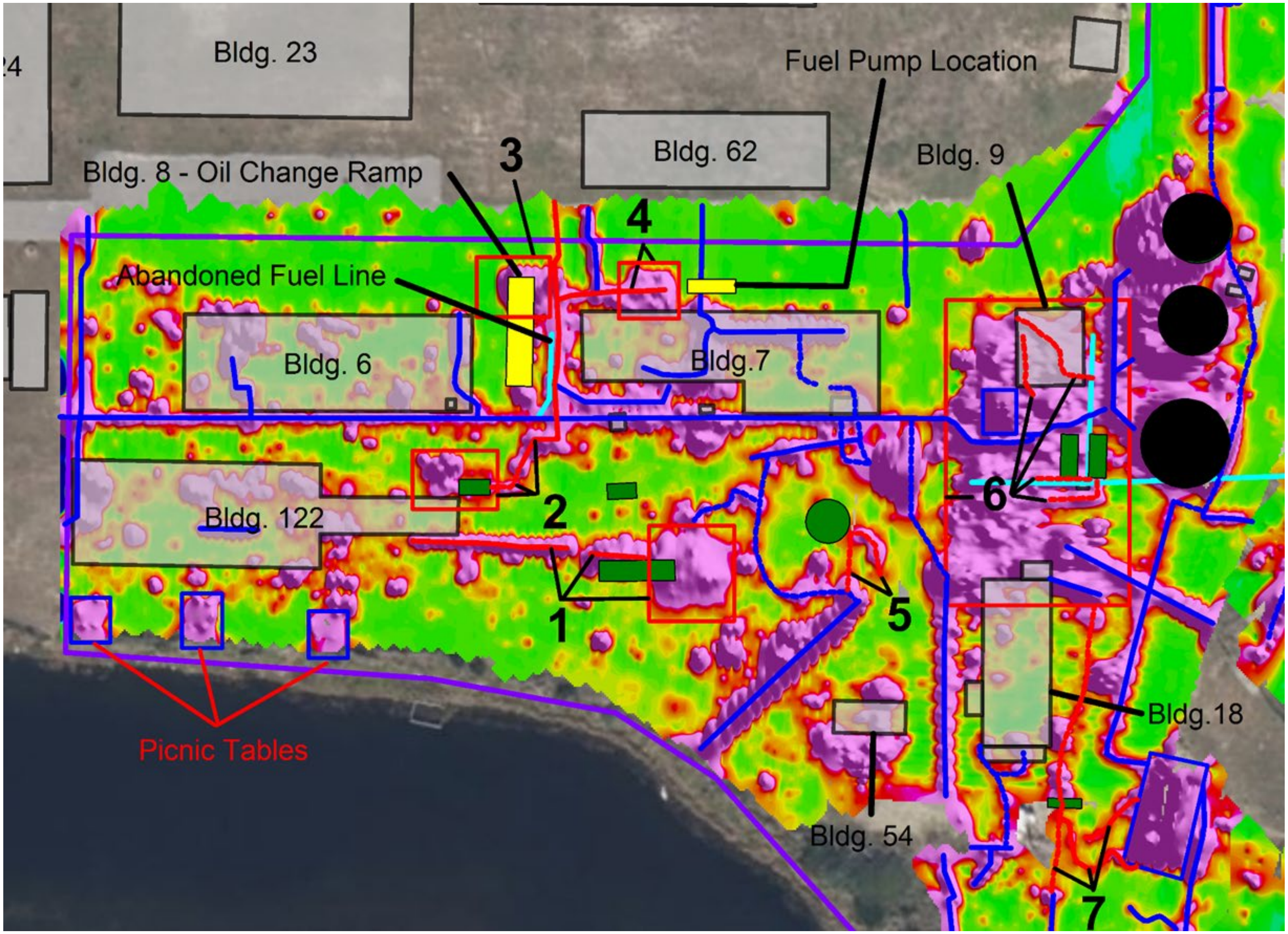


Figure 15: Close-up of Geophysical Interpretations – Panel 1 (Not to Scale, North Up)

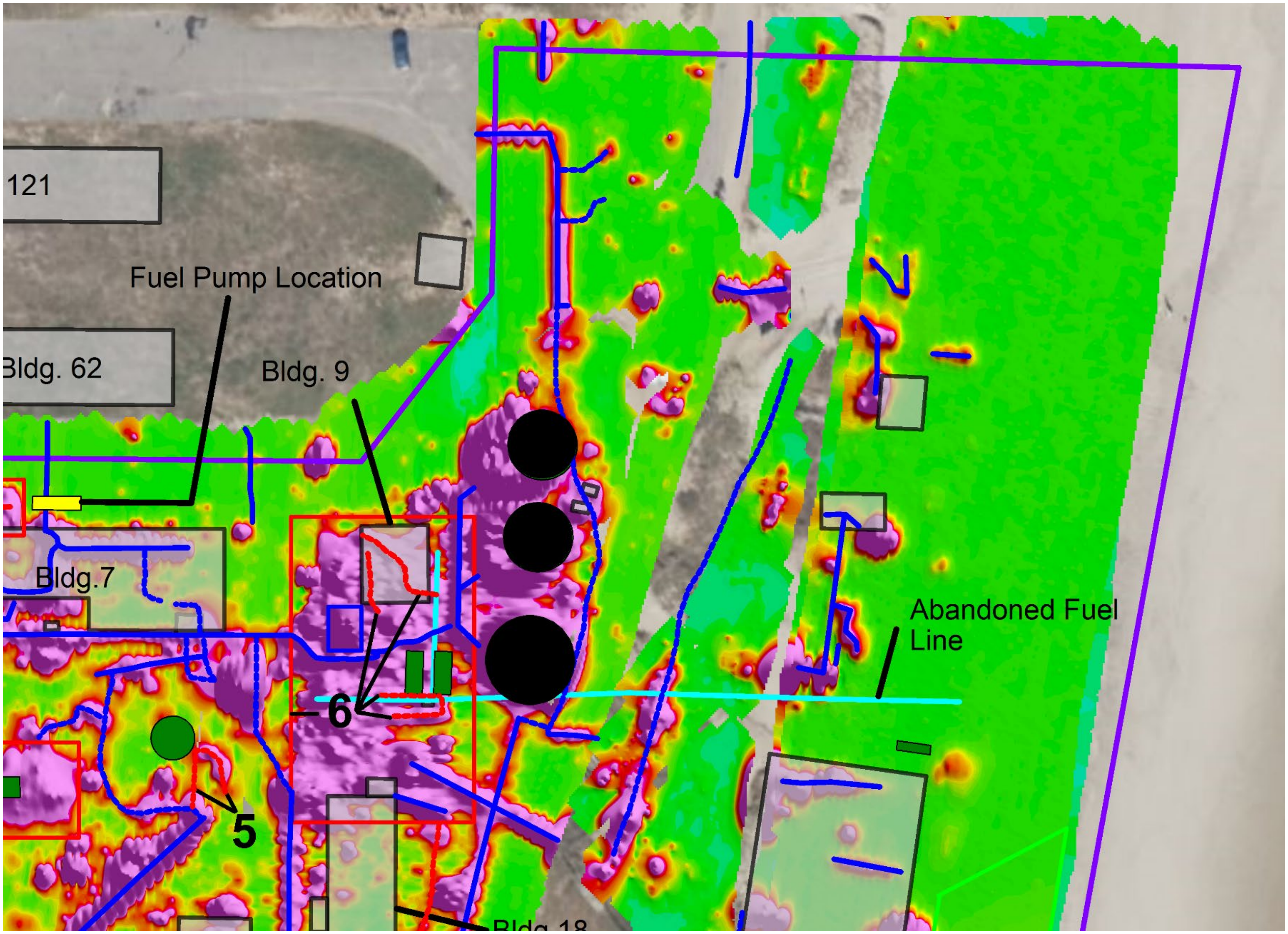


Figure 16: Close-up of Geophysical Interpretations – Panel 2 (Not to Scale, North Up)

