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MAGNETIC SIGNATURE ANALYSIS & VALIDATION SYSTEM

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INTRODUCTION

The Magnetic Signature Analysis and Validation (MAGSAV) System is a mobile platform that is used to measure, record, and analyze the perturbations to the earth's ambient magnetic field caused by objects such as armored vehicles. Figure 1 depicts MAGSAV during the measurement process.

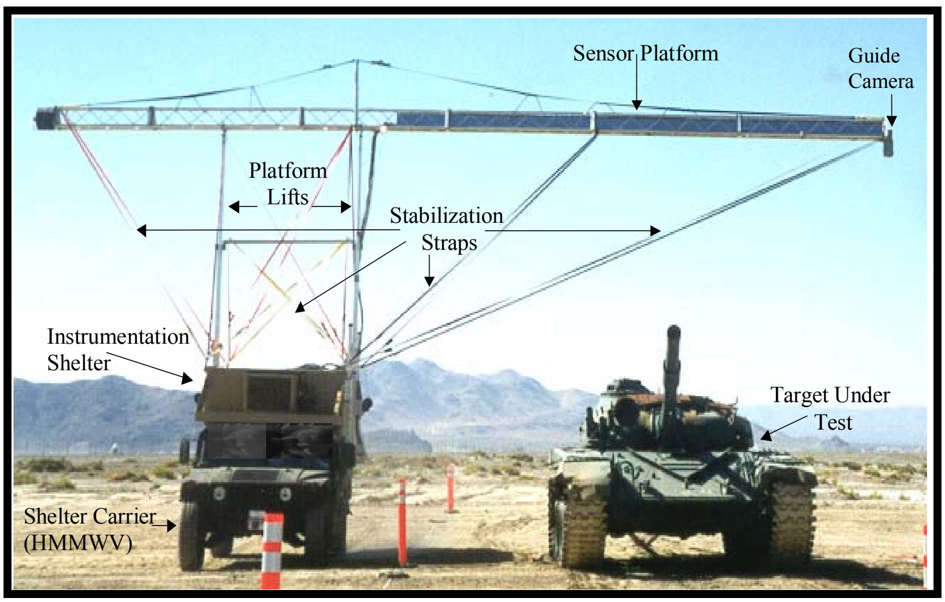

Figure 1. MAGSAV Measuring Magnetic Field Over Target

MAGSAV was developed in order to efficiently obtain magnetic flux density maps of armored vehicles. The field maps have a spatial extent of 24.75 m by 24.75 m in a given horizontal plane above ground level (AGL). A field map is composed of a grid, or matrix, of 99 cells by 99 cells. Each cell has a spatial extent of 0.25 m by 0.25 m and possesses a single magnetic flux density value, in units of mgauss, which represents the

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Abstract

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total static field at a point in space relative to the target. The target center[1] is registered in the grid center. The field measurement process is conducted at four heights AGL and then intermediate planes are obtained through interpolations. The resultant "magnetic field cube" provides a three-dimensional matrix of magnetic flux density values spatially registered to the target.

System operations are efficiently completed by four people: 1) a test director, 2) a HMMWV driver, 3) an instrumentation operator, and 4) someone to assist with adjusting the sensor platform height. Subsequent references of time-durations for system operations assume a four-person crew. Other people may be needed to position the target under test depending on target condition (mobile or immobile) and required test-site armored vehicle operator certifications.

Static Magnetic Fields Surrounding Armored Vehicles

The static magnetic field surrounding an armored vehicle arises from non-linear interactions among the three types of magnetic moments:

1. Permanent - due to permanently magnetized materials,
2. Induced - due to the response of magnetic materials[2] to the intensity and direction of external magnetic fields such as the earth's or transient fields, and
3. Transient - due to direct current flows within the vehicle.

Each moment possesses a magnetic intensity and direction. In the near field,[3] the magnetic intensity decreases with increasing range, R, as a function of R^{-1} or R^{-2}; in the far field, it decreases as a function of R^{-3}. Constructive and destructive interference among instances of the three types of moments will produce the net magnetic field.

At close ranges, the field map may appear complex because of multiple magnetic fields arising from objects such as a gun barrels and machine gun mounts are evident. At longer ranges, the field map appears "smoother" as magnetic contributions of individual objects blur into the bulk field of the vehicle.

The magnetic field surrounding a vehicle will vary with the local geomagnetic field conditions (angles of inclination and declination and intensity), the vehicle's heading, positions of the turret and gun barrel relative to the hull (if so equipped), manufacturing processes, materials and geometry of construction, damage and repair processes, and magnetic history. Due to these dynamic influences and the non-linear behavior of magnetic materials the best way to determine the magnetic field characteristics in the vicinity of an armored vehicle is through a measurement process.

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[1] Target center is defined as the intersection of the two diagonals across the top surface. Each diagonal begins and ends at one of the four corners of the hull (the hull excludes track covers or other appendages).

[2] Magnetic materials can be classified as ferromagnetic or diamagnetic.

[3] An approximation provided by Dr. Arthur Green of the U.S. Geological Survey, is that the near field extends to 10 times the maximum dimension of the object.

Furthermore, exploitation of the static field surrounding an armored vehicle is not sufficient for its identification. The perturbation to the earth's field is indicative only of the presence of magnetic materials; additional information is required to distinguish an armored vehicle from an automobile or a dumpster filled with ferrous waste.

