GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7660

Geological Survey of Canada aeromagnetic surveys: design, quality assurance, and data dissemination

M. Coyle, R. Dumont, P. Keating, F. Kiss, and W. Miles

2014

Natural Resources Canada Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7660

Geological Survey of Canada aeromagnetic surveys: design, quality assurance, and data dissemination

M. Coyle, R. Dumont, P. Keating, F. Kiss, and W. Miles

2014

doi:10.4095/295088

Recommended citation
Coyle, M., Dumont, R., Keating, P., Kiss, F., and Miles, W., 2014. Geological Survey of Canada aeromagnetic surveys: design, quality assurance, and data dissemination; Geological Survey of Canada, Open File 7660, 48 p. doi:10.4095/295088

Abstract

The Geological Survey of Canada has acquired aeromagnetic data over much of the Canadian landmass and continues to acquire data in support of geological mapping projects. With the evolution of aeromagnetic survey technology over the last 65 years, the GSC has defined, applied, and refined survey design, survey specifications, quality control procedures, post-processing standards, and publication products to ensure quality data acquisition and delivery.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

The Geological Survey of Canada (GSC) has acquired aeromagnetic survey data across Canada (Fig. 1) since 1946 as an aid to geological mapping and mineral exploration. Large portions of the country are covered by glacial overburden and outcrop is scarce making geological mapping difficult. Magnetic maps determine trends, extents, and geometries of magnetic bodies in an area, and can be interpreted in terms of geology and alteration. Essentially magnetic surveys map magnetic minerals, not lithology, since there is no direct relationship between magnetic mineral content and rock type. Magnetic responses depend mainly on the presence of magnetite and to a lesser extent pyrrhotite. The degree of magnetisation of a body is determined by its magnetic susceptibility which is the ratio its magnetic polarisation (or magnetisation intensity) to the inducing field i.e., the Earth's magnetic field. There must be a susceptibility contrast between a given geological unit and its surroundings to produce an anomaly that will be detected by an aeromagnetic survey. If not, then no anomaly is produced and the geological unit cannot be mapped from magnetic data. Identification of lithology from magnetic field maps is ambiguous as the magnetic properties of different rock types can be very similar. Nevertheless, individual anomalies may signify the presence of a specific lithology or formation. Patterns of anomalies and the shapes of groups of anomalies may also reflect certain lithologies, formations or geological domains. They can also indicate different styles of deformation, i.e., brittle versus ductile.

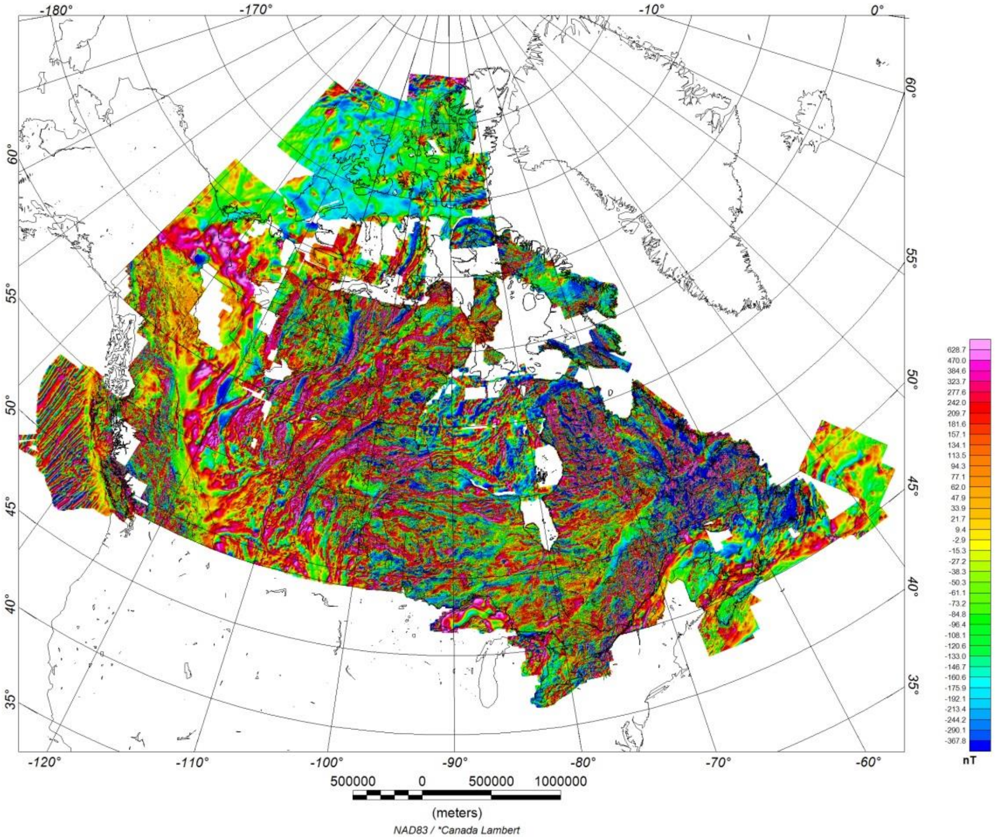


Figure 1. Aeromagnetic map of Canada

Fluxgate magnetometers were used to measure the magnetic field until 1961 when more accurate proton magnetometers were introduced (Teskey et al., 1993). Digital data recording was introduced in 1974. Flight path information was obtained by using a vertically mounted camera until the introduction of GPS navigation in the late 1980s. The advent of high resolution digital terrain models, such as SRTM, has allowed widespread application of pre-defined flight surfaces. These innovations and the experience gained with more than 12 million line km of surveying has been instrumental in the development of modern survey design criteria, quality assurance and control practices, and improved data compilation and processing techniques.

The acquisition of high quality aeromagnetic data follows a step-by-step process that has evolved over time. The process is initiated with a requirement for geophysical data over a certain area. This is followed by survey design, development of specifications, a request for proposals from contractors, evaluation of bids, awarding of a contract, quality assurance, quality control, data acceptance, appropriate post-flight processing (levelling), map generation, data archive, and publication. Lessons learned from each step of the process become part of our corporate knowledge and are used to refine the process in order to enhance the effectiveness and utility of the outputs of future surveys. This feedback loop is a key aspect of the quality management strategy ensuring continual improvement in the final product.

In the following sections we document the practices currently in use at the GSC and justify these choices. We discuss survey design, survey specifications, contractor bid evaluation, quality assurance, quality control, post-processing (levelling), data archiving and publication.

2. Survey Design

Typically, geoscientists request aeromagnetic coverage to support geological mapping. The proposed area is evaluated for boundaries with existing high-resolution surveys and an analysis of pre-existing data is performed. An analysis of survey feasibility is performed which compares the availability of funding and the project defined deadlines to the ability of airborne contractors to successfully complete the work. The typical factors affecting successful completion include: weather (precipitation, cloud cover, extreme cold temperature), diurnal activity, available daylight, topography, base of operations (airstrip length/composition, ferry distance to survey area, availability of fuel/accommodations), volume of work (line km), availability of contractors, permit restrictions (research licenses, national park permits, wildlife preserve restrictions), and availability of GSC personnel (Technical Authorities) to oversee survey contracts.

2.1 Survey Area

The area of the survey is determined by the scientific requirement and funding available. The survey boundary is similarly controlled, but also takes in to consideration the adjacent or pre-existing aeromagnetic coverage and any flight restrictions (national parks etc). In the event that adjacent areas have high-resolution and sufficiently detailed coverage, the new survey should abut the adjacent area and provide sufficient overlap (usually 1 km) to avoid data gaps and facilitate levelling the new survey to the existing data. When constructing survey boundaries, it is best to minimize short lines (< 10 km) as longer lines will actually be required and turn around costs will be part of the contractor's final price.

2.2 Timing

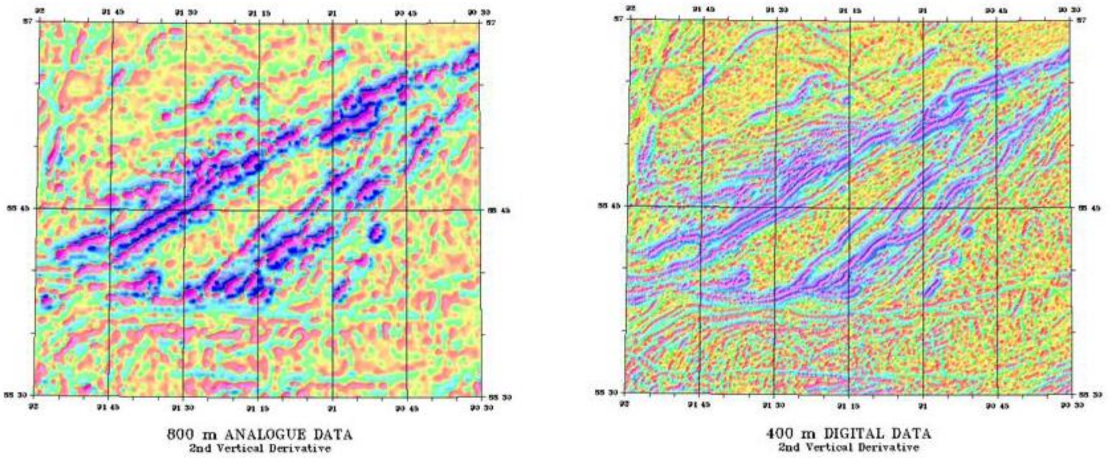
The overall timing of the survey is dictated by the availability of funds. The timing of the acquisition stage of the survey is controlled by operational considerations. These include safety considerations that restrict low level survey flight operations below -30^{o}C. In areas of Canada's north, this can limit surveying to a few summer months. Similarly, available daylight will limit the time of year aeromagnetic surveys can be flown north of N60^{o}. Wildlife, such as caribou, muskoxen, and migratory birds may be sensitive to low level survey flying. Mating, calving and migrating seasons must be understood and surveys must be timed to mitigate any impact. In the territorial areas of Canada, research licenses are required and can take two months or longer to procure. The availability of contractors may affect the timing of surveys. In remote areas, the availability of fuel must also be considered.

2.3 Flight height and line spacing

Aeromagnetic surveys are flown perpendicular to the strike of the regional geology to maximize the geological contacts detected by the magnetometer and to reduce power aliasing effects, thereby allowing flying at lower altitudes to increase survey resolution (Reid, 1980). GSC aeromagnetic surveys have a ratio of flying height to line spacing of

1:2.5, considered by Reid (1980) to be acceptable when flying perpendicular to geological strike.

Historically, most aeromagnetic surveys flown by the GSC have been regional surveys primarily used to aid in geological mapping. In general, a line spacing of 800 m and a flight height 300 m were used over the Precambrian Shield; this was deemed suitable for geological mapping at 1: 50 000 scale (Fig. 2a). These specifications correspond to the survey parameters later recommended by Reid (1980). However, recent surveys (since 2001) have been flown at a line spacing of 400 m and a height of 150 m (Fig. 2b) which also has a flying height to line spacing ratio close to 1:2.5. In the case of a combined radiometric and magnetic survey the flight height is reduced to 125 m to increase the measured radiometric responses. Many modern aeromagnetic surveys have been flown in areas that had already been flown at wider line spacing prior to the introduction of GPS navigation and digital data recording. These modern specifications are deemed to be more appropriate for 1:50 000 scale geological mapping.



a) b)

Figure. 2. Second vertical derivative of the magnetic field a) 800 m line spacing, analogue survey and b) 400 m line spacing, digitally recorded.

It is important to note that racetrack flying is not permitted for GSC aeromagnetic surveys. Racetrack flying minimizes short, tight turns at the end of lines by turning more broadly and flying subsequent lines several lines apart (Fig. 3). This results in many adjacent lines flown in the same direction. This makes identification of lag and noise problems on a flight or directional basis extremely difficult. The GSC specifications require contractors fly all lines such that adjacent lines are flown in the opposite direction.

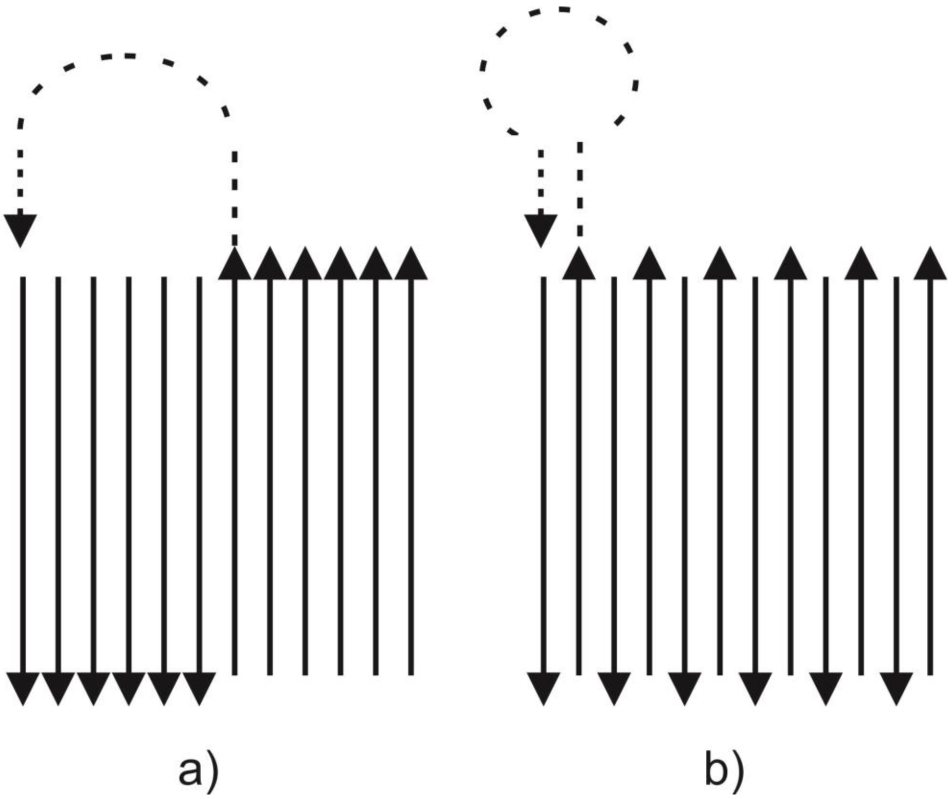


Figure 3. a) Racetrack flying where loose, looping turns result in a series of lines flown in the same direction. b) GSC requires adjacent lines be flown in opposite directions.

