EDCON-PRJ

# Magnetic Survey Design

## by Richard Hansen

EDCON-PRJ, INC.
6900 W. JEFFERSON AVE. SUITE 150
DENVER, COLORADO 80325-2307 USA

TEL: 303.980.6556
FAX: 303.989.3480
www.edcon-prj.com

Magnetic survey design is driven by a combination of technical and practical considerations. This report explains EDCON-PRJ's view of current best practices in planning a magnetic survey, considering both the technical and practical issues. However, each survey is different, and special circumstances in any given area may dictate a different approach to the survey layout.

Another useful summary with a slightly different point of view can be found at http://www.geoexplo.com/airborne_survey_workshop.html.

1. Measurement Accuracy

Obviously enough accuracy must be available to resolve the targets of interest. There are two primary components to survey accuracy: that of the magnetic measurements and of the locations.

a. Magnetic Measurement Accuracy

Commercial magnetometers in use today have a sensitivity of 0.01 nT and a noise envelope of around 0.05 nT at 10 Hz sampling rate. Note that for normal small-aircraft speeds 10 Hz sampling corresponds to roughly 5 meter sample spacing.

However, the overall measurement accuracy is almost always determined by system interference. The best installations provide accuracies in the 0.1-0.2 nT range; obtaining precise figures is quite difficult.

b. Location Accuracy

Using GPS systems with WAAS or commercial satellite differential corrections, location accuracies of around 5 meters are available under reasonable conditions. Generally this is adequate for standalone magnetic surveys. If the survey happens to be combined with one requiring better positioning, such as gravity, the locations may be accurate to a few cm.

2. Survey Platforms

a. Ground

Although various vehicles are used for ground surveys, the most common configuration is a hand-held sensor with a backpack-mounted GPS system and integrated data recording in a waistband-mounted unit. The whole system weighs about 10 kg.

Because ground surveys are normally very detailed, geodetic-grade GPS units with an accuracy of a few cm are often used for location.

For very small survey areas, ground surveys are obviously the method of choice. However, as the area increases to more than a few square km the labor-intensive nature of ground surveys rapidly makes them uncompetitive with airborne surveys.

Issues of land access and difficulty of terrain also arise. Finally, depending on culture and the surficial geology ground surveys may be badly contaminated with very near-surface magnetic signal of no geophysical interest.

b. Fixed-wing Aircraft

By far the largest number of surveys and quantity of data are collected from magnetometers on fixed-wing aircraft. The sensor is typically mounted in a tube aft of the aircraft called a *stinger* to minimize the effect of the aircraft's magnetic field. Either hardware or software is used to further reduce these effects to a level as small as 0.1-0.2 nT.

Using a fixed-wing aircraft, large areas can be covered economically and rapidly. Because the measurements are made in the air, issues of land access (at least in the United States) and the effects of ground clutter are avoided. However, it is clearly impossible to achieve the level of detail that is possible with ground surveys, and in very steep terrain the only possible flight path may lie at an unacceptable altitude above the sources. In the latter case a helicopter may be required.

c. Helicopter Surveys

Helicopters are used for low-level surveys in terrain that would be impossible to follow in a fixed-wing aircraft. Helicopter surveys are conducted with a magnetometer sensor slung from a long cable below the vehicle, or in a forward-mounted stinger. Because helicopters have much higher operating costs than fixed-wing aircraft, helicopter surveys are significantly more expensive than fixed-wing surveys. Furthermore, the data quality is usually not quite as good for a variety of reasons, perhaps most significantly variations in flight elevation due to the steepness of the terrain.

Obviously it makes no economic sense to use a helicopter for large regional surveys where close terrain following is unimportant.

d. Ultralight Surveys

This configuration is very similar to that for a fixed-wing survey, except that the platform is an ultralight aircraft. These aircraft can fly lower and more slowly than conventional fixed-wing systems, and have better climb rates. Thus, they are a good platform for small surveys where the performance characteristics of a helicopter are not needed, because their operating costs are much lower. They are also competitive with large ground surveys, and typically give more useful data except where very near-surface sources are of interest.

