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Development of Autonomous Magnetometer Rotorcraft For Wide Area Assessment

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ABSTRACT

Large areas across the United States and internationally are potentially contaminated with unexploded ordinance (UXO), with some ranges encompassing tens to hundreds of thousands of acres. Technologies are needed which will allow for cost effective wide area scanning with 1) near 100 % coverage and 2) near 100 % detection of subsurface ordnance or features indicative of subsurface ordnance.

The current approach to wide area assessment is a multi-level one, in which medium - altitude fixed wing optical imaging is used for an initial site assessment. This assessment is followed with low altitude manned helicopter based magnetometry. Subsequent to this wide area assessment targeted surface investigations are performed using either towed geophysical sensor arrays or man portable sensors. In order to be an effective tool for small UXO detection, the sensing altitude for magnetic site investigations needs to be on the order of 1 to 3 meters. These altitude requirements mean that manned helicopter surveys will generally only be feasible in large, open and relatively flat terrains. While such surveys are effective in mapping large areas relatively fast there are substantial mobilization/demobilization, staffing and equipment costs associated with these surveys, resulting in costs of approximately $100-$150/acre. In addition, due to the low altitude there are substantial risks to pilots and equipment. Surface towed arrays provide high-resolution maps but have other limitations, e.g. in their ability to navigate rough terrain effectively.

Thus there is a need for other systems, which can be used for effective data collection. An Unmanned Aerial Vehicle (UAV) magnetometer platform is an obvious alternative. The motivation behind such a system is that it reduces risk to operators, is lower in initial and Operational and Maintenance (O&M) costs (and can thus potentially be applied to smaller sites) and has the potential of being more effective in terms of detection and possibly characterization (through the use of dynamic acquisition, i.e. survey mission in- flight reprioritization).

However, while UAV data acquisition from fixed wing platforms for large (> 60 meters) stand off distances is relatively straight forward, a host of challenges exist for low stand- off distance (~ 2 meters) UAV geophysical data acquisition. This paper discusses the challenges associated with construction of an effective autonomous UAV magnetometer platform and demonstrates that construction of a successful autonomous UAV magnetometer platform is feasible through a "modular system" approach using readily available components and technology. The paper further discusses the results of testing of surrogate UAVs used to demonstrate key technologies necessary for successful deployment of autonomous unmanned magnetometer rotorcraft for wide area surveys.

Key Words: UAV, Rotorcraft, UXO, Autonomous, Magnetometer, Terrain Following

1 INTRODUCTION

In order for UAV rotorcraft systems to be applicable and relevant to UXO sites two conditions must be met: one, these systems must either allow for acquisition where current sensing modalities are not feasible or provide a benefit in cost, performance or data quality over these existing modes and two, the expected performance envelope of these systems must map to a substantial percentage of UXO sites.

1.1 UAV Rotorcraft Performance

There is a significant experience within both the Department of Defense (DoD) and a number of commercial companies on the cost, performance and data quality associated with the three primary modes of geophysical data collection at UXO and MEC (munitions and explosives of concern) sites: manually carried sensors, towed systems/carts and manned helicopter systems. It is thus important to formulate expectation on cost, performance and data quality for an UAV rotorcraft system, which can be compared against existing sensing modalities. This serves two important objectives; first, it provides a initial insight on what such a system can do, and second, such an expectation can be used to guide rotorcraft choice, the number and configuration of magnetometers, as well as the performance specifications of one or more prototype systems.

1.1.1 Cost

The cost of deploying a system can be separated in three areas; depreciation, mobilization, and operational costs. Depreciation costs are a function of the initial system cost and the effective life and use of the system. The initial system cost will obviously depend strongly on the component choice of the system. Rotorcraft systems can range from several thousand dollars to about $60-80 K for the upper end of the spectrum. Similarly, the magnetometer cost will be linear with the number of magnetometers in the sensor array, which could range from two to eight, and will also be dependent on the type of magnetometer selected. Based on what is currently known, (and realizing that component costs are likely to change over the coming years) we feel that for an operational system produced in modest quantities the lowest achievable initial system cost would be about $120 K for a system with two magnetometers and up to about $250 K for a system with eight magnetometers. Note however that with judicious design some or most of the components may be swappable between systems. The effective life of a system is estimated to be three years. This is likely to be conservative and some components are likely to have a longer lifespan. However, based on this (and ignoring some other factors), a yearly depreciation cost would be around $40K to $80K. If a system sees use for 60 days a year, the depreciation cost would be some 600 to 1200 dollars a day[1].