Once the optimum survey line spacing and flying altitude are determined, the suitability of a multi-sensor aeromagnetic/gamma-ray spectrometric survey is commonly considered. If the survey can be flown with an expected mean terrain clearance suitable for spectrometric surveys (125 m to a maximum of 300 m), and if the region will be free of snow and ice in the proposed timeframe, and the survey area is not under water, adding a spectrometric component can be considered as incremental costs may be minimal.

While most of the aeromagnetic surveying undertaken by the GSC is flown in support of regional geological mapping, there are requirements within some GSC programs for site-specific surveys. These are typically in support of mineral deposit or aquifer studies. Typically, these surveys acquire magnetic data as a secondary dataset with the primary dataset being electromagnetic or gravity gradiometry. The line spacing of these surveys reflects the size of the target.

2.4 Tie line spacing and geometry

Reford and Sumner (1964) showed that the error due to geomagnetic activity increases with the time between tie (or control) lines and that it is preferable to have a short distance between tie lines to reduce the geomagnetic noise. The acceptance criterion, or tolerance, is defined as the maximum accepted deviation in the variation of the magnetic field from a long chord or strait line between two points over an interval of time of one minute. In the case of fixed-wing aircraft, this results in a distance between control lines of 4 km to 5 km. This was the tie-line spacing used by the GSC for regional surveys prior to 1995. The increased accuracy provided by GPS control of positioning required much tighter tie line spacing on the order of 2400 m, about the distance flown in 30 seconds. Tighter tie line spacing greatly improves the effectiveness of the levelling network and minimises the influence of diurnal variations. This allows greater tolerance of the higher diurnal variation expected in the Arctic and minimizes survey downtime due to this variation. Although the reduction in tie-line spacing was initially used in the Arctic it was later adopted for all GSC surveys as it was realised that this procedure greatly improves the levelling of magnetic data even in the southern part of the country.

Tighter control line spacing should be considered in areas where the magnetic intensity is expected to have a low dynamic range, such as sedimentary basins and offshore regions, and when diurnal magnetic variations are expected to be active. Surveys over offshore regions present an added complication caused when conductive seawater moves across flux lines of the Earth's magnetic field generating electric currents which, in turn, generate their own magnetic fields. An ocean swell with a period of 20 s and an amplitude of 10 cm induces a magnetic field of 0.1 nT at an altitude of 50 m above the sea (Weaver, 1965).

To ensure that all of the data within the boundary of a survey area are properly levelled, all flight (or traverse) lines must start and end at a tie line; it follows that survey edges can have the shape of a staircase (Fig. 4) and that no perimeter lines are required. In the case of adjacent surveys a 1 km overlap zone is used in order to facilitate the stitching of these surveys into a homogeneous grid.

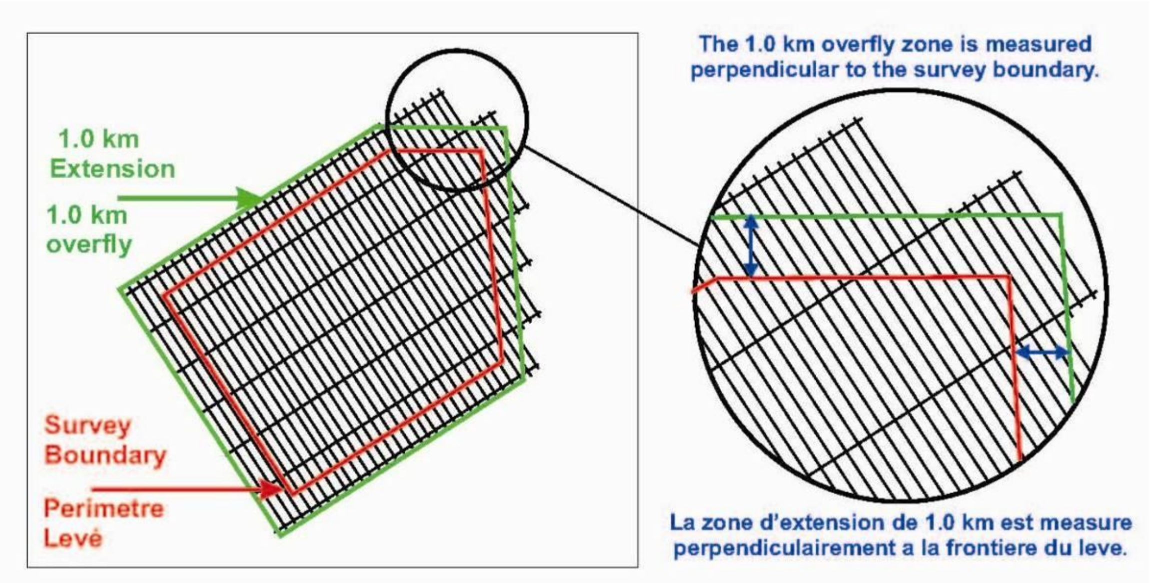


Figure 4. The survey boundary is extended by 1 km and all flight lines must start and end on a tie line.

2.5 Smooth drape

A smooth drape surface (Fig. 5) approximates the expected flight path and altitude of which a survey aircraft is capable. The first GSC smooth drape survey was flown in the early 1990s. By 1995, it had become a widely accepted practice. All GSC aeromagnetic surveys are now flown using a pre-planned smooth drape surface, calculated from digital terrain models, designed to conform to the maximum rate of climb and descent of the aircraft (Dumont, 2005), approximately 5% for fixed-wing and 30% for helicopter. The drape surface is followed using GPS navigation. The vertical tolerance should not exceed 15 m. As a result, all tie-line intersections will be within 30 m. Minimising height differences helps in the levelling procedure in that the magnetic differences will also be minimized at the intersection points. Furthermore, smooth drape surfaces ensure line-to-line altitudes are consistent, not varying based on topography and flight direction.

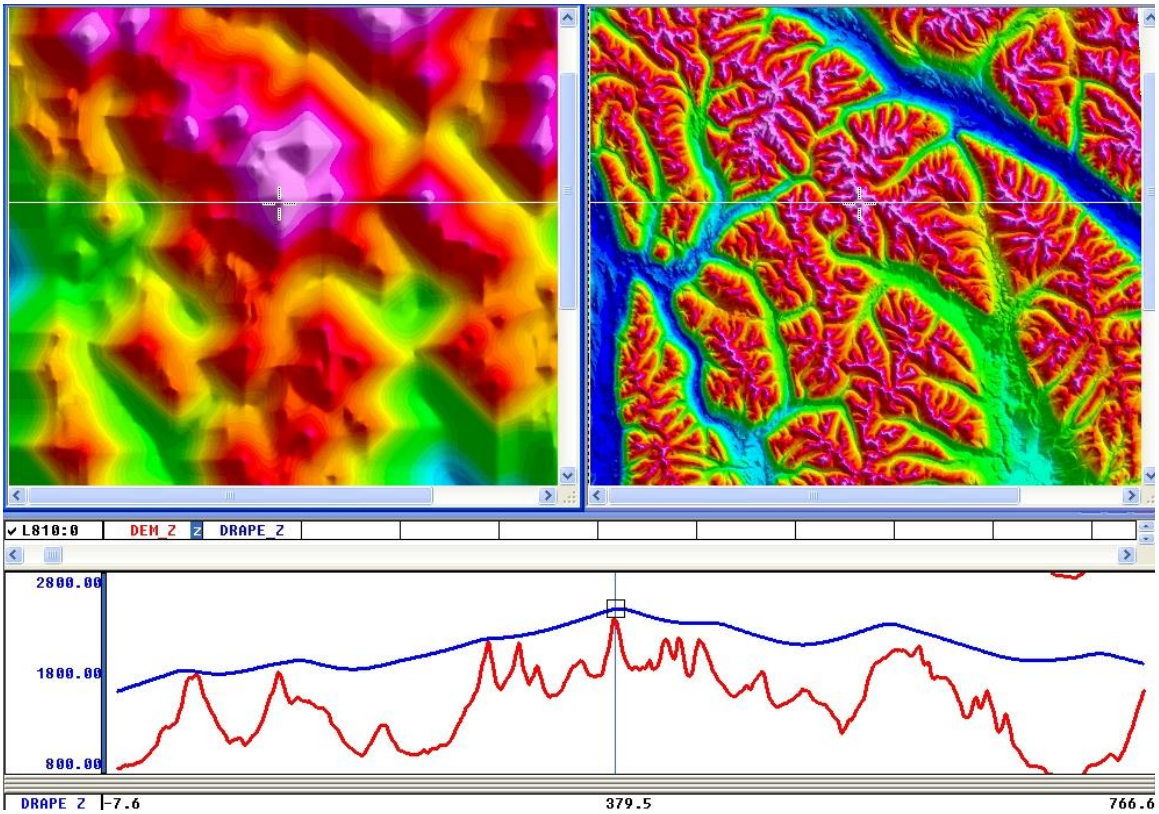


Figure 5. Drape Surface. The digital elevation model (top right) is smoothed to a maximum 5% gradient and the nominal terrain clearance is added (top left). The profile shows the digital terrain model in red and the drape surface in blue.

Generating a smooth drape surface and subtracting the digital elevation model gives a measure of the expected mean terrain clearance. This leads to informed decisions on line spacing and aircraft type (fixed-wing versus helicopter).

2.6 Survey platform

The climb and descent rate of fixed-wing aircraft (Fig. 6) over areas of rugged terrain may create high mean terrain clearances. If the smooth drape surface's mean terrain clearance approaches the line spacing, the measured data will be attenuated to the point where the detail expected from the given line spacing will be greatly diminished. While a 1:1 ratio is ideal to minimize power aliasing and for computing the vertical derivative (Reid, 1980), the attenuation of signal by the increased distance to magnetic sources may be undesirable. A wider line spacing that preserves the 1:2.5 ratio for altitude-to-line spacing may be considered. If budget allows, a helicopter-borne survey will have a steeper climb/descent rate which will result in lower mean terrain clearance.

Figure 6. Britten-Norman Islander fixed-wing aircraft (Sander Geophysics Ltd.).

2.7 Community engagement and licensing/permitting

Once a survey design has been developed and funding has been allocated, local community engagement is required before the contracting process can begin. Local aboriginal community locations and governance information are available from Aboriginal Affairs and Northern Development Canada. Engagement may take the form of introductory letters and informational posters or may require visits to the communities. Research Licenses are required for airborne geophysical surveys in all northern territories. This process requires detailed project summaries and application processes that outline any project activity that may trigger concern for local communities or environmental agencies. Permitting may also be required in certain provinces and over national parks.

3 Quality Assurance

Quality assurance of airborne geophysical data includes all activities for ensuring quality in the processes by which data are acquired. This includes the determination of specifications for survey contracts, verification of contractor services and personnel, and instrument calibrations. Quality control ensures quality in the final data and identifies and corrects issues with production data and data processing.

3.1 Contract Specifications

The elements of the survey design (survey area, line spacing, line orientation, survey altitude, and platform) are incorporated in the survey specifications to be included in a Request for Proposals from airborne geophysical contractors. The specifications also describe the instruments required (magnetometer, base station, GPS receivers, altimeters, and flight path video camera), required personnel, and aircraft. This includes all required instrument calibrations.

3.1.1 Airborne Magnetometers

Commercial magnetometers that meet GSC specifications are widely available. Sensitivity is particularly important in areas with a low dynamic range of magnetic intensity; over deep water or thick sedimentary basins. Typically, these are optically pumped cesium vapour magnetometers. High sensitivity is critical in order to have the ability to compute higher order derivatives used in interpretation and altitude correction.

The magnetometer must be mounted in a stinger rigidly attached to the aircraft. Magnetometers in a towed bird are susceptible to noise. Bird motion, mostly oscillations, can induce a few nT noise in the data. Towed magnetometers may be used for fixed-wing and helicopter-borne electromagnetic surveys as the magnetic data are then considered ancillary.

The following defines the performance capabilities of that are minimally acceptable:

Table 1: Airborne magnetometer specifications

Sensitivity	0.01 nT
Absolute Accuracy	±10 nT
Noise Envelope	0.10 nT
Ambient Range	20,000 to 100,000 nT
Sampling Interval	0.1 second
Heading Effect	< 2.0 nT

3.1.2 Magnetic Base Station

Daily geomagnetic field variability is a major survey issue, especially in the auroral zone of Canada's northern regions. The traditional practice has been to monitor these variations using one or more base stations located within or nearby the survey area (Nabighian et al., 2005) and later attempt to remove the diurnal variation from the measured data. Lilley (1982) and Vallée et al. (2006), among others, show that magnetic base stations can only be used with limited success to correct temporal variations observed during an aeromagnetic survey.

Temporal variations of the magnetic field are continuously monitored during GSC surveys using one or more magnetic base stations located within or as near as possible to the survey area. Forecasts can also be obtained from NRCan's Geomagnetic Laboratory (http://www.spaceweather.gc.ca/index-eng.php). For convenience, a base station is typically located near the base of operations (an airstrip) which can be hundreds of kilometres away from the survey area. A second base station may be located closer to or within the survey boundary but this is often difficult to achieve in remote areas.

The criteria used at the GSC is that when the diurnal variation is greater than a 3.0 nT (peak to peak) deviation from a long chord equivalent to a period of one minute, (Teskey et al., 1991), the part of the survey flown during that period must be reflown. In addition, if before the start of a flight the activity monitored at the base station is above this tolerance, the flight is cancelled. It follows that the magnetic base stations are mostly used to monitor survey conditions and determine if the data are acceptable. Diurnal variation can only be subtracted from the survey magnetic data when it can be demonstrated that the variation within the survey area is closely correlated, or in phase, with the variation at the base station. This is done by comparing the preliminary tie line levelling network to the diurnal variation. Base station magnetometers are therefore mostly used to determine if the diurnal variation is within survey specifications thereby allowing data acquisition. They are rarely used in the levelling process as, for most surveys, base stations are often far away from the survey area (Fig. 7).