FAA regulations limit commercial ultralight operations to remote areas, so it is necessary to avoid inhabited cultural features, and built-up areas cannot be surveyed at all.

Currently ultralight-borne surveys are only available through EDCON-PRJ.

e. Unmanned Airborne Vehicles

Unmanned airborne vehicles (UAVs) have characteristics similar to fixed-wing aircraft, but have no pilot aboard. Current configurations are autonomous, with pre-planned survey paths, and much smaller than fixed-wing aircraft.

The great advantage of UAVs is in areas where there is considerable risk to a pilot. Early applications have been far offshore, which is a particularly hazardous environment. The main disadvantages currently are cost, which should fall as development expenses are amortized; and the fact that, like the ultralight system, operation over inhabited structures is prohibited.

f. Shipborne Surveys

Because commercial ships contain very large quantities of steel, the magnetometer is always towed behind the ship on a cable at least 150 meters long. Unless some location system is packaged with the magnetometer, which is usually not the case, this makes the magnetometer location somewhat uncertain. Furthermore, because there are normally no nearby base stations the external field correction is usually not very accurate. As a result, while shipborne data is often very useful for regional mapping, it is typically not accurate enough for detailed work. However, in far offshore locations a ship may be the only practical platform for magnetic data acquisition.

3. Line Direction

Where there is a dominant strike direction, the survey lines are normally laid out perpendicular to the strike of the dominant geology or structures of interest. To see why this strategy is used, suppose that the opposite were the case: that the survey lines ran parallel to the dominant strike direction. Then the magnetic field would be approximately constant along each survey line and all of the variation would be from one line to the next. Since line-to-line variations are difficult to resolve (this subject will be discussed further when the issue of tie lines is discussed), the resolution of the survey would inevitably suffer.

When there are two major strike directions at an obtuse angle to each other, the survey line direction may be taken to split the difference between the two strike directions. If the geology is not two-dimensional, and especially if the lateral extent of the sources is small compared to the depth of burial, the maximum gradient of the anomalies will be in the magnetic north-south direction, so the survey lines should be oriented along this direction.

Regional surveys, where no dominant strike direction is normally present, are usually laid out with north-south survey lines to maximize the average spatial frequency of the anomalies.

Finally, at low magnetic latitudes, say less than fifteen degrees, survey lines should always be flown in the magnetic north-south direction, as anomalies are always highly extended in the east-west direction (see, for example, Kis (1990)).

4. Survey Elevation

A major consideration in designing an airborne survey is elevation, because many other parameters follow from that. The main consideration in deciding on survey elevation is optimizing the signal-to-noise ratio between the targets of interest and the sources of interference. This analysis is simpler where the topography is very gentle; the question of how (and whether) to drape steep terrain will be taken up later.

For example, suppose that for measurements on the surface there are shallow sources, not of interest, buried at depth $z$, and targets buried at depth $Z$. If these can be treated as point sources, the signal from the shallow sources, which for the present purpose is noise, varies as $1/z^3$, while the signal from the target varies as $1/Z^3$. If $z$ is much smaller than $Z$, the signal from the shallow sources will overwhelm that from the target.

Now suppose that the field is measured at height $h$. Then the field of the shallow sources is attenuated by $1/(z+h)^3$, while that of the target is attenuated by $1/(Z+h)^3$. Clearly, there is a tradeoff between flying too low, which will not attenuate the surficial noise sufficiently, and flying too high, which will attenuate the target signal excessively. It can be shown that if the RMS magnetization of the target is $A$ and the RMS magnetization of the shallow sources is $a$, then the optimum flying height $h$ is

$$h = 2\left(\frac{a}{A}\right)^{2/3}(Z - z) - z ,$$

in the case that h << Z, which is almost always true. Also, usually z = 0; i.e., the source of interference is ground clutter.