Measurement Platform Mobility

The mobile platform provides the capability to generate field maps of both mobile and stationary vehicles or objects. It also minimizes the logistics burden associated with inter- and intra-site transport of the system.

For inter-site transport, the sensor platform components and other external items are secured inside the instrumentation shelter. The system can then be driven to the test site or shipped by air or truck. Figure 2 depicts a similar HMMWV, with a mounted instrumentation shelter, being unloaded from a C-130 military aircraft. Upon arrival at a test site, the set-up and calibration processes can be completed in eight hours.

Figure 2. MAGSAV Inter-site Transport

For intra-site transport the sensor platform can be rotated and secured as depicted in Figure 3. The time duration to convert from measurement configuration to intra-site transport configuration is under one hour. The ease of intra-site transport minimizes the logistics burden associated with measuring armored vehicles that may be dispersed throughout a large test site and or measuring non-functional vehicles that may be remotely emplaced; a mobile measurement system is easier to move than a 50,000 kg main battle tank.

Figure 3. MAGSAV Intra-site Transport

MAGSAV SYSTEM COMPONENTS

An inherent concern of a mobile platform is that it not interfere with the magnetic field surrounding the object during the measurement process. Great care was taken in the design and fabrication of the physical system and development of a data processing technique to eliminate sources of interference. Non-magnetic components were used to the maximum extent possible and a differential data processing technique was employed to remove the magnetic contributions from MAGSAV components. The absence of interference is evident in the plots of the magnetic field maps.

The major components of MAGSAV, to be described in subsequent sections, include:

1. A shelter carrier,
2. An instrumentation / personnel shelter,
3. A sensor platform and associated mounting, stabilization, and platform height adjustment equipment,
4. A data acquisition system, and
5. A data analysis and display system.

Shelter Carrier

The purpose of the shelter carrier is to provide support and mobility for the other MAGSAV components while traveling over unimproved roads in arctic, tropic, temperate, and desert environments. The High-mobility Multi-purpose Wheeled Vehicle[i] (HMMWV) was chosen for the shelter carrier because it met these requirements and a compatible instrumentation / personnel shelter was available.

Instrumentation / Personnel Shelter

The instrumentation / personnel shelter provides:

1. Environmental control for personnel and equipment,
2. Power for environmental control unit (ECU), instrumentation, and equipment,
3. Physical interface for the sensor platform and associated lift components,
4. Housing for equipment and operators,
5. Storage of sensor platform and lift components for logistics transport, and
6. Illumination of target and test site.

The shelter[ii] is designed to interface with the HMMWV. Its walls are fabricated with an aluminum honeycomb structure overlaid with aluminum sheets. The mechanical interfaces between the shelter and the sensor platform components are implemented in aluminum and non-ferrous steels. A 10 kw, 3-phase auxiliary power unit[iii] (APU) and a 22,000 BTU ECU[iv] are supported by the shelter. The electrical start for the APU is provided by the HMMWV. The APU uses glow plugs for cold-weather starts. The shelter provides storage for all sensor platform and associated components during inter-site transport.

Sensor Platform

The purpose of the sensor platform is to mount, position, house, and protect the sensors used to measure the magnetic field. It also establishes the spatial relationship between the target and its magnetic field map. Commercial-off-the shelf components, with some custom modifications, were used to construct the sensor platform[v] and lifts.[vi]

The sensor platform is fabricated from non-magnetic components. It is composed of eight-foot sections of triangular trusses that are bolted together through flanges at the ends of each section. The top surfaces are covered by aluminum-backed styrofoam sheets that provide a sun and rain shield. A counterbalance is located on the end of the sensor platform opposite from the magnetometers. The counterbalance includes a mounting fixture, weight plates and a locking mechanism to secure the plates.

Various dimensions of the sensor platform are depicted in Figure 4. The sensor platform is 13.7 m (~ 45 feet) in length. The platform is cantilevered beyond the longitudinal edge of the shelter carrier by 8.8 m (~ 29 feet). Sixteen magnetometers are spaced along the sensor platform at 0.5-m increments. The first magnetometer is laterally offset 1.3 m from the edge of the shelter. The sixteenth magnetometer is 0.25 m from the end of the sensor platform. The length of platform that includes magnetometers is 7.5 m.