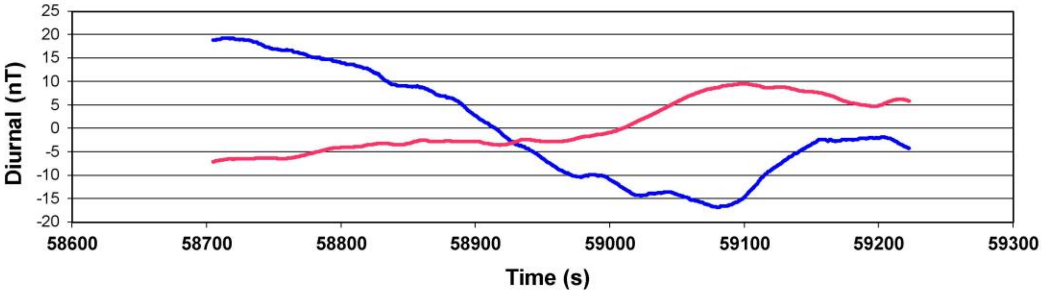


Figure 7. Variability in diurnal variation at two magnetic base stations separated by 150 km (blue – Kugluktuk, NU, red – Ross Point, NU)

The Earth's magnetic field is also subject to shorter period variations. In order to limit ultra-low frequency (ULF) waves, or micropulsations, an additional maximum tolerance of 0.5 nT (peak to peak) deviation from a long chord equivalent to a period of 15 seconds for each base station is imposed.

A total field magnetometer ground station must be calibrated and operated continuously throughout the survey operation. It must be set up at the base of operations or within the survey area, at a magnetically noise-free location, away from moving steel objects, vehicles and DC electrical power lines, which could interfere with the recording of the magnetic field diurnal variation (Fig. 8). There can be no gaps in the recording of base station data during actual survey flying.

Figure 8. Magnetic base station.

GPS clock time must be used to record the time of the ground magnetometer readings for all base stations. The time readings of the base station(s) must be synchronized with the time reading onboard the aircraft. The specifications for the base station magnetometers are:

Table 2: Base magnetometer specifications

Sensitivity	0.01 nT
Recording	1 sec. or better
Noise Level	0.10 nT or better

3.1.3 Altimeters

A radar altimeter is used to determine distance from the aircraft to the ground. This information can be used to construct a digital elevation model when subtracted from the GPS altimetry.

Radar altimeter with digital output and a precise radar display, must form part of the ancillary equipment for the survey aircraft. The specification for range may vary depending on survey area topography and survey platform.

Table 3: Radar altimeter specifications

Minimum range:	**0-800** m
Accuracy (minimal)	**5%**

3.1.4 Satellite navigation

Global navigation satellite systems (GNSS) have greatly improved positional accuracy for airborne geophysical surveys, which has resulted in higher quality magnetic data as tie line-flight line intersection differences used in the levelling process are more accurate.

Currently, there are two fully operational GNSS, the American NAVSTAR **G**lobal **P**ositioning **S**ystem (GPS) and the competing Russian **Glo**bal **Na**vigation **S**atellite **S**ystem (GLONASS). Both systems require 24 operational satellites in circular orbit to complete the constellation for total global coverage. The GPS constellation of satellites orbit along six planes with a 55° inclination while the GLONASS constellation has 3 planes at 64.8° inclination. Augmenting GPS with an additional constellation such as GLONASS (Fig. 9) can be useful in special circumstances where the survey area is located in high latitudes, where there may be a poor distribution of satellites, or in mountainous areas, where satellites may be blocked from view, making positional calculations less accurate.

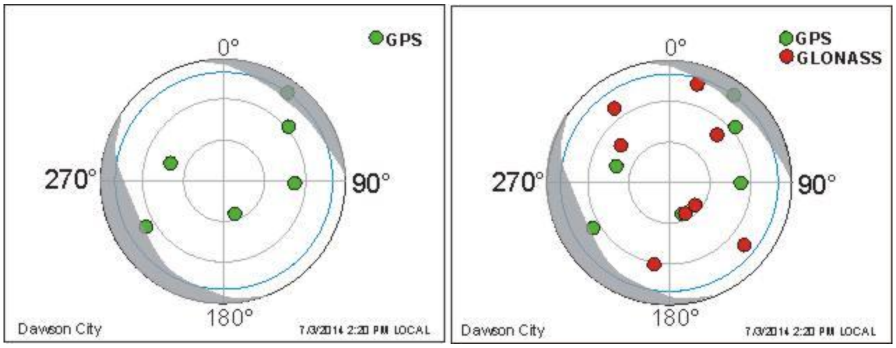


Figure 9. Sky plot of satellites in view in mountainous area in Yukon: (a) At 2:30 PM local time, only five GPS satellites are in view; (b) By adding GLONASS, thirteen satellites are available for positional calculations.

Most current commercial receivers used by the airborne geophysical survey community are integrated allowing for the option to operate either in GPS or GLONASS mode separately or in combination for optimum results. Currently, other satellite navigational systems including Galileo (European), Beidou/COMPASS (Chinese), and Quasi-Zenith Satellite System (Japanese) are under development or are now partially deployed. Since GPS has been in continuous and reliable service for civilian use since 1995, it is a mature navigational system that is preferred on Canadian airborne surveys. In this context, GNSS and GPS are considered synonymous for the purpose of this section.

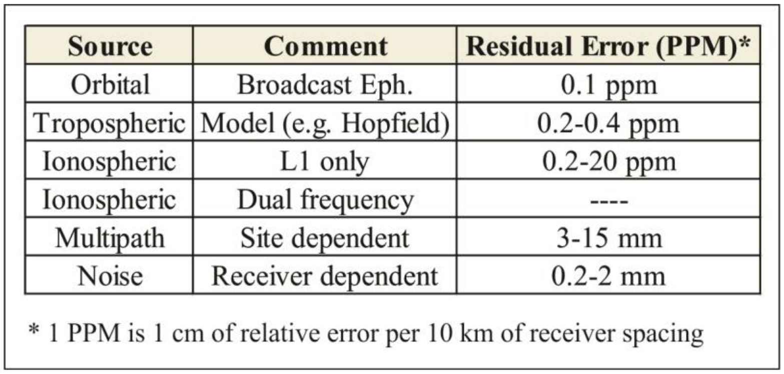
All airborne geophysical survey aircraft used in GSC surveys must be equipped with dual frequency GPS receivers capable of tracking civilian L1 Band Coarse Acquisition code signal and L1, L2 Band carrier phase satellite signals that are made available through the Standard Positioning Service (SPS). These signals provide kinematic positional measurements for fixed-wing surveys at no less than 1Hz (equivalent to a position fix approximately every 75 metres), which can then be processed post-flight to achieve aircraft position to within sub-metre accuracy. Most receivers are also configured to receive L-Band signals for real-time positional guidance to navigate pre-planned flight path and variable height levels conforming to a drape surface. Multiple GPS receivers, mounted on the longitudinal, transverse and vertical axes of aircraft, are currently being used successfully to calculate aircraft orientation parameters at 10 Hz for the purpose of gradient measurements on multi-sensor magnetic surveys, with or without augmentation by Inertial Navigation Systems (INS).

Sub-metre real-time positional guidance for the survey aircraft is possible through commercial correction service providers (Trimble, Novatel, etc). These corrections are transmitted from geo-synchronous satellites in line of sight, so the receiver must have an unobstructed view of the geo-synchronous satellite.

The survey aircraft's position can be improved post-flight where the GPS signals are processed either by the differential correction technique (DGPS) or alternatively by the Precise Point Positioning (PPP) technique. DGPS involves the use of two receivers (a fixed reference base station GPS and a moving aircraft GPS) which track the visible satellite constellation ranging signals simultaneously. The fixed reference receiver at a precisely known location measures the systematic GPS biases which are also common with the remote aircraft's GPS receiver operating in the same general geographic area. These biases are removed from the measurements taken by a moving aircraft's GPS receiver, so long as the survey is in the same general vicinity as the reference base station. The farther the aircraft GPS receiver is from the fixed referenced base, the more the biases will differ resulting in a less accurate aircraft position. PPP performs precise position determination by making use of accurately determined satellite position and clock correction estimates such as those provided for example by the International GNSS Service (IGS) (Dow et al., 2009) as well as accurate modeling to account for centimetre-level effects. The satellite orbit and clock corrections data are computed from pseudo-range and carrier phase observations obtained from a network of fixed Continuously

Operating Reference Stations (CORS). The availability of IGS data and the PPP process thus eliminates the need for a static GPS base station on location.

To achieve sub-metre accuracies post-flight, differential GPS processing has an advantage in providing accurate results where the distance or base line length between the base station GPS and the dual-frequency aircraft GPS receiver is relatively small, since common but significant errors (Table 4, GPS error sources) such as ephemeris errors or signal path delays through the ionosphere and troposphere are relatively similar and thus cancel out. Positional solutions with baselines of 100 kilometres, or more, separating the aircraft and the GPS base station become increasingly less accurate.



Source	Comment	Residual Error (PPM)*
Orbital	Broadcast Eph.	0.1 ppm
Tropospheric	Model (e.g. Hopfield)	0.2-0.4 ppm
Ionospheric	L1 only	0.2-20 ppm
Ionospheric	Dual frequency	----
Multipath	Site dependent	3-15 mm
Noise	Receiver dependent	0.2-2 mm

* 1 PPM is 1 cm of relative error per 10 km of receiver spacing

Table 4. GPS error sources and their magnitudes (Lachapelle, 2005)

PPP has gained support in airborne survey circles since the latency of clock data has been significantly reduced in the past decade. Users now have access to rapid and more accurate orbit ephemeris data (Kouba, 2009) for real-time and post-survey computations resulting in much higher quality accurate flight path data. Several organizations including the Natural Resources Canada (NRCan) provide free Internet on-line web services to process up-loaded raw dual-frequency GPS observation data. NRCan’s CSRS-PPP software (Kouba and Héroux, 2001) utilized by this service has a long reliable history in the processing of static ground-based observation data as well as kinematic data for airborne survey applications.

The ability to process kinematic dual-frequency GPS data on an airborne survey in a remote location without the need to deploy and maintain a GPS base station to record static data can improve the efficiency of the survey. However, the accuracy of the kinematic GPS positional data processed by the PPP technique can still be affected by the quality of the airborne GPS receiver’s clock, the accuracy of the satellite clock corrections and the success in solving for ambiguities in the carrier phase of the satellite signals. At times interruptions in signal reception, or loss of lock on the carrier phase signal tracking while the aircraft is manoeuvering, can result in the degradation of the accuracy until these ambiguities are better resolved. This segment of degraded data may persist for several kilometres of flight tracking. GPS positional data processed by differential technique recovers much more quickly from these loss-of-lock occurrences than non-differential kinematic processing methods (PPP).

Access to reliable and uninterrupted fast Internet service to download IGS data or alternatively to access a PPP web service is a prerequisite for the use of the PPP technique. As a consequence of a breakdown in Internet service, a delay in the processing of GPS positional flight data may prevent complete quality control of the data in a timely manner. For these reasons, it is prudent to deploy a GPS base station for the purpose of differential processing in the field.

For differential processing purposes, once the dual-frequency GPS base station is set up at a suitable open-sky location, it is critical to be sure that the receiver antenna is secure and stable. Building obstructions, trees, fences, antennae, sloping roof around the GPS base station that would block part of the sky, or allow signal to be reflected from surrounding surfaces will likely produce multipath interference resulting in incorrect phase ambiguity resolution in the airborne positional data and potentially cause decimetres to metres of error.

GSC specifications require that complete GPS coverage must be obtained. The positional outputs are to be digitally recorded to 0.000001 degree to provide a final and minimal positional error. A twelve channel receiver is minimally acceptable for a single constellation survey. A dual-frequency 12-channel GPS acquisition system with adequate memory to record aircraft position once per second is required. A dual-frequency GPS base station set up near the base of operations is also required. The GPS system must have the capacity to record and store all parameters to permit post-flight differential correction of the GPS navigational data.

In the collection of GPS positional data, one must ensure that its quality is the best possible throughout any survey if the geophysical data are to be mapped accurately. In the magnetic levelling technique described later in more detail, correct determination of the exact intersection points between the tie-line and traverse lines is crucial.

Careful installation of the GPS equipment onboard the aircraft and mounting of the antennae on the exterior of the aircraft is important in minimizing positional inaccuracies. Leakage or interference form external electronic signals my also degrade the data quality.

Frequent inspection of the raw GPS data followed by careful processing is an integral part of the quality control of the survey data. A speed calculation on the recorded GPS Easting and Northing coordinates is a basic check that will usually reveal any major data gaps or unexpected irregularities in the flight path data. But, in order to assess the overall quality of the data post-flight on a sample to sample basis, there are a number of open-source and commercial software that are available to evaluate airborne kinematic data. Currently, commercial and open-source software by NovAtel, Trimble, Bernese Gipsy-Oasis, RTKLIB and others are capable of handling most GPS/GNSS data processing and analysis tasks.

GPS software will present several options to evaluate basic quality factors such as the number of visible satellites at any instant, the Position Dilution of Precision (measure of accuracy in 3-D position), velocity and sky plot of the visible satellites. In addition, to be sure that the recorded GPS data for a complete flight is in the accuracy range (10-20 cm) expected of a dual-frequency system operating in kinematic mode, diagnostic tools are needed for further analysis such as Combined Separation (Forward / Reverse solutions) solution estimation, Quality Factor, Satellite Lock condition (Cycle slips), Float/Fixed Ambiguity status, C/A Code Root Mean Square (RMS) error, Carrier Phase RMS and horizontal and vertical Standard Deviations Measurement error estimates.

A sample of a flight's data quality is examined by two software tools in Figure 10 where the Quality Factor is displayed along with the Forward/Reverse Separation diagnostics involving the loss of satellite lock events. These trigger instantaneous loss of Carrier Phase signals necessary for very precise positional measurements. Each incident in the sample data, detected at approximately 10 minute intervals, is traced to periodic electronic interference signals created on board the aircraft. Such incidents curtail ambiguity resolution and consequently cause significant trajectory measurement uncertainties and even damaging data gaps lasting for several seconds in differential processing mode, and even worse, lasting more than several minutes in PPP mode. The Quality Factor tool in some software packages will flag problem areas, with pre-set sensitivities, that can then be utilized to omit unreliable data. Most software will provide the Forward/Reverse Separation tool which records the calculated position of the aircraft in the horizontal and vertical plane as data is processed forward in time, then processed in reverse. The difference between the two trajectories is displayed in profile as residuals (East, North and Up) to detect abnormal variations that are a sign of non-confidence in the solution to the aircraft's position.

