An Advanced Radiological Survey and Mapping System – 9359

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ABSTRACT

A variety of radiological surveying systems have been described in the literature. This paper describes relative performances of a system that can employ a variety of radiological sensors including NaI, LiI, and LaBr$_3$ units of various sizes. The system includes navigation and data collection software that facilitates surveying without the use of survey gridlines. Parameters presented to the operator via a graphical user interface (GUI) for monitoring system performance and navigation are described. Radiological spectra are logged along with position data from three differential GPS sensors to enhance position accuracy by taking into account the pitch and roll as the survey vehicle moves over uneven terrain. Accuracy of position data increases the potential for, and value of, data fusion with other survey data such as electromagnetic induction images.   The survey system described has been developed around a zero turn radius lawn mower equipped with on-board generator/inverter for powering electronic and data communication equipment to maximize surveying effectiveness.

Detection limits for U-238 will be discussed for the NaI (FIDLER, 75x75 mm, and 100x100x400 mm) and LaBr$_3$ (75x75 mm) detectors. These parameters will be reported for a variety of survey speeds (stationary, 1, 2, and 3 m/s), with and without the use of advanced signal processing to increase detection sensitivity. A background subtraction algorithm evaluating each spectrum for the presence of naturally occurring radiological materials will also be described for correcting each datum prior to mapping using Geosoft Oasis montaj.

BACKGROUND

Radiological surveys for locating contamination in the field have traditionally utilized hand-held portable detectors such as G-M tubes and a manual method of marking contaminated areas such as the use of flags or marking paint. This is a less than ideal way of characterizing an area due to the length of time the survey takes and the difficulty in ensuring complete coverage of an area. Also, traditional surveys have not incorporated spectral data, which is useful in isotopic identification, and which can yield information about whether or not the material is naturally occurring radioactive material (NORM). This being said, there are certain attributes that the ideal survey system should possess:

(1) *Detector optimized for sensitivity to the radiation of interest*. Survey systems can be developed for a variety of applications and it is essential that designs begin with selection of detectors capable of detecting and/or identifying materials of interest. Options for beta, X-ray, gamma, and neutron radiation include the following detectors:

- The FIDLER (Field Instrument for the Detection of Low Energy Radiation) is a thin-film NaI:Tl detector and was developed to increase detection sensitivity of NaI:Tl units to low energy gammas and X-rays and has been used in radiological surveys described in the literature.

- NaI:Tl crystals, available in various sizes and geometries, are useful for detection of gamma rays. The 75 x 75 mm (3x3") NaI:Tl detector has served as the baseline technology for field studies possessing an optimum blend of counting efficiency and energy resolution. The large 100 x 100 x 400 mm (4x4x16") NaI:Tl crystal, such as those used for uranium exploration and for DHS-related measurements, is costly but the larger crystal volume of this unit facilitates detection at lower depths than the 75x 75 mm crystal or FIDLER at faster survey speeds.

- The $LaBr_3$:Ce crystal is also useful for gamma detection and provides even greater sensitivity and energy resolution than the NaI:Tl. Recently available in crystal sizes as large as 75 x 75 mm, their only drawback is cost.

- Plastic scintillators are highly efficient detection units capable of beta and photon detection but do not provide energy resolution.

- Europium-activated Lithium Iodide (LiI:Eu) detectors are sensitive to gamma and X-rays and have a good absorbance cross section for neutrons. However, they have significantly less light output than NaI and are utilized more frequently for neutron detection.

- The ^{3}He detector is a gas-filled proportional detector widely used for neutron detection in industry for nuclear material measurements, neutron ambient measurements (Rem-counters), and for various industrial measurements such as soil humidity and oil prospection.

(2) *Isotope Identification*. Some survey systems are designed to simply identify areas of elevated count rates, but more sophisticated systems are also concerned with energy resolution. The detection system should be able provide good energy resolution of photons for positive identification of isotopes of interest and identify isotopes of interest for background subtraction. Detectors with better energy resolution for X- and gamma radiation include:

- The High Purity Germanium (HPGe) detector is currently the benchmark technology for energy resolution. However, the necessity to cool the detector to cryogenic temperature and the use of heavy shielding around the detector makes fieldability poor and makes it predominately useful as a lab unit only.

- $LaBr_3$:Ce detectors are not as influenced by temperature changes and function well even in elevated ambient conditions. Their ability to provide energy resolution that is between that of the NaI:Tl and HPGe and yet is equally as portable as the NaI:Tl detector makes them an ideal choice. $LaBr_3$:Ce detectors are approximately 40% more sensitive than NaI:Tl units and have energy resolutions much closer to that of HPGe detectors without requiring use of cryogenic liquids for cooling. This improved sensitivity and energy resolution allows them to be used for both identification of radioisotopes and quantification of their amounts. $LaBr_3$:Ce crystals (75 x 75 mm) have recently become available with their only drawback being cost.