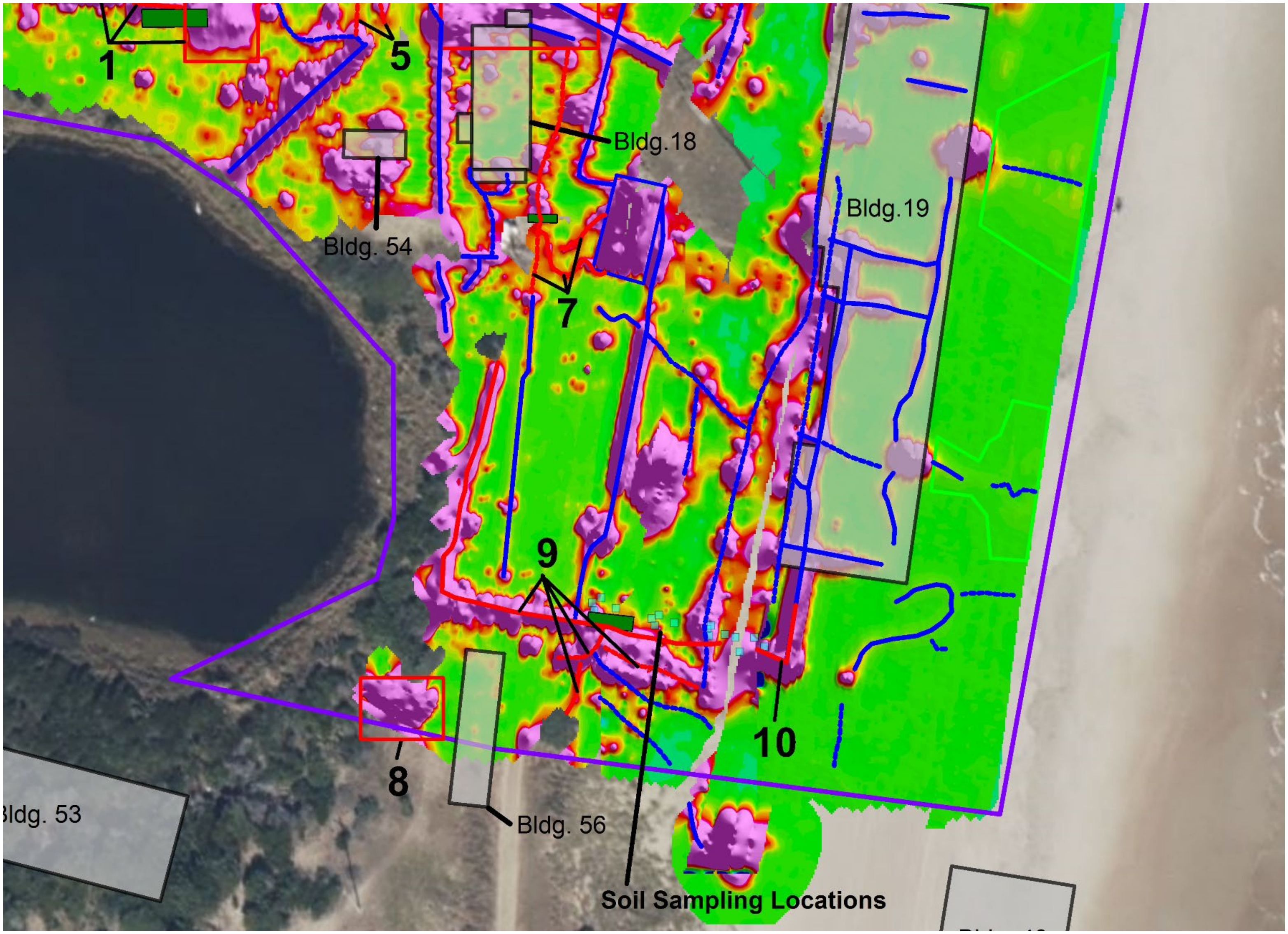


Figure 17: Close-up of Geophysical Interpretations – Panel 3 (Not to Scale, North Up)

9. CONCLUSIONS

The primary objective of this investigation was to detect, and map former underground features to include utilities, potential underground storage tanks, concrete pads, and other metallic features associated with the Buxton Naval Facility FUDS Property, and to determine whether specific features may be related to POL contamination at the site.

The project involved comprehensive geophysical mapping using two types of EMI sensors and a magnetometer. Digital maps revealed linear features indicating underground utilities and areas of elevated geophysical response. These features were compared with GIS data on storage tanks, the oil change ramp, and field observations.

10. LIMITATIONS

It is important to note that while the geophysical surveys can provide valuable information about the subsurface, it is limited by the depth and resolution of the measurements and the assumptions made about the subsurface materials. It is important to acknowledge that, like any geophysical testing method, the effectiveness of these processes relies on the detection of instrument signals that reflect the physical conditions in the field. The interpretation of these signals is a combination of the expertise not only of the geophysicist, but the entire project delivery team.

11. DELIVERABLES

The following products will be provided as deliverables to complete the work described in this report.

- Geophysical Investigation Report (electronic version of this report).
- Raw Geophysical field data and associated positioning information (electronic files)

.

APPENDICES

This page is intentionally left blank

.

APPENDIX A: GEOPHYSICAL INVESTIGATION METHODS

A.1 TIME DOMAIN ELECTROMAGNETIC INDUCTION (TDEM)

The specific EMI method used in this investigation is Time Domain Electromagnetics (TDEM). The equipment is often referred to as a metal detector because TDEM instruments determine measure the decay of eddy currents induced in metal.

1) Electromagnetic techniques can be broadly divided into two groups. In frequency-domain instrumentation (FDEM), the transmitter current varies sinusoidaly with time at a fixed frequency which is selected based on the desired depth of exploration of the measurement (high frequencies result in shallower depths). FDEM instrumentation is described in Appendix A.2 of this document. In most time-domain (TDEM) instrumentation, on the other hand, the transmitter current, while still periodic, is a modified symmetrical square wave, as shown in Figure 4-25. It is seen that after every second quarter-period the transmitter current is abruptly reduced to zero for one quarter period, whereupon it flows in the opposite direction.

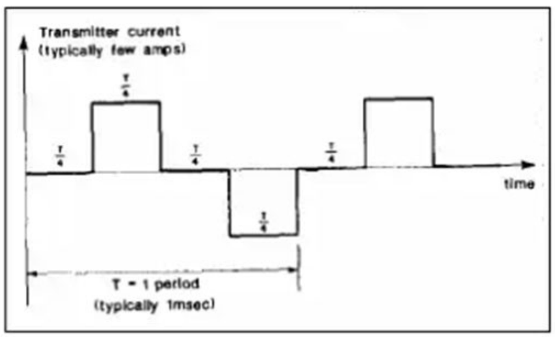


Figure 4-25. Transmitter current wave form

2) A typical TDEM resistivity sounding survey configuration is shown in Figure 4-26, where it is seen that the transmitter is connected to a square (usually single turn) loop of wire laid on the ground. The side length of the loop is approximately equal to the desired depth of exploration except that, for shallow depths (less than40 m) the length can be as small as 5 to 10 m in relatively resistive ground. A multi-turn receiver coil, located at the center of the transmitter loop, is connected to the receiver through a short length of cable.

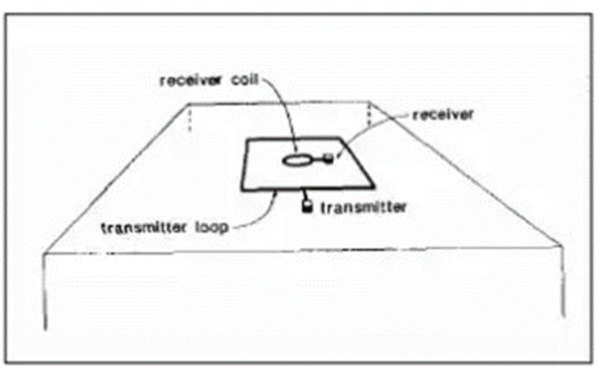


Figure 4-26. Central loop sounding configuration

(3) The principles of TDEM resistivity sounding are relatively easily understood. The process of abruptly reducing the transmitter current to zero induces, in accord with Faraday's law, a short-duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire, as shown in Figure 4-27. In fact, immediately after transmitter current is turned off, the current loop can be thought of as an image in the ground of the transmitter loop. However, because of finite ground resistivity, the amplitude of the current starts to decay immediately. This decaying current similarly induces a voltage pulse which causes more current to flow, but now at a larger distance from the transmitter loop, and at greater depth, as shown in Figure 4-27.