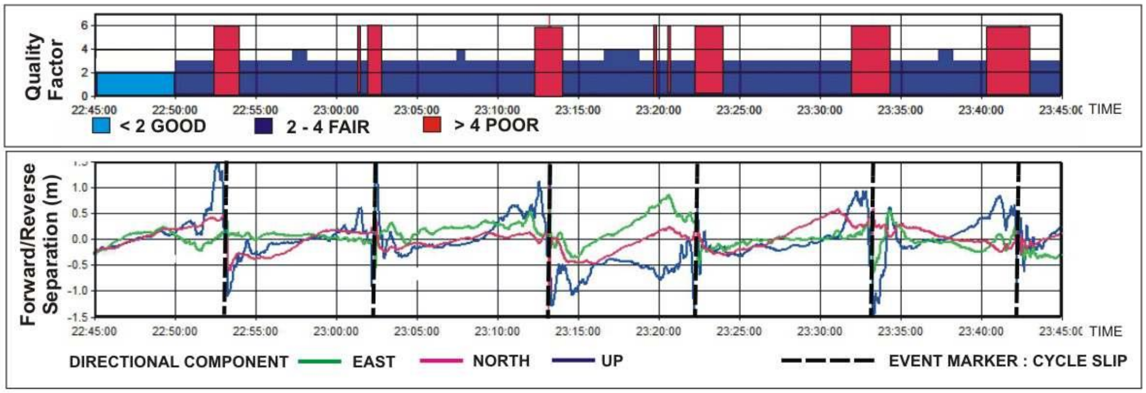


Figure 10. Upper panel: Quality Factor diagnostic plot of segments (*in red*) designated as poor quality data to be considered for omission in processing. Lower panel: Forward and Reverse Separation plot where cycle slips have caused damage resulting in unreliable data indicated by large residuals in each of the East, North and Up directions.

3.1.5 Flight Path Video Camera

Flight path cameras were an integral part of flight path recovery before the advent of satellite positioning. The main purpose of a video record of the flight path in modern surveys is to identify cultural features that may cause anomalies in the data (Fig. 11). This can be a permanent cultural feature such as house or barn, or a transient feature such as a ship in an offshore survey. A vertically-mounted, continuous-recording video camera, with a wide angle lens to maximize ground coverage at survey altitude, is operated while the aircraft is surveying. Time stamp updates must be displayed on the video image with the display of real time GPS positional information being optional.

Figure 11. Picture of a boat captured from onboard video, Western Newfoundland Offshore Aeromagnetic Survey.

3.1.6 Aircraft

Contractors must have experience and demonstrated capability to carry out the required airborne survey and to compile the resultant data into aeromagnetic map form. This will require that contractors have suitable survey aircraft, equipment, instrumentation and compilation facilities. All eligible contractors have demonstrated this capability by having flown and compiled at least one regional total field aeromagnetic survey of at least 10,000 line kilometers for fixed-wing surveys (2,500 line kilometers for helicopter-borne surveys) using GPS navigation aids to fly a pre-planned drape surface.

Contractors must supply, maintain and operate aircraft, suitably equipped and Transport Canada approved, to carry out a given survey, including the supply of required fuel, oil and lubricants. Back-up aircraft must be identified and ready for mobilization within thirty days of receiving a request in writing from the survey's Technical Authority.

For any proposed aircraft that has not been engaged in a prior aeromagnetic survey for the Geological Survey of Canada, calibration results are required as part of any proposal.

In describing the proposed aircraft, contractors must supply information about their capabilities and availability in order to determine suitability and readiness. These include aircraft type, registration, number of engine hours remaining after mobilization and before overhaul, range, cruising speed in knots, climb/descent gradient performance, aviation fuel used, hourly consumption for aviation fuel and oil.

3.1.7 Qualified Personnel

Contractors are required to provide names and curriculum vitae for proposed survey personnel. This is to ensure survey staff are qualified to complete the project and suitably experienced to identify and correct technical issues. The positions required for each survey are Project Manager, Field Manager, Pilots, Field Quality Controller, Instrument Operator or co-pilot, and Aircraft Maintenance Engineer.

The Project Manager is responsible for all aspects of the survey with signing authority for all reports and deliverables. The Project manager must be a geophysicist, with a degree in earth sciences from a recognized university or a geoscientist with applied experience in aeromagnetic surveys. The proposed person must have 3 years of related experience in airborne geophysical survey projects that were comparable in scope, instrumentation and survey parameters to that required for a given contract.

The Field Manager has full field responsibility for daily operations of the survey and ensuring data quality. The Field manager should be onsite for the duration of the survey. The position requires two years of related experience in aeromagnetic survey projects.

All pilots must hold a valid commercial pilot license, applicable to the type of aircraft to be flown, issued by Transport Canada and must be able to provide proof on demand. In addition, pilots must have at least 300 hours of flying on low level airborne geophysical surveys and must be able to provide proof on demand.

The Field Quality Controller is an assistant to the Field Manager and performs data quality control including flight path, magnetic data, and diurnal monitoring. The position requires related experience on at least two airborne geophysical survey projects of this type within the last 3 years and must be able to provide proof on demand.

The Instrument Operator is onboard the aircraft and monitors the geophysical instruments. This function may be performed by a co-pilot or may be automated. This work requires familiarity with contract specifications regarding noise levels. The requirements of the position are at least one year of operational experience on aeromagnetic surveys and must be able to provide proof on demand.

The Maintenance Engineer can perform aircraft inspections and preventative maintenance on an ongoing basis. This position may be subcontracted. The requirements of the position are a valid Category M licence and be able to provide proof on demand.

A minimum of 3 field members excluding the Aircraft Maintenance Engineer are required for each survey.

3.2 Bid/Proposal Evaluation

The GSC requires geophysical contractors to pre-qualify for its airborne survey contracts. This is accomplished by the establishment of Supply Arrangements between contractors and Natural Resources Canada. Contractors are invited to submit proposals to pre-qualify. Prospective contractors must submit a digital dataset for evaluation. This dataset always includes high-resolution total magnetic field data and may include gamma-ray spectrometry, electromagnetic, gravity, or gravity gradiometer data. The dataset must be no less than 10,000 line kilometres for fixed-wing magnetic-only pre-qualification. The proposal must include line data sampled at 10 Hz, gridded data, and supporting maps and documentation to portray and demonstrate acquisition and compilation capabilities. The data must be flown on a drape surface, be within the specified noise envelope (0.1 nT based on fourth difference of the magnetic field), and continuously recorded. The contractors must demonstrate that they have suitable personnel, aircraft, magnetometers, radar/laser altimeters, GPS, and base stations. The contractor must be capable of acquiring, compiling and presenting aeromagnetic data to GSC specifications. If a contractor is deemed to be pre-qualified, an NRCan Supply Arrangement is established. NRCan issues a Request for Supply Arrangements twice a year.

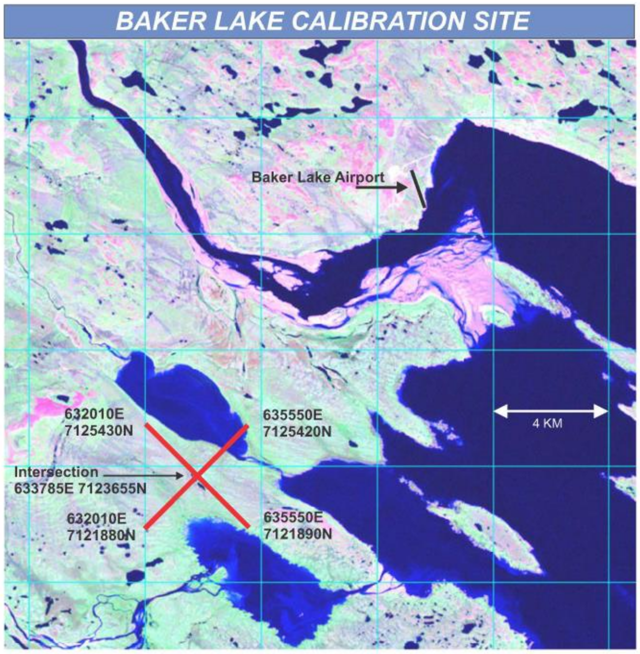
As the GSC requires new aeromagnetic surveys, Requests for Proposals, based on specifications particular to the specific survey and the specifications of Supply Arrangements, are sent to all pre-qualified contractors. Contractors have ten to fifteen days to submit proposals for the survey. The proposals are evaluated against mandatory and rated criteria. The successful bidder will have passed the evaluation process and provided the lowest cost per evaluation point. The elements of the contractors’ bids to be evaluated include proposed qualified personnel, aircraft, airborne magnetic system, base station, satellite navigation system, field verification system, recent past performance, current workload, reconnaissance of the project and quality control.

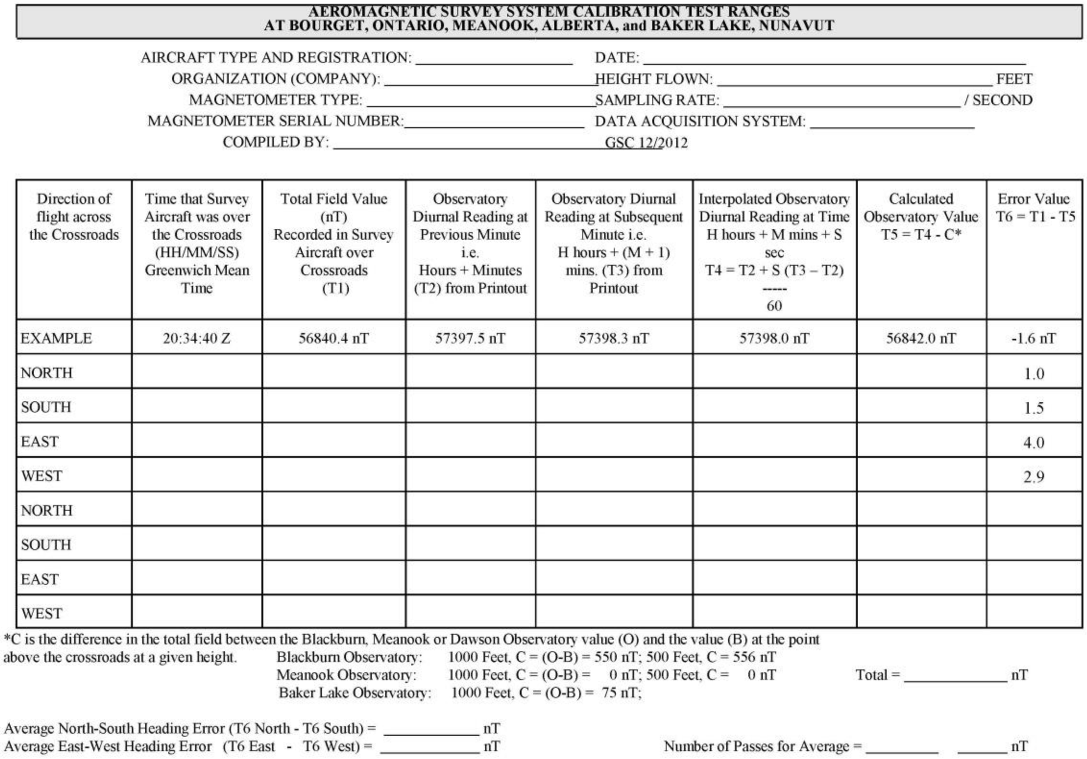
3.3 Calibrations

The quality assurance of GSC aeromagnetic surveys is achieved through the specifications and calibrations required in contracts, through a field inspection of the survey system, and quality control of the early production data, as well as at all stages of post-processing. Instrument calibrations ensure all acquired data will be accurate and tied to national standards. From the contract, the contractor is made aware of all required calibrations and the requirement to present the results to the GSC Technical Authority.

3.3.1 Magnetometer Absolute Reference Test/Magnetometer Calibration Check

A calibration check of the aircraft magnetometer system ensures that total magnetic field measurements are consistent between multiple platforms on a single survey and across multiple surveys. In order to verify that the measured magnetic value and the heading errors are within specification, calibration checks are carried out using one of the Geological Survey of Canada (GSC) calibration check ranges at the start and end of survey operations. These calibration ranges are located at Bourget, ON, Meanook, AB and Baker Lake, NU (Fig. 12). This calibration check involves measuring the magnetic field while the aircraft overflies a reference position at a specified altitude (usually 500 ft or 1000 ft) and comparing these measured values with those as measured at local geomagnetic observatories. The magnetic offset between the observatory and calibration location is predetermined. Two passes in each of the north, south, east, and west directions are flown to obtain sufficient data to calculate a statistically valid error value for the magnetometer system.





AEROMAGNETIC SURVEY SYSTEM CALIBRATION TEST RANGES
AT BOURGET, ONTARIO, MEANOOK, ALBERTA, and BAKER LAKE, NUNAVUT

AIRCRAFT TYPE AND REGISTRATION: ____________________ DATE: ____
ORGANIZATION (COMPANY): ____________________________ HEIGHT FLOWN: __________________________________ FEET
MAGNETOMETER TYPE: ____________________________ SAMPLING RATE: ______________________________ / SECOND
MAGNETOMETER SERIAL NUMBER: ______________________ DATA ACQUISITION SYSTEM: _____________________
COMPILED BY: ___________________________________ GSC 12/2012

Direction of flight across the Crossroads	Time that Survey Aircraft was over the Crossroads (HH/MM/SS) Greenwich Mean Time	Total Field Value (nT) Recorded in Survey Aircraft over Crossroads (T1)	Observatory Diurnal Reading at Previous Minute i.e. Hours + Minutes (T2) from Printout	Observatory Diurnal Reading at Subsequent Minute i.e. H hours + (M + 1) mins. (T3) from Printout	Interpolated Observatory Diurnal Reading at Time H hours + M mins + S sec T4 = T2 + S (T3 – T2) ----- 60	Calculated Observatory Value T5 = T4 - C*	Error Value T6 = T1 - T5
EXAMPLE	20:34:40 Z	56840.4 nT	57397.5 nT	57398.3 nT	57398.0 nT	56842.0 nT	-1.6 nT
NORTH							1.0
SOUTH							1.5
EAST							4.0
WEST							2.9
NORTH							
SOUTH							
EAST							
WEST							

*C is the difference in the total field between the Blackburn, Meanook or Dawson Observatory value (O) and the value (B) at the point above the crossroads at a given height.