(3) *GPS registration of data.* Systems developed using today's components need to include simultaneous collection of detection and position data. The data logging frequencies should be rapid enough to produce accurate maps of the area surveyed. An ideal system will store the full energy spectrum for each position. Positional accuracy of logging data is important for a variety of reasons. The ability to precisely identify the location of contamination facilitates removal and monitoring for in-place management. Additionally, it is often desirable to merge (fuse)

radiological data with measurements made by other technologies. Imprecise position data dramatically limits the ability to fuse data.

(4) *Real-time background subtraction.* Storing the full energy spectrum for surveys offers a distinct advantage for accomplishing background subtraction. The current method of conducting a background subtraction is strictly manual. Once the survey has been completed, data are manually processed by subtracting the average background count rates from an area presumed to be clean from values collected during the survey. This method can be dramatically improved by employing a near real-time assessment of the survey data to identify the presence of radionuclides other than the radionuclides of interest. This dynamic estimation of background levels can then be incorporated into the mapping process, thereby taking into account variability of background radiation across the surveyed area. This technique provides two important improvements: (1) identification of naturally occurring (background) radiation from the survey data will account for hot spots as opposed to assuming even background levels equivalent to a reference location, and (2) the algorithm can contain a component specifically designed to discriminate between NORM and the radionuclides of interest.

(5) *Enhanced low count rate capabilities.* Areas contaminated with long half-life isotopes pose a more difficult problem with respect to evaluating data in the field. Dealing with low count rates or difficult to measure radiation of the isotopes of concern frequently involves surveying for daughters possessing more prominent detection signatures. Advanced digital signal processing algorithms can be developed to facilitate identification of contamination where it might not have been previously possible. Two issues predominate the difficulties associated with detection and identification of low activity radionuclides. The low activity radionuclides make for low gamma ray fluxes for detection. Background concentrations of naturally occurring radioactive material (NORM) can easily overwhelm the detection signals contributed by low activity radionuclides. Discriminating these nuclides from naturally occurring uranium or other NORM emphasizes the need for good energy resolution. Advanced signal processing algorithms developed for remote sensing and other applications may represent a powerful tool for enhancing the performance of detection systems for low activity radionuclides.

(6) *Quality assurance and control measures.* Deployment to a site to conduct surveys is a major portion of the overall cost of the effort. It is highly desirable to be able to assess the data collected while the team is at-site to prevent a repeat trip for further investigations. An evaluation of data should include the following data quality parameters:

- The ability to verify proper survey speed thereby ensuring detection sensitivity of the survey is important. This parameter should be reviewed as part of the overall data quality assessment of the survey.

- The survey data should be reviewed to ensure that the entire area has been covered. Documentation should also be developed at site to identify areas that were missed due to rough terrain, vegetation coverage, etc.

- Detector calibration and gain control is a prerequisite to having defensible data and accurate isotopic identification. These parameters are to be included in the overall assessment of data quality for the survey.

- In-field review of data is important to be able to identify questionable findings to be repeated before leaving the area. Areas surveyed with ambiguous results should be identified and

additional survey activities conducted prior to leaving the site. These additional efforts may include surveying at slower speeds or collecting static measurements.

- Assurance of the continuity of GPS data is paramount to the software merge with radiological and other data, such as electromagnetic induction, for making maps. Data logging of GPS and radiological information is not simultaneous.   GPS data are prone to gaps due to atmospheric, terrain, and vegetative interference. Data are to be reviewed relative to pre-established parameters to ensure capabilities for data fusion.

(7) *Map a wide range of physical environments.* A robust system needs to be able to function in a variety of environments. This includes different terrain types, degrees of vegetative coverage, and weather conditions. Environments that may be encountered include those that are highly uneven, mountainous, flat, rocky, sandy, wet, marshy, having various amounts of vegetative coverage, and hot or cold climates. The motorized or pushcart systems described in this paper may not be ideal for all environments. In those instances, various other deployment platforms can be used such as a suspending a sling detector system from a helicopter or equipping a platform for remote operation.