The mobilization costs are dependent on the size of the system. Several of the rotorcraft candidates could be shipped by commercial carriers at modest costs (few hundred $). Larger systems, (such as the Mosquito shown below in figure 1) would require transportation in a dedicated trailer or flatbed, with mobilization costs dependent on the distance, but typically in the order of $2K.

The operational costs depend on the number of acres per day that such a system would cover, the number of operators (and the skill level of operators) required to operate this system, and the O&M costs (mainly fuel). We consider here the operator cost. As discussed in the performance section below, we expect that systems like this would be able to cover between about 5 and 20 acres an hour (dependent on configuration). As these systems are autonomous, they do not require licensed pilots (like manned helicopter systems require), and in theory operators would require only limited skill sets. Note that one of the issues which would need to be decided is whether operators need to be able to remotely pilot the rotorcraft (which is a non-trivial skill), or whether they are essentially there to push a stop button which would automatically abort the mission and return the rotorcraft to base. We currently estimate that we would need two operators at a burdened cost of $600/day each.

1.1.2 Performance (acres/day)

The performance of UAV rotorcraft systems is given by the combination of the system speed, the flight path spacing and the effective number of hours per day that such a system can fly. The following numbers are an educated guess based on the experiments and the data collected.

Table I. Estimate for performance of two different configurations and 25% flight line overlap

	Configuration 1	Configuration 2
Speed (m/s)	5	10
Number of magnetometers	3	7
Sensor spacing (m)	0.5	0.5
Array width (m)	1	3
Flight path Spacing (m)	0.75	2.25
Acres/day (6 hr flight time)	20	119

In table I we give our best guess estimates for two different configurations using a path overlap of 25 %. Table I assumes a rotorcraft with a fairly decent payload capability (including fuel required for flight time). While the exact payloads for each configuration can vary based on the final component choice, configuration 1 will likely require at least a 40 lb payload, and configuration 2 at least a 60 lb payload. Of course, more payload translates in more fuel and flight-time.

It is obvious that by playing with the different numbers one can change the bottom line substantially. Arguments can be made to substantially change the numbers for each

[1] Cost estimate based on 2009 market values.

configuration. For instance, terrain topography and system responsiveness to obstacles will significantly impact the attainable speed

With current manned systems a flight-line overlap of 25-40 % is a typical number used in survey design and execution to provide confidence in the ability to get complete coverage. The amount of overlap required for autonomous rotorcraft helicopter to avoid coverage gaps will be dependent on a number of factors. These include the navigation accuracy of the combined sensor suite and navigation filter, latency in both the measurements and the control system, the speed of travel, the control power available and the bandwidth of control achieved on the helicopter, the helicopter's mass properties and aerodynamics, and the atmospheric conditions.

No attempt was made in the current control software to optimize the autopilot installation and control loops to achieve the best possible tracking of lines in the horizontal plane, and no tests have been performed that provide any meaningful measure of what level of tracking performance has or ultimately can be accomplished in this regard. Thus, for the purpose of generating initial estimates, it is appropriate to employ the overlap requirement typically employed in manned helicopter operations (e.g. 25%). However, it is anticipated that with the right combination of equipment and fine-tuning, the required amount of overlap to ensure no gaps in sensor coverage when employing the unmanned helicopters could be significantly less than this.

1.1.3 Performance (data quality)

The testing shows that under good condition a helicopter-based system can collect datasets with comparable quality and noise to that of ground-based datasets. Data was collected at relatively slow speeds (~ 3 m /second), required by the 20 Hz acquisition rate of the Geometrics G823A Cesium magnetometers used for the data acquisition, however it is likely that similar data quality would be attained at higher speeds.