Blackburn Observatory: 1000 Feet, C = (O-B) = 550 nT; 500 Feet, C = 556 nT
Meanook Observatory: 1000 Feet, C = (O-B) = 0 nT; 500 Feet, C = 0 nT
Baker Lake Observatory: 1000 Feet, C = (O-B) = 75 nT;

Total = _____________ nT

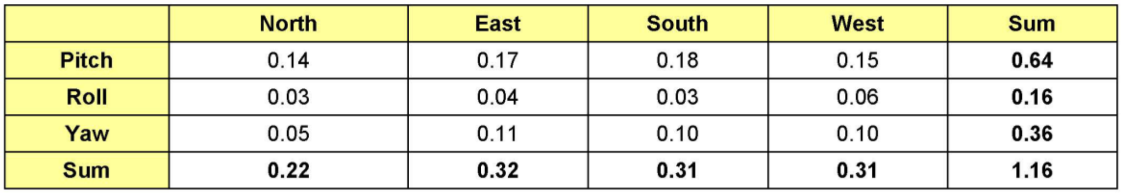
Average North-South Heading Error (T6 North - T6 South) = ____________ nT
Average East-West Heading Error (T6 East - T6 West) = ____________ nT
Number of Passes for Average = _________ ______ nT

Figure 12. Baker Lake, NU magnetic calibration site and calibration document.

When more than one aircraft are used on an aeromagnetic survey, each aircraft must fly a common line segment of at least 50 km in length. The data are compared to ensure that all systems (magnetometer, GPS, radar altimeter) produce similar results within the error ranges of the instruments. This test ensures that survey specific parameters such as flying height and drape surface are consistent across multiple platforms. Data should be collected in survey mode in a dynamic part of the survey block with varying altitude and magnetic response. Preferably, this comparative line is flown near the beginning of a survey and is repeated any time equipment is changed on an aircraft.

3.3.2 Compensation Test (Figure of Merit)

As the aircraft manoeuvres to follow the predefined flight track, the aircraft's orientation with respect to the ambient magnetic field changes causing a high frequency signal to be added to the true total magnetic field value. This is due to the interaction of the permanent magnetization in the aircraft and transient magnetic fields produced by the varying electrical load of systems onboard and moving flight control surfaces. A compensation test is performed to measure this magnetic response and, through the use of an onboard magnetic compensator or post-processing software, adjustments are made to the measured total magnetic field intensity to reduce these motion effects. This compensation relies on a fluxgate magnetometer to provide input. The fluxgate magnetometer measures the magnetic field strength in three orthogonal directions whereas the main optical vapour magnetometer is scalar and measures only the total field value. The three components of the field vary disproportionately as the aircraft manoeuvers in the ambient magnetic field and are used to reduce the manoeuvering effect on the main sensor. The relationship between the manoeuvering, the effect on the main magnetometer, and the fluxgates is determined by a compensation test. The test involves determining the effect on the system for each of roll, pitch and yaw. These tests are performed over a magnetically quiet zone and at a high altitude (usually 3000m) in order to reduce magnetic effects from the ground. They consist of flying +/-10 degree rolls, +/-5 degree pitches and +/-5 degree yaws peak- to-peak along north, south, east, and west headings over periods of 4 to 5 seconds. With this information, a compensation Figure of Merit (FOM) for the aircraft can be calculated (see Figure 13). This involves summing the peak-to-peak amplitudes of the 12 magnetic signatures (three manoeuvres in four directions each). An improvement factor of 10 to 20 is regularly attainable (see Figure 14). For fixed-wing surveys, the FOM must not exceed 1.5 nT for systems that have a 0.1 nT maximum noise limit. The maximum FOM for helicopter surveys is 2.0nT. An FOM is typically performed before the Magnetometer Absolute Reference Test and again at the survey location prior to acquiring production data.



	North	**East**	**South**	**West**	**Sum**
Pitch	0.14	0.17	0.18	0.15	**0.64**
Roll	0.03	0.04	0.03	0.06	**0.16**
Yaw	0.05	0.11	0.10	0.10	**0.36**
Sum	**0.22**	**0.32**	**0.31**	**0.31**	**1.16**

Figure 13. Example of a Figure of Merit (test units are nT).

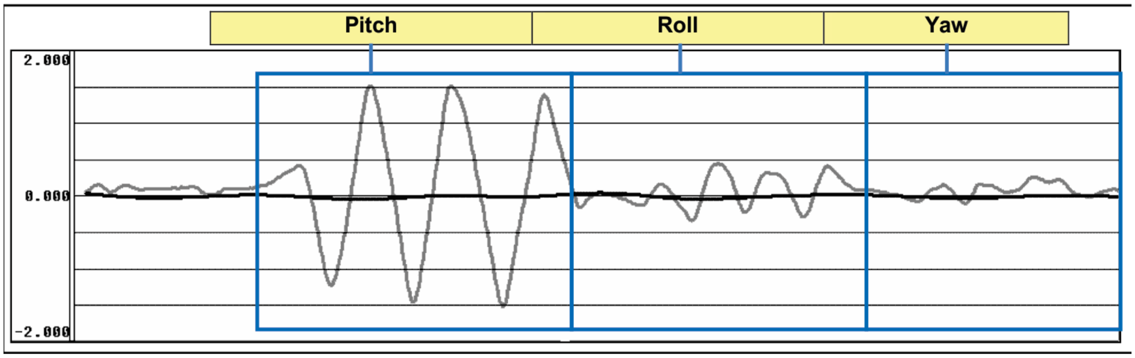


Figure 14. Compensated (Black) vs uncompensated(Gray) magnetic signal. One direction only. Units are nT.

3.3.3 Lag (Parallax) Test

A lag test is the determination of the difference in time a GPS position is recorded and the time a corresponding magnetometer reading is recorded. The lag is a result of instrument synchronisation issues as well as the horizontal distance between the GPS antenna and the magnetic sensor. Before the commencement of a survey, a lag test must be performed to ascertain this difference. Test lines are flown in opposite directions at the normal survey height across a sharp magnetic anomaly. To ensure that the lag remains constant, lag tests may be conducted throughout the survey. This is particularly important following any major survey equipment alteration or replacement on the aircraft or when a variable lag is suspected.

A second method of determining lag is to statistically examine the magnetic differences at intersections of a levelled dataset. The lag is varied in small increments and the most appropriate lag will correspond to the lag that minimises the closure error (standard deviation) of the magnetic differences at the intersections. It can be performed on a flight-by-flight basis or for each aircraft on multi-aircraft survey. This may be more reliable than the flight method and is a good check that the lag used is correct.

An incorrect lag may manifest as a herringbone-like effect when the data are gridded (Fig. 15). Adjacent flight lines have to have been flown in opposite directions for this to occur.

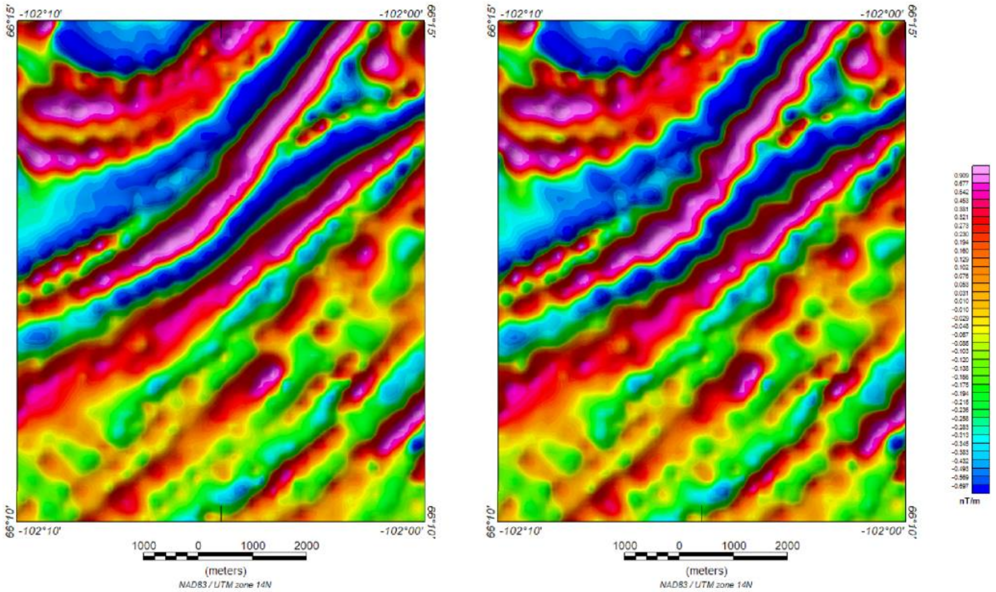


Figure 15. a) First vertical derivative of the magnetic field. b) First vertical derivative of the magnetic field with a 0.5 s lag.

3.3.4 Radar Altimeter Calibration

Calibration of the radar altimeter is required for generating accurate digital terrain models from GPS altimetry. Pre- and post-survey calibrations are performed by flying a range of altitudes, representative of the survey area conditions, above and below the designated survey altitude. These altitudes must cover the minimum and maximum expected range at 5 or more altitudes of equal increments. Typically, the calibration is determined by comparing the GPS altimetry data at the different altitudes above a known elevation such as an air strip with the altitude as determined by the radar altimeter. The GPS and radar altimetry (plus the known elevation) should agree within the error ranges of the instruments. An additional line is flown at survey height crossing over a lake (preferably 1 km in width) to ascertain the radar unit's sensitivity to the reflectivity difference of dry land and water.

3.4 Site Inspection

A site inspection of the contractor at the base of operations is typically performed by the Technical Authority. The purpose of this inspection is to ensure the contractor follows contract specifications and supplies all equipment and personnel as described in their bid. In addition, the Technical Authority works with the contractor's personnel to ensure installations are appropriate, calibrations are verified, and data processing is valid. The inspection takes place after the contractor has mobilized to the base of operations and has acquired a few thousand line km of production data.

The verification of equipment includes all airborne and ground based systems. This includes an inspection of the type and function of:

Survey aircraft (on-site as proposed)
Airborne magnetometer
Data acquisition system
Onboard magnetometer compensator (if employed)
Navigational System with pilot steering display
GPS subsystems:
  - dual frequency 12 channel GPS
  - dual frequency base station receiver
Barometric altimeter
Radar altimeter
Digital video camera

There must be an inspection of the ground magnetic base station(s) to ensure sampling rate and that the bases are installed in an area unaffected by transient magnetic effects (moving magnetized objects). The GPS base station receiver must be observed to have an unobstructed view of the sky. In addition, the inspector must ensure that all data acquisition systems are synchronized to GPS time pulses in real time.

Tests and calibrations are also verified and these include:

- magnetometer calibration for all aircraft
- on-site Figure of Merit results
- radar altimeter calibration
- lag tests

All personnel must meet minimum requirements for experience and qualification. The Technical Authority will ensure that these personnel are on-site and qualified as described in the contractor's proposal.

3.5 Quality Control

Quality control of airborne surveys begins with the production of data and ends with acceptance of final processed data and data products.

3.5.1 Production Data Verification

The contractor must supply the first few thousand line kilometres of production data to the Technical Authority as soon as possible for quality control purposes. Contractors are obligated to supply all data collected on a weekly basis via the internet. The Technical Authority reviews these data with emphasis on the noise envelope, adherence to the drape surface, tie-line intersections, diurnal magnetic variation, and issues relevant to the current survey. All ground and airborne data must be complete, continuous, synchronized, and recorded to specification. The data are examined as profiles, grids, and filtered products to determine any undesirable characteristics. A fourth-difference filter is applied to profile data to identify noise above the survey specification limit (0.1 nT, Fig. 16). Any issues with data quality must be resolved by the contractor immediately. Data quality issues can prompt a requirement for reflights. Once satisfied with the quality of all data, the Technical Authority can authorize the contractor to demobilize.

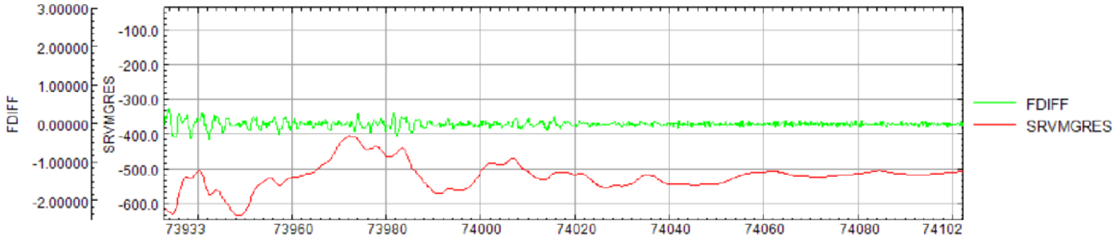


Figure 16. Residual total magnetic field (red) and its fourth difference (green).

3.6 Post-processing - Levelling

Various techniques can be used to remove the effects of the temporal variation of the Earth’s magnetic field on magnetic survey measurements (Luyendyk, 1997). The GSC uses an iterative levelling procedure to minimise the difference in magnetic field values at intersections between control lines and traverse lines. Differences at intersections can be caused by lag misadjustment, horizontal position imprecision, flight altitude differences and, finally, diurnal variations.

3.6.1 Lag

The lag is a time shift in the magnetic data caused by electronic circuit delay and sensor position relative to the GPS antenna. The appropriate lag adjustment restores the magnetic readings to their true location in time as detected by the acquisition system. A pre-survey lag calibration is usually done by flying over a sharply peaked magnetic anomaly in opposite directions at constant speed. This was explained in greater detail in the calibrations section. Figure 17 (a) shows traverse line intersections along a selected control line. Of the four traverse line flights intersecting this control line, in Figure 17 (b) Flight 5 has an inappropriate lag, as shown by the saw-tooth pattern in the intersection difference values. In this case adjacent traverse lines were flown in opposite directions.