SYSTEM DESIGN

Detectors. The survey system described in this paper is designed for detection and mapping of gamma-emitting radionuclides. With this objective in mind, the detectors used include four-3x3 inch (75 x 75 mm) $LaBr_3$:Ce detectors and a single 4x4x16" (100x100x400 mm) NaI:Tl detector like those shown in Figure 1. The $LaBr_3$:Ce detectors have been selected for their superior counting efficiency and energy resolution, and the 4x4x16" NaI:Tl detector has been included based on performance in earlier field studies. Use of both types of detectors allows head-to-head comparison, as well as taking advantage of the attributes of each detector. The detection hardware includes powering each detector with an ORTEC digiBASE that also provides ORTEC MAESTRO 32 multichannel analysis software. Each detector is interfaced with a computer via USB connections.
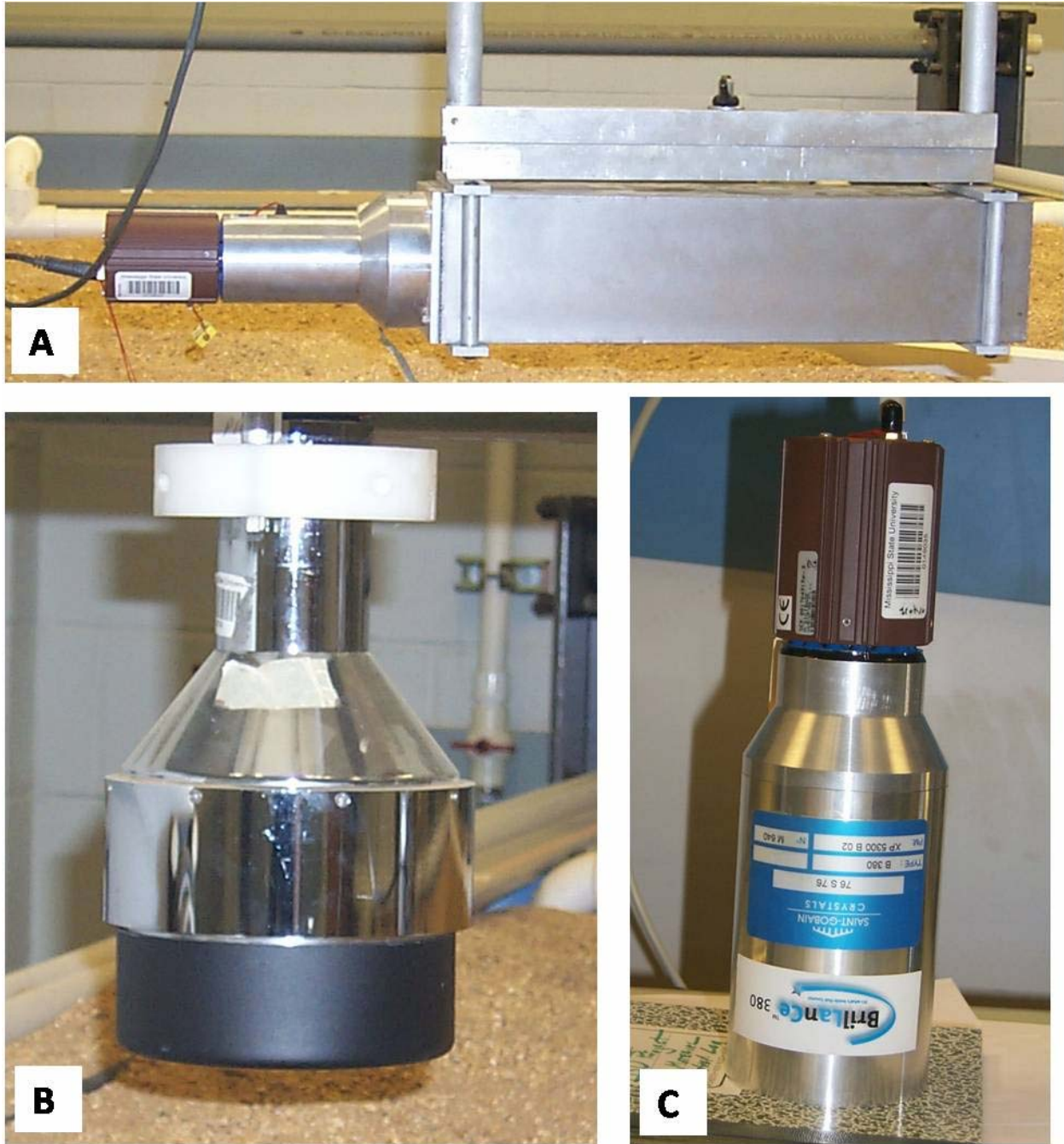
Fig. 1. 4x4x16" NaI:Tl detector (A), FIDLER detector (B), and LaBr$_3$:Ce Detector (C).
Deployment Platform. The deployment platform selected for conducting surveys may change as a function of terrain, level of vegetation, environmental conditions, or presence of hazards such as UXO. It is unlikely that a single deployment platform can suffice for all survey conditions at sites and the system described in this paper has been designed for deployment on two different platforms. The first is a zero turn radius (ZTR) mower that provides maximum maneuverability in the field but may be limited in very irregular terrain. Another strength of this platform stems from its hydraulic drive and steering system. Steering control arms regulate valves on the hydraulic pumps driving the rear wheels. This configuration lends itself to easy modification for remote control of the unit.