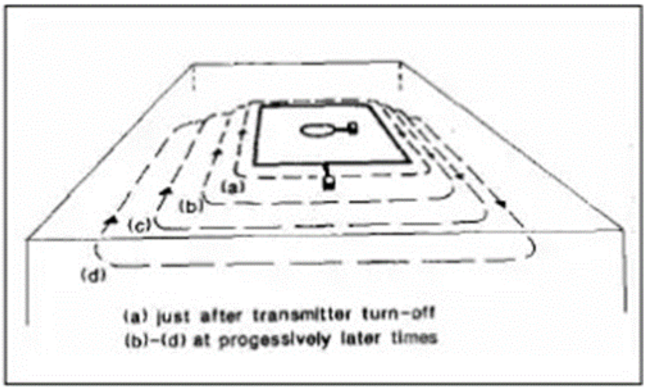


Figure 4-27. Transient current flow in the ground

This deeper current flow also decays due to finite resistivity of the ground, inducing even deeper current flow and so on. The amplitude of the current flow as a function of time is measured by measuring its decaying magnetic field using a small multi- turn receiver coil usually located at the center of the transmitter loop. From the above it is evident that, by making measurement of the voltage out of the receiver coil at successively later times, measurement is made of the current flow and thus also of the electrical resistivity of the earth at successively greater depths. This process forms the basis of central loop resistivity sounding in the time domain. (4) The output voltage of the receiver coil is shown schematically (along with the transmitter current) in Figure 4-28.

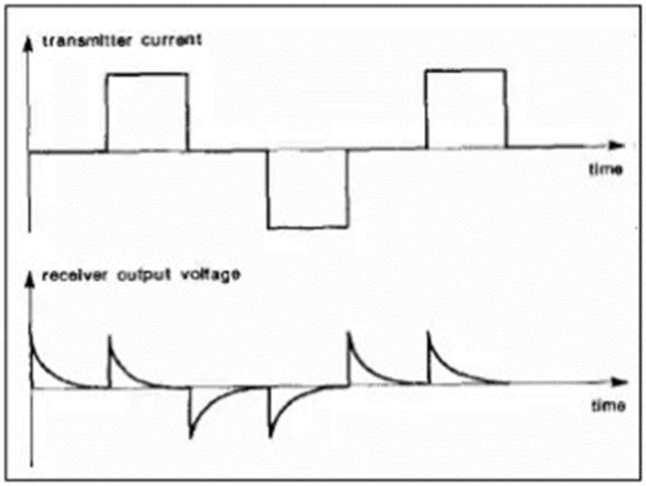


Figure 4-28. Receiver output wave form

To accurately measure the decay characteristics of this voltage the receiver contains 20 narrow time gates (indicated in Figure 4-29), each opening sequentially to measure (and record) the amplitude of the decaying voltage at 20 successive times. Note that, to minimize distortion in measurement of the transient voltage, the early time gates, which are located where the transient voltage is changing rapidly with time, are very narrow, whereas the later gates, situated where the transient is varying more slowly, are much broader. This technique is desirable since wider gates enhance the signal-to-noise ratio, which becomes smaller as the amplitude of the transient decays at later times. It will be noted from Figure 4-28 that there are four receiver voltage transients generated during each complete period (one positive pulse plus one negative pulse) of transmitter current flow. However, measurement is made only of those two transients that occur when the transmitter current has just been shut off, since in this case accuracy of the measurement is not affected by small errors in location of the receiver coil. This feature offers a very significant advantage over FDEM measurements, which are generally very sensitive to variations in the transmitter coil/receiver coil spacing since the FDEM receiver measures while the transmitter current is flowing. Finally, particularly for shallower sounding, where it is not necessary to measure the transient characteristics out to very late times, the period is typically of the order of 1 msec or less, which means that in a total measurement time of a few seconds, measurement can be made and stacked on several thousand transient responses. This is important since the transient response from one pulse is exceedingly small, and it is necessary to improve the signal-to-noise ratio by adding the responses from a large number of pulses."

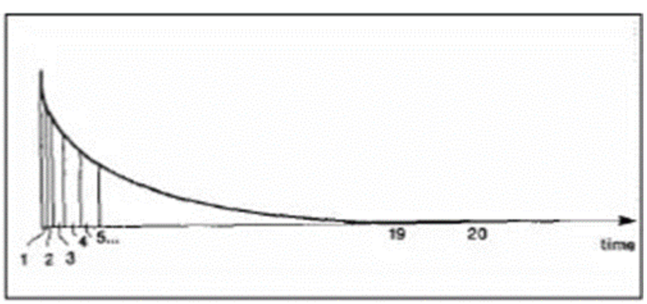


Figure 4-29. Receiver gate locations

Excerpt from: US Army Corps of Engineers, EM 1110-1-1802: Geophysical exploration for engineering and environmental investigations (1995). Washington, D.C.

A.2 FREQUENCY DOMAIN ELECTROMAGNETIC INDUCTION (FDEM)

The electromagnetic induction process is conceptually summarized in Figure 4-39 from Klein and Lajoie (1980). An EM transmitter outputs a time-varying electric current into a transmitter coil. The current in the transmitter coil generates a magnetic field of the same frequency and phase. Lines of force of this magnetic field penetrate the earth and may penetrate a conductive body. When this occurs, an electromotive force or voltage is set up within the conductor, according to Faraday's Law:

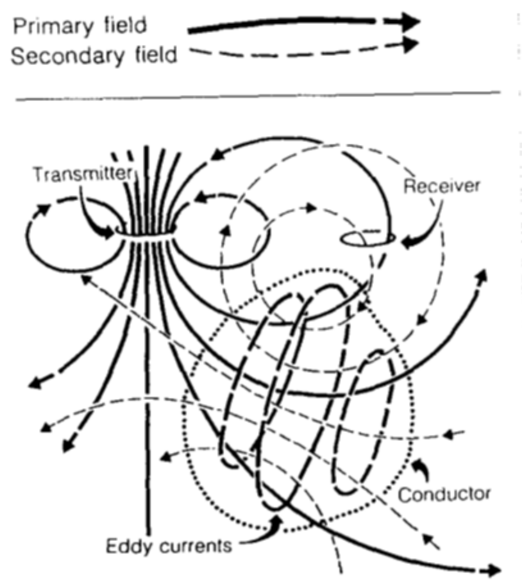


Figure 4-39. Generalized picture of electromagnetic induction prospecting (Klein and Lajoie 1980; copyright permission granted by Northwest Mining Association and Klein)

Current will flow in the conductor in response to the induced electromotive force. These currents will usually flow through the conductor in planes perpendicular to lines of magnetic field of force from the transmitter, unless restricted by the conductor's geometry. Current flow within the conductor generates a secondary magnetic field whose lines of force, at the conductor, are such that they oppose those of the primary magnetic field. The receiver coil, at some distance from the transmitter coil, is therefore energized by two fields: from the transmitter and from the induced currents in the ground.

Note that the induced currents occur throughout the subsurface, and that the magnitude and distribution are functions of the transmitter frequency, power, and geometry and the distribution of all 'electrical properties' in the subsurface, i.e., everything (not just an isolated 'conductor'). The above discussion simplifies the problem by assuming the presence of only one conductor embedded in a much less conducting medium.

In the frequency domain method, the transmitter emits a sinusoidally varying current at a specific frequency. For example, at a frequency of 100 Hz the magnetic field amplitude at the receiver will be that shown in the top part of Figure 4-40. Because the mutual inductance between the transmitter and conductor is a complex quantity, the electromagnetic force induced in the conductor will be shifted in phase with respect to the primary field, similar to the illustration in the lower part of Figure 4-40. At the receiver, the secondary field generated by the currents in the conductor will also be shifted in phase by the same amount.