It is possible to detect small targets such as individual golf ball sized submunitions (BLU 26s) and 60mm mortar rounds. So long as the data quality is high, parameters such as magnetic dipole moment and orientation can be obtained through automated inversion methods, and these parameters can be used to adjust the ordering of a list of anomalies in terms of ordnance likelihood. Although magnetic data alone are usually insufficient for reliable discrimination in mixed ordnance sites, even a modest improvement in dig list ordering obtained through analysis of inversion results can cut field remediation costs. If discrimination becomes a high priority for autonomous survey platforms, one option is to add one at a time or frequency domain electromagnetic (EM) system combined with a cued survey approach in which the unmanned helicopter can switch to a slow speed mode and collect high-density data around a suspected target using a hover mode. While this effort was outside the scope of this effort, the technologies required for autonomous rotorcraft magnetometer systems would provide a natural basis for autonomous rotorcraft EM systems.

1.2 Field Site Applicability

We currently conceive of two potential types of systems, which can cover 20 to 100 acres per day. A database with the results of a recently completed survey of available FUDS (formerly used defense sites) site characteristics was provided by the SERDP office (http://www.serdp.org). This database has information on 2514 sites, containing information on site location, site size, topography, vegetation and types of ordnance. It should be noted that this database does not break out any detail for large sites (in which there is likely to be a range of topographies and vegetation). Thus, the information in this database can only be used as an indicator. It states that over 50 % of sites have between 10 and 1000 acres. One thousand acres is typically considered the current lower limit of application of a manned helicopter airborne system but unmanned autonomous systems with the capabilities would be well suited for surveys of these and smaller sites. While manned helicopter systems are currently likely to keep on dominating for surveys of large, flat sites, it is conceivable to apply autonomous rotorcraft systems to selected portions of large sites.

1.3 Feasibility of Modular Approach and Component Availability

The feasibility of a modular approach to the design of autonomous UAV rotorcraft magnetometer systems depends on the availability of mature components, including; rotorcraft which lend themselves to RC control/control by an autopilot, rotorcraft autopilots and control laws and magnetometers which can collect data at sufficient acquisition rates.

Obviously there are a number of other components, which are part of such systems (RTK DGPS, laser altimeters, communication hardware and so on). While it will be important to select components, which have favorable characteristics in terms of power use, weight and accuracy, finding such components is relatively straightforward.

A large number of rotorcraft exist which can be controlled by an autopilot (which typically uses the same control interface as used by a Remote Control (RC) interface. New and enhanced rotorcraft, which integrate novel technologies and materials continue to come on the market and are used interchangeably for hobby purposes, commercial applications and R&D. One way to consider rotorcraft candidates is by grouping them into five basic size categories;

1. Nano scale - systems less then 1 lb
2. Miniature – 1 lb – 5 lb
3. Small – 5 lb to 50 lb
4. Midsized – 50 lb – 300 lb
5. Large – 300 lb+

The nano scale systems cannot carry much payload, perhaps a very small camera or an infrared sensor, and are limited in operating range and flight duration. Miniature scale systems, while a little larger, can carry some bigger payloads but are still limited in range and capability and do not form realistic candidates. Therefore, our focus has been on the three size categories capable of deploying useful payload, that of a payload of 2lb and larger and a useful operating range. Note that a payload of 2 lbs does not allow for a full-fledged system, but is useful to investigate e.g. terrain following or obstacle avoidance abilities. As such abilities can be transferred between categories this allows development on one type of (cheap) hardware before deploying to more expensive hardware.

Earlier efforts[1] had focused on integrated systems such as the Yamaha Rmax or the Neural Robotic Autocopter. However, in this effort we chose a modular approach. For this modular approach we only required the availability of RC controllable rotorcraft. Multiple such systems exist, including the Maxi Joker, the Mongoose and the Mosquito. Figure 1 show the Maxi Joker, Mongoose and Mosquito rotorcraft.

Figure 1, (left to right) Maxi-Joker, Mongoose, Mosquito

1.4 Autopilot/Control Laws Availability for Modular Systems

Due to the complexity of controlling system stability, the first successes in autonomous flight of UAV helicopters only occurred in the late 1990s[2]. Since then several commercial platforms have been developed which offer autonomous flight capability. However, only recently have autopilots with generic rotorcraft capability become available. For our tests we selected an autopilot that was developed through collaboration between Cloud Cap Technologies and Guided Systems Inc. This controller is known as the Piccolo II with rotorcraft capability. The controller uses Guided Systems developed Neural Network control laws to control the rotorcraft, and by an adjustment of the control laws to a specific rotorcraft the adaptive controller can control a broad range of rotorcraft. Specifically, the Piccolo II has successfully flown an electric powered Maxi- joker (both without camera and with camera), a gas powered Mongoose, Logo, Leptron Aggressor, a Vario XLC, and the Bergen Industrial Twin. The Piccolo will be flown on the Mosquito in the near future.