Figure 2 (A) and (B) shows the completed system based on a ZTR mower. The system is built on an Exmark ZTR mower and has been equipped with differential GPS equipment and both NaI:Tl and LaBr:Ce detectors. Ground clearance for the detectors is 15 cm (6 inches), and these units are protected by steel enclosures offering an unobstructed view of the ground. The mower deck has been removed to allow room for installation of the detector system and a generator to be installed under the engine. Figure 2(A) shows the location of onboard electronics including an inverter, computer, and power strip for auxiliary units.
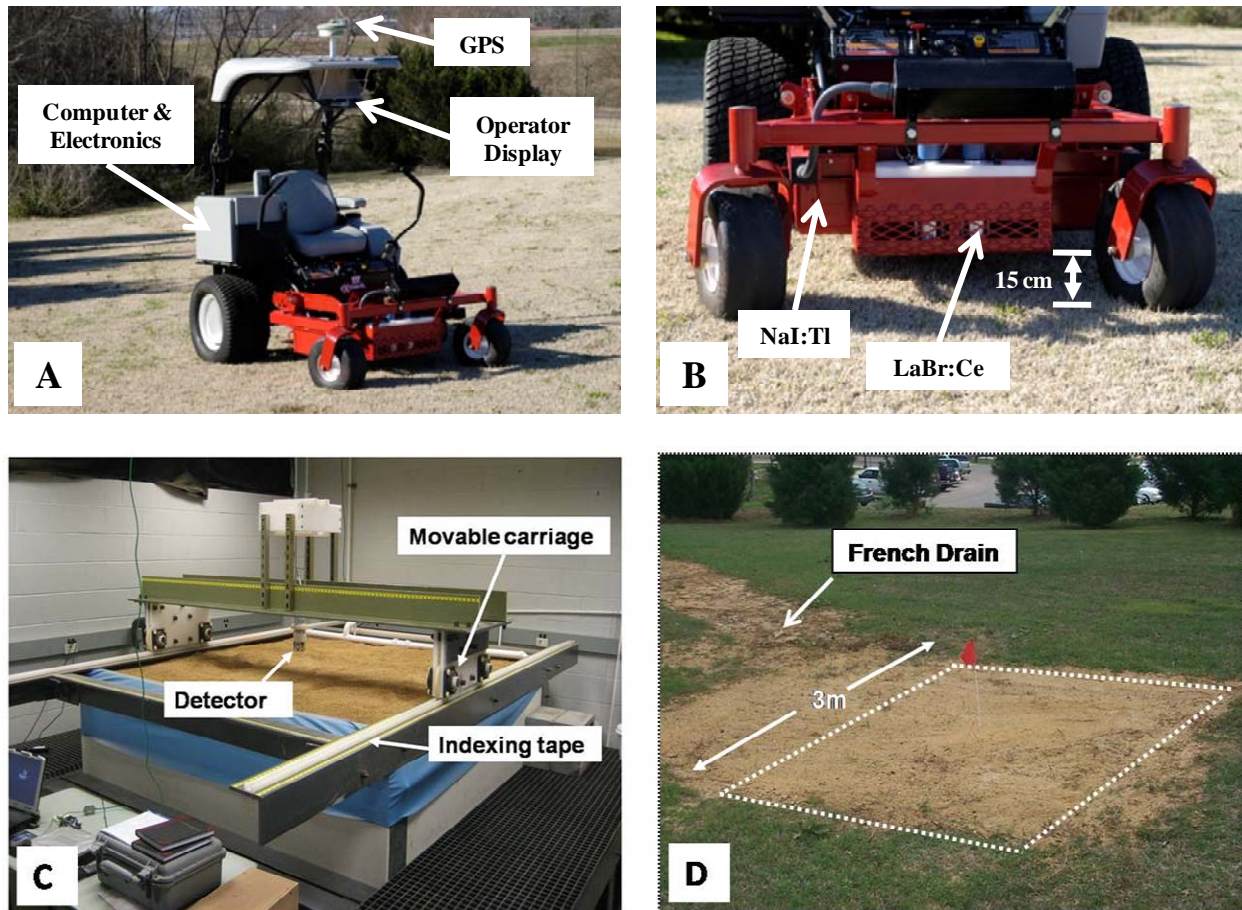

Fig. 2. Survey Platform (A), Detector Cage and Ground Clearance (B), Indoor Sand-Filled Test Bed (C), and Outdoor Sand Pit (D).
Figure 2 also contains pictures of test beds that have been employed to collect libraries of data for system development and for detector testing.