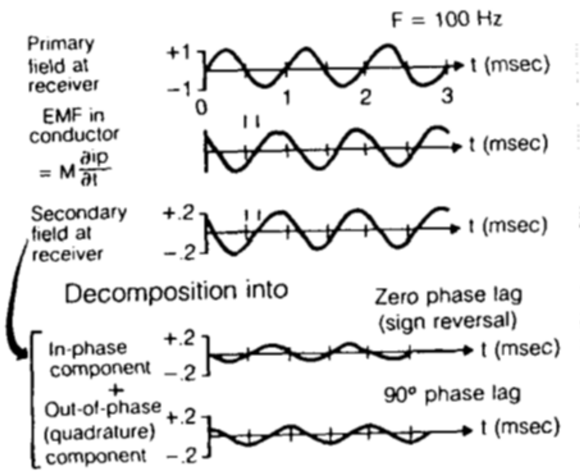


Figure 4-40. Generalized picture of the frequency domain EM method (Klein and Lajoie 1980; copyright permission granted by Northwest Mining Association and Klein)

There are three methods of measuring and describing the secondary field.

(1) Amplitude and phase. The amplitude of the secondary field can be measured and is usually expressed as a percentage of the theoretical primary field at the receiver. Phase shift, the time delay in the received field by a fraction of the period, can also be measured and displayed.

(2) In phase and out-of-phase components. The second method of presentation is to electronically separate the received field into two components, as shown in the lower part of Figure 4-40.

(a) The first component is in phase with the transmitted field while the second component is exactly 90 deg out-of-phase with the transmitted field. The in-phase component is sometimes called the real component, and the out-of-phase component is sometimes called the “quadrature” or “imaginary” component.

(b) Both of the above measurements require some kind of phase link between transmitter and receiver to establish a time or phase reference. This is commonly done with a direct wire link, sometimes with a radio link, or through the use of highly accurate, synchronized crystal clocks in both transmitter and receiver.

(3) Tilt angle systems. The simpler frequency domain EM systems are tilt angle systems which have no reference link between the transmitter and receiver coils. The receiver simply measures the total field irrespective of phase, and the receiver coil is tilted to find the direction of maximum or minimum magnetic field strength. As shown conceptually in Figure 4-39, at any point the secondary magnetic field may be in a direction different from

the primary field. With tilt angle systems, therefore, the objective is to measure deviations from the normal infield direction and to interpret these in terms of geological conductors.

(4) The response parameter of a conductor is defined as the product of conductivity-thickness (st), permeability (µ), angular frequency (w = 2pf), and the square of some mean dimension of the target (a2). The response parameter is a dimensionless quantity. In MKS units, a poor conductor will have a response parameter of less than about 1, whereas an excellent conductor will have a response value greater than 1,000. The relative amplitudes of in-phase and quadrature components as a function of response parameter are given in Figure 4-41 for the particular case of the sphere model in a uniform alternating magnetic field. For low values of the response parameter (< 1), the sphere will generally produce a low amplitude out-of-phase anomaly; at moderate values of the response parameter (10-100), the response will be a moderate-amplitude in-phase and out-of-phase anomaly, whereas for high values of the response parameter (>1,000), the response will usually be in the in-phase component. Although Figure 4-41 shows the response only for the particular case of a sphere in a uniform field, the response functions for other models are similar.

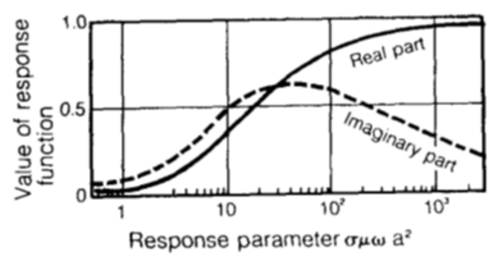


Figure 4-41. In-phase and out-of-phase response of a sphere in a uniform alternating magnetic field (Klein and Lajoie 1980; copyright permission granted by Northwest Mining Association and Klein)

(5) In frequency domain EM, depth and size of the conductor primarily affect the amplitude of the secondary field. The quality of the conductor (higher conductivity means higher quality) mainly affects the ratio of in-phase to out-of-phase amplitudes (AR/AI), a good conductor having a higher ratio (left side of Figure 4-41) and a poorer conductor having a lower ratio (right side of Figure 4-41).

(6) Of the large number of electrical methods, many of them are in the frequency domain electromagnetic (FDEM) category and are not often used in geotechnical and environmental problems. Most used for these problems are the so-called terrain conductivity methods, VLF (very low frequency EM method), and a case of instruments called metal detectors.

Excerpt from: US Army Corps of Engineers, EM 1110-1-1802: Geophysical exploration for engineering and environmental investigations (1995). Washington, D.C.

A.3 MAGNETIC METHOD

Basic Concept

The magnetic method was one of the first geophysical methods used for mineral exploration. Though, the scope of applications of the magnetic-survey method has increased with advances in instrumentation that improve data resolution, -quality, and -quantity. Magnetic data can be used to map large geologic structures, characterize bedrock, and aid high-resolution near-surface engineering-, geotechnical-, and environmental investigations (Thompson and others, 1980; Nabighian and others, 2005; Sharma, 2012).

Subsurface materials with high magnetic susceptibility can increase the flux of earth's magnetic field lines and strengthen the magnetic-field intensity observed at the ground surface. The magnetic method employs a magnetometer to passively measure Earth's magnetic field at points along the earth's surface. Anomalies in magnetic data can indicate the presence of subsurface zones with high magnetic susceptibility and, thus, be used for site characterization (Burger, 1992; Telford, 1990).

Theory

Earth's magnetic field, which is generated by the outer core and protects the planet from solar energy, behaves as if a giant bar magnet ran along Earth's axis. Because it is composed of two poles (i.e., positive and negative), a bar magnet is called dipolar and forms a closed-field loop. Like poles are repelled from each other while opposite poles attract, and this behavior can generate magnetic fields that can be observed at multiple scales.

All matter consists of moving electrical charges, which create magnetic dipole moments that can influence and be influenced by other magnetic fields. The magnetic susceptibility (Xm) of a material is a measure of its response to an applied magnetic field and related to its atomic structure and subsequent magnetic properties. Magnetic susceptibility, which is defined as the ratio of magnetization to magnetizing-field strength, depends on the type(s) and concentration(s) of magnetic materials.

Most earth materials fall within one of three magnetic classifications: ferromagnetic, diamagnetic, or paramagnetic. Ferromagnetic materials (e.g., iron, nickel, cobalt) have permanent magnetic properties. Permanent magnetization forms during material formation wherein groups of internal iron atoms align with (i.e., are magnetized by) Earth's magnetic field. However, this depends on the formation environment and will only occur if it is below the Curie temperature, above which, materials lose their permanent magnetic properties.

When exposed to an external magnetic field, ferromagnetic materials produce a strong internal field as they become attracted to it (e.g., fridge magnets). The fridge and magnet are ferromagnetic, but the magnet was strongly magnetized during manufacturing. In contrast, diamagnetic and paramagnetic materials lack permanent magnetic properties and respond oppositely to external magnetic fields. Diamagnetic materials (e.g., lead, water) slightly oppose the external field, whereas paramagnetic materials (e.g., magnesium, aluminum) are slightly attracted to it.

The character of alignment of iron atoms determines the object's magnetic susceptibility and, therefore, how intensely their presence can alter Earth's magnetic field. Of course, objects containing no iron will have a very low magnetic susceptibility affect Earth's magnetic field minimally or negligibly (Moskowitz, 2015). The goal of magnetic surveying is to reveal the subsurface locations and variations of ferromagnets such as magnetic minerals or buried utilities.

Compared to Earth's magnetic field, magnetic fields generated by ferromagnetic materials in the near subsurface are relatively weaker, irregular, and/or anomalous (Burger, 1992). Depending on the orientation of its source object, a magnetic anomaly may have only a single pole (i.e., monopole) or a high- and low-magnetic intensity (i.e., dipole). The polarity of the total magnetic field anomaly allows for the interpretation of the depth, location, and orientation of the anomaly-producing subsurface material (Mussett and Khan, 2000).

For example, consider a magnetic field-producing ferromagnetic material that is oriented so that its field lines are in the direction of the external (i.e., Earth's) field lines. Such objects can produce a positive (+) anomaly in magnetic data. A data anomaly is negative (-) if the field-producing ferromagnetic is oriented opposite to the direction of the external field. Additionally, objects oriented normal (i.e., perpendicular) to the external field result in no data anomalies.

Applications

Field applications of magnetic surveys require an understanding that Earth's magnetic field changes daily and can be disrupted by solar storms. Therefore, a base station is required to monitor diurnal magnetic-field fluctuations and can be used to correct data for drift and other required data corrections. The instrument used to meet the objectives of environmental investigations is usually a cesium-vapor magnetometer that measures magnetic-field intensity in nanoteslsa (nT) (i.e., 1 T = 1 newton/amp-meter).