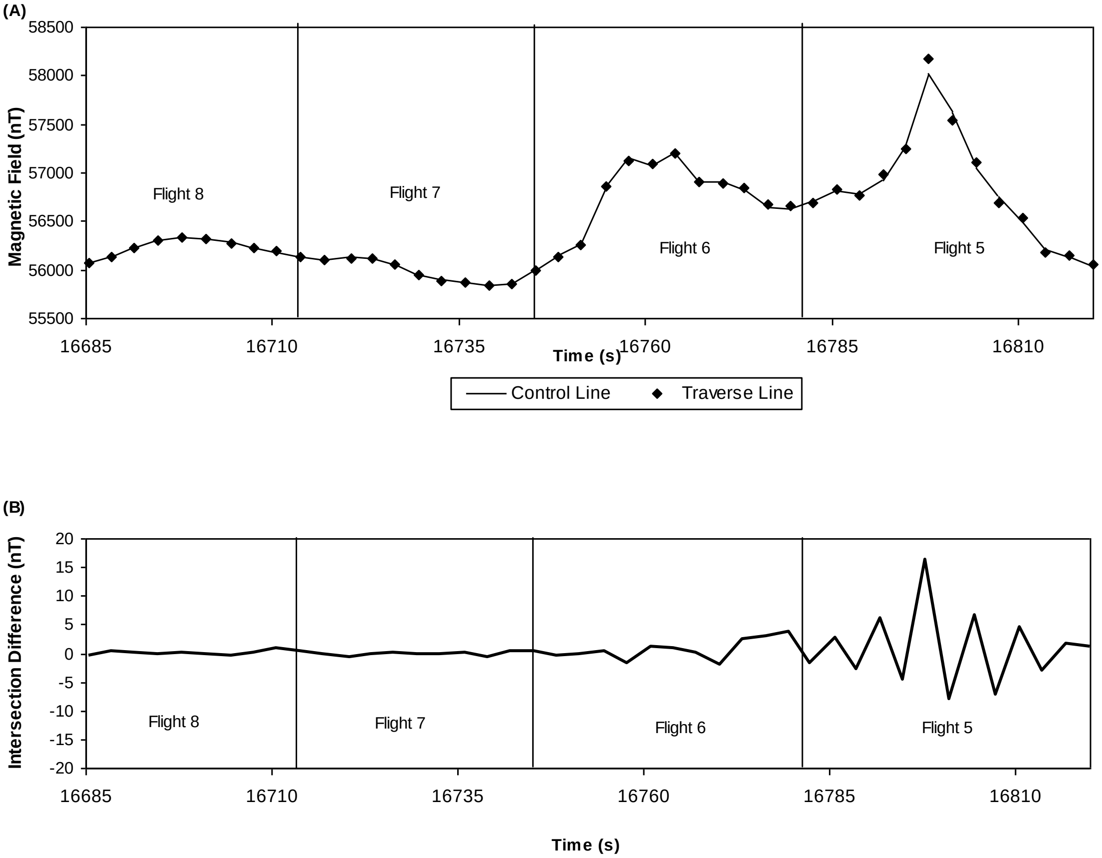


Figure 17. Lag effect on intersection differences. (a) Traverse line intersections on a control line. (b) Effect of the bad lag adjustment along Flight 5 on intersection differences on the control line

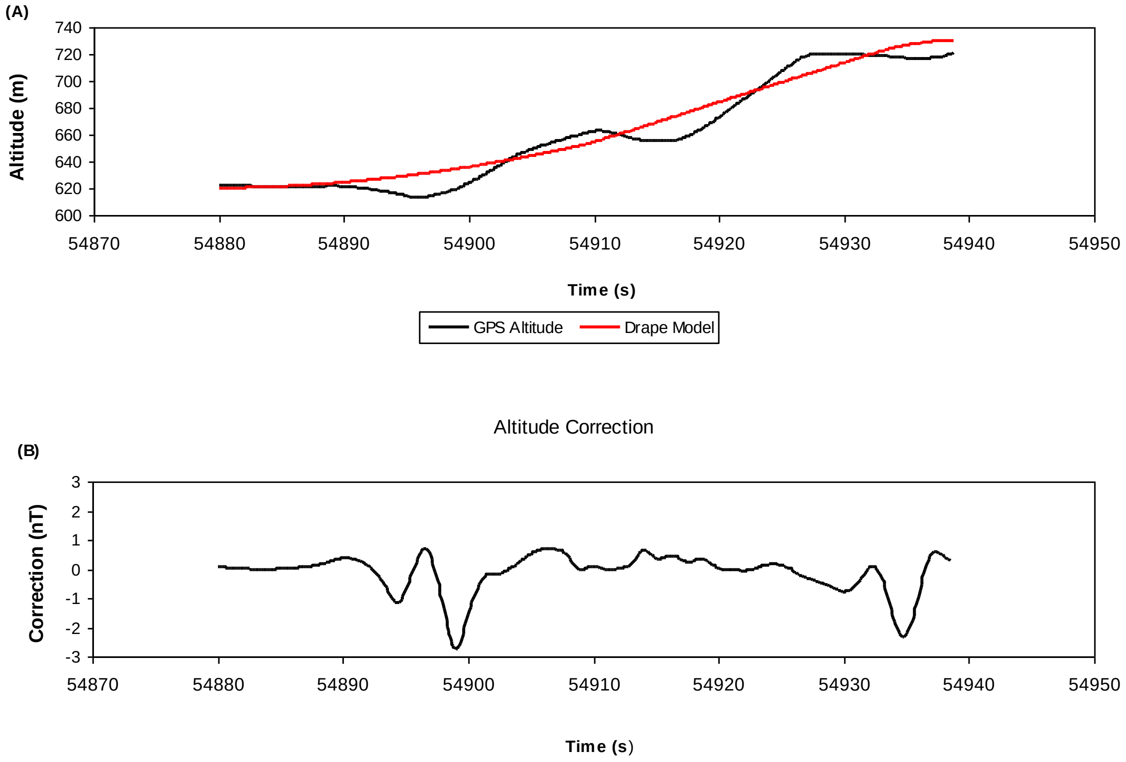
3.6.2 Positioning

Horizontal position errors are caused by measurement imprecision resulting from the GPS navigational system operating in kinematic mode. The magnitude of these errors is a function of satellite geometry, tropospheric and ionospheric conditions, system noise, multipath interference and distance from the aircraft to a reference station. All of these factors contribute to the accuracy of the location to a greater or lesser degree depending on survey circumstances. Methods to minimize these errors are described in the section on GPS flight path processing and quality control.

3.6.3 Altitude differences

Differences in magnetic field values are also caused by flight altitude differences between control and traverse lines. This means the distance of the causative source to the magnetic sensor is unequal at the intersection point. To mitigate the severity of the differences in the magnetic values due to height differences, the survey is planned so that the intersections between control and traverse lines are flown at the same altitude. This involves adhering to a pre-planned flight surface. Such a surface, known as the drape surface, is based on a smooth version of the topographic relief and a maximum slope limitation (5% for a fixed wing aircraft) based on the climbing capability of the survey aircraft. The drape surface is used for the flying with a limitation of no more than +/- 15 metres of deviation from the intended surface. This practical limitation prevents the occurrence of large altitude differences. Yet, this still leaves a possible altitude variation of approximately 15 per cent when flying at an altitude of 100 m. The standard deviation of the variation of the aircraft altitude with respect to the drape surface is generally between 4 to 6 metres.

In order to bring the intersections to the same altitude, the magnetic data along control and traverse lines are continued to the intended drape surface height. Since the continuation distances are relatively small compared to the flying altitude, the continuation is applied to the profile data relative to the drape surface height with a Taylor series expansion using the smooth drape surface as the datum. In this calculation, the first term of the series is the first vertical derivative of the magnetic field calculated from the profile data (Fig. 18).



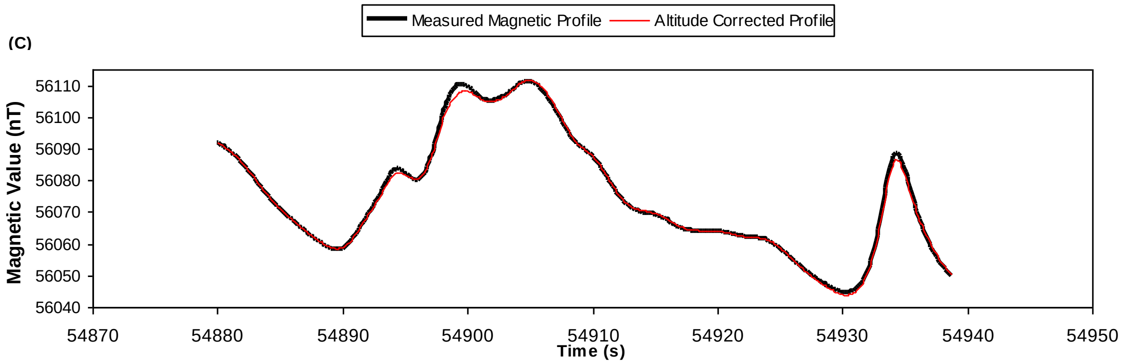


Figure 18. Altitude correction: (a) drape model and actual height of the aircraft. (b) calculated correction caused by the variation in height between the drape model and the height of the aircraft. (c) original magnetic profile and the corrected height profile.

To demonstrate the effect of the altitude correction in the levelling process, a survey was partially levelled using the first order trend adjustment procedure, which is described below, with and without altitude correction. The 79,000 line-kilometre Mistastin survey straddles the Quebec-Labrador provincial boundary. The traverse lines were flown at a spacing of 200 metres, crossed by control lines every 1,200 metres while adhering to a prescribed drape surface. The magnetic data were first levelled without altitude correction using the Geosoft Oasis montaj Iterative Levelling GX, which levels control lines to traverse lines, then traverse lines to control lines. This iterative process involves the application of a zero order trend adjustment to all lines until the process converges, followed by another iteration sequence with a first order trend until final convergence. The standard deviations of the magnetic differences at the intersections were calculated before altitude correction. The same process was then repeated after applying altitude corrections and both sets of the results are tabulated in Table 5 for comparison.

Table 5. Statistics on levelling adjustments

Trend order	**Iteration**	**Without altitude correction Std. dev. (nT)**	**With altitude correction Std. dev. (nT)**
0	1	5.81	5.35
0	2	5.71	5.23
1	1	3.75	2.83
1	2	3.75	2.83

The last iterative levelling cycle shows that the standard deviation of the magnetic differences is 3.75 nT without altitude correction compared to 2.83 nT with altitude correction. This represents an approximate reduction of 25% in the amplitude of the levelling corrections to the raw magnetic field that would have otherwise not been handled correctly in the levelling process. This effect becomes even more significant in areas of high magnetic gradient.

The application of a correction for altitude variation is an essential step that must be completed prior to subsequent stages in the levelling procedure. Only after all intersections have been brought to the same height, the flight path is positioned accurately and all lag issues have been resolved, can one assume that the remaining magnetic differences at intersections are due solely to diurnal variation.

3.6.4 Diurnal variation

The diurnal variations are monitored by a magnetic base station generally located near the base of survey operations. A maximum tolerance of 3.0 nT (peak-to-peak) deviation from a long chord equivalent to a period of one minute is the standard specification for GSC surveys (Fig. 19).

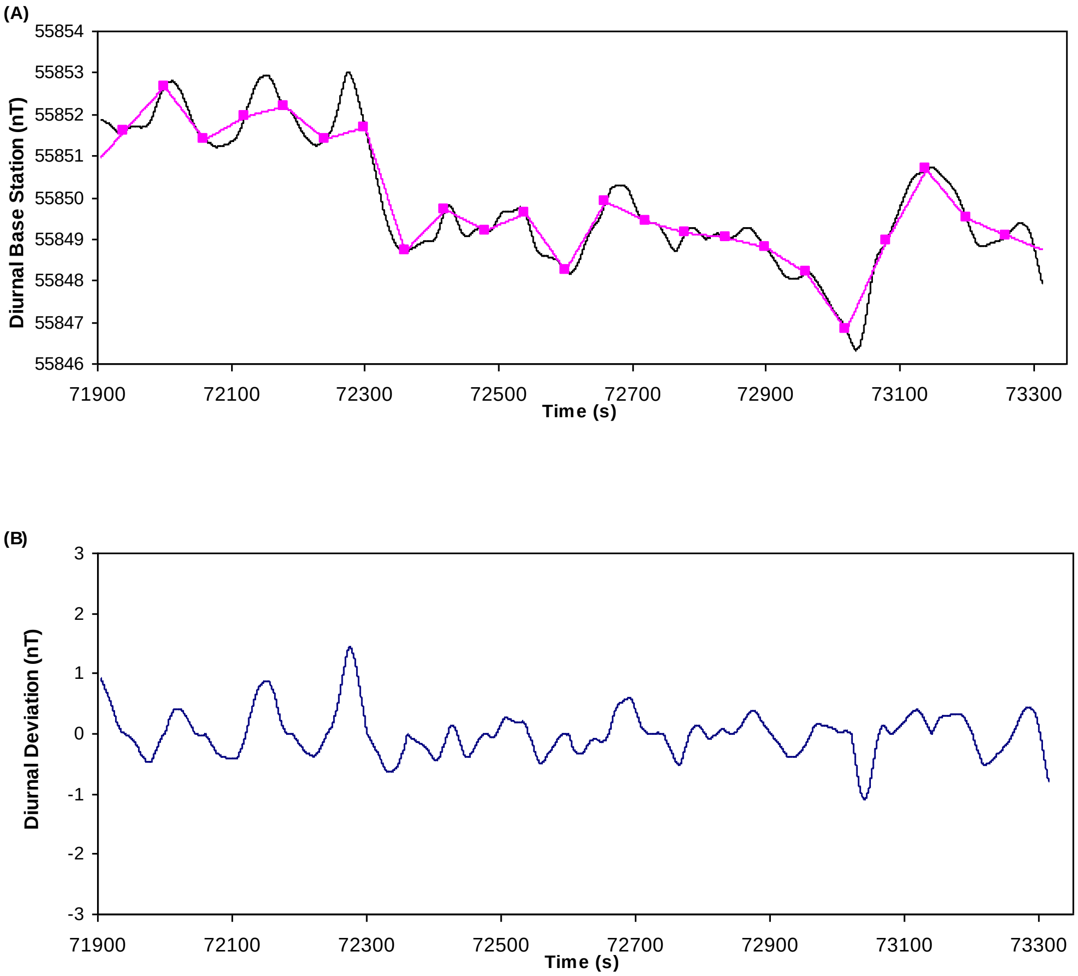


Figure 19. Magnetic base station diurnal monitoring: (a) recorded diurnal variation at the base station with 1 minute long chord segments linearly interpolated. (b) resulting deviation from the chord segments.

The principle behind the levelling method used at the GSC is very simple and has proved over the years to generate reliable results. The GSC's approach is to level the control lines first, followed by tying the traverse lines to the levelled control lines. In the vast expanses of the Canadian north, it is rarely possible to have the base of operations and the magnetic base station within the survey area. Most likely, they are located hundreds of kilometres apart and, as a result, the magnetic diurnal variations at the two distant locations can be different. For this reason, the GSC does not exercise the option of direct subtraction of the magnetic diurnal variation from the airborne magnetic survey data prior to levelling.

The control and traverse lines are statistically levelled to each other at their intersections using the first order trend adjustment procedure described above. A higher trend order is not recommended since it can create problems at line ends. Assuming that this iterative levelling process has removed the equivalent of a first order trend of the diurnal variation, at the aircraft location, the rest of the diurnal variation is estimated along the control lines from the remaining intersection differences. As the control lines are crossed by closely spaced traverse lines (200 m), corresponding to a time interval of approximately 2.5 seconds along the control line, this provides a series of points which are a reliable statistical estimate of the diurnal variation along each control line (Fig. 20).