There are areas to be surveyed where a ZTR unit will not be able to navigate. An alternative platform has been selected for use in those applications, a rugged three-wheeled jogging stroller. The 3-wheeled jogger requires extended life battery units to provide power.

Figure 3 provides additional pictures of the ZTR system hardware. Figure 3(A) shows the location of the large NaI:Tl detector including an ORTEC digiBASE. Figure 3(B) shows the interior of the weatherproof electronics box. A ruggedized computer is used for system control and data storage. The pouch attached to the lower right portion of the electronics box contains a wireless keyboard for altering user defined setting or troubleshooting the system. Figure 3(D) shows the display panel suspended from the roof that

routinely displays the system dashboard but can also serve as the display for the computer, allowing maximum flexibility for the user while in the field.
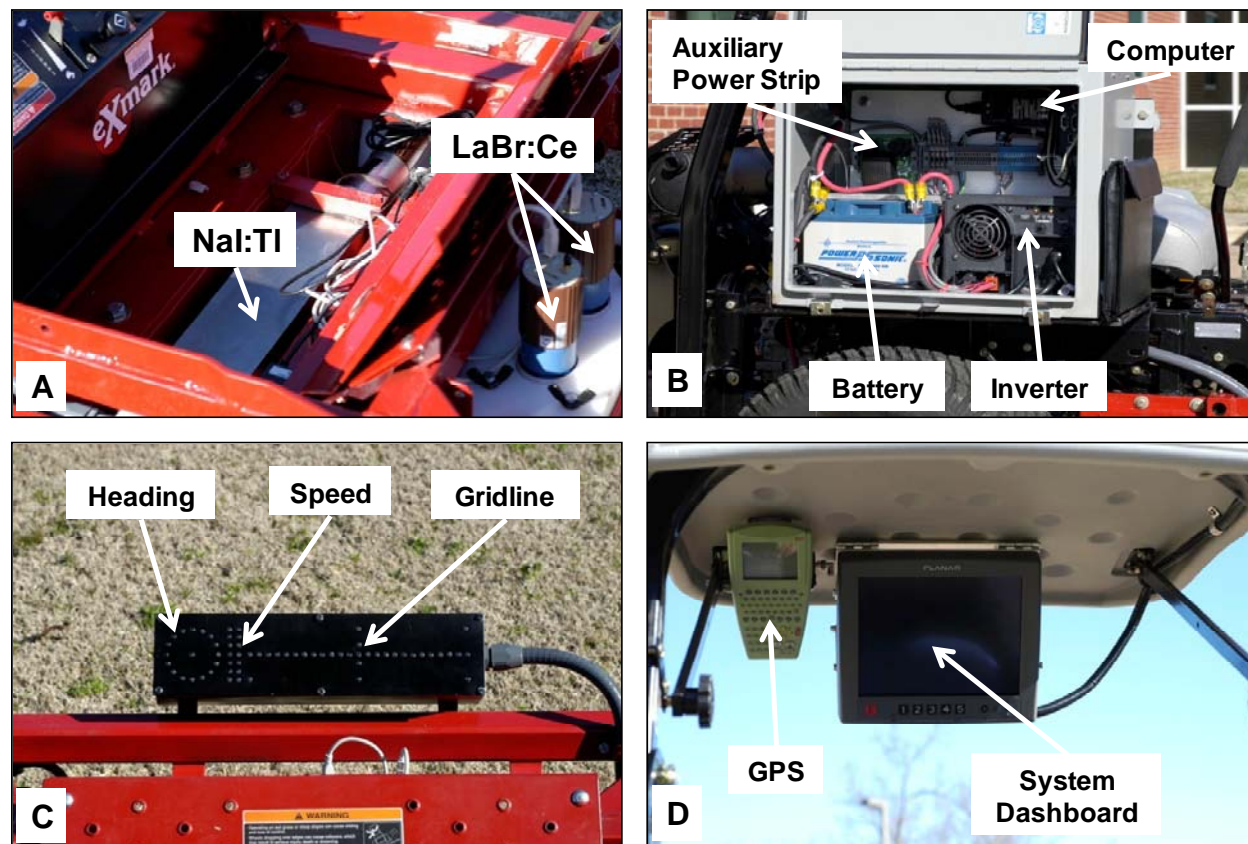

Fig. 3. Detectors (A), Electronics (B), Navigation Bar (C), Operator Displays (D).