The magnetic method is used for identifying and mapping anomalous magnetic field intensities. Commonly, these are caused by discrete objects (e.g. underground storage tanks), utilities, or other subsurface objects that may be a contaminant source or related to contaminant transport. Recent research has revealed that magnetic susceptibility alteration can also occur due to biomineralization from natural or active remediation. Though novel, it is suggestive of a new environmental application of the magnetic method (Mewafy and others, 2015).

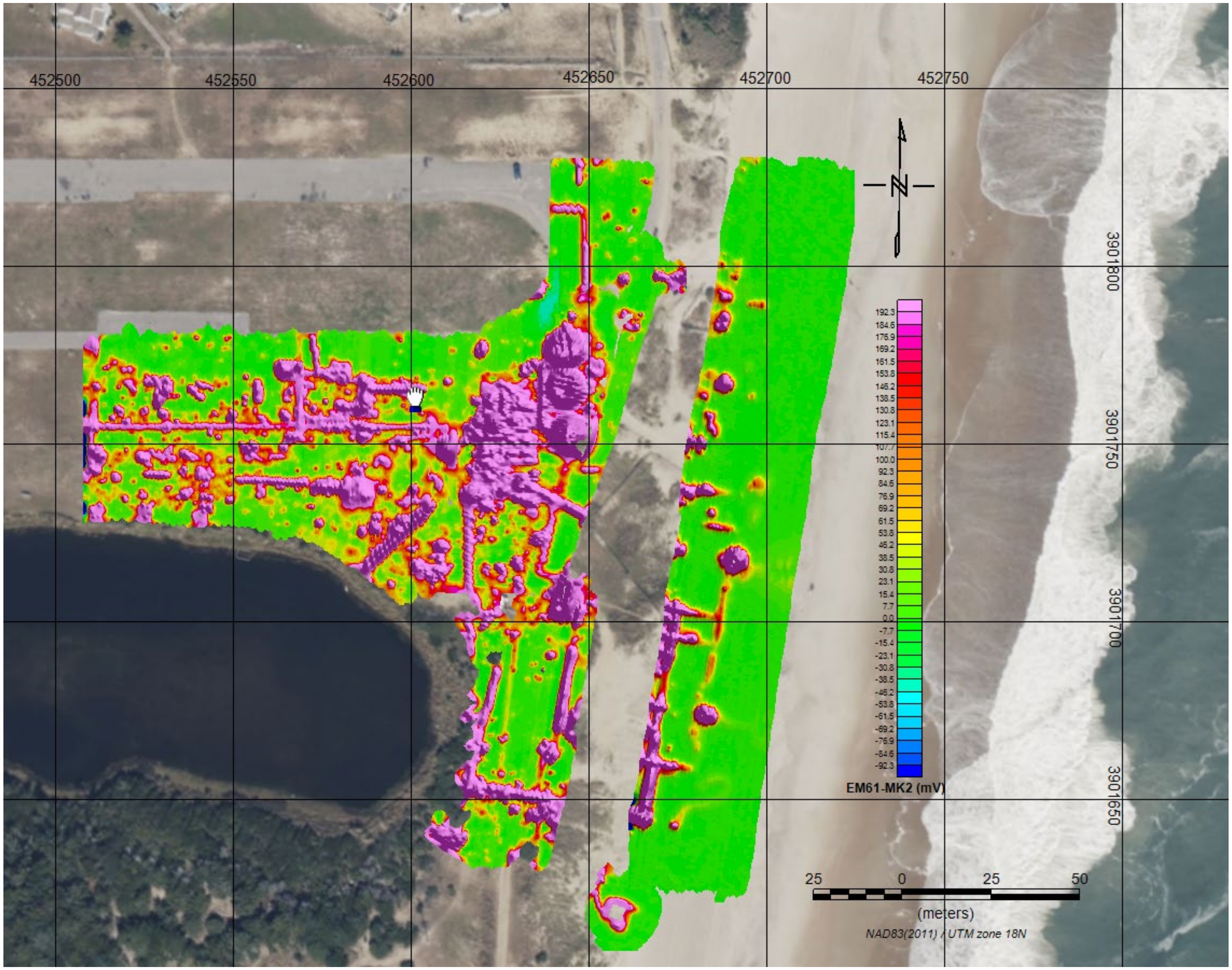
Typically, magnetic surveys are conducted via field personnel walking in a grid pattern with a handheld magnetometer. Magnetic instruments can be either a cesium-vapor magnetometer, proton-precession magnetometer, or flux-gate magnetometer, each of which has a unique purpose. Grid-pattern surveys render two-dimensional (2-D) maps of the magnetic-field intensity, which can reveal the locations of subsurface ferrous objects with high magnetic susceptibilities. Generally, such objects produce high-magnitude data anomalies (positive and/or negative) as they alter the earth's magnetic field.

Because the magnetic method only responds to alterations in the earth's magnetic field, merging multiple methods to achieve a common interpretation is always good practice. For instance, the magnetic survey only identifies ferromagnetic objects, so a complementary electromagnetic induction survey could elucidate the location of other non-ferrous metallic objects. However, the magnetic surveying method has aided the following applications (Thompson and others, 1980):

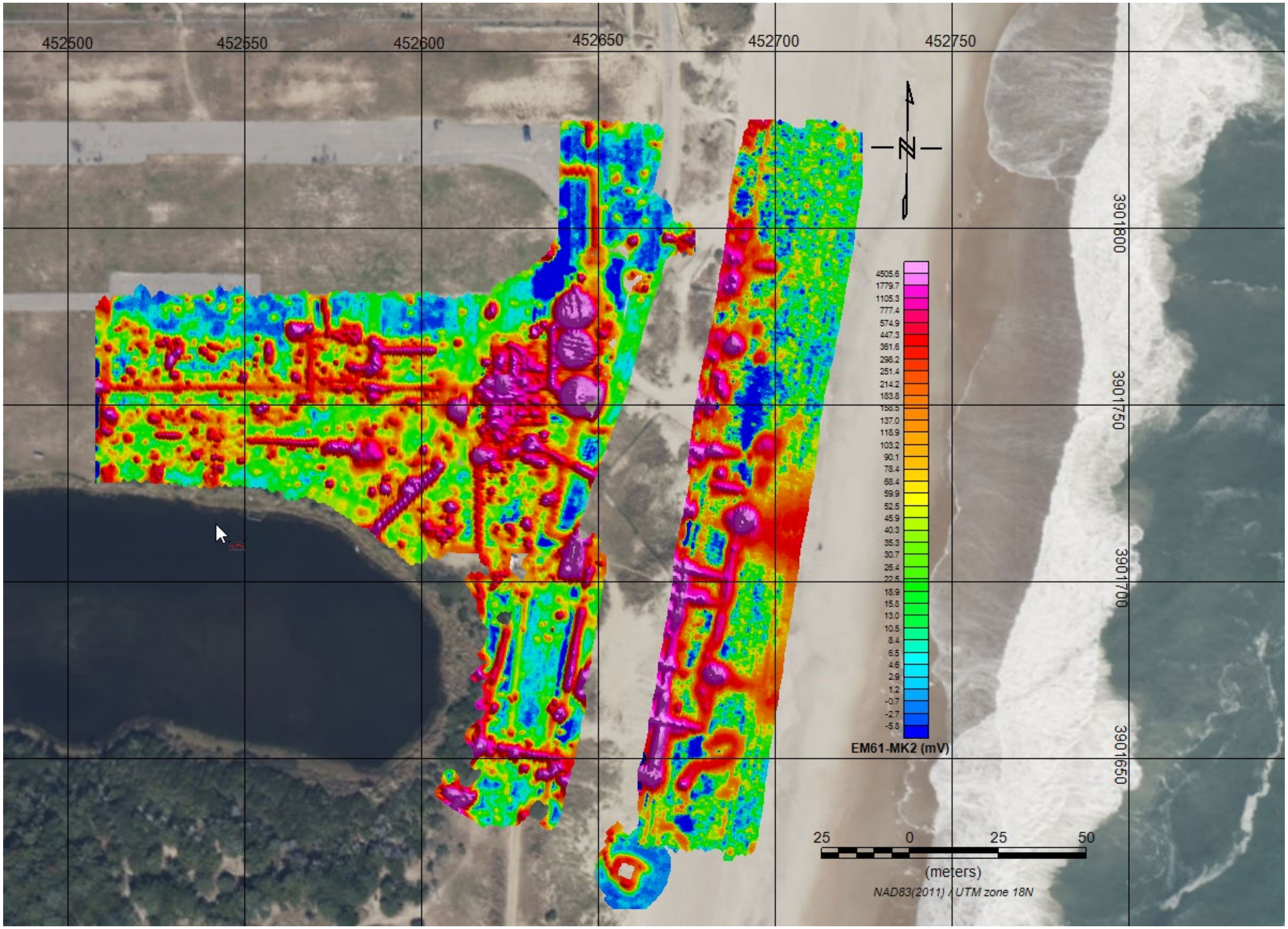
- Locating subsurface or sub-aqueous ferrous utilities or objects (e.g. shipwrecks)
- Locating underground storage tanks
- Mapping landfills contents
- General geologic mapping aiding development of conceptual site models (CSMs)
- Magnetic response associated with biomineralization from iron reduction
- Locating unexploded ordinance (UXO)