1.5 High Acquisition Rate Magnetometers

One of the primary needs for airborne data acquisition is the availability of high quality magnetometers, which can be sampled at sufficiently high sample rates. What "sufficiently high" means is still to be decided, but it will likely be in the order of several hundred Hz. For this effort Geometrics G823-A units were used with a maximum sample rate of 40 Hz.

2 FEASIBILITY OF MODULAR APPROACH

In order to assess both the feasibility of modular component integration into a system and the performance of different aspects of autonomous UAV rotorcraft, several field-testing efforts were undertaken. First, the feasibility of an autonomous UAV rotorcraft to perform terrain following and support magnetometer integration on an autonomous UAV rotorcraft was assessed. Second, the determination of the flight controller's performance to a boom structure mounted on an autonomous UAV rotorcraft was evaluated. Lastly, collection of high quality magnetic data from modular "Helimag" system was completed.

These tests were successful in their respective objectives. From this we conclude that both our original premise (that autonomous UAV rotorcraft magnetometer systems can be successfully constructed) and the premise investigated in this report, (that a modular approach is likely to be the most successful one) are correct.

2.1 Autonomous Terrain Following

The ability to autonomously terrain follow is a critical one. It requires that the controller utilize input from a real time height sensor into the control of the rotorcraft in such a way that the system follows terrain in a way which maintains an as constant as possible height above ground.

Because terrain following algorithms is integral to the flight controller, Guided Systems was subcontracted to provide this capability. This system was used for a number of test flights. Figure 2 presents a representative flight test result from the flight-testing of closed-loop above-ground -level (AGL) altitude tracking conducted with the Mongoose unmanned helicopter.

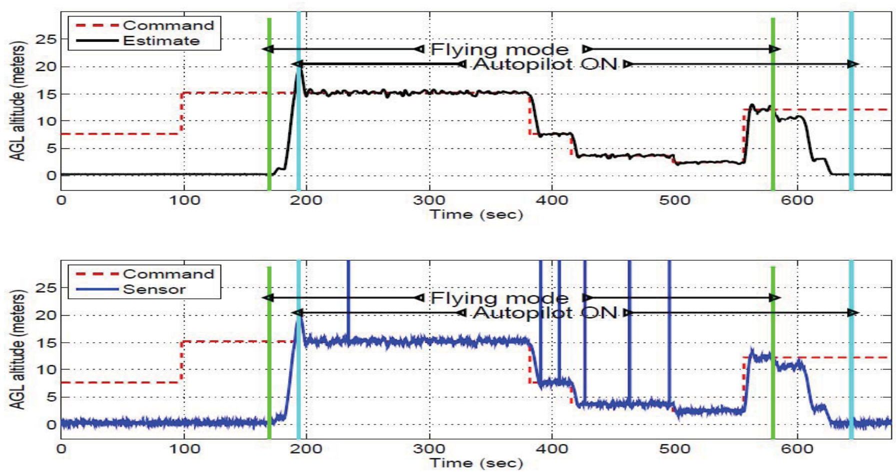

Figure 2 Initial flight test results of closed loop AGL tracking using Mongoose unmanned helicopter (filter output above, raw laser output below).

The upper half of Figure 2 presents the time history of both commanded and measured AGL altitude for one of the flight tests. The measurement plotted is the estimate of AGL altitude produced by the navigation filter, which forms a best estimate using the raw range data from the laser altimeter combined with inertial sensors and GPS. The entire flight operation from take-off (at about 180 seconds) to landing (at about 630 seconds) is shown. The lower portion of Figure 2 presents data for the same flight, again comparing the commanded height above ground and the response, but this time presents the raw height data being output by the laser altimeter in blue. The laser altimeter output is combined with inertial sensor data and a single point GPS solution to build an estimate of AGL altitude. No attempt was made to optimize the filter or controller performance to meet a specific requirement, and no evaluation was made of the influence that a precision GPS solution would have on the AGL estimate. In fact, the filter parameters where chosen such that step changes in altitude, as might occur when passing over a man-made object purposely placed on the field as a target, are smoothed. The laser sensor is a single point unit fixed in the airframe (i.e. it does not scan over an area and produce an average). The laser does not see through vegetation as radar can. The laser thus instantaneously “sees” the vegetation on the ground at a single point and its output includes the noise created by flight over this vegetation in motion, since the vegetation is being disturbed by the rotor downwash.