Figure 3(C) shows the navigation bar that provides the equivalent of a heads up display for the operator. One of the important additions to this system is the ability to conduct gridless surveys. A map of the area to be surveyed can be entered into the computer and the spacings of gridlines specified. The computer uses the navigation bar to provide the user with all of the information necessary to regulate speed and direction. The circle of lights on the left gives headings where very coarse direction changes need to be made, such as when moving from one area to another or return to where the survey was stopped. The vertical array of lights (center grouping) provides a speed indication with alerts for traveling to fast. The horizontal array provides steering guidance to allow the operator to accurately follow the survey gridline.

System Software. The operator of the system maintains control of detectors and all ancillary equipment using a suite of software packages that have been developed by MSU researchers. The individual software packages can be categorized under one of three general headings: (1) data collection, (2) navigation, and (3) supervisory functions.

Detectors. The ORTEC tool kit has been used to develop an interface with the gamma spectrometry instruments to control, monitor, and log the time and energy level of all observed gamma events. This module of the software also manages all communications, calibration, data logging, and status monitoring and logging. The most important control parameters are provided to the system operator via the graphical display shown in Figure 3(D) consisting of the real-time spectra and instrument status.

GPS Units. Software for interfacing with positioning instruments manages the linkage between system

computer and GPS antenna. This software package controls and logs data from one or more high accuracy differential GPS units, and also controls inertial (accelerometer/gyro) and magnetic (digital compass) guidance components. Position data as well as instrument status are logged and displayed.

Communication with GPS satellites is by line of sight so that mountainous terrain or working under a canopy of vegetation can reduce the ability to establish positional data for individual measurements. Inertial and/or magnetic systems are used to augment GPS systems to aid positioning in such areas. The system being described in this paper is equipped with a magnetic system serving double duty by also enhancing navigation during gridless surveys.

Navigation. Software capable of providing navigation assistance to the survey operator has been developed. Most surveys are conducted by establishing grid lines with either string or painted lines at spacings of one meter to guide the process of collecting data. This effort is quite time consuming, and a great enhancement to survey efficiency is to include an on-board navigation system to allow the operator to conduct a gridless survey. The system developed includes the potential to display a graphical map with the ability to overlay local topographic maps, aerial photographs, or any arbitrary digital image. The operator has the ability to input the corners of the desired survey area and have an efficient survey path displayed on the map. During survey operations the software displays graphic "swathing" to show the operator which areas have already been surveyed and reveal areas that have been missed.

Supervisory Functions. Software has been developed that can provide supervisory functions to insure that all subsystems have been properly configured and are operational throughout the survey. A pre-survey checklist is included in the operator interface to insure that all instrument configuration, calibration, and setup has been completed before the survey begins. During survey operations the software monitors all subsystems and provides graphic and/or audible indication of malfunctions that might occur.

Data Merging. A software module capable of providing a data merge function that prepares data for analysis in commercial data mapping software (Geosoft Oasis montaj) has been developed. Position and gamma spectrum raw data are merged into a single file consisting of XY(Z) position and gamma spectra.

A software package has also been developed that provides the capability to remotely monitor progress of a survey which increases the overall effectiveness of a survey. Wireless networking components allow a user at a remote computer to monitor the position, speed, and area covered as well as conduct rudimentary mapping of the gamma activity of the survey site.

Advanced Digital Signal Processing. MSU researchers have also developed a set of digital signal processing algorithms to enhance identification of selected isotopes under low count conditions. A library of DU detection data has been collected using NaI:Tl and $LaBr_3$:Ce detectors and DU penetrators under a variety of soil depths and measurement times to completely evaluate their performance. These data have been employed to facilitate evaluation of advanced signal processing algorithms for the $LaBr_3$:Ce detectors. Data have been collected with DU penetrators, naturally occurring uranium ores and oxides, and commonly encountered naturally occurring environmental radionuclides (K-40, Th-234, and Rn-222).

The spectra contained in this library have been used to evaluate the performance of at least four different mathematical treatments to enhance identification of individual radionuclides. The intent of employing advanced signal processing algorithms is to enhance current detection systems performance in identifying the presence of contamination at greater depths or at lower concentrations, more effectively resolve contamination from the presence of NORM, and accurately estimate depth of material in order to better estimate the amount of contamination present. The techniques include the wavelet method, matched filter method, Gaussian Mixture Model, and a Z-transform technique. The current technique being used by the

survey system is the matched filter method; however, it is hoped that the Gaussian technique will prove the more robust technique when used with energy spectra from the $LaBr_3$:Ce detectors.

SYSTEM PERFORMANCE
FIELD STUDIES

The ultimate output for a radiological survey should be a map that clearly and accurately identifies the location of areas with count rates above background. Survey accuracy for mobile or self-propelled systems is dependent on a variety of parameters including: linear rate of travel, completeness of areal coverage, calibration of detectors, and accuracy in determining/logging location information.