APPENDIX B: ADDITIONAL DATA FIGURES

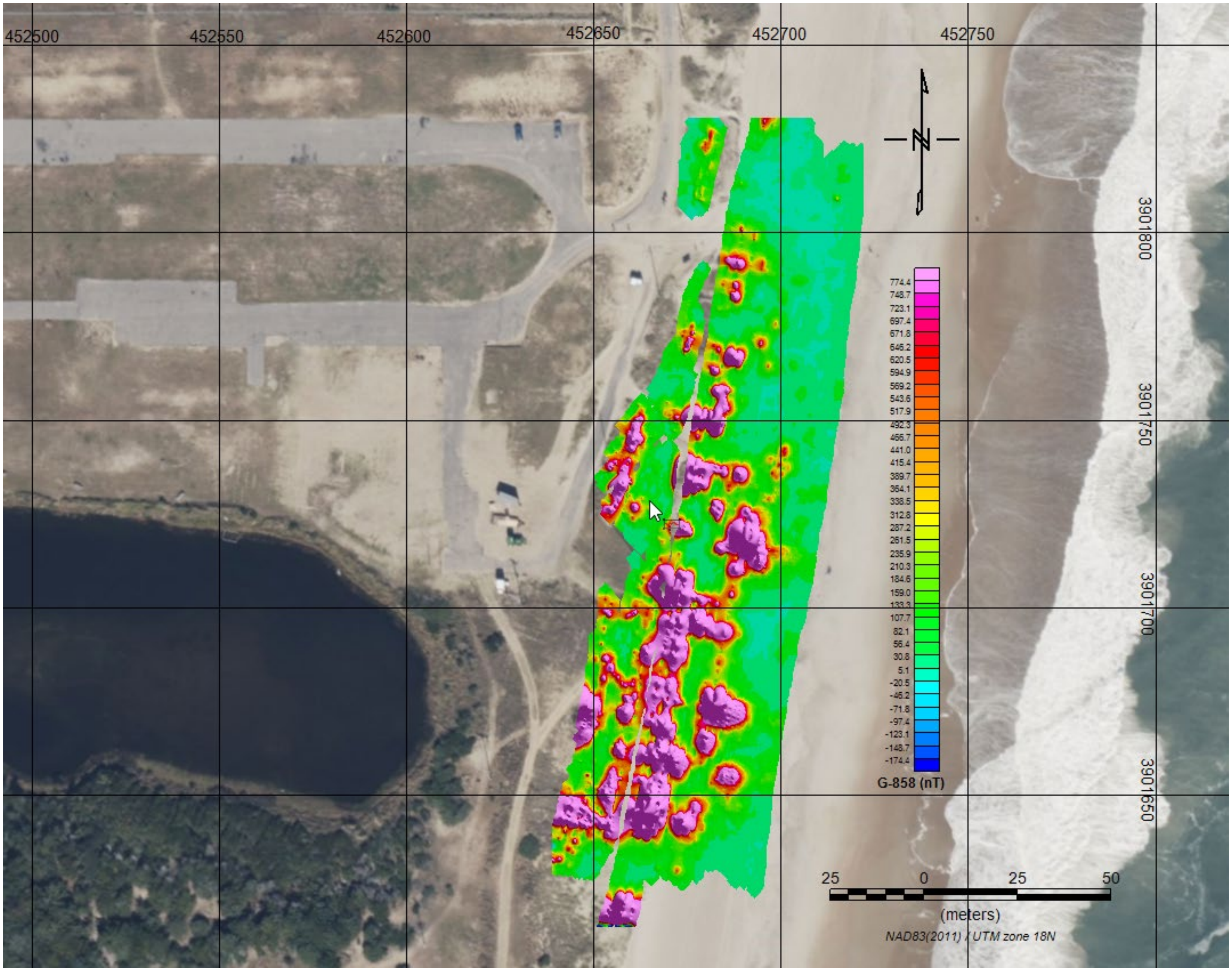
This page is intentionally left blank



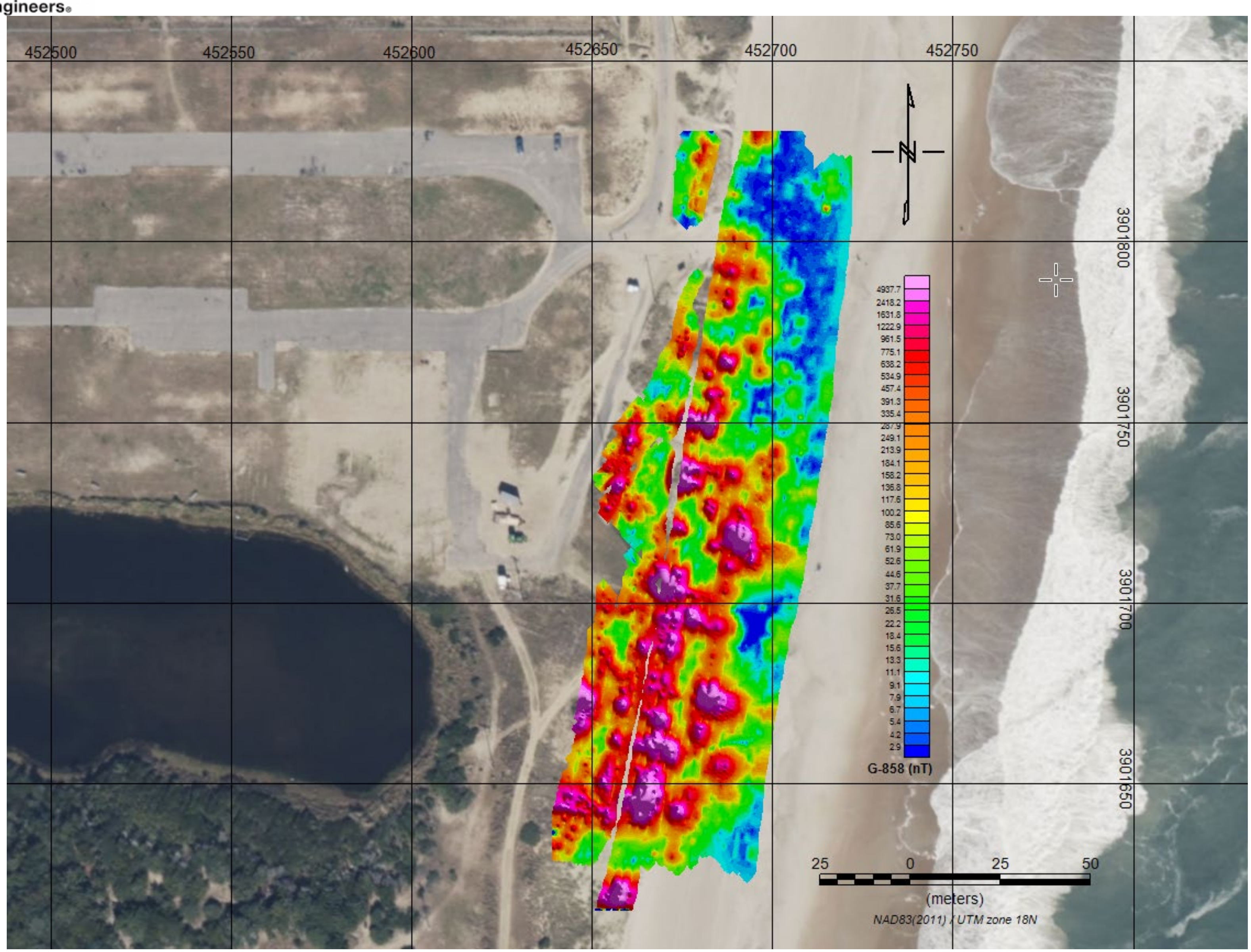
EM61-MK2 Data Portrayed in Linear Transform



