ATV magnetometer systems for efficient ground magnetic surveying

NOAH D. ATHENS, JONATHAN M. G. GLEN, and ROBERT L. MORIN, U.S. Geological Survey
SIMON L. KLEMPERER, Stanford University

Ground magnetic data contain information, not present in aeromagnetic data, which may be useful for precisely mapping near-surface faults and contacts, as well as constraining or aiding interpretation of other geophysical methods. However, collecting ground magnetic data on foot is labor-intensive and is therefore limited to small surveys. In this article, we present two newly developed all-terrain vehicle (ATV) magnetometer systems that significantly expand the survey area that is possible in a ground magnetic survey without greatly reducing the quality of data.

In conventional ground magnetic surveys, the survey equipment (magnetometer sensor, GPS, and data logger) is either mounted to a backpack or held by the surveyor. This simple setup makes it easy and inexpensive to quickly conduct a small survey, but extensive surveys are too time-intensive to be practical. The adaptation of a vehicle for more efficient magnetic surveying is by no means a novel idea, but there are disadvantages to the vehicle systems that we have seen in the past. Truck-towed magnetometer systems, such as the towed-magnetometer (TOM) system (Tilden et al., 2006) and truck-mounted magnetometer platform (Gettings et al., 1995), produce a large heading error, as much as 250 nanoTesla (nT). Heading error is a magnetic-field component that depends on the direction the truck is driving, and is caused by the induced and remanent magnetic field from the vehicle's steel components interacting with the Earth's magnetic field. The heading error is corrected during processing of the data by applying a dc-shift based on the survey direction (in most cases the dc-shift can be satisfactorily approximated by a linear interpolation between predetermined heading-error corrections); the survey direction is taken to be the compass heading of the vehicle and (in this application) does not account for the pitch and roll of the vehicle. However, imprecise heading information from GPS measurements, commonly due to quick changes in direction (GPS measurements are recorded just once per second) or poor GPS reception from overhanging trees (less of a problem with new high-sensitivity GPS units), can cause significant errors that cannot be accounted for by a simple heading correction. This limits most truck-towed systems to fairly straight roads with little vegetation cover. However, the heading error can be vastly reduced simply by using a vehicle with lower magnetization, such as an ATV. An additional advantage of our ATV systems is that they can be driven in a variety of terrain conditions.

Figure 1. (a) The towed system. The magnetometer sensor and GPS antenna are on an aluminum carraige that is towed 9 m behind the ATV. (b) The tower system. The magnetometer sensor is placed 3.6 m directly above the ATV and the GPS antenna is on the front of the ATV. (c) Ruggedized tablet PC and data logger on the tower system. Magnetic readings and GPS locations are streamed in real time to the tablet PC via a Geometrics data-logger console.

ATV magnetometer system design

We designed two ATV magnetometer systems. The first of these, the *towed system* (Figure 1a), is an adaptation of our truck-towed system (Tilden et al., 2006) in which the magnetometer sensor and GPS are mounted to an aluminum nonmagnetic carriage that is towed 9 m behind the ATV. The towing structure is assembled from five pieces of aluminum tubing ~1.5 m in length that connect to each other and link to the carriage (1.5 m high by 1 m wide) and the hitch attachment, which was designed to swivel during turns; the system can be fully assembled in 20 minutes. For the towed system, we used a Kawasaki Prairie (US $4799 MSRP) because it is stable, easy to operate, relatively nonmagnetic compared to similar ATVs, and has a hitch for attaching the towing structure. The main disadvantage of the "towed" design is that the mobility of the ATV is restricted by the towed carriage, making some tortuous four-wheel-drive tracks inaccessible.