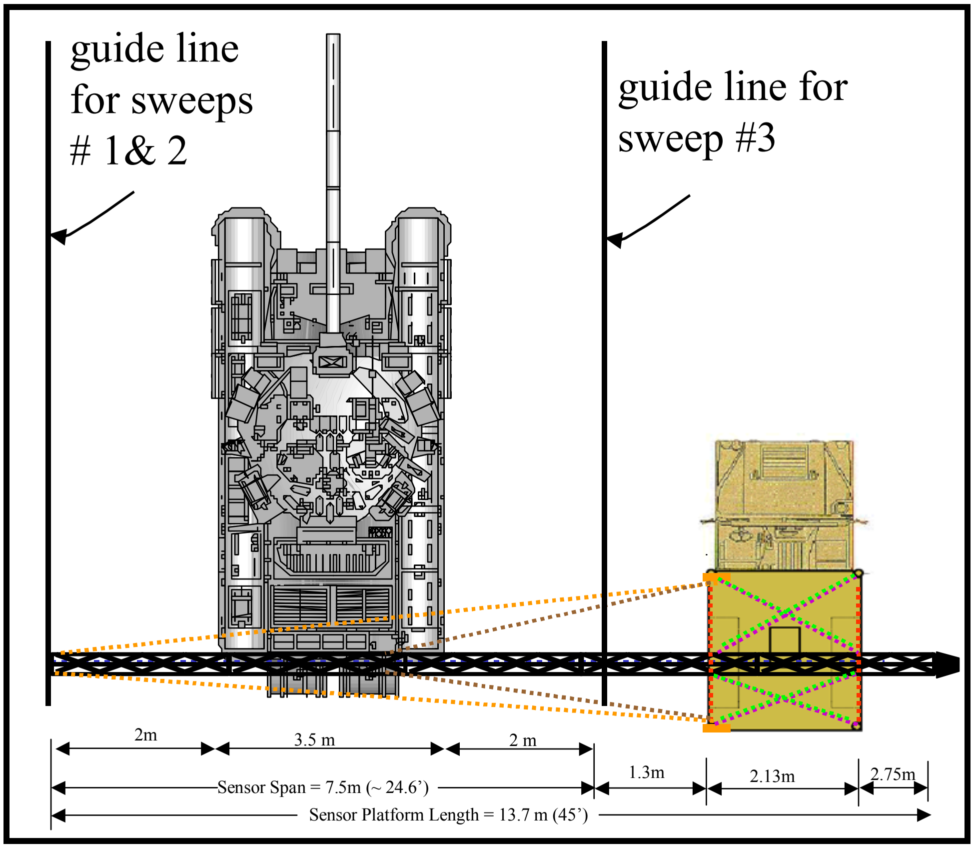

Figure 4. MAGSAV Sensor Platform Dimensions

Figure 5 is a side-view picture of the sensor platform, counterbalance, lifts, and stabilization struts and straps. The height of the sensor platform is manually adjustable, via hand cranks mounted on both sides of the shelter, from 3.3 m (~ 11 feet) to 6 m (~ 20 feet) AGL in 0.1 m (~ 4 inch) increments. The height range is constrained by the maximum retraction and extension of the platform lifts, as mounted on the carrier.

Figure 5. Sensor Platform & Associated Supports

Custom stabilization struts provide a secondary physical support[4] to the sensor platform. The telescoping struts can either extend or collapse based on the position of a pair of cams that ride each strut. The struts are extended upwards by the sensor platform during height increases but will not collapse, if a lift should suddenly fail. When it is desired to lower the sensor platform, the cam positions are rotated to allow the struts to collapse.

Four people are involved during the process of changing platform heights; one person operates each lift crank and inserts safety pins into the lifts, one person adjusts the stabilization straps and strut cams, and one person directs the other three to ensure synchronous operations. Tape measures near the first and last magnetometers are used to verify that the platform is level. Height changes require approximately 30 minutes.

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[4] The pair of lifts, alone, or the four struts, alone, are sufficient to support the sensor platform.

Data Acquisition System

The purpose of the data acquisition (DAQ) system is to acquire and spatially register magnetic field data to the target. The registration requirement is that each magnetic field value has to be spatially registered only within its 25-cm by 25-cm cell boundary, referenced to the target center.

Digital magneto-resistive magnetometers[vii] are used to measure the magnetic field along three orthogonal axes. The field value for each axis is composed as a signed 16-bit binary coded decimal (BCD) value;[5] the full-scale is ±1 gauss and the resolution is 66.67 μgauss. Each total field measurement is formatted as a serial 28-byte sequence and is transmitted over an EIA-422 interface.[6] The magnetometers are housed in aluminum boxes[viii] that provide a weather seal and shielding from stray electric fields.

Three of these boxes also include temperature sensors[ix] that are used to generate temperature corrections for the magnetometers. The temperature values are transmitted over an EIA-232 interface. The magnetometers and temperature sensors are connected to breakout boxes, located within the shelter, through double-shielded, twisted-pair cables.[x]

Field and temperature data acquisition is controlled by a custom Labview[7, xi] program that is hosted on a personal computer[xii] (PC). There are two identical breakout boxes; each is a component of a 16-port I/O controller[xiii] that includes a DAQ card resident in a peripheral component interconnect (PCI) bus slot on the PC. Each port is configurable as an EIA-232 or EIA-422 standard as needed by the temperature sensors and magnetometers, respectively. The DAQ cards include data buffers with sufficient memory to hold all measured values obtained during the data acquisition cycle; afterwards the values are downloaded into PC memory. This data buffering process precludes PC operating system interrupts from disrupting the data acquisition cycle.

A distance measurement device[xiv] (DMD) interfaces with the HMMWV through the speedometer cable; it provides a data pulse every 5 cm of travel. Every 5th pulse is used to trigger a new data acquisition event, thus the 16 magnetometers simultaneously perform a field measurement every 25 cm of travel. The DMD pulse is transmitted to the PC over an EIA-232 interface; it propagates from the DMD through a connector block[xv] to a DAQ card[xvi] resident in a PCI slot. The average measured accuracy of the DMD, as integrated in MAGSAV, was found to be -0.1cm per 25-cm cell or 0.4%.