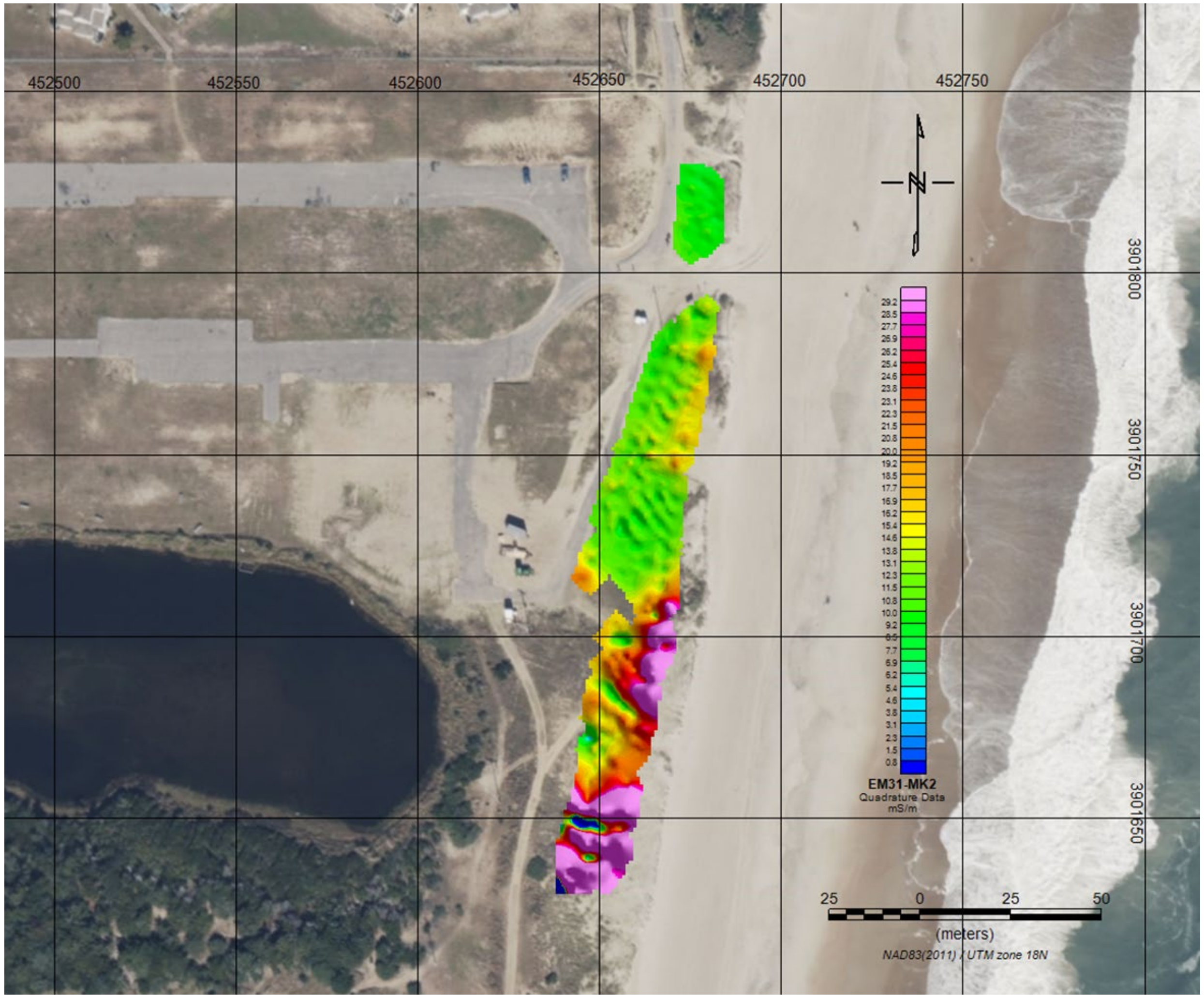
EM61-MK2 Data Portrayed in Histogram Equalization Transform



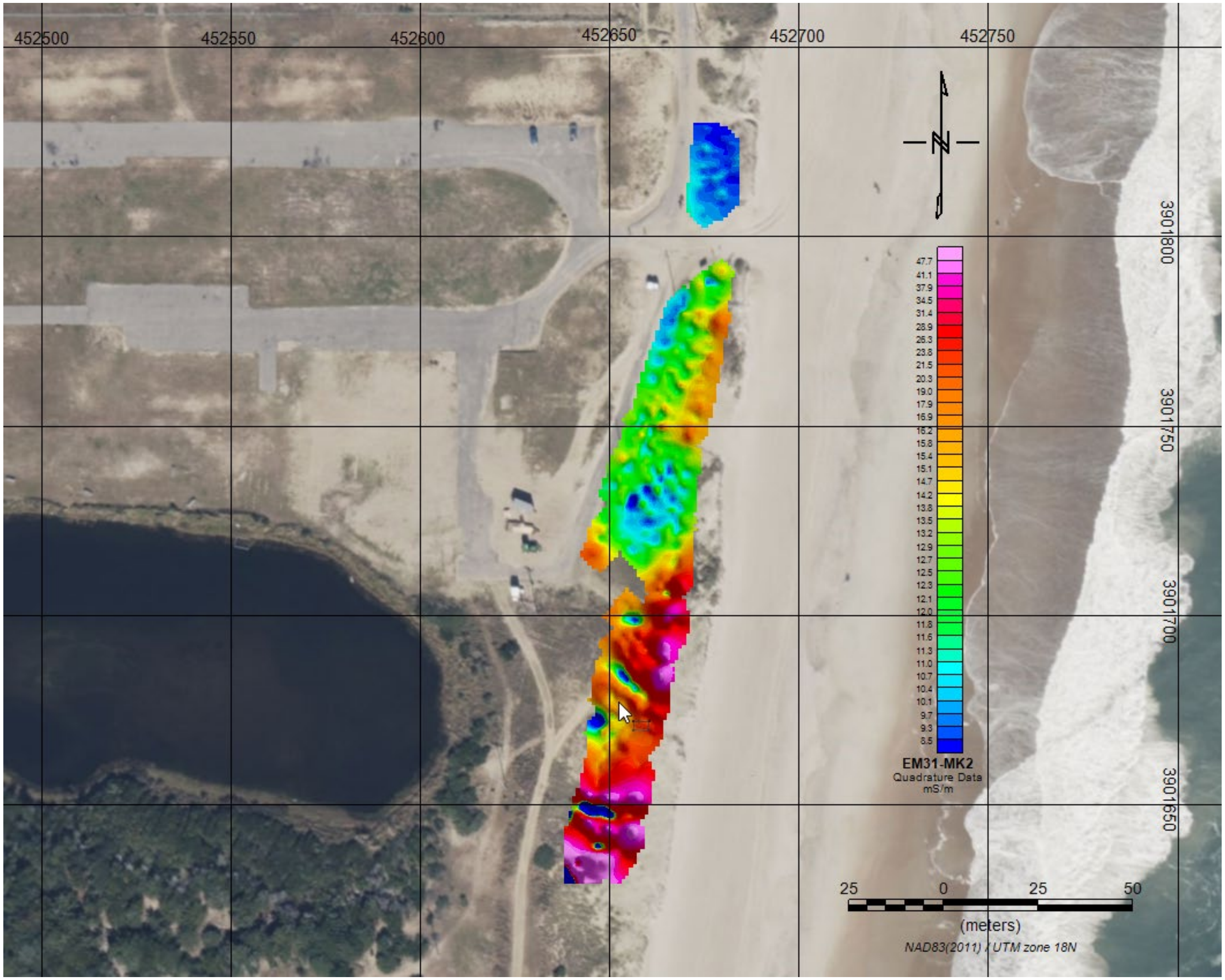
G-858 Data Portrayed in Linear Transform