The faster the rate of forward speed, the higher the detection limits. Identifying an optimum speed and providing the operator with a means to maintain that speed will maximize the area covered per unit time while preserving detection accuracy. Determination of an appropriate survey speed requires establishing a target detection limit for the system. This must include a given activity/mass of the isotope of interest, geometry of the source, and depth below ground surface (or equivalent distance/shielding considerations). Once these parameters have been established, testing can be accomplished to establish the optimum survey speed.

Figure 4 provides an example of how this has been determined for the MSU system. This figure displays a false color survey map and a plot of count rates for a specific path of data. The map
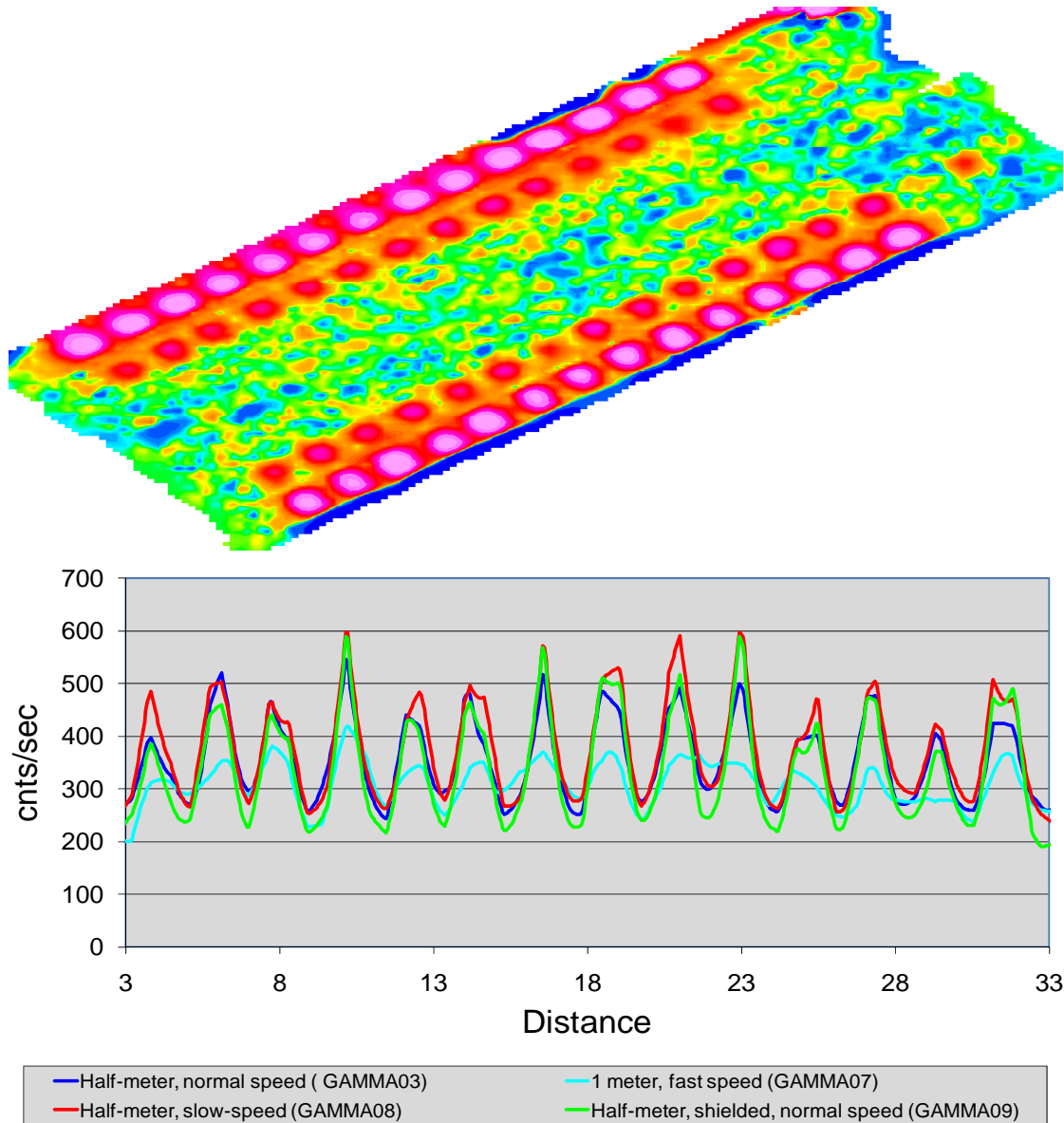
Fig. 4. Map of YPG DU Garden (top); Plot of total counts per second (FIDLER) versus linear distance for DU penetrators buried at a depth of 30 cm in the YPG DU Garden (bottom).

shows where individual radioactive articles were placed at different depths. The outside set of rows showing pink signatures had targets buried at 4 cm and the inside rows (red) had equivalent targets buried at a depth of 30 cm. The map was generated from data collected at a linear survey speed of 2 m/s.