The second design, the *tower system* (Figure 1b), has the magnetometer sensor placed 3.5 m above the ATV on an aluminum tower so as not to inhibit the ATV's mobility. The aluminum tower is welded into one piece but can be collapsed for storage in an ATV trailer; it takes two people ~25 minutes to set up the tower. The GPS and other equipment are mounted to the front end of the ATV. Since the sensor is in close proximity to the ATV, reducing magnetization of the ATV is imperative. Therefore, for the tower system, we

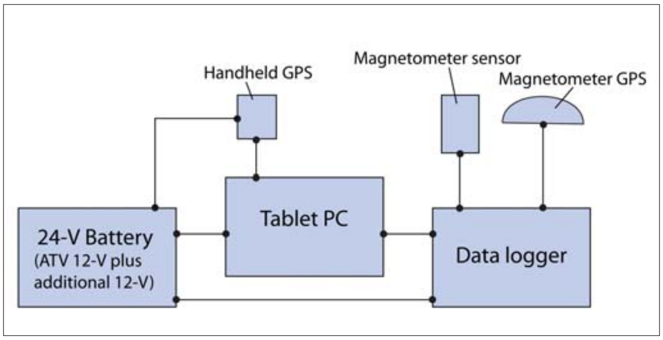

Figure 2. *Schematic representation of the magnetometer equipment mounted to the ATVs. Magnetometer readings and GPS coordinates (from the magnetometer GPS) are streamed in real time to the tablet PC where they are displayed using Geometric's MagLog software. The tablet PC also runs National Geographic's program Topo! which synchronizes to the handheld GPS for navigating the survey.*

used a Kawasaki KFX 450R ($7949 MSRP), a lightweight unit with a nonmagnetic aluminum frame (ATV models that are specifically designed for racing, such as this model, often have an aluminum frame as opposed to steel). We also fabricated stainless steel and aluminum parts to replace some of the magnetic steel parts including new pedals, heat shield, and disc brakes. Other ATV parts that could be replaced include the handlebars, A-arms, rear axle, tires (which typically contain a steel wire that holds the tire to the hub), and gears, but at a cost of $2000 or more.

The setup of the magnetometer equipment on the two systems is essentially the same (Figure 2). The magnetometer sensor, a cesium-vapor total-field magnetometer, and GPS are connected to a data-logger console, which sends data to an onboard, fully-ruggedized tablet PC (Figure 1c); for this system, monitoring of the magnetic field and GPS data were viewed by the surveyor in real time using Geometrics' MagLog program. For navigation during the survey, a