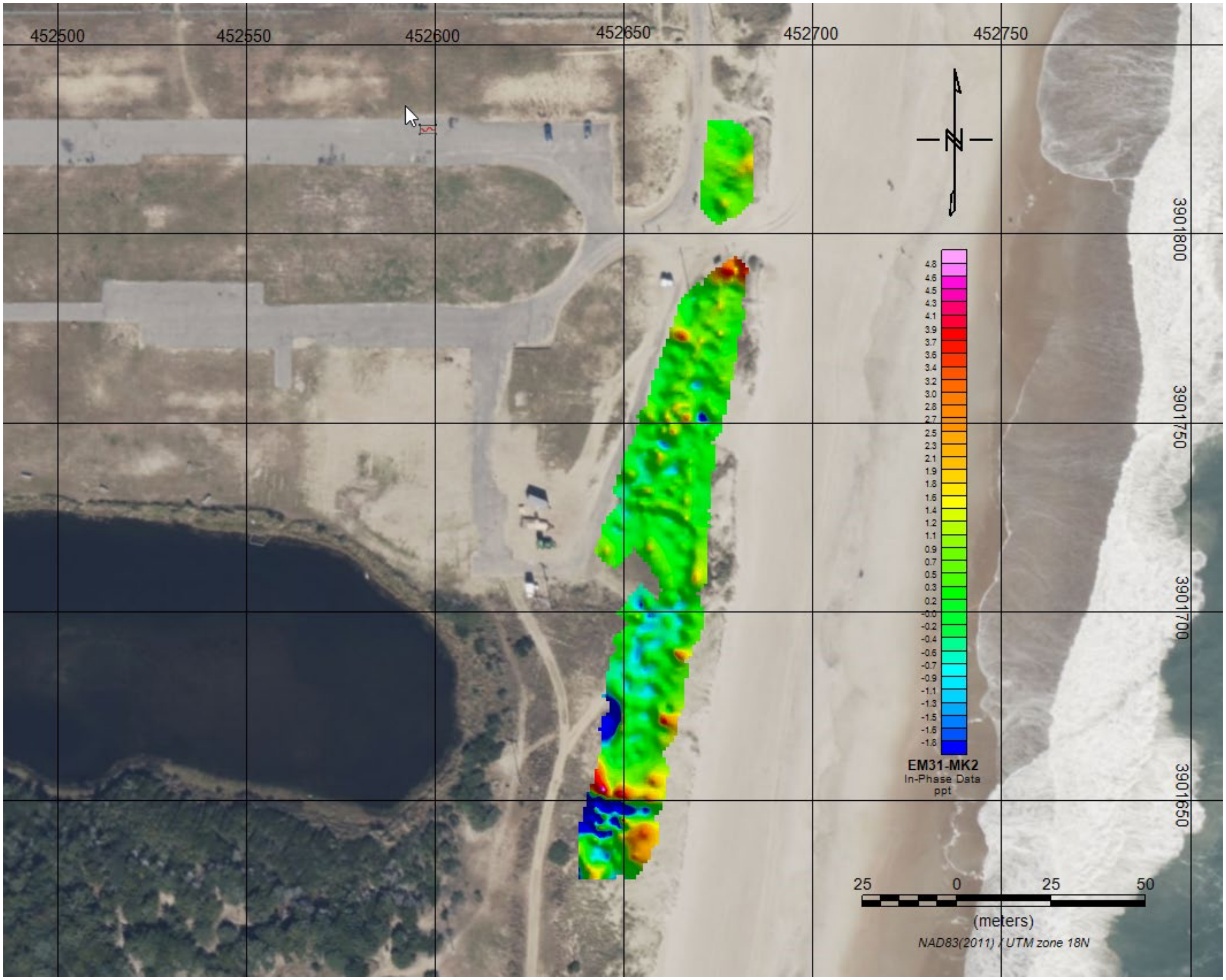
G-858 Data Portrayed in Histogram Equalization Transform



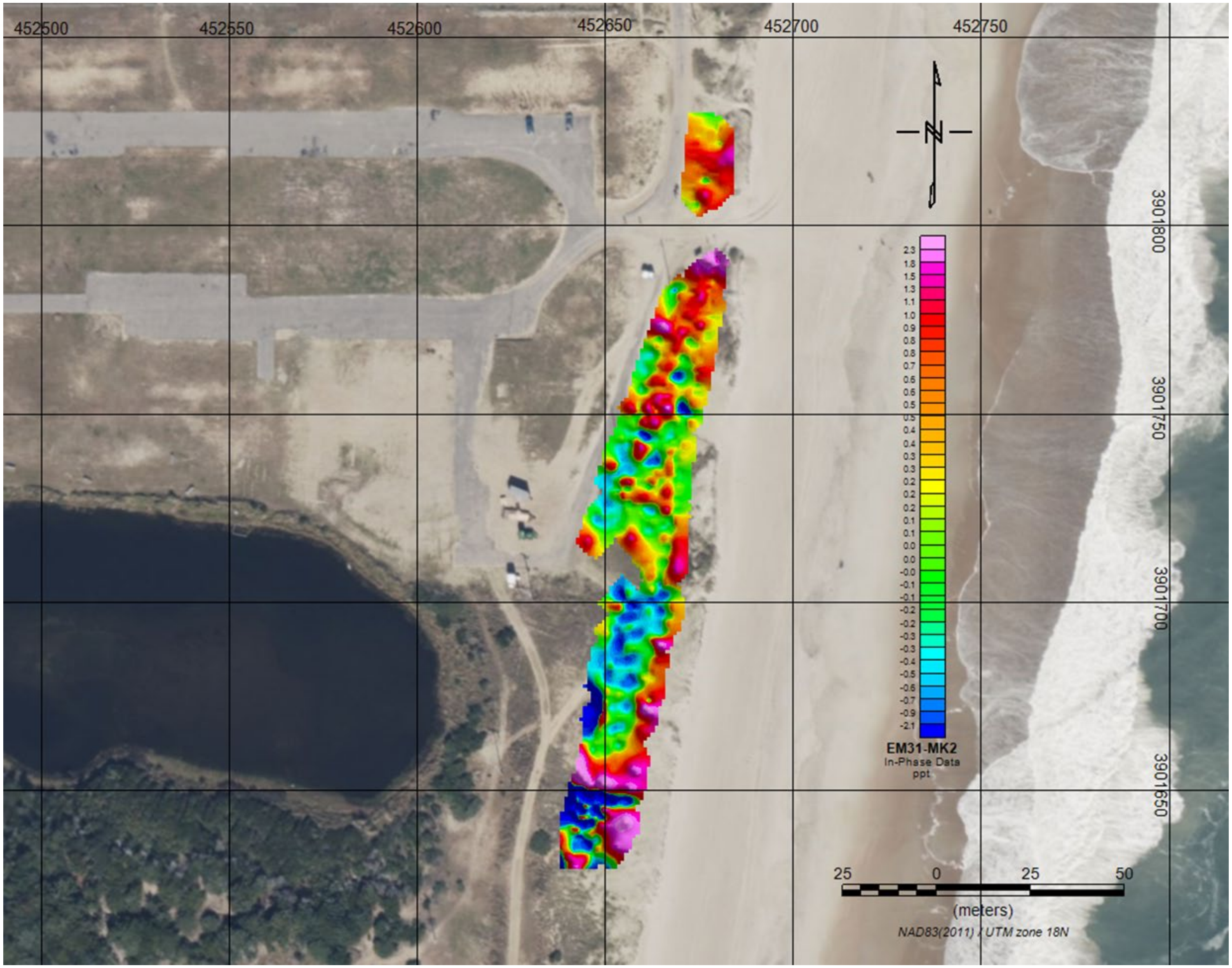
EM31-MK2 Quadrature Data Portrayed in Linear Transform



EM31-MK2 Quadrature Data Portrayed in Histogram Equalization Transform



EM31-MK2 In-Phase Data Portrayed in Linear Transform



EM31-MK2 In-Phase Data Portrayed in Histogram Equalization Transform