A Video Encoder/Decoder[xvii] (VED) is used to acquire universal time code (UTC) from global positioning satellites when triggered by the DMD. The VED produces a time stamp that is recorded with each data acquisition event. Also, the VED superimposes the day of year, time of day, and bore sight cross hairs on the guide camera video image.

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[5] The BCD values are ASCII characters representing signed decimal numbers ranging between ±30,000.
[6] This Electronics Industry Association communication standard uses a balanced differential, full-duplex signal scheme.
[7] Labview is an instrumentation control application that is commercially available.

The data coordinate system is depicted in Figure 6. All spatial measurements are in units of meters. The field measurements occur in the x-y plane at four heights (3.3, 4.2, 5.2, and 6.0 m) AGL along the z-axis. For targets whose height exceeds 3.3 m, the lowest height is increased to ensure clearance of the sensor platform during the acquisition process.

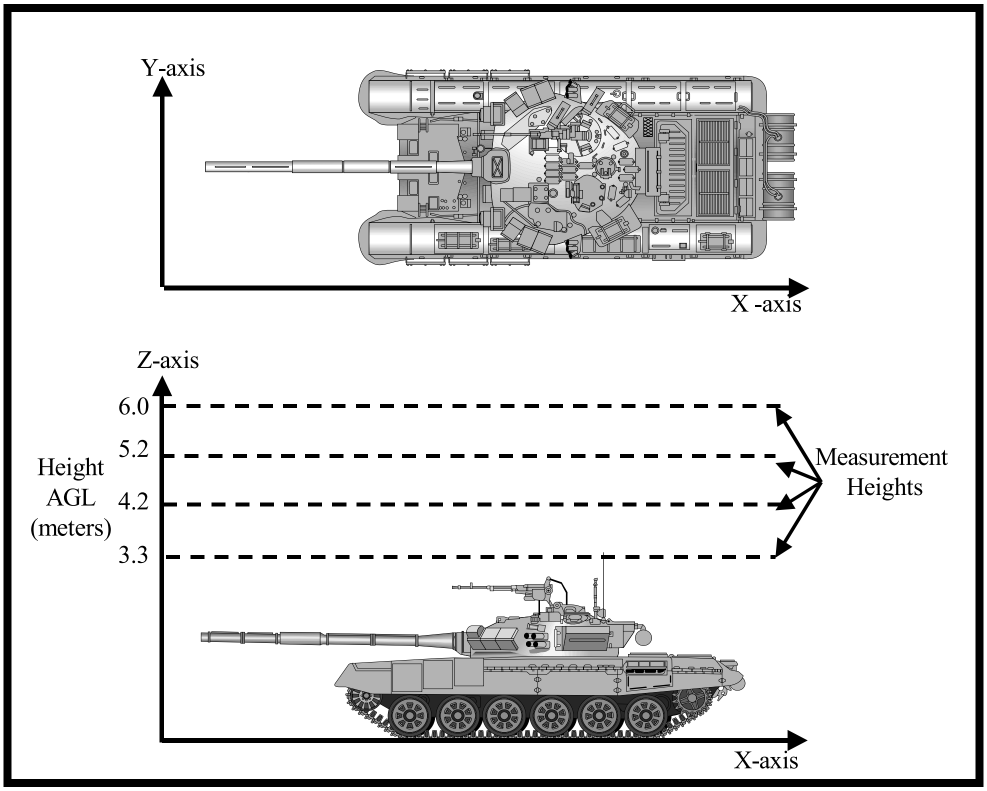

Figure 6. Data Coordinate System

The DAQ system spatially registers the magnetic field flux density readings to the target under test. The registration grid used to accomplish this is depicted in Figure 7. The spatial registration is aided by two guide lines[8] are laid on the ground parallel to the longitudinal edges of the target. A video camera[xviii] is mounted at the outboard end of the sensor platform with its field of view (FOV) centered on the guide line. The camera's zoom lens[xix] is adjusted via a controller[xx] such that the driver views a 25-cm wide FOV on a video monitor,[xxi] regardless of sensor platform height. During the acquisition process, the HMMWV driver maintains the image of the guide line on the video monitor in order to ensure that a sufficiently parallel path is achieved.[9] This process results in a lateral (y-axis) registration accuracy of ± 12.5 cm.

The image of the guide line and target edge reference lines is recorded on a video cassette recorder[xxii] (VCR) and is used identify the front and rear edges of the target after the measurement sweep is completed. The cross hairs and UTC time, superimposed during

[8] The guide lines are spool-type tape measures.
[9] If the image of the guide line does not remain on the monitor, the driver repeats the process.

recording, are used to discern the time of front and rear edge crossings. The Labview program then associates the edge crossings with their respective time-stamped data events such that the target position can be registered within the magnetic field map.