Subsequent to the tests described above (which used the Mongoose) a test was performed which combined terrain following and real time magnetic data acquisition. For this test a Maxi

Joker was used. This platform is equipped with a Gimbal Pilot, which employs the same electronics and software as the Guided System Piccolo II autopilot. An Applied Physics 534D three-component fluxgate magnetometer and a 30 Hz altimeter were also mounted on this platform. The data stream of the Applied Physics magnetometer was integrated into the Piccolo autopilot communications. This enabled us to stream sensor data directly to the ground station recorder during flight. The capability for terrain following which was developed on the Mongoose was integrated (in about 4 days) on the Maxi Joker controller (demonstrating the portability of code as well as the advantages of modularity). A test flight was performed to demonstrate terrain following capability and data acquisition. The results are shown in Figure 3. Figure 3 shows a composite picture of the results of two flights with terrain following turned on and off, while figure 4 only shows the terrain following flight. For the terrain following flight shown in figure 3 the controller was commanded to hold altitude starting at 8 ft above the ground and fly from a GPS waypoint on the left to a GPS waypoint on the right of the image and back again. Subsequent to this, terrain following was turned off, and the same flight was repeated.

Figure 3 Results of terrain following test using the INL Maxi Joker comparing terrain following flight vs non terrain following flight.

Figure 4 Composite image of the terrain following flight

As part of the terrain following tests with the Maxi Joker, magnetic data was collected and streamed in real time to the UAV Operator Control Unit. To assess the performance of the magnetic data acquisition data was collected both at 8 ft and 6 ft above ground. In order to obtain a clear magnetic signature data a trailer with some metal was placed underneath the flight path (Figure 5).

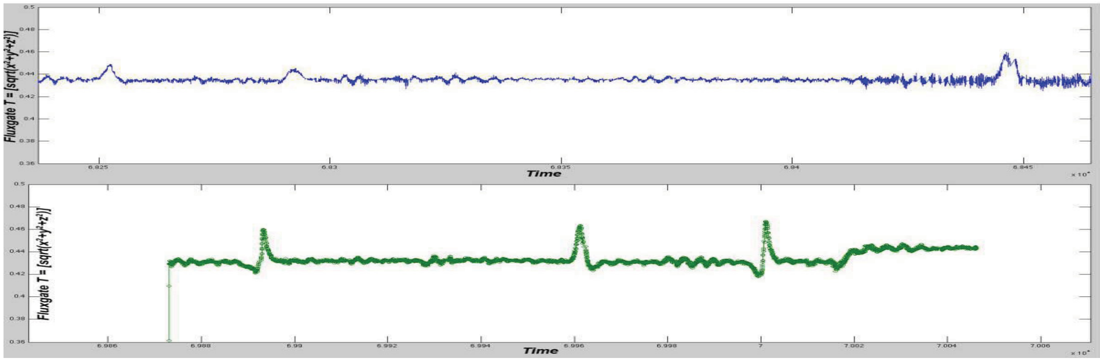

Figure 5 Value of magnetic field at different altitudes. Top: result of flight at 8 ft. above ground at 2 Knots. Data peaks correspond to the helicopter passing over the trailer. The speed was changed from 2 to 1 Knot for the second part of the first test. Bottom: results at 6 ft. above ground with a speed of 2 Knots.

Figure 5 shows the results of test flights at 8 ft and 6 ft above ground. During these tests the helicopter flew over the obstacle multiple times. The value of the total magnetic field is shown.

2.2 Helimag System Testing

The objective of this activity was to assess the capability of the autonomous UAV rotorcraft controller to adapt to the sensor boom mounted on the UAV and also to show the ability to collect high quality magnetic data from modular Helimag system. Because of available funding levels the latter portion of this test was flown manually. Extensive planning was undertaken to ensure that all data collection objectives were met.

2.2.1 Mongoose Scale Boom Flight Tests

To accomplish the first portion of this effort, the Mongoose system owned by Guided Systems was equipped with a scale sensor boom. The boom was designed by Geometrics and constructed by INL. The boom did not have any sensors integrated in it, but was meant to be a prototype of a boom which would be utilized on this class of rotorcraft. Test flights were conducted to assess the stability of the system with a boom as well as to collect more data on the ability to do terrain following.