While interesting, this formula is seldom used for two reasons. First, neither $A$ nor $a$ is likely to be well known, although it might be possible to estimate them from regional data. Second, the flight height is usually constrained by legal and operational considerations. For example, it is not legal to fly below 1000 feet above the ground in populated areas, and many fixed-wing aircraft operators will not fly below 500 feet anywhere. However, in northern Australia where very near-surface sources are of interest surveys have been flown at about 20 m altitude using aircraft designed for crop dusting.

Note that if very shallow features are of primary interest the survey should ideally be conducted on the ground. This is generally the case for engineering and archaeological studies. However, if the area of interest is impracticably large for a ground survey it may be necessary to use an airborne survey to obtain the desired coverage.

Conversely, if the target sources are deep, there is little loss in flying at a reasonable height, because the signal attenuates much more slowly than that of a shallow source. For a geological perspective on this issue, see Gay (2004).

5. Flight Line Spacing

Once the survey elevation has been selected, the choice of flight line spacing is relatively straightforward. The closer the line spacing used, the better resolved are the anomalies; however, the cost increases accordingly. Evidently, there is a point of diminishing returns. Reid (1980) analyzed this issue carefully, and current practice based on his analysis is usually to space the flight lines at approximately one-half the depth to the shallowest significant sources, which results in roughly five per cent loss of anomalies between flight lines. Exceptions to this rule are primarily where the data are to be used in profile form only or where the geology is unusually two-dimensional. Profile flying is unusual today, but in the past lines were frequently flown in triplets, in which case the same rule for line spacing would apply.

Note that it is the depth to the shallowest significant sources, not to the target sources, which is important. In areas where relatively shallow, but high-susceptibility, volcanics overlie basement, this rule results in a line spacing much smaller than would be suggested by basement depth alone.

6. Tie Line Spacing

Tie lines are used primarily to adjust the levels from one survey line to the next, using some kind of statistical adjustment algorithm. The need for such adjustments arises from a number of sources, including residual base station correction error and residual heading error (i.e., the presence of different levels on reciprocal headings).

One approach does not use tie lines, using instead an approach called microleveling to adjust the flight line data (see, for example, Minty (1991). The difficulty with this approach is that anomalies perpendicular to the survey line direction tend to be lost in the processing. Under some conditions this is acceptable, but EDCON-PRJ and most other contractors do not favor this idea.

Probably the most typical choice is a flight line to tie line ratio of about 8:1 or 10:1. This allows for adjustment of the survey line data with relatively small investment in tie lines. Often the tie lines are discarded before mapping in this approach.

EDCON-PRJ favors a ratio of about 4:1 in most circumstances. This better resolves anomalies parallel to the survey line direction. With this many tie lines discarding them before mapping is obviously unacceptable.

7. Draped versus Constant Elevation Flying

Most surveys today are flown at approximately a constant elevation above the ground, as opposed to a constant altitude. Of course, aircraft performance characteristics usually do not permit an exact drape. As it turns out, an exact drape would usually not be a good idea anyway.

The main purpose of draping is to minimize the variation in distance from the sensor to the target sources. If the depth to the target is uncorrelated with the terrain, draping is counterproductive. This is usually the case if the target sources are deep. In this case, a constant elevation survey (for historical reasons, often called a *constant barometric altitude survey*) is preferable for several reasons. First, the distance to the sources is in fact kept more-or-less constant. Second, constant elevation surveys are easier to fly and suffer much less than draped surveys from differences in elevation between flight and tie lines at intersections. Finally, most interpretation algorithms assume, at least implicitly, that the data lie on a constant elevation surface.

One common misconception is that draping reduces the effects of terrain. This is not the case; in fact, draping exaggerates these effects (see Grauch and Campbell, 1984).

Where it is not possible to maintain a constant distance from the target anomalies, it is important to fly in such a way that the elevations of the flight lines and tie lines are as nearly as possible the same at their intersections. This is, of course, a function of the performance characteristics of the aircraft, and is most easily achieved using a pre-planned drape as discussed next.