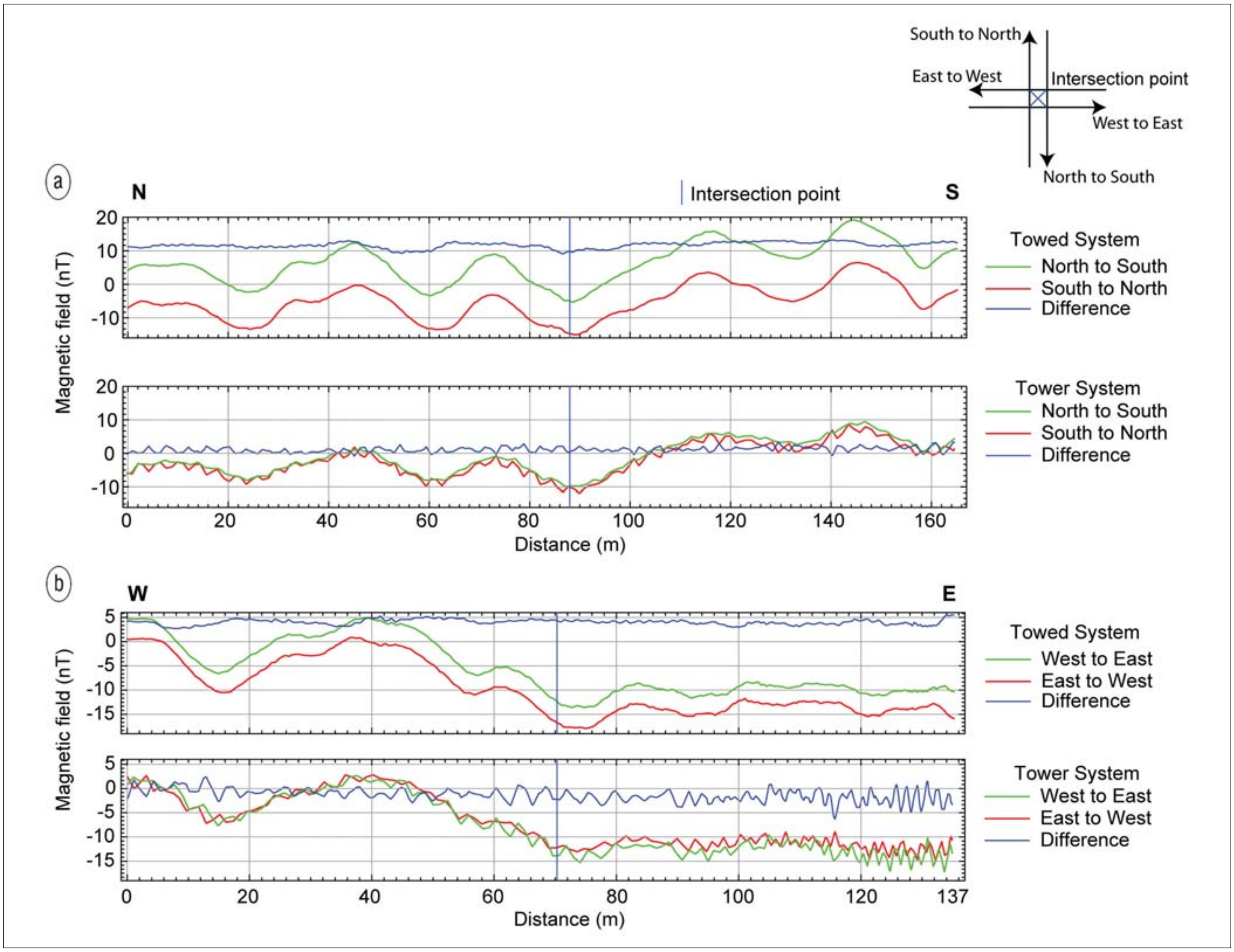

Figure 3. *Tests used to determine heading error due to survey direction. The towed and tower systems were each driven over a single point in directions (a) north and south and (b) east and west. In both (a) and (b), the difference in magnetic field values is substantially greater in the towed system due to that system's ATV model, which has a magnetic steel frame. The ATV model in the tower system has a nonmagnetic aluminum frame which produces less heading error. However, the closer location of the sensor to the ATV in the tower system (see Figure 1 for the design) leads to comparatively noisy measurements.*