Figure 6 Mongoose with boom in flight

Figure 6 shows the Mongoose with the scale boom in flight. The addition of a boom to the helicopter significantly altered the helicopter's mass properties and flight characteristics, especially for a relatively small helicopter. The introduction of the boom on the UAV dramatically altered the mass moment of inertia about the yaw axis. Additionally, the boom causes increased drag and added destabilizing disturbance to the UAV. A forward velocity of 1 meter per second was achieved, test day winds of 10 to 15 Knots were a disturbing factor. As expected, this increased disturbance caused oscillations in both pitch and roll axis with response delays in the yaw axis. Tests were conducted with both boom off and boom on. With the addition of the boom the pitch and roll loops tracked their respective commands reasonably well. Figure 7 illustrates the performance terrain following of the UAV with the addition of the boom.

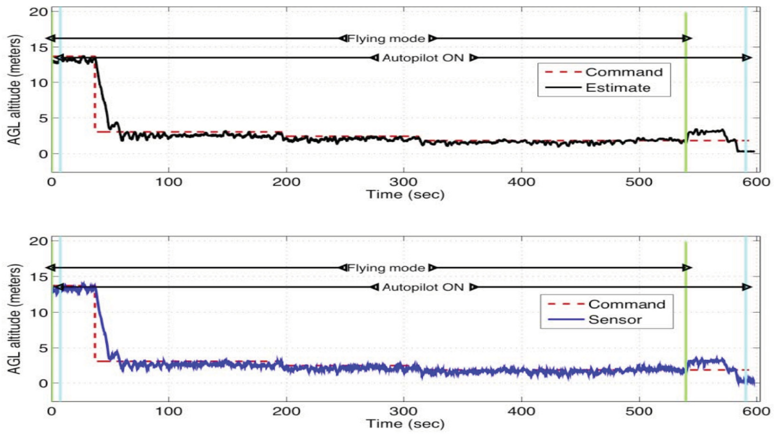

Figure 7 Mongoose Terrain Following with Boom

2.2.2 Mosquito Flight Tests

In the second effort, a Mosquito, (a single seat rotorcraft designed and constructed by Composite Systems FX in Trenton, Florida) was equipped with a two-magnetometer boom, designed and built by Geometrics, a logging system, differential GPS, a laser altimeter and a fluxgate magnetometer, as shown in Figure 8. The full-scale system was flown by a pilot over a number of targets provided by Battelle to assess the ability to collect high quality data with a modular system

Figure 8 Mosquito equipped with sensor boom during test flight

The system flew well up to the designer-imposed VNE (Velocity to Never Exceed) of 40 Knots indicated airspeed. The biggest challenge with this type of boom design is to ensure that the boom's natural frequencies do not add with those of the aircraft (or vice versa) and create a vibration condition in the boom. This is important both for data quality and for safety consideration if vibration were to occur at higher speeds. The prototype boom developed for this project phase performed very well at all operating speeds.

2.2.2.1 Mosquito Test results

The data sets used for processing were GPS, Cesium magnetometers and flux gate magnetometer data. The main purpose of this test was to evaluate detect ability of targets and not their precise positions; no specific effort was made to identify and minimize latency issues.