The plot included in Figure 4 shows the total count rate collected when the system made equivalent paths through the test area at one of three different speeds: slow (1 m/s), medium (2 m/s), and fast (3m/s). The survey speed selected as optimum based on these data was 2 m/s. The navigation bar shown in Figure 3 is used to provide the operator with speed and heading information necessary to successfully complete a gridless survey. The system has the ability to review all survey data and identify any areas surveyed at speeds exceeding a user defined linear rate.

False positives and false negatives are concerns for any radiological survey system or process. Clearly, there is a depth beyond which detection is not possible, virtually regardless of the strength of the source. The survey system described in this paper has been developed to extend the detection sensitivity for DU as much as possible while still maintaining a reasonable survey rate. The detector height of 15 cm was selected as an optimum compromise between counting efficiency and ground clearance. Survey speed of 2 m/s was selected, as shown above, because faster speeds led to significant decrease in detection.

CONCLUSIONS

Characterizing the performance of a new technology is best accomplished by comparing it to a baseline technique or technology. Little data has been located in the literature for what may be considered the radiological surveying baseline, other than use of hand held survey meters.

UNEP reports from DU field studies conduced in Kosovo and Serbia indicate that a reasonable survey rate for hand held units is approximately 2 m^2/min. The current system being described here has the ability to exceed that by a factor of 10 when gridlines are manually laid out. The gridless system is even more efficient and requires less manpower to complete.

Field deployments to at least two DoD facilities are scheduled for the next six months. Activities conducted during these trips will provide additional information to quantify the performance with respect to a set of parameters that have been identified to characterize the technology for DoD use.

Minimum Detection Limit. The current configuration of the system will undergo optimization for detection of depleted uranium (DU), with detection limits specified for two masses of metallic (zero valence) DU at depths of 30 and 45 cm. Further, these MDLs will be identified for a given linear speed of 2 m/s for the survey using one-meter grid spacings.

Incidence of False Positives/Negatives. The incidence of false positives and negatives is stated for specific test and survey conditions. These values are established by conducting repeated surveys over an area with known masses of zero valence DU buried at known depths. Surveys will be conducted by a variety of operators with varying degrees of experience with the system.

Matrix Effects. The effect of soil moisture, soil consolidation, and soil composition on detection limits on detection limits and incidence of false positives and negatives will be stated for two different masses of zero valence DU at given depths.

Survey Rate. The number of square meters per hour that can be surveyed by the system will be specified. This will be a time weighted average value determined for an eight-hour period. The survey rate will include time spent servicing the unit.

Service Duty Cycle. The length of time that the system can be deployed before servicing (exchanging batteries, refueling, down-loading data, etc.) will be specified. Additional information regarding the amount of time required to conduct these servicing activities will be included. Any routine maintenance or calibrations that need to be conducted at the beginning of the day or at specified times during the day need to be specified along with the number of persons needed to accomplish the task(s) and the time required.

Performance in Various Terrains and Environmental Conditions. Specific limitations of the deployment platform and detector system will be identified. This will include a description of terrain or

topography that restricts application along with environmental conditions (temperature, weather, day/night, vegetative cover, etc.).

Positional Accuracy. The accuracy with which detected material is positioned on a survey map will be evaluated. This will be determined by collecting multiple surveys of an area containing known masses of DU buried at known depths. Data sets will be collected by a variety of operators with varying degrees of system experience. Maps will be generated using Oasis montaj, and data from these surveys will be evaluated for positional accuracy of the individual DU targets.

Operator Training. Multiple surveys will be conducted a highly experienced operator for comparison with a set of surveys conducted by personnel with much less experience. Maps prepared from these data sets will be compared to known position data for the DU targets to determine the degree to which operator experience impacts data quality.

Field Review of Data. The ease with which data can be reviewed while the survey team is still in the field is important. The review of data will also include information on the time, personnel, and equipment/setting required to accomplish the data review.

System Transportability. Surveys will almost invariably require deploying equipment to a site to conduct the survey. An indication of the ease with which a deployment can be made requires information on steps that must be taken to package equipment for deployment, any special arrangements that are necessary (permission to transport and use calibration sources, etc.), and a description of equipment needed to accomplish the transportation (trailer, truck, etc.). Finally, it is also important to specify the number of persons and length of time required to prepare equipment for use once it has been delivered to the survey site.

Supporting Equipment. Different technologies require different types and amounts of supporting equipment. A listing of all materials and equipment necessary to support a field deployment of several days is identified. This will include tools, spare parts, consumable supplies, etc.

ACKNOWLEDGMENT

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