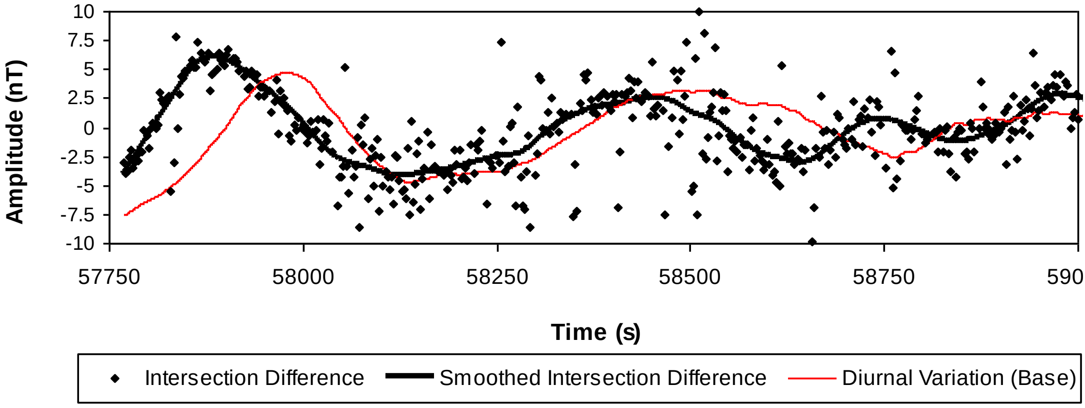


Figure 20. Plot of the intersection difference for a control line (black dots) and the corresponding smoothed intersection difference which is the intended leveling correction. The recorded diurnal variation profile is shown in red

Furthermore, the point plot of the intersection difference is compared with the recorded magnetic base station diurnal variation profile. Although there may be offsets and amplitude differences between the intersection difference trends and the magnetic diurnal profile, the diurnal profiles' amplitudes and frequencies are a helpful reference to select a spline or a rolling mean function to smooth the intersection differences to provide an appropriate levelling correction for the control line. As shown in Figure 20, the smoothed intersection difference profile is similar in shape to the magnetic diurnal profile, but there is an obvious offset with the recorded diurnal profile. It is clear from this example that the subtraction of magnetic base station data from the raw aeromagnetic data, a common practice, would not have been helpful to the levelling process.

Ordinarily, most levelling corrections between intersection locations as outlined above are simple and straightforward. One must always keep in mind that the variation in the levelling adjustment along any line or control line should be relatively small as there is a maximum magnetic diurnal deviation tolerance specification of 3 nT for a period of 1 minute during the survey. If there are levelling adjustments along a control line that are significantly larger than the specification, especially over high magnetic gradients, and there is no evidence at all of a similar trend in the diurnal profile, a further step in the processing must be taken. This problem usually relates back to flight path inaccuracy. Despite our best efforts in correcting for this inaccuracy, even sub-metre misplacement of the magnetic field values can still introduce undesirable intersection discrepancies. Assuming that no further improvement in flight path accuracy is truly possible by means of processing methods due to the limitations of current GNSS (GPS) technology, the only solution that remains is to exclude these large intersection differences from the intersection network prior to re-running the iterative levelling procedure. The following example illustrates the problem and its effects.

In Figure 21 (a) the magnetic profile of a control line with traverse line intersection levels (diamonds) are shown after they have all been levelled with the first order trend adjustment procedure. The traverse line values seem to fit those of the control lines. But upon closer examination of Figure 21 (b) there are large intersection differences highlighted as red squares on the selected control line which are coincident with areas of high magnetic gradient as illustrated by the profile in Figure 21 (a). The red profile in Figure 21(b) shows that there is no evidence of high magnetic diurnal activity that could have caused the large differences. The solution is to exclude these intersections and the trend adjustment process should be restarted without these problematic intersections. Experience with many surveys has shown that these excluded intersection cases generally represent less than 5% of all intersections.

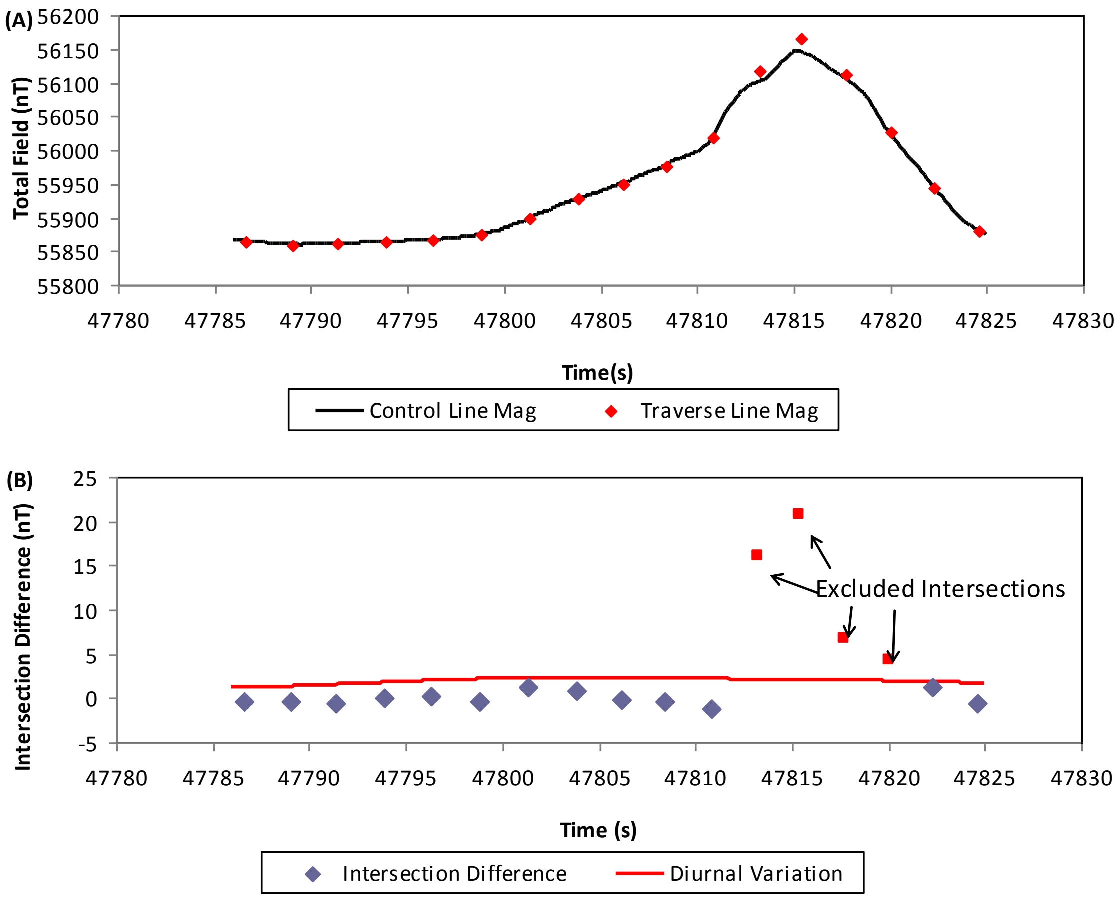


Figure 21. Intersection on control lines. (a) magnetic profile of a control line with intersections of the traverse lines as diamonds (b) amplitude of the intersection difference. Red squares represent intersections to be excluded. The red profile is the diurnal variation at the base station.

The remaining step in the levelling process consists of tying the traverse lines to the levelled control lines. This is accomplished by applying a spline interpolator to the valid intersection differences along each traverse line and subtracting the result from the magnetic field values of the traverse line. In addition, the splined profiles are high-pass filtered using a cut-off wavelength of twice the control line spacing and plotted as a map to show the so-called levelling network.

A visual overview of the levelling network in a map format is the best way to evaluate and refine the level adjustments to the control lines. The plotted profile of adjacent traverse line corrections should vary randomly, as would the plot of the magnetic diurnal profile. Additionally, there should not be any correlation in the level adjustments from line to line. If a correlation is visible then the corresponding control line section must be readjusted manually to remove the correlated trend it caused on the levelling profiles of the traverse lines.

The amplitude of the readjustment correction to a control line is directly measurable on the map. The residual levelling network of the traverse lines in Figure 22 demonstrates cases where correlated corrections occur on a series of control line sections on the right side of the map.

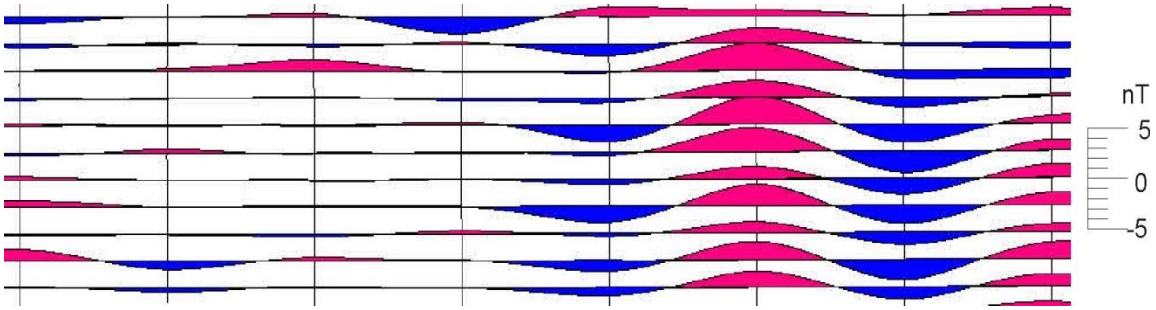
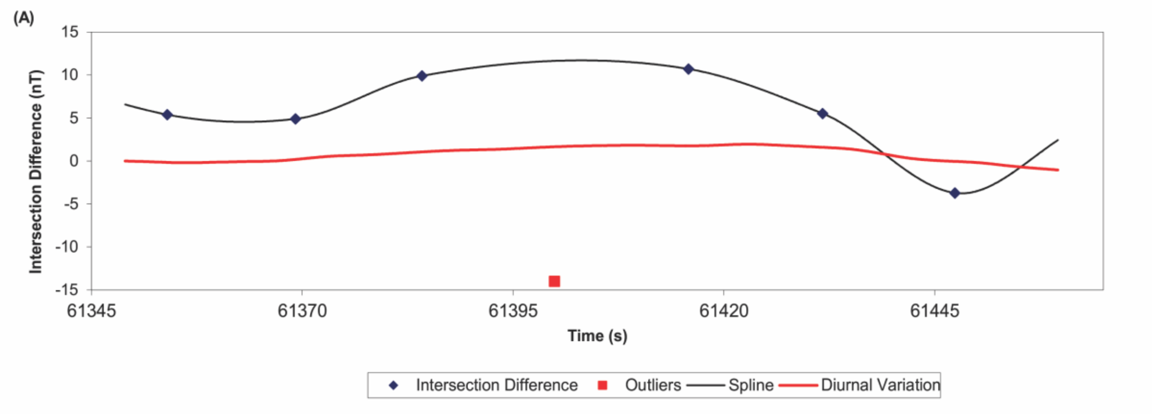


Figure 22. Plot of the high-pass filtered levelling correction of the traverse lines showing that readjustment is needed on the four rightmost control lines. The traverse line spacing was 200 meters.

After the levelling refinements to the control line, the levelling of the traverse lines can be finalized. Figure 23 (a) shows the levelling adjustment of a traverse line. The intersection differences between the traverse line and the levelled control lines are interpolated using the spline method. The excluded intersections are ignored in this interpolation as well (Fig. 23).



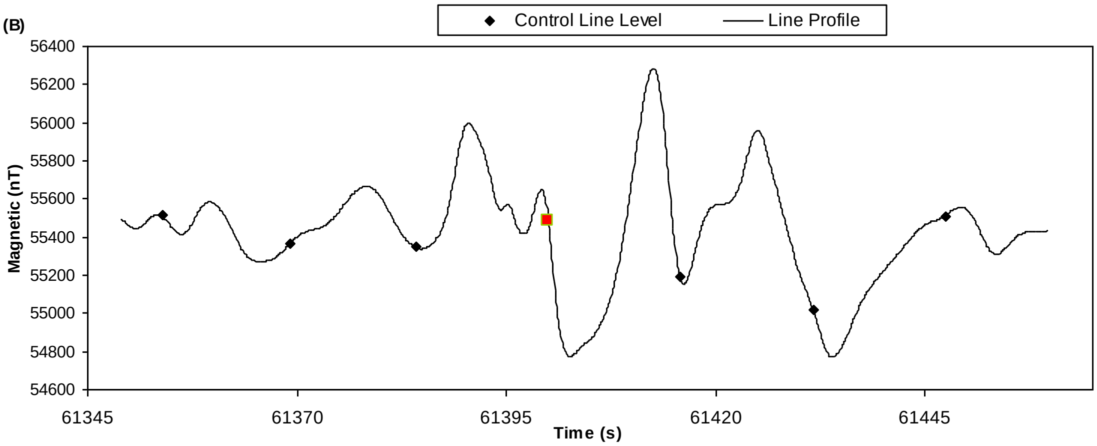


Figure 23. Traverse line levelling adjustment; (a) shows the residual intersection differences as black diamonds. The red square represents the excluded intersection. The red profile is the diurnal variation at the base station. The black interpolated profile is the final levelling adjustment; (b) shows the magnetic profile of the traverse line with intersections of the control lines.

The final levelled magnetic field is then gridded from which reliable first and/or second vertical derivatives can be calculated. Micro-levelling is generally not needed, providing that the control lines spacing is not too large, that the diurnal tolerance is within an acceptable level and that the levelling procedure above was followed.

All of the above steps are necessary to ensure that unwarranted artificial long wavelength errors are not introduced into the magnetic survey data and that the integrity of the original profile data is preserved. In many cases, such unwarranted anomalies are quite subtle due to their long wavelengths, but their introduction can lead to misleading results in subsequent processing and/or interpretation.