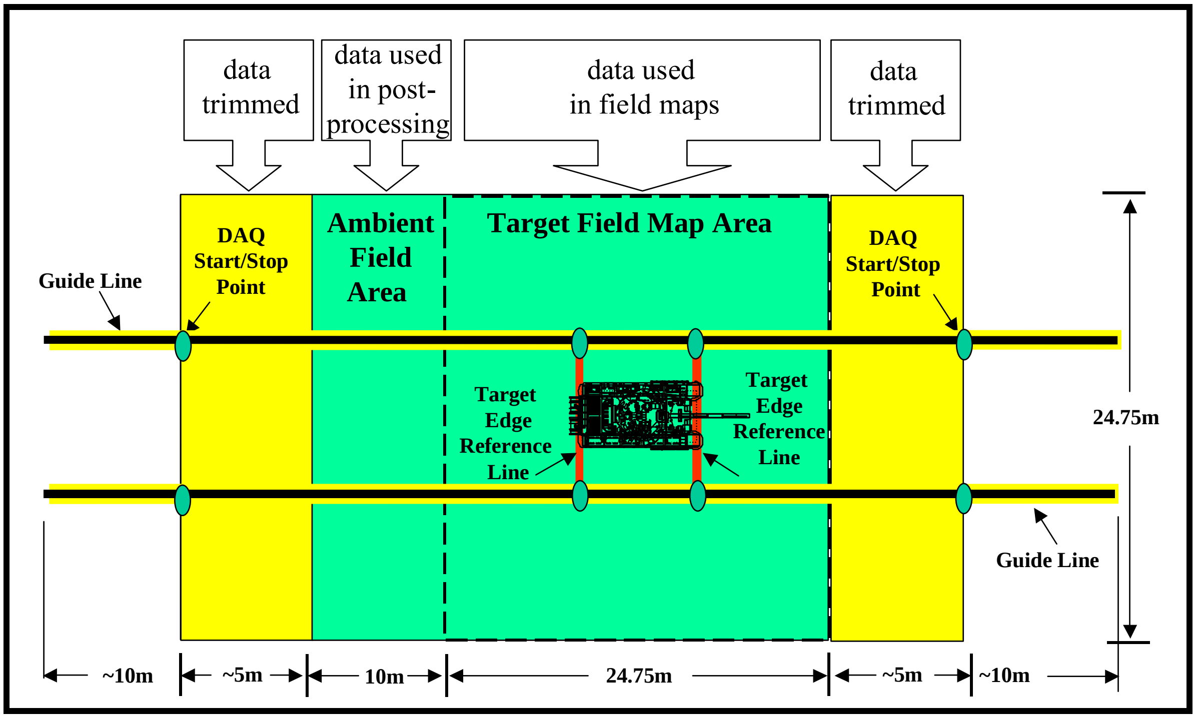

Figure 7. Registration Grid

A target sweep is the process of moving the sensor platform over an area in order to measure and record the magnetic field. The data collected over the yellow areas depicted in Figure 7 is deleted after the sweep is completed and the target has been spatially registered; its collection provides the instrumentation operator with a sufficient window of opportunity for beginning and ending data acquisition during each sweep.

The yellow area also provides the driver with an opportunity to accelerate to a constant speed, nominally less than 5 miles per hour (mph), and get the HMMWV traveling parallel to the guide line. Although, the DAQ system can acquire data at speeds up to 15 mph, a constant idle speed of approximately 3 mph is maintained because it simplifies the driver's task of guiding along the guide line.

A second video camera[xxiii] is mounted in the middle of the sensor platform. This camera is used to view the top surface of the target during sweep #1. Its image is recorded on a VCR[xxiv] and used to help identify a feature or object mounted on the tank responsible for a particular magnetic characteristic.

Both video cameras are charge-coupled device types with auto-iris lenses; thus, they function from dawn to dusk without the need for human adjustment. Lights,[xxv] co-located with the cameras, provide guide line and target illumination during night operations.

Three sweeps are needed to obtain a 24.75-m by 24.75-m map of the magnetic field in a given horizontal plane AGL. See Figure 8. The first sweep always covers the target. Sweeps 2 and 3 cover the area on each side of the target. The three sweeps are combined into a single map, also referred to as a "survey", by the data analysis & display system. Target surveys are performed on level surfaces such that the sensor platform remains level through the measurement process.