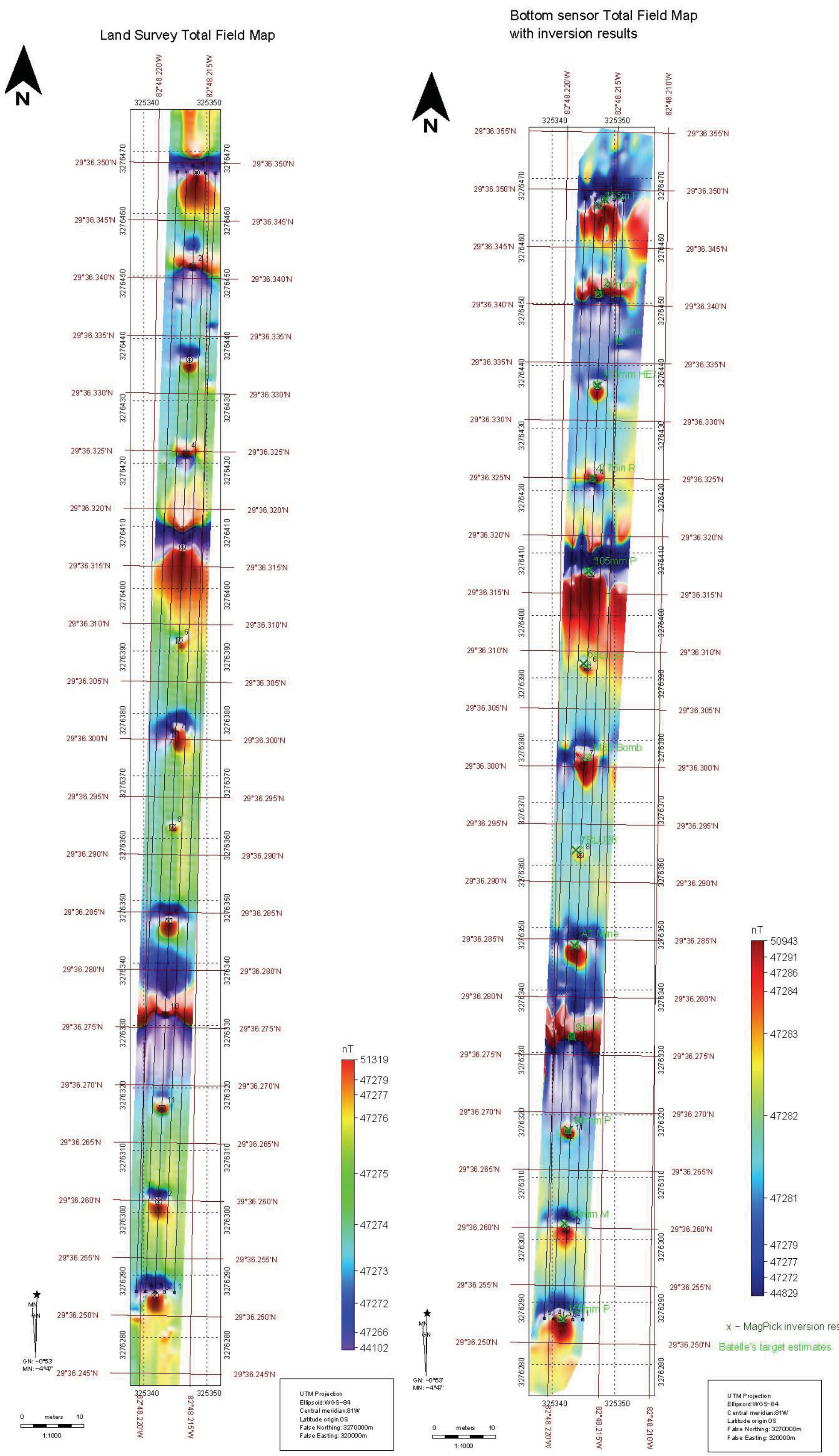

Figure 9 Manually collected data (left) vs data collected with Helimag system (right)

In order to assess the performance of the system an ad hoc test site was constructed at a small private field. Five parallel lines were measured out and marked with agricultural paint. Along the center line thirteen targets were laid out at 15 m spacing. The first target was at 0 m, and the last target at 180 m. Figure 10 show the targets used in the test.

Figure 10 Targets used for magnetic detect ability assessment survey

Data was collected over this site both with and without the targets emplaced both with a handheld Geometric G823A gradiometer and with the Mosquito system. The Helimag system was able to detect all targets (and even allowed for the inversion for these data as shown in figure 9), and the data quality of the Helimag system was comparable to that of the manual collected land data. As is expected from the difference in height in the survey altitude the footprint of the data for the airborne system is somewhat larger than the footprint of the data for the land dataset. Also, the min and max amplitudes associated with each target are lower for the airborne data than for the land data.

3 CONCLUSIONS

The field efforts were successful in demonstrating both the feasibility of a modular approach to UAV magnetic rotorcraft as well as the feasibility of individual components of such a system. Specifically, we demonstrated the stability and ability to terrain follow of a boom equipped autonomous rotorcraft as well as the ability to collect high quality magnetic data from a small manually piloted rotorcraft which could be made autonomous.

4 ACKNOWLEDGMENTS

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