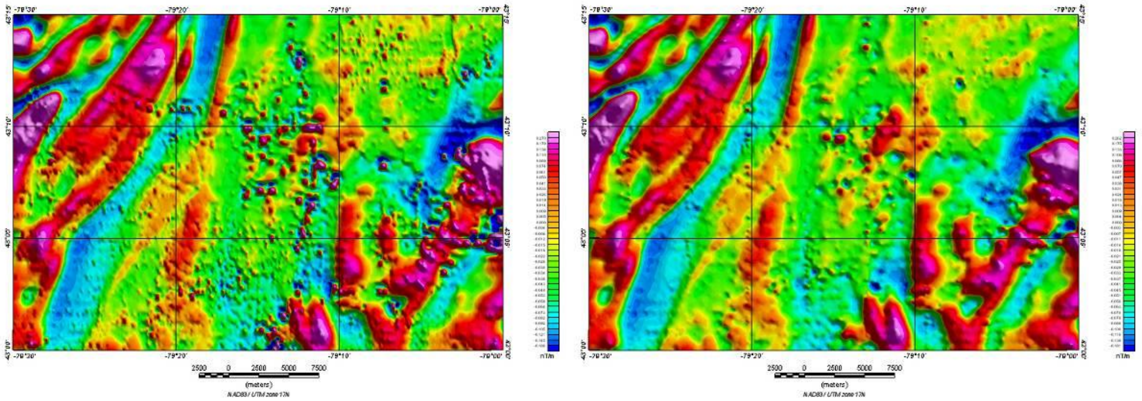
3.7 Post-processing – Other

3.7.1 Micro-levelling

Micro-levelling (Minty, 1991) is a method of isolating and removing low amplitude anomalies parallel to the flight line direction. The purpose of this process is to eliminate tie-line levelling issues and base level corrections not removed during the levelling procedure. Modern well-levelled surveys do not need micro-levelling; in fact the first and second vertical derivatives can be calculated without having to use any low-pass filtering. Micro-levelling is used to improve surveys flown before the advent of GPS navigation, modern data processing techniques and quality assurance/control.

3.7.2 Removal of cultural anomalies

Cultural anomalies are normally not removed from GSC survey data. This is particularly true of surveys flown north of N60^{o} where cultural anomalies are minimal. Cultural anomalies have been removed, by painstaking examination of flight path video and manual editing of magnetic profiles, in only one case: the Ontario-New York aeromagnetic survey of flown in 1999. Figure 24 presents examples of the magnetic data with and without cultural editing. In recent surveys, cultural editing is limited to removal of magnetic effects due to transient sources eg. trains, boats, etc.

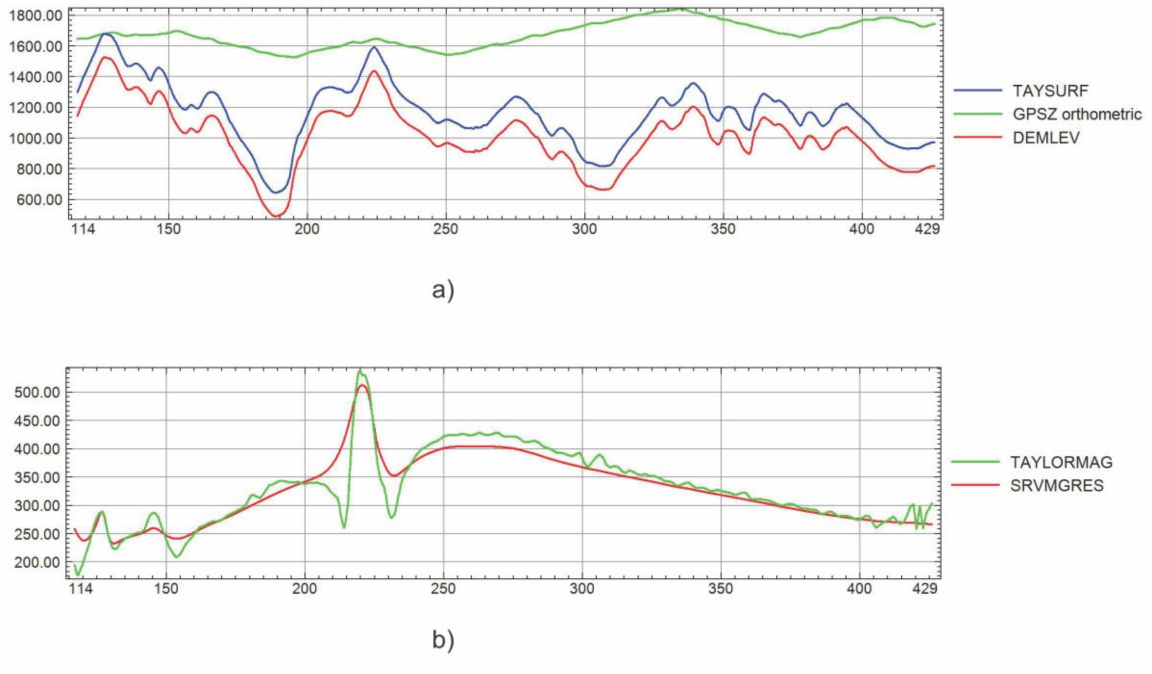


a) b)

Figure 24. a) First vertical derivative b) First vertical derivative, cultural anomalies removed. Ontario-New York Aeromagnetic Survey, 1999.

3.7.3 Draping to constant height above topography

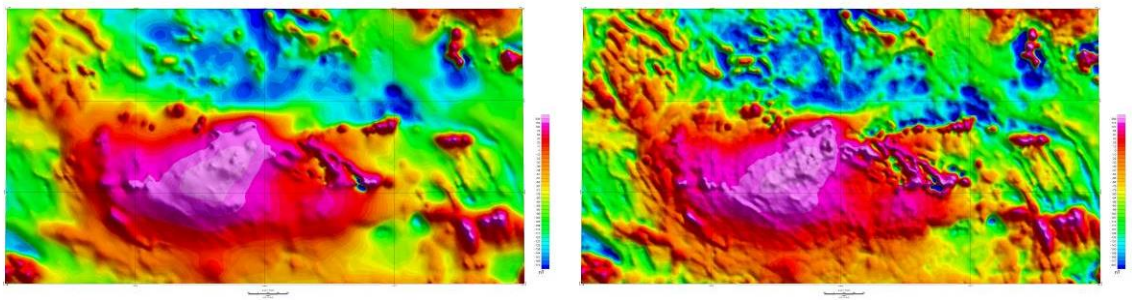
Terrain clearances of fixed-wing surveys in areas of rugged terrain are increased as a result of the aircraft's limited climb and descent rate (5%). The actual mean terrain clearance of a survey may be significantly higher than the nominal terrain clearance. As a result, measured magnetic anomalies may be of lower amplitude and greater wavelength than anticipated at the nominal terrain clearance (Fig. 25a). This causes obvious magnetic pattern contrasts when such surveys are merged with helicopter-borne surveys or surveys flown over less rugged terrain. The magnetic intensities at the nominal terrain clearance can be approximated using a Taylor series expansion (Pilkington and Thurston, 2001). In practice, the measured magnetic intensity is corrected by adding terms based on increasing orders of vertical derivatives multiplied by the height difference to the power of the derivative, all divided by the factorial of the power (Fig. 25b). Usually, only two terms are required as the contribution from the third vertical derivative is minimal. Figure 26 below represents the residual total magnetic field of the Nisling River, YT aeromagnetic survey as acquired (a) and with Taylor series expansion corrections (b).



a)

b)

Figure 25. a) GPS aircraft altitude (green), topography (red), and the nominal terrain clearance (blue) and b) the residual total magnetic field (red) and the enhanced (Taylor series expansion) residual total magnetic field.



a) b)

Figure 26. a) Residual Total Magnetic Field and b) Enhanced (Taylor series expansion) Residual Total Magnetic Field, McQuesten survey, YT.

4. Archiving and Publication

All GSC aeromagnetic surveys are published as GSC Open File maps and the corresponding grids and profile data are made available online for free download.

Once the Technical Authority has accepted the compiled and levelled survey data, GSC Open File maps are generated. The residual total magnetic field and either the first or second vertical derivative are usually published. The order of the vertical derivative is a reflection of the local geology. A low dynamic range of the magnetic intensity can dictate a higher order derivative. These maps are generated in-house or by the survey contractor. The maps must meet the specifications of the Earth Science Sector Scientific Editor.

The Technical Authority delivers the data, map products, ancillary data and survey documentation to the Database Administrator (DBA). The DBA ensures that database standards are maintained including channel naming conventions, metadata generation, and data and map product verification. The data and metadata are delivered through GeoGratis (http://www.geogratis.gc.ca/) and the Geoscience Data Repository for Geophysical Data (http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php). Technical reports are scanned and linked to metadata. Deliverables from the contractor, including ancillary data, are archived in triplicate and stored at separate locations.

The GSC has maintained an aeromagnetic database in several forms over the years. The current database consists of a PostgreSQL metadata database linked to directories containing profile and gridded data. The profile and gridded data are stored in Geosoft .GDB and .GRD format, respectively. The data directories are catalogued with a Geosoft Data Access Protocol (DAP) server. This allows free, online data access in several ways.

The DAP server is the basis of the Geoscience Data Repository for Geophysical Data. This application allows users to search for data by latitude and longitude extents, NTS map sheet, data type, and dataset name keyword. As a result of a search, users are presented with a list of surveys. Each survey contains profile and gridded datasets. Each dataset contains a link to the GSC aeromagnetic metadata database to provide all the ancillary information required about a survey to process or interpret the data. Datasets can be selected and downloaded with user-specified projections and formats.

As the data are stored in a DAP server, they are readily accessible from Geosoft's Oasis montaj software. Geosoft provides free Viewer software with access to the GSC's DAP server. Once a map area is defined in the software, magnetic data can be downloaded and automatically inserted into the map. Geosoft makes this service available to other software through downloadable plugins for ArcGIS, MapInfo and ER Mapper Viewer.

A third form of access is the DAP's built-in WMS server (http://wms.agg.nrcan.gc.ca/wms2/wms2.aspx?request=GetCapabilities). This allows users to see georeferenced images of gridded datasets, as well as profile data locations. The WMS server can be referenced in viewers, such as Google Earth and DAPPLE.

5. Conclusion

The survey design, quality assurance, and quality control processes describe the framework under which the GSC provides its partners with high quality aeromagnetic data acquisition processing and final outputs. The pre-qualification of contractors is the first step in the contracting process that ensures that the work will be performed by suitably equipped, capable and experienced personnel. Quality is assured through existing contract specifications which include setting minimum requirements for equipment and personnel as well as establishing the required tests and calibrations. Quality is controlled by highly qualified and experienced Technical Authorities through the inspection of production data and processed data products.

Every survey presents different challenges. Canada has a diverse landscape with significant variations in geology, topography, weather, and daylight from place-to-place and from season-to-season. The targets of surveys, from bedrock mineral deposits to groundwater aquifers, offer special challenges. Variations in instrumentation, platform, processes, software, and personnel can affect data quality as well. Diligent and vigilant application of the scientific method at each stage of the survey, from concept to final delivery, is required to minimize, identify, and overcome the unique challenges of each survey.

The quality assurance/quality control process of aeromagnetic surveying is strengthened by lessons learned from each survey through changes in survey design, contract specification, and quality control processes.

References

Dow, J.M., Neilan, R.E. and Rizos, C., 2009. The international GNSS Service in a changing landscape of Global navigation satellite systems. Journal of Geodesy, 83, p. 191-198, DOI: 10.1007/s00190-008-0300-3.

Dumont, R., 2005. Drape DTM 1.0: software to calculate a smooth drape surface for an airborne geophysical survey: Geological Survey of Canada, Open File 4937.

Kouba, J., 2009. A Guide to using International GNSS Service (IGS products, Natural Resources Canada, http://igscb.jpl.nasa.gov/components/usage.html (accessed Feb. 2014).

Kouba, J. and Héroux, P., 2001. GPS Precise Point Positioning Using IGS Orbit Products.GPS Solutions, **5**, (2), pp.12-28.

Lachapelle, G., 2005. Advanced GPS Theory and Applications, ENGO625 Lecture Notes. Department of Geomatics Engineering, University of Calgary.

Lilley, F.E.M., Hitchman, A.P., and Wang, L.J., 1999. Time-varying effects in magnetic mapping: Amphidromes, doldrums, and induction hazard: Geophysics, **64**, 1720-1729.

Luyendyk, A.P.J., 1997. Processing of airborne magnetic data: AGSO Journal of Australian Geology & Geophysics, **17** (2), 31-38.

McDonald, K.D. and Hegarty C., 2000. Post-Modernization GPS Performance Capabilities, *Proceedings of the IAIN World Congress and the 56th Annual Meeting of The Institute of Navigation*, San Diego, CA, June 2000, pp. 242-249.

Minty, B. R. S., 1991. Simple micro-levelling for aeromagnetic data: Exploration Geophysics, **22** (4), 591-592.

Nabighian, M.N., Grauch, V.J.S., Hansen, R.O., LaFehr, T.R., Li, Y., Peirce, J.W., Phillips, J.D., and Ruder, M.E., 2005. The historical development of the magnetic method in exploration: Geophysics, **70**, 33ND-61ND.

Pilkington M., Thurston J.B., 2001. Draping corrections for aeromagnetic data: line versus grid-based approaches. Exploration Geophysics **32**, 95–101.

Reford, M.S., and Sumner, J.S., 1964. Review article aeromagnetics: Geophysics, **29,** 482-516.

Reid, A. B., 1980. Aeromagnetic survey design: Geophysics, **45**, 973 – 976.

Teskey, D. J., Barlow, R., Hood, P. J., Lefebvre, D., Paterson, N., Reford, M., and Watson, D., 1991. Guide to aeromagnetic specifications and contract: Geological Survey of Canada, Open File 2349.

Teskey, D.J., Hood, P.J., Morley, L.W., Gibb, R.A., Sawatzky, P., Bower, M., and Ready, E.E., 1993. The aeromagnetic survey program of the Geological Survey of Canada: contribution to regional geological mapping and mineral exploration: Canadian Journal of Earth Sciences, **30**, 243-260.

Vallée, M. A., Craven, J., Newitt, L., Keating, P., Dumont, R. and Ferguson, I., 2006. Guidelines for location and use of base station data in aeromagnetic survey processing: SEG, Expanded Abstracts, 25, 933-937.

Weaver, J. T., 1965. Magnetic variations associated with ocean waves and swell, J. Geophys. Res., **70,** (8), 1921–1929.

Yuan, J., Gu, X., Jacob, T. and Schanzer, G., 1990. “Error Correction for Differential GPD with Long Separated Ground Stations and User for Aircraft Landing”. Institute of Guidance and Control. Technical University Braunschweig (Germany).