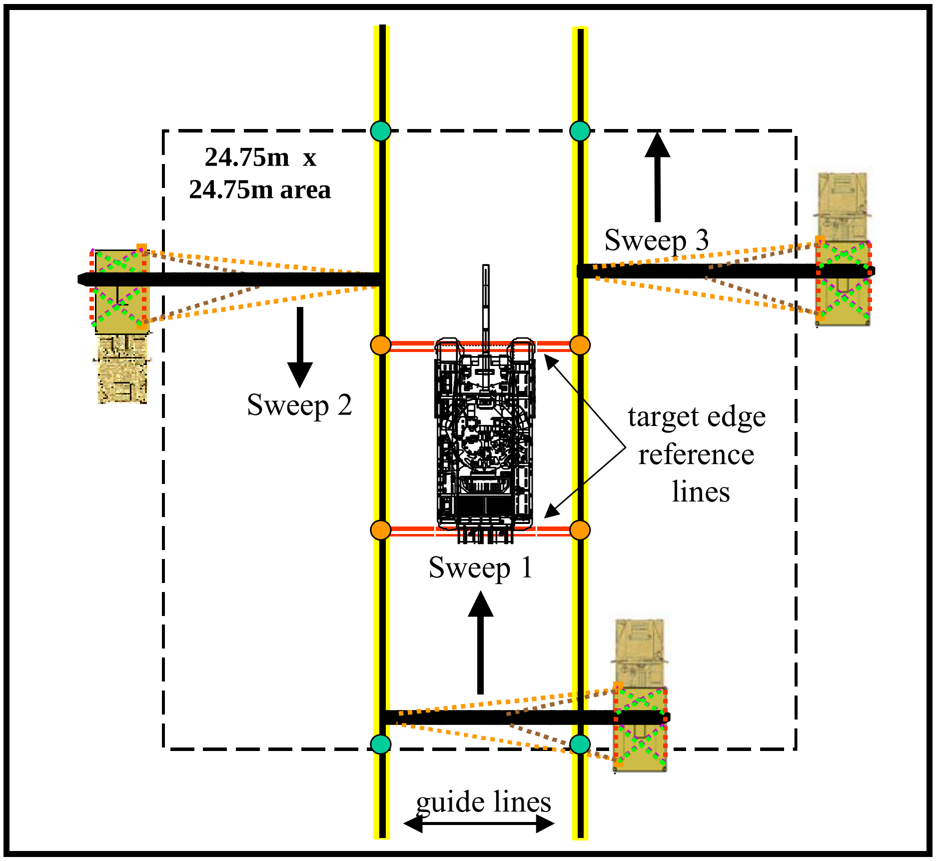

Figure 8. Target Survey Sweeps

A target survey can be completed within four hours after the target has been positioned in the desired magnetic heading. This includes laying the registration grid and conducting three sweeps at each of four heights. The Labview program guides the instrumentation operator through the survey process. Filenames for each of the surveys is automatically composed from information the instrumentation operator is prompted to provide. The instrumentation operator is given an opportunity to include notes for each sweep; the sweep notes are saved with the file.

Prior to a target survey, an ambient field survey is performed. An ambient survey is performed, before the target is positioned, in order to detect potential magnetic anomalies in the registration grid area. This ensures that subsequent target surveys are not polluted by non-target influences. The ambient surveys are conducted only at the lowest sensor platform height. A field survey can be completed within an hour.

Data Analysis and Display System

The purpose of the data analysis and display (DAD) system is to post-process data and to aid in the analysis and visualization of the magnetic field maps. The DAD system utilizes custom Matlab[xxvi] scripts to generate graphical user interfaces and data processing, plotting and file management routines. Post-processing includes:

1. Conversion from BCD values to magnetic field flux density values in mgauss,
2. Temperature correction,
3. Removal of the earth's ambient field and MAGSAV field contributions,
4. Creation of additional data points between the magnetometers via interpolations in order to develop a 25-cm resolution of field values along the y-axis,
5. Combining the three sweeps to form a single field map,
6. Performing a surface interpolation across a field map in order to "smooth" the seams between the sweeps, and
7. Performing surface interpolations through the four heights to create field maps from 3.3 m (or lowest measured height) to 6 m AGL, in 0.1m height increments.

The field contributions from MAGSAV are due to current flows and magnetic materials in the HMMWV, APU, ECU, counterbalance, video cameras, and camera lights. All of these, as well as the earth's field, produce a constant offset (i.e. a steady-state bias) in the magnetometers throughout the short duration of a target sweep because they remain spatially fixed relative to one another.

The removal of the earth's ambient field and MAGSAV field contributions is accomplished as follows. Forty ambient field values are collected by each magnetometer, during each sweep, over the "ambient field area" depicted in Figure 7. These ambient field values include the earth's ambient field and field contributions from MAGSAV. The forty values are averaged and then subtracted from each of the subsequent field values collected during the sweep corresponding to that magnetometer. This differential technique produces a magnetic field map, referenced to 0 mgauss, with positive values indicating flux concentrations and negative values indicating flux rarefactions.

The result of all post-processing is a target magnetic field cube, which represents the perturbation to the earth's ambient field due to the target's presence. Each cube is composed of a series of field maps corresponding to x-y planes at specific heights AGL.

In the associated magnetic field cube files, the data (magnetic flux density values in units of mgauss) in each field map is formatted as space-delimited text in a 99-row by 99-column matrix. Within the matrix the target center is registered in cell 50, 50 with the target heading towards column 1. See Figure 9. The columns correspond to the x-axis and the rows correspond to the y-axis.[10]

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[10] Due to an artifact in the Matlab surface plot routine, the rows of the data matrix in the files had to be interchanged such that the field maps would be correctly displayed. Therefore, the first row in the data file contains the field values associated with the bottom edge, i.e. the edge closest to the left edge of the vehicle as depicted in Figure 9, of the field map.

Each field map is separated by two rows to differentiate between the successive planes within a cube. Each cube's data file begins with the lowest field map followed in ascending height by the higher field maps.