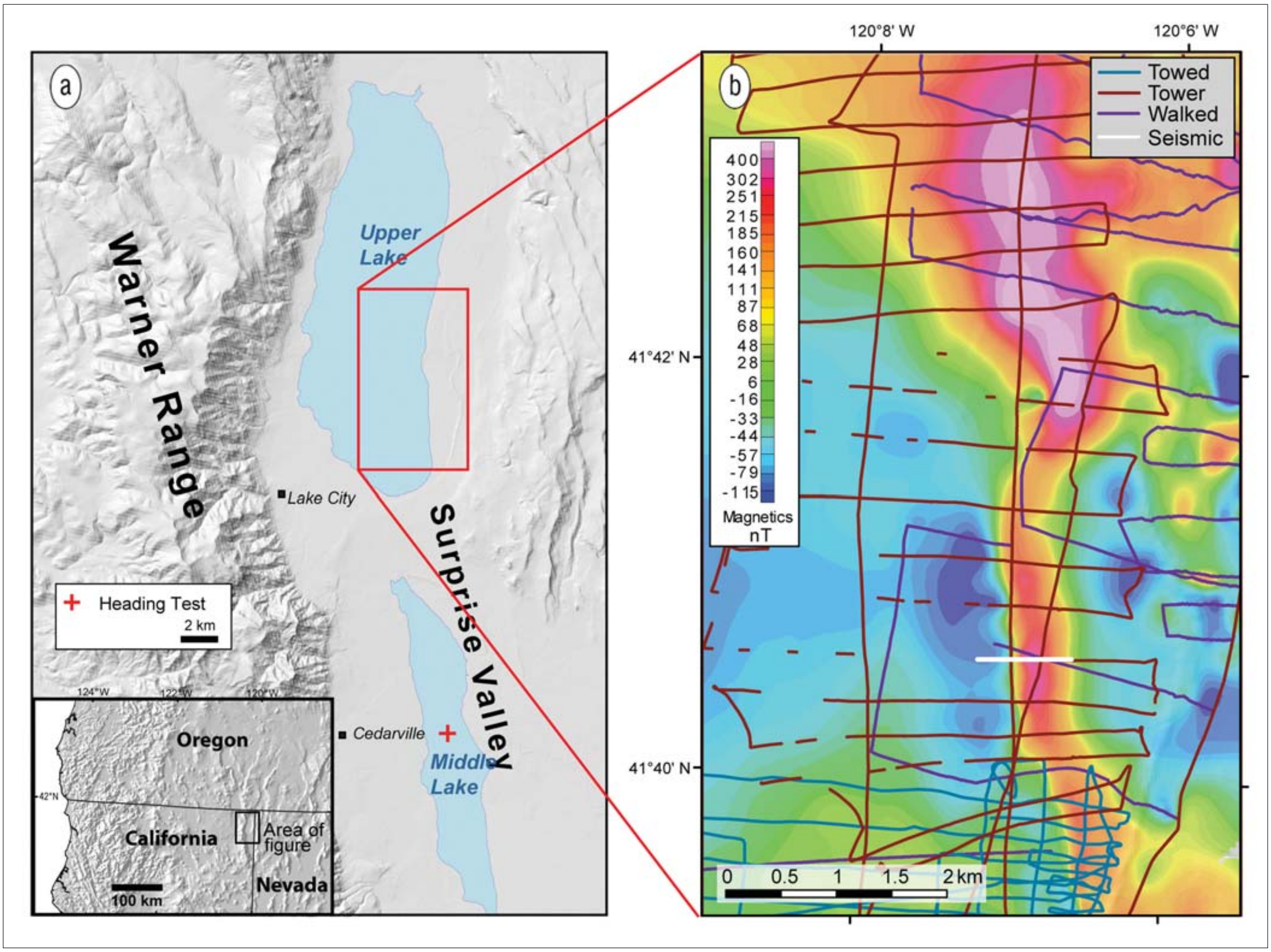

Figure 4. (a) Topographic index map showing the location of the heading correction test and the magnetic survey area in Surprise Valley. The lakes—Upper, Middle, and Lower (not shown)—are dry in the summer and accessible by ATV. (b) Magnetic map that integrates data from the towed system, tower system, and walking mag system. Processing steps included diurnal correction, removal of dropouts, filtering to remove cultural noise, heading correction (ATV systems only), and leveling. Gaps in the survey lines of the tower system occurred during one day's survey due to unknown magnetometer sensor error. The magnetic map was used to identify a location for a 2D high-resolution seismic experiment shown by the white line in (b).

hand-held GPS was connected directly to the tablet PC and was synchronized with Topo!, *National Geographic's* mapping software. Using Topo!, the surveyor can either follow an uploaded survey route or deviate from the planned survey to map interesting magnetic features in detail. All equipment is powered by a battery box that is connected in series to the ATV's 12-volt battery via a battery inverter. Total cost of the magnetometer sensor, data-logger console, GPS, ruggedized tablet PC, hand-held GPS, and mapping software is ~$35,000 depending on particular models.

Testing the ATV magnetometer systems

We tested the ATV magnetometer systems in a dry lake bed with low magnetic gradients to determine noise levels and heading errors. The heading error should be determined either in the direction of the planned survey or in the direction of largest and smallest heading errors (likely the four magnetic cardinal directions). In our case, the heading error was determined by driving the ATV system over a single point in the directions of our planned survey (north, south, east, and west) and comparing the magnetic field strength at the intersection point. Once the heading error is determined, a heading correction can be applied to the survey data. This was performed in the Geosoft software package Oasis Montaj using the Heading Correction GX.