8. Pre-planned Drape Flying

Jensen (1965) discussed the effects of mispositioning on the recovery of anomalies. His conclusion was that even in very low gradients an error of 100 feet (30 m) in lateral position or of 20 feet (6 m) in vertical position produces an error of 0.1 nT. Today, horizontal mispositioning is of less concern because the actual flight path is usually known to five meters or so, but the vertical positioning error is not so harmless. Even though the vertical position of the sensor may be known to five meters, the elevation mismatch at crossovers between flight and tie lines cannot be corrected exactly, and leads to undesirable artifacts in the mapped data.

At least in part as a response to this problem, flying on a pre-planned flight surface has become more common. In this mode, a terrain model is used to generate a surface to be flown based on the performance characteristics of the aircraft to be used for the survey. The pilot then follows a display which indicates whether the aircraft is above or below this surface.

There are two main purposes for using a pre-planned drape. First, the surface flown is guaranteed to be within the performance characteristics of the aircraft. This is an enormous safety advantage. Second, although line misties resulting from elevation mismatches can be mitigated through the use of equivalent source methods, these tend to limit the frequency content of the data (see, for example, Cordell (1992)). Pre-planned drape flying places the flight lines and tie lines on a consistent surface resulting in smaller line misties and a vastly improved final product.

EDCON-PRJ anticipates that pre-planned drape flying will become almost universal over the next few years.

9. Gradiometers

Gradiometers are configurations that consist of more than one magnetometer, in which the difference in readings between the sensors is taken as an approximation of the gradient along the direction between them. Note that this difference is a useful quantity only if it exceeds the noise threshold in the difference between the two magnetometer readings. In practice, this means that all gradiometers are near-surface devices.

Gradiometers generally have one of two configurations: vertical or horizontal. Some systems are combinations of these two, but the vertical and horizontal components can be discussed separately.

In a vertical gradiometer (Hood and Teskey, 1989), the magnetometers are aligned along the vertical direction, so the measurement is approximately a first vertical gradient. This configuration is extremely popular in engineering and archaeological work on the ground because it suppresses the effects of deeper sources. In airborne exploration, the major application of vertical gradiometers has been in preCambrian shield regions, where the target geology is basically in outcrop. Since many of these regions are also subpolar locations with strong external field variations, the fact that the gradiometer suppresses the effects of external field variations (to be discussed later) is a bonus.

Horizontal gradiometers (Hardwick, 1984) usually consist of two sensors, one on each wingtip, and often a third in a tail stinger. They are comparatively uncommon in ground surveys. With three sensors it is possible to measure both components of the horizontal gradient. The component perpendicular to the flight line (which may not be the same as the wingtip to wingtip measurement because of aircraft crab) is particularly interesting because it gives information about the behavior of the field off the flight path. In this respect, it complements the data obtained on adjacent flight lines and can be used to help in interpolating between lines (O'Connell et al., 2005). Note, however, that the limitation to comparatively shallow sources still holds.

Experiments with horizontal gradiometers show that, in the right kinds of geologic settings, they can significantly enhance final products, but the targets have to be picked with some care and with a clear understanding of the system noise floor.

One advantage of all types of gradiometers is that, as differences between closely-spaced sensor readings, they are essentially immune to external field variations. In auroral zones, particularly where no reasonable base station location can be found, this advantage may outweigh numerous disadvantages. The same is true at sea, where an inline configuration called a *longitudinal gradiometer* is sometimes used (Eggers and Thompson, 1984). The difficulty with this configuration is that the inline gradient is not especially easy to interpret. Algorithms for reconstructing the total field have therefore been developed, but these too have limitations.

## Conclusions

Best practices in survey design are based on a combination of technical, logistical and economic considerations. Examination of the technical issues can help to avoid surveys which do not achieve the desired technical goals, and will always save money in the long run. Design practices have advanced a great deal in the last twenty-five years or so, but they continue to evolve with the available technologies.

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