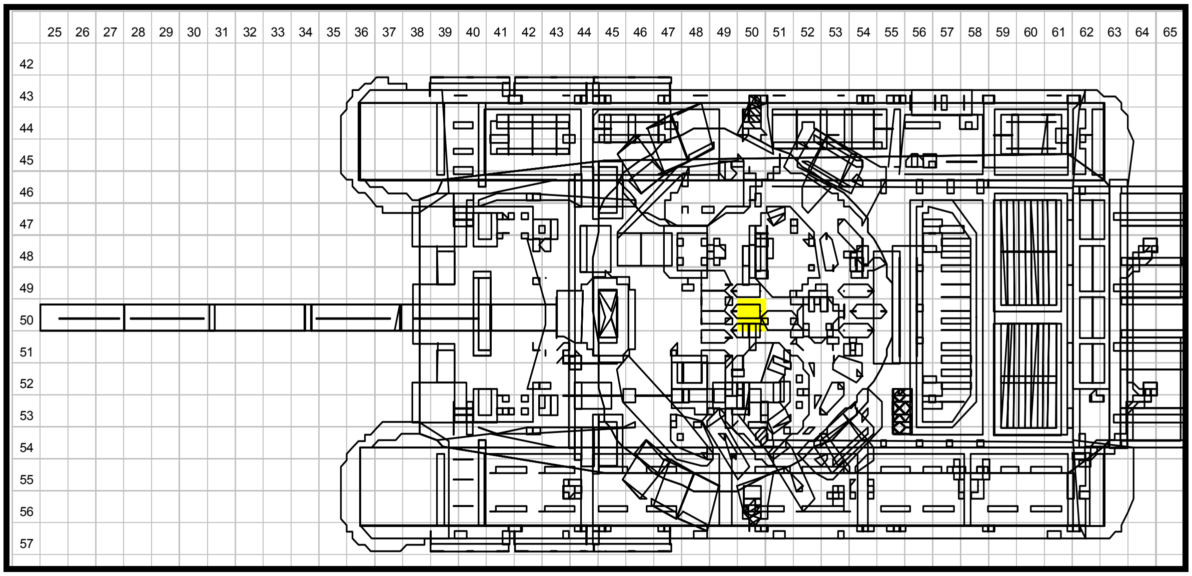

Figure 9. Target Registered Within Matrix

The DAD system generates and displays target field maps as surface and contour plots as depicted in Figure 10. The associated Matlab script "view_magsav_cubes.m" provides the utility to view a surface plot from any aspect in order to analyze field characteristics anywhere in the given x-y plane.

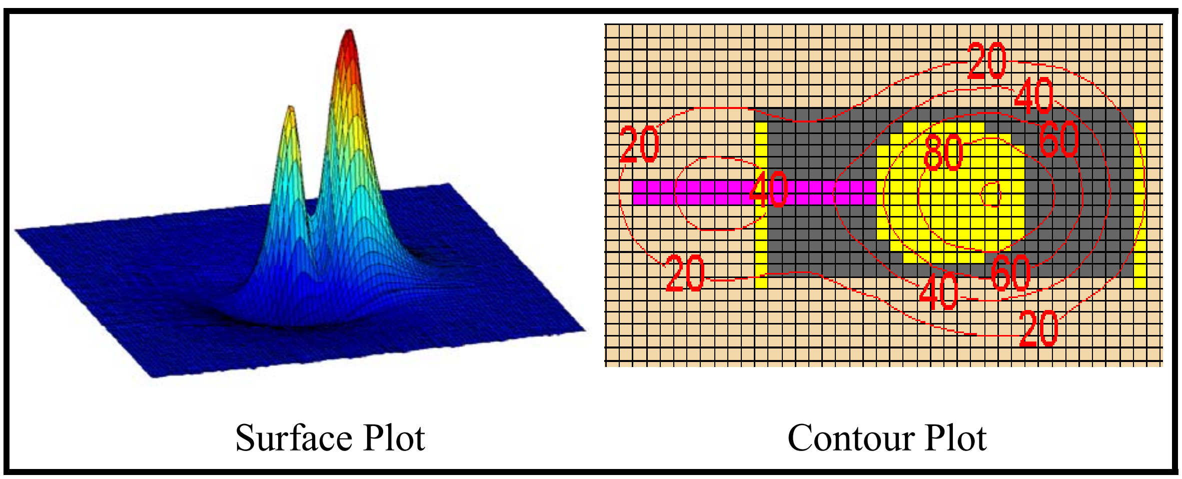

Figure 10. Surface and Contour Plots

The plots provide a means to visualize how the field changes as a function of range, vehicle heading and geolocation, or any of the other magnetic variables. Comparisons between vehicles of the same class or among classes are readily made. Furthermore, the field maps can be used in performance simulations of sensors or systems that exploit the static magnetic field of a target or object of interest.

MAGSAV SYSTEM-LEVEL ACCURACIES

The system-level accuracies of the total field measurement and the spatial registration of the field values to the target are addressed in the following sections.

Magnetic Field Measurement

MAGSAV was taken to the Fredericksburg Geomagnetic Observatory (FGO) on 5 January 2000 to determine its magnetic field measurement accuracy. The FGO is a U.S. Geological Survey Station and as such maintains highly accurate and calibrated magnetometers for the purposes of measuring and reporting changes in the earth's field over time. It is also used to perform magnetic instrument calibrations for international instrument standardization, private industry, and government agencies.[11]

The earth's field measurements collected by the FGO were used to compare and calibrate the MAGSAV magnetometers. The manufacturer data sheets report a ± 2.4 mgauss accuracy (typical) in the total root-sum-square (RSS) field measurement over the ± 1 gauss range. The RSS of the values measured by the three magnetometer axes represents the total field. All magnetometers used in MAGSAV, after calibration and temperature correction, demonstrated a total-field accuracy within ± 1 mgauss of the 532 mgauss earth's field measurement by the FGO.