The results of our heading error tests (Figure 3) show that the two ATV magnetometer systems have distinct magnetic characteristics. The tower system has a relatively small heading error (magnetic readings at the intersection point differ by less than 1 nT), whereas the towed system has a more substantial heading error (as much as 10 nT). Using a heading correction, the heading error for both systems is reduced to less than 1 nT in the chosen grid directions. In other directions, the heading error may be slightly greater than 1 nT since the correction is linearly interpolated between the defined directions (a more comprehensive heading error test

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with more than four directional tests could be used to reduce these errors further). Nevertheless, when targeting geologic features with anomalies on the order of 100—1000 nT, the towed system's more substantial heading error is completely acceptable.

A significant difference in the results obtained with the tower and towed systems for the heading test is the noise-level of the magnetic field data. Readings from the tower system fluctuate by ~1 nT leading to comparatively noisy data. The noise is largely due to rotating magnetic steel parts (in the ATV axle and tires) and the magnetometer sensor's close proximity to the ATV; stationary tests indicate that the engine causes spikes in the data only on start-up, so it is not the cause of the noise. Although the noise can be smoothed after processing with a low-pass filter, there will inevitably be some loss in the quality of data when compared to walked magnetic data. In contrast, there is little high-frequency noise in the towed system because the sensor is further from the ATV.

Performance

We used both ATV systems to conduct a magnetic survey in Surprise Valley, California, targeting intrabasin structures that may control geothermal fluid flow. The magnetic profiling was then used to identify a specific target for a more intensive and expensive seismic profile, the interpretation of which was validated by potential-field modeling (for details on the experiment, see Athens et al., 2009; Fontiveros, 2010). Figure 4 shows a subset of the magnetic survey and illustrates the integration of data from both ATV magnetometer systems and previously walked magnetic transects. Magnetometer readings were recorded at 0.1-s intervals, which, at an average speed of 20 mph, correspond to approximately one measurement every 0.9 m. The initial processing steps included diurnal correction, removal of dropouts, filtering to remove cultural noise (culverts, fences, and power lines), and the heading correction. Leveling was used to merge the data sets by bringing all data to the reference level set by the tower system, and reduction-to-pole was applied to center the anomalies over their sources.

Although successful, this initial survey revealed some design issues in the ATV systems. While surveying, welds on both the tower and towed carriage failed due to the jarring that occurs on some four-wheel-drive tracks. Fixing this in the field required the services of an aluminum welder. Also, the initial heading test revealed an offset in the data due to asynchronicity of the data-logger console clock and GPS clock (the data-logger clock is set manually at the beginning of the survey). A difference of 0.3 s between the two clocks at 20 mph driving speed will produce a 4.5 m offset in the data. In our survey data, the offset was evident at certain intersections where the two processed magnetic field values differed by several nT. This led us to apply a tie-line leveling correction that minimized the differences at intersections to less than 1 nT.

One consideration before employing the ATV magnetometer systems is the terrain of the survey area and the potential for lasting environmental impact. In general, dirt roads and four-wheel-drive tracks are ideal for using the ATV magnetometer systems and pose no undue risk of impact. ATVs should not be driven on terrain with significant brush or a sensitive ground surface as this may be detrimental to both the ATV operator and the environment. To learn more about appropriate terrain conditions and how to safely operate an ATV, we recommend taking an ATV safety training course.

Conclusions

The ATV magnetometer systems are efficient tools, capable of gathering over 150 km of magnetic profile data in a single day. On suitable roads these systems can easily survey at 20 mph. For geophysical researchers, the increased efficiency is a boon, allowing more detailed surveys with fewer days in the field. The quality of magnetic data is much improved from the truck-towed systems because of the much smaller heading errors and the increased mobility, especially in the tower system. Future work will include better characterization of the magnetic fields produced by the ATVs and their effect on the data so that these systems can be used in surveys requiring very high precision. TLE

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Corresponding author: nathens@usgs.gov

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