It is unlikely that the peak magnetic flux concentration and rarefaction values of any of the targets were captured since magnetometer spacing along the sensor platform is 50 cm. If one had a specific requirement to determine the absolute peak values, the magnetometers would have to be arrayed to form a continuous line across the platform and they would have to be continosly measuring the field during a sweep. Even if they were captured, their values are only valid under the exact conditions that existed during the measurment process.

Spatial Registration

The spatial registration accuracy is a function of the lateral (y-axis) and longitudinal (x-axis) registration accuracies. The lateral registration accuracy is ± 12.5 cm from cell center; it is a function of the HMMWV driver maintaining the image of the guide line on the video monitor. The longitudinal registration accuracy is -0.1cm per cell; it is a function of the DMD accuracy. Thus, over the target field map area, each field value is spatially registered to the target within its 25-cm by 25-cm cell.

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[11] See website for further details, http://GEOMAG.USGS.GOV/frames/mag_obs.htm

CONCLUSION

MAGSAV is used to efficiently measure, record, plot, and analyze the static magnetic field surrounding an object. The magnetic characteristics of a particular vehicle and the general trends of many vehicles measured over a wide range of conditions can be examined. This information is valuable for developing and improving multi-sensor systems that exploit magnetic fields as an indicator of target presence. The field cubes can be used in modeling and simulation endeavors to provide realistic and varied magnetic sensor stimuli and or responses.

In a given class of vehicles, general trends are apparent due to the presence or absence of magnetic materials and corresponding similarities in size, amounts, and configurations of those materials. For instance, the M113 armored personnel carrier has an aluminum hull and weighs approximately 10,000 kg as compared to the M-60 main battle tank that has a ferrous steel hull and weighs approximately 50,000 kg. Under identical measurement conditions, the M-60 will cause a much greater pertubation to the earth's field, both in density and in spatial extent, than the M113. However, trends can be obscurred by the many magnetic influences that exist.

The magnetic field surrounding a complex object such as an armored vehicle is dependent on numerous factors such as the earth's field direction and intensity at a given location, diurnal changes in the earth's field, the object's orentation with respect to the earth's field, transient fields arising from the object, etc. Over time unmagnetized components become magnetized, and vice versa, due to damage and repair processes, temperature cycling, vibrations, and long-term interactions with the earth's field. Changes in component configurations may also occur. Furthermore, one should not assume that a particular armored vehicle will share the magnetic characteristics of another vehicle in the same class if thier magnetic histories differ or they were manufactured on different production lines with dissimilar processes and magnetic material compositions. The magnetic field surrounding an armored vehicle is not sufficent, by itself, for reliable target detection, identification, or fuzing.

To date, twenty-five magnetic field cubes have been prepared. The vehicle types include artillery command and reconnaissance vehicles,[xxvii] armored personnel carriers[xxviii], and main battle tanks.[xxix] The measurement locales included China Lake, California, Eglin Air Force Base, Florida, and Fort Greeley, Alaska.

A Matlab script, entitled "view_magsav_cubes.m", allows the user to display the field maps within each cube. This report provides sufficient information to the users of the magnetic field cubes such that they can directly use or further process the data. The cubes and script are available through the National Ground Intelligence Center, Measurements Signatures Division (IANG-CE-MA/MS404).

MAGSAV COMPONENT AND TARGET REFERENCES

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[i] HMMWV model M1097A2
[ii] Gichner model S-788 Type III Lightweight Multipurpose Shelter
[iii] Power Tech model PTS10-3RALI
[iv] Specific Systems model 60-M-38
[v] Applied Electronics TR-14 triangle trusses
[vi] Applied Electronics L-16 lifts
[vii] Honeywell model HMR 2300r-422
[viii] Bud Aluminum Cast Box model AN-1304
[ix] Analog Devices Serial Digital Output Thermometer model TMP04 in TO-92 package
[x] Belden part 8165
[xi] Labview version 5.1
[xii] Gateway custom configured model with Pentium III 500Mhz processor, Windows 98 operating system.
[xiii] MultiCom version 5.00 for Labview for Windows 95/98/NT
[xiv] HMR Communications model DP-520S
[xv] National Instruments model SCB-100 100-pin Shielded Connector Block.
[xvi] National Instruments Multifunction I/O DAQ Card model PCI-6033E.
[xvii] V-data model VED-A with custom firmware
[xviii] Sony model FCB-IX470P (camera and lens are housed in Pelco Enclosure model EH5723-2)
[xix] Rainbow model G10 x 16 MEA Type-II
[xx] Rainbow model A-III
[xxi] Sony model PVM-97
[xxii] Chugai Video Cassette Recorder model CTR-480N
[xxiii] Sony FCB-IX470P with Cosmicar/Pentax lens model EX-ASP
[xxiv] Chugai Video Cassette Recorder model CTR-480N
[xxv] Super-Trak 12v d.c. lights model 758582
[xxvi] Matlab version 5.3
[xxvii] Type 1V14 and 1V15
[xxviii] Type MT-LB and BTR-60
[xxix] Type T-54, T-55, T-72, 